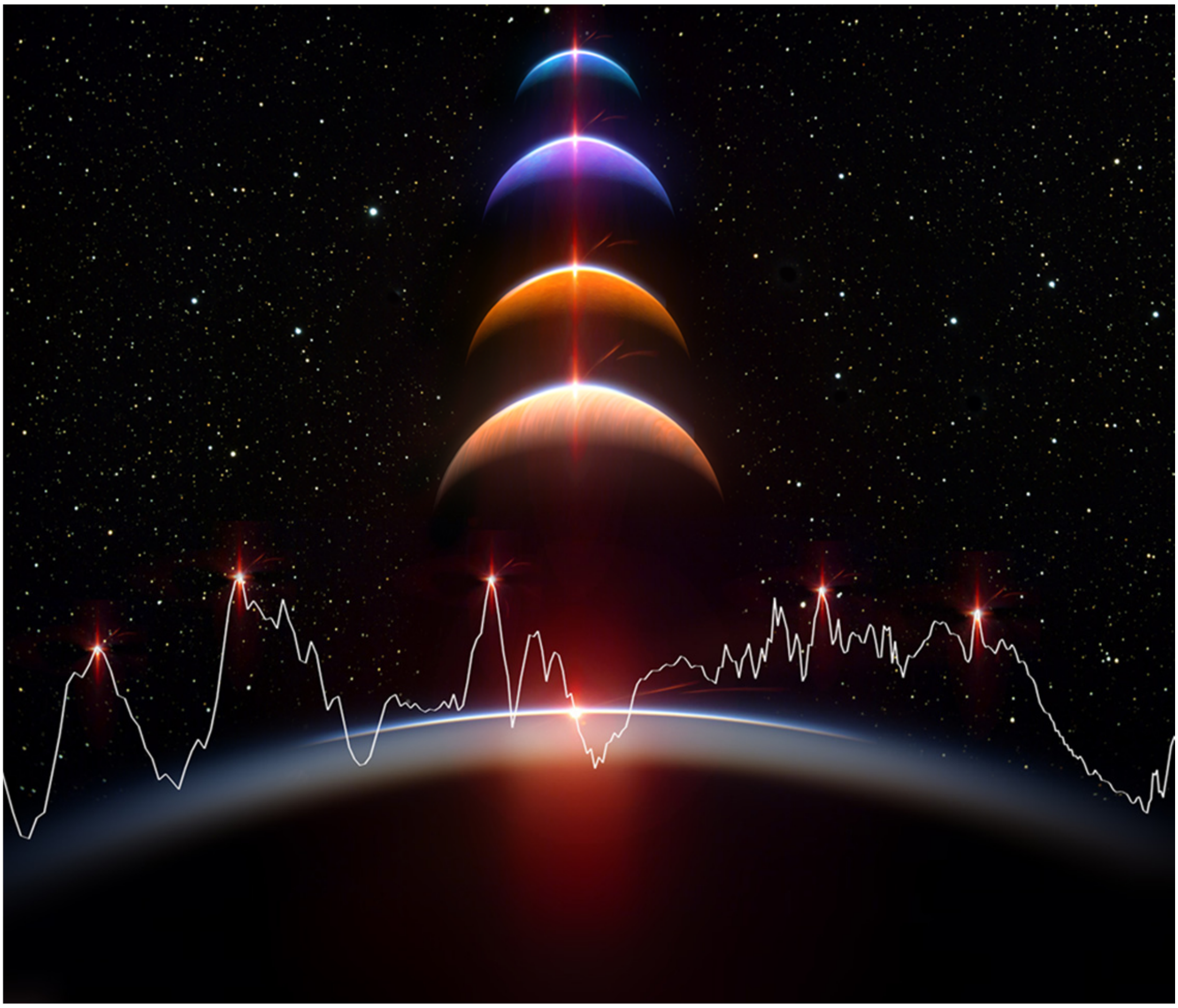
ESA/SRE(2013)2
December 2013

EChO

Exploring the atmospheres of diverse worlds beyond our Solar System



Assessment Study Report

European Space Agency

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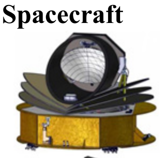
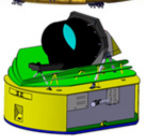
EChO – Exoplanet Characterisation Observatory – Mission Summary	
Key Science Questions to be Addressed	• Why are exoplanets as they are? • What are the causes for the observed diversity? • Can their formation history be traced back from their current composition and evolution? • How does the Solar System work compared to other planetary systems? • Are planets in the Solar System special in any way?
Science Objectives	• Detection of planetary atmospheres, their composition and structure • Determine vertical and horizontal temperature structure and their diurnal and seasonal variations • Identify chemical processes at work (thermochemistry, photochemistry, transport quenching) • Constrain planetary interiors (breaking the radius-mass degeneracy) • Quantify the energy budget (albedo, temperature) • Constrain formation and evolution models (evidence for migration) • Detect secondary atmospheres around terrestrial planets (evolution) • Investigate the impact of stellar and planetary environment on exoplanet properties
EChO Core Survey	• Three-tier survey of 150-300 transiting exoplanets from gas giants to super-Earths, in the very hot to temperate zones of F to M type host stars • Target selection before launch based on ESA science team and community inputs • Chemical Census: statistically complete sample detecting strongest atmospheric molecular features • Origin: retrieval of vertical thermal profiles and abundances of trace gases • Rosetta Stone: high signal-to-noise observations yielding refined molecular abundances, chemical gradients and atmospheric structure; diurnal and seasonal variations; presence of clouds and measurement of albedo • Delivery of a homogeneous catalogue of planetary spectra
EChO Observational Strategy	• Transit and eclipse spectroscopy with broad, instantaneous, and uninterrupted spectra covering all key molecules • High photometric stability on transit timescales • Required SNR obtained by summing a sufficient number of transits or eclipses • Large instantaneous sky coverage
Payload Telescope	• Afocal 3-mirror, off-axis Korsch-like system, 1.5 m x 1 m elliptical M1, unobstructed (effective area 1.13 m^2), diffraction-limited at 3 μm; <3 μm, 80% encircled energy within diameter of 1.6 arcsec.
Payload Instrument	• Highly-integrated broadband spectrometer instrument with modular architecture • Common optical train for all spectrometers and the fine guidance system optical module • Continuous wavelength coverage from 0.4 - 11μm in baseline design • Goal wavelength coverage from 0.4 – 16 μm. • Resolving powers of $\lambda/\Delta\lambda$ >300 below 5 μm, and >30 above 5 μm • Passively cooled MCT detectors at ~40K for FGS and science channels < 5μm • Active Ne JT Cooler provides cooling to ~28K for science channels > 5μm
Spacecraft  	• Launch mass ~ 1.5 tonnes • Dimensions: Ø 3.6 m x 2.6 m. Designs from the two industrial studies shown to the left. • Pointing requirements: coarse APE of 10 arcsec (3σ); fine APE of 1 arcsec (3σ); PDE of 20 milli-arcseconds (1σ) over 90s to 10hrs; RPE of 50 milli-arcsecond over 90s (1σ) • Attitude control system: reaction wheels and cold gas system complemented by a Fine-Guidance System operating in the visible within the AOCS control loop. • Thermal Control System: Passive cooling via 3 V-grooves to ≤ 47 K • Telecommand, Telemetry and Communication: X-band, 35 Gbit of science data per week transmitted with a High Gain Antenna to a 35 m ESTRACK station
Launcher, Orbit, Mission Phases and Operations	• Launch from Kourou on a Soyuz-Fregat MT into L2 orbit in 2024 (possible option of launch in 2022) • Nominal mission duration 4 years (goal 6 years) • MOC at ESOC, SOC at ESAC, Instrument Operations and Science Data Centre distributed across consortium members states • 14 hours ground contact/week: 2x2 hours for telecommand uplink and science downlink, remainder for determination of orbital parameters
Data Policy	• Short proprietary period after nominal SNR is reached, shrinking to 1 month after 3 years

Foreword

The concept of a mission devoted to atmospheric characterization of planets through transit spectroscopy was first considered in Europe in 2007, shortly after the DARWIN proposal submitted to ESA for the first Cosmic Vision call for L-class missions was rejected because of scientific and technical immaturity. Following the decision, both ESA (EP-RAT panel – report in October 2010) and the Exoplanetary Community (Blue Dot Team – Barcelona conference in September 2009) started a discussion to define a scientific and technological roadmap for exoplanetary research. Both groups concluded that an intermediate step was needed, both scientifically and technically, before the characterisation of Earth-like planets could be tackled, and recommended a transit spectroscopy mission as a first step to atmospheric characterisation. A short study was undertaken at ESTEC in the context of the ExoPlanet Roadmap Advisory Team mandate: the THESIS mission concept, the subject of one of the EP-RAT white papers, was studied under the name ESM (Exoplanet Spectroscopy Mission). The EChO proposal is directly derived from this study.

EChO, the **E**xoplanet **Ch**aracterisation **O**bservatory, was proposed as a medium class mission candidate in 2010 by a consortium of institutes and universities from ESA member states, in response to the second call for medium class missions in the Cosmic Vision 2015 – 2025 programme. The mission was one of four selected in February 2011 for further study in a Phase 0/A assessment study. Soon after, an ESA study team, and a Science Study team comprising scientists from the consortium and beyond, were assembled, and work began on the EChO assessment study.

In the summer of 2011, an internal ESA pre-assessment study of EChO was undertaken in the Concurrent Design Facility at ESTEC that provided a baseline mission concept for subsequent study. An Invitation to Tender was then released for a 1 year industrial assessment study. Tenders were accepted from Astrium (Toulouse) and TAS-F (Cannes), and the studies started in early 2012. In parallel, a call for Declarations of Interest in Science Instrumentation was issued in autumn 2011 inviting proposals for studies on the science instrumentation that could be provided for EChO, should the mission be selected. Two proposals were received and accepted, with both studies starting at the end of 2011.

Following lessons learned from the M1/M2 mission selection process, the Science Programme Committee (SPC) recommended that the assessment phase be extended to include selection of the science instruments, thus reaching the full Phase A level for the entire space segment. With this new approach, an announcement of opportunity for the provision of the scientific payload, including science ground segment elements, was issued in September 2012, and the parallel industrial studies were extended by a further 6 months to July 2013. A single consortium, led by the UK, was subsequently selected by the SPC in February 2013 to provide the scientific payload; this consortium has evolved since the selection with new members joining to participate in the instrument provision.

The industrial and scientific payload studies concluded in July and September, 2013, respectively. The industrial studies included a review of the mission requirements, the technical design and analysis of the S/C and a programmatic analysis of the mission. Similar tasks were performed as well for the instrument by the instrument study team including an end-to-end performance simulation of the complete system. Dedicated iterations were done in conjunction with both industrial and instrument studies to harmonise the interfaces between the S/C and the instrument, and to consolidate the instrument accommodation. At the time of writing, the results of these studies are under review in the Preliminary Requirements Review.

An EChO Community workshop was held at ESTEC in early July 2013 to share the results of the Assessment Phase study with the Astronomical and Solar System Sciences Communities, and to inform them of the capabilities of the EChO mission.

This study report presents a summary of the very large body of work that has been undertaken on the EChO mission at scientific and technical levels over the 32-month period of the EChO pre-assessment and assessment phase. As such, it represents the contributions of a large number of parties (ESA, industry, institutes and universities from many ESA member states), encompassing a very large number of people, Over this same period the number of confirmed exoplanets has increased from 500 to over 1000, providing an ever-more tantalising prospect of exploring the diversity of planets beyond our own Solar System.

EChO Science Study Team – December 2013

Authorship, acknowledgements

This report has been prepared by the *EChO* Team listed below:

ESA Science Study Team (SST)		
Name	*Affiliation*	*City, Country*
Pierre Drossart	Observatoire de Paris	Paris, France
Paul Hartogh (from April 2013)	Max-Planck-Institut für Sonnensystemforschung	Katlenburg-Lindau, Germany
Oliver Krause (until March 2013)	Max-Planck-Institut für Astronomie	Heidelberg, Germany
Christophe Lovis	Geneva Observatory, University of Geneva	Geneva, Switzerland
Giusi Micela	INAF: Osservatorio Astronomico di Palermo G.S. Vaiana	Palermo, Italy
Marc Ollivier	Institut d'Astrophysique Spatiale and Observatoire de Paris	Orsay/Paris, France
Ignasi Ribas	Institut d'Estudis Espacials de Catalunya (ICE-CSIC)	Barcelona, Spain
Ignas Snellen	Leiden University	Leiden, The Netherlands
Bruce Swinyard	RAL Space, STFC/ University College London	Didcot/London, UK
Giovanna Tinetti	University College London	London, UK
Instrument Consortium Leadership		
Name	*Affiliation*	*City, Country*
Giovanna Tinetti (Consortium PI)	University College London	London, UK
Paul Eccleston (Consortium Project Manager)	RAL Space, STFC	Didcot, Oxon, UK
Marc Ollivier (Instrument Scientist)	Institut d'Astrophysique Spatiale and Observatoire de Paris	Orsay/Paris, France

The ESA Team supporting the activities comprises:

ESA study team		
Ludovic Puig (Study Manager)	ESTEC	Noordwjik, The Netherlands
Kate Isaak (Study Scientist)		
Martin Linder (Payload Manager)		
Roger Walker (System Engineer)		
Isabel Escudero Sanz (Optical Engineer)		
Pierre-Elie Crouzet (Detector Expert)		
Matthias Ehle (Science Ops Study Manager)	ESAC	Madrid, Spain
Rainer Timm/Jutta Hübner (Mission Operations)	ESOC	Darmstadt, Germany
Bram de Vogeleer (Mission Analysis Expert)		
ESA Coordinator		
Luigi Colangeli	ESA	Noordwjik, The Netherlands

The Co-PIs of the payload instrument consortium team are:

Co-PI's – Jean-Philippe Beaulieu, Institut d'Astrophysique de Paris, France; Denis Grodent, Université de Liège, Belgium**;** Manuel Guedel, University of Vienna, Austria**;** Paul Hartogh, Max Planck Sonnnensystem, Germany**;** David Luz, Universidade de Lisboa, Portugal**;** Giusi Micela, INAF – Osservatorio Astronomico di Palermo, Italy**;** Hans Ulrik Nørgaard-Nielsen, DSRI, Denmark**;** Tom Ray, Dublin Institute for Advanced Studies, Ireland**;** Ignasi Ribas, CSIC – ICE, Spain; Hans Rickman, Space Research Centre, Polish Academy of Science, Poland / Department of Physics and Astronomy at Uppsala University**;** Avri Selig, SRON Netherlands Institute for Space Research, Netherlands**;** Mark Swain, NASA Jet Propulsion Laboratory, USA**;** Bruce Swinyard, RAL Space / University College London, UK**.**

A detailed list of consortium members and their roles is included in Appendix A.

The instrument consortium is supported by their respective national funding agencies. The team would like to thank the agencies for their support during the assessment study.

We would like to thank the ESA CDF team, as well as TEC and SRE directorate colleagues who provided support during the course of the study.

The sections on mission design were compiled by the ESA study team based on the outputs of the industrial studies, led by:

- Astrium France and Astrium UK
- TAS France and TAS Italy

The graphics of the title page were prepared by ESA/C.Carreau and ATG medialab

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1 Executive summary

ESA's Cosmic Vision for 2015-2025 sets ambitious goals for European leadership in Space Science and Astrophysics. Amongst the noble objectives set out for the programme is to investigate *what are the conditions for planet formation and the emergence of life?* Indeed, the discovery of even the precursor environment for life on worlds other than our own could not be of higher interest both to scientists and the public who fund their activities. It is in this context that the Exoplanet Characterisation Observatory – EChO – has been under study for the past two and a half years.

Primary Science Objectives – The discovery of over a thousand exoplanets has revealed an unexpectedly diverse planet population. We see gas giants in few-day orbits, whole multi-planet systems within the orbit of Mercury, and new populations of planets with masses between that of the Earth and Neptune – all unknown in the Solar System. Observations to date have shown that our Solar System is certainly not representative of the general population of planets in our Milky Way. The key science questions that urgently need addressing by EChO are therefore: *What are exoplanets made of? Why are planets as they are? How do planetary systems work and what causes the exceptional diversity observed as compared to the Solar System*? The EChO mission will take up the challenge to explain this diversity in terms of formation, evolution, internal structure and planet and atmospheric composition. This requires in-depth spectroscopic knowledge of the atmospheres of a large and well-defined planet sample for which precise physical, chemical and dynamical information can be obtained.

In order to fulfil this ambitious scientific programme EChO is designed as a dedicated survey mission for transit and eclipse spectroscopy capable of observing a large, diverse and well-defined planet sample within its four-year mission lifetime. The transit and eclipse spectroscopy method, whereby the signal from the star and planet are differentiated using knowledge of the planetary ephemerides, allows us to measure atmospheric signals from the planet at levels of at least 10^{-4} relative to the star. This can only be achieved in conjunction with a carefully designed stable payload and satellite platform. It is also necessary to provide a broad instantaneous wavelength coverage to detect as many molecular species as possible, to probe the thermal structure of the planetary atmospheres and to correct for the contaminating effects of the stellar photosphere. This requires wavelength coverage of at least 0.55 to 11 μm with a goal of covering from 0.4 to 16 μm. Only modest spectral resolving power is needed, with R~300 for wavelengths less than 5 μm and R~30 for wavelengths greater than this. The transit spectroscopy technique means that no spatial resolution is required. A telescope collecting area of about 1 m^2 is sufficiently large to achieve the necessary spectro-photometric precision: in practice the telescope will be 1.13 m^2, diffraction limited at 3 μm. Placing the satellite at L2 provides a cold and stable thermal environment as well as a large field of regard to allow efficient time-critical observation of targets randomly distributed over the sky. EChO is designed, without compromise, to achieve a single goal: exoplanet spectroscopy. The spectral coverage and signal-to-noise to be achieved by EChO, thanks to its high stability and dedicated design, will be a game changer by allowing atmospheric compositions to be measured with unparalleled exactness: at least a factor 10 more precise and a factor 10 to 1000 more accurate than current observations. This will enable the detection of molecular abundances three orders of magnitude lower than currently possible. We anticipate at least a fourfold increase from the handful of molecules detected to date. Combining these data with estimates of planetary bulk compositions from accurate measurements of their radii and masses will allow degeneracies associated with planetary interior modelling to be broken, giving unique insight into the interior structure and elemental abundances of these alien worlds.

EChO will allow scientists to study exoplanets both as a population and as individuals. The mission will target super-Earths, Neptune-like, and Jupiter-like planets, in the very hot to temperate zones (planet temperatures of 300 K - 3000 K) of F to M-type host stars. The EChO core science will be delivered by a three-tier survey. The EChO *Chemical Census*: This is a broad survey of one- to a few-hundred exoplanets, which allows us to explore the chemical diversity of the exoplanet population as a whole. The EChO *Origin*: This is a deep survey of a subsample of a few tens of exoplanets for which significantly higher signal to noise spectra will be obtained to explain the origin of the exoplanet diversity (such as formation mechanisms, chemical processes, atmospheric escape). The EChO *Rosetta Stones*: This is an ultra-high accuracy survey targeting more than ten exoplanets. These will be the bright "benchmark" cases for which a large number of measurements will be taken to explore temporal variations, and to obtain two and three dimensional spatial information on the atmospheric conditions through eclipse-mapping techniques.

We show that if EChO were launched today, the exoplanets currently observed are sufficient to provide a large and diverse sample. The Chemical Census survey would contain would consist of over 150 exoplanets with a range of planetary sizes, temperatures, orbital parameters and stellar host properties. Additionally, over the next three to five years, several new ground- and space-based transit photometric surveys and missions will come on-line (e.g. NGTS, CHEOPS, TESS), which will specifically focus on finding bright, nearby systems. The current rapid rate of discovery will allow the target list to be further optimised in the years prior to EChOs launch.

Complementarity with other facilities – Launching EChO in the 2022-2024 timeframe, i.e. as the M3 mission, is timely and critical since it will enable EChO to be operational in conjunction with the James Webb Space Telescope (JWST) as well as the ground-based European Extremely Large Telescope (E-ELT). Having all three facilities operational at the same time will enable the very best use of the particular strengths of each of them and will be both highly complementary and mutually beneficial. For instance, JWST can provide high spectral resolution measurements for a small number of the most-optimal target planets, over narrow wavelength ranges. The E-ELT can provide targeted observations for some planets at ultra-high spectral resolution at specific wavelengths. The role of EChO will be crucial, as the only facility able to provide the broad picture through a large sample of targets observed with instantaneous coverage of the full wavelength range of interest. The three facilities together will enable transformational science in the field of exoplanets.

Mission and Payload Design – EChO will be launched on board the Soyuz launcher from Kourou (FR) between 2022 and 2024, into a direct transfer leading to a large amplitude orbit around the Sun-Earth L2 point. This science operations orbit provides a stable environment, along with a large instantaneous field of regard, both of which are key to allowing EChO to meet its science objectives. The spacecraft is designed in a modular way, with a service module and a payload module that can be procured and tested in parallel. The payload module hosts the telescope, the science instrument and the Fine Guidance System (FGS) that is needed to achieve the fine pointing stability required. It also contains the thermal shield assembly, which is used to passively cool the complete telescope assembly to ≤ 47 K, to minimise the thermal background fluctuations and the noise of the focal plane detectors. As the observation technique makes use of the combined light from a single exoplanet - host star system, there is no need for a large field of view, nor for angular resolution. The selected telescope is a three mirror elliptical off-axis Korsch design providing an effective collecting area of 1.131 m^2 and a small collimated input beam to the instrument. The service module contains all the units required to operate the spacecraft and maintain the payload nominal operating conditions. The spacecraft has a wet mass of about 1.6 t and a power generation capability of about 1 kW.

EChO will carry a single, high stability, spectrometer instrument. The baseline instrument for EChO is a modular, three-channel, highly integrated, common field of view, spectrometer that covers the full EChO required wavelength range of 0.55 µm to 11.0 µm. The baseline design includes the goal wavelength extension to 0.4 µm while an optional LWIR channel extends the range to the goal wavelength of 16.0 µm. Also included in the payload instrument is the FGS, necessary to provide closed-loop feedback to the high stability spacecraft pointing. The required spectral resolving powers of 300 or 30 are achieved or exceeded throughout the band. The baseline design largely uses technologies with a high degree of technical maturity.

The spectrometer channels share a common field of view, with the spectral division achieved using a dichroic chain operating in long-pass mode. The core science channels are a cross-dispersed spectrometer VNIR module covering from 0.4 to ~2.5 µm, a grism spectrometer SWIR module covering from 2.5 to 5.3 µm, and a prism spectrometer MWIR module covering from 5.3 to 11 µm. All science modules and the FGS are accommodated on a common Instrument Optical Bench. The payload instrumentation operates passively cooled at ~45K with a dedicated instrument radiator for cooling the FGS, VNIR and SWIR detectors to 40 K. An Active Cooler System based on a Neon Joule-Thomson Cooler provides the additional cooling to ~28 K which is required for the longer wavelength channels.

EChO Performance – The performance of EChO has been assessed using computational models based on two approaches. The first approach taken is based on a static radiometric model that takes the required performance figures for the payload to 'size' the mission. This model has been used to calculate the number of transit/occultation revisits necessary to achieve a specified SNR and the revisits possible during a given mission lifetime. The second approach is to construct a model that simulates the actual performance of the mission as realistically as possible. This end-to-end simulation is fully dynamic and accounts for the major systematic influences on the performance such as pointing jitter, internal thermal radiation sources, detector dark current and noise etc. Both models have been used to calculate the observation duration on the targets needed to fulfill the EChO mission described above. We find that a nominal mission lifetime of four years is sufficient to fulfill the science requirements and a mission of six years will fulfill the more ambitious EChO goals. The use of separate performance models with similar results gives confidence that the mission can be undertaken as planned and will result in a revolution in understanding the origin and evolution of planets.

Mission operations and ground segment – Responsibility for, and provision of, the EChO ground segment is split between ESA and a payload consortium-provided, nationally-funded, Instrument Operations and Science Data Centre (IOSDC). The ground segment and operations infrastructure for the Mission Operations Centre (MOC) will be set up at the European Space Operations Centre in Darmstadt, and the EChO Science Operations Centre (SOC) set up at the European Space Astronomy Centre in Madrid which will also host the EChO Science Archive. Lower-level data products will be produced at the SOC using processing pipelines based on algorithms and software models that will be developed by the IOSDC, and delivered to the SOC. Final exoplanet spectra will be produced using state-of-the-art tools developed at the IOSDC, and delivered to the SOC for ingestion into the EChO Science Archive. The pipeline, as well as scripts with critical parameters used to generate the final exoplanet spectra, will be available to users to enable reprocessing of data taken with EChO. Long-term mission planning, which will include scheduling of the time-critical observations of EChO target transits, will be a joint MOC-SOC-IOSDC activity with scientific guidance provided by the EChO Science Team.

Access to EChO data – The nominal duration of the EChO mission is four years. The exoplanet target list for the EChO core programme will be finalised before launch. Input will be solicited from the Scientific Community, with involvement of the Advisory structure. A fraction of the mission lifetime (~10-15%) will be devoted to an open time program to which the Scientific Community will be able to subscribe through announcements of opportunity, with proposal evaluation to be undertaken by a Time Allocation Committee made up of scientists with expertise covering scientific disciplines appropriate to EChO. EChO will have an open data policy, enabling rapid access by the Community to the high-quality exoplanet spectra that the core survey will deliver. Data will be released on a target-by-target basis, once the proprietary period has expired. During the first year of the mission the proprietary period will be 6 months from the date on which the last observation needed to achieve the signal-to-noise requirements for a given mode, for an individual target, is taken; this interval will reduce as the mission progresses, and a more complete understanding of the instrument characteristics, calibration needs and data processing/correction for systematics is gained. In Year Two the period will be reduced to three months, dropping to one month by Year Three and onwards.

Management – ESA will provide the spacecraft and the telescope assembly through industrial contractor(s) that will be selected through responses to Invitations To Tender. An Instrument Consortium funded by national agencies will provide the EChO instrument including the Fine Guidance Sensor. Payload (telescope and instrument) procurement and tests are on the critical path but current schedule analysis shows that the mission is compatible with a launch in late-2022 / mid-2023. An early start to procurement activities will be considered in order to demonstrate key performances and to minimise risk to the schedule.

Our knowledge of planets other than the eight "classical" Solar System bodies is in its infancy. We have discovered hundreds of planets orbiting stars other than our own, and yet we know little or nothing about their chemistry, formation and evolution. Planetary science therefore stands at the threshold of a revolution in our knowledge and understanding of our place in the Universe: just how special are the Earth and our Solar System? It is only by undertaking a comprehensive chemical survey of the exoplanet population that we can hope to answer this critical question and EChO is the only planned facility that can provide the necessary observations.

The time is right for a change to mankind's Solar-centric cosmogony similar to that provided by Galileo: EChO will be the mission that will start the paradigm shift.

2 Scientific objectives

2.1 Introduction

Current exoplanet observations demonstrate that the Solar System is NOT the paradigm in our Galaxy: one of the outstanding questions of modern astrophysics is to understand why.

EChO will address this fundamental question by measuring directly the chemical components of hundred(s) of exoplanetary atmospheres. The atmospheric composition will be used as a tracer of the formation and evolution history of the planets.

2.1.1 Exoplanets today

Roughly 400 years ago, Galileo's observations of the Jovian moons sealed the Copernican Revolution, and the Earth was no longer considered the centre of the Universe [*Sidereus Nuncius,* 1610]. We are now poised to extend this revolution to the Solar System. The detection and characterisation of exoplanets force the Sun and its cohorts to abdicate from their privileged position as the archetype of a planetary system.

Recent exoplanet discoveries have profoundly changed our understanding of the formation, structure, and composition of planets. Current statistics show that planets are common; data from the Kepler Mission and microlensing surveys indicate that the majority of stars have planets [Fressin et al. 2013; Cassan et al., 2012]. Detected planets range in size from sub-Earths to larger than Jupiter (Figure 2-1). Unlike the Solar System, the distribution of planetary radii appears continuous [Batalha et al., 2013], with no gap between 2 to 4 Earth radii. That is, there appears to be no distinct transition from telluric planets, with a thin, if any, secondary atmosphere, to the gaseous and icy giants, which retain a substantial amount of hydrogen and helium accreted from the protoplanetary disk.

The orbital characteristics among the over 1000 exoplanets detected also do not follow the Solar System trend, with small rocky bodies orbiting close to a G star and giant gas planets orbiting further out, in roughly circular orbits. Instead giant planets can be found within 1/10 the semi-major axis of Mercury. Planets can orbit host stars with an eccentricity well above 0.9 (e.g. HD 80606b), comparable to Halley's comet. Planets can orbit two mother stars (e.g. Kepler-34b, Kepler-35b, and Kepler-38b). This is not an oddity any more. Planetary systems appear much more diverse than expected. The Solar System template, well explained by our current understanding of planetary formation and evolution, does not seem to be generally applicable.

The range of orbital parameters and stellar hosts translate into planetary temperatures that span two orders of magnitude (Figure 2-1). This range of temperatures arises from the range of planet-star proximities, where a year can be less than 6 Earth-hours (e.g. KOI-55b), or over 450 Earth-years (e.g. HR 8799b), and host star temperatures, which can range from 2200 K to 14000 K. Conditions not witnessed in the Solar System lead to exotic planets whose compositions we can only speculate about. Currently, we can only guess that the extraordinarily hot and rocky planets CoRoT-7b, Kepler-10b, Kepler-78b and 55 Cnc-e sport silicate compounds in the gaseous and liquid phases [Léger et al., 2011, Rouan et al., 2011]. "Ocean planets" that have densities in between those of giant and rocky planets [Léger et al., 2004, Grasset et al., 2009] and effective temperatures between the triple and critical temperatures of water, i.e. between 273 and 647 K (e.g. GJ 1214b) may have large water-rich atmospheres. The diversity of currently detected exoplanets not only extends the regime of known conditions, it indicates environments completely alien to the Solar System.

Observations demonstrate that the Solar System is NOT the paradigm in our Galaxy: one of the outstanding questions of modern astrophysics is to understand why.

Over the past two decades, primary transit and radial velocity measurements have determined the sizes and masses of exoplanets, thereby yielding constraints on the bulk composition of exoplanets. The missions ESA-Cheops and NASA-TESS will increase by a factor of five the number of planets for which we have an accurate measurement of mass and radius. While measurements of the masses and radii of planetary systems have revealed the great diversity of planets and of the systems in which planets originate and evolve, these investigations generate a host of important questions:

(i) *What are the planets' core to atmospheric composition relationships*? The planetary density alone does not provide unique solutions. The degeneracy is higher for super-earths and small Neptunes [Valencia et al., 2013]. As an example, it must be noted that a silicate-rich planet surrounded by a very thick atmosphere could have the same mass and radius as an ice-rich planet without an atmosphere [Adams et al., 2008].

(ii) *Why are many of the known transiting gaseous planets larger than expected*? These planets are larger than expected even considering that they could be coreless hydrogen-helium planets [Bodenheimer et al. 2001, Guillot et al. 2006]. There is missing physics that needs to be identified.

(iii) *For the gaseous planets, are elements heavier than hydrogen and helium kept inside a central core or distributed inside the planet?* The distribution of heavy elements influences how they cool [Guillot 2005, Baraffe et al. 2008] and is crucial in the context of formation scenarios [Lissauer & Stevenson 2007].

(iv) *How do the diverse conditions witnessed in planetary systems dictate the atmospheric composition*? An understanding of the processes that steer planetary composition bears on our ability to extrapolate to the whole galaxy, and perhaps universe, what we will learn in the solar neighbourhood.

(v) *How does the large range of insolation, planetary spin, orbital elements and compositions in these diverse planetary systems affect the atmospheric dynamics?* This has direct consequences for our ability to predict the evolution of these planets [Cho et al., 2003, 2008].

(vi) *Are planets around low mass, active stars able to keep their atmospheres*? This question is relevant e.g. to the study habitability, as given the meagre energy output of M dwarfs, their habitable zones are located much closer to the primary than those of more massive stars (e.g.~ 0.03 AU for stars weighting one tenth of the Sun) [Lammer et al., 2013].

We cannot fully understand the atmospheres and interiors of these varied planetary systems by way of analogy with the Solar System, nor from mass and radii measurements alone. As shown by the historical investigations of planets in our own Solar System, these questions are best addressed through spectroscopic measurements. However as shown by the historical path taken in astronomy, a large sample and range of planetary atmospheres are needed to place the Solar System in an astronomical context.

Spectroscopic measurements of a large sample of planetary atmospheres will divulge their atmospheric chemistry, dynamics, and interior structure, which can be used to trace back to planetary formation and evolution.

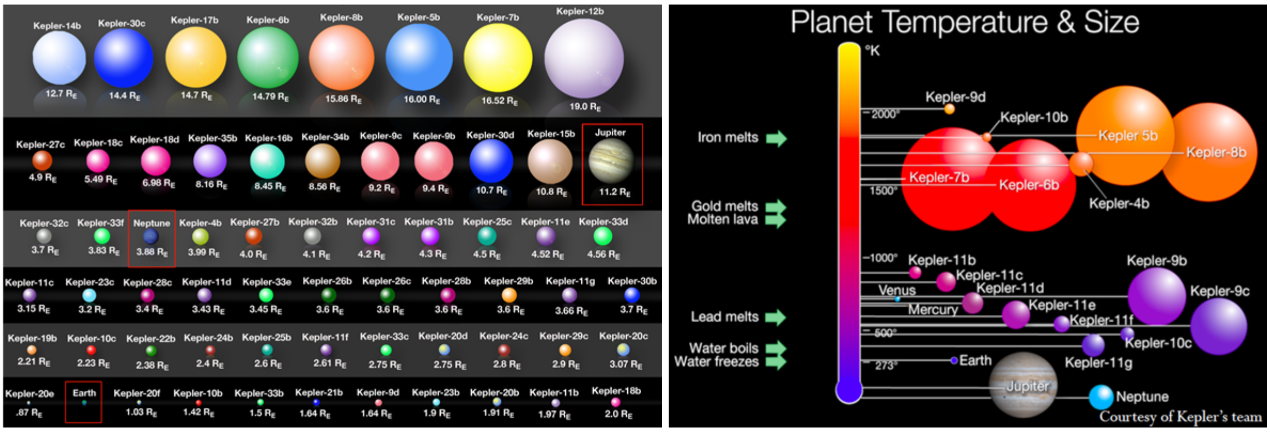


Figure 2-1: Two snapshots of NASA-Kepler planets (courtesy of the Kepler team, see also [Batalha et al., 2013]. Left: Distribution of exoplanetary radii suggesting a continuous distribution from sub-Earths to super-Jupiters. Right: Exoplanetary temperatures, the range spans two orders of magnitude.

In the past decade, pioneering results have been obtained using transit spectroscopy with Hubble, Spitzer and ground-based facilities, enabling the detection of a few of the most abundant ionic, atomic and molecular species and to constrain the planet's thermal structure [e.g. Charbonneau et al., 2002; Vidal-Madjiar et al., 2003; Knutson et al., 2007; Swain et al., 2008; Linsky et al., 2010; Snellen et al., 2010; Majeau et al., 2012]. The infrared range, in particular, offers the possibility of probing the neutral atmospheres of exoplanets. In the IR the spectral features are more intense and broader than in the visible [Tinetti et al., 2007b] and less perturbed by clouds, hence easier to detect. On a large scale, the IR transit and eclipse spectra of hot-Jupiters seem to be dominated by the signature of water vapour [Barman 2007, Beaulieu et al. 2010; Berta et al., 2012; Burrows et al. 2007, Charbonneau et al. 2008; Crouzet et al., 2012; Deming et al., 2013; Grillmair et al. 2008; Swain et al., 2008, 2009; Tinetti et al. 2007, 2010], whereas warm Neptunes, such as GJ 436b and

GJ 3470b, are expected to be methane-rich [Beaulieu et al. 2011; Fukui et al. 2013]. The analysis of GJ 436b cannot be considered conclusive, though, given the activity of the star [Knutson et al. 2011] and the lack of spectroscopic data; only photometric data, often recorded at different times, are available for this target [Stevenson et al., 2010].

Despite these early successes, the data available are still too sparse to provide a consistent interpretation, or any meaningful classification of the planets analysed. The degeneracy of solutions embedded in the current transit observations [Swain et al., 2009; Madhusudhan and Seager, 2009; Lee et al., 2012] inhibits any attempt to estimate the elemental abundances. New and better quality data are needed for this purpose. For instance, recent observations of the transiting hot-Jupiter Wasp-12b have been interpreted using an atmosphere abundant in CO and deficient in H_2O, hinting at an atmospheric C/O ratio > 1, in contrast to the stellar value of C/O=0.54 [Madhusudhan et al., 2011]. This interpretation was challenged by later observations [Cowan et al., 2012]. The analysis of the transmission and day-side spectra for the transiting 6.5 M_{Earth} super-Earth GJ 1214b suggests a metal-rich atmosphere [Bean et al. 2010, Berta et al., 2012], in agreement with the general expectation that low mass planets will be well-endowed with heavy elements. The derived carbon chemistry mixing ratios are consistent with chemical models that assume a heavy element abundance enhanced above solar by a factor > 50 [Moses et al., 2013].

Although these and other data pertaining to extrasolar planet atmospheres are tantalising, uncertainties originating in the relatively low signal to noise ratio, narrow-band spectra and sparsity of the data, mean that definitive conclusions concerning atmospheric abundances cannot be made today. The data do not allow one to discriminate between different formation and evolution scenarios for the observed planets.

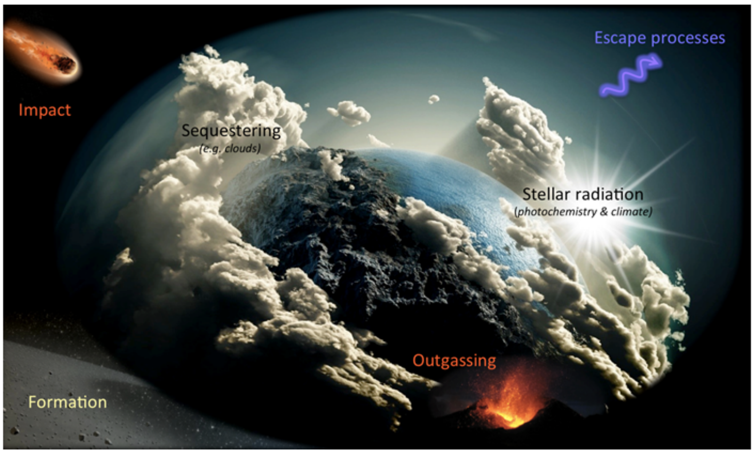


Figure 2-2: Key physical processes influencing the composition and structure of a planetary atmosphere. While the analysis of a single planet cannot establish the relative impact of all these processes on the atmosphere, by expanding observations to a large number (~ 150 to 300) of very diverse exoplanets, we can use the information obtained to disentangle the various effects.

The spectral coverage and stability to be achieved by EChO will be a game changer, allowing atmospheric compositions to be measured with unparalleled exactness: statistically speaking, at least a factor 10 more precisely and a factor 10 to 1000 more accurately than current observations. This will enable the detection of molecular abundances three orders of magnitude smaller than currently possible. We anticipate at least a fourfold increase from the handful of molecules currently detected today. Each of these molecules tells us a story, and having access to a larger number means understanding aspects of these exotic planets that are today completely ignored. Combining these data with estimates of planetary bulk compositions from accurate measurements of their radii and masses will allow degeneracies associated with planetary interior modelling to be broken [Adams et al 2008, Valencia et al., 2013], giving unique insight into the interior structure and elemental abundances of these alien worlds.

2.1.1.1 Major classes of planetary atmospheres: what should we expect?

EChO will address the fundamental questions "*what are exoplanets made of?*" and "*how do planets form and evolve*?" through measurement of bulk and atmospheric chemical composition. EChO will target super-Earths, Neptune-like and Jupiter-like exoplanets around stars of various masses. These broad classes of planets are all expected to have very different formation, migration and evolution histories that will be imprinted on their atmospheric and bulk chemical signatures. Many theoretical studies have tried to understand and model the various processes controlling the formation and evolution of planetary atmospheres, with some success for the Solar System. However, such atmospheric evolution models need confirmation and tight calibrations from observations. In Figure 2-3 we show the predicted bulk atmospheric compositions as a function of planetary temperature and mass [Leconte, Forget & Lammer, 2013; Forget et al., 2013] and we briefly describe in the following paragraphs the possible origins of the various scenarios.

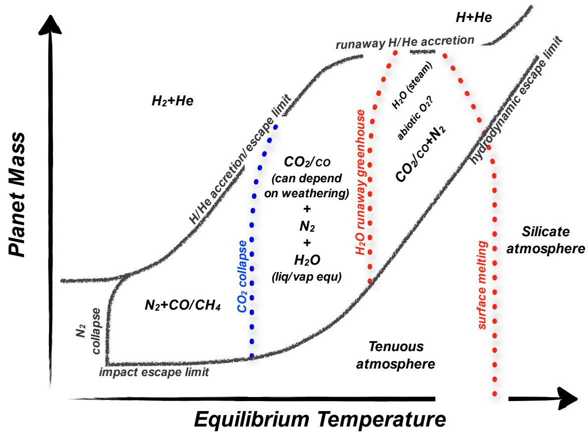


Figure 2-3: Schematic summary of the various classes of atmospheres as predicted by Leconte, Forget & Lammer [2013]. Only the expected dominant species are indicated, other (trace) gases will be present. Each line represents a transition from one regime to another, but these "transitions" need tight calibrations from observations. Interestingly, many atmospheric-regime transitions occur in the high-mass/high-temperature, domain which is exactly where EChO is most sensitive.

H/He dominated – Hydrogen and helium being the lightest elements and the first to be accreted, they can most easily escape. The occurrence of H/He dominated atmospheres should thus be limited to objects more massive than the Earth. Because giant planets play a pivotal role in shaping planetary systems [e.g. Nelson, Turrini, Barbieri, TN], determining precisely their internal structure and composition is essential to understand how planets form. In particular, the abundances of high-Z elements compared to the stellar values and the relative ratios of the different elements (e.g. C, N, S) represent a window on the past histories of the extrasolar systems hosting the observed planets.

In the Solar System, none of the terrestrial planetary bodies managed to accrete or keep their primordial H/He envelope, not even the coldest ones which are less prone to escape. The presence of a large fraction of primordial nebular gas in the atmosphere of warm to cold planets above a few Earth masses should be fairly common. However, being more massive than that is by no means a sufficient condition: some objects have a bulk density similar to the Earth up to 8-10 M_{Earth}. Possibly planets forming on closer orbits can accrete less nebular gas, or hotter planets exhibit higher escape rates.

Thin silicate atmospheres – For very hot or low mass objects (lower part of Figure 2-3), the escape of the lightest elements at the top of the atmosphere is a very efficient process. Bodies in this part of the diagram are thus expected to have tenuous atmospheres, if any. Among the most extreme examples, some rocky exoplanets, such as CoRoT- 7 b or 55 Cnc e, are so close to their host star that the temperatures reached on the dayside are sufficient to melt the surface itself! As a result some elements, usually referred to as "refractory", become more volatile and can form a thin "silicate" atmosphere [Léger et al., 2011]. Depending on the composition of the crust, the most abundant species should be, by decreasing abundance, Na, K, O_2, O and SiO. In addition, silicate clouds could form.

$H_2O/CO_2/N_2$ atmospheres – In current formation models, if the planet is formed much closer to –or even beyond– the snow line[1], the water content of the planetesimals could be significantly large and tens to thousands of Earth oceans of water could be accreted. This suggests the existence of a vast population of planets with deep oceans (aqua-planets) or whose bulk composition is dominated by water (Ocean planets [Léger et al., 2004]). Another source of volatiles are the planetesimals that accrete to form the bulk of the

[1] *Snow line*: distance from a central protostar at which ice grains can form. This occurs at temperatures of ~ 150-170 K

planet itself. These will be the major sources of carbon compounds (mainly CO_2 and possibly CH_4), water (especially if they formed beyond the snow line), and, to a lesser extent, N_2/NH_3 and other trace gases.

In the case of rocky planets, their low gravity field leads to H_2 escape. On a much longer, geological timescale, the volatiles that remained trapped in the mantle during the solidification can be released through volcanic outgassing. Along with H_2O and CO_2, this process can bring trace gases to the surface, such as H_2S, SO_2, CH_4, NH_3, HF, H_2, CO and noble gases. On Earth and Mars, there is strong evidence that this secondary outgassing has played a major role in shaping the present atmosphere [Forget et al., 2013].

Water vapour has a tendency to escape, as illustrated by the atmospheric evolutions of Mars and Venus. This certainly happened to the terrestrial planets in our Solar System. In Venus' and Mars' atmospheres the D/H ratio is between 5 and 200 times the Solar ratio, suggesting water on the surface was lost through time. Also their global atmospheric compositions, with mostly CO_2 and a few percent of N_2, are similar. The surface pressures and temperatures are very different, though, as a result of their different initial masses and evolutions. The Earth is an exception in the Solar System, with the conversion of CO_2 in the water oceans to $CaCO_3$ and the large abundance of O_2 (and its photodissociation product O_3) as a consequence of the appearance of life [Lovelock 1965; Rye & Holland 1998].

Within each of the above planet taxonomic classes, the stochastic nature of planetary formation and evolution will be reflected in significant variations in the measured abundances, providing important information about the diverse pathways experienced by planets that reside within the same broad class. Our Solar System only provides one or two particular examples, if any, for each of the aforementioned planetary classes. It is therefore impossible to understand the "big picture" on this basis. This is where extrasolar planets are an invaluable asset. This means that, even before being able to characterise an Earth-like planet in the habitable zone, we need to be able to characterise giant planets' atmospheres and exotic terrestrial planet atmospheres in key regimes that are mostly unheard of in the Solar System. Thus, the first observations of exoplanet atmospheres, whatever they show, will allow us to make a leap forward in our understanding of planetary formation, chemistry, evolution, climates and, therefore, in our estimation of the likelihood of life elsewhere in the universe. Only a dedicated transit spectroscopy mission can tackle such an issue.

2.1.2 The case for a dedicated mission from space

EChO is designed as a dedicated survey mission for transit and eclipse spectroscopy capable of observing a large, diverse and well-defined planet sample within its four year mission lifetime. The transit and eclipse spectroscopy method, whereby the signal from the star and planet are differentiated using knowledge of the planetary ephemerides, allows us to measure atmospheric signals from the planet at levels of at least 10^{-4} relative to the star. This can only be achieved in conjunction with a carefully designed stable payload and satellite platform. It is also necessary to have a broad instantaneous wavelength coverage to detect as many molecular species as possible, to probe the thermal structure of the planetary atmospheres and to correct for the contaminating effects of the stellar photosphere. This requires wavelength coverage from at least 0.55 to 11 μm with a goal of covering from 0.4 to 16 μm. Only modest spectral resolving power is needed, with R~300 for wavelengths less than 5 μm and R~30 for wavelengths greater than this. The transit spectroscopy technique means that no angular resolution is required. A telescope collecting area of about 1 m^2 is sufficiently large to achieve the necessary spectro-photometric precision: in practice the telescope will be 1.13 m^2, diffraction limited at 3 μm. Placing the satellite at L2 provides a cold and stable thermal environment as well as a large field of regard to allow efficient time-critical observation of targets randomly distributed over the sky. **EChO is designed, without compromise, to achieve a single goal: exoplanet spectroscopy.**

It is important to realise that a statistically significant number of observations must be made in order to fully test models and understand which are the relevant physical parameters. This requires observations of a large sample of objects, generally on long timescales, which can only be done with a dedicated instrument like EChO, rather than with multi-purpose telescopes such as JWST or the ELT. Another significant aspect of the search relates to the possibility to discover unexpected "Rosetta Stone" objects, i.e. objects that definitively confirm or inform theories. This requires wide searches that are again possible only through dedicated instruments. **EChO will allow planetary science to expand beyond the narrow boundaries of our Solar System to encompass our Galaxy. EChO will enable a paradigm shift by identifying the main constituents of hundred(s) of exoplanets in various mass/temperature regimes, we will be looking no**

longer at individual cases but at populations. Such a universal view is critical if we truly want to understand the processes of planet formation and evolution and how they behave in various environments.

2.2 EChO Science Objectives

In this section we explain the key science objectives addressed by EChO, and how we will tackle these questions through the observations provided by EChO, combined with modeling tools and laboratory data.

2.2.1 Key science questions addressed by EChO

EChO will address the following fundamental questions:

- Why are exoplanets as they are?
- What are the causes for the observed diversity?
- Can their formation and evolution history be traced back from their current composition?

EChO will provide spectroscopic information on the atmospheres of a large, select sample of exoplanets allowing the compositions, temperature (including profile), size and variability to be determined at a level never previously attempted. This information will be used to address a wide range of key scientific questions relative to exoplanets:

- *What are they made of?*
- *Do they have an atmosphere?*
- *What is the energy budget?*
- *How were they formed?*
- *Did they migrate and if so how?*
- *How do they evolve?*
- *How are they affected by starlight, stellar winds and other time-dependent processes?*
- *How do weather conditions vary with time?*

And of course:

- *Do any of the planets observed have habitable conditions?*

These objectives are in line with ESAs Cosmic Vision themes: "What are the conditions for planet formation and the emergence of life? How does the Solar System work?". These objectives, tailored for gaseous and terrestrial planets, are detailed in the next sections and summarised in Figure 2-4 and Table 2-1.

In the next sections we also explain how we will tackle these questions through the observations provided by EChO, combined with modelling tools and auxiliary information from laboratory data and preparatory observations with other facilities prior to the EChO launch.

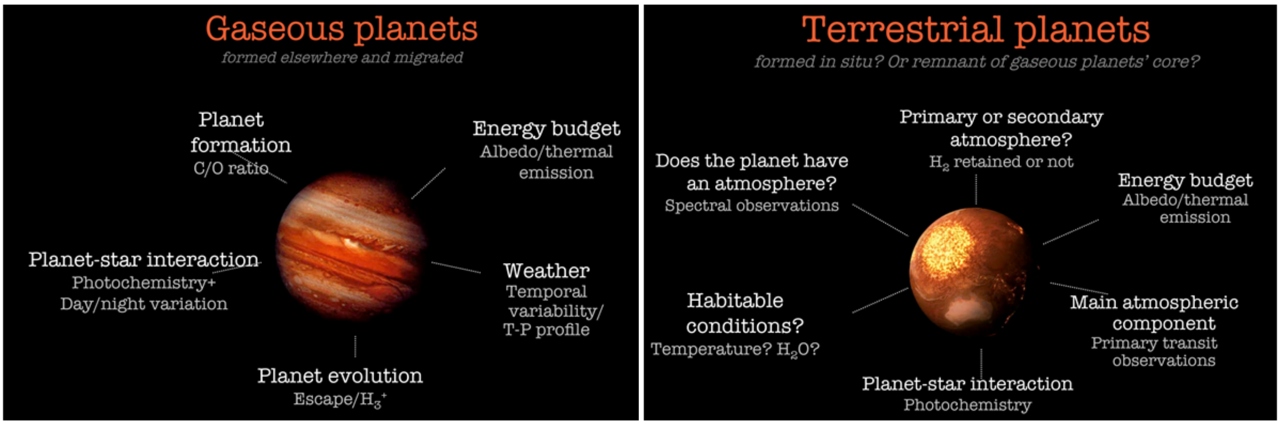


Figure 2-4: Key questions for gaseous & rocky planets that will be addressed by EChO [Tinetti et al. 2013].

Planet type	Scientific question	Observable	Observational strategy	Survey Type
Gaseous planets	Energy budget	Incoming and outgoing radiation	Stellar flux + planetary albedo and thermal emission with VIS and IR photometry during eclipses	Chemical Census
	Planetary interior	a. Density b. Hints from atmospheric composition?	a. Transit spectra b. Transit and eclipse spectra	Chemical Census
	Chemical processes: Thermochemistry? Transport + quenching? Photochemistry?	a. Chemistry of planets around different stars & different temperatures b. Day/night chemical variations c. Vertical mixing ratios	a. Transit and eclipse spectra of planets around different stars & different temps. b. Relative abundances of minor molecular species (HCN, NH_3, C_2H_2, etc.)	Origin
	Dynamics: Time scale of horizontal and vertical mixing	a. Vertical thermal profile b. Horizontal gradients c. Diurnal variations d. Temporal variability, seasonal/inter-seasonal variations…	a. IR eclipse spectra b. IR Eclipse mapping c. IR orbital phase lightcurves d. Repeated observations & use of chemical species as tracers (e.g. CH_4, NH_3, CO_2, and HCN etc)	Origin & Rosetta Stone
	Formation: Core accretion or gravitation instability?	a. Planetary density b. C/O ratio	a. Transit + mass from Radiative Velocity b. Relative abundances of carbon versus oxygen-bearing molecules	Origin
	Migration: Any evidence of the initial conditions?	a. Comparison star/planet metallicity (C/O, O/H, C/H..) b. Chemistry of planets around different stars.	a. Relative abundances of carbon-, oxygen-, bearing molecules, etc. b. Transit and eclipse spectra of planets around different stars & different T	Origin
	2D and 3D maps	Exoplanet image at multiple wavelengths	Ingress and egress eclipse spectra Orbital phase-curves	Rosetta Stone
	Evolution: Escape processes	H_3^+ detection and ionospheric temperature measurement	Transit and eclipse spectra	Origin
Terrestrial planets	Energy budget Albedo & Temperature	Incoming and outgoing radiation	Stellar flux + planetary albedo and thermal emission with VIS and IR photometry during eclipses	Chemical Census
	Is there an atmosphere?	Featureless spectrum or not	Transit spectra at multiple wl (IR in particular) to constrain the scale height	Chemical Census
	Primary or secondary atmosphere?	Hydrogen rich atmosphere?	Transit spectra at multiple wl (IR in particular) to constrain the scale height	Chemical Census
	Main atmospheric component	Scale height	Transit spectra at multiple wl (IR in particular) to constrain the scale height	Chemical Census
	Planetary interior	a. Density b. Hints from atmospheric composition?	a. Transit + mass from Radial Velocity b. Transit and eclipse spectra	Chemical Census

	Formation: Formed in situ? Migrated? Core of a giant planet? Frequency of Venus-like, Mercury-like, Ocean planets..	a. Density b. Is there an atmosphere? c. Primary (H_2-rich) or secondary atmosphere? d. Atmospheric composition?	a. Transit + mass from Radial Velocity b. c. d. Transit and eclipse spectra	Chemical Census
Temperate terrestrial planets	Habitability	a. Temperature b. Chemical composition (H_2O? CO_2? O_3?)	a. Eclipse measurements b. Transit or eclipse measurements at low resolution.	Challenging, need a late M star, bright in the IR

Table 2-1: Traceability matrix

2.2.2 Terrestrial planets

Several scenarios may occur for the formation and evolution of terrestrial-type planets (see 2.1.1.1 and Figure 2-3). To start with, these objects could have formed *in situ*, or have moved from their original location because of dynamical interaction with other bodies, or they could be remnant cores of more gaseous objects which have migrated in. Having a lower mass, their atmospheres could have evolved quite dramatically from the initial composition, with lighter molecules, such as hydrogen, escaping more easily. Impacts with other bodies, such as asteroids or comets, or volcanic activity might also alter significantly the composition of the primordial atmosphere. **EChO will confirm the presence or absence of a substantial atmosphere enveloping terrestrial planets. On top of this, EChO will detect the composition of their atmospheres (CO_2, SiO, H_2O etc.), so we can test the validity of current theoretical predictions (section 2.1.1.1 and Figure 2-3)**. In particular:

(i) A very thick atmosphere (several Earth masses) of heavy gas, such as carbon dioxide, ammonia, water vapour or nitrogen, is not realistic because it requires amounts of nitrogen, carbon, and oxygen with respect to silicon much higher than all the stellar ratios detected so far. **If EChO detects an atmosphere which is not made of hydrogen and helium, the planet is almost certainly from the terrestrial family, which means that the thickness of the atmosphere is negligible with respect to the planetary radius.** In that case, theoretical works provided by many authors in the last decade [Léger et al., 2004; Valencia et al., 2007; Adams et al., 2008; Grasset et al., 2009] can be fully exploited in order to characterise the inner structure of the planet (Figure 2-5).

(ii) If an object exhibits a radius that is bigger than that of a pure water world (water being the least dense, most abundant material except for H/He) of the same mass, this tells us that at least a few % of the total mass of the planet is made of low density species, most likely H_2 and He. The fact that many objects less massive than Neptune are in this regime shows that it is possible to accrete a large fraction of gas down to 2-3M_{Earth}, the mass of Kepler-11 f (Figure 2-5). **EChO will test this hypothesis by probing the presence of H_2, He and H_2O through primary transit spectroscopy (Figure 2-5 bottom).**

(iii) A major motivation for exoplanet characterisation is to understand the probability of occurrence of habitable worlds, i.e. suitable for surface liquid water. **While EChO may reveal the habitability of one or more planets – temperate super-Earths around nearby M-dwarfs are within reach of EChOs capabilities – its major contribution to this topic will result from its capability to detect the presence of atmospheres on many terrestrial planets even outside the habitable zone, and, in many cases, characterise them.**

2.2.3 The intermediate family (Neptunes and Sub-Neptunes)

Planets with masses between the gas giants and the small solid terrestrial planets are key to understanding the formation of planetary systems [Guillot, Stixrude TN]. The existence of these intermediate planets close to their star, as found by radial velocity and transit surveys (see Figure 2-1), already highlights the shortcomings of current theoretical models.

(i) Standard planet formation scenarios predict that embryos of sufficient mass (typically above 5 M_{Earth}) should retain some of the primordial hydrogen and helium from the protoplanetary disc. **With EChO**

primary transit spectroscopic measurements, we will probe which planets possess a hydrogen helium atmosphere and directly test the conditions for planet formation (Figure 2-5).

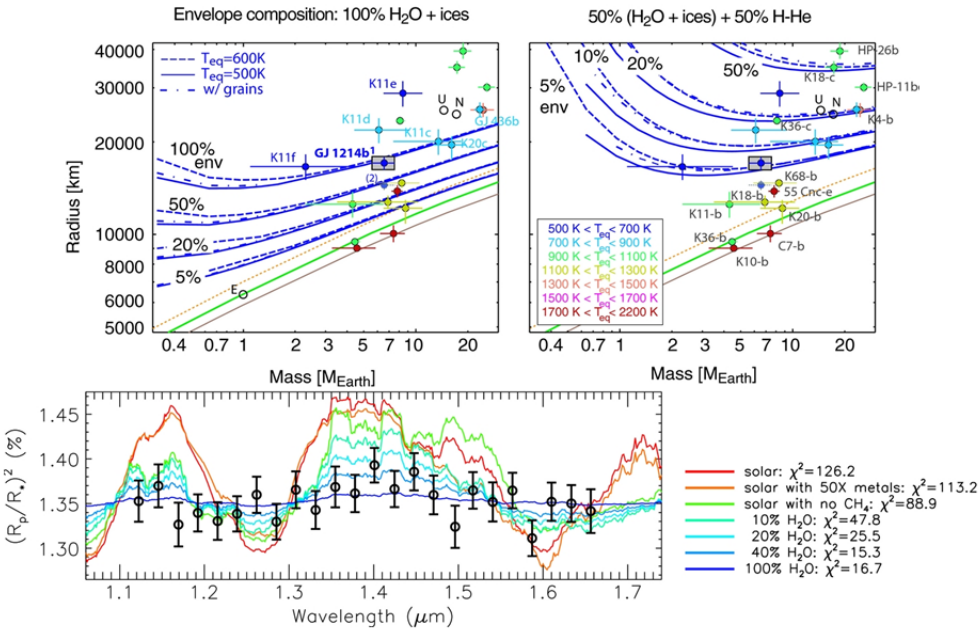


Figure 2-5: Top: Mass–radius relationships for Ocean planets and sub-Neptunes [Valencia et al., 2013]. Two envelope compositions are shown: 100% H_2O/ices (left) and with 50% (H_2O/ices)+50% H/He (right): they both explain the M-R of the planets identified with blue dots. Planets are colour coded by their equilibrium temperature. Uranus and Neptune are shown for reference. The mass–radius relationships for three rocky compositions are shown: an Earth-like composition (green), a Mercury-like (brown), and one voided of iron completely (pure magnesium-silicate oxides, (orange)). Bottom: WFC3 transmission spectrum of GJ1214b (black circles with error bars) compared to theoretical models (colourful lines) with a variety of compositions [Berta et al., 2012]. The amplitude of features in the model transmission spectra increases as the mean molecular weight decreases between a 100% water atmosphere (μ = 18 amu) and a solar composition atmosphere (μ = 2.36 amu). This property allows discrimination of the various compositions.

(ii) The only two intermediate solar system planets that we can characterise –Uranus and Neptune– are significantly enriched in heavy elements, in the form of methane. The reason for this enrichment is unclear: is it due to upward mixing, early or late delivery of planetesimals? **EChO will allow these measurements in many planets thereby providing observations that are crucial to constrain models (see Section 2.4).**

(iii) We do not know where to put the limits between solid, liquid and fluid (gaseous) planets. **While EChO will not directly measure the phase of a planet as a whole, the determination of its size and of the composition of its atmosphere will be key to determining whether its interior is solid, partially liquid, or gaseous**.

2.2.4 Gaseous exoplanets

Giant planets are mostly made of hydrogen and helium and are expected to be always in gaseous form. Unlike solid planets, they are relatively compressible and the progressive loss of heat acquired during their formation is accompanied by a global contraction. Inferring their internal composition thus amounts to understanding how they cool. The dominance of hydrogen and helium implies that the degeneracy in composition (i.e. uncertainty on the mixture of ices/rocks/iron) is much less pronounced than for solid planets, so that the relevant question concerns the amounts of all elements other than hydrogen and helium, i.e. heavy elements, that are present. A fundamental question is by how much are these atmospheres enriched in heavy elements compared to their parent star. Such information will be critical to:

- understand the early stage of planet and atmosphere formation during the nebular phase and the immediately following few millions years [Nelson, Turrini, Barbieri, TN]
- test the effectiveness of the physical processes directly responsible of their evolution.

We detail below the outstanding questions to be addressed by EChO and how this will be achieved.

2.2.4.1 The chemistry of gaseous planets' atmospheres

(i) *The relative importance of thermochemical equilibrium, photochemistry, and transport-induced quenching* in controlling the atmospheric composition of gaseous exoplanets largely depends on the thermal structure of the planets. Transport-induced quenching of disequilibrium species allows species present in the deep atmosphere of a planet to be transported upward in regions where they should be unstable, on a time scale shorter than the chemical destruction time. The disequilibrium species are then "quenched" at observationally accessible atmospheric levels. In the solar system, this is the case, in particular, for CO in the giant planets, as well as PH_3 and GeH_4 in Jupiter and Saturn [Encrenaz, 2004]. Another key process, which also leads to the production of disequilibrium species, is photochemistry [Liang et al., 2003, Zahnle et al., 2009]. The energy delivered by the absorption of stellar UV radiation can break chemical bonds and lead to the formation of new species. In the solar system, the photochemistry of methane is responsible for the presence of numerous hydrocarbons in the giant planets. In the case of highly irradiated hot Jupiters, these disequilibrium species are expected to be important. In some of the known hot-Jupiters, CH_4 and NH_3 are expected to be enhanced with respect to their equilibrium abundances due to vertical transport-induced quenching. These species should be dissociated by photochemistry at higher altitude, leading, in particular, to the formation of C_2H_2 and HCN on the day side [Moses et al., 2011, Venot et al., 2012]. **EChO will address these open questions, by deriving the abundances of both key and minor molecular species, with mixing ratios down to 10^{-5} to 10^{-7} (Figure 2-6), temporally and spatially resolved in the case of very bright sources (see 2.3.2.3).**

(ii) *Chemistry and dynamics* are often entangled. Agúndez et al. [2012] showed that for hot-Jupiters, for instance, the molecules CO, H_2O, and N_2 and H_2 show a uniform abundance with height and longitude, even including the contributions of horizontal or vertical mixing. For these molecules it is, therefore, of no relevance whether horizontal or vertical quenching dominates. The vertical abundance profile of the other major molecules CH_4, NH_3, CO_2, and HCN shows, conversely, important differences when calculated with the horizontal and vertical mixing. **EChO spectroscopy of the dayside and terminator regions will provide a key observational test which will constrain the range of models of the thermochemical, photochemical and transport processes shaping the composition and vertical structure of these atmospheres.**

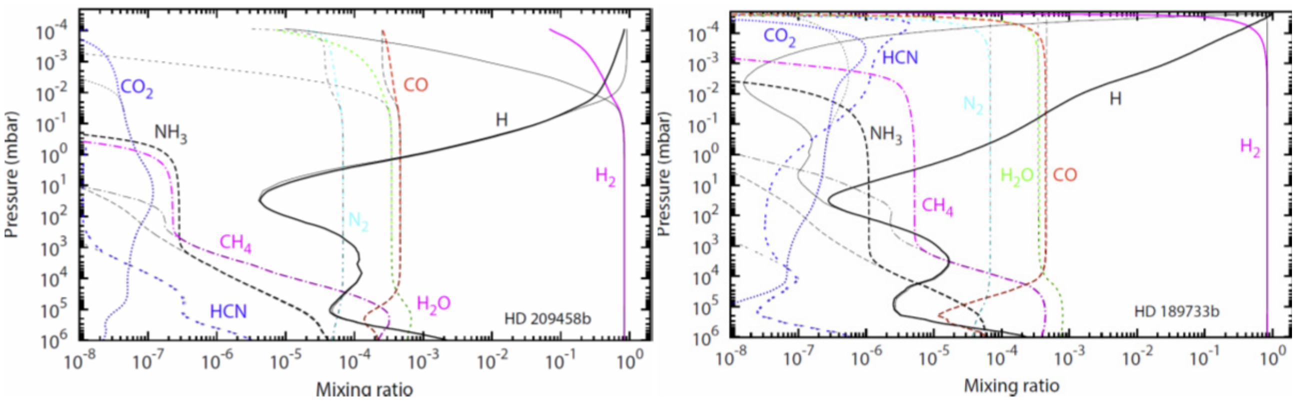


Figure 2-6: Steady-state composition of HD 209458b (left) and HD 189733b (right) calculated with a non-equilibrium model (colour lines), compared to the thermodynamic equilibrium (thin black lines) [Venot et al. 2012]. For HD 189733b, one can clearly notice the higher sensitivity to photolyses and vertical mixing, with all species affected, except the main reservoirs, H_2, H_2O, CO, and N_2. Since the atmosphere of HD209458b is hotter, it is mostly regulated by thermochemistry. The EChO Origin survey will measure these differences by deriving the abundances of both key and minor molecular species, with moles down to 10^{-5} to 10^{-7}(see Section 2.3.2.2 and 2.3.2.3).

2.2.4.2 Energy Budget: heating and cooling processes

(i) *Albedo and thermal emission*. The spectrum of a planet is composed mainly of reflected stellar light and thermal emission from the planet; the measurement of the energy balance is an essential parameter in quantifying the energy source of dynamical activity of the planet (stellar versus internal sources). The Voyager observations of the Giant Planets in the Solar System have allowed an accurate determination of the energy budget by measuring the Bond albedo of the planets (Jupiter: Hanel et al., 1981; Saturn: Hanel et al, 1983; Uranus: Pearl et al, 1990; Neptune: Pearl & Conrath, 1991). **EChO will extend these methods to exoplanets: the reliable determination of the spectrum in reflected versus thermal range will provide a powerful tool for classifying the dynamical activity of exoplanets.**

(ii) *Non-LTE emissions.* Observation of the CH_4 non-LTE emission on the day side of Jupiter and Saturn [Encrenaz et al, 1996; de Graauw et al, 1997] is an important new tool to sound the upper atmosphere levels around the homopause (typically at the microbar level for giant planets), the layer separating the turbulent mixing from the diffusive layers where molecules are separated by their molecular weight. This region is an important transition between the internal dynamical activity and the radiatively controlled upper atmosphere, with the breaking of gravity waves identified as an important mechanism responsible of high thermospheric temperatures in giant planets. Swain et al. (2010) and Waldmann et al. (2011) identified an unexpected spectral feature near 3.25 μm in the atmosphere of the hot-Jupiter HD 189733b which was found to be inconsistent with LTE conditions holding at pressures typically sampled by infrared measurements. They proposed that this feature results from non-LTE emission by CH_4, indicating that non-LTE effects may need to be considered, as is also the case in our Solar System for Jupiter and Saturn as well as for Titan. **We intend to specifically address this question for many hot gaseous planets with EChO, making use of the improved observing conditions from space.**

(iii) H_3^+ emission (3.5-4.1 μm). Of particular interest in the study of gas giants within our own solar system are emissions of H_3^+ which dominate their emissions between 3 and 4 μm. H_3^+ is a powerful indicator of energy inputs into the upper atmosphere of Jupiter [Maillard et al., 2012], suggesting a possible significance in exoplanet atmospheres as well. As the unique atmospheric constituent radiatively active, H_3^+ plays a major role in regulating the ionospheric temperature. Simulations by Yelle [2004] and Koskinen et al. [2007] have investigated the importance of H_3^+ as a constituent and IR emitter in exoplanet atmospheres. A finding of these calculations is that close-orbiting extrasolar planets (0.2 AU) may host relatively small abundances only of H_3^+ due to the efficient dissociation of H_2, a parent molecule in the creation path of H_3^+. As a result, the detectability of H_3^+ may depend on the distance of the planet from the star. **EChO will test this hypothesis by detecting or setting an upper limit on the H_3^+ abundance in many giant planets.**

(iv) Clouds may modify the albedo and contribute to the green-house effect, therefore their presence can have a non-negligible impact on the atmospheric energy budget. **If present, clouds will be revealed by EChO through transit and eclipse spectroscopy in the VIS-NIR.** Clouds show, in fact, distinctive spectroscopic signatures depending on their particle size, shape and distribution (see Figure 2-7). Current observations with Hubble and MOST have suggested their presence in hot-Jupiters atmospheres [Rowe et al., 2006; Sing et al., 2011].

2.2.4.3 Spatial and temporal variability: weather, climate and exo-cartography

(i) *Temporal variability*: Tidally synchronised and unsynchronised gaseous planets are expected to possess different flow and temperature structures. Unencumbered by complicating factors, such as physical topography and thermal orography, the primary difference will be in the amplitude and variability of the structures. An example is shown in Figure 2-7 for the case of HD 209458b, a synchronised hot-Jupiter. The state-of-the-art, high-resolution simulation shows giant, tropical storms (cyclones) generated by large-amplitude planetary waves near the substellar point. Once formed, the storms move off poleward toward the nightside, carrying with them heat and chemical species, which are observable, and which dissipate to repeat the cycle, in this case, after a few planet rotations [Cho et al., 2003, 2008]. Storms of such size and dynamism are characteristic of synchronized planets, much more so than unsynchronized ones. There are other even more prominent periodicities (e.g., approximately 1.1, 2.1, 4.3, 8.3, 15 and 55 planet rotations), all linked to specific dynamical features. **Through its excellent temporal coverage of individual objects (i.e. tens of repeated observations as part of the Rosetta Stone survey, see Section 2.3.2.2), EChO will be able to distinguish the two types of planets.**

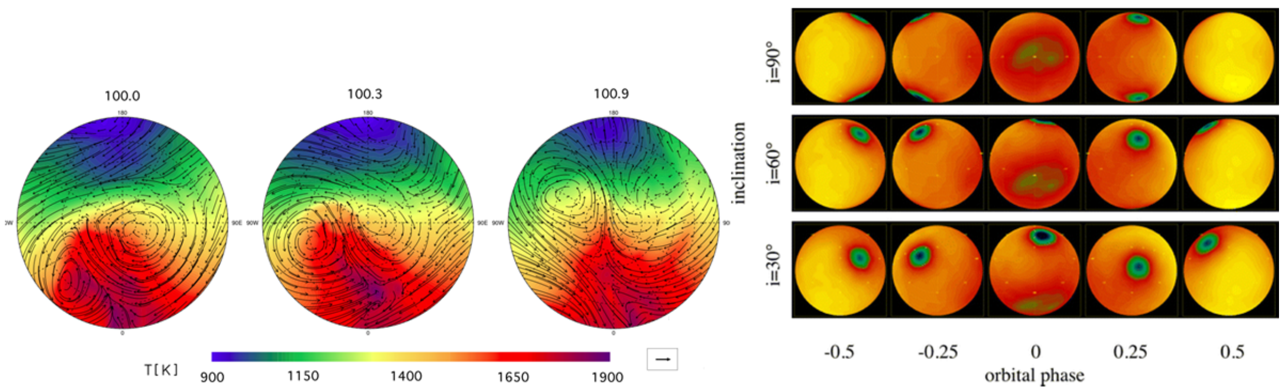


Figure 2-7: Left: Giant storms on a synchronized, gaseous planet. Wind vectors superimposed on temperature map over approximately one planet rotation period, viewed from the north pole. Synchronized planets experience intense irradiation from the host star (at lon = 0 point), exciting large-amplitude planetary waves and active storms that move off to the night side (top half in each frame). The storms dissipate and regenerate with a distinct period of a few planet rotations [Cho et al., 2003, 2008, TN]. Other dynamically-induced periodicities are present on synchronized planets. The periodicities can be used to distinguish synchronized and unsynchronized planets, among other things. Right: Simulated phase variations for a hot-Jupiter with different inclinations [Rauscher et al., 2008].

(ii) *Horizontal thermal structure*: phase curves, spherical harmonics & eclipse mapping. Longitudinal variations in the thermal properties of the planet cause a variation in the brightness of the planet with orbital phase (Figure 2-7, left). This orbital modulation has been observed in the IR in transiting [Knutson et al., 2007] and non-transiting systems [Harrington et al., 2006]. One of the great difficulties in studying extrasolar planets is that we cannot directly resolve the surfaces of these bodies, as we do for planets in our solar system. The use of occultations or eclipses to spatially resolve astronomical bodies, has been used successfully for stars in the past. Most recently Majeu et al. [2012] derived the two-dimensional map of the hot-Jupiter HD189733b in the IR (Figure 2-12). They combined 7 observations at 8 μm with Spitzer-IRAC and used two techniques: slice mapping & spherical harmonic mapping. Both techniques give similar maps for the IR dayside flux of the planet. **EChO will provide phase curves and 2D-IR maps recorded simultaneously at multiple wavelengths, for several gaseous planets, an unprecedented achievement outside the solar system. These curves and maps will allow one to determine horizontal and vertical, thermal and chemical gradients and exo-cartography (Figure 2-8).**

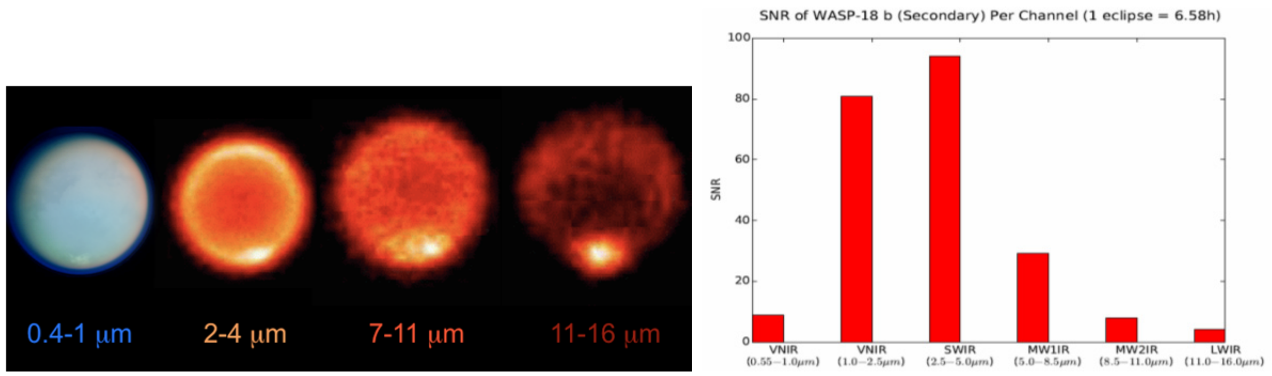


Figure 2-8: Left: Demonstration of possible results from exo-cartography of a planet at multiple photometric bands. Right: simulations of EChO performances for the planet WASP-18b: the SNR in one eclipse is high enough at certain wavelength to allow one to resolve spatially the planet through eclipse mapping.

2.2.4.4 Planetary interior

Although EChO will by definition measure the characteristics of planetary atmospheres it will be also crucial in improving our knowledge of planetary interiors [Guillot, Stixrude, TN]. EChO will of course be able to measure with exquisite accuracy the depth of the primary transit and thus the planetary size. But the major improvements for interior models will come from the ability to characterise the atmosphere in its composition, dynamics and structure. As described in the previous sections, this will be achieved by a combination of observations of transits and of observations of the planetary lightcurve during a full orbital cycle.

EChO will directly contribute to improving our understanding of the interiors of giant exoplanets with the following measurements:

(i) <u>*Measurements on short time scales*</u> (a few hours of continuous observations) of the primary or secondary transit will reveal the abundances of important chemical species globally on the terminator or on the day side. The comparison of these measurements with the characteristics of the star and of the planet, in particular the stellar metallicity and the mass of heavy elements required to fit the planetary size will be key in the determination of whether the heavy elements are mixed all the way to the atmosphere or mostly present in the form of a central core.

(ii) <u>*Measurements on long time scales*</u> (a half or a full planetary orbit, i.e. hours/days of continuous observations) will lead to a very accurate description of the atmospheric dynamics (wind speed, vertical mixing from disequilibrium species), atmospheric structure (vertical and longitudinal temperature field, presence of clouds) and variability. This will be extremely important to estimating the depth at which the atmosphere becomes well mixed and therefore the heat that is allowed to escape.

2.2.4.5 Chemical composition of gaseous planets: a pointer to planet formation and migration history

Formation and migration processes play fundamental roles in determining planetary bulk and atmospheric compositions that ultimately reflect the chemical structure and fractionation within nascent protoplanetary discs. For the purpose of illustration, Nelson, Turrini & Barbieri [2013] have considered a number of simplified planetary accretion and migration scenarios within discs with Solar chemical abundance. They show that models of accretion onto planetary cores can lead to final envelope C/O values that range from less than 0.54 up to 1, and correlate with where and how the planet forms and migrates in a predictable manner. **EChO will provide much needed observational constraints on the C/O values for many gaseous planets.** In the following paragraphs we outline how key formation and migration processes may lead to diverse chemical signatures.

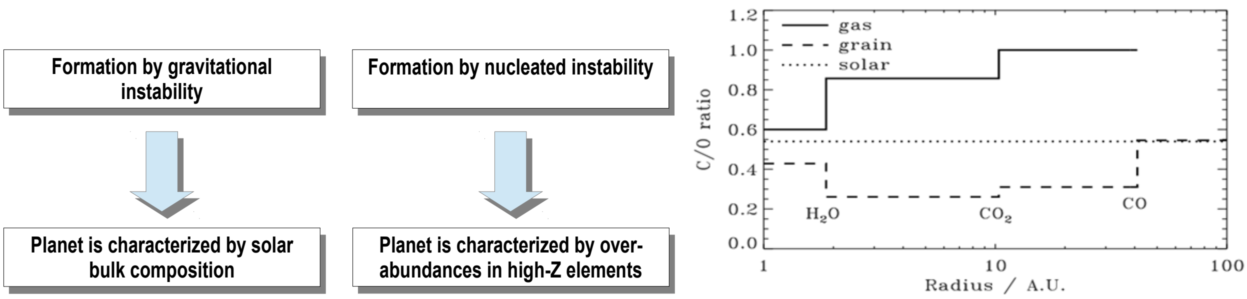


Figure 2-9: Left: expected differences in the atmospheric composition due to different formation scenarios. Right: Locations of the ice-lines and their influence on the C/O ratios for the gas and solids (adapted from Oberg et al 2011).

(i) Giant planet formation via *gravitational instability* that occurs during the earliest phases of protoplanetary disc evolution will result initially in planets with bulk and atmospheric abundances reflecting that of the protoplanetary disc. Recent studies show that formation is followed by rapid inward migration on time scales ~ 10^3 years [Baruteau et al 2011, Zhu et al 2012], too short for significant dust growth or planetesimal formation to arise between formation and significant migration occurring. Migration and accompanying gas/dust accretion should therefore maintain initial planetary abundances if protoplanetary discs possess uniform elemental abundances. Post-formation enrichment may occur through bombardment from neighbouring planetesimals or star-grazing comets, but this enrichment will occur in an atmosphere with abundances that are essentially equal to the stellar values, assuming these reflect the abundances present in the protoplanetary disc.

In its simplest form, the *core accretion model* of planet formation begins with the growth and settling of dust grains, followed by the formation of planetesimals that accrete to form a planetary core. Growth of the core to a mass in excess of a few Earth masses allows for the settling of a significant gaseous envelope from the surrounding nebula. Halting growth at this point results in a super-Earth or Neptune-like planet. Continued growth through gas and planetesimal accretion leads to a gas giant planet. A key issue for determining the atmospheric abundances in a forming planet is the presence of ice-lines at various distances from the central star, beyond which volatiles such as water, carbon dioxide and carbon monoxide freeze-out onto grains and are incorporated into planetesimals. Fig 2-8 shows the effect of ice-lines associated with these species on the local gas- and solid-phase C/O ratios in a protoplanetary disc with solar C/O ratio ~ 0.54. A H_2O ice-line is located at 2-3 AU, a CO_2 ice-line at ~10 AU, and a CO ice-line at ~ 40 AU [Oberg et al 2011)]. Interior to the H_2O ice-line, carbon- and silicate-rich grains condense, leading to a gas-phase C/O ~ 0.6 (due to the slight overabundance of oxygen relative to carbon in these refractory species). The atmospheric abundances of a planet clearly depend on where it forms, the ratio of gas to planetesimals accreted at late times, and the amount of accretion that occurs as the planet migrates. As a way of illustrating basic principles, we note that a planet whose core forms beyond the H_2O ice-line, and which then accretes gas but no planetesimals interior to 2 AU as it migrates inward will have an atmospheric C/O ~ 0.54. Additional accretion of planetesimals interior to 2 AU would drive C/O below 0.54. Similarly, a planet that forms a core and accretes all of its gas beyond the CO_2 ice-line at 10 AU before migrating inward without further accretion will have an envelope C/O ~ 1. Clearly a diverse range of atmospheric C/O values are possible. More realistic N-body simulations of planet formation that include migration, gas accretion and disc models with the chemical structure shown in Fig 2-9 have been performed recently by Coleman & Nelson [2013] . These show a range of final C/O values for short-period planets, as illustrated by the example run shown in Figure 2-9.

(ii) Gas disc-driven migration is only one plausible mechanism by which planets can migrate. The large eccentricities (and obliquities) of the extrasolar planet population suggest that planet-planet gravitational scattering ("Jumping Jupiters") may be important [Weidenschilling & Marzari 1996; Chatterjee et al 2008], and this is likely to occur toward the end of the gas disc lifetime, when its ability to damp orbital eccentricities is diminished. When combined with tidal interactions with the central star, planet-planet scattering onto highly eccentric orbits can form short-period planets that have not migrated toward the central star while accreting from the protoplanetary disc. These planets are likely to show chemical signatures that reflect this alternative formation history, being composed of higher volatile fractions if they form exterior to the H_2O ice line. Measurements of bulk and atmospheric chemical compositions by EChO will provide important clues regarding the full diversity of the formation and migration pathways that were followed by the observed planetary sample.

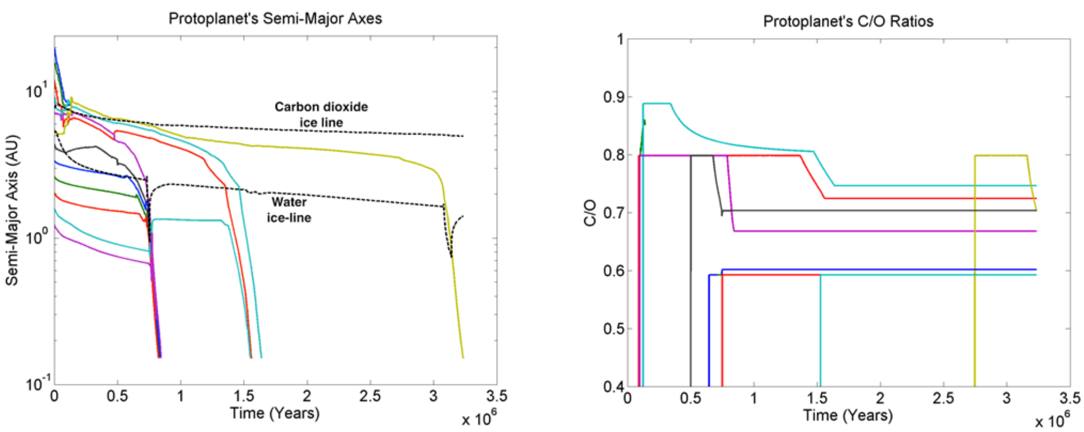


Figure 2-10: Left panel: migration trajectories of forming planets. Right panel: Corresponding C/O ratios of planetary envelopes as they accrete and migrate. Note the initially high C/O ratios of planets forming beyond CO_2 ice-line and reductions in C/O as planets migrate inward where the local disc gas C/O ratio is close to the solar value of ~ 0.54. Images taken from Coleman & Nelson [2013].

2.3 EChO observational techniques

In this section we detail the observational techniques and strategies that EChO will adopt to maximise the scientific return.
The transit and eclipse spectroscopy allow us to measure atmospheric signals from the planet at levels of at least 10^{-4} relative to the star. Analysis techniques to decorrelate the planetary signal from the astrophysical and instrumental noise are presented.
A broad instantaneous wavelength coverage is essential to detect as many chemical species as possible, to probe the thermal structure of the planetary atmospheres and to correct for the contaminating effects of the stellar photosphere.
The EChO core science will be delivered by a three-tier survey, distinguished by the SNR and the resolving power of the observations. Those are tailored to achieve well defined scientific objectives.

2.3.1 Transits, eclipses and phase-curves

EChO will probe the atmospheres of extrasolar planets using temporal variations to separate out planet light from the star - a technique that has grown to be incredibly powerful over the last decade. It makes use of (a) planet transits, (b) secondary eclipses, and (c) planet phase variations (Figure 2-11).

(i) *Transmission spectroscopy*: When a planet moves in front of its host star, starlight filters through the planet's atmosphere. The spectral imprint of the atmospheric constituents can be distilled from the spectrum of the host star by comparing in-transit with out-of-transit spectra [Seager & Sasselov, 2001; Brown, 2001; Tinetti et al., 2007]. Transmission spectroscopy probes the high-altitude atmosphere at the day/night terminator region of the planet. The absorption signals mainly depend on the temperature and the mean molecular weight of the atmosphere, and on the volume mixing ratio of the absorbing gas. If present, clouds can be detected mainly in the VIS.

(ii) *Secondary eclipse spectroscopy*: On the opposite side of the orbit, the planet is occulted by the star (the secondary eclipse), and therefore temporarily blocked from our view. The difference between in-eclipse and out-of-eclipse observations provides the planet day-side spectrum. In the near- and mid-infrared, the radiation is dominated by thermal emission, modulated by molecular features [Deming et al., 2005; Charbonneau et al., 2005]. This is highly dependent on the vertical temperature structure of the atmosphere, and probes the atmosphere at higher pressure-levels than transmission spectroscopy. At visible wavelengths, the planet's spectrum is dominated by Rayleigh and/or Mie scattering of light from the host star [Rowe et al., 2006; De Kok & Stam, 2012]. For the latter, clouds can play an important role.

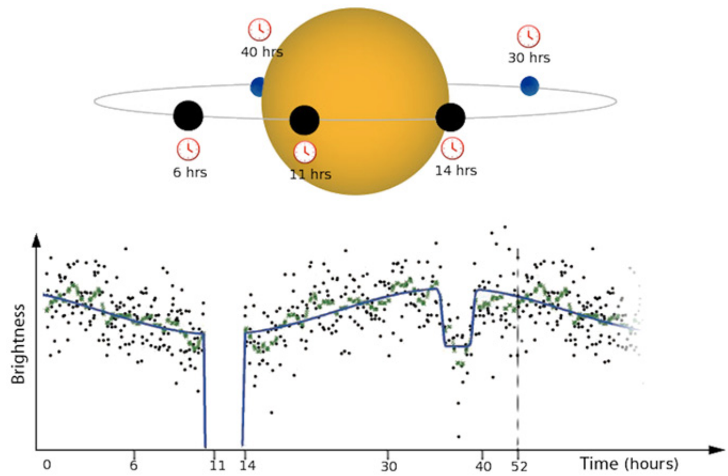


Figure 2-11: Optical phase curve of planet HAT-P-7b observed by Kepler [Borucki et al., 2009] showing the transit, eclipse, and variations in brightness of system due to the varying contribution from the planet's day and night-side as function of orbital phase.

(iii) *Planet phase variations*: In addition, during a planet's orbit, varying parts of the planet's day- and night-side are seen. By measuring the minute changes in brightness as a function of orbital phase, the longitudinal brightness distribution of a planet can be determined [Knutson et al., 2007; Borucki et al., 2009; Snellen et al., 2009]. On the one hand, such observations are more challenging since the time-scales over which the planet contributions vary are significantly longer than for transmission and secondary eclipse spectroscopy. On the other hand, this method can also be applied to non-transiting planet systems [Harrington et al., 2006; Crossfield et al., 2010]. Phase variations are important in understanding a planet's atmospheric dynamics and redistribution of absorbed stellar energy from their irradiated day-side to the night-side.

(iv) *Exoplanet mapping and meteorological monitoring*: The combination of the three prime observational techniques utilized by EChO provides us with information from different parts of the planet atmosphere; from the terminator region via transmission spectroscopy, from the day-side hemisphere via secondary eclipse spectroscopy, and from the unilluminated night-side hemisphere using phase variations. In addition, eclipses can be used to spatially resolve the day-side hemisphere. During ingress and egress, the partial occultation effectively maps the photospheric emission region of the planet [Rauscher et al., 2007]. Figure 2-12 illustrates possible results from eclipse mapping observations [Majeau et al., 2012]. In addition, an important aspect of EChO is the repeated observations of a number of key planet targets in both transmission and secondary eclipse mode. This will allow the monitoring of global meteorological variations in the planetary atmospheres (see Section 2.2.4.3).

All three techniques have already been used very successfully from the optical to the near- and mid-infrared, showing molecular, atomic absorption and Rayleigh scattering features in transmission [Charbonneau et al., 2002; Vidal-Madjar et al., 2003; Redfield et al., 2007; Tinetti et al., 2007, 2010; Snellen et al., 2008; Swain et al., 2008; Beaulieu et al., 2008, 2010; Linsky et al., 2010; Sing et al., 2011; Berta et al., 2012; Crouzet et al., 2012; Deming et al., 2013] and/or emission spectra [Charbonneau et al., 2008; Grillmair et al., 2008; Swain et al., 2009a,b; Stevenson et al., 2010] of a few of the brightest and hottest transiting gas giants, using the Hubble and Spitzer space telescopes. In addition, infrared phase variations have been measured at several wavelengths using Spitzer, showing only a relatively small temperature difference (300 K) between the planet's day and night-side - implying an efficient redistribution of the absorbed stellar energy [Knutson et al., 2007]. These same observations show that the hottest (brightest) part of this planet is significantly offset with respect to the sub-stellar point, indicative of a longitudinal jet-stream transporting the absorbed heat to the night-side.

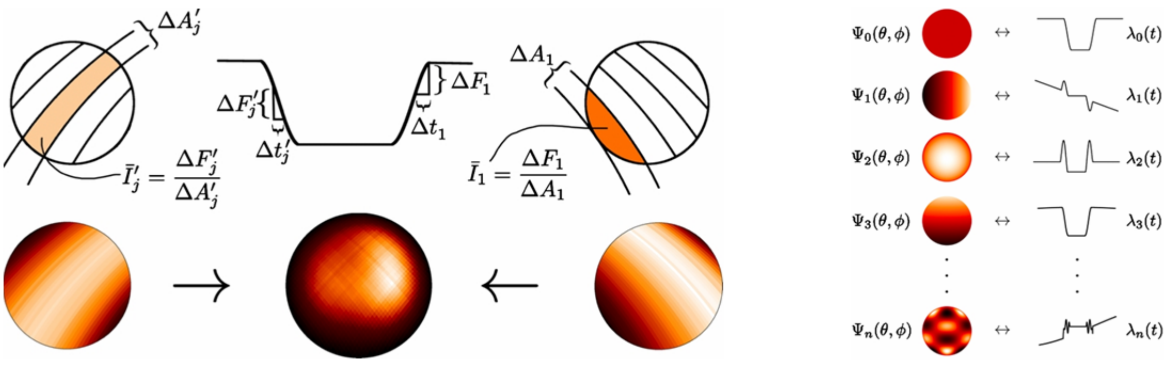


Figure 2-12: Two techniques to spatially resolve the planet. Right: spherical harmonics; Left: slice mapping with ingress and egress maps as well as a combined map of HD189733b at 8 µm. These were achieved with Spitzer [Majeau et al., 2012]. See also [Parmentier et al., TN].

2.3.2 EChOs observational strategy

To maximise the science return, EChO will study exoplanets both as a population & as individual objects. We describe in the following sections how EChO will achieve its objectives.

2.3.2.1 EChOs spectral coverage & resolving power

To maximise the scientific impact achievable by EChO, we need to access all the molecular species expected to play a key role in the physics and chemistry of planetary atmospheres. It is also essential that we can observe planets at different temperatures (nominally from 300 K to 3000 K, Figure 2-13) to probe the differences in composition potentially linked to formation and evolution scenarios. A broad wavelength coverage is therefore required to:

- Measure both albedo and thermal emission to determine the planetary energy budget.
- Capture the variety of planets at different temperatures [Tessenyi et al., 2012].
- Detect the variety of chemical components present in exoplanet atmospheres [Tessenyi et al., 2013] .
- Guarantee redundancy (i.e. molecules detected in multiple bands of the spectrum) to secure the reliability of the detection – especially when multiple chemical species overlap in a particular spectral range (Tessenyi et al., 2013; see Tables 2-2 to 2-14).
- Enable an optimal retrieval of the chemical abundances and thermal profile, Figure 2-17 [Barstow et al., 2012].

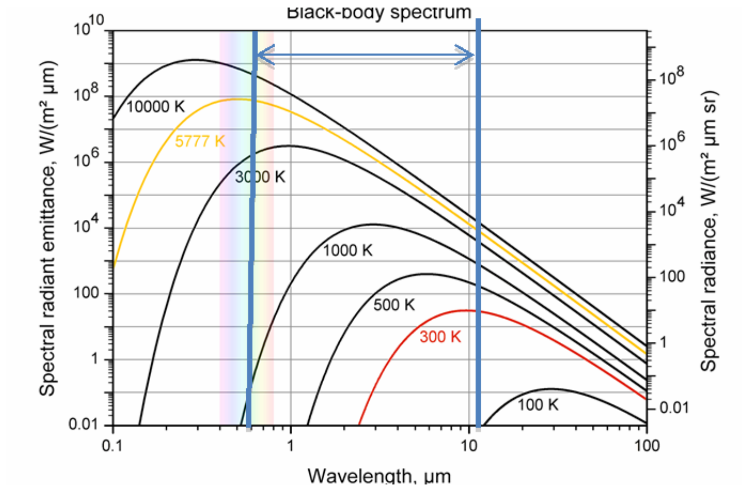


Figure 2-13: Blackbody curves corresponding to different temperatures: the colder the temperature, the longer the wavelengths where the Planckian curves peak. The two blue lines show optimal wavelength range to characterise planets from 300 K to 3000 K.

This means covering the largest wavelength range feasible, given the temperature limits (i.e. from the visible to the Mid-IR, ~0.4 to 16 µm). Some spectral regions are more critical than others, as is explained in the following paragraphs.

(i) The wavelength coverage 0.55-11 µm is critical for EChO, as it will guarantee that ALL the key chemical species (H_2O, CH_4, CO, CO_2, NH_3) and all other species (Na, K, H_2S, SO_2, SiO, H_3^+, C_2H_2, C_2H_4, C_2H_6, PH_3, HCN etc.) can be detected, if present, in ALL the exoplanet types observed by EChO, with the exception of CO_2 and C_2H_6 in temperate planetary atmospheres (see Figure 3-1).

Molecular species such as H_2O, CH_4, CO_2, CO, NH_3 are key to understand the chemistry of those planets: the broad wavelength coverage guarantees that these species can be detected in multiple spectral bands, even at low SNR, optimising their detectability in atmospheres at different temperatures. Redundancy (i.e. molecules detected in multiple bands of the spectrum) significantly improves the reliability of the detection, especially when multiple chemical species overlap in a particular spectral range. Redundancy in molecular detection is also necessary to allow the retrieval of the vertical thermal structure and molecular abundances. The wavelength range 0.55-11 µm will guarantee the retrieval of molecular abundances and thermal profiles, especially for gaseous planets, with an increasing difficulty in retrieving said information for colder atmospheres [Barstow TN].

For hot planets, opacities in the visible range are dominated by metallic resonance lines (Na at 0.59 µm, K at 0.77 µm, and possibly weaker Cs transitions at 0.85 and 0.89 µm). TiO, VO and metal hydrides are also expected by analogy to brown dwarfs [Allard, TN].

(ii) The target wavelength coverage of 0.55-16 µm would guarantee that CO_2 and C_2H_6 can be detected in temperate planetary atmospheres. It will also offer the possibility of detecting additional absorption features for HCN, C_2H_2, CO_2 and C_2H_6 for all other planets and improve the retrieval of thermal profiles [Barstow et al. TN].

(iii) The target wavelength coverage of 0.4-11 µm would improve the detection of Rayleigh scattering in hot and warm gaseous planets if clouds are not present. In a cloud-free atmosphere, the continuum in the

UV-VIS is given by Rayleigh scattering on the blue side, i.e. for wavelengths shorter than 1 μm (Rayleigh scattering varies as $1/\lambda^4$). If there are clouds or hazes with small-size particles, those should be detectable in the visible even beyond 0.55 μm (see Figure 2-14).

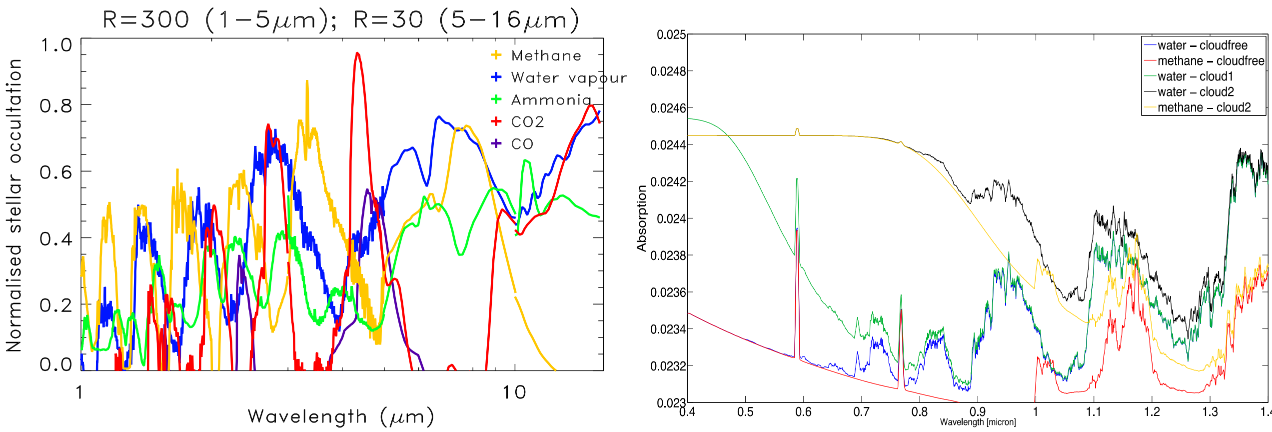


Figure 2-14: Simulated transmission spectra of a gaseous exoplanet at 800 K [Hollis et al., 2013]. The atmospheric absorption is normalised to 1; typically the fraction of stellar flux absorbed by the atmosphere of a hot planet is 10^{-4}-10^{-3}. The spectra were generated at an optimal resolving power R=300 for $\lambda < 5$ μm and R =30 for $\lambda > 5$ μm (left). Right: transmission spectra of cloud-free and cloudy atmosphere of a gaseous planet. Particle size, shape, distribution and the pressure of the atmospheric layer where clouds/hazes form cause changes in the spectra in the VIS-NIR [Liou, 2002].

(iv) A spectral resolving power of R = 300 for $\lambda < 5$ μm will permit the detection of most molecules at any temperature. At $\lambda > 5$ μm, R = 30 is enough to detect the key molecules at hot temperatures, due to broadening of their spectral signatures. For temperate planets, R = 30 at longer wavelengths is also an optimal solution, given there are fewer photons [Tinetti, Encrenaz, Coustenis, 2013].

In Figure 2-14 left, two values (300 and 30) are used for the spectral resolving power of the simulated transmission spectra. In addition to the main candidate absorbers (H_2O, CH_4, NH_3, CO, CO_2), Figure 3-1 shows the contributions from HCN, O_3, H_2S, PH_3, SO_2, C_2H_2, C_2H_6 and H_3^+. Among those, H_3^+ around 2 μm and 3-4 μm is easily detectable with a resolving power of ~ 300.

While R=30 enables the detection of most of the molecules absorbing at $\lambda > 5$ μm, especially at higher temperatures, we would lose the possibility of resolving the CO_2, HCN and other hydrocarbon Q-branches, for which R>100 is needed. The current instrument design allows a spectral resolving power between the two.

In the visible, for cloud-free atmospheres, a resolving power of ~ 100 is still sufficient for identifying the resonance lines of Na and K, but not to resolve the centre of the lines. For the star, Hα can be easily identified at 0.656 μm.

2.3.2.2 EChOs three surveys

The EChO science case will be captured through three survey tiers. These are briefly described below and summarised in Table 2-2 and in Figure 2-15.

Chemical Census

- For all planetary cases (150 to 300), this tier will detect the strongest features in most molecular spectra (e.g. CH_4, CO, CO_2, NH_3, H_2O, C_2H_2, C_2H_6, HCN, H_2S and PH_3), provided the molecular abundance is large enough (e.g. mixing ratios ~ $10^{-6}/10^{-7}$ for CO_2, $10^{-4}/10^{-5}$ for H_2O), see Tables 2-3, 2-4, 2-5.
- For the temperate super-Earths, we also show that with SNR=5, O_3 can be detected with an abundance of 10^{-7} at 9.6 μm, see Table 2-5.

Origin survey

A subsample of the Chemical Census (tens of planets). The Origin tier will allow:

- Detection of key molecular features in multiple bands (see Tables 2-3, 2-4, 2-5, Figure 2-17) enabling the retrieval of the vertical thermal profile (Figure 2-17)
- Measurement of the abundances of trace gases (see Tables 2-3, 2-4, 2-5) constraining the current proposed scenarios for the chemical and physical processes in place for exoplanet atmospheres (see Section 2.2.4 and Figure 2-6).
- Allow determination of the C/O ratio and constrain planetary formation/migration scenarios (see Section 2.2.4.5)

Rosetta Stones

Benchmark cases we plan to observe in great detail, to understand an entire class of objects. For these planets we will observe:

- Weak spectral features for which the highest resolving power and SNR is needed.

Among Rosetta Stones, a good candidate for the Exo-Meteo & Exo-Maps survey, is a planet whose requirements for the Chemical Census can be achieved in one transit or eclipse. Gaseous planets such as HD 189733b, HD 209458b, or GJ 436b are the most obvious candidates for this type of observations, meaning we can observe:

- Temporal variability, i.e. Exo-Meteo (weather, Section 2.2.4)
- Spatial resolution, i.e. Exo-Maps (2D and 3D maps, Section 2.2.4)

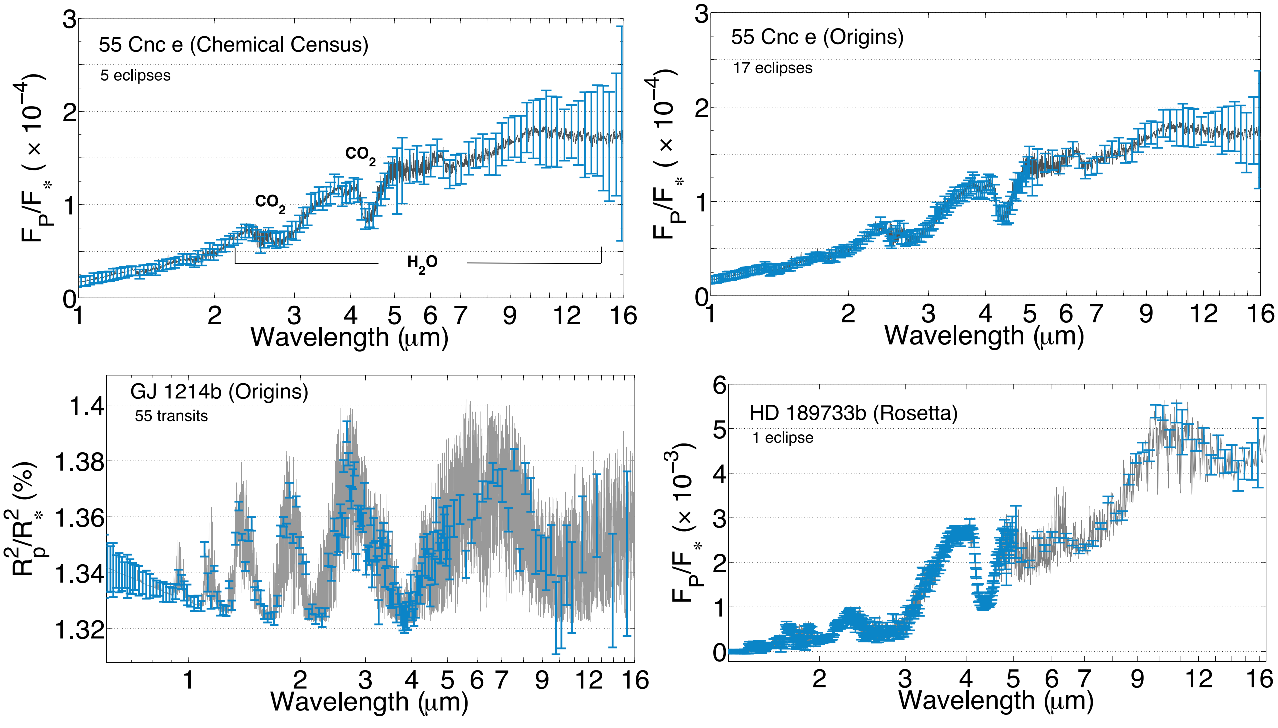


Figure 2-15: EChOSim simulations (see Section 5.3.1.2) of transmission and emission spectra as observed by EChO with different survey programs. The transits or eclipses needed are reported in the figure. Top: emission spectra of super-Earth 55 Cnc e with Chemical Census and Origin surveys. The spectral features of CO_2 and water vapour are detectable in Chemical Census, their abundances and thermal profile retrievable in Origin. Bottom left: transmission spectrum of GJ 1214b observable in Origin. The water vapour abundance is easily retrievable given the error bars (see Figure 2-5 for comparison). In particular we can distinguish scenarios where the atmosphere is hydrogen-rich, water rich or somewhere in between. Bottom right: emission spectrum of hot Jupiter HD 189733b (Rosetta Stones program). The key trace gases are retrievable very precisely, see Figures 2-17 & 2-18.

Tier	Key science objectives	Observables & derived products	Observational strategy
Chemical Census *(Survey)*	• *Exploring the diversity of exoplanet atmospheres* • *What are exoplanets made of?*	***Presence of most abundant atmospheric components, e.g. H_2O, CH_4, CO, CO_2, NH_3 etc.*** ***Albedo and thermal emission***	***A sample of planets (150 to 300) which is representative of the local volume (super-earths, Neptunes & Jupiters, with a range of temperatures, orbital and stellar parameters).*** **SNR~5** **R~50 for $\lambda < 5\mu m$** **R~30 for $\lambda > 5\mu m$** Transits or eclipses until the required R & SNR is reached to detect most abundant atmospheric molecules.
Origin *(Deep survey)*	a. *Understanding the origin of exoplanet diversity & the physical mechanisms in place* b. *How do planet form and evolve?*	- Molecular abundances of both key components and trace gases in the atmosphere, - vertical thermal profiles, - constraints on clouds/albedo.	***A subset (tens)of the planets analysed through the Chemical Census tier, with a prevalence of Neptunes and Jupiters.*** **SNR~10** **R~100 for $\lambda < 5\mu m$** **R~30 for $\lambda > 5\mu m$** Transits + eclipses until the required SNR & R are reached to retrieve molecular abundances for most trace gases and vertical thermal profiles.
Weather, Exo-maps & Rosetta Stones *(Ultra deep survey)*	*A very detailed and exhaustive study of a select sample of benchmark cases.*	- Very precise molecular abundances of key components and trace gases, - vertical and horizontal thermal profiles and chemical gradients, - spatial and temporal variability, - orbital modulations, - constraints on clouds/albedo.	A select sample chosen among the most favourable exoplanets in their own category (typically 10 or 20). For the Exo-Meteo and Exo-Maps, exoplanets whose stars are very bright should be selected (e.g. HD 189733b). **SNR~20** **R~300 for $\lambda < 5\mu m$** **R~30 for $\lambda > 5\mu m$** Many repeated obs. of transits and/or eclipses + orbital lightcurves + eclipse mapping.

Table 2-2: Summary of EChOs three tiers: objectives addressed and observational strategies adopted.

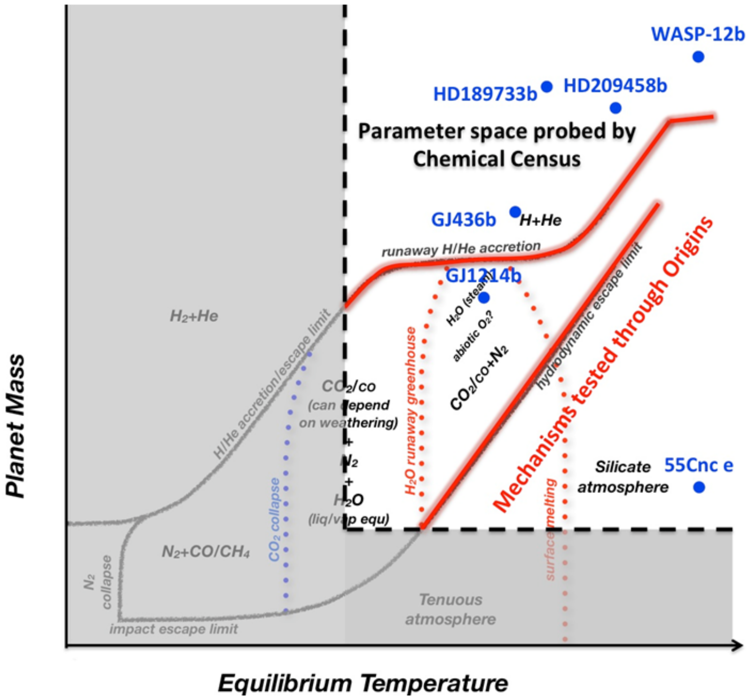


Figure 2-16: Parameter space probed by the Chemical Census, i.e. a large number of planets with masses ranging from ~ 5 Earth Masses to very massive Jupiters, and temperatures spanning two orders of magnitude, i.e. from temperate, where water can exist in a liquid phase, to extremely hot, where iron melts. A few known planets, benchmark cases representative of classes of objects, are shown in the diagram to orientate the reader. These will be excellent objects to study as Rosetta Stones. Key physical processes responsible of transitions among classes of exoplanets are identified: these mechanisms will be tested through the Origin survey.

2.3.2.3 Optimal SNR & information retrieved

Most of the science objectives detailed in Section 2.3.2, are based on the assumption that EChO will be able to retrieve the molecular composition and the thermal structure of a large number of exoplanet atmospheres at various levels of accuracy and confidence, depending on the scientific question and target selected.

We consider here the goal wavelength coverage assumed by EChO, i.e. 0.4 to 16 μm, and investigate the key molecular features present in a range of planetary atmospheres with a temperature between ~300 K and 3000 K. In a planetary spectrum, as measured through a transit or eclipse, the molecular features appear as departures from the continuum. At a fixed temperature-pressure profile, the absorption depth or emission features will depend only on the abundance of the molecular species. Tables 2-3 to 2-5 show the minimum abundance detectable for a selected molecule absorbing in a planetary atmosphere, as a function of wavelength and observing tier, i.e. Chemical Census, Origin, Rosetta Stones (see Table 2-2). We show here the results for three planetary cases: warm Neptune, hot and temperate super-Earth. The spectral resolving power is lowered to R=20 in the 5 to 16 μm spectral interval for the temperate super-Earth, being the most challenging planet type that EChO might observe. For simulations on hot and temperate Jupiters see [Tessenyi et al., 2013].

As shown by Tables 2-3, 2-4 and 2-5, for most planetary cases, **the Chemical Census tier is enough to detect the very strongest spectral features for the most abundant molecules, whereas Origin tier can reveal most molecules with mixing ratios of 10^{-6} or lower, often at multiple wavelengths, which is excellent for constraining the type of chemistry or the C/O ratio.** The robustness of these results was tested by exploring sensitivity to parameters such as vertical thermal profile, mean molecular weight of the atmosphere and relative water abundances: the main conclusions remain valid except for the most extreme cases [Tessenyi et al., 2013].

	CH_4		CO		CO_2			NH_3			H_2O		
Obs. Mode	3.3μm	8μm	2.3μm	4.6μm	2.8μm	4.3μm	15μm	3μm	6.1μm	10.5μm	2.8μm	5-8μm	11-16μm
Rosetta St.	10^{-7}	10^{-6}	10^{-4}	10^{-6}	10^{-7}	10^{-7}	10^{-7}	10^{-7}	10^{-6}	10^{-7}	10^{-6}	10^{-6}	10^{-5}
Origins	10^{-7}	10^{-6}	10^{-3}	10^{-5}	10^{-6}	10^{-7}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-5}	10^{-4}
Ch. Census	10^{-7}	10^{-5}	10^{-3}	10^{-4}	10^{-6}	10^{-7}	10^{-5}	10^{-5}	10^{-5}	10^{-5}	10^{-5}	10^{-5}	10^{-4}

	HCN			PH_3		C_2H_6		H_2S			C_2H_2		
Obs. Mode	3μm	7μm	14μm	4.3μm	10μm	3.3μm	12.2μm	2.6μm	4.25μm	8μm	3μm	7.5μm	13.7μm
Rosetta St.	10^{-7}	10^{-5}	10^{-7}	10^{-7}	10^{-6}	10^{-6}	10^{-6}	10^{-5}	10^{-4}	10^{-4}	10^{-7}	10^{-5}	10^{-7}
Origins	10^{-6}	10^{-5}	10^{-6}	10^{-7}	10^{-6}	10^{-5}	10^{-5}	10^{-5}	10^{-4}	10^{-3}	10^{-7}	10^{-4}	10^{-6}
Ch. Census	10^{-6}	10^{-4}	10^{-5}	10^{-7}	10^{-5}	10^{-5}	10^{-5}	10^{-4}	10^{-3}	-	10^{-7}	10^{-3}	10^{-5}

Table 2-3: Examples of average detectable abundance for a warm-Neptune (e.g. GJ 436b) for the three tiers [Tessenyi et al., 2013]. The molecular abundance is expressed as mixing ratio.

	H_2O			CO_2		
Obs. Mode	2.8μm	5 - 8μm	11 - 16μm	2.8μm	4.3μm	15μm
Rosetta St.	10^{-4}	10^{-4}	10^{-4}	10^{-5}	10^{-7}	10^{-5}
Origins	10^{-4}	10^{-3}	10^{-3}	10^{-5}	10^{-6}	10^{-4}
Ch. Census	10^{-3}	-	-	10^{-4}	10^{-5}	-

Table 2-4: Examples of average molecular detectability for a hot super-Earth around a G-type star (e.g. 55 Cnc e) for the three tiers. The molecular abundance is expressed as mixing ratio.

	H_2O		CO_2	NH_3		O_3	
SNR	5 - 8 μm	11 - 16 μm	15 μm	6 μm	11 μm	9.6 μm	14.3 μm
10	10^{-6}	10^{-4}	10^{-6}	10^{-6}	10^{-6}	10^{-7}	10^{-5}
5	10^{-6}	10^{-4}	10^{-6}	10^{-5}	10^{-6}	10^{-7}	10^{-5}

Table 2-5: Examples of average molecular detectability for a temperate super-Earth (~ 320 K) around a late M for fixed SNR and R=20. The molecular abundance is expressed as mixing ratio.

Similar conclusions were reached through simulations with the NEMESIS (Non-linear optimal Estimator for Multivariate spectral analysis) radiative transfer and retrieval tool [Barstow et al., 2012; 2013] to explore the potentials of the proposed EChO payload to solve the retrieval problem for a range of H_2-He planets orbiting different stars and Ocean planets such as GJ 1214b.

NEMESIS results show that EChO should be capable of recovering all gases in the atmosphere of a hot-Jupiter to within 2-sigma for all tiers. However, we see differences in the retrieved T-p profile between the Chemical Census, Origin and Rosetta tiers. As expected, for the Chemical Census the spectral resolution is too low to fully break the degeneracy between temperature and gas mixing ratios, so the retrieved profile is less accurate. This is not the case for Origin and Rosetta (Figure 2-17). Examples of spectral fits for the Rosetta case are also shown in Figure 2-17. The temperature prior chosen does not affect the retrieval or the spectral fit.

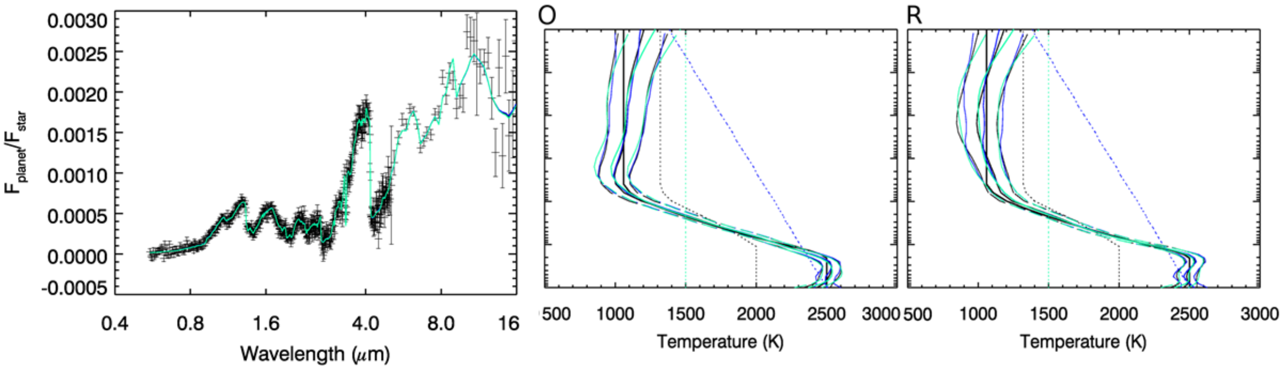
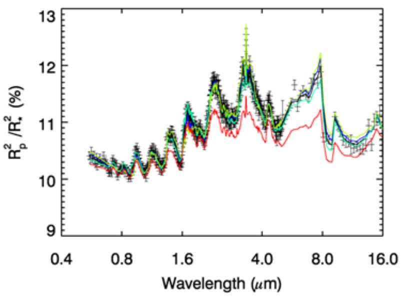


Figure 2-17: Left: Eclipse spectra for a hot-Jupiter observed in Rosetta Stone program. The fitted spectra colours correspond to different temperature priors, as on the right. The temperature prior used does not affect the resultant spectral fit. Right: Temperature retrievals of a hot-Jupiter from eclipse observations (L-R: Origin, Rosetta Stone). The three different temperature priors used are shown by dotted lines; the thick black line is the input profile, and the three retrieved profiles are shown by the thin solid lines. The retrieval error is shown by the dashed lines.

Similar results were obtained for the hot-Jupiter's transit spectra and for the hot-Neptune's transit and eclipse spectra (Figure 2-18; Barstow, TN). In primary transit, it is not possible to independently retrieve the T-p profile due to the limited sensitivity to temperature, but by performing multiple retrievals with different assumed T-p profiles and comparing the goodness-of-fit of the resulting spectra, we can obtain the constraints needed. In Figure 2-18, the different colours correspond to retrievals using different model T-p profiles, with the best fit being provided by the input temperature profile, as expected. From this, we can correctly infer the temperature and gaseous abundances from primary transit.

As well as constraining the temperature of hot Jupiters and Neptunes, with a few tens of eclipses we can obtain sufficient signal-to-noise to allow a retrieval of the stratospheric temperature of super-Earths atmospheres, such as GJ 1214b, which has not been achieved to date [Barstow et al., 2013a]. An independent constraint on the temperature will be valuable for interpreting the better-studied transit spectrum of GJ 1214b, which will also be significantly improved in quality by EChO observations (see Fig. 2-15).



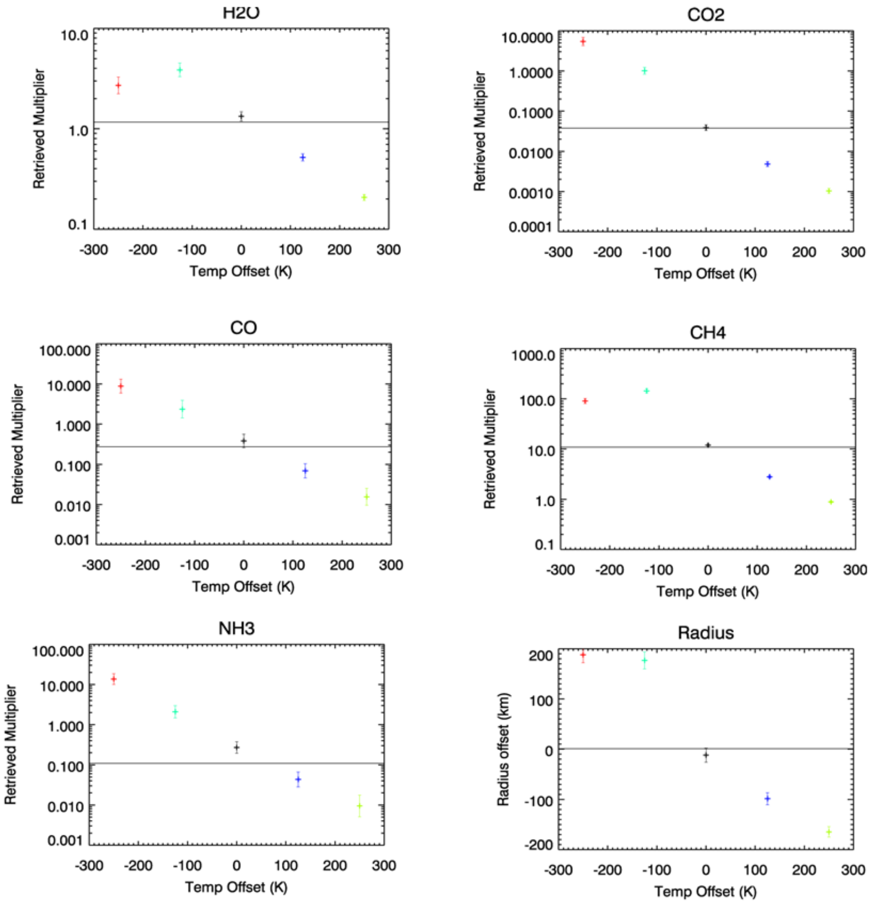


Figure 2-18: Retrieved results for a hot Neptune transit spectrum observed in the Rosetta Stone tier.

Colours correspond to different reduced χ2: red=17.1, green=2.0, black=1.2 (best fit), blue=1.6, yellow=2.8. For a good retrieval the reduced χ2 should be close to 1. The best fit is the black one, for which the temperature and gases are correctly retrieved.

2.3.3 Laboratory data for EChO

2.3.3.1 Linelists

Interpreting exoplanetary spectra requires access to appropriate laboratory spectroscopic data, as does the construction of associated radiative transport and atmospheric models. These objects may reach temperatures up to about 3000 K meaning that billions of transitions are required for an accurate model. A dedicated project is in progress to provide comprehensive sets of line lists for all the key molecules expected to important in exoplanet atmospheres (both hydrogen-rich gas giants and oxygen-rich terrestrial-like atmospheres). The ExoMol project (www.exomol.com) aims to provide complete lists for the 30 most important species (including methane, water, ammonia, phosphine, hydrogen sulphide, a variety of hydrocarbons and a long list of stable and open shell diatomics) by 2016. These data will therefore be available for pre-launch testing and design studies [Tennyson & Yurchenko, TN].

2.3.3.2 Reaction / photodissociation rates

The diversity of exoplanetary atmospheres observable with EChO spans a broad range of physical conditions. Individual reaction rates must therefore be known at temperature ranging from below room temperature to above 2500 K and - because the deep atmospheric layers are chemically mixed with the layers probed by spectroscopic observations – at pressures up to about 100 bars. Today these rates are well-known at room temperature, but only rarely determined at high temperature. The teams from University of Bordeaux and LISA Créteil, France, are measuring new photoabsorption cross-section at high temperatures, at wavelengths shorter than 200 nm [Venot et al., 2013]. The first measurements for CO_2 have been performed at the synchrotron radiation facility BESSY, in Berlin, and at LISA, Créteil.

2.3.3.3 Optical properties of gases at high Pressure-Temperature

Despite various measurements and theoretical models dedicated to the optical properties of gases, accurate data at different temperatures and pressures are still lacking in numerous spectral regions. Little or no data in some case are available for continuum absorption, line mixing, far wings and collision induced absorption, even for the well-studied carbon dioxide. The scenario is further complicated by the need to reproduce in the lab very long path able to measure weak but important absorption and/or to boost the sensitivity and accuracy of the setup. New data are and will be further more available in future thanks in support to the operational or planned solar system missions. In particular recent measurements are available from the lab at INAF-IAPS Rome (http://exact.iaps.inaf.it) performed for Venus Express orbiting around Venus [Stefani, et al.], and more measurements are planned for JUNO presently in cruise to Jupiter. Finally, the increasing availability of new tuneable lasers in the EChO spectral range makes possible to use the cavity ring down technique demonstrated to be very effective for example in the continuum measurements of the atmospheric windows of Venus [Snels et al., 2014].

2.3.4 Dealing with systematic & astrophysical noise

2.3.4.1 Decorrelating instrument systematics

Detecting the atmospheric signal of an exoplanet requires high precision measurements. Limitations to said precision come from the systematic noise associated with the instrument with which the data are observed. This is particularly true for general, non-dedicated observatories. In the past, parametric models have been used extensively by most teams in the field of exoplanet spectroscopy/differential band photometry to remove instrument systematics [Agol et al. 2010; Beaulieu et al. 2008, 2010, 2011; Charbonneau et al. 2005, 2008; Crouzet et al., 2012; Deming et al. 2013; Grillmair et al. 2008; Knutson et al. 2007; Stevenson et al. 2010; Swain et al. 2008, 2009a,b; Tinetti et al., 2007, 2010]. Parametric models approximate systematic noise via the use of auxiliary information about the instrument, the so called Optical State Vectors (OSVs). Such OSVs often include the X and Y-positional drifts of the star or the spectrum on the detector, the focus and the detector temperature changes, as well as positional angles of the telescope on the sky. By fitting a linear combination of OSVs to the data, the parametric approach derives its systematic noise model. We refer to this as the `linear, parametric' method. In many cases precisions of a few parts in 10000 with respect to the stellar flux were reached.

In the case of dedicated missions, such as Kepler [Borucki et al. 1996, 2011], the instrument response functions are well characterised in advance and conceived to reach the required 10^{-4} to10^{-5} photometric precision. EChO aims at reaching the same level of photometric precision. For general purpose instruments, not calibrated to reach this required precision, poorly sampled OSVs or a missing parameterisation of the instrument often become critical issues. Even if the parameterisation is sufficient, it is often difficult to determine which combination of these OSVs may best capture the systematic effects of the instrument. This approach has caused some debates for current instruments regarding the use of different parametric choices for the removal of systematic errors.

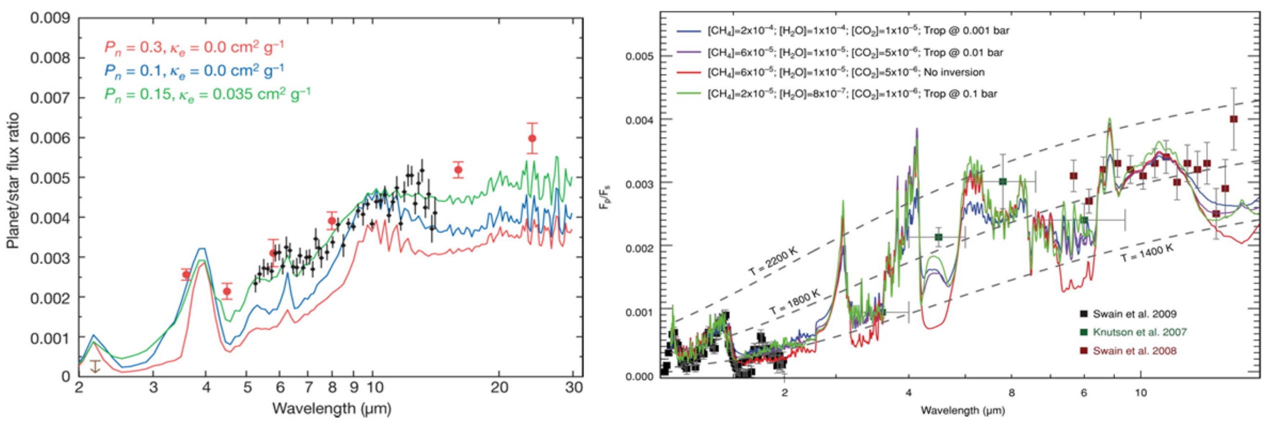


Figure 2-19: Eclipse spectra and photometric data for hot-Jupiters observed with Hubble (NICMOS) and Spitzer (IRS & IRAC). Left: MIR observations of HD 189733b. Simulated spectra of water vapour are overlapped [Grillmair et al., 2008]. Right: NIR and MIR observations compared to synthetic spectra for three models that illustrate the range of temperature/composition possibilities consistent with the data

[Swain et al., 2009]. For each model case, the molecular abundance of CH_4, H_2O, and CO_2 and the location of the tropopause is given. Note that the mid-infrared data are not contemporaneous with the near-infrared data, and attempting to "connect" these data sets with a model spectrum is potentially problematic if significant variability is present.

Given the potential intricacies of a parametric approach, in the past years alternative methods have been developed to de-correlate the data from instrumental and stellar noise. The issue of poorly constrained parameter spaces is not new in astrophysics and has given rise to an increased interest in unsupervised (and supervised) machine learning algorithms [e.g. Wang et al. 2010]. Unsupervised machine learning algorithms do not need to be trained prior to use and do not require auxiliary or prior information on the star, instrument or planet but only the observed data themselves. The machine learning approach will then (from observations) 'learn' the characteristics of an instrument and allows us to de-trend systematics from the astrophysical signal. This guarantees the highest degree of objectivity when analysing observed data. In Waldmann [2012, 2013b] and Waldmann et al. [2013], Independent Component Analysis – ICA has been adopted as an effective way to decorrelate the exoplanetary signal from the instrument in the case of Hubble-NICMOS and Spitzer/IRS data or to decorrelate the stellar activity from the exoplanet transit lightcurve, in Kepler data. The error-bars for non-parametric approaches can be sometimes larger than those reported by parametric approaches. This difference is due to the higher amount of auxiliary information injected in the parametric approach. Ultimately, it is a trade-off between a higher degree of objectivity for the non-parametric methods and smaller errors for the parametric detrending.

In the case of EChO we will make use of both methods to correct instrumental systematics and astrophysical noise. Very thorough tests and calibration of the instrument before launch (especially detector performances), will substantially help to constrain the auxiliary information of the instrument hence the decorrelation process.

2.3.4.2 Correcting for stellar activity

The impact of stellar activity on the EChO data has been carefully evaluated by many teams working on EChO. Results from the Kepler mission [Basri et al. 2013] indicate that most G dwarfs have photometric dispersions less than 50 ppm over a period of 6 hours, while most late-K and M dwarfs vary at a level of some 500 ppm. Note that Kepler operates in the visible where stellar photometric variability is over a factor of 2 higher than in the "sweet spot" of EChO – the NIR and MIR – because of the contrast between spots and the stellar photosphere. The effects of stellar activity on EChOs observations will vary for transit and eclipse observations. Alterations in the spot distribution across the stellar surface can modify the transit depth (because of the changing ratio of photosphere and spotted areas on the face of the star) when multiple transit observations are combined, potentially giving rise to spurious planetary radius variations. The situation is simpler for occultations, where the planetary emission follows directly from the depth measurement. In this case, only activity-induced variations on the timescale of the duration of the occultation need to be corrected for to ensure that the proper stellar flux baseline is used. The EChO mission has been designed to be self-sufficient in its ability to correct for the effects of stellar activity. This is possible thanks to the instantaneous, broad-wavelength coverage and the strong chromatic dependence of light modulations caused by stellar photospheric inhomogeneities (star-spots and faculae). We have explored several possible approaches to evaluate the effect of stellar activity and developed methodologies to prove the performance of EChO data in reaching the required precision [Ribas, Micela, Tinetti TN].

Method 1 – We have investigated a direct method of correlating activity-induced variations in the visible with those in the IR. The underlying hypothesis is that variations of the transit depth in the visible are solely caused by stellar activity effects and not influenced by the atmosphere of the transiting planet. To test this approach, a realistic stellar simulator has been developed that produces time series data with the same properties as the measurements from EChO. The simulator considers surface inhomogeneities in the form of (dark) starspots and (bright) faculae, takes into account limb darkening (or brightening in the case of faculae), and includes time-variable effects such as differential rotation and active region evolution. We have generated series of transits at wavelengths 0.8, 2.5, and 5.0 μm. Then, we have measured the transit depths and calculated the variations of those depths with time. We have found that there is a well-defined correlation between activity-induced transit depth variations in the visible (0.8 μm) and the IR (2.5 and 5.0 μm). An illustration of the transit light curves generated by the simulator and the correlation between visible and IR transit depth variations (TDV) can be seen in Figure 2-20 (left & middle). In practice, the correction of EChO data for stellar activity using, for example, a series of measurements in the visible and an IR band can be done using the following expression: $d_{IR}^{corr} = d_{IR} + a_0 + a_1 \cdot (d_{VIS} - \langle d_{VIS} \rangle)$, where d stands for the transit depth, and a_0 and a_1 are the coefficients of a linear fit that can be determined from simulations.

A number of combinations of stellar photospheres and active region parameters (size and location of spots, temperature contrast) were considered to obtain a statistical view of the method. The results can be seen in Table 2-6. The cases that we have analysed represent standard stars of GKM spectral types with filling factors of 1-7%, i.e., corresponding to stars that are ~4-30 times more spotted than the active Sun. The case in row 1 has parameters similar to HD 189733. As can be seen from Table 2-6, the direct procedure provides a correction of the transit data to a few times 10^{-5}, and thus is fully compliant with EChO noise requirements.

T_{eff} (K)	ΔT_{sp} (K)	Filling Factor	rms_T (0.8μm)	rms_T (2.5μm)	rms_T (5.0μm)	$rms_{T(corr)}$ (2.5μm)	$rms_{T(corr)}$ (5.0μm)	Corr. fact (2.5μm)	Corr. fact (5.0μm)
5060	500	0.061	9.0e-3	3.9e-3	3.0e-3	1.7e-5	2.3e-5	2.3e2	1.3e2
5850	500	0.053	7.3e-3	2.9e-3	2.9e-3	4.0e-5	2.5e-5	7.3e1	1.2e2
6200	550	0.049	4.4e-3	1.7e-3	1.8e-3	5.3e-6	5.9e-6	3.2e2	3.1e2
3580	400	0.055	1.1e-2	6.2e-3	4.7e-3	3.8e-5	2.2e-5	1.6e2	2.1e2
4060	400	0.035	7.1e-3	5.3e-3	2.6e-3	4.4e-5	3.4e-6	1.2e2	7.6e2
5850	500	0.008	1.9e-4	1.4e-4	1.5e-4	8.9e-6	9.8e-6	1.6e1	1.5e1
5850	500	0.060	6.3e-3	2.6e-3	2.7e-3	3.2e-5	2.7e-5	8.1e1	1.0e2
3580	400	0.066	1.5e-2	8.3e-3	6.4e-3	3.0e-5	2.2e-5	2.8e2	2.9e2
5850	500	0.020	2.0e-3	9.2e-4	9.7e-4	1.9e-5	2.4e-5	4.8e1	4.0e1
5060	500	0.074	5.1e-3	2.2e-3	1.7e-3	1.4e-5	1.5e-5	1.6e2	1.1e2

Table 2-6: Results for the simulations of 10 cases of star-planet systems randomly selected from a set of 6 stellar models and 4 different possible active region maps, and with a rotation period of 15 days. The planet parameters were fixed to R_p=0.05 R_{star}, P_{planet}=2.54 days, b=0.2 (impact parameter). The facula temperature contrast and the facula-to-spot area ratio (Q) were fixed to ΔT_{fac}=+100 K and Q=7.0, respectively. The first three columns indicate the temperature for the quiet photosphere, the spot contrast and the spot filling factor. The following three columns list the rms of the in-transit sections at 0.8, 2.5, and 5.0 μm. The next two columns give the rms of the in-transit sections at 2.5 and 5.0 μm after correcting for activity effects using the procedure described in the text. The final two columns give the correction factor at 2.5 and 5.0 μm.

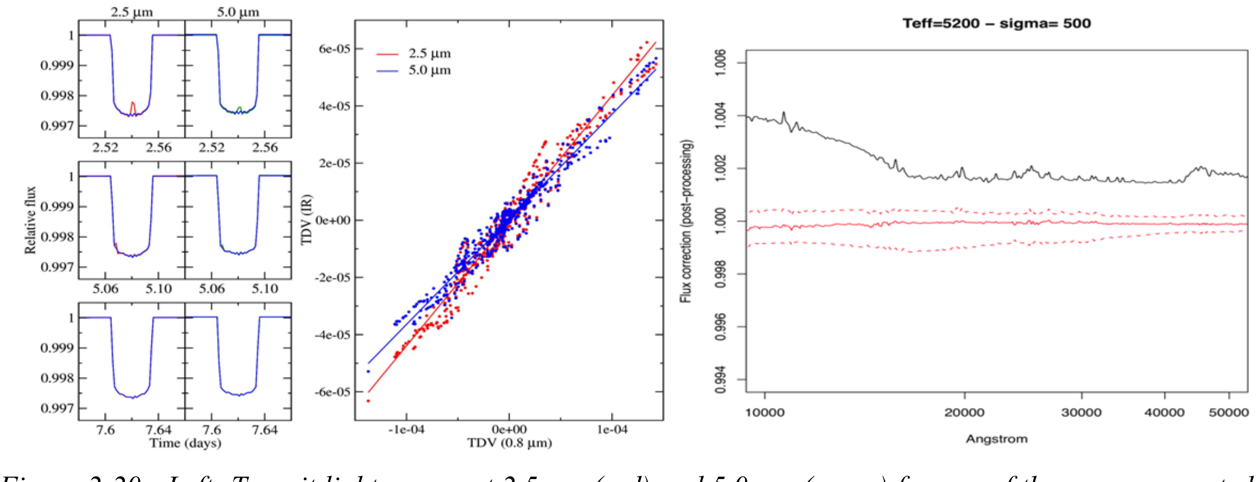


Figure 2-20: Left: Transit light curves at 2.5 μm (red) and 5.0 μm (green) for one of the cases generated in the sample, compared with the transit light curve of an immaculate star. Note the small systematic deviations and the more apparent spot crossing events. Middle: Correlation of activity-induced transit depth variations (TDV) in the visible (0.8 μm) and the IR (2.5 and 5.0 μm). Right: Spectrum distortion without corrections (solid black line), residual distortion after correction with method 2 (median and 25 -75% percentiles of simulations).

Method 2 **–** A complementary method has been developed to reconstruct the spectral energy distribution of the target stars in the IR using the visible spectrum (0.55-1 μm) as an instantaneous calibrator. Having a sufficient number of spectra of a given stars observed at different levels of activity, it is possible to calibrate the method for each star. Presently, the approach has been developed on a grid (in spot temperature and filling factor) of simple models of active stars and has been tested through simulations taking into account for photon noise. The method is based on principal component analysis. Since the new variables are chosen to maximize the variance, it is possible to reduce the dimensionality of the space, eliminating dependences among the original variables and noise. In all explored cases the first two components are retained: the first component is related to the slope of the spectrum while higher order components are related to features of the spectrum.

The procedure involves the following steps: 1) generation of 1000 simulations of the input model assuming a given average SNR per resolution element; 2) projection of the simulated spectra on the space of the first two components; 3) identification of the best fit spectrum of the grid in the principal component space, and choice of the corresponding NIR spectrum as the "best estimate" of the NIR stellar spectrum; and 4) comparison of the spectral distortion without any corrections (assuming unspotted star) and the residual after adopting the best estimate. Figure 2-20 shows as an example the median correction of the 1000 simulations and the 25% and 75% quartiles for T_{eff}=5200 K and stellar SNR=500. To quantify the correction we compare the distortion before applying our method, measured as the average value in the 1-2 μm band (where the effect is larger), and the equivalent average of the median and 25-75% quartiles of the residuals after correcting. Table 2-6 shows that the method allows significant reduction in spectral distortion.

		Residual distortion after correcting		
T_{eff} [K]	**No correction (1-2 μm)**	**SNR=200 (±25-75% quartiles)**	**SNR=500 (±25-75% quartiles)**	**SNR=1000 (±25-75% quartiles)**
6000	2.2e-3	-6.4e-5 [-9e-4 / 7e-4]	8.6e-5 [-5e-4 / 4e-4]	1.2e-4 [-4e-4 / 4e4]
5200	2.5e-3	-2.9e-4 [-1e-3 / 3e-4]	-6.8e-5 [-5e-4 / 2e-4]	5.2e-5 [-2e-4 / 2e-4]
4200	4.8e-3	3.0e-6 [-2e-3 / 1e-3]	4.0e-6 [-1e-3 / 9e-4]	0 [-3.8e-4 / 5e-4]

Table 2-7: Results of the comparison between spectral distortion before applying the corrections and the residuals after correcting, as a function of stellar effective temperature and SNR. The average values in the 1-2 μm band and the 25-75% percentiles derived from 1000 simulations are given.

Method 3 – A further approach has focused on statistical methods to de-correlate astrophysical noise from the desired science signal. Whilst the statistical fundamental of these methods are very different and often complementary, they all try to disentangle the astrophysical signal from various noise sources using the coherence of the exoplanetary transit/eclipse signature over time and/or frequencies of light. Figure 2-21 shows two examples of such a decorrelation. Given single time series on an active star with various modes of pulsation obtained by the Kepler space telescope, Waldmann [2012] showed that a randomly chosen pulsation mode of the star could be isolated and the remaining autocorrelative noise of the star suppressed, resulting in a strong reduction of the stellar noise component (Figure 2-21 left). Similar concepts apply to periodic exoplanetary lightcurves observed over multiple transits and/or wavelengths.

The results were repeated successfully for a sample of Kepler stellar light curves, spanning from M to G types. In all cases a correction of the order of 10^{-5} to 5 10^{-4} depending on the frequency of the sampling (i.e. 10 hours continuous observations every day or 10 hours once a week), was obtained [Danielski et al., 2013].

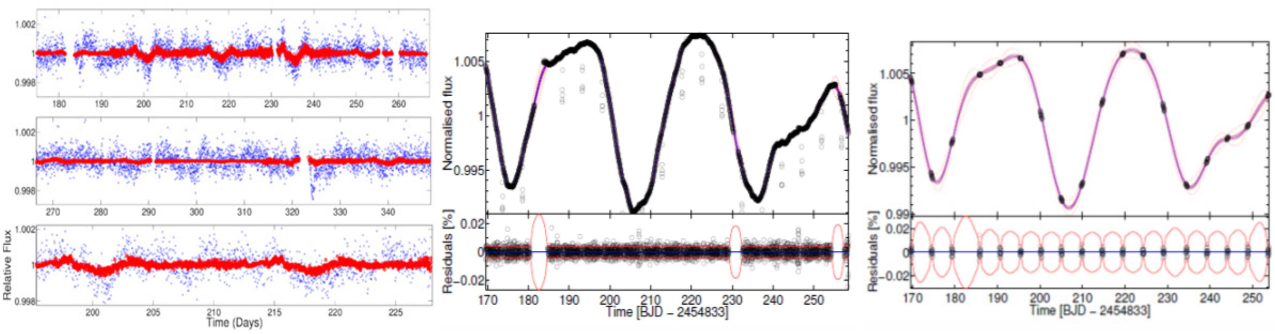


Figure 2-21: Left: Kepler time series of an active M0 star (blue dots). Using Independent Component Analysis, the periodic pulsation filter at t=202, 218 and 235 was filtered from other correlated noise in the time series. The filtered signal is shown in red [Waldmann 2012]. Centre and Right: Kepler time series of another active K4 star. Using a Gaussian Process based method the stellar activity was successfully filtered out, with residuals as small as 10^{-5} when considering daily observations of 10 hours (Centre) and 10^{-4} when data are acquired for 10 hours every 5 days (Right) [Danielski et al., 2013].

2.4 Mission strategy

In this section we describe the list of currently available targets for EChO (> 150), and we discuss the foreseen developments for the future, given the large number of ground and space dedicated facilities to discover new exoplanets in the next decade. The final list is expected to include between 150 and 300 exoplanets, with a variety of sizes, temperatures, stellar hosts and orbital parameters.

2.4.1 EChOs current Core Sample

To produce a sample of potential targets for EChO using known systems we first drew up a "long list" of known targets with well characterised stellar and planetary parameters. This list has been generated using the EChO Target List Observation Simulator (ETLOS) [Varley et al., TN] and will be continuously updated. ETLOS extracts the star/planet information from the Open Exoplanet Catalogue [Rein et al, 2013]; further verification is done using SIMBAD, the 2MASS catalogue and exoplanet.eu [Schneider, 2013] where appropriate. The Core Survey targets were then selected to ensure as diverse range stellar types, metallicities and temperatures as possible to fulfil the requirements of the Chemical Census. Suitable targets for the Origin and Rosetta Stone tiers were further selected to fulfil the SNR requirements expressed in (Table 2-2). The contents of this target list are discussed further in EChO-Design Reference Mission.

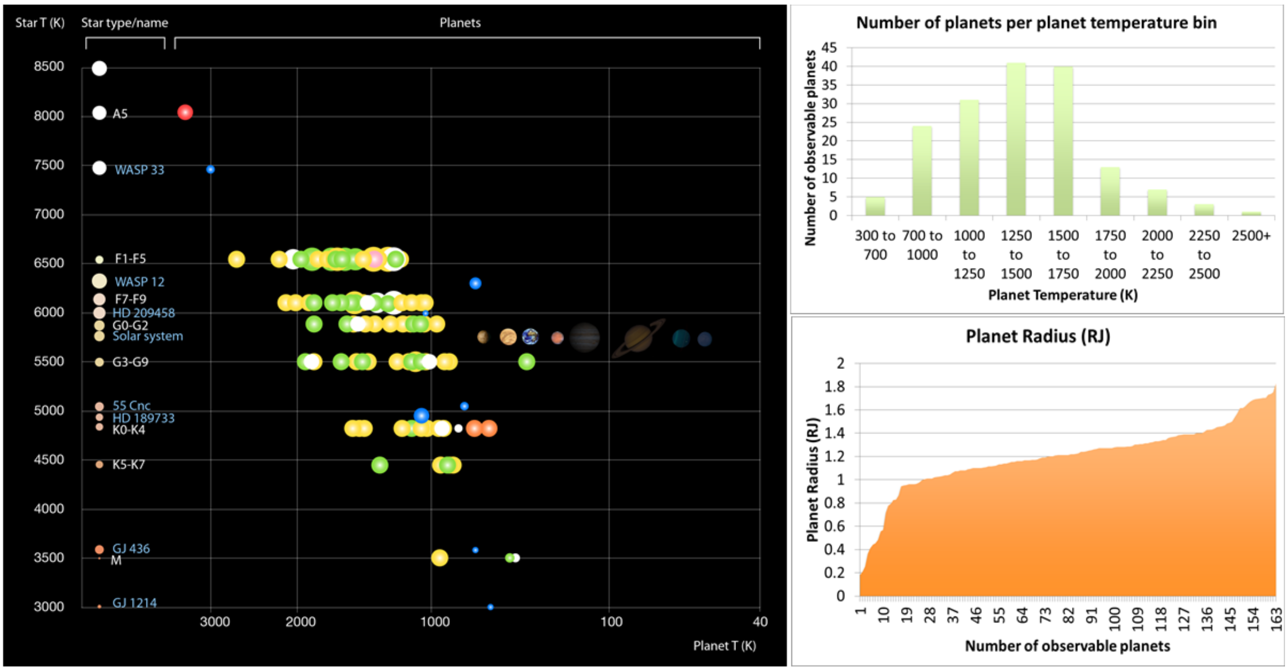


Figure 2-22: Left: type of planets/stars observable by EChO as of December 2013. Right top: planetary temperature in K. Right bottom: planet radius for exoplanets observable by EChO as of December 2013.

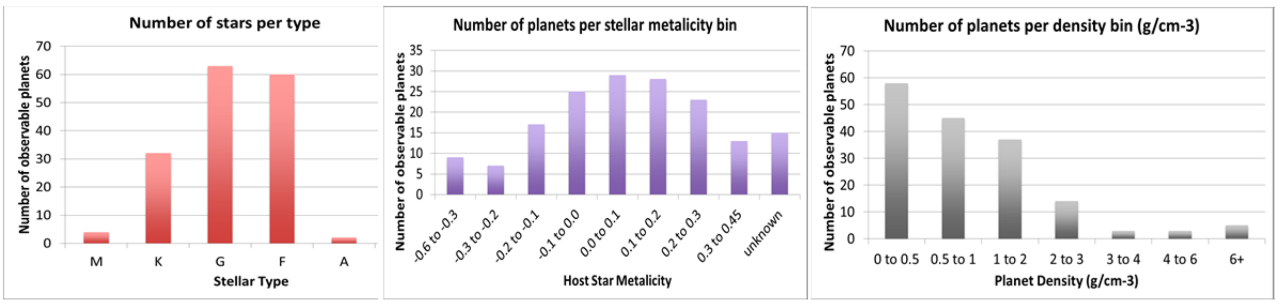


Figure 2-23: Left: Stellar Type, Middle: Stellar Metallicity, Right: Planetary density in g/cm^3 for exoplanets observable by EChO as of December 2013.

In order to assess the time needed to observe the required number of targets in the three survey tiers we have undertaken simulations of the mission and instrument performance. Two rather different approaches were taken for this. The first is a static model built using more generic assumptions about the instrument and mission performance [ESA Radiometric Model, SRE-PA/2011.040]. The second approach models the instrument as designed and uses a dynamic approach to the performance simulation using realistic stellar and planetary parameters to model to actual time domain signal from the observation (*EChOSim,* see Section 5.3.1.2). The list of known targets reported in DRM was run through the ESA–RM and *EChOSim* performance models. Although some differences are expected due to the different parameterisation of the instrument and other model assumptions (see [Waldmann et al., TN] for a detailed comparison), the results spread over the Core Survey are quite consistent, and the discrepancies for specific targets are understood and traceable. We are therefore confident of the robustness of the estimates obtained.

The selected Chemical Census, Origin and Rosetta Stone samples populating the required EChO Core Survey are listed in the DRM. This does not represent a unique list as the science objectives can be reached in a number of ways by increasing and diversifying the Chemical Census, Origin and Rosetta Stones samples. We stress that this is just one example worth considering among the many achievable possibilities. The diversity of the selection is shown in Figures 2-22 and 2-23 where we show how the numbers of targets are distributed between stellar type, metallicity, orbit type, density and temperature. Observations of all the planets were simulated with EChOSim to assess the number of transits required to reach the baseline and goal SNRs. The integration times needed for each observing mode and the detectability for key molecular species are reported in [Varley et al., TN].

2.4.2 New targets for EChO

Target selection is a key aspect of EChO. The choice of the targets will determine the planetary parameter space we will explore. The scientific outcome of the mission will depend on the observed sample.

There is no need to select the sample ten years before launch but we need a good plan to select the best sample immediately prior to launch. In the present phase we are defining the primary physical planetary parameters that define the "diversity" of planet population. These include:

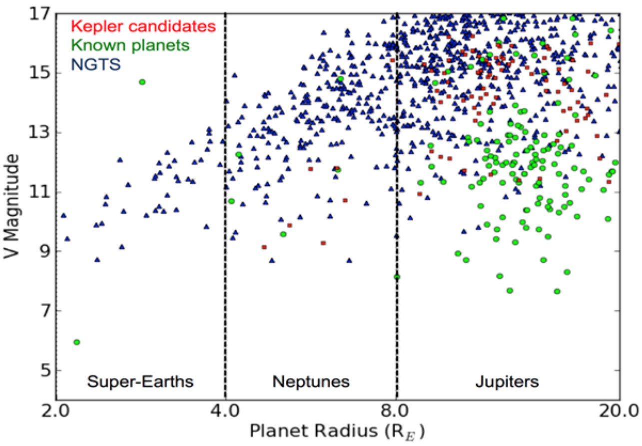
- *Stellar metallicity, age, temperature,*
- *Planetary temperature, mass and density.*

A sub-space of this parameter space will be explored by EChO. The mission is designed to fill such space. Several surveys both from ground and from space will provide targets with the necessary characteristics to meet the objectives of the mission. Table 2-8 summarises the most important surveys from which we expect a significant contribution to the final core sample. The list is not exhaustive.

Name of Survey/Mission	Key characteristics	Target stars relevant for EChO	Expected planets relevant for EChO	Notes
WASP/SuperWASP (Pollacco et al., 2006, PASP, 118, 1407)	• Ground photometric survey - broad band • All sky • Ongoing	G-early K	100 *J* Few *N*	Porb <10d > 70 J already discovered
HATNet/HATSouth (Bakos et al., 2002, PASP, 114, 974; 2013, PASP, 125, 154)	• Ground photometric survey - broad band • All sky • Ongoing	G/K	100 *J* Few *N*	Porb < 10d > 50 J already discovered
HARPS, HARPS-N, Keck, ESPRESSO, CARMENES, SPiROU	• Ground Doppler surveys - VIS/IR • Transit search through photometric follow-up • All sky, bright stars • Ongoing/being built	G/K/M	See below	Discovered the brightest known targets in each category
CHEOPS (Broeg et al., 2013, EPJWC, 47, 3005)	• Space photom. follow-up • 2017-2021 (3.5yr) • Monitoring of bright stars with Doppler-detected planets	G/K/M	10 *N* 5 *SE*	Also used to refine parameters of planets detected by ground-based transit surveys

Name of Survey/Mission	Key characteristics	Target stars relevant for EChO	Expected planets relevant for EChO	Notes
NGTS (Chazelas et al., 2012, SPIE, 8444)	• Ground photometric survey – broad band • Coverage 1,920° • -50 < dec < -30 • 2014 – 2019	G/K/M	100 *J* 20 *N* 20 *SE*	Porb < 16d
APACHE (Sozzetti et al, 2013, EPJWC,47, 3006)	• Ground photom. survey • Monitoring of 3,000 M • 2012-2017	M	5 *SN/SE*	Porb < 10d
GAIA (Lindegren, 2010, IAUS, 261, 296)	• Space astrometric survey • All sky • 2014-2019	All	10-15 *J*	Around M stars 0.5-3 AU
MEarth (Nutzman et al., 2008, PASP, 120, 317)	• Ground photom. survey • Ongoing	Late-M	5 *SN/SE*	Porb < 10d Discovered GJ 1214
TESS (Ricker et al., 2010, AAS, 42, 459)	• Space photometric survey • 45,000 sq degree • 2017-	G/K/M	650 *J* 1000 *N* 700 *SN* 300 *E & SE*	Porb < 50d

Table 2-8: Summary of the main surveys/projects that will provide targets for EChO in the next few years. The columns on target stars and expected planets refer specifically to the observations relevant for EChO. Legend: (J=Jupiters, N=Neptunes, SN=sub-Neptunes, SE= Super-Earths, E=Earths).



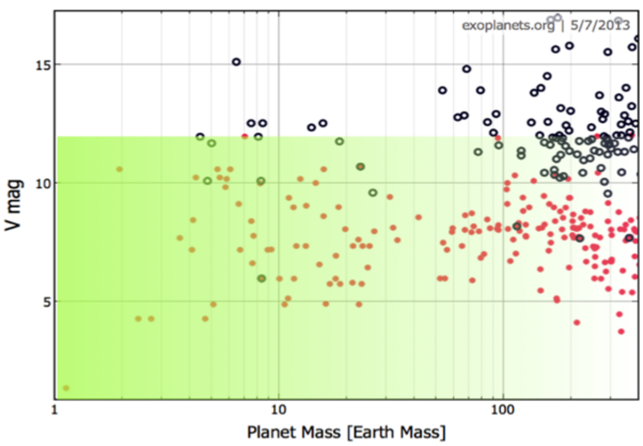


Figure 2-24: Left: Simulated planet population from NGTS. This assumes a survey of 1920 square degrees over five years. Each of the plotted simulated planets can be confirmed with HARPS or ESPRESSO in less than 10h exposure time. This instance of the simulation shows 39 confirmable super-Earths and 231 Neptunes. Of these, 23 super-Earths and 25 Neptunes orbit stars brighter than I=11. These planets will be the optimal targets for EChO. Right: Planets with measured mass from RV survey (red dots). Planets with measured radius from transit survey (black circles). The green shaded area is where CHEOPS will provide accurate radius measurements

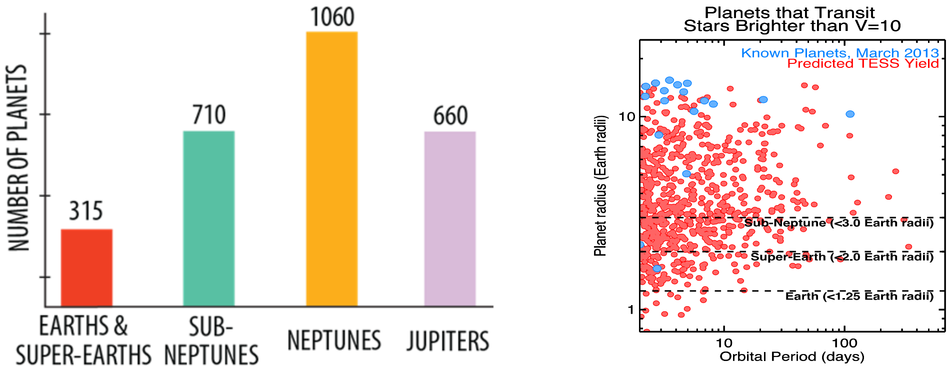


Figure 2-25: Left: Expected science yield from the TESS mission. Right: *Radius-Orbital period distribution of transiting exoplanets found around nearby stars brighter than V=10 as of March 2013 (blue dots), versus the number of such planets expected to be discovered by TESS (red dots). These planets will be the optimal targets for EChO.*

2.4.3 The future EChO Core Sample

A comprehensive exercise has been run to establish a target statistical sample of transiting targets for EChO that would cover the widest possible range of exoplanet/host star parameter space. This is an evolution of the Mission Reference Sample (MRS) described in [Ribas and Lovis, TN]. As a first step, star counts were estimated using (a) new catalogues [Lepine et al., 2013, Frith et al., 2013] making cuts based on spectral type and magnitude directly, and (b) using the combination of the stellar mass function derived from the 10-pc RECONS sample and the mass-luminosity-K-band relationship from [Baraffe et al., 1998]. Estimates were then made of the maximum number of exoplanets of a given exoplanet class (mean radius/mass: Jupiter-like 10 R_{Earth}/300 M_{Earth}; Neptune-like 4 R_{Earth}/15 M_{Earth}; Small Neptune 2.6 R_{Earth}/6 M_{Earth}; Super-Earth-like 1.8 R_{Earth}/7 M_{Earth}) and fiducial equilibrium temperature (T_{hot} = 1500 K; T_{warm} = 600 K; $T_{temperate}$ = 320 K) that transit a selection of stellar spectral types from K to M. This was done using statistics from the Kepler mission determined by Fressin [private communication], and adopting a methodology similar to that described in a recent paper by Fressin et al. [2013].

Planet occurrence rates based on Kepler results were calculated for all spectral types. These rates are weighted towards solar-like stars because of the predominance of FGK hosts in the Kepler survey itself. An analysis of the planet occurrence rates for M hosts observed by Kepler indicates that the rates are consistent with those found for earlier spectral types, albeit at low statistical significance (e.g. [Dressing et al., 2013]). Star counts, planet temperatures and types, and the transiting planet occurrence rate were then used to determine the numbers and types of transiting exoplanets around host stars down to a K-band magnitude of 9, with the overall total number in good agreement with estimates from HARPS [Mayor et al., 2011] as well as other estimates based on Kepler data [Howard et al., 2012]. Exoplanet orbital periods and transit times were then derived for each exoplanet target, and a heat re-distribution factor of 1, an impact parameter of 0.5 and albedos of 0.1 and 0.3 for Jupiters/Neptunes and Super-Earths, respectively, were assumed. Further details on the MRS and its definition can be found in [Ribas and Lovis, TN]. The resulting hypothetical so-called Mission Reference Sample (MRS, Fig. 2-26) illustrates a possible parameter space that EChO may observe in the Chemical Census and Origin surveys according to current SNR requirements and conservative assumptions on instrument performance. The tables also include information on the technique best used to observe the planet (i.e., transit/transmission or occultation/emission) for optimal results. The total number of targets is 238, with the following distribution:

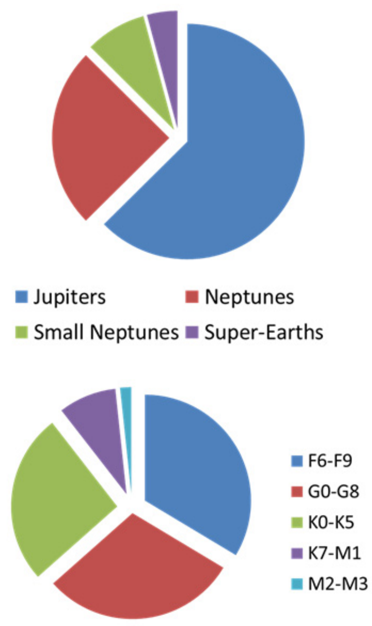


Figure 2-26: Pie charts illustrating the different planetary classes considered for the future core sample

- 10 Super-Earths (hot), complete out to 30 pc
- 20 Small Neptunes (hot and warm), complete out to 40 pc
- 59 Neptunes (hot and warm), complete out to 70 pc
- 149 Jupiters, complete out to 150 pc (hot) and 100 pc (warm)

2.5 Synergy with other facilities

EChO, JWST and E-ELT are highly complementary facilities. Together they will guarantee transformational exoplanet science. We discuss here their strengths and limitations, and how they should be used in synergy to accomplish outstanding achievements.

2.5.1 EChO in context of the JWST and ELT

The planned timing for the ESA-M3 would make the EChO mission operational in conjunction with the James Webb Space Telescope (JWST) (assuming its goal lifetime of 10 years and an on schedule launch in 2018, http://www.jwst.nasa.gov/faq.html#howlong) and the ground-based European Extremely Large Telescope (E-ELT) (assuming first operations in 2022). In this way EChO, JWST and E-ELT observations, which are highly complementary, will be mutually beneficial. While JWST will provide state-of-the-art measurements for a select number of planets, mostly over a limited wavelength range, the E-ELT will provide targeted observations for some planets at ultra-high spectral resolving power at specific wavelengths. **The role of EChO will be to provide the broad picture by performing a systematic and uniform survey of exoplanets (between 150 and 300). This will enable scientists to glue together the pieces of the puzzle by providing the instantaneous broad wavelength coverage, which is inaccessible to pointed observations of individual objects by JWST and E-ELT (Figure 2-27).** Such instantaneous broad wavelength coverage is also essential to for correct the stellar activity (see Section 2.3.4.2). **The three observatories together will deliver transformational science**.

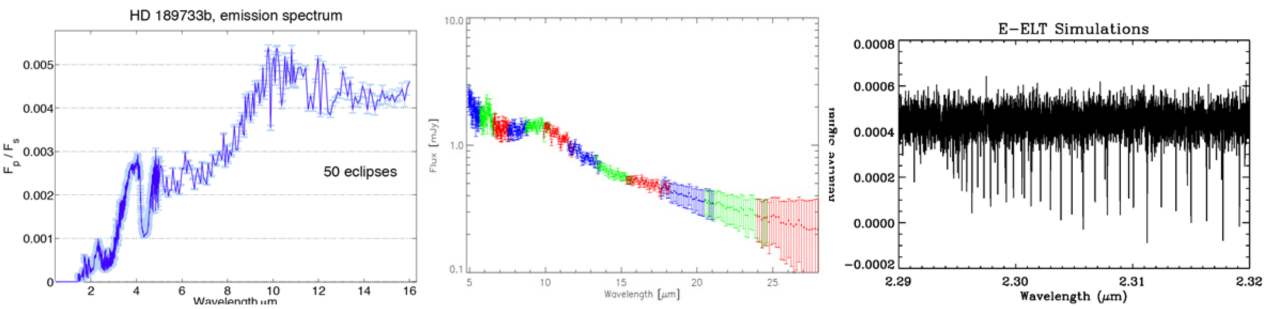


Figure 2-27: Synergy between EChO, JWST and E-ELT: comparison of eclipse spectra of the hot-Jupiter HD 189733b as observed by the three facilities. Left: simulations of EChO performances when co-adding 50 eclipses. Centre: Smoothed model MIRI-MRS spectrum. The JWST MRS SHORT, MEDIUM and LONG spectra are plotted as blue, green and red lines respectively, they cannot be observed simultaneously (A. Glasse, private comm). Right: simulated spectrum as obtained by HIRES.

2.5.1.1 EChO & the JWST

JWST is the largest space telescope ever conceived, with an equivalent telescope diameter of 5.8 m and 22 m^2 collecting area. It is designed to operate over the visible (~0.6 µm) to mid-IR waveband (28 µm) providing very high sensitivity imaging and spectroscopy of faint astronomical targets. It is a true observatory with multiple capabilities, instruments and operating modes, optimised for background limited observations. JWST is scheduled for launch in late 2018. Although primarily designed for observations of very faint targets (in the µJy range), JWST will do a great deal of ground breaking exoplanetary science.

Instrument	Mode	Resolving power	Wavelength range (µm)	Comments
NIRISS	Grism, cross-dispersed, slit-less	700	0.6 - 2.5	Saturates at K<9 at some part of band
NIRCam	Grism, slit-less	2000	2.4 - 5.0	Not proposed for transit spectroscopy in SODRM

Instrument	Mode	Resolving power	Wavelength range (µm)	Comments
NIRSpec	Prism, wide slit (1.6")	100	0.6 - 5.0	Saturates at K<8.5 at some part of the band. Wavelength range covered using 3 separate orders
NIRSpec	Grating, wide slit (1.6")	1000 or 2700	(0.7)1.0 - 1.8 1.7 - 3.0 2.9 - 5.0	Uses three grating settings to cover wavelength range. Effective SW cut on is 0.9 µm
MIRI	Prism, 0.6" slit or slit-less	100	5.0 - 11.0	Saturates at 2.9 Jy at 10 µm (K~6)
MIRI	IFU (0.2" - 0.27"/pixel)	2400–3600	5.0 - 7.7 7.7 - 11.9 11.9- 18.3 18.3 - 28.3	Each band uses 3 sub-bands with separate gratings.

Table 2-9: JWST instruments and observing modes useful for transit spectroscopy

Table 2-9 summarises the JWST instruments and operating modes that will be useful for exoplanet transit spectroscopy. Studies of the performance of the instruments for transit spectroscopy have been carried out notably for NIRISS and NIRSpec (Dorner Phd Thesis Universite de Lyon 2012, Clampin 2010, http://www.cosmos.esa.int/web/jwst/exoplanets). Both transit & eclipse measurements over the full waveband from 0.6 to 28 µm are possible with the combination of the instruments and modes on JWST. However, both its extremely high sensitivity and observatory nature mean there are significant restrictions on the type and number of targets that will be observable. Some of these are indicated in Table 2-9 together with the primary observing modes expected to be used for transit spectroscopy. In addition to these instruments/modes there are a number of direct imaging possibilities using JWST and much of the exoplanet observing time will be dedicated to direct imaging – for a full summary see http://www.stsci.edu/jwst/doc-archive/white-papers).

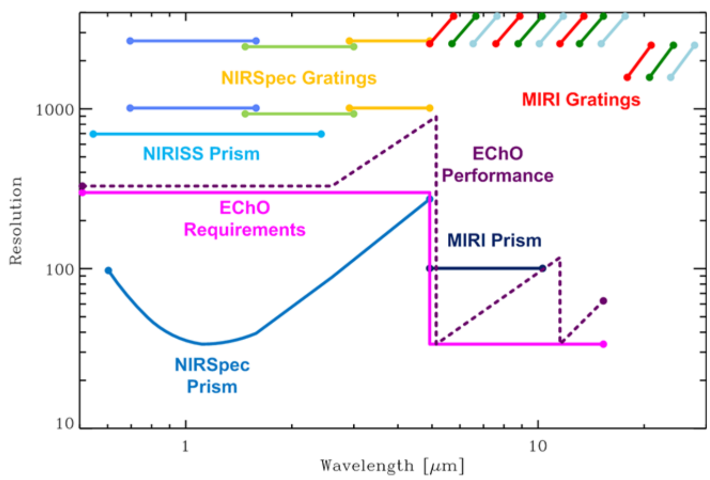


Figure 2-28: Wavelength coverage and spectral resolution of JWST spectrometers and the EChO instrument. NIRISS, NIRSpec and MIRI have to be used sequentially in any mode.

Observing constraints – The main difference between JWST and EChO is that to cover the core band of interest (0.6-11 µm) with JWST, even for targets which do not saturate the detectors, requires the use of at least two instruments – NIRSpec and MIRI in prism mode – operated serially. Although, the instantaneous sensitivity in these modes is very much higher than EChO, JWST will be restricted to fainter targets – roughly K > 8.5 magnitude (EChO is optimised for K < 9). In addition, unlike EChO, to get the entire spectrum one must patch together multiple observations from different instruments. These will be taken, necessarily, at different observing times and with, generally, separate re-pointings to the target. In order to do this without adding systematic noise requires high accuracy inter instrument calibration combined with extremely high temporal stability. Also, stellar activity will make it very challenging to combine observations of sub-bands into one overall spectrum. EChO has the great advantage that it is designed from the outset to tackle these issues.

Brighter targets will be observed using the medium resolution grating spectrometer modes on JWST. Here the issue of covering the wavelength range becomes even more marked as it will require three grating settings for NIRSpec and three for MIRI (see Figure 2-28). This implies six separate observations of a target to cover a single transit. This would a) not be a very efficient use of JWST time and b) the ability to piece together six separate spectra with the accuracy required will require lengthy detailed and dedicated calibration observations. EChO solves this issue, as it could provide the continuum at lower resolution.

What will JWST observe? – According to their respective schedules (late 2018 for JWST and 2022-2024 for EChO) there should be at least one year of overlap between the missions allowing synergistic observing programs to be enacted. In this case, the rather higher calibration precision offered by EChO for a subset of the JWST targets could be used to provide templates to allow the high resolution spectra to be accurately pieced together. **Once both observatories are in operation, a truly synergistic observing program can be built with EChO rapidly identifying targets of interest for JWST's higher resolution spectrometers to be used to full advantage.**

Before EChO is launched, and again assuming it launches on time, JWST will have about three years observing time in orbit, enabling the JWST observing teams to conduct observations of exoplanet spectra targeting the most promising candidates. A first cut, notional observing program for the JWST is encompassed in the Science Observations Design Reference Mission (SODRM - http://www.stsci.edu/jwst/science/sodrm/jwst/science/sodrm/). This consists of a number of observing programs built around seven science themes designed to allow the mission team test the observation planning tools. The JWST SODRM shows that there are three main transit spectroscopy programs utilising NIRISS, NIRSpec and MIRI for exoplanet science. The NIRSpec program has about 25+ targets, NIRISS 15 targets, and MIRI 9 targets**.** Typically then some tens of targets will have been assessed in the visible and NIR band and about ten to fifteen may have been observed across the full NIR/MIR range in both primary and secondary transit. To optimise the use of EChO, we would need to assess whether these targets should be re-observed, and what advantage there might be in doing so.

2.5.1.2 EChO & the E-ELT

With the EChO launch and operation foreseen in the early 2020s, it means that it will be perfectly timed to work in conjunction with the next-generation ground-based telescopes, such as the Extremely Large Telescope. ELT and EChO observations will be highly complementary and mutually beneficial. Ground-based observations of exoplanet atmospheres have many challenges and limitations. Large parts of the electromagnetic spectrum are blocked from view due to absorption and scattering in the Earth's atmosphere. In addition, the thermal background from the sky and telescope are strongly variable, making high-precision ground-based transit or eclipse spectroscopy practically impossible from the ground at >5 μm. However, the ELT will be very valuable in specific ways. One particularly successful observing strategy makes use of spectroscopy at a very high dispersion of R=100,000. At this resolution, molecular bands in exoplanet spectra are resolved into hundred(s) to thousands of individual lines, whose signals can be combined to secure a more robust molecular detection. Only astrophysical information over small wavelength scales is preserved, hence the line-contrast is being measured with respect to a local pseudo-continuum. This technique has been used very successfully using the VLT, for both exoplanet transmission spectroscopy [Snellen et al. 2010] and emission spectroscopy [Brogi et al. 2012], and will be up to two orders of magnitude more powerful on the next-generation ELT.

ELT observations will be highly complementary to EChO. The EChO spectra, which will be obtained over a large instantaneous wavelength range, are crucial for measuring the most important planetary atmosphere parameters – the temperature-pressure profile and the main molecular abundances. With these parameters determined by EChO, high-resolution ELT observations, providing planet differential transmission and day-side spectra at specific wavelengths, can be calibrated and used to target other, specific aspects of the planetary atmospheres. For the best observable targets, e.g. those targeted by EChO in the Origin and Rosetta tiers, the ELT can provide information on the rotation of the planet and high-altitude wind speeds using the absorption line profiles – important ingredients for global circulation models (e.g. see Showman et al. 2013 for theoretical simulations). Using the high-dispersion technique, the line-contrasts can be measured for a large part of the planet orbit, meaning that variations in molecular abundance ratios (when linked to EChO observations) and/or the atmospheric temperature-pressure profile could be traced from the night, morning, to evening-side of the planet, revealing the influences of possible photo-chemical processes. It may even be possible to detect different molecular isotopologues and determine isotope ratios, giving insights into the evolutionary history of the atmospheres. Other examples of synergies between the ELT and EChO are for detecting trace gases in the planet atmospheres with only weak molecular features only marginally detected with EChO. Interesting spectral regions for specific planets can be identified by the EChO tiers and subsequently targeted with the ELT.

Telescope	Diameter	Instrument	Spectral Range	Instant coverage	spectral dispersion
E-ELT	39 m	METIS	2.9-5.3 μm	0.1 μm	R=100,000
		HIRES	0.4-2.3 μm	0.4-2.3 μm	R=100,000
		MOS	0.4-1.7 μm	0.4-1.7 μm	R<30,000
GMT	24.5 m	MOS	0.4-1.0 μm	0.4-1.0 μm	R<5000
		NIR-HRS	1.0-5.0 μm	TBD	R~50-100,000
		G-CLEF	0.4-1.0 μm	0.4-1.0 μm	TBD
TMT	30 m	WFOS	0.3-1.0 μm	0.3-1.0 μm	R<7,500
		HROS	0.3-1.0 μm	0.3 -1.0 μm	R~50-90,000
		IRMOS	0.8 - 2.5 μm	0.3 μm	R=2,000-10,000
		MIRES	9-18 μm	8-14 μm	R=100,000
		NIRES	1-5 μm	~2 μm	R=100,000

Table 2-10: Planned next-generation telescopes and their instrumentation relevant to transiting exoplanet characterization science. Currently, three ELTs are on the drawing board, the European ELT (E-ELT - http://www.eso.org/public/teles-instr/e-elt.html), the Giant Magellan Telescope (GMT - http://www.gmto.org), and the Thirty-Meter Telescope (TMT - http://www.tmt.org/). Note that at the time of writing, funding has not been completely secured for any of the three telescope projects. The earliest deployment for any of these will be the early 2020s. Also, the instrumentation for the telescopes has by no means been finalised, and a significant fraction of these instruments may never be developed, or change.

2.6 EChO science beyond exoplanets

In addition to the science of exoplanets, EChO has the capability to make important observations in the field of planetology, stellar physics, disks and brown dwarf studies, exploring a continuum of objects between planets and stars [Drossart et al., TN], in particular:

(i) **Stellar physics –** A relevant part of stellar science will come from the activity analysis that is needed to extract the planetary signal. So most of the material is described in the main activity plan.

(ii) **Physics of circumstellar disks around young stars –** a list of accessible objects shows that tens of T Tauri stars are potentially accessible for EChO. Physics of circumstellar disks with spectral variability in the 0.4/11 μm range is of interest for disk astrophysics and planetary systems' formation.

(iii) **Solar System objects –** Planetary objects can be observed with EChO (even with the slit aperture of 2x10 arcsec in the visible channel limiting the FOV) mainly for calibration purpose. Planetary satellites are also good reference objects to observe. This can be done with limited pointing accuracy (~1 arcsec). Comets (if a bright comet is available) can also be observed with EChO.

(iv) **Stellar occultations on Solar System Kuiper Belt Objects –** Planetary occultations can search for atmospheric perturbations during occultation. An occurrence of ~1 event/year for large KBO objects (Pluto, Quaoar, Eris...) is expected. Nevertheless, these occultations are rare.

(v) **Planetary seismology –** Due to the EChO aperture, only Uranus and Neptune are observable. Search for planetary oscillations through long duration continuous spectral observations in the infrared.

(vi) **Brown dwarf observations** – Homogenous sample of brown dwarfs (K=10-15), spanning the range of known spectral types, each observed during one rotational period (typically 10 hours).

2.7 Conclusions

Our knowledge of planets other than the eight "classical" Solar System bodies is in its infancy. We have discovered over a thousand planets orbiting stars other than our own, and yet we know little or nothing about their chemistry, formation and evolution. Planetary science therefore stands at the threshold of a revolution in our knowledge and understanding of our place in the Universe: just how special are the Earth and our Solar System? It is only by undertaking a comprehensive chemical survey of the exoplanet zoo that we can hope to answer this critical question. EChO is the <u>only</u> planned facility that can provide the necessary observations.

The time is right for a change to mankind's Solar-centric cosmogony similar to that provided by Galileo. EChO will be the mission that will start the paradigm shift.

3 Scientific requirements

In this chapter we provide the flow-down from the science objectives of EChO to the science requirements. We summarise both the science requirements for the EChO core survey, and the key science requirements for the mission. Examples of current and future core surveys are given in the Design Reference Mission (DRM) document [EChO-SRE-SA-PhaseA-010]. Further details on the science requirements can be found in the EChO Science Requirements Document [SciRD, SRE-PA/2011.037]. Both documents, along with technical notes providing a more extensive justification for selected requirements, can found on the ESA EChO webpage (see Chapter 10 (References) for details of the link).

3.1 The EChO sample

The high-level science objectives of EChO are summarised in Table 2-1 in Chapter 2. These in turn place requirements on the breadth and depth of the EChO Core Survey.

- EChO shall observe a core sample of > 100 exoplanet targets, known as the EChO Core Survey, with a goal of > 200 exoplanet targets. The mission design shall allow observations of a wide range of planetary sizes from gas giants to super-Earths to be carried out. These exoplanets will have a range of temperatures from hot (up to 3000K) to temperate (350 K) and will be found orbiting a range of stellar types and magnitudes from cool M-dwarfs to hot F-stars.
- The mission design shall encompass both the faintest and brightest expected targets: nominally these are exemplified by the systems GJ1214 (faint cold dwarf star) and 55Cnc (bright G star) (see Section 3.2.7).
- The survey will be divided into three survey tiers – Chemical Census, Origin and Rosetta Stone: a description and the characteristics of each of the tiers are given in Table 2-2. More than 25 of the planets observed in Chemical Census tier shall be observed in Origin tier, with a goal for the number to exceed 50. More than 10 of the planets observed in the Chemical Census tier shall be observed in the Rosetta Stone tier, with a goal for this number to exceed 20.

Examples of current and future core surveys are given in the DRM [EChO-SRE-SA-PhaseA-010].

3.2 EChO science requirements

3.2.1 Wavelength coverage

Spectral coverage over a broad wavelength range is required to cover the wide range of planetary temperatures and molecular/atomic features which are the key EChO observables (see Section 2.3.2.1) but also to monitor the stellar activity (see Section 2.3.3.2).

- The baseline requirement for the instantaneous spectral coverage of EChO is 0.55 – 11 μm, with a goal to reach 0.4 – 16 μm.

Given an instantaneous baseline wavelength coverage spanning over 4 octaves, it will be necessary to split the waveband in a series of discrete spectrometer channels. Baseline and goal requirements have been formulated that prioritise the protection of key wavelength intervals, based on the importance of a given spectral feature. These are summarised in Table 3-1 and Figure 3-1.

In-band (where in-band refers to a wavelength interval in which cuts cannot be made) performances should meet all other science requirements. In the transition region between two adjacent bands, relaxation of in-band performance to 50% is allowed taking into account both adjacent channels i.e. at any wavelength in the transition band at least one of the two adjacent channels or the combination of signals from these channels has to have at least 50% performance. Overlap between spectral channels shall be ≥ 5 resolution elements for λ <5 μm (assuming R≥300) and ≥ 1 resolution element for λ>5 μm (assuming R≥30). A minimum of 80% of the in-channel average performance is required for each resolution element.

KEY SPECIES		
Molecule/ion	Centre wavelength (µm)	
	Wavelengths ≤ 3 µm	Wavelengths > 3 µm
H_2O	1.13 (1.10, 1.20), 1.38 (1.31, 1.50), 1.90 (1.75, 2.02), 2.69 (2.38, 3.00)	6.20 (5.70, 8.00)
CH_4	1.13 (1.10, 1.20), 1.38 (1.31, 1.50), 1.70 (1.60, 1.85), 2.31 (2.11, 2.52)	3.30 (3.00,3.60), 7.70 (6.30, 8.30)
NH_3	3.00	6.10 (5.70,6.50), 10.50 (9.30,11.00 including O_3)
CO_2	1.60 (1.55, 1.67), 2.03 (1.91, 2.10), 2.80 (2.65, 2.82)	4.35 (4.10, 5.00 to include CO), 15.0 (13.50, 16.00)
CO	2.35 (2.30, 2.39)	4.7 (4.10, 5.00 to include CO_2 @4.35)
O_3		9.60 (9.30, 11.00 including NH_3)
H-alpha	0.66 (0.645, 0.665)	
Na	0.59 (0.56, 0.62)	
K	0.77 (0.74, 0.80)	
CaH/TiO bands	0.69 – 0.72	
GOAL SPECIES		
	Wavelengths ≤3 µm	Wavelengths > 3 µm
H_3+	2.0 (1.95, 2.10)	3.20 (3.00, 3.60), 4.00 (3.85, 4.10)
C_2H_2+HCN	3.0 (2.90, 3.10)	7.00/7.53 (6.50-8.00), 13.80 (13.00-14.00)
C_2H_6		3.40 (3.30, 3.50), 12.00 (11.5-13.00)
PH_3		4.30 (4.10, 4.40 to include H_2S @ 4.30), 8.90 (8.50-9.00), 10.10 (10.00-10.50)
H_2S	2.6 (2.50, 2.70)	4.30 (4.10, 4.40 to include PH_3 @ 4.30), 8.00 (7.50-8.50)
SO_2		7.30 (7.00-7.50), 8.80 (8.20-9.00)

Table 3-1: A table of wavelengths of spectral features in the EChO waveband at which subdivision should not be made. Associated with each wavelength is an interval (lower/ upper bound) in which the cut should not fall.

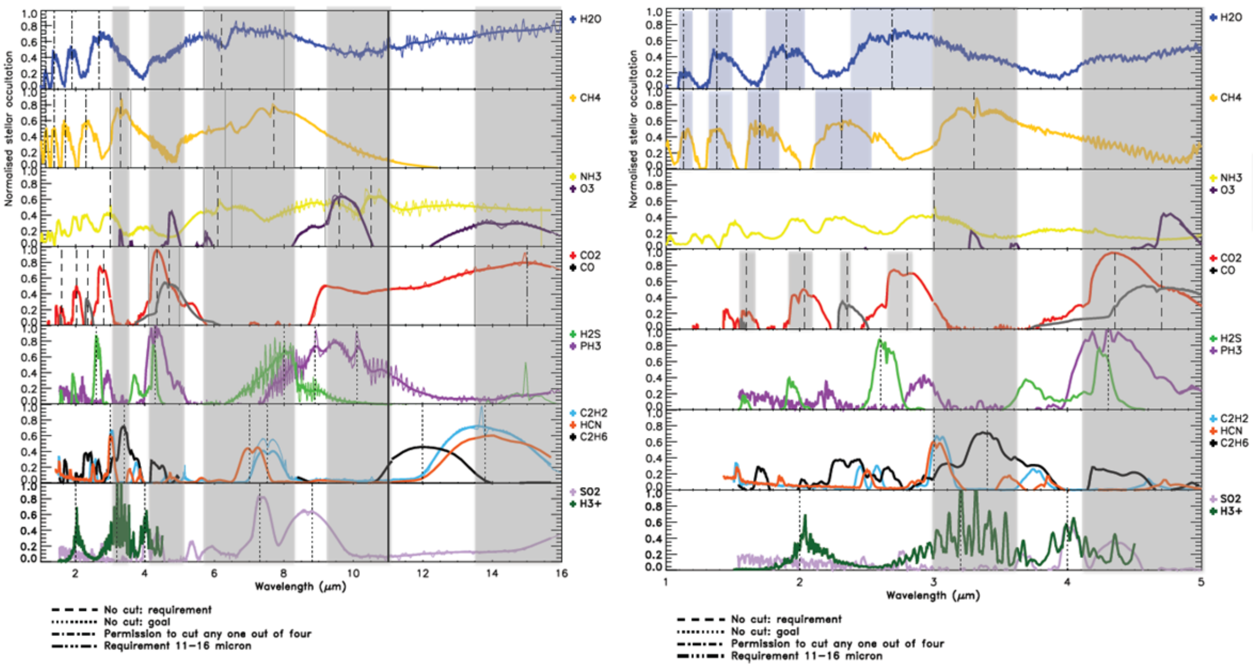


Figure 3-1: Left panel: Plots of the normalised expected signal from a modelled exoplanet atmosphere with a single observed during stellar occultation, as a function of wavelength for key and goal species. Vertical lines indicate the centres of spectral features (see legend for further detail). Lightly shaded bands indicate

the intervals around a spectra feature in which a cut must not fall. Right panel: as left panel, with detail covering the 1 – 5 μm interval. In the case of H_2O and CH_4 where necessary a cut can be made in any one of the four shaded (light blue) intervals indicated for each molecule

3.2.2 Spectral resolving power

The final resolving power, R (λ/Δλ), and ultimately resolution achieved for any observation will be trade-off between the desire to resolve as many spectral features as possible and the need to detect these same features at a statistically significant level. It will therefore depend on the brightness of the star, planet/star contrast and the observing time available, as well as the sensitivity of the EChO instrument.

The scientific rationale for the baseline and goal spectral resolving power is presented in Section 2.3.2.1. Based on this,

- EChO shall have a resolving power of R ≥ 300 for λ<5 μm, R≥ 30 for λ>5 μm where R is defined as *λ/Δλ* where Δλ ≥the full width half maximum of the monochromatic system point spread function. The goal is to reach a resolving power of R ≥ 300 over the goal wavelength range specified in Section 3.2.1

In Section 3.2.3 we tailor the spectral resolution and SNR to the different EChO survey tiers.

3.2.3 Signal-to-noise ratio and noise requirements

In Section 2.3.2.3 we presented the optimal SNR and spectral resolving power needed for the spectral retrieval of molecules and thermal profiles for a range of planetary atmospheres, hence to achieve the EChO science objectives. Here we summarise the required and goal SNR and spectral resolving power for the three tiers of the EChO Core Survey:

- The average SNR achieved per spectral element for targets defined in the Chemical Census shall either be ≥5 at R=50 averaged over the 2 μm ≤ λ ≤ 5 μm wavelength interval, or shall be ≥5 at R=30 over the 5 μm < λ ≤ 11 μm wavelength, whichever is less demanding. The planet shall be observed in primary transit or occultation/eclipse, whichever is less demanding.
- The average SNR achieved per spectral element for targets defined in the Origin tier shall be either ≥10 at R=100 averaged over the 2 μm ≤ λ ≤ 5 μm wavelength interval, or ≥10 at R=30 over the 5 μm < λ ≤ 11 μm wavelength interval, whichever is less demanding. The planet shall be observed in primary transit and occultation/eclipse.
- The average SNR achieved per spectral element for targets defined in the Rosetta Stone tier shall either be ≥20 at R=300 averaged over the 1 μm ≤ λ ≤ 5 μm wavelength interval, or shall be ≥20 at R=30 over the 5 μm < λ ≤ 11 μm wavelength, whichever is less demanding. The planet shall be observed in primary transit or occultation/eclipse, whichever is less demanding. As a goal, the planet shall be observed in both transit and occultation.
- All targets observed in the Chemical Census and Origin tiers shall be observed with at least 90% of the SNR above, with a goal to reach at least 95%.
- For all targets observed in primary transit the average SNR on the stellar signal per spectral resolution element at R=300 in the 0.55 – 1.0 μm waveband shall be ≥ 200 per transit event.

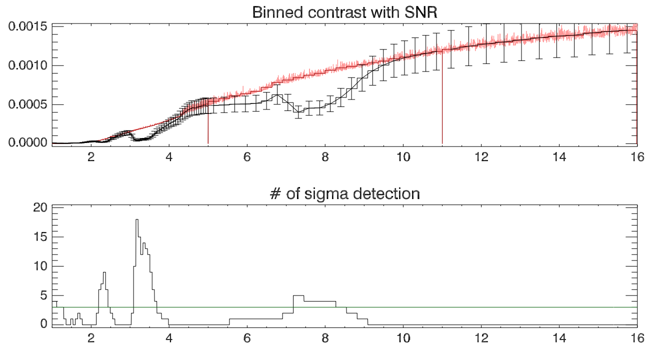


Figure 3-2: Simulations of a planet to star flux ratio for a warm Neptune around an early M dwarf. In the planetary atmosphere we have included molecular hydrogen and helium, and methane as trace gas (based on [Tessenyi et al., 2013]). Left: detectability of methane with a SNR and R compatible with the Chemical Census as a function of wavelength in μm. The methane mixing ratio is 10^{-5}. The figure at the bottom shows the level of confidence of the detection. Right: detectability of methane with a SNR and R for the Rosetta Stone tier. The methane mixing ratio is 10^{-6}.

Two sources of astrophysical noise shall be minimised when selecting targets for the EChO core survey: neighbouring sources that fall within the field of view of target stars shall make a negligible contribution to the noise budget; stellar variability (post-processing) shall make a negligible contribution to the noise budget (< 10% in root sum square), where measurements of the continuum stellar flux below < 1.0 μm will be used to monitor and correct for stellar variability across the full EChO waveband, as described in Section 2.3.4.2. Confirmation of inclusion of targets in the EChO core survey will be made on a case-by-case basis following an assessment of the likelihood of targets complying with these requirements.

3.2.4 Photometric stability

Photometric stability is the critical requirement of the mission. EChO will observe exoplanets with contrast ratios between the exoplanet and host star of as low as 10^{-5} and typically 10^{-4}. To achieve this with SNR and at the spectral resolution called for in the different survey tiers may require the co-addition of data taken over a few to a few to tens of transit events, depending on the source characteristics. In order that the co-addition itself does not add a systematic noise component to the data, a stability of 10^{-4} or better is needed in each transit event. This stability is required over a frequency range defined by the timing of the transit event itself, which is known with high accuracy. Based on the target lists described in Section 2.4 and in the DRM [EChO-SRE-SA-PhaseA-010], the maximum timescale is set by the duration of an observation which, assuming an equal observing time spent in- and out- of transit, is around 10 hours. The minimum relevant timescale is that required resolve temporally ingress/egress with durations of 10s of minutes (see Section 3.2.6). Taking these limiting cases into account sets the baseline frequency interval to be considered to 2.8×10^{-5} Hz to 3.7 mHz; with a goal to reach 3.8×10^{-6}Hz to 16mHz which is set by the duration of a representative phase curve observation and a shorter cadence time.

3.2.5 Sky visibility/source accessibility

EChO will visit a large and well-defined set of targets (see Section 2.4). Repeated visits may be required to build up the SNR of individual target spectra. The maximum duration of a visit to a target system will be ~10 hours – the time of the transit itself, plus half that time before and then after the transit. The time between successive transit observations will depend on orbital period and scheduling, and could be as little as a day, to as long as a few tens of days. In principle, the targets may be in any part of the sky, and as such the satellite needs a large field of regard, with minimal constraints (due to Earth/Sun) on the direction in which it can be pointed. The most challenging targets for EChO will be temperate super-Earths around M-type stars. Given the orbital radius and so period of a typical temperate planet (T_p~300K), a maximum number of a couple of hundred transits (depending on the effective temperature/spectral type of the host star) would occur during a mission lifetime of 4 years. Without access to a significant fraction of these transits it will not be possible to achieve the required SNR. The requirement on sky visibility is that 40% of the sky shall be accessible at any one time. The same 40% shall be accessible over a period of ~10 hrs. The complete sky shall be accessible within a year, with a source at the ecliptic observable for 40% of the mission lifetime.

Shown in Figure 3-3 is a plot of the sky visibility for EChO, superposed on which are targets from the different tires of the EChO core survey.

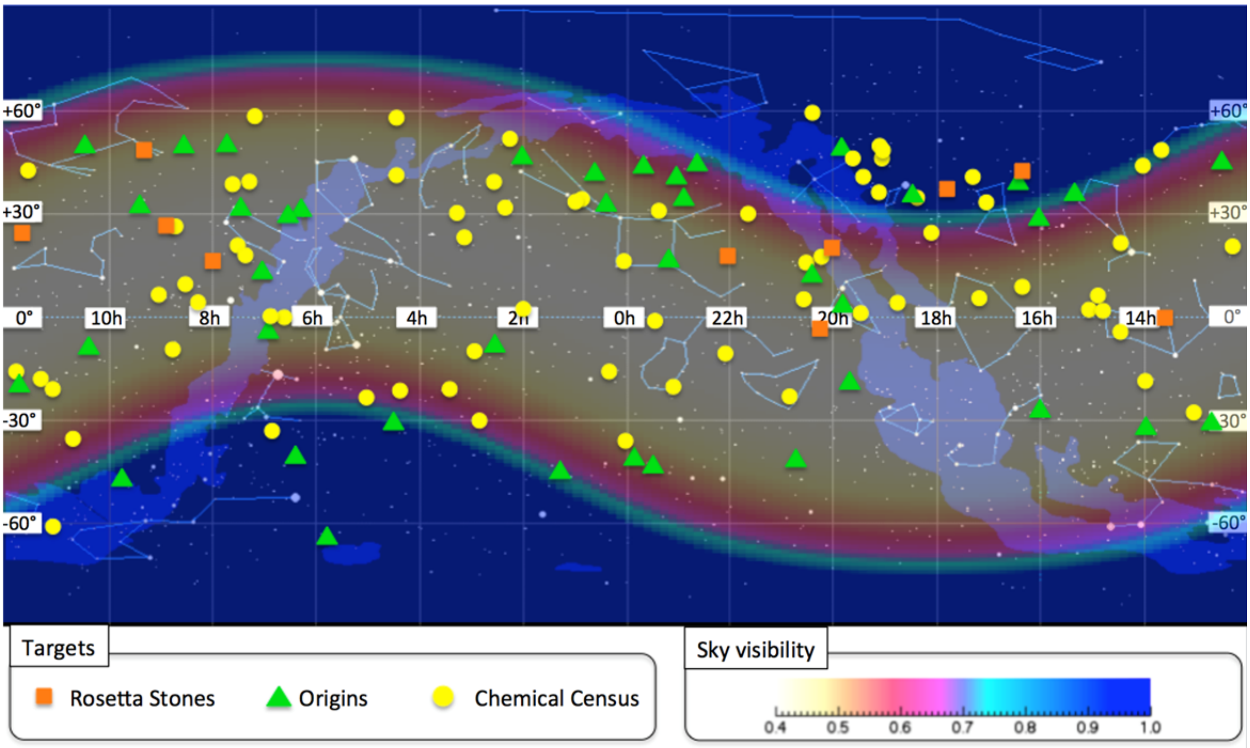


Figure 3-3: A plot illustrating the fraction of the year for which a given location in the sky (in equatorial coordinates) is visible to EChO, as seen from a representative operational orbit of EChO at L2. Superposed are known exoplanets that would be targets in the EChO Core Survey, as described in Sections 2.3.2.2 and 2.4.1).Each target is accessible for at least 5 months (40% of time).

3.2.6 Temporal resolution

The accuracy and reliability with which atmospheric parameters can be derived will depend not only on the final SNR of the spectra, but also on the temporal sampling that can be achieved – additional constraints on the atmospheric models are provided by a knowledge of the *shape* as well as the *depth* of the transit events. One of the shortest ingress periods known to-date is that of GJ 436, a hot Neptune. The ~15 minute duration sets the baseline requirement on the interval between successive samples during a single transit event to less than or equal to 90 seconds, with a goal of less than or equal to 30s. Achieving the minimum cadence is a requirement for targets observed in the Origin and Rosetta Stone tiers, but is more relaxed for observations in the Chemical Census, where the SNR in a single event will not be high enough to be able to resolve the transit itself. The cadence requirement is commensurate with the sampling times required in order to be able to detect spot crossing over the stellar disk in the visible.

3.2.7 Limiting targets – pointing and sensitivity

A series of sizing targets have been specified in order to establish the maximum and minimum stellar flux levels that can be expected over the EChO wavelength range (Table 3-2). The choice of these targets does not preclude the observation of brighter or fainter examples, and is only used to set the mission requirements. At the bright end, the stellar flux can potentially impact on the maximum sampling time for the detector readout, and also on the pointing stability requirements of the satellite itself; at the faint end, the target host stars play an important role in defining the performance requirements for the detectors and determines the accuracy of the fine pointing.

Target	Descriptor	Comment
GJ1214 (M5V, Ks=8.8) (M5V, Ks=9.8)	Faintest target shortward of 3 µm (baseline)	Effective temperature = 3200K, distance = 13pc Effective temperature = 3200K, distance = 20.6pc
(G0V, Ks=9.0) (G0V, Ks=10.)	Faintest target between of 3 – 8 µm (baseline/goal)	Effective temperature = 6050K, distance = 150pc Effective temperature = 6050K, distance = 238pc
(G0V, Ks=9.0) (G0V, Ks=10.0)	Faintest target longward of 8 µm (baseline/goal)	Effective temperature = 6050K, distance = 150pc Effective temperature = 6050K, distance = 238pc
55Cnc (K0V, Ks=4.0) v And (F9V, Ks=2.9)	Brightest target (baseline/goal)	Effective temperature = 5250K, distance = 12.3pc Effective temperature = 6115K, distance = 13.5pc

Table 3-2: Sizing host stars: brightest and faintest targets for which EChO will be designed to observe

3.2.8 Calibration

Calibration of spectra covers both amplitude and wavelength, and can be both relative and absolute. Here absolute calibration is defined as the conversion of the recorded signals from the instrument into physical units and comparison to some standard system. Absolute knowledge of the target flux is not necessary for the detection of spectral features or, for the most part, recovery of planetary atmosphere models as models typically rely on line-to-continuum ratios and, importantly, knowledge of the relative variation of the continuum as a function of wavelength. Relative calibration between the various channels of the instrument is therefore much more critical than absolute knowledge of the flux. Reference of the fluxes to a common standard is required, however, if one needs to compare and/or combine measurements taken using different facilities. For this reason a requirement on the absolute knowledge of the flux measured by EChO is defined. This is set to 5%, similar to that quoted for Spitzer/IRAC and readily achievable using a network of stars with well-calibrated spectra.

In all but the brightest cases, the SNR will be achieved over a number of repeated visits to the targets. The stacking and averaging of the spectra require that each recorded spectrum is accurately aligned in wavelength. This requires accurate relative wavelength calibration, i.e. each spectrum must have the same relationship between pixel position and wavelength, with high stability over time. Absolute calibration of the wavelength -- knowledge of the actual wavelength -- of the detected spectral features is important to allow correct identification of molecular species and, again, to allow comparison of spectra taken with different facilities. Given the relatively low spectral resolving power of EChO (see Section 3.2.2), this requirement is wavelength knowledge to within 1/3 of the width of the spectral element. This will be easily achieved using high SNR measurements of stars with known spectral features.

3.2.9 EChO Science beyond exoplanets

The key EChO requirements of very wide instantaneous spectral coverage and high photometric stability access a wide range of science cases beyond the characterisation of exoplanet atmospheres, some of which are described in Section **Error! Reference source not found.**. The science cases listed place additional requirements on the spacecraft that are considered to be goals only, and that will not drive the mission requirements. The ability to observe Uranus Neptune, brown dwarfs and comets with the same performance as for exoplanets has been identified as a goal requirement, along with the ability to track solar system objects at nonsidereal rates of up to 10 arcsec/minute. Neither of these goals is considered to be challenging – for example the ability to track Solar system objects was realised by the Herschel spacecraft – and will be considered in a future study phase.

3.3 Characterising the host system

A precise knowledge of the host star fundamental parameters is important for EChO. Stellar radius in particular directly impacts the derived planetary radius, and thus has an influence on the physical scaling of the exoplanet transmission spectrum and the physical interpretation of the exoplanet emission spectrum. Other relevant stellar parameters include stellar mass, age, luminosity, effective temperature, metallicity, and abundances of various individual elements. Below we provide an overview of the methods and instruments that will be used to measure these properties at a precision that is sufficient to make stellar parameters only a minor contributor to the overall error budget in EChO spectra.

Distance, luminosity, effective temperature, radius: The most accurate path towards these parameters will make use of the ultra-precise GAIA parallaxes and measured spectral energy distributions (SEDs) of the targets. SEDs will come both from GAIA and EChO itself. Provided an absolute flux calibration for EChO can be obtained at the few percent level over the broad wavelength range of EChO, the obtained SEDs combined with GAIA distances will yield the luminosity, effective temperature and radius of the target to unprecedented accuracy [ECHO-TN-0001-INAF]. Effective temperature can also be measured through ground-based high-resolution spectroscopy. While this method works well for solar-type stars, it is expected to be less accurate for late-K and M stars. In some cases, the stellar radius can also be measured directly through long-baseline interferometry, using instruments like CHARA, VLTI-PIONIER and the MRO interferometer.

Mass: This fundamental property can be estimated through stellar evolution models given luminosity, effective temperature, radius and metallicity.

Metallicity, chemical abundances: High-resolution spectroscopy of essentially all EChO targets will be available through the Doppler monitoring programs aiming at measuring the planet mass (HARPS, HARPS-N, ESPRESSO, Keck/HIRES, CARMENES, SPiROU, etc.). Metallicity and abundances of various elements can be determined from these data.

Activity level, rotation period: We will have simultaneous activity monitoring from EChO observations itself (see Section 2.3.4.2). Additional information will be available from high resolution Doppler surveys, that will yield measurements of lines sensitive to the activity (e.g. Ca_{II}, H & K, Na doublet, H_{α}). For most targets, rotation periods will be known from photometric light curves available for all the transiting targets, provided rotational variability is at level of at least a few milli-magnitude for the ground-based light curves, or even smaller for space- based light curves. For the remaining cases, rotation- activity calibration can be used, although with relatively large errors for individual objects. Note that the presence of close-in giant planets may influence the rotational and evolution of a star, making the latter method unreliable in such cases.

Age: This property can be obtained indirectly, either through stellar evolutionary models, gyrochronology (rotation-age calibration), or asteroseismology. Models are sensitive probes only in the regions of the HR diagram where stellar evolution is fast, i.e. at young ages (< 1 Gyr) or at the end of the main sequence lifetime , which are potentially the most interesting epochs from a planetary perspective. Gyrochronology gives population-wide relations between rotation period and age, but may fail to give accurate ages for individual objects. Asteroseismology (coupled to stellar models) is potentially the most accurate technique but is demanding in terms of observational effort: long, uninterrupted time series of high-precision photometric or spectroscopic measurements are needed. The TESS mission may be able to constrain the ages of EChO targets through this technique.

4 Payload

In order to carry out its scientific objectives, the EChO mission consists of a spacecraft placed into orbit around L2 with a cooled telescope and spectroscopic instrument designed for high stability spectro-photometry. In this chapter we describe in detail the design of the payload, i.e. the telescope and instrument. To set the payload design in context, we first give a brief overview of the major components of the spacecraft which are described in more detail in Chapter 6.

4.1 System overview

The main structural elements that comprise the EChO S/C and that are regularly referred to throughout this document are illustrated in the simplified block diagram shown in Figure 4-1. These are:

- The service module (SVM), containing all the units required to keep the S/C operational and support the payload
- The payload module (PLM), which includes:
  - The 3 glass-fibre reinforced plastic (GFRP) bi-pods that support the PLM on the SVM
  - The thermal shield assembly (3 V-Grooves)
  - The EChO telescope assembly (ECTA), which includes:
    - ▪ The telescope optical bench (TOB)
    - ▪ The 3 telescope mirrors (including the re-focussing mechanism on M2) and the 2 flat fold mirrors
    - ▪ The telescope baffle
  - o The instrument Focal Plane Unit (FPU): the Instrument Optical Bench (IOB), carrying the instrument channels, instrument radiator and fine guidance sensor (FGS)

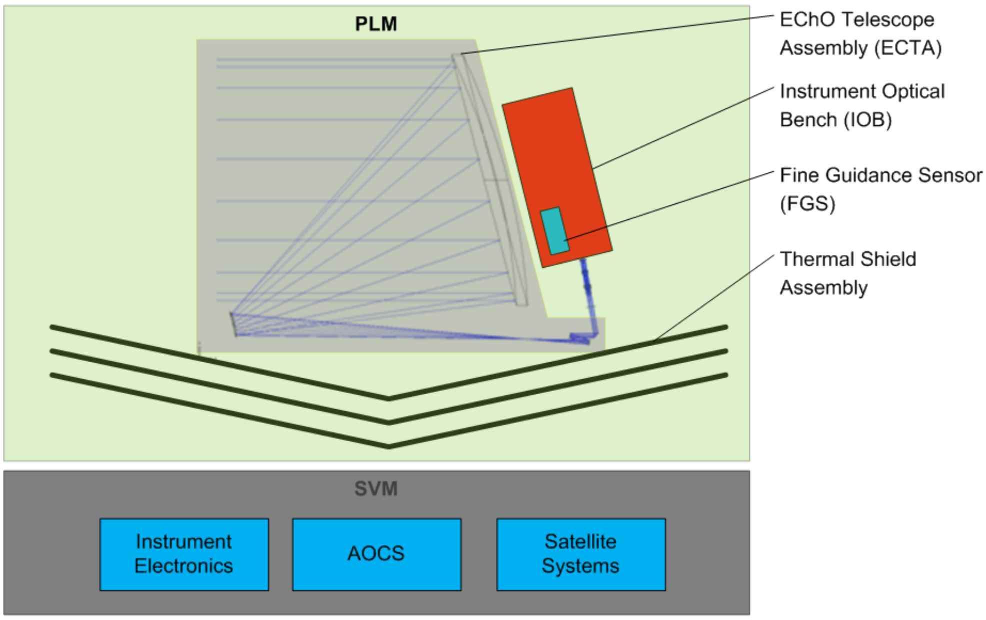


Figure 4-1: Simplified block diagram of the EChO spacecraft system

4.2 The payload complement

The EChO PLM consists of the Telescope Assembly (ECTA, described in Section 4.3) and the passive cooling system , the science instrument (described in Section 4.4) and the Fine Guidance Sensor (FGS, described in the Sections 6.2.3 and 4.4.8). The Telescope Assembly and passive cooling system are under the responsibility of ESA, through the Spacecraft Prime Contractor, while the science instrument and the FGS are procured by the instrument consortium.

The FGS has been placed under the responsibility of the Consortium since this unit is physically part of the Instrument Optical Bench (IOB) and requires a good co-alignment with the science channels. In addition this allows maximum synergies between the Visible-Near InfraRed (VNIR) channel and the FGS (e.g. detectors, electronics etc.), and is preferred by the Consortium and scientists since the FGS can also be used to extract science data (e.g. for on-ground post-processing of the science instrument data, for visible photometry etc.).The FGS needs to interface with the S/C AOCS subsystem, as it is an integral part of the AOCS control loop. Therefore, the FGS hardware and software is under the responsibility of the Consortium, but the calculated centroid is then transferred to the S/C On-Board Computer (OBC) and used in the AOCS control loop, under the responsibility of the S/C prime.

4.3 Telescope design

EChO will observe the combined light from the exoplanet-host star system and will make use of the temporal variations in the light to separate the exoplanet contribution. There is therefore no requirement to spatially resolve the exoplanet-host system and as a result the requirements on optical quality and spatial resolution are rather relaxed (setting aside the FGS requirements to measure the centroid of the star). EChO will observe a single exoplanetary system at a time, which requires a small Field of View (FoV) only. This small FoV and relaxed optical quality requirements allow emphasis to be placed on optimising other aspects of the telescope such as e.g. thermo-elastic stability, stray light and thermal background, the interfaces with the instrument etc.

The EChO telescope design underwent a trade-off study at the beginning of the Phase 0/A study to select the optimal design. The trade-off was led by ESA, with all parties involved (ESA, both S/C study prime contractors and instrument consortia) invited to propose telescope concepts. A total of 10 designs were proposed and traded-off, based on a system level set of trade-off parameters summarised in Table 4-1.

Impact on photometric stability	Complexity/feasibility/technology readiness of thermal design
Effective area and throughput	Complexity/feasibility/technology readiness of structural design
Accommodation in PLM and on SVM	Manufacturing and procurement
Complexity of interfaces and impact on instrument design	Verification, testing and calibration
Telescope thermal control and performance	Telescope cost and impact on system level cost
Baffling and stray light control	Necessity, feasibility and accommodation of re-focussing and tip/tilt mechanisms
Complexity/feasibility/technology readiness of optical design	Flexibility and growth potential

Table 4-1: Telescope trade-off parameters

This trade-off enabled an early selection of a baseline telescope concept to be made, as well as a list of interface requirements between the telescope, the instrument and the PLM to be set, in order that the instrument consortia and industry could continue the design and analysis activities of their respective systems following a commonly agreed set of interfaces.

The selected baseline telescope concept is an afocal, elliptical, off-axis, 3 mirror Korsch-like system with a 1 m class primary mirror. In contrast to a typical Korsch system for a big FoV, the telescope has been optimised to produce a very small exit pupil. This simplifies the procurement and minimises both the volume and cost of the optics for the instrument. The instrument is accommodated directly in the back of the M1 support structure (part of the Telescope Optical Bench, TOB, as can be seen in Figure 4-9) on an Instrument Optical Bench (IOB). The telescope is diffraction limited at 3 µm, implying a WFE budget of 167 nm rms. For wavelengths below 3 µm, the diameter of the 80% encircled energy is set to be ≤ 1.6 arcsec. During the study, both industrial contractors were left free to optimise their own telescope design (curvature, location and size of each mirror), while complying with the selected concept and the agreed interfaces. This resulted in very similar designs, which can be summarised as follow:

- Effective area of 1.131 m^2
- Throughput ≥ 85% in the Vis and ≥ 90% in the IR

- Intermediate focus between M2 and M3 available for accommodation of a field stop
- Elliptical M1 (mechanical dimensions of ~1 m x1.5 m, with a slightly smaller optical surface)
- Collimated beam of 25x17 mm^2 at the exit pupil (i.e. ellipticity ≤ 1.5)
- Exit pupil located within the IOB volume, accessible by the instrument Consortium to position a cold stop
- A re-focussing mechanism is accommodated on M2
- 2 small flat folding mirrors after M3 are incorporated to rotate the collimated beam and the PSF 90°, so that the dichroic mirrors within the instrument design fold the optical beam in the plane of the IOB (not out of plane, to minimise the volume needed for the instrument in the PLM) and in the small dimension of the collimated beam (so that the ellipticity of the beam and PSF is reduced rather than enhanced)

The flat folding mirrors have 2 additional benefits: they keep the possibility of easily accommodating a fine steering tip/tilt mechanism on one of them open, if required in the future study phases, and they provide flexibility in the location and inclination of the light beam at the entrance of the instrument box, to match what required by the Consortiums instrument design.

The telescope optical design is illustrated in Figure 4-2 and Figure 4-3 with different views.

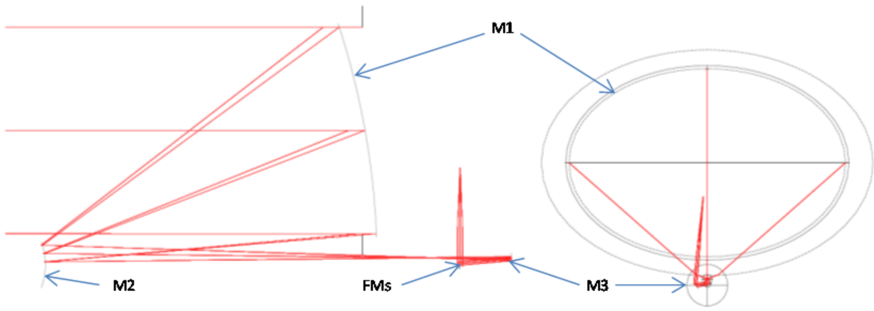


Figure 4-2: Telescope design, showing M1, M2, M3 and the Fold Mirrors (FMs) – Industry A

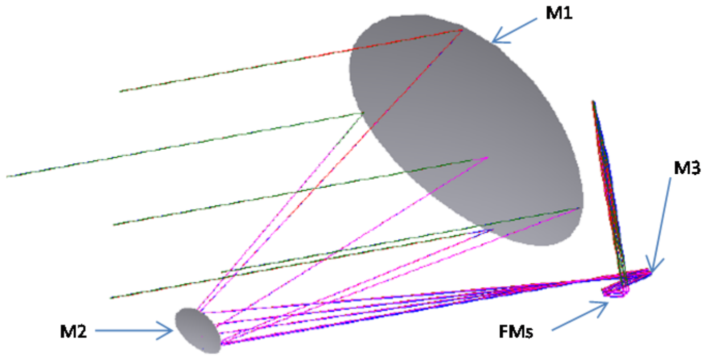


Figure 4-3: Telescope design, showing M1, M2, M3 and the Fold Mirrors (FMs) – Industry B

Preliminary stray light analyses have shown that in general out-of-field stray light from nearby sky sources has a negligible impact on the EChO noise budget. In addition, scheduling constraints will be used to ensure that bright sources (e.g. bright stars, planets, the Moon etc.) are sufficiently far from the telescope line-of-sight and instrument FoV. A telescope baffle is also incorporated in the design: it is not needed to meet the stray light requirements, however it is used both as an additional radiator (top surface of the baffle, looking towards the dark sky) and to cancel the stray light from the thermal background radiation of the thermal shield that would otherwise be scattered on the mirrors (bottom surface of the baffle, looking towards the thermal shields and the SVM). This provides an additional ~2 K passive cooling capability to ensure the TOB, telescope and instrument remain below ≤ 47 K (to minimise the thermal background noise, but also to relax the thermal stability requirement which is the more important contributor to the noise budget). In the case of industry B, this baffle is also a structural element as it supports M2.

Similarly, the equivalent preliminary analyses for in-field stray light have shown that this contribution is also negligible. The constraints that are imposed on the cleanliness and contamination of mirrors (1000 to 5000 ppm) and the surface roughness (2 to 3 nm) are within existing technological achievements on existing telescope mirrors. Further details on the thermal control system that is used to passively cool the telescope assembly are provided in Section 6.2.2.

Figure 4-4: Telescope Optical Bench and baffle. Left: Industry A. Right: Industry B.

4.4 EChO Payload Instrument

4.4.1 Instrument architecture and system design

The baseline design is for a 3 channel, highly integrated, common field of view, spectrometer that covers the full EChO required wavelength range of 0.55 µm to 11.0 µm. An optional LWIR channel extends the range to the goal wavelength of 16.0 µm, while the baseline design of the VNIR channel includes the goal wavelength extension to 0.4 µm. Also included in the Payload Instrument is the Fine Guidance System necessary to provide closed loop feedback to the high stability AOCS of the Spacecraft. The required spectral resolving powers of 300 or 30 are achieved or exceeded throughout the band. The baseline design largely uses technologies with a high degree of technical maturity and almost entirely European technologies (with the exception of the detectors).

4.4.1.1 Architecture, modularity and responsibilities

The EChO Payload Instrument baseline design incorporates five spectrometer bands divided into three channel modules plus the Fine Guidance System, mounted on a single Instrument Optical Bench (IOB), amongst which the field of view is divided by a series of dichroics. This scheme is illustrated in Figure 4-6 below.

There are two fibre-fed VNIR bands (one visible and one near-infrared) covering the 0.4-2.47 µm wavelength range, one SWIR band covering the 2.42-5.45 µm range, two MWIR bands covering the 5.05-11.5 µm range (5.05-8.65 µm and 8.25-11.5 µm) and a LWIR band covering the 11–16 µm range (which is a goal). The two VNIR and MWIR bands are each imaged on a single focal plane within a channel module. The placement of the channel boundaries complies with the critical wavelength regions defined in the science requirements detailed in Section 3.2.1. The channel boundaries were chosen in such a way as to avoid potential weaknesses in the optical performances of the dichroic elements, and to ensure overlapping of spectral ranges between modules for full wavelength coverage and cross-calibration. This implies that the detectors are then optimised for the necessary wavelength coverage for each channel. The split between the channels and the work division is illustrated schematically in Figure 4-5

The baseline design architecture has been selected to maintain a high degree of modularity in the design. This helps both technically and programmatically in allowing independent development of the channel module designs and in giving the maximum flexibility programmatically to the consortium partners. To this end the optical design of the modules is decoupled from one another, and a common optical interface has been defined for all modules.

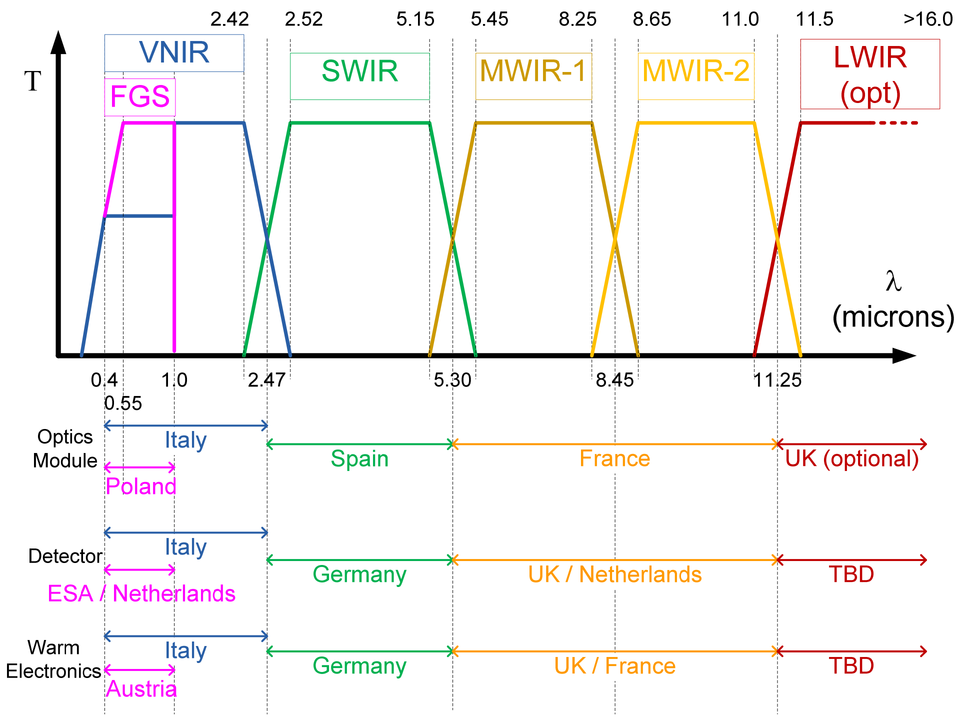


Figure 4-5: EChO Payload Instrument Channel Division and Channel Responsibilities

4.4.2 Noise budget

The detailed noise budget for the EChO Payload Instrument is contained in the Assessment Study Design Report [ECHO-TN-0002-RAL]. In the past, general-purpose, space-based instruments used for exoplanet atmosphere characterisation have suffered from a high level of systematic error. EChO will be an instrument that performs time series spectroscopy with unprecedented photometric stability from the visible to the mid-IR, simultaneously.

The total noise budget is divided into a number of different components for which the radiometric noise contributions have been determined using EChOSim (see Section 5.3.2) for a number of different conditions corresponding to the faintest and brightest target required to be observable with EChO, as expressed in R-PERF-090 and R-PERF-110, respectively, of the MRD. These are shown in Figure 5-2 and Figure 5-3.

4.4.2.1 Photometric stability

The photometric stability is a key factor in the noise budget of the observations. The photometric stability of the instrument throughout consecutive observations lasting up to tens of hours (to cover the goal of phase curve observations) is mainly governed by the following factors:

- Pointing stability of the telescope quantified in terms of Mean Performance Error (MPE), Pointing Drift Error (PDE) and Relative Performance Error (RPE) for the different AOCS solutions considered in the study (see Section 5.3.2.2, [ECHO-TN-0002-RAL] and [ECHO-TN-0003-UCL]).
- Thermal stability of the optical-bench and mirrors: thermal emission of the instrument can be regarded as negligible for most wavelengths, but become observable at wavelengths beyond 12µm. The stability payload module (instrument and telescope) is therefore an important factor for the photometric stability in MWIR and LWIR channels.
- Stellar noise and other temporal noise sources: whilst beyond the control of the instrument design, noise is an important source of temporal instability in exoplanetary time series measurements. This is particularly true for M dwarf host stars as well as many non-main sequence stars. Correction mechanisms of said fluctuations must and will be an integral part of the data analysis of EChO - see Section 2.3.4 and [ECHO-PL-0009-RAL].

4.4.3 Detector systems

If the EChO mission had been started a few years ago, it is almost certain that the baseline detector selection would have been US sourced detectors for all the IR channels – Mercury Cadmium Telluride (MCT) for 1 to ~5µm and Silicon Arsenide for the remainder. However there has been significant recent and on-going investment by ESA and some National Agencies/Institutes in European suppliers of MCT-based detectors and in a European equivalent to the SIDECAR ASIC. Together these all form part of a larger ESA roadmap process which would long term give ESA more control/independence in mission design and reduced issues with International Trade in Arms Regulations (ITAR).

In November 2012 the project elicited preliminary compliance data from the various potential suppliers against outline EChO detector requirements which confirmed the growing credibility of European suppliers. Those dialogues have continued in parallel with more detailed modelling and development of the requirements specification. Details of the detector system requirements derivation and the responses received from the suppliers are contained in [ECHO-RP-0001-RAL §5].

4.4.3.1 FGS, VNIR & SWIR detectors

The Consortium Management Team decision, after considering both the technical and programmatic responses, was to baseline the Teledyne H2RG device for the FGS, VNIR and SWIR channels. It was noted that the European SELEX-ES devices were also potential candidates for these three channels, however the current Technology Readiness Level (TRL) is relatively low when compared to Teledyne's device. The preferred solution would have been to work with SELEX to fund development of their devices but after investigation it was decided that the predicted cost of this work would be prohibitive unless strategic development funding for European IR detectors is available in the near-term from outside the consortium funding constraints.

4.4.3.2 MWIR & LWIR detectors

One key outcome during the assessment phase was the identification of an MCT detector with TRL approaching 5 that worked up to 11 µm at an operating temperature of ~40K. This device has been developed by Teledyne working with JPL and University of Rochester in the frame of a Phase A study for NEOCam (a Near Earth Object detection mission being studied for a potential 2018 launch). This led to a change in instrument baseline with the expectation that we could have an all MCT solution with operating temperatures no lower than 28K (somewhat lower than the NEOCam baseline due to the desired lower dark current in the EChO application). The big advantage of this is the simplification in the payload cooler by avoiding the risks associated with a 7K detector operating temperature associated with SiAs detectors, and the two-stage cooler which this implies.

Due to the lack of a European solution for the MWIR channel, the Teledyne NEOCam device has been selected as the baseline. The only readily available alternative is the SiAs device from Raytheon, but this requires cooling to 7K.

The consortium is maintaining a dialogue with suppliers, especially in Europe to establish if they could meet a lower performance specification for the LWIR channel and that work will be on-going through phase B1 before a final detector freeze at the SRR. Investigations are also underway into an alternative SiGa-based devices and in MCT developments at University of Rochester / Teledyne for low background devices with a cut-off wavelength of up to 15 µm. However, for the LWIR the best option currently available remains the 7K Raytheon SiAs device.

4.4.4 System optical design

4.4.4.1 Optical interface to telescope

The optical interface for the EChO Payload Instrument to the telescope (described in Section 4.3) is a collimated elliptical beam of size 25 x 17 mm. All instrument channels (including the FGS) share the field of view; their fields of view are shown in Figure 4-6 below.

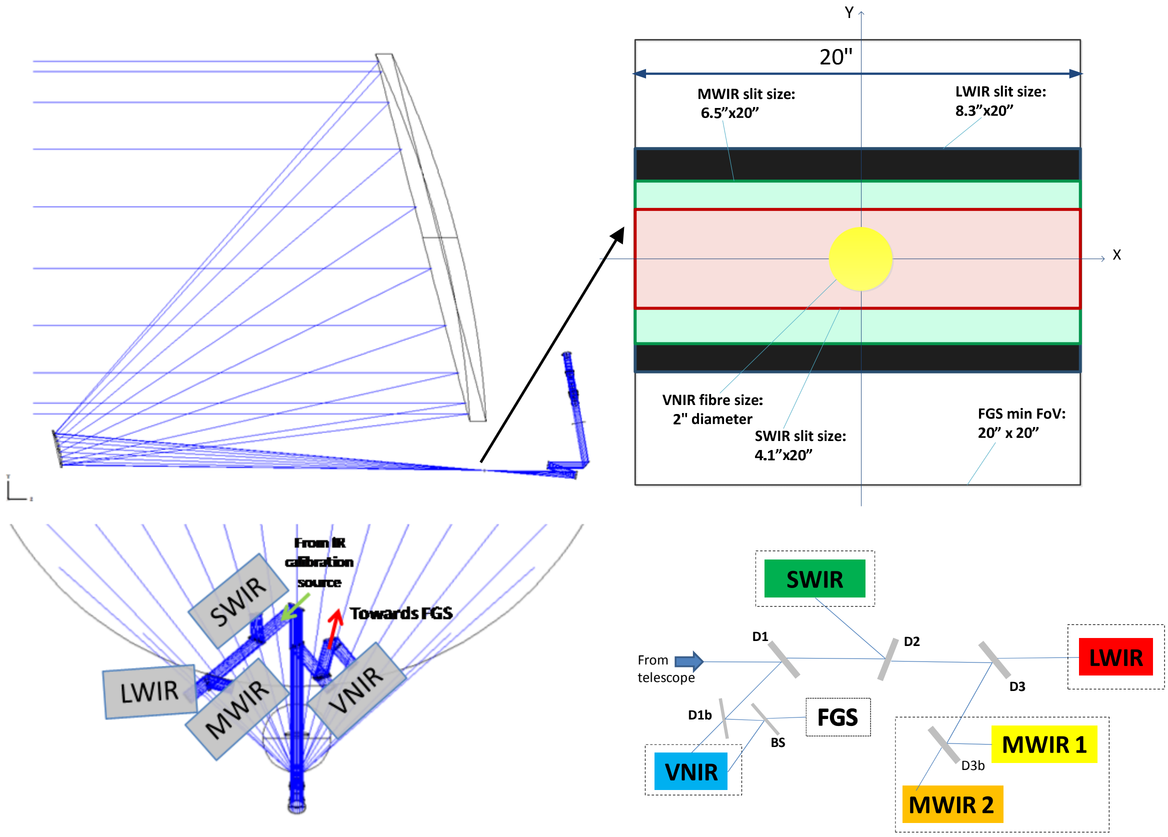


Figure 4-6: Both upper and lower left: optical layout of the EChO front and common optics concept. Upper right: the relative size, nominal position and orientation of the different spectral modules' fields-of-view at the telescope intermediate focus are indicated. Lower right: schematic of channel division by dichroics

4.4.4.2 Channel division

In parallel to this process, spectral regions within the full EChO spectral range, of particular interest due to the presence of important spectral lines were defined by the Science Study Team in agreement with ESA. From these, regions avoiding the "no-cut" zones have been defined for inter-channel and intra-channel transitions. In agreement with the modules design iteration, the "core" spectral range of each module is: VNIR from 0.4 µm to 2.47 µm, SWIR from 2.47 µm to 5.3 µm, MWIR from 5.3 µm to 11.25 µm, LWIR from 11.25 µm to 16 µm. The resulting updated baseline scheme, illustrated in the lower right of Figure 4-6, can be summarised as: 4 main spectral modules VNIR, SWIR, MWIR and LWIR separated by 3 main wide band dichroics and 2 internal-to-module dichroics and 1 beamsplitter (for FGS separation).

4.4.4.3 Common Calibration Unit

An additional item in the common optics is the provision of internal calibration sources for the instrument. These calibration sources will provide relative photometric calibration of the instrument throughout the mission, used in conjunction with on-sky calibration as detailed in [ECHO-PL-0009-RAL]. Injection into most of the instrument modules (SWIR and longer wavelength) is via transmission through a small hole in the fold mirror located in the optical chain after the VNIR / FGS Dichroic (D1). The nominal calibration source design is an integrating sphere (a few cm diameter maximum) with thermal broadband sources. Existing space qualified sources such as those used for JWST-MIRI will adapted for use over the EChO SWIR, MWIR and LWIR channels. The planned IR calibration source is a wound tungsten coil, spot-welded with copper-clad nickel-iron core alloy, this is shown in Figure 4-7. The planned VNIR calibration source is a Halogen-Tungsten lamp with a dedicated injection fibre-feed from an integrating sphere located on the side of the VNIR channel.

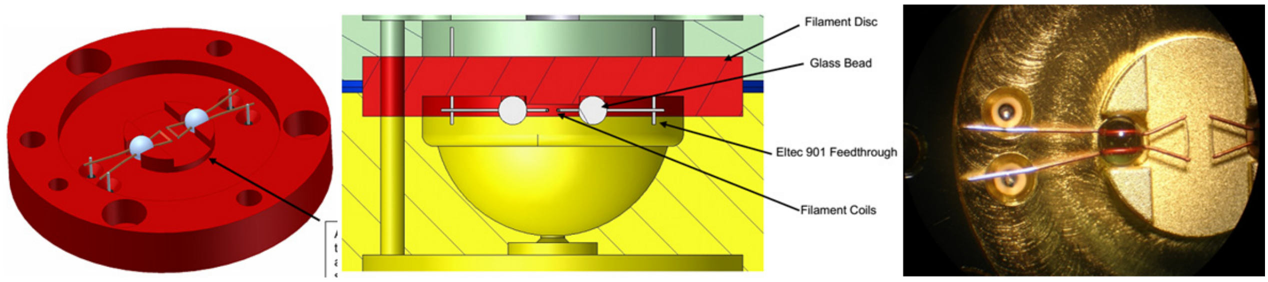


Figure 4-7: Common Calibration Unit: The two redundant filaments are shown at the centre of the assembly. The glass beads which achieve mechanical bonding of the filaments are also visible.

4.4.4.4 Optical budgets and performance

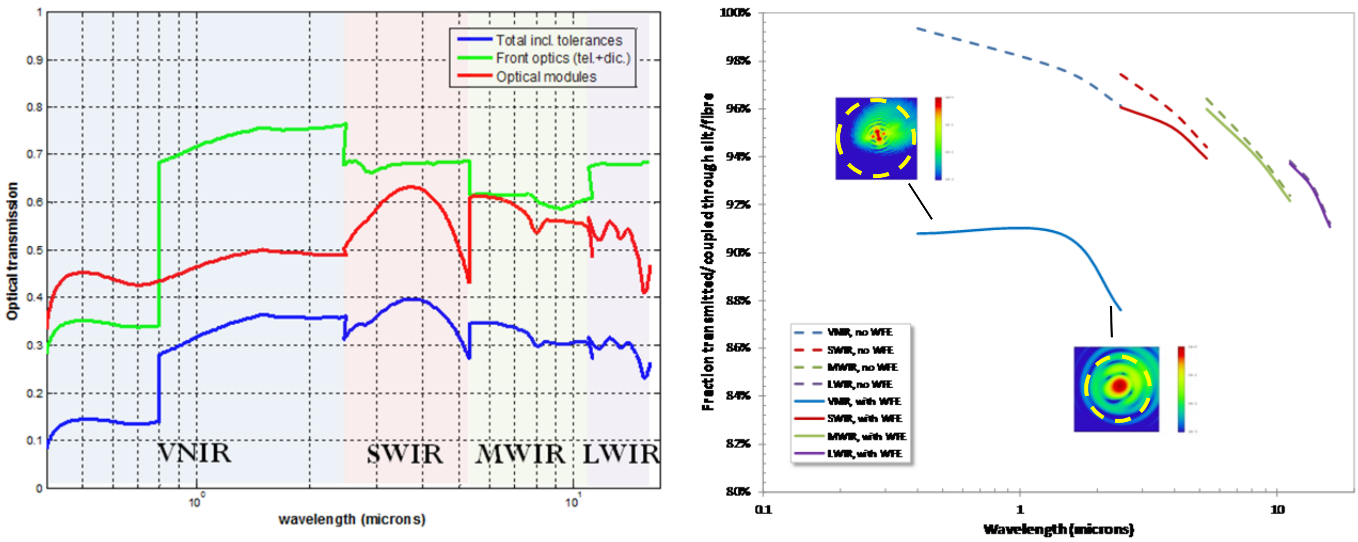


Figure 4-8: Estimates of the total average optical transmission over the entire EChO spectral range (left) and details of the coupling/transmission at module slit/fibre planes (right) w/wo WFE in the input collimated beam from telescope. The WFE distribution, associated with diffraction-limited level at 3 μm, is based on equal spread over all primary aberrations (defocus, astigmatism, coma, spherical) and resulting log-scale PSFs for the edge of the VNIR channel spectral range are added as insert within the extent of the VNIR fibre core size, illustrating the high coupling.

The system throughput estimates are shown in Figure 4-8 above. The allocations for the instrument alignment for Wave Front Error and Pupil Shear budgets are detailed in [ECHO-RP-0001-RAL §6.5]

4.4.5 System mechanical design

4.4.5.1 Mechanical baseline design

The optical modules have been arranged to provide the best compromise between packing density and optical path. Minimising the overall size of the layout has helped significantly with achieving the design goal of >80Hz first resonant frequency for the Instrument Optical Bench (IOB). The modules are arranged on the optical bench as shown in Figure 4-9 (note that the instrument-dedicated radiator is hidden in the left view).

The EChO IOB has been designed as an all-aluminium structure to match sub-module interfaces and to allow room-temperature alignment of the optics. This alignment methodology was successfully implemented on the Herschel SPIRE and JWST-MIRI instruments. Aluminium is the lowest risk option for the IOB manufacture, as it is a very well-known material which responds well to both machining and post processing. The mounting between the IOB and the TOB is a kinematic interface and hence no additional stress will be introduced due to dissimilar CTE between the instrument and telescope. Structural analysis has been conducted during the assessment study that shows that the bench design proposed meets the stiffness and strength requirements for the instrument.

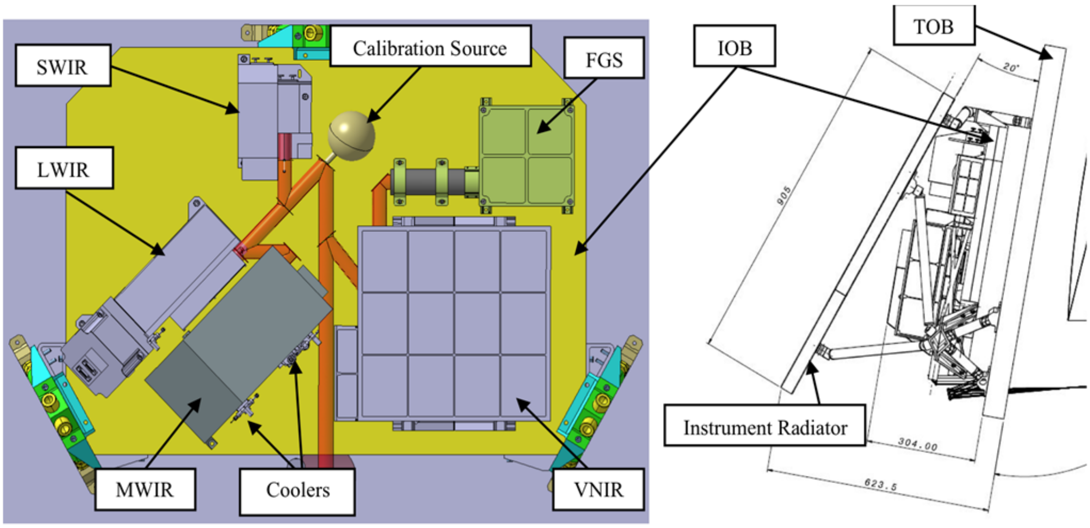


Figure 4-9:Left: chosen layout of the optical modules. Right: MICD extract showing dimensions and location of instrument dedicated radiator

4.4.5.2 Mass budget

The overall mass budget (including appropriate uncertainty figures for the design maturity of at least 20%) for the instrument is shown in Table 4-2 below.

Focal Plane Unit Mass Budget		
System	**Subsystem**	**Nominal Mass (kg)***
Optical Modules (inc. Detectors)	VNIR Channel	6.62
	SWIR Channel	5.59
	MWIR Channel	5.79
	LWIR Channel	5.47
	FGS Channel	3.68
	Cooler HXs	0.65
FPU Support Equipment	IOB & Support KMs	28.27
	Common Optics (inc. IR Cal Source)	1.80
	FPU Harnesses	3.02
	Radiator & Supports	18.00
	Thermal Hardware	1.88
Total Focal Plane Unit Mass		**80.77**
Compare to EID-A Requirement		121.0
FPU Mass Margin		**33.2%**

Service Module Mass Budget		
System	**Subsystem**	**Nominal Mass (kg)***
Active Cooler System	J-T Compressor	7.20
	Cooler Aux Panel	1.80
	Cooler Harnesses	1.80
	Cooler Control Electronics (CCE)	7.80
Instrument Electronics Boxes	Detector Warm Electronics Unit (DWEU)	4.20
	Instrument Control Unit (ICU)	9.00
	FGS Control Unit (FCU)	7.80
Total Service Module Mass		**39.6**
Compare to EID-A Requirement		137.0
SVM Mass Margin		**71.1%**

Table 4-2: Payload Instrument Mass Budget, including contingency

4.4.6 System thermal and cryogenics design

4.4.6.1 Baseline thermal architecture

The thermal architecture of the EChO payload is based on a combination of passive and active cooling systems (Figure 4-10). The first three cold temperature stages consist of V-Grooves passive radiators that, exploiting the favorable conditions of the L2 thermal environment will provide stable temperature references for the modules, for parasitic heat leaks (harness, struts, piping, radiation) interception and for cryo-system pre-cooling. Three channel detectors (FGS, VNIR and SWIR) will be cooled around 45K by means of a dedicated radiator that will benefit from the cold radiative environment set by the last V-Groove. Two channels' (MWIR and LWIR) detectors and cold inner sanctum optical boxes need to work at a lower temperature, T < 30K; this is achieved by using a Neon JT cryocooler. The general scheme of the EChO thermal architecture, with the six main thermal interfaces identified in the study, is shown in Figure 4-10.

4.4.6.2 Thermal Budgets & Performance

The PLM TMM/GMM is based on the coupling of a "standard" M-size SVM with the baseline configuration for the cold passive PLM. In the model are simulated the main radiative surfaces and representative supporting structures between the different stages. Details of the thermal model are presented in [ECHO-TN-0001-IASFBO]. The results from the thermal model are illustrated in Figure 4-11.

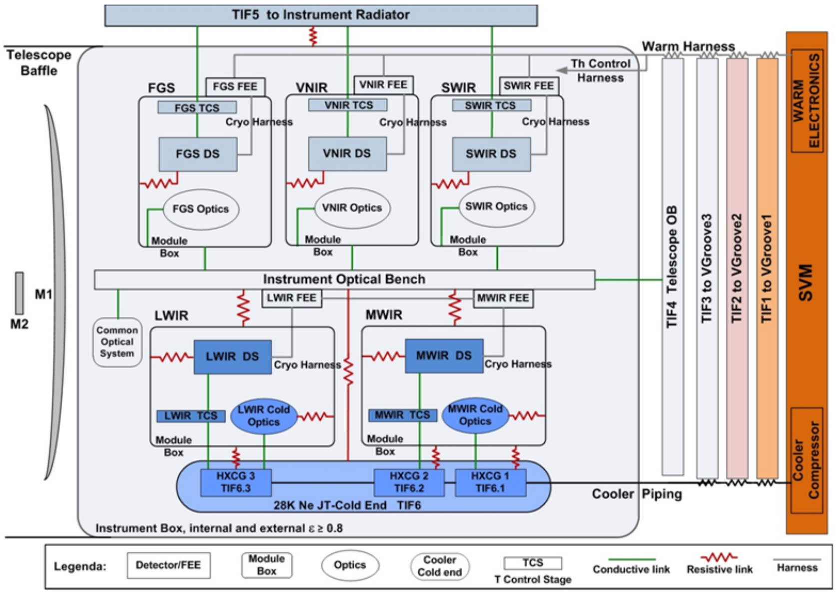


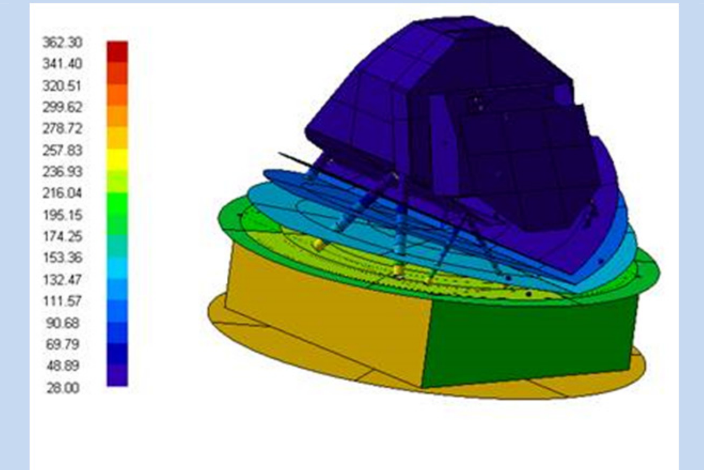
Figure 4-10: EChO thermal scheme with main thermal interfaces to S/C

Another key issue for the thermal control system is the thermal stability of the detectors. In order to meet the necessary photometric stability the background and gain drift of the detector systems must be controlled, requiring tight control of the detector temperatures. An active control system is included in a thermally isolated stage of each detector that uses a heater and feedback thermometer to control the detector temperatures. Analysis and previous experience shows that thermal stability to the level of few mK can be achieved with thermal control power of 4.0 mW on the 45K (passively cooled) stage and 3.2 mW on the 28K (actively cooled) stage.

4.4.6.3 Active Cooling System design

The baseline for the Active Cooling System (ACS) on EChO is a Neon Joule-Thomson (JT) system making use of the advanced compressor systems designed as part of the ESA 2K cooler development system. The RAL Cryogenics and Magnetics group provided the 4K cooler for the Planck spacecraft and have designed and built many coolers for spacecraft. The designs of these coolers have been licensed to industry and have built up a reputation for being robust and having a long lifetime. There have been no failures in space. The basic design has been widely copied. The system incorporates a compressor stage that boosts the gas pressure from around 1 bar to 11 bar. The gas then passes through an ancillary panel where the flow is measured and the gas is cleaned through a getter. The gas then passes through the connecting pipework, heat exchanger system and filters on each of the stages. The gas is expanded on the focal plane assembly where it is heat exchanged with the elements to be cooled. The gas returns to the compressors through the heat exchangers back to the compressors.

The compressors are balanced in that they run in a head to head configuration. The exported vibration from balanced compressors on similar systems has been reduced to around 100mN with crude amplitude balancing. On Planck, with active vibration control, levels of a few milli-Newton were achieved. If required, algorithms that can be used to reduce the 100mN to lower levels are available and proven.



Instrument Interface	Thermal Path	Heat flux (mW)
Cold Radiator	Conductive heat leaks from spacecraft	5.7
	Conductive load from detectors	42.5
	Radiative load from warmer stages (VG3 and SVM)	14.0
	Net heat flux rejected to Space	62.7
JT Cold-end	Conductive leaks from L/MWIR modules and detector dissipations	40.0

Figure 4-11: Results of coupled S/C, PLM and Instrument thermal models – (left) temperature map, (right) predicted heat fluxes at instrument main thermal interfaces

The ACS design has been currently sized to provide 200mW of cooling power at 27K. To achieve this performance approximately 35 mg/s of Ne flow is required at the planned operating pressure drop. This leads to a pre-cooling requirement of approximately 0.65 W at the 100K V-Groove and ~550 mW on the 45K V-Groove. The input power required to provide this cooling is 130 W including margin.

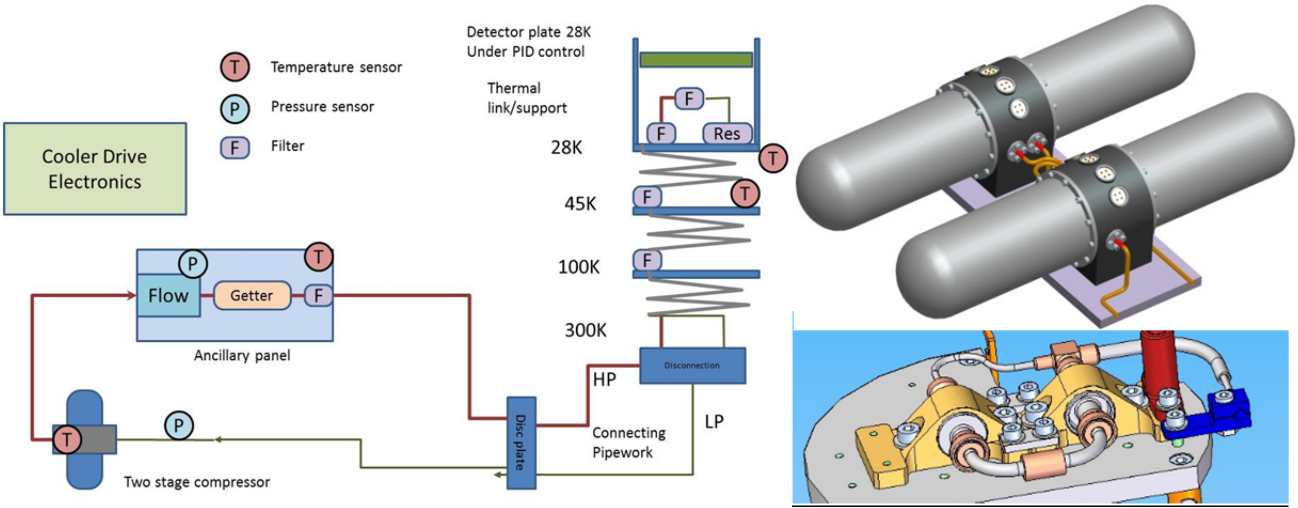


Figure 4-12: Active Cooler System. (left) system schematic, (right top) Four-stage compressor designed for ESA 2K cooler contract as evolution from Planck design - EChO would use half use of this; (right bottom):Final stage filter, J-T expansion valve and heat exchanger CAD model.

4.4.7 System electrical design

4.4.7.1 Baseline electrical architecture

The EChO payload overall electrical architecture (Figure 4-13) can be basically subdivided in two sections: spectrometer's FPA detectors with their ROICs (Read Out Integrated Circuits) and cold front-end electronics (cFEEs) on one side and warm electronics on the other side. The cold detectors cavities are maintained at 45 K in order to meet the strict operative thermal requirements and are connected to the cFEEs and to the warm electronics by means of very low thermal conductance cryo-harnessing. For further details of the electrical architecture see [ECHO-RP-0001-RAL §10].

The Instrument Control Unit (ICU) is structured in three main sub-units:

1. *Data Processing Unit (DPU)*: a digital sub-unit with processing capabilities to implement the scientific digital data on-board processing, the data storage and packetisation, the telemetry and telecommand packets handling and the clock/synchronization needed

2. *Housekeeping and Calibration source Unit (HCU)*: a sub-unit designed to provide instrument/channel thermal control, calibration source and HKs management.
3. *Power Supply Unit (PSU)*: it will distribute the secondary voltages to the instrument subsystems and ICU boards by means of DC/DC converters.

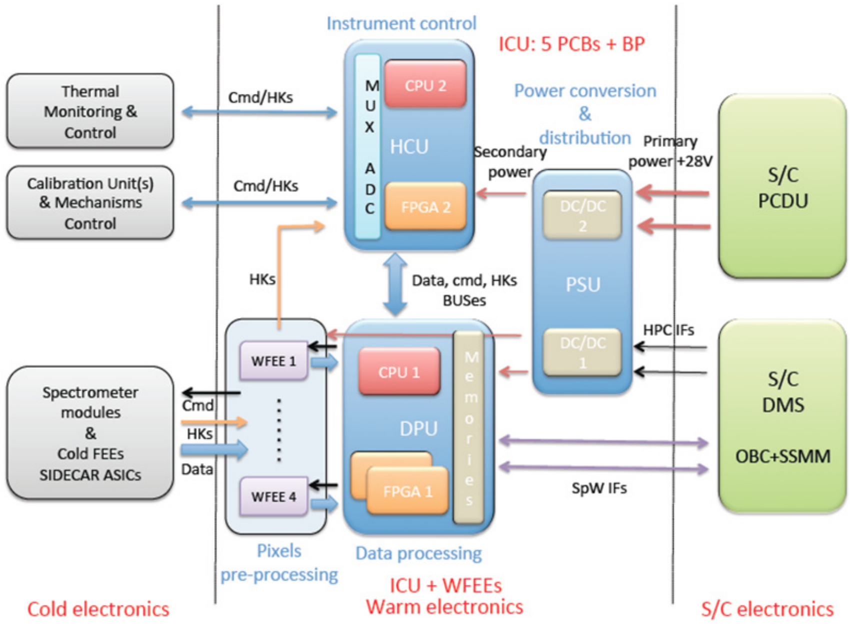


Figure 4-13: EChO payload electrical architecture block diagram (baseline solution).

A single common TM/TC interface is foreseen at ICU level to minimize and simplify the number of interfaces towards the spacecraft. The ICU electronics will rely on a cold-strapped redundant architecture with trade-off solutions removing or reducing any electronics single-point failures.

A separate electronics box for the Fine Guidance System (FGS) is supplied – this dedicated unit interfaces to the FGS CFEE and provides all control and processing activities. See Section 4.4.8 for details.

4.4.7.2 Flight software and On-board processing

The EChO ICU is responsible for the: Telemetry and Telecommand exchange with the spacecraft; Instrument Commanding, based on the received and interpreted telecommands; Instrument monitoring and control, based on the Housekeeping data acquired from the focal plane instrument units; Synchronization of all the scientific payload activities; Detectors readout data acquisition, pre-processing and formatting; and the Science Data download to the Spacecraft Mass Memory. These activities can be grouped into the Instrument Control and Data Processing software: these two SWs will constitute the On Board Software of the EChO science payload. For further details see [ECHO-RP-0001-RAL §10] and [ECHO-TN-0001-OAA].

EChO Payload Instrument Power Budget	
Unit	**Power (W)**
Cooler Control Electronics (CCE)	30.0
Cooler Compressors	100.0
Instrument Control Unit (ICU)	24.0
Detector Warm Electronics Unit (DWEU)	21.6
FGS Control Unit (FCE)	12.0
Total Instrument Power	**187.6**
Compare to EID-A Requirement	298.0
EChO Instrument Power Margin	**37.0%**

Table 4-3: Payload Instrument Power Budget, including contingency

4.4.7.3 Electrical Budgets

Power Budget: The overall power budget (including appropriate uncertainty figures) for the instrument is shown in Table 4-3.

Data Rate Budget: The current observing scheme uses three observing modes, bright, normal and faint with different read-out schemed optimised for the target (as detailed in [ECHO-RP-0001-RAL §10.4]. The sampling scheme is currently under study with options such as sampling up the ramp, grouping samples and Fowler sampling being considered. Initial results from this study are given in [IAPS/ECH/TN/01-013].

The weekly allocated data rate is 35 Gbits/week or 5 Gbits/day average. Assuming a H/K rate of 0.2 Gbits/day, a realistic duty cycle of 90% and a compression ratio of 2, then spending 10% of the mission in bright mode, 80% in normal mode and 10% in faint mode gives a data rate of 4.72 Gbits/day.

4.4.8 Fine Guidance System

The main task of the FGS is to ensure the centering, focusing and guiding of the satellite, but it will also provide high precision astrometry and photometry of the target for complementary science. In particular, the data from the FGS will be used for de-trending to aid in the data analysis on ground. During the measurement phase of the instrument a very stable pointing is required which cannot be achieved using conventional attitude sensors. Therefore a dedicated sensor is placed in the EChO optical chain, close to the VNIR as it is shown in Figure 4-9.

The sensor uses star light coming through the optical path of the telescope to determine the changes in the line of sight of the EChO instrument. The attitude measurement is then used as input with the other AOCS sensors in the control loop to keep the spacecraft pointing stable. The Fine Guidance Sensor is a critical module as it is an important contributor for the AOCS RPE performance in terms of the achievable single-star centroiding accuracy.

The FGS optical module is designed for a 20 arcsec square field of view using 50% of the flux of the target star below 1.0 μm wavelength. The optical module provides for internal cold redundancy of the detector chain through the use of an internal 50/50 beam-splitter and two independent detector channels with their own cold and warm drive electronics. A common Gregorian telescope feeds both detectors. The baseline plan includes a small de-focus offset on each detector (in opposite directions) to allow the FGS to be used during spacecraft ground testing and commissioning as a coarse wave-front sensor (Shack-Hartmann interferometer) for the telescope. The baseline optical module design is shown in Figure 4-14.

A consortium provided dedicated FGS Control Electronics (FCE) unit provides the control and processing of the FGS data and passes centroid information to the S/C AOCS. The assessment of the FGS accuracy for the faintest target goal star defined for EChO (considering the effective collecting area of the telescope, efficiency parameters of optical elements, beam splitter and QE of the detector) lead to a photo-electron count of more than 10^4 per second. Combined with a pixel scale of 0.1" and an FWHM of 2-3 pixels, the centroiding accuracy will be less than 0.1 pixel (following the relations in [Lieve, 2002] and [ECHO-TN-0001-UVIE]) or better than 10 milli-arcsec. This is well in line with the required precision.

4.4.9 VNIR channel

The VNIR channel total coverage is from 0.4 to 2.47 μm. The spectrometer will be fed by means of two optical fibres working in the wavelength ranges of 0.4-1.0 μm and 1.0-2.5 μm respectively. The one for the 0.4-1.0 μm range shares the input light with the FGS. Two separate focusing elements have to be placed after the dichroic D1b and the FGS beam splitter as input to VNIR, these focus the light onto the two fibres.

The effects of pointing jitter and telescope WFE variations on the coupling of the fibres have been extensively studied during the assessment phase. The results of these simulations are reported in [ECHO-RP-0001-RAL §15.2.6]. They show that the effects of the jitter and WFE on the fibre coupling (both at the entrance and through the fibre) are negligible contributions to the total photometric error and noise budgets.

The resolving power is nearly constant and it is R≈330 on the binning that will be operated on the detectors pixels. The baseline solution is a detector of 512 x 512 pixels with a 18-μm pixel pitch. This solution implements a 5x5 binning to obtain the given resolving power.

The wide spectral range is achieved through the combined use of a grating with a ruling of 14.3 grooves/mm and blaze angle of 3.3° for wavelength dispersion in horizontal direction and an order sorting calcium fluoride prism (angle 22°), which separates the orders along the vertical direction. The collimator (M1) and the prism are used in double pass (see Figure 4-14). The prism is the only optical element used in transmission. All remaining optical elements are used in reflection: 2 off-axis conic mirrors, 1 spherical mirror, 1 flat mirror and 1 grating. All reflecting elements will be made of the same aluminium alloy as the optical bench. This simplifies the mechanical mounts and alignment of the system.

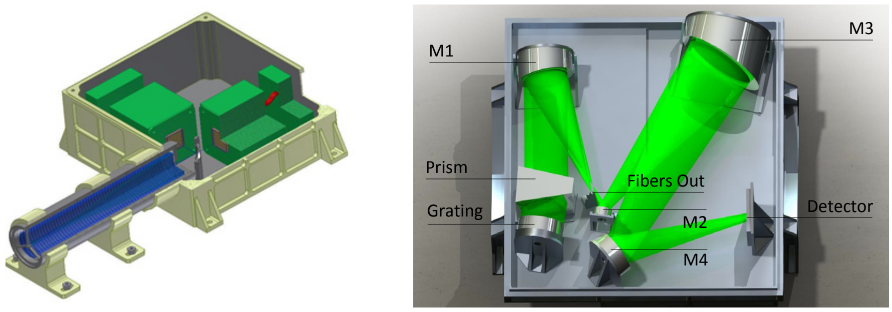


Figure 4-14: (left) FGS Optical Module design including Gregorian telescope, beamsplitter and two redundant detector modules; (right) VNIR Optical Module spectrometer design.

4.4.10 SWIR Channel

The SWIR module is a grating spectrometer providing the required R>300 coverage from 2.42 to 5.45 µm. After several optical design trades, and taking into account the available detector technology in this spectral range, a detector pixel size of 18 µm was set. The baseline design of the spectrometer is based on the use of a relay to adapt the incident beam size, in this case, the common elliptical input beam of 25mm x 17mm to the output beam at relay second mirror. A slit between relay mirrors is used as a field stop. A deliberate de-focus is introduced into the module design to provide approximately constant PSF sampling across the wavelength band and to maximise the S/N at the long wavelength end where the channel would first become detector noise limited for faint targets.

4.4.11 MWIR Channel

The MWIR module covers the bandpass from 5.15 to 11.5 µm and is split into two channels: MWIR1 from 5.15µm to 8.65µm and MWIR2 from 8.25 µm to 11.5 µm. The MWIR resolving power increases from 32 to ~115 across the passband of the module.

The collimated beam coming from the common optics is refocused on the module entrance slit by an off-axis parabola. Another off-axis parabola collimates the beam to an internal dichroic that splits the bandpass: MWIR1 band is reflected whereas MWIR2 band is transmitted. A set of two flat mirrors (the roof mirrors) folds back the long wavelength channel to the common path in order to focus the two spectra on a unique detector. A prism is used to spectrally disperse the beams that are re-imaged by three-lens objectives on the detector. Classical space qualified optical materials (Cleartran and ZnSe) are chosen to avoid any absorption feature in the bandpass. All materials are well known and already used in previous space missions for spectrometers. The spectra imaged on the MCT detector cover 55 and 80 pixels for respectively MWIR1 and MWIR2. To allow windowing with optimized integration time, the spectra are offset by 45 rows on the chip.

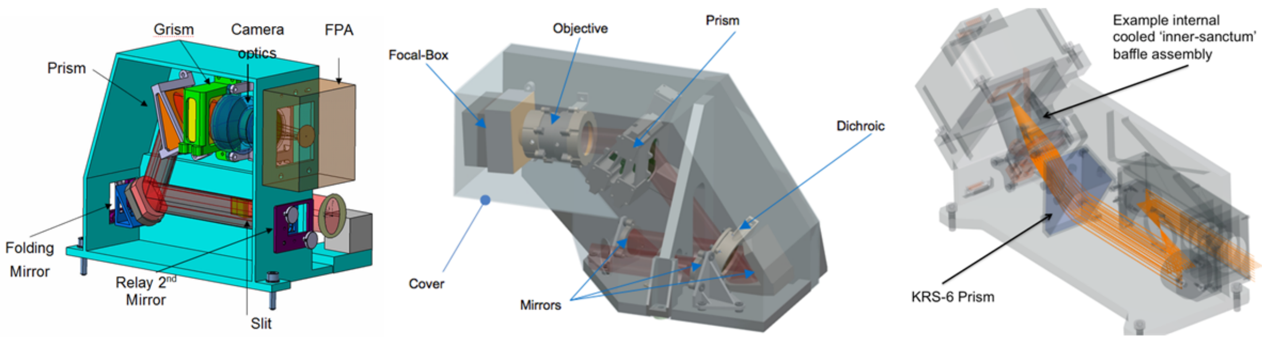


Figure 4-15: (left) SWIR Channel Optical Module design; (centre) MWIR Channel Optical Module Design; (right) LWIR Channel Optical Module design

4.4.12 LWIR Channel

The LWIR is a goal channel and is dependant on the availability of detectors and additional consortium participation to allow its inclusion. The baseline design developed during the study phase is a prism-based spectrograph using a detector array with a 25 µm pitch. The LWIR channel provides spectral coverage from 11 - 16 µm, with a spectral resolving power ($\lambda/\Delta\lambda$) of R=30. The choice of prism material having both sufficient dispersion and low absorption (<0.7) is somewhat limited in the 11 - 16 µm wavelength range; however there are options. The material selected for the baseline design is KRS-6, a thallium bromide/chloride crystal. The final focusing optic is a coated germanium lens. Many different prism materials were considered during the study phase and alternative designs using Cadmium Telluride and Zinc Selenide were also developed.

4.4.13 Instrument AIV, Ground Calibration and Development Status

The EChO instrument will follow a PFM approach to overall qualification. Some major design aspects will be de-risked earlier in the program using the development models where possible within the programmatic constraints. The development and verification of the instrument will be undertaken in accordance with the requirements in the EID-A and the guidance in the applicable ECSS standards.

In order to allow early de-risking the consortium plan to build a Performance Verification Model (PVM) of the instrument Focal Plane Unit (FPU) and electronics units that will be form, fit and functionally compliant but with no compulsion that the units within it are capable of undergoing environmental testing to qualification level. This model will not be environmentally tested to qualification levels and is not proposed to be deliverable to spacecraft level. By following this programme rather than committing to a full qualification model we allow flexibility in the schedule. That is, the consortium is not dependent on completion of all unit qualification programmes to start the interface and performance verification activities at Instrument level.

The instrument performance verification and ground calibration will be carried out in a test facility modified from that used to test the JWST MIRI instrument. This provides a 40K low IR background environment allowing simulation of the thermal environment of the instrument. A dedicated set of simple OGSE with an ultra-high stability blackbody source (from heritage of the calibration of space-based radiometer instruments to mK level) will be used to verify the instrument photometric stability.

The baseline instrument design uses only technologies that are already TRL of at least 4. There are funded development plans in place to improve the TRL of the MWIR MCT detectors and Ne JT Cooler to TRL of at least 5 by the end of 2014, well before the planned M3 mission adoption. Additional development of European detector options for the VNIR and SWIR channels is also on-going through ESA TRP funding.

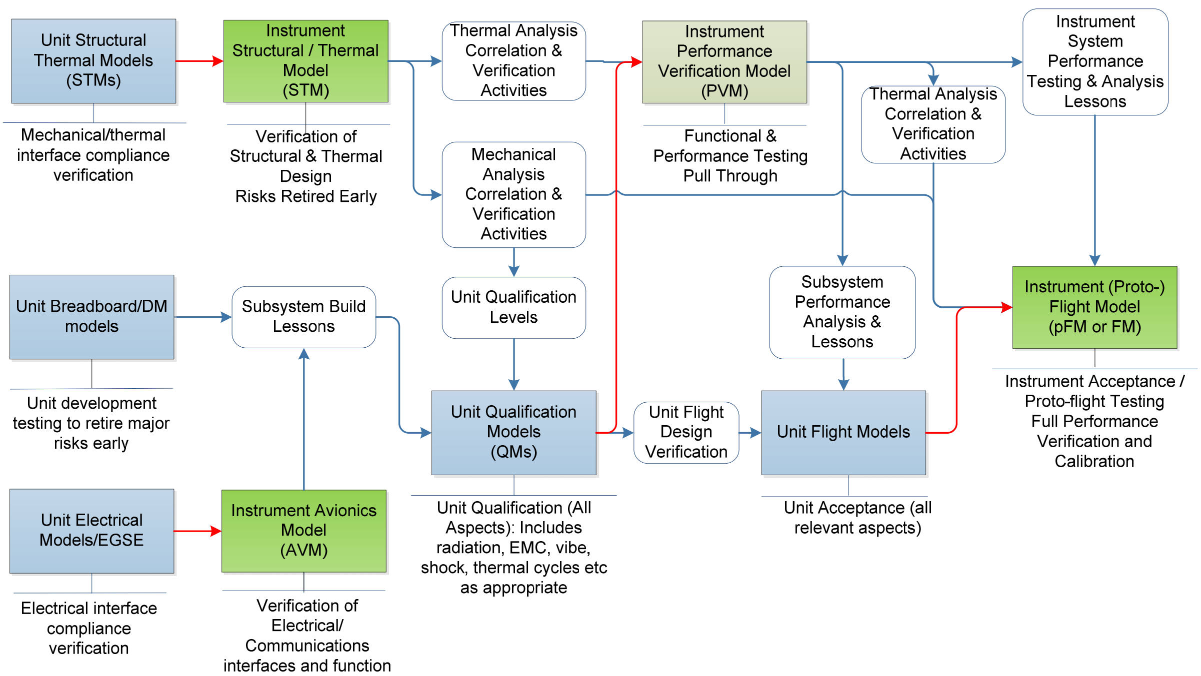


Figure 4-16: General verification flow for the EChO Instrument programme. Blue boxes represent subsystem level hardware activities, Green boxes are instrument level hardware models (only the bright green are delivered onwards to ESA / Spacecraft), Red lines represent hardware deliveries, Blue lines are information or specification flow.

5 Evaluating the performance of EChO

The ability of EChO to reach its scientific objectives is completely linked to the ability of building a stable, accurate spectro-photometer covering a large spectral range from the visible to the mid infrared. In that context, it is very important to monitor at each phase of the project development the expected performance of instrument with respect to the scientific and technical requirements. In this chapter, we describe the strategy developed for the evaluation of EChOs performance, and the evaluation performed during the Phase A study.

5.1 EChO performance requirements

The performance required for EChO is extensively described in Chapter 3. The top-level requirement is that the photometric stability over the frequency band of interest shall not add significantly to the photometric noise from the astrophysical scene (star, planet and zodiacal light). The frequency band over which the requirement applies is also defined in Chapter 3 – i.e. between 2.8×10^{-5} Hz and 3.7 mHz or ~5 minutes to 10 hours. This implies having capability to remove any residual systematics and to co-add the elementary observations from many repeat visits to a given target.

The photometric stability budget is specified in the EChO Mission Requirements Document (MRD) by a mission requirement on the total noise value (R-PERF-350) expressed, in version 3.0 [SRE-PA/2011.038] as a function of the photometric noise due to the stellar flux and the zodiacal light level (see Section 5.3.2). Subsequent to the start of the study, an absolute noise floor requirement has been added to the photometric noise to account for the noise expected from the detectors. We do not discuss this in this Section as the study has been carried out in relation to the applicable version of the MRD, [SRE-PA/2011.038].

The noise requirements shall be fulfilled for a large range of target fluxes. The instrument design has been optimised for the range of fluxes defined in the MRD. The range is defined by a faintest star (R-PERF-090), for which the observation SNR is limited by the detector noise, and a brightest star (R-PERF-110), for which the observation SNR is limited by the stellar photon noise. These requirements are summarised in Section 3.2.7 of this document. However, these requirements do not prevent the observation of fainter stars where the instrument may be detector noise limited. All the performance evaluations will be done for these two extreme cases. The performance is evaluated for the instrument design described in the Chapter 4 of this document.

5.2 Achieving the performance requirements

To achieve the required performance, particular care is given to:

- the design of the instrument and the ability to characterise all possible systematic variations in performance via the calibration strategy;
- the optimisation of the observation program;
- the data processing pipeline(s).

We briefly discuss the issues arising from these topics in the following sections.

5.2.1 Design of the instrument and knowledge of its characteristics

The most important factor determining the final performance of the mission is the way the instrument is designed. Even though the whole wavelength range is divided into bands observed using different physical spectrometer modules, the instrument is designed to operate as a single entity within the same thermal, optical, electrical and mechanical environment.

Particular care has been given to the way the modules are designed in order to share similar technological solutions for each module. For example, the detector technology is similar between all the modules (based on MCT) and the readout units and the common electronics are designed as a single unit to simplify the electro-magnetic compatibility. All the modules as well as the Fine Guiding Sensor share a common field of view and telescope optical train with specific dichroics mounted on the same optical bench (Figures 4-5 and 4-8). They are thus at the same temperature and see the same mechanical environment. In this way optical path errors between modules and the common optics are reduced to a minimum and thermo-mechanical drift within the instrument is eliminated by having an isothermal design of the optical modules. Any pointing jitter is seen directly by both the FGS and the spectrometer instrument and can be accounted for in the data processing. Likewise, through calibration, performance monitoring and use of the FGS data, changes in optical path between the telescope and the instrument (such as "breathing" of the PSF or changes in telescope focus) can be identified and calibrated out of the data.

During the development phase all the critical components (particularly the detectors) will be intensively tested to determine their intrinsic characteristics. This will include determining their sensitivity to environmental variations such as temperature variations, pointing jitter, high-energy particles, electro-magnetic contamination etc. The aim is to understand and predict the evolution of the instrument response when the environmental conditions vary, and therefore to optimise the correction pipeline and the housekeeping monitoring needed as input to the pipeline. The overall instrument will thus be fully calibrated and its performance verified at subsystem and system level before launch in order to check its global behaviour and evaluate its performance using laboratory calibration sources (see Chapter 4).

5.2.2 The calibration strategy

As defined in Chapter 4, photovoltaic detectors based on MCT will be used for EChO, however, they are known to have various non-linear behaviours both in regard to responsivity and dark current. Whilst we have designed an instrument that will allow us to monitor continuously as much of this behaviour as possible during observation phases, it will also be necessary to verify the behaviour of the detectors and instrument in flight over a number of timescales (in-flight calibration). These will range from determining the short term response of the detectors through to slow changes in the instrument performance due to the effects of the space environment and component ageing. It is therefore necessary to consider regular calibration phases between the observations and, possibly, during them. Depending on the final temporal stability of the instrument, several parameters will be checked at different timescales from several hours to days. The calibration strategy includes the use of both an internal calibration unit within the instrument and a list of stable stars (known to be stable to 10^{-5} over the necessary timescales) spread all over the sky [ECHO-TN-0001-IAP]. The calibration strategy is fully described in a technical note, which details how each effect is considered and will be monitored [EChO-SRE-SA-PhaseA-003].

5.2.3 The optimization of the observation program

The ability to fulfil the scientific program strongly depends on the optimization of the observation program. Because the planetary transits and occultations happen at specific epochs (given by ephemerides), the observation program, the data transfer sequences and the on-board calibration phases have to be well-defined and are time critical. The final performance evaluation of EChO also needs to take into account the way the observation and calibration/data transfer phases are optimized (see Chapter 7).

We have simulated an observing programme with an assumed target reference sample using scheduling simulation tools [ECHO-TN-0001-CNES], [ECHO-TN-0001-ICE] & [ECHO-TN-0002-ICE]. These tools aim to check the feasibility and efficiency of the observation program. They include optimisation routines that allow the scheduling assuming knowledge of the visibility of the objects, the transit/occultation ephemerides, the expected spacecraft performance and some assumed calibration and data transfer phases. The net result of the overall process is that, using the target lists described in Section 2.4, the EChO mission requires four years to meet its scientific objectives.

5.2.4 The data processing

It is crucial to correct the raw observed signal time series to account for variations in the signal which are not directly linked to the planetary transit or occultation. The methods for doing this will be encapsulated in the data processing algorithms to be employed in the data pipeline and the final data quality and performance of EChO are highly dependent on the performance of these algorithms. There may be many systematic variations to account for, most of which will be negligible, but we highlight two areas requiring particular attention:

- The astrophysical scene contributions: the stellar variability, the local zodiacal cloud contribution, the exozodiacal cloud contribution and any contaminating stars. These are independent of the instrument performance but may add systematic signals that masquerade as the transiting planet.

- The instrument drifts, pointing jitter, detector non-linearity and any dependence on environmental variations and ageing. These effects will be highly correlated between the spectral bands and many of the effects will be monitored by, for example, off axis detectors, thermistors, the Fine Guidance Sensor and will ultimately be assessed through dedicated calibration observations.

Both of these will be addressed by sophisticated data reduction techniques. They will use the inherent redundancy in the data, knowledge of the target planetary orbital phase and secondary information from the instrument and satellite to remove unwanted systematic effects. The on-board processing, ground segment and calibration plan, taking into account the effect of each contributor and leading to the final scientific data are detailed in a specific technical note [EChO-SRE-SA-PhaseA-003].

5.3 Evaluation of EChO performance

At each phase of the mission development the performance will be assessed using several computational tools based, at the beginning of the project, on the simulation of the observations and, later, on the knowledge of the spacecraft, instrument and the targets themselves.

In this section, we present the evaluation tools presently in use, and the evaluation of the EChO performance.

5.3.1 Performance evaluation tools

5.3.1.1 The Static Radiometric Model

The static radiometric model, hereafter the RM, approach is a simulation of the detection chain applied to targets defined by a number of characteristic quantities. The main hypotheses made in the RM description are:

- That the photometric signal from the star, planet, thermal contributions, zodiacal emission etc. are linear and stable with time – i.e. it is a static model.
- The detection chain is linear and can be described by a set of simple parameters such as optical transmission, quantum efficiency of the detectors, linear electronics gain etc.
- All noise contributions (stellar noise, detector noise, thermal noise etc.) are stochastic and independent – i.e. can be described by a Gaussian distribution
- The post processing of the data is able to remove all systematic biases at the level of the noise.
- Each contributor can described by its characteristics, for instance:
- Stars are described by their effective temperature (and associated SED), radius and distance to the observer.
- Planets are described by their radius, surface temperature, atmospheric molecular density.
- The payload can be described by a number of fixed parameters including the telescope effective area, the telescope and instrument optical transmission, working temperatures, a field of view, the spectral resolution, the spectral range etc.
- The detector can be described by its physical parameters - including the pixel angular field of view on the sky, the full well capacity, the quantum efficiency, the dark current, the readout noise and the readout time.

The model approach provides a description of the source and payload in the case in which noise sources can be considered as Gaussian, and therefore provides a theoretical measure of performance that can be achieved by the observatory. Non-accounted for noise sources such as variation of the source signal, variation of the temperature of the payload etc. can also be included through an allocation in the noise budget.

The model provides the means to calculate, for a given host star/exoplanet target:

- The SNR that can be achieved in a single primary transit
- The SNR that can be achieved in a single occultation
- The number of transit/occultation revisits necessary to achieve a specified SNR
- The total number of revisits that could be achieved during the proposed mission lifetime

The approach is described in more detail in the EChO radiometric model description document [SRE-PA/2011.040].

5.3.1.2 The ESA Radiometric Model (RM) – mission sizing

Several versions of a static radiometric model for EChO have been implemented, including one by ESA in the form of an Excel spread sheet that we refer to as the ESA-RM. In this implementation, a noise budget has been set which includes the noise contributors listed above. Conservative performance estimates have been adopted as appropriate to this early phase of the mission study. As such, the observing time estimates that are derived using the ESA-RM are at the upper end of those expected from EChO by time of launch.

The ESA-RM version used for the calculations reported here was issued in September 2013. The critical parameters assumed are listed in Table 5-1. Here the "noise floor" and the "Nmin" values are set to allow some margin for the performance of the system with respect to the ideal situation where the measurement is photon noise limited. The "QE" is the quantum efficiency of the detectors, η the optical transmission from the telescope entrance aperture to the detectors and "R" the resolving power evaluated at the lowest wavelength in each of the spectrometer bands.

SNR CALCULATION PARAMETERS						
Channel limits [µm]	*Relative noise floor X*	*Absolute noise floor Nmin*	*QE*	*η*	*R*	*Aeff [m2]*
0.4	[%.(N0+zodi)]	[e-/s/spectral bin]	[p/e-]			1.131
1	200%	20	60%	10%	300	*1+1/Y*
5	50%	20	70%	23%	300	2
11	30%	200	50%	23%	30	
16	30%	200	50%	23%	30	

Table 5-1: Parameters used in the ESA RM (September 2013)

5.3.1.3 The end-to-end simulation: EChOSim

When estimating the real performance of the mission, one needs to take into account all expected effects from the astrophysical scene to the final pipeline products and adopt the most accurate description of each step. This is the purpose of the end-to-end simulation software EChOSim which allows the simulation to go beyond the classical radiometric description and to study the impact of specific effects and/or optimise the choices during the instrument design.

The philosophy of EChOSim and its realisation are fully described in the EChOSim User Requirement Document [ECHO-TN-0001-CDF] and EChOSim Software Requirement Document [ECHO-TN-0002-CDF]. The EChOSim model has been validated against the different cases of the radiometric model [ECHO-TN-0002-UCL] and found to give good agreement.

EChOSim is presently used as a predictive model, but will evolve during future phases of EChO into a real model of the instrument and spacecraft, which will include measured performance and/or calibration data. In this way the model elements used for the detection process description will be replaced, one by one, by an actual description of the process based on laboratory measurements. Additionally, simulated parameters will be refined as and when accurate models of the payload are available (e.g. thermal and mechanical model of each module, global architecture of the instrument, model of the satellite pointing performance etc.).

In future versions of EChOSim, or other stand-alone software modules as appropriate, we will include additional functionality to simulate the data as they come from the satellite, using the right data packet format, and link the model to the initial versions of the complete data processing pipeline.

5.3.2 Evaluation of EChO performance

Using the EChOSim tool, we can evaluate the performance by evaluating the overall noise allocation and comparing this to the requirements laid out in the science requirements document [SRE-PA/2011.037] and the MRD [SRE-PA/2011.038]. The procedure is extensively described in [ECHO-RP-0001-RAL] and here we only summarise the main results.

5.3.2.1 Overall noise allocation

Noise associated to the astrophysical scene:

The number of detected photons from the planet and star, N_0, and zodiacal background photons in a sampling interval, Δt, is used to estimate the level of photon noise from the astrophysical scene. This is

$$\sigma_N^S = \sqrt{N_0 + Zodi} \qquad \frac{e^-}{pixel} - rms$$

It is convenient to refer the noise in one sampling interval to the noise per unit time:

$$\sigma_N = \sigma_N^S / \sqrt{\Delta t} \qquad [e^- pixel^{-1} s^{-1/2} - rms]$$

Noise associated with the instrument:

In this performance evaluation, we considered several instrumental sources of noise:

- The detection chain associated with the detector: its photometric response is supposed to be linear with the flux, stable with time at a given working temperature or at least can be corrected to be considered as linear, and stable with time. An inflight calibration strategy has been proposed in that way (see Section 5.2.2). The detection chain noise can thus be described only by a detector readout noise and a dark current.
- The telescope thermal emission: it is described by a constant flux at a given temperature (and thus an electron bias after detection that can be removed) and its associated photon noise.
- The instrument thermal emission: it is also described by a constant flux at a given temperature and its associated photon noise.
- The pointing jitter: the jitter leads to several photometric perturbations linked to the slit losses, the vignetting at fibre stops in the case of fibre-linked modules, the inter- and intra-pixel response non-uniformity for each detector. The importance of these effects strongly depends on the instrument design and the strategy adopted for the spacecraft pointing stabilisation. A specific study has been performed to compare the performance of 3AOCS implementations, based on a cold gas system or reaction wheels with various accuracies (see [ECHO-TN-0003-UCL] – see also Section 5.2.3). The conclusion of this study is that the use of specific de-trending algorithms can limit the impact of jitter noise on the photometric stability to two contributions. A first one, linked to the relative performance (high frequency unresolved jitter component) named RPE (relative pointing error) and another to the performance reproducibility (low frequency resolved pointing drift) named PDE (Pointing Drift Error). In the global performance evaluation, all the jitter noise contributions are considered as Gaussian. Figure 5-1hows the estimation of the relative jitter noise in the case of a bright target (55 Cnc e).

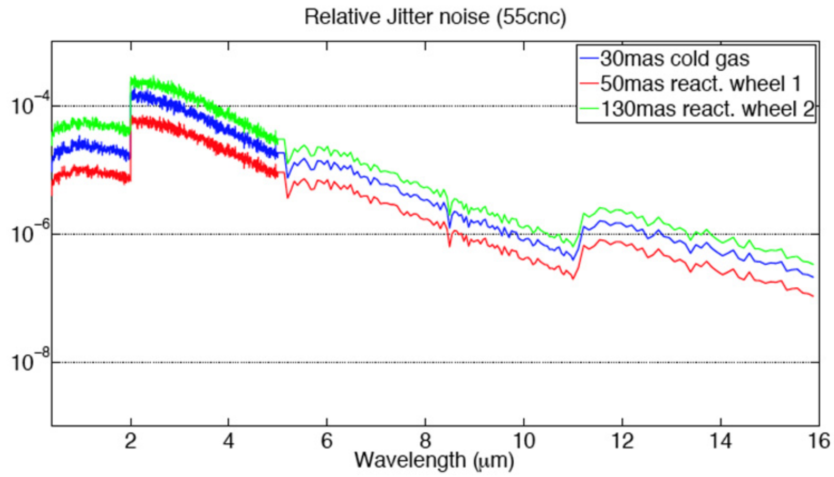


Figure 5-1 : Relative error as function of wavelength for the photon noise limited case (55 Cnc e). Here RPE and residual PDE noise after preliminary de-trending are shown, for three AOCS solution. Blue: Cold gas system. Red: reaction wheel performance of 50 mas. Green: reaction wheel performance of 130 mas.

All sources of instrumental noise contribute to the total system noise level, σ_{SN}. The system noise level is then given by the sum in quadrature of all individual noise components**:**

$$\sigma_{SN} = \sqrt{\sigma_{RO}^2 + \sigma_{DC}^2 + \sigma_{Tel}^2 + \sigma_{Opt}^2 + \sigma_{RPE+PDE}^2} \qquad [e^- pixel^{-1} s^{-1/2} - rms]$$

σ_{RO} is the detector readout noise, σ_{DC} is the dark current noise, σ_{Tel} is the combined photon noise associated to the thermal emission of all optical surfaces in the line of sight, σ_{Opt} is the photon noise associated to the thermal emission of the module enclosure, and $\sigma_{RPE+PDE}$ expresses the photometric noise associated to the pointing jitter.

5.3.2.2 Simulation of EChO performance

EChOSim simulations have been used to estimate the contribution each noise source makes to the total noise budget according to the current design of the instrument as detailed in Chapter 4. The estimated photon noise from the astrophysical scene is used to express the requirement on the system noise. Following R-PERF-350, the requirement is:

$$\sqrt{\sigma_{SN}^2 + \sigma_N^2} < \sqrt{{\sigma_{SN}^R}^2 + \sigma_N^2} = \left(\sqrt{1+X}\right)\sigma_N$$

Where σ_{SN}^R is the maximum system noise allowed by the requirement. The parameter X is the excess noise-variance and it is set to X = 2 at wavelengths λ < 1 μm, and X= 0.3 at longer wavelengths.

For each noise source contributing to σ_{SN}, we estimate its contribution to the excess noise-variance, *X*.

$$X = \left[\frac{\sigma_{SN}}{\sigma_N}\right]^2$$

We can use this to quantify the relative contribution each noise component has to the system noise. Since this number is independent from the integration time and spectral binning, it provides a convenient quantitative way to break down the noise budget in individual components.

Figure 5-2 and Figure 5-3 below show the contributions to the system noise-variance. Here, the black solid line is the requirement, i.e. the R-PERF-350 X value, and the red solid curve is the value of X achieved combining all noise sources from simulations. The detector noise is evaluated assuming that the detectors are read "sampling-up-the-ramp", with 12 non-destructive readings for the bright source case (Figure 5-2) and 30 for the faint source case (Figure 5-3). The performance evaluation process includes a data reduction pipeline that allows reducing detector timelines into calibrated spectra with removal of the expected systematics. It includes a procedure to remove the jitter noise discussed above and shown in Figure 5-1 these errors are strongly correlated with line of sight direction monitored by the FGS, see [ECHO-TN-0003-UCL].

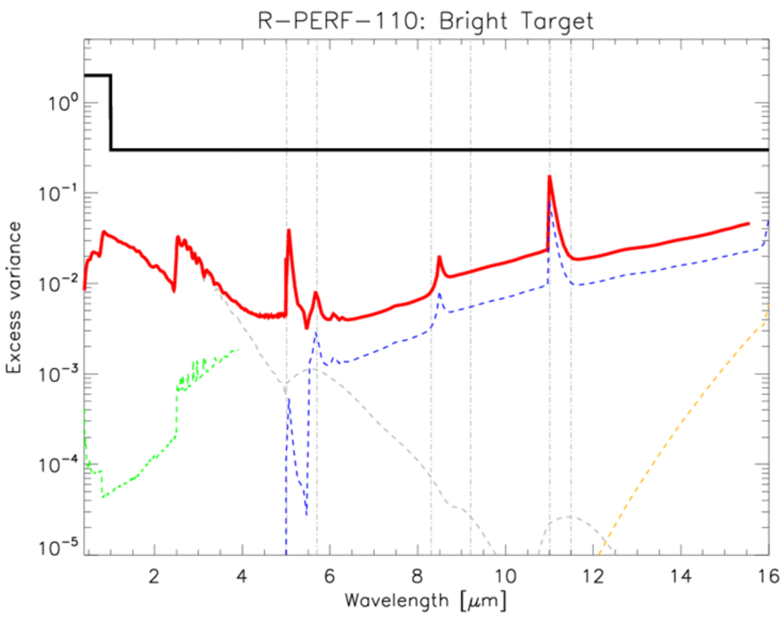


Figure 5-2: Noise breakdown for the brightest target to be observed by EChO. The individual noise components are as follows: readout noise excess variance (dashed green); dark current excess variance (dashed blue); thermal emission from instrument enclosures excess variance (dashed violet); thermal emission from optical surfaces excess variance (dashed yellow); post-processing RPE+PDE photometric excess variance (dashed grey). The total variance is shown as the solid red curve and the requirement as the solid black line.

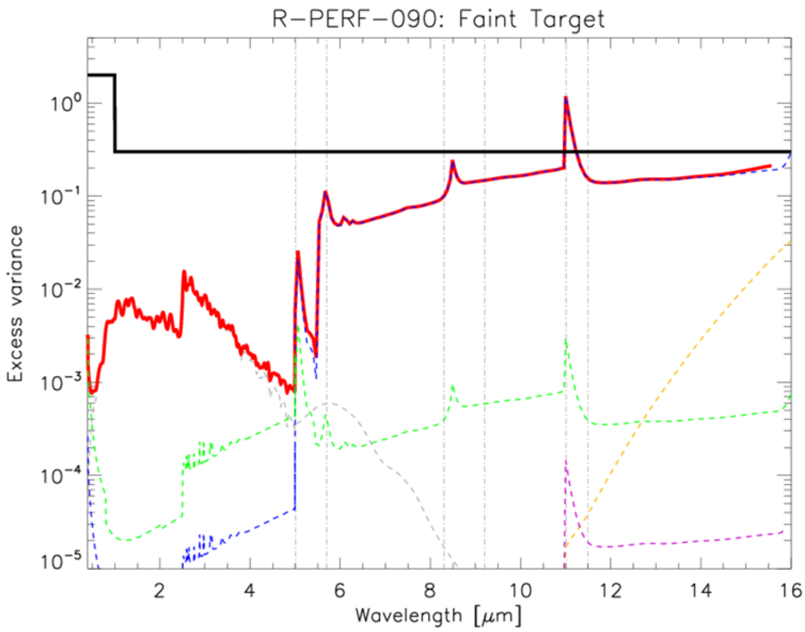


*Figure 5-3: Noise breakdown for the faintest target to be observed by EChO. The individual noise components are as detailed in the caption for Figure 5-2 above**Error! Reference source not found.**. The total variance is shown as the solid red curve and the requirement as the solid black line.*

The simulations show that the baseline EChO design is compliant with the requirements over all required channels (VNIR+SWIR+MWIR). The system variance exceeds the requirement only in the spectral region allowed by the "no wavelength cut" prescription, corresponding to the channel dichroic transitions. We note that the mission goal LWIR channel is non-compliant. Provision of the LWIR channel is considered as a goal and this has no impact on the mission requirements. However, because the excess variance is, to first order, proportional to the spectral resolution in this case (detector noise dominates), it is possible to reduce the spectral resolution of the LWIR channel in post-processing. Since the feature of interest here is the broad CO_2 absorption, this is not considered a problem

5.3.3 Planetary spectra reconstruction

Using the EChOSim tool, we can go on to simulate the observation of key targets and see how the overall requirements translate into reconstructed spectra. To that end, two target observations were simulated end-to-end: the transit of a warm Neptune around a faint object (GJ 3470) in the Rosetta Stone tier, and the eclipse (occultation) of this same object in the Origin tier. Both transit and eclipse observations allow determining the structure and the composition of the atmosphere.

5.3.3.1 GJ3470b

GJ 3470b is a 0.0437 M_J planet with a radius of 0.374 R_J (where M_J and R_J are respectively the mass and the radius of Jupiter), orbiting at 0.036 AU with a period of 3.3367 days around its parent star (M1.5V star, mV=12.27, T_{eff} = 3600 K at 30.7 pc). The transit (and occultation) duration is about 1 hour and 45 minutes. The effective temperature of the planet, assuming the thermal equilibrium is 615 K. The atmospheric model used for this spectrum reconstruction simulation is assumed to be methane-poor and water rich.

5.3.3.2 Transit observation (Rosetta Stone)

The observation of GJ3470b in the Rosetta Stone tier requires the co-addition of 21 transits, assuming the current design of the mission and the known parameters of the planetary system. We estimated the observable $(R_p/R_s)^2$ (the transit depth, where R_p and R_s are the planetary and the stellar radius respectively) as a function of the wavelength (Figure 5-4). The associated error bars are computed using a dynamical fitting method implemented in the observation pipeline. This figure clearly shows that the transit depth chromatic variations associated with atmospheric absorptions can be detected all over the IR spectral range even with a limited number of transit observations. The SNR decreases over 12 µm due to the increase noise in the detection chain and the contribution from thermal noise. The transit spectrum exhibits various spectral features associated not only with water vapour but numerous other molecules.

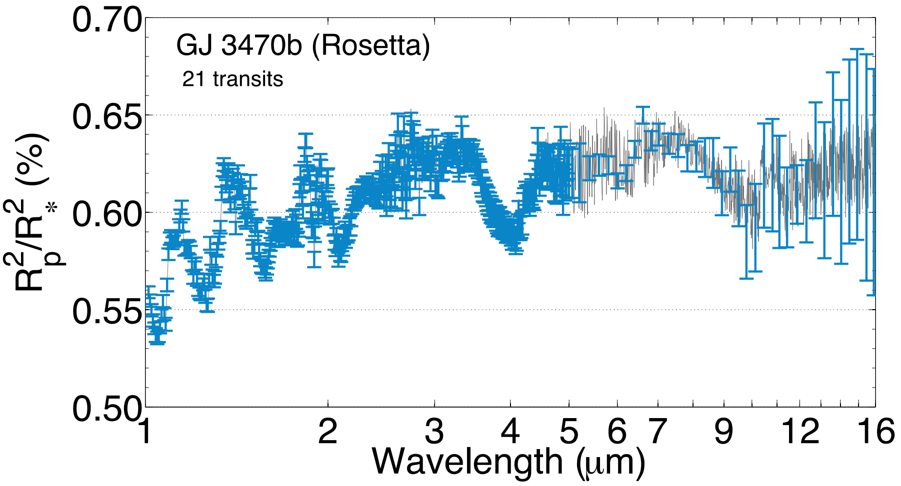


Figure 5-4: Transit depth as a function of the observation wavelength with EChO for GJ3470b, assuming the co-addition of 21 transits and the present design of the instrument and data processing pipeline.

5.3.3.3 Occultation (eclipse) observation (Origin tier)

Because of the high contrast between the star and the planet (higher than 10^4) and the low intrinsic emission flux from the planet due to its moderate temperature (about 600 K) it is not possible to observe the emission spectrum of GJ 3470b using the eclipse in the Rosetta mode within a reasonable observation duration (mission lifetime). The emission spectrum can thus only be obtained in the Origin tier. The reconstructed spectrum after observation simulations is presented in Figure 5-5. The emission spectrum clearly exhibits a strong absorption due to the presence of water vapour in the atmosphere.

Using both transmission and emission spectra together, one can determine the vertical height of the atmosphere. The mean molecular weight is estimated thanks to the identification of key molecules in the transmission spectrum. The atmospheric temperature is estimated thanks to the effective temperature measured using the emission spectrum, and the local gravity is determined using the mass of the planet measured by radial velocity.

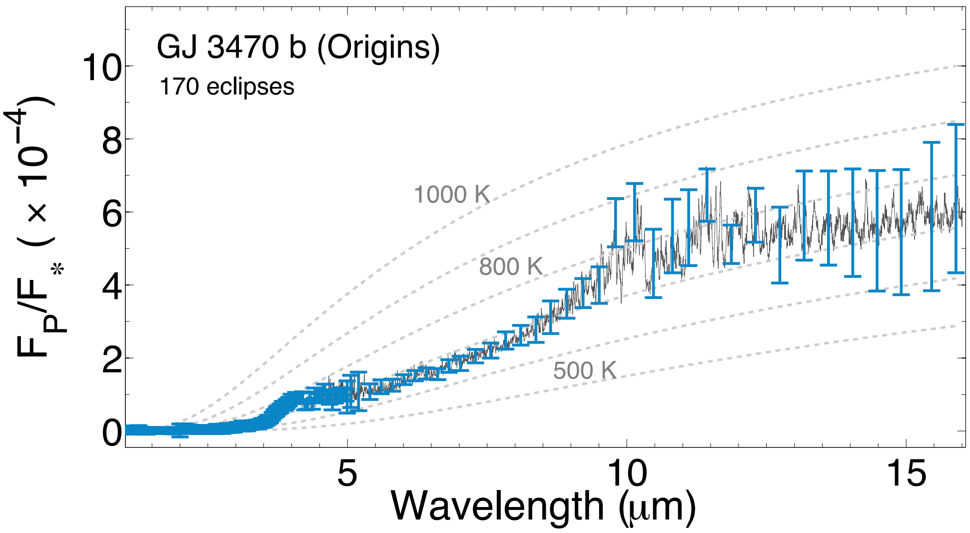


Figure 5-5: Contrast ratio (planetary/stellar fluxes) as a function of the wavelength assuming the co-addition of 170 secondary eclipses.

This example and the associated spectra reconstruction exercises can be generalized to every target of the reference sample to optimize the observation strategy. It demonstrates the enormous scientific return EChO will generate.

5.4 Conclusion

High accuracy spectro-photometry requires particular care in the design, calibration, and operation of the instrument, and also a clever data processing pipeline to limit the noise contributions to their lowest values. In this chapter we have shown, using simulation tools, that the photometric stability requirement for EChO can be achieved with the current instrument and mission design for the complete set of targets defined for each part of the scientific program.

Throughout the instrument development phase performance will be carefully monitored to identify potential deviations to the required performance and to enable the rapid development of appropriate mitigation strategies.

6 Mission design

This chapter presents the EChO mission analysis (section 6.1), the S/C design (sections 6.2 and 6.3) and provides a description of the development plan (section 6.4).

The spacecraft axes referred to throughout this chapter are illustrated in Figure 6-2 below.

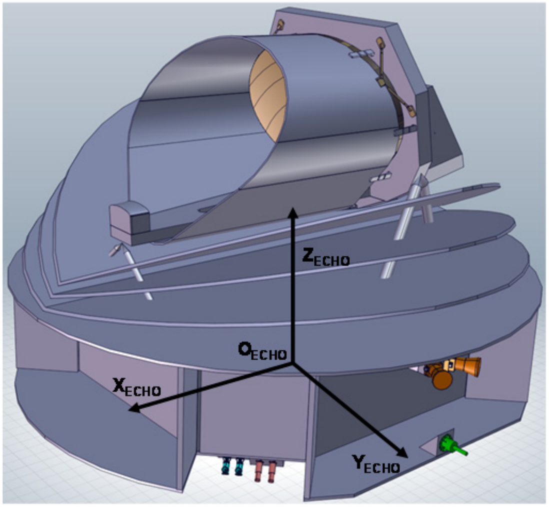


Figure 6-1: EChO S/C schematic with reference frame. The origin is at the geometrical centre of the separation plane between the LV adapter and the S/C. The Z_{ECHO} axis is coincident with the LV longitudinal symmetry axis. The X_{ECHO} axis is in the separation plane between the LV adapter and the S/C and is parallel to the telescope pointing axis. The Y_{ECHO} axis completes the right-handed orthonormal triad. The Sun is underneath the SVM, in the $-Z_{ECHO}$ direction, during nominal science operations, so that the PLM is obscured and can be passively cooled.

The main structural elements that comprise the EChO spacecraft and that are regularly referred to throughout this document are illustrated in Figure 6-2.

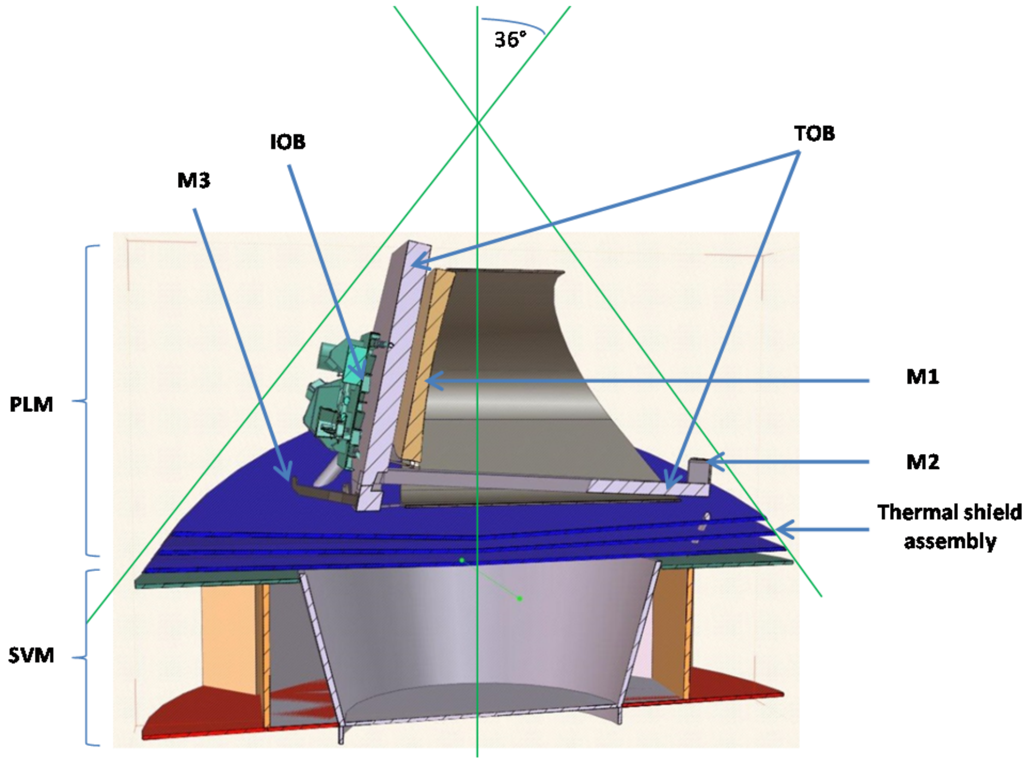


Figure 6-2: Cross-section of EChO showing the main structural elements within the PLM and the angular constraints imposed by the observable sky requirement

6.1 Mission Analysis

6.1.1 Launcher, launch window and orbit selection

The EChO spacecraft science operations orbit is an eclipse-free (Earth and Moon) large amplitude orbit around the Sun-Earth L2 point. This orbit is key to meeting two of the most important science requirements: it offers a very stable environment (for thermal, power and communication purposes), combined with a very large instantaneous field of regard.

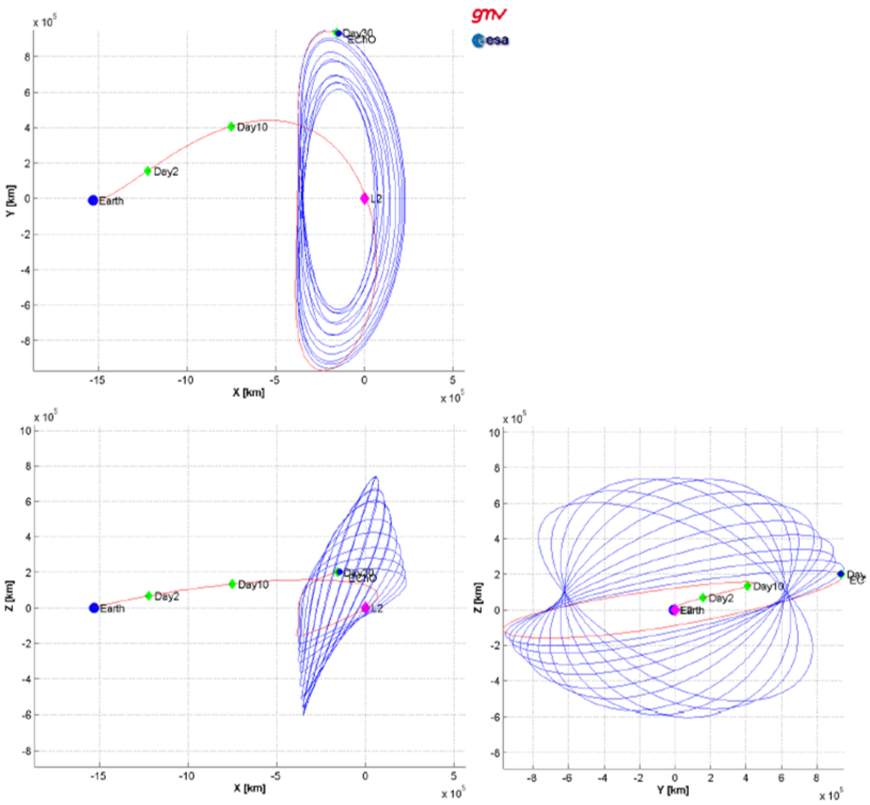


Figure 6-3: Example of EChO orbit around L2

This orbit offers several other advantages. The radiation environment in L2 is much more benign compared to LEO orbits, and it is not too distant from the Earth, allowing a simple communication strategy and communication subsystem design.

The baseline launch strategy consists of a Soyuz launch (see Figure 6-4) from Kourou into a direct transfer orbit to L2. The transfer and insertion into L2 is designed to be propellant free, however opportunities at day 2, 5 and 10 after launch are available to correct for launcher dispersion and perigee velocity errors. An alternative launch strategy exists and consists of launching into a highly elliptical parking orbit (~ 300.000 km apogee). The increased launcher performance would then be used to add extra propellant for apogee raising up to L2. This strategy takes more time and uses more manoeuvres, but it removes the criticality of the day 2 correction manoeuvre (this manoeuvre needs to be performed in a tight window, and if missed results in a significant delta-V (ΔV) loss during day 5 and 10 manoeuvres. However, the baseline strategy is considered to be sufficiently robust (heritage exists), so this alternative is only kept as an option.

Soyuz provides an injected mass performance of about 2.2 tonnes to this orbit. The EChO launch mass (wet mass + adapter) is ~1.5 tonnes (see detailed mass budget in 6.3.1), including the typical 20 % system level margin. This leaves about 700 kg un-used. Combined with the large volume margin of EChO inside the Soyuz fairing, this could allow launching EChO on top of the SYLDA-S adapter with a small companion underneath.

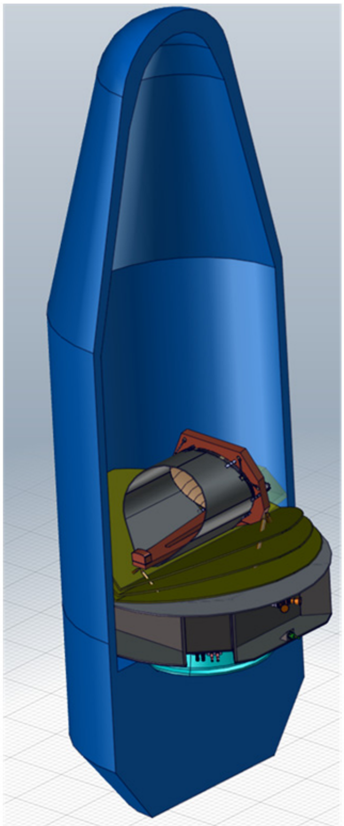


Figure 6-4: EChO in Soyuz fairing

Daily launch windows of at least 1.5 hours exist throughout the year, with the exception of 2 outages of ~1 month each around the 2 solstices. Four conditions have been used to constrain the launch window:

- No eclipses during the mission lifetime (including the transfer and the 2 year goal extension), for thermal and power generation stability
- Propellant free injection into L2 for minimal propellant mass
- Amplitude around L2 ≤ 1.5 million km to minimise the S/C to Earth distance for the communications subsystem, leading to a Sun-S/C-Earth angle ≤ 45°
- The Sun shall not be in the $+Z_{ECHO}$ half-sphere for more than 10 min, between fairing jettisoning and S/C separation

The last condition results from the horizontal accommodation of the telescope and PLM on top of the SVM, without any lateral Sun shield. During nominal science operations the Sun must remain below the SVM (in the $-Z_{ECHO}$ half-sphere), as the SVM acts as a Sun shield to passively cool the PLM. However during the launch phase, the Sun is located above the PLM as the launch will happen during day-time, so this last condition ensures the PLM does not over-heat during this phase (i.e. stays within qualified temperature ranges of the materials used). Practically, this last condition means the daily launch window cannot start before 14h UTC (see Figure 6-5.) This results in temperatures not exceeding 80 °C on the thermal shields, while a 12h UTC launch time would results into temperatures above 100 °C.

In addition to the constraints listed above, the S/C is positioned on the launch vehicle so that the Sun is in the $+Y_{ECHO}$ axis while the Earth is in the $-Y_{ECHO}$ axis (or the opposite, both options are identical). This ensures the direct sunlight and the sunlight that is scattered/reflected on the Earth do not enter the telescope and instrument FoV and cause irreversible damage to either. The LV spin rate around its roll axis should be lower than a few degrees per minute to ensure that this condition remains valid throughout the launch phase. An additional risk mitigation measure would be to add a mirror cover or a shutter on the common optical path to all instrument channels. This will be investigated further in the next study phase.

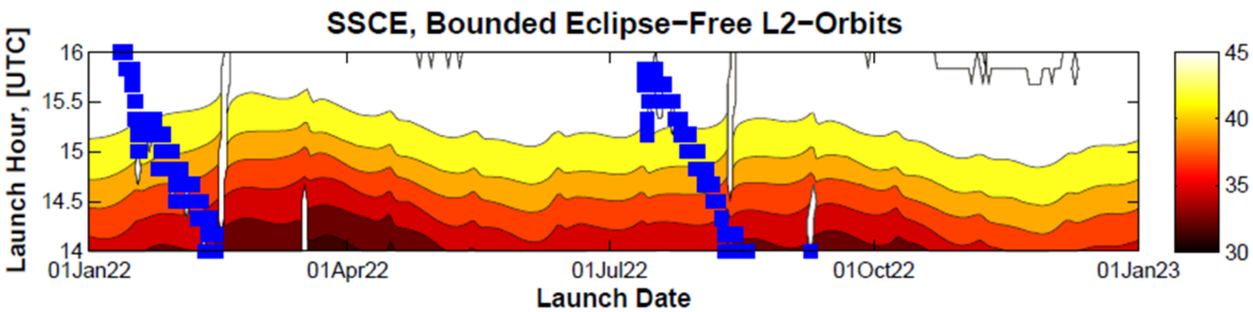


Figure 6-5: EChO launch window, showing daily launch windows between 14:00 and 15:30 UTC apart for 2x 1 month outages around both equinoxes (blue area). The later the launch time, the larger the amplitude of the orbit around L2 (dark red to yellow for Sun-S/C-Earth angle from 30 degrees to 45 degrees respectively).

6.1.2 Operations

Before the nominal science operations phase (starting within no more than 6 months after launch), a maximum of 3 months are dedicated to S/C commissioning, followed by 3 months of instrument performance verification and science demonstration. Standard tasks that are undertaken during these phases include commissioning of all the S/C subsystems and verification of the instrument performance and calibration. Additional activities that are specific to EChO and that will be carried out during these phases are:

- De-contamination of the optics and detectors, to prevent performance degradation from moisture release and out-gassing.
- PLM cool-down, from the warm launch conditions to ~ 47 K.
- Determination of the optimum focus, using the M2 re-focussing mechanism in the loop with the FGS.

During the nominal science phases, an observation efficiency ≥ 85% is guaranteed by design. The main outages relate to station keeping (8 hours every 28 days), ground contacts (average contact frequency of 2 hours twice a week for telecommand uplink and science downlink), slews between targets (average of 15 minutes between each target) and an expected average of 2 safe modes per year. An outage of 1 hour per day is allocated to periodic calibration of the instrument using celestial sources; further time will be allocated to calibration, however this appears in the science budget. Between those outages, the S/C will observe continuously science targets, in succession after each other. The average transit observation is ~3.7 hours, while the maximum is 10 hours. Because of the uniform distribution of targets across the sky, the average separation between successive targets is set to 90° for design purposes. While the target planning algorithm can optimise the scheduling of observations based on their relative locations with respect to each other, this design constraint is a worst case scenario and leads to the selection of reaction wheels that allow for fast slews (several degree per minute) to minimise the impact on the observation efficiency.

An additional 2x5 hours of ground contacts per week are also required to improve the orbit determination accuracy to a level that is consistent with ESA heritage (i.e. Planck). These contacts will make use of the S/C Low Gain Antennas (LGA) which have a full sky coverage; as a result science observations can continue in parallel, and the contacts have no effect on the observation efficiency.

The S/C and instrument are designed for a 4 year lifetime, implying a 3.5 year nominal science operations phase. The S/C consumables are sized for an additional 2 year goal extension. The mission will be ended by a de-commissioning phase similar to that planned for Gaia, whereby 2 manoeuvres will be used to remove the S/C from the L2 orbit and ensure it will not come back to Earth with a probability > 99 % in the next 100 years.

6.2 Spacecraft design

6.2.1 Structures and Configuration

The spacecraft is designed in a modular way, with a clear physical separation between the SVM and the PLM (see Figure 6-6). This will simplify the procurement and Assembly, Integration and Verification (AIV) approach by allowing both modules to be procured and tested in parallel and independently.

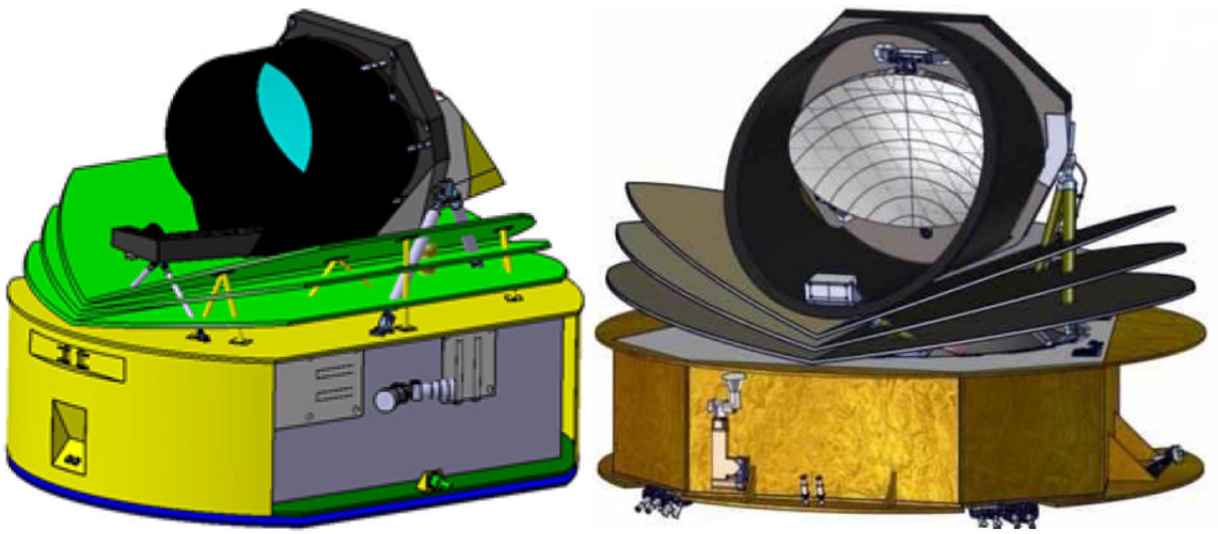


Figure 6-6: EChO S/C, with SVM on the bottom and PLM on the top. Left: Industry A. Right: Industry B.

The PLM is composed of the thermal shield assembly (a set of 3 shields in a V-groove configuration) and the TOB, carrying both the telescope and the instrument box. The TOB is supported on the SVM through 3 GFRP bi-pods. These are designed to carry the PLM during launch, transferring the loads down to the stiff

SVM structure, while minimising the conductive heat transfer from the SVM to the PLM during nominal science operations thanks to a very low thermal conductivity. In addition, these bi-pods are thermally anchored to each thermal shield, to intercept as much heat as possible coming from the SVM before it reaches the PLM.

The SVM structural design differs between the industrial contractors. It is a rectangular parallelepiped for Industry A, optimised with respect to the EChO observational angles, while it is n hexagonal parallelepiped for Industry B. Both designs are completed with near-circular bottom and top SVM floors, extended to the full diameter capability of the Soyuz fairing to maximise the obscured volume in which to position the PLM units.

The SVM contains a stiff central cylinder (Industry A) / cone (Industry B) that is directly mounted on the Launch Vehicle (LV) adapter to transfer all the launch loads. In the case of Industry B, this cone extends up all the way to the PLM GFRP bipods for a direct transfer of the PLM structural loads, while in the case of Industry A these bipods are mounted on the lateral panels of the SVM. In this second case, the PLM loads during launch are transferred through shear panels inside the SVM that attach the lateral panels onto the central cone. The central cylinder / cone also contains the mono-propellant tank (hydrazine).

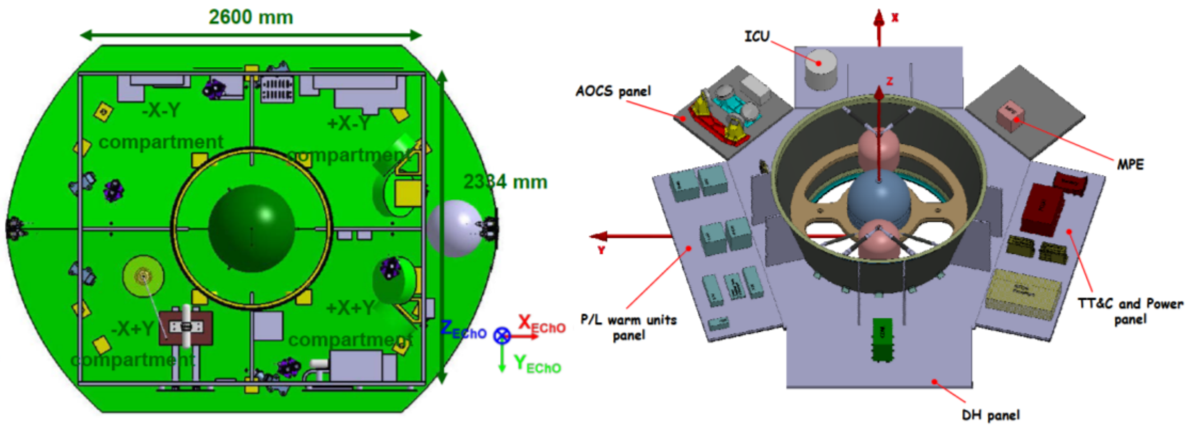


Figure 6-7: Inside view of the EChO SVM. Left: Industry A. Right: Industry B.

6.2.2 Thermal

The SVM is thermally controlled at around 20°C for nominal operations of all the S/C subsystem units. This is achieved through dedicated heaters where required and radiator areas are available on some of the side panels of the SVM that are constantly looking towards the cold sky.

The complete telescope assembly is passively cooled by the SVM and the thermal shield assembly. The SVM top floor acts as the first main barrier between the PLM and the Sun (and the warm SVM), and is covered with high efficiency Kapton MLI. It is then followed by a set of 3 thermal shields in a V-groove assembly similar to the configuration in Planck. The successive temperature stages are ~140 K, 90 K and 50 K (V-Groove shields 1, 2 and 3). This enables the Telescope Assembly to be cooled below 47 K by passive means only. The additional heat load from the instrument will be either dissipated on the V-Grooves or the Telescope assembly (e.g. harness, cooler pipes, pre-amplifiers) or by using instrument provided radiators mounted on the IOB (~1 m^2) for cooling of the detector assemblies at even lower temperatures (~30 K).

Temperature variations on the PLM are kept under 200 mK / 10 hours to avoid the thermal background stability becoming a major contributor in the instrument noise budget. The most significant temperature variation will happen when the Sun aspect angle changes while slewing to observe a new science target. The maximum slew angle between successive targets is set to 36° around the Y_{ECHO} axis (see Figure 6-2). The temperature variation induced by this change in attitude is smaller than 10K in the SVM top floor. This variation is further damped by more than 2 orders of magnitude at the PLM level, well below the temperature stability requirement. As a result, it is not anticipated that significant temperature regulation is needed for the units inside the SVM. However, Industry B has added a significant amount of power for heaters inside the SVM for additional safety in this early phase of the study, which is visible in the power budgets shown in Section 6.3.2 and is the main difference between both contractors in this budget.

The passive cooling strategy described above is under the responsibility of the S/C prime. In addition to passive cooling, further cooling is required by the detectors that are used in the science channels of the instrument operating above 5 µm to minimise the detector noise, and also for the instrument box of these channels to minimise the thermal background noise. This requires the implementation of an active cooling chain down to ~28 K, which is under the responsibility of the instrument consortium and described in Section 4.4.6.3

6.2.3 AOCS

The Attitude and Orbit Control Subsystem (AOCS) provides control of the S/C attitude and of the telescope and instrument Line of Sight (LoS). The AOCS requirements are split into 2 pointing modes: a coarse pointing mode and a fine pointing mode.

The coarse pointing mode is achieved by only using the star trackers as the sole attitude sensors, and reaction wheels as the actuators (i.e. without the FGS in the loop). This mode is used:

- To slew to and locate the target stars, so that the FGS can acquire the target before the S/C enters into the fine pointing mode for the science observation
- To observe other targets that cannot make use of the FGS, because they are either too faint in the visible, too big to fit in the FGS FoV, or moving too fast (e.g. Solar System planets, moons, asteroids, KBOs etc.)

The fine pointing mode is the precise pointing mode that will be used during observations of all exoplanet targets. It is achieved with the FGS that provides fine pointing knowledge around 2 axes, hybridised with the star trackers for a coarse determination of the attitude around the 3rd roll axis. In addition Industry B has added a fine gyroscope for enhanced robustness to FGS performance degradation. These AOCS sensors are used in a closed control loop with a cold-gas micro-propulsion system. The reaction wheels are only used to slew the S/C between targets, and are then stopped during science observations as they induce unacceptably large micro-vibrations. The fine pointing requirements achieved by this system are:

- A fine Relative Pointing Error (RPE) of 50 mas (1-sigma) over 90 s
- A Pointing Drift Error (PDE) of 20 mas (1-sigma) up to 10 hours

The RPE contains all the high frequency jitter terms. This jitter is un-resolved, because the detector read out rates are slower than 1 Hz. Rather, it induces a (negligible) blur in the 1.6 arcsec PSF described in Section 4.3, but does not result in photometric variations in the frequency range of the science observations (see Section 5.3.2.1). Simulations by the instrument consortium have shown that the RPE given above can be relaxed by a factor of 2 to 3, leading to potential simplifications in the design of the AOCS subsystem that will need to be investigated in the next study phase (e.g. reaction wheels only, with no cold gas system).

The PDE is the most important pointing requirement, as it translates directly into photometric variations that add to the instrument noise budget. As the PSF moves on the focal plane detectors during this time scale, the number of photons incident on the individual pixels will vary. This photometric variation is taken into account in the instrument noise budget (see Section 5.3). Since the PDE applies to very low frequencies (minutes to hours), it is more easily met than the RPE. The only contributor to attitude drifts in this frequency range is the Solar Radiation Pressure (SRP); in the case of EChO this is more than one order of magnitude lower than that of typical astrophysics missions with telescopes that are accommodated vertically (e.g. Herschel or Euclid). This is because the horizontal accommodation of the PLM on the SVM allows for a well-balanced S/C which minimises the torque that originates from the misalignment between the centre of gravity of the S/C and the centre of pressure of the SRP.

The RPE and PDE requirements given above are applicable when observing the brightest targets of EChO. This is because the brighter the target is, the larger the photometric variation induced by a small pointing variation is. As a corollary, for fainter targets, these pointing requirements are more relaxed. This benefits the EChO AOCS system, since the FGS centroiding error is much smaller when observing a brighter target. The optical flux ratio between brightest to faintest targets is a factor of ~100, which translates into a SNR improvement on the FGS centroid of ~sqrt(100)=10 when observing brighter targets. In addition to an improved centroid accuracy, the FGS read out rate can also be increased (up to 10 Hz), allowing further measurement and correction for higher frequency terms in the pointing jitter to be made.

In addition to the RPE and the PDE, the fine APE needs to be at the level of 1 arcsec (3-sigma). It translates into a mechanical co-alignment requirement between the FGS and the different science channels, and has been budgeted into the dimension of the slits and the mechanical tolerances of the instrument channels on the IOB.

6.2.4 Propulsion

The propulsion system is a simple mono-propellant system (hydrazine) that is based around standard qualified off-the-shelf components (typically 1 to 20 N thrusters). Two redundant sets of thrusters are accommodated around the S/C to provide control around the 6 degrees of freedom (3 translations and 3 rotations), and the propellant tank is accommodated in the central cylinder /cone described in Section 6.2.1.

This system will be used during the transfer phase, and for the monthly orbit maintenance manoeuvres, in addition to the safe modes in case of a reaction wheel failure. The thrusters pointing in the $+Z_{ECHO}$ direction have no direct view to the optics and instruments to minimise the risk of contamination. As an additional contamination mitigation measure, the thrusters are only used during the transfer phase, when the telescope is warm, so that contaminants will not collect on the optical surfaces. During nominal operations in L2, the selected orbit is "biased", so that no manoeuvres are needed along the $+Z_{ECHO}$ direction, i.e. only thrusters pointing towards the $-Z_{ECHO}$ direction will be used, with no risk of contamination.

An additional ΔV of 50 m/s was added towards the end of the study to comply with the requirements on orbital debris mitigation. This was not included in the industrial designs, so additional propellant will have to be added in the next study phase (less than 50 kg extra to be added to the mass budget in Table 6-1. This is not considered to be critical as EChO is neither mass nor volume limited.

6.2.5 SVM electrical architecture

The power subsystem uses standard qualified off-the-shelf components. It is based on a 28 V regulated bus system, with power conditioning provided by a Maximum Power Point Tracker. Solar cells are accommodated on the bottom floor of the SVM, covering an area of about 5 m^2 in constant view to the Sun. Since the orbit is eclipse-free, batteries are only necessary during the launch phase. The packaging ratio of the cells does not exceed 70% of the available surface, leaving sufficient margins. The power requirements of the S/C are of the order of 1 kW, with differences in the two contractors as explained in Section 6.3.2

The general data handling architecture uses a MIL-1553 bus, while instrument and FGS data are transferred through Spacewire.

The communication subsystem uses X-band, with 2 to 3 (depending on the industrial contractor) Low Gain Antennas (LGA) distributed around the S/C with a full 4π sky view to allow for S/C recovery in case of safe mode or loss of attitude. The science data is downlinked with a 30 to 40 cm (depending on the industrial Contractor) High Gain Antenna (HGA) located on the bottom of the SVM. The complete S/C needs to slew to point the HGA towards the Earth for science data down-link, meaning no science observation can be planned during these ground contacts as the telescope and instrument line of sight can no longer be controlled. The New Norcia ground station (35 m diameter) is assumed in the baseline. The 2-hour contact duration is split into a first 15 minutes for contact acquisition and ranging, with the remaining 105 minutes used for data uplink (software updates and weekly observation plan) and data downlink (science data, including the FGS data, and S/C housekeeping data).

A dedicated instrument computer is located inside the SVM. All data from the science instrument (including calibration data for post-processing on ground) is sent to the instrument computer and processed, before being sent to the S/C OBC for storage until the next ground contact. Raw data from the science instrument will be downlinked as far as possible for ground post-processing. The nominal ground contact frequency for science downlink is twice per week. The point at which an exoplanet transit is observed is time-critical (determined by their ephemerides) - to account for this, a ±10% flexibility in the exact timing of the ground contact is allowed to facilitate the efficient scheduling of the EChO core survey programme. The downlink strategy described above has the capacity to downlink up to 35 Gbit of science data every week. This allocation is very close to the actual amount of data produced, meaning some data processing will have to be done on board (e.g. binning of some resolution elements in some channels). The amount of data produced by the FGS will be low. Only the star centroid and the FWHM are required on-ground for data correction (at a frequency of 1 Hz) during nominal operations, as opposed to data from all the pixels of the FGS detector. A higher amount of FGS data is downloaded on ground during calibration observations.

The mass memory is dimensioned to store the complete data accumulated over 1 week, assuming one of the bi-weekly communication passes is missed.

6.3 Spacecraft budgets

6.3.1 Mass budget

The EChO mass budget is presented in Table 6-1

		Industry A	*Industry B*
PLM	Telescope structure, optics and baffles	209.2	175.4
	Thermal control	5.8	9.6
	Thermal shields and struts	89.1	129.3
	Harness	15.6	14.4
	Instruments and FGS	80.8	80.8
Total PLM		**400.5**	**409.5**
SVM	Structure and thermal control	314.3	216.8
	TT&C	28.1	27.0
	CDMS	32.1	21.6
	AOCS	38.1	69.2
	Cold gas	48.9	47.1
	Propulsion	48.1	32.3
	Electrical power	62.1	87.7
	Harness	72.5	48.6
	Warm instrument units	39.6	39.6
Total SVM		**683.8**	**589.9**
S/C total dry		**1084.3**	**999.4**
20% system margin		216.9	200.0
S/C total dry with margin		**1301.2**	**1199.3**
Propellant		93.0	103.2
Cold gas		10.0	15.9
Wet mass		**1404.2**	**1318.4**
LV adapter		115.0	135.0
Launch mass		**1519.2**	**1453.4**
Margin wrt Soyuz capacity		**680.8**	**746.7**

Table 6-1: EChO mass budget (in kg). The PLM represents about 1/3rd of the S/C dry mass.

The main differences in mass between the industrial designs are by:

- The material and general structural architecture of the telescope bench
- The general structural architecture of the SVM
- The selection of AOCS units

Note that all subsystem masses quoted in Table 6-1 include a subsystem level contingency margin.

In general, the conclusion of both industrial contractors is very similar. The EChO wet mass, including the system level margin, is ≤ 1.5 tonnes at this stage of the study.

6.3.2 Power budget

The EChO power budget is presented in Table 6-2 in two different modes:

- L2 transfer and commissioning mode. The assumptions here are that the science instrument and the cryo-cooler will be kept in a stand-by mode during this period (ready for calibration), communications will also occur frequently for SVM commissioning, the AOCS system will also be commissioned (power from the reaction wheels and the fine gyroscope), and all the heaters on the

PLM will also be turned on for the de-contamination phase. In addition, a significant amount of heating power within the SVM is added to ensure a high thermal stability, as explained in Section 6.2.2 by Industry B. This mode is overly pessimistic, since all these power consuming actions will not all occur simultaneously.

- Science and communications mode. Although science and communications (with the HGA for science telemetry) should not happen simultaneously (since the fixed HGA requires pointing the complete S/C down to Earth), the assumption here is rather that the instrument will remain "switched on" during communication, i.e. the coolers will keep the detectors at their operational temperature (so that no time is lost after communication while waiting to cool down the detectors).

		L2 transfer and commissioning	Science and communications
PLM	thermal control	129	0
SVM	thermal control	208	6
	TT&C	117	103
	Data handling	54	50
	AOCS	213	17
	Cold gas	64	5
	Propulsion	8	20
	Electrical power	62	39
	Instrument electronics	24	58
	Cryo-cooler	30	130
Total power		**909**	**428**
)% system margin + PCDU & harness losses		248	122
Total power with margins		**1157**	**550**

Table 6-2: EChO power budget for 2 different modes (in W)

6.4 Spacecraft Assembly, Integration and Verification (AIV) and development plan

This section addresses the spacecraft AIV and development plan. The instrument model philosophy and AIV is described in Section 4.4.12.

The spacecraft development plan assumes a Proto Flight Model (PFM) approach, slightly adapted for the specifics of the EChO mission (optics + cryogenic conditions). This means all final tests at spacecraft level are conducted on a PFM. The modular architecture allows procurement and testing of the SVM and PLM models separately, early during the development phase to mitigate any issue well before the final S/C level tests and minimise the risks on the schedule. Both these modules will have a Structural Thermal Model (STM), or rather a Cryogenic Qualification Model (CQM) for the PLM (as required by the cryogenic nature of the payload), and an Avionics Model (AVM) that will be tested separately. These will then be partly re-furbished and assembled to produce a complete S/C level PFM. This approach carries an acceptable risk and avoids having to produce and pay for two full models in parallel (one for testing and one for launch). To consider environmental tests only at final S/C level would further decrease the cost but would increase the risks to a level that is no longer acceptable.

Early Engineering Models (EM) will also be produced on dedicated units as required. For instance, an Development Model (DM) of the cryo-cooler (located in the SVM) is required for CQM testing of the PLM, even though the cooler is physically located inside the SVM. Dedicated GSE will be required for this purpose, to accommodate the cooler below the PLM model. Similarly, an EM of the FGS electronics (including a simulator of the FGS output) can be integrated in the SVM AVM.

The models that are anticipated are described in Table 6-3

	SM	CQM	AVM	PFM
SVM	X STM	NA	X	X Re-furbished SM
PLM	X With mirror dummies	X SM equipped with instrument CQM and cooler EM	NA	X Re-furbished CQM
S/C	X	(X) optional	X Including EMs of the instrument electronics	X

Table 6-3: EChO models

The AVMs will be used as an early test of all the electronic units and their electrical interfaces for software development, ensuring they all communicate properly. This includes tasks such as:

- Checking interfaces between all units
- Verifying the functionality of the avionics and the software
- Validation of the operations procedures
- Verification of the communication and power interfaces between the payload and the S/C OBC
- Electromagnetic compatibility tests (EMC)

The STMs will be used to test all the structural and thermal hardware against the mission environmental requirements, including launch and space conditions. This includes mechanical vibration and shock tests and thermal vacuum cycling tests. The CQM tests will require a separate dedicated facility due to the cryogenic environment under which the EChO payload is supposed to operate. Tasks undertaken within these tests include:

- Thermal qualification against the operational conditions (i.e. ~20°C for the SVM and ~47 K for the PLM)
- Mechanical qualification against the launch conditions (random and sine sweep vibrations + shock)

The SVM and PLM structural and thermal /cryogenic models will be re-furbished as far as possible into S/C level models. Additional cryogenic tests at complete S/C level are currently considered to be optional, since only the PLM will reach cryogenic conditions and is already tested with the CQM.

Testing of the optics is part of the PLM development. The telescope mirrors will be tested independently, and the complete bench with all telescope mirrors will be assembled and tested at room temperature. Cryogenic testing of the PLM CQM will allow to measure thermo-elastic deformations on the telescope assembly, but will not measure optical performance (i.e. Wave Front Error (WFE) rms), since flight mirrors will not be available yet (i.e. only dummy mirrors will be used at this stage).

The selected interface between the telescope and the instrument optics (afocal, collimated beam) allows the assembly and testing of both systems independently. The AIV required at S/C level is then significantly simplified, as all the instrument channels will be assembled and calibrated by the instrument Consortium on the IOB. The S/C prime then only needs to align the IOB relatively to the TOB. Cold alignment of the complete optical system in operational conditions is verified at PLM PFM level.

At PFM level, final tests will be conducted for full validation of the S/C. This includes repetition of tasks already performed at individual module level (e.g. thermal and mechanical qualification), but also full functional and performance qualification of the complete system (e.g. alignment of the complete optical system), which will at this stage include the final instrument (P)FM.

6.5 Technology developments

A number of Technology Development Activities (TDA) required for EChO, or that could be beneficial as back-up technologies, have been implemented over the course of the study. The objective of these activities is to ensure that all elements of the EChO design have reached a TRL ≥ 5 by mission adoption, which is expected towards Q1/2016. TDAs for technologies required for EChO include:

- Cryogenic M2 re-focussing mechanism. This activity aims at qualifying, under cryogenic conditions, a re-focussing mechanism that will be put behind M2. It will use existing technologies (e.g. based on the GAIA mechanism) and provide 3 degrees of freedom in the position of the mirror. This activity is under preparation and should kick-off by the end of 2013.
- Testing of existing European MCT detectors in cryogenic conditions. This activity aims at testing existing detectors from 2 European suppliers down to cryogenic conditions and measure the improvement achieved in dark current, to see whether these devices are good enough to comply with the EChO stringent noise requirement. This activity was kicked-off at the end of 2012.
- Performance verification of a Ne JT cooler at ≤ 30 K. This activity aims at verifying the performance of the European JT cooler (evolution from Planck) with Ne instead of He as the working fluid. This activity should be initiated in 2014, depending on the M3 down-selection.
- Adaptation of the European Large Format Sensor Array (LFSA, European alternative for Euclid) to meet the EChO requirements. Based on the activity on-going for the Euclid mission, this activity aims at verifying the performance of the LFSA detector (low noise MCT detector with a 2.1 μm cut-off) against the EChO requirements (longer wavelength range compared to Euclid and cryogenic conditions). This activity should be initiated in 2014, depending on the M3 down-selection.

There may be additional technology development activities to support alternative options for EChO.

7 Mission Operations and Ground Segment

EChO is a survey-type mission, with the prime objective to complete a three-tier, core survey described in previous chapters. EChO will also have an open-time, observatory-like component comprising ~10-15% of the total available observing time which will be available through responses to Announcements of Opportunity. ESA will be responsible for provision of the EChO Mission Operations Centre, the tracking station network and the Science Operations Centre, including the EChO science archive. The Instrument Consortium will be responsible for Instrument Operations and Science Data Centre (IOSDC).

7.1 EChO observations

7.1.1 The EChO Core Survey

EChO is a survey mission, with the primary objective being to observe a core sample of known transiting exoplanets. The EChO Core Survey comprises a three-tier survey of exoplanets, the requirements of which are detailed in Section 2.3.2.2. Two possible realisations of target lists for the core survey are presented in the design reference mission document: the first is based on targets known today and is used to set the required mission lifetime of 4 years, whilst the second is based on a statistical sample based on an assessment of the maximum number and diversity of exoplanets in the local neighbourhood which in turn is derived from the local star counts and planet occurrence frequencies, and used to set a goal lifetime of 6 years. The final choice of targets to be included in the core survey will be made before launch. Inputs will be solicited from the Scientific Community and, as usual, the Advisory structure will be involved in the process.

The data policy for the core EChO programme will provide rapid access to the Scientific Community - details of the proposed data policy are given in Section 8.4.4, and will be detailed in the Science Management Plan that will be written in the next phase of the study.

7.1.2 Open time

The performance specifications of EChO have applications outside exoplanet transit and occultation spectroscopy, examples of which are given in Section 2.7. With this in mind, EChO will have an observatory component, with a fraction of the mission lifetime (~10-15%) to be devoted to an open time programme to which the Community will be invited to subscribe through announcements of opportunity (AO). A first AO is envisaged 1.5 years before launch, with at least one call to be made during the mission.

Proposals will be accepted from all scientific fields, including exoplanets. The EChO core survey will require the scheduling of a very large number of individual, time-critical transit events. It is therefore envisaged that only a fraction (~20%) of the open time will be available for other time-critical observations in order to minimize scheduling conflicts between open time programme observations and EChO core targets, and to ensure the successful completion of the EChO core survey.

Proposals will be evaluated by a Time Allocation Committee (TAC) comprising scientists with expertise covering all disciplines appropriate to EChO. Membership of the TAC will be based on scientific excellence. The TAC will establish criteria for selection, based on guidelines to be detailed in the Science Management Plan, as developed in a future project phase, and to be approved by the Advisory Groups and the SPC. Assessment of the technical feasibility of open-time proposals will be undertaken by the Science Operations Centre (SOC).

7.2 Mission phases

The nominal lifetime of EChO is 4 years (6 years goal), and is divided into the following operational phases:

- Launch (L) and Early Operations Phase (LEOP, duration max. 3 days): the period from activation of the spacecraft to acquisition of the transfer orbit (including the first spacecraft orbit correction manoeuvre).
- Transfer Phase (completion L+3 months): to include the period from the first trajectory correction manoeuvre until insertion into the final science operational orbit; a period during which the

spacecraft will be commissioned and which includes the cool-down time of the payload (telescope and instrument).

- Calibration and Performance Verification Phase, including Science Demonstration Phase (completion L+6 months): period during which the instrument will be calibrated and performances verified. A representative set of observations drawn from the EChO core survey and the open time programmes will be undertaken to establish performance capabilities and to enable optimisation of all observing programmes. All observing modes required by the Core Survey will be checked, along with as many additional modes that are used in the open time programmes as can be accommodated in the time available.
- Nominal Science Operations Phase (duration 3.5 years): covers the period of routine science operations, during which EChO science observations will be executed.
- Extended Science Operations Phase (goal duration 2 years): covers the period from the end of nominal, baseline science operations to switch-off of the science instruments, and is subject to the approval of a mission extension.
- Post-science Operations Activities: covers the period at the end of nominal science operations or, in the event of a mission extension, the end of extended science operations. Parallel activities include:
  - At the Mission Operations Centre: spacecraft decommissioning during which the standard disposal option for L2 will be applied.
  - At the Science Operations Centre (duration 2 years): final calibration products, pipelines, documentation and catalogues will be consolidated and final products produced and archived.

7.3 Overview of the ground segment and operations

7.3.1 Overview of the operational centres

The EChO Ground Segment (GS) provides the means and resources with which to manage and control the mission via telecommands, to receive and process the telemetry from the satellite, and to produce, disseminate and archive the generated data products. Responsibility for and provision of the EChO ground segment is split between ESA and a nationally-funded Instrument Operations and Science Data Centre (IOSDC).

A schematic illustrating the elements of the EChO ground segment, along with their operational interfaces is shown in Figure 7-1.

ESA will be responsible for the following GS elements:

- The Mission Operations Centre (MOC)
- The ESA tracking station network
- The Science Operations Centre (SOC)

7.3.2 Overview of the science operational concept of EChO

The following is a list of the key tasks that will be performed during EChO operations:

- Science planning (target selection and long term planning)
- Mission operations planning
- Production and execution of operations requests (including spacecraft and instrument sequences)
- Ground control and monitoring at MOC
- Contingency isolation, management and recovery
- Mission (including science) data processing, distribution and archiving
- Ground infrastructure operations and management
- Spacecraft and ground segment performance analysis and tuning
- Community support

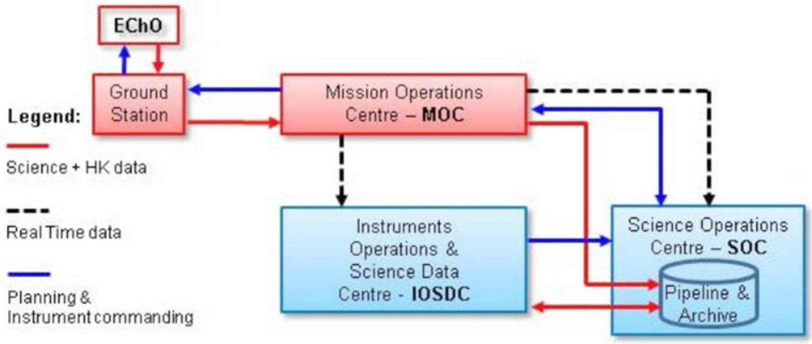


Figure 7-1: A schematic overview of the flow of data and control in the Ground Segment during operations. A real-time data interface between the MOC and IOSDC is assumed to be available during all operational phases (black dashed line); the exchange of science and housekeeping data is via a Data Disposition System (TBC; MOC→SOC) or via the EChO science archive (SOC→IOSDC) and is marked in red. Blue lines show the exchange of information for mission planning – this includes (a) delivery of the long-term mission plan by the IOSDC to the SOC; (b) provision by MOC of information on ground station passes, visibility constraints etc.; (c) delivery by SOC of the short-term mission planning files to MOC.

Together these support the steps from the preparation of observations (based on core and open time programmes and calibration/engineering requests) to the generation and storage of calibration files and final scientific data products ready for scientific exploitation.

In a first step, and drawing from the pool of approved core and open time observations, observation requests together with mission-level constraints will be analysed for feasibility and checked for visibility based on EChO orbit predictions. The result will be a long-term observation plan covering the whole mission. It is noted that a critical aspect of the EChO observing principle that differentiates EChO observations from previous astronomy and planetary missions is the need to schedule a very large number of individual, time-critical transit events around mission-level constraints such as data down-links, satellite station-keeping and target visibility. Meeting this need will be key to the success of the mission, and a task that cannot be done by hand. Work on a long-term mission planning tool for EChO has started within the Instrument Consortium [ECHO-TN-0001-ICE], [ECHO-TN-0001-CNES]. The tool will be used to establish, optimise and maintain the long-term mission plan that is weighted to account for scientific priorities, mission constraints and to guide observing strategy. The tool can also be used to determine mission efficiency and sample completeness. It is foreseen that the long-term mission planning input from IOSDC/SOC can be used by MOC to optimise the GS contact periods in order to accommodate scheduling of critical targets.

Short-term mission planning by SOC and MOC will take into account the maintained long-term plan and latest predictions for the EChO orbit provided by MOC. Finally scheduled pointings and payload settings as provided by SOC will be converted by MOC into master timelines consisting of payload and spacecraft commands and uplinked to EChO during ground contacts.

During the downlink, telemetry from the EChO spacecraft and payload will be received by the MOC. The housekeeping data is used by MOC to monitor the spacecraft and instrument health as well as for contingency isolation, investigation and recovery. All science data will be sent/distributed to the SOC where it will be unpackaged and processed with data processing pipelines based on best algorithms and calibration currently available, as described in Section 7.4.2.

The pipeline will generate science products that will be used by IOSDC for further processing, see Section 7.3.5. The pipeline will also produce a quality product that will be used to check the data.

All product levels plus telemetry, calibration data, and ultimately software and documentation on pipelines etc. will be stored in the EChO archive. In this way users can use either fully processed data or reprocess the data themselves.

User support will accompany all operational phases, enabling access to EChO by the wider astronomical community through calls for the open time observer programme, as well as facilitating the exploitation of EChO core science through data processing workshops and documentation.

In Sections 7.3.3 to 7.3.5 we describe the main tasks to be undertaken by the different Centres that make up the Ground Segment.

7.3.3 Mission Operations Centre and ground stations

The ground segment and operations infrastructure for the Mission Operations Centre (MOC) of the EChO mission will be set up by ESA at the European Space Operations Centre (ESOC) in Darmstadt, Germany, and will be based on an extension of the existing ground segment infrastructure, customised to meet the mission specific requirements. The concept for establishing the EChO ground segment is one that will maximise the sharing and reuse of facilities and tools made available for other Science Observatory missions. The MOC will be responsible for all operations of the EChO spacecraft and instruments during both nominal operations and contingency. Principal responsibilities include:

- Mission operations, including implementation of the observation and ground contact schedule
- Spacecraft and instrument operations, which for example comprises:
    - Maintaining the health and safety of both the instrument and the spacecraft, intervention in case of anomalies.
    - Generation and upload of all spacecraft and instrument (based on SOC operations requests) commands.
    - Flight dynamics support, including determination and control of the satellite's orbit and attitude.
    - Receipt of all telemetry including science data.
- Collaboration on ground infrastructure operations and management
- Distribution of all data to the SOC and IOSDC (see Figure 7-1) and archiving of all housekeeping data.
- Spacecraft maintenance, in particular on-board software maintenance

The responsibility for the design, implementation, and operation of the MOC rests with ESOC, with ground segment development phase to start 8 years prior to launch and ground segment implementation phase to start 4 years prior to launch.

The 35m ground stations of the ESTRACK network comprising New Norcia, Cebreros and Malargue will be used for communication and precision orbit determination, with additional support provided during LEOP by the small station infrastructure (as available in the 2016 – 2020 time frame) and potentially the NASA Deep Space Network. The principle ground station for use during normal operations is assumed to be New Norcia.

All communication and tracking will be done at X-Band. Details on the tracking and telecommunications approach are given in Chapter 6.

7.3.4 Science Operations Centre

The EChO Science Operations Centre (SOC) will be set up at ESAC, which also hosts the archives of all ESA science missions. The SOC will design and coordinate the ESA-funded part of the EChO science ground segment. The SOC will be responsible for the following activities required for the EChO science operations system functionalities:

- Centralised planning and scheduling system to produce the planned observation sequence (POS) of instrument and spacecraft commanding files as these will have to include pointing commands and may configure pointing modes if more than one is necessary.
- Design, procurement and maintenance of the processing system; operation of the data processing system to process core and open time science data products, and auxiliary data products.
- Responsibility for pointing reconstruction
- Operating the quality control systems dedicated to instrument and FGS data quality analysis, with mission planning feedback as appropriate.
- Support instrument operations and support preparation of payload operational procedures and instructions
- Tracking of observations and provision of performance statistics
- Proposal handling system for open time; centralised Astronomical Observation Request (AOR) database for core & open time, and planning of calibration/engineering observations

- User Support including documentation, HelpDesk, Announcements of Opportunity (AOs) and workshops
- Development, operation and maintenance of the EChO Science Archive

In the area of scientific mission planning, SOC activities include the specification of science planning requirements and support to the IOSDC which provides the long term planning activity (shared task as described in Section 7.3.2). SOC designs, develops and runs a centralised science planning and scheduling system, including testing of software tools for proposal handling. SOC incorporates proposals accepted in the two planned AOs. SOC prepares the final Science Operation Plan, optimising the scientific mission planning based on priorities set by the Project Scientist (supported by the EChO Science Team for the EChO Core Sample, and by the Time Allocation Committee for the open time programme). Finally, SOC generates and delivers POS to MOC. MOC then generates the conflict-free, verified master timelines and uploads them on board EChO for timeline execution.

Science data will be received from the spacecraft via the MOC at the SOC. The development of the data processing software (automatic pipeline and/or customized processing, or Interactive Analysis software) and infrastructure will be coordinated between SOC and IOSDC.

SOC maintains overall control over the operational S/W through testing and validation of the IOSDC provided pipeline(s) & quality control systems. Together with IOSDC, SOC will set up configuration control tools on the pipeline(s), data products, on-board software and calibration files.

The SOC will support the Community User in access to and exploitation of EChO data. Regarding open time, the SOC will issue and manage calls for observing proposals from the Scientific Community. Support will also be provided for exploitation of EChO core programme data, including the running of data processing workshops.

Communication with the scientific community on all EChO activities, including open time calls, will be coordinated through a help desk system which will run at the SOC. Documentation covering the use of the instrument and data processing will be distributed by the SOC, with significant inputs coming from IOSDC.

SOC will be responsible for the development and maintenance of the EChO archive. SOC, with the support of the PS, will specify archiving requirements, as well as supervise archive development, operations and maintenance during all operational phases.

7.3.5 Instrument Operation and Science Data Centre (IOSDC)

The IOSDC is a distributed centre involving a network of instrument consortium partners and led from RAL (UK). The IOSDC responsibilities can be summarised as follows:

- Provision and maintenance of instrument on-board software and tables
- Provision and maintenance of instrument command and telemetry definitions
- Provision and maintenance of observing templates
- Provision and maintenance (for IST and to MOC) of instrument related EGSE including a quick-look analysis (QLA) system
- Provision and maintenance of the long term planning software and long term planning according to priorities set by the science team
- Provision of calibration observations and scheduling instructions
- Support of MOC in the investigation and resolution of instrument anomalies
- Monitor instrument health and performance, trend analysis
- Provision and maintenance of instrument and spacecraft data processing software from telemetry to level 0
- Provision and maintenance of science data processing software and associated calibration tables
- Provision and maintenance of a quality control system for the offline data processing pipeline
- Optimisation of instrument performance
- Provision and maintenance of a software (SPR/SCR) ticket system and maintenance of the instrument related reports within that system
- Provision and maintenance of a software storage system
- Provision and maintenance of a ground segment information exchange system (EChO Wiki)

- Contribution to, in collaboration with SOC, interactive analysis
- Provision of instrument related documentation
- Contribution to, in collaboration with SOC, community support

The IOSDC will be organised into functional teams and sub-teams. The team leaders plus data centre managers constitute the IOSDC management team. All non-confidential aspects of IOSDC including management team minutes will be published on the ground segment Wiki. The UK will act as the lead contact point for SOC.

7.4 Processing and storage of EChO data

7.4.1 Data level products

EChO data level products represent natural breakpoints in the data flow through the data processing pipeline that starts with the raw telemetry received from the spacecraft and ends in a single, fully-calibrated exoplanet spectrum for each of the core targets observed. The data level products for EChO are defined below.

- Level 0: Unpackaged/decompressed raw spacecraft data for each observation/target visit. This will include payload, spacecraft/ground segment data.
- Level 1: Individual calibrated light curves for each target visit. Data will be in the form of cubes containing spectral timelines that record the observed flux as a function of time (binned per cadence interval), per spectral bin of the EChO spectrometer.
- Level 1.5: All available spectral timelines for each target stacked in a single data structure to include all transits/occultations observed over the course of the mission.
- Level 2: Averaged exoplanet spectra for each planetary phase studied: around occultation (emission/reflection), primary transit (transmission) and phase curves.
- Level 3 (TBC): a catalogue of exoplanet and stellar spectra, to include derived parameters.

The exact definition of Level 2 products for observations of targets other than exoplanets (AO targets for example) will be on a case-by-case basis, and will be discussed in future phases.

7.4.2 Science data processing

Science data processing and analysis software will be developed through close collaboration between the SOC and the IOSDC. Provision of algorithms and processing blocks falls under the responsibility of the IOSDC, with the SOC participating in areas such as the interfacing with the archive, validation and testing, and the development of software tailored to support Community users.

IOSDC will provide the payload-specific software, modules and processing blocks that will be used to: (a) convert instrument telemetry, FGS data and spacecraft HK data to Level 0 products; (b) generate Level 1 and Level 1.5 products. Generation, maintenance and delivery of the calibration files necessary for data processing will also be done by the IOSDC. A preliminary pipeline that runs up to Level 1.5 will be provided by the IOSDC by the time of the start of normal operation. The pipeline will be improved upon and will evolve over the course of the mission, with bulk data reprocessing using improved calibration products to be undertaken by the SOC at regular intervals (at least yearly). The intention is that all IOSDC-provided software will be executable in two ways: firstly, as an automatic and complete pipeline system and, secondly, in a user-controlled interactive way, i.e. allowing a step-wise data analysis with user-definable parameters.

The SOC will run the pipelines and generate data products up to Level 1.5. All products will be stored in the EChO archive and will be made available to the science community following expiration of the proprietary period (see Section 8.4.4). All products relating to core survey targets and open time exoplanet observations will be sent on to the IOSDC for generation of Level 2 products.

During the mission, the IOSDC will deliver Level 2 data products for all targets in the EChO core programme for ingestion into the archive. The products will be delivered once the SNR requirements appropriate to the different survey tiers have been achieved (see Section 3.2.3) and in accordance with the EChO data policy. The Level 2 data products will be handcrafted on a source-by-source basis. The pipeline modules that are used to realise the spectra will be available, along with details of the parameters used.

Level 1.5 data products for programmes to observe sources other than exoplanets will be produced where instrumental effects have been removed to the best of the Consortium's knowledge/understanding. In some cases, long-term trends may be left in; however, these will be flagged in some way so that the observer is aware of what has been done.

The instrument consortium will have the opportunity to deliver their final data products (format to conform with specs to be written in future phases) for ingestion into the archive, although the primary archive product will be the IOSDC pipeline product.

By the end of nominal science operations phase the IOSDC will provide a pipeline that will generate Level 2 products using IOSDC-provided scripts with default parameters that provide a good quality reduction for a generic/average target, along with supporting documentation to guide users in the use of the pipeline. It is noted that the pipeline, as opposed to a sequence of scripts, will be delivered only if it can be shown that it provides added-value.

Generation of a Level 3 data product in the form of an EChO Mission Catalogue is under discussion. The catalogue would reside in the EChO archive at ESAC. The scope of the catalogue will be studied in the next study phase. Generation of all elements of the catalogue would be under the responsibility of the IOSDC.

7.4.3 The EChO science archive

The archive will be developed under the responsibility of the SOC and will be located at ESAC.

The EChO science archive will be the repository for all data associated with all phases of the mission, and will fulfil the role of both the operational archive and the legacy archive. Before launch, it will be used for instrument level testing and on-ground calibration. Relevant support data (e.g. host star parameters and spectra, associated photometry, exoplanet parameters etc.) will also be stored in the archive. During operations, the archive will be used to store the raw telemetry, processed science products and calibration products.

Access to the archive will be through a user-friendly interface, with data products made available to users whilst respecting proprietary periods and data rights.

At the end of the nominal science operations phase, or the extended science operations phase if there is one, the EChO archive will become a legacy archive, acting as the repository for final version of calibration files, data products and support data. Final versions of all processing software, including user documentation, will also be stored in the archive.

8 Management

8.1 Project management

8.1.1 Overview

The science and project management will follow the current practices of ESA science missions. Following the selection of EChO as the sole M3 mission in February 2014 by SPC, ESA will release an Invitation to Tender (ITT) for the selection of two competitive industrial contractors for the Definition Phase (B1), for a typical duration of 18 months. This phase will build upon the results of the Assessment Phase (0/A) study both at S/C level and at instrument level. Phase B1 will be concluded by a System Requirements Review (SRR) to be completed by January 2016, after which EChO will go through the process of mission adoption and SPC approval in February/March 2016. By the time of the SRR, all science requirements should be frozen, the subsystem level requirements documents should be available and the overall technical and programmatic feasibility of the mission should be confirmed with a design supported by detailed analyses. In parallel, all Technology Development Activities (TDAs) required will have been issued and completed by the SRR, so that all S/C and instrument units have a TRL ≥ 5 before mission adoption.

Following mission adoption, EChO will move into the Implementation Phase (B2/C/D/E1). A Prime industrial contractor will be selected via a further ITT. The final industrial organisation will be completed in Phase B2, mostly through a process of competitive selection and by taking into account geographical distribution requirements. At the start of this phase, a project team will be established in the Project Department of the Science and Robotics Exploration directorate (SRE-P). This team will be led by the Project Manager (PM), who will have overall responsibility for implementing the EChO mission. The PM will be supported by the Project Scientist (PS) who will have responsibility for science-related aspects of the mission.

Over the course of the implementation phase, the project team will conduct a Preliminary Design Review (PDR), a Critical Design Review (CDR) and finally a Flight Acceptance Review (FAR).

Responsibility for the EChO mission will transfer from the PM to the Mission Manager, located at ESAC, following the successful commissioning of the satellite and scientific payload. The task of the PS will continue throughout the operations and post-operations phases.

8.1.2 Management of operations

ESA will be responsible for the launch, checkout and operation of the EChO spacecraft. ESA will establish a mission operations centre (MOC), to be located at ESOC, and a science operations centre (SOC) that will be located at ESAC.

Definition of the MOC will commence at the beginning of the definition phase, under the responsibility of a Ground Segment Manager located at ESOC who will report to the Project Manager. The responsibility for the MOC will transfer from the Ground Segment Manager to the EChO Spacecraft Operations Manager (SOM, located at ESOC), following the successful commissioning of the satellite and scientific payload.

Definition of the SOC will commence at the same point in time, and will be under the responsibility of a SOC Development Manager in the Operations Development Division at ESAC. The SOC Development Manager will work closely with the PS, but will formally report to the Project Manager.

Management of the Science Ground Segment will be transferred from the Operations Development Division to the Operations Division following successful commissioning of the satellite and scientific payload. As described in Chapter 7 the mission operations will be under the overall control of the EChO SOC at ESAC in close collaboration with the IOSDC provided by the instrument consortium.

8.2 Procurement philosophy

ESA will have overall responsibility for the following items:

- The overall design of the mission and spacecraft (Industrial contract)

- Provision of the spacecraft, to include provision of the EChO telescope assembly and integration of the bus and payload modules (Industrial contract)
- Launch (Arianespace)
- Mission and science operations (ESOC and ESAC)
- Data acquisition and distribution (ESOC and ESAC)

The instrument team will have responsibility for the following items:

- The cold instrument unit (Focal Plane Assembly) including:
    - An Instrument Optical Bench including support structure mounted onto the support structure of the primary mirror
    - The VNIR module from 0.4 – 2.47 µm including detectors and cold Front End Electronics
    - The SWIR module from 2.47 – 5.5 µm including detectors and cold Front End Electronics
    - The MWIR module from 5.5 – 11.25 µm including detectors and cold Front End Electronics
    - The LWIR module from 11.25 – 16 µm including detectors and cold Front End Electronics. Note this module is optional and dependent on additional national funding from the current approved consortium baseline. It is therefore not included in the baseline instrument description shown in Figure 8.1.
    - The common optics, including the dichroics to separate the light for the various channels
    - The Fine Guidance System (FGS) optical module
    - Calibration system
    - Thermal control (radiators, insulation, active cooler I/F)
- The warm instrument units located in the SVM
    - The Instrument Control Unit (ICU) including the Warm Front End Electronics, Data Processing Unit and Power distribution
    - The Active Cooling System (ACS) including the Ne JT cooler with associated Cooler Drive Electronics (including JT-pipes interconnecting the warm units and the Focal Plane Assembly)
    - The Fine Guidance System Control Electronics providing control, readout and centroiding to provide the input necessary for the AOCS system.
- Elements of science ground segment:
    - Provision of the Instrument Operations and Science Data Centre (IOSDC; note: instrument operations will be performed by MOC)
    - Payload-specific software, modules and processing blocks for processing up to Level 2 data products
    - Long-term mission planning tool
    - Calibration and instrument-monitoring
    - Support to the MOC and SOC (contingencies, expert advice, instrument monitoring)

Figure 8-1 summarises the hardware activities of the consortium, including the representatives from different countries. The scientific instrument and the FGS will be procured by national agencies and institutes with some support from ESA for the detector procurement (e.g. FGS detectors).

The procurement approach has a significant influence on the development and AIV plan and therefore on cost, schedule and risk. An early start to the instrument development programmes is required to demonstrate the key performances of critical technologies (e.g. cooler/detector) early in the programme.

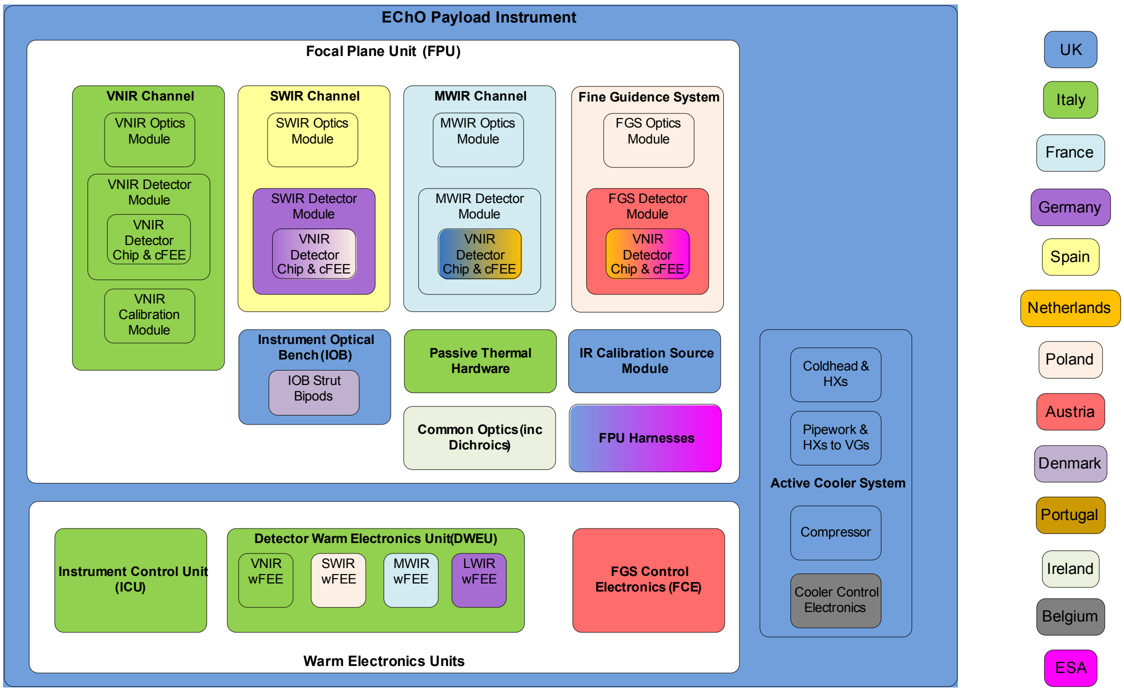


Figure 8-1: An illustration of the division of work on the EChO science instrument and Fine Guidance System amongst the countries in the instrument consortium and ESA.

8.3 EChO schedule

The EChO project top level schedule is shown in Figure 8-2 below.

	Taaknaam	Duration	Start	Finish	Predec
1	PRR	40 days	Thu 03/10/13	Wed 27/11/13	
2	M3 down-selection	0 days	Fri 28/02/14	Fri 28/02/14	1
3	Phase B1	400 days	Thu 08/05/14	Wed 18/11/15	2
4	SRR	50 days	Thu 19/11/15	Wed 27/01/16	3
5	M3 adoption	0 days	Sun 28/02/16	Sun 28/02/16	4
6	Instrument development till FM delivery	1260 days	Wed 03/02/16	Tue 01/12/20	5
7	Phases B2/C/D	1600 days	Wed 01/06/16	Tue 19/07/22	5
8	Launch	0 days	Mon 05/12/22	Mon 05/12/22	7,6

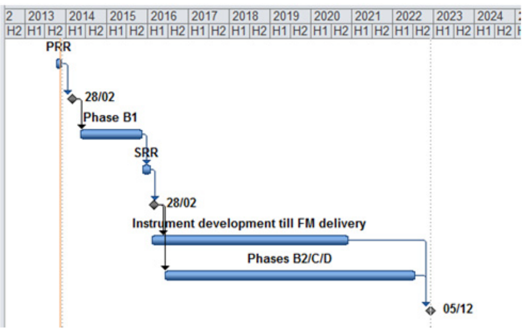


Figure 8-2: EChO overall project schedule

The required launch date for M3 is in 2024. At present the mission schedule is designed to enable a launch in 2022, in case of a delay in mission adoption of JUICE as the L1 mission. With the kick-off of the Implementation Phase in Q3 2016, this leaves 6 years for the complete development, manufacturing, assembly, integration, testing and launch campaign. This tight schedule has been evaluated as potentially risky by the recent Preliminary Requirements Review panel: a launch in mid 2023 instead would be more realistic and should be assumed as the baseline.

The critical path contains the manufacturing, testing and assembly of the telescope, followed by the PFM and FM tests, and finally the launch campaign. An important consequence of this is that procurement of the telescope needs to start as soon after the start of Phase B2 as possible. The criticality of this step has been anticipated, with many of the telescope characteristics and interfaces set during a trade-off/telescope review conducted during the Phase 0/A study (see Section 4.3). Following this review, both industrial contractors proposed optimisations of the selected concept. These have been used by ESA to produce a single, baseline telescope specification. Pending final optimisation during Phase B1, the telescope will be ready for early procurement immediately after mission adoption. Instrument models are planned to be delivered early enough by the Consortium so as not to further constrain the S/C schedule. It is expected that instrument CQM (STM FPU and DM Cooler) and AVM models will be delivered to the spacecraft prime in 2018 ready for test and qualification. The instrument FM will be delivered to the spacecraft in Q3 2020.

8.4 Science management

In this section we outline the current assumptions for science management responsibilities for the EChO mission. These will form the basis of the science management plan (SMP) that will be written in the next stage of the study. The SMP is the top-level science management document for the mission, and will be agreed on by the Science Programme Committee (SPC)

8.4.1 Project scientist

At the start of the implementation phase ESA will appoint a Project Scientist (PS). The task of the EChO Project Scientist shall be to ensure the maximum science return from EChO within the technical, financial, programmatic and safety constraints of the mission. The PS shall act as the interface between internal ESA teams and external science teams, the payload consortium and the wider scientific Community. The PS shall prepare and monitor the scientific priorities of the mission, in close coordination with the EChO Science Team. In particular, the PS will be responsible for the DRM for EChO which will detail target lists for EChO that meet all science requirements and which, by the time of launch, will have evolved into the final EChO target list. The PS will coordinate and execute, with support from the SOC as required, calls for observing proposals for the open time component of the EChO mission, discretionary time proposals and all data rights issues associated with EChO mission data.

8.4.2 EChO Science Team

The EChO Science Team (EST) will comprise the instrument consortium PI and scientists who are both internal and external to the instrument consortium, as well as the PS. The EST will be chaired by the EChO PS. The team will support the PS in the preparation and execution of the scientific operation of the mission, and will advise on all aspects of the mission that have an impact on scientific performance. Members of the team will be asked to undertake EChO-specific tasks related to all mission phases, and may also be asked to participate in major project reviews.

8.4.3 Observing with EChO

EChO is a survey mission with the primary objective to observe a diverse sample of known, transiting exoplanets as described in Chapters 2 and 3. The choice of targets shall meet the science requirements that govern the core sample (see Chapter 3), and will be made before launch. Inputs will be solicited from the Community and, as usual, the Advisory structure will be involved in the process.

A fraction of the mission lifetime (~10-15%) will be devoted to an open time programme to which the Community will be able to subscribe through announcements of opportunity (AO). A first AO is envisaged 1.5 years before launch, with at least one additional call to be made during the mission. Proposals will be evaluated by a Time Allocation Committee made up of scientists with expertise covering scientific disciplines appropriate to ECHO, with membership based on scientific excellence.

8.4.4 Data rights and proprietary periods

The data policy for the core EChO programme will provide rapid access to high quality exoplanet spectra by the Community. Datasets up to and including Level 2 data products (see Section 7.4.1 for a definition of data products) for individual targets observed in the survey tiers will be released a fixed number of months after the signal-to-noise ratio (SNR) defined for each mode has been achieved, through multiple visits where necessary. At the beginning of the mission the proprietary period, defined as the time elapsed between the date on which the last observation required to meet the SNR requirement is taken, and the date on which the data products are released, will be 6 months. This interval will reduce as the mission progresses, and a more complete understanding of the instrument characteristics, calibration needs and data processing/correction for systematics is gained by the IOSDC. In Year 1 of the mission data products will be released after 6 months; in Year 2 the period will be reduced to 3 months, falling to 1 month by Year 3 of the mission.

The proprietary period for open time observations will be 1 year during the first 2 years of the mission, reducing to 6 months from Year 3 onwards.

9 Communications and Outreach

A mission to characterize the atmospheres of diverse worlds beyond our Solar System provides an excellent opportunity to harness curiosity, interest and familiarity in many diverse ways. The discovery of more than 1000 exoplanets in the last 15 years is possibly one of the most exciting developments of modern astronomy. The discoveries resonate with the Public who have already shown very strong curiosity and interest in the exploration of the diverse worlds in our own Solar System. Closer to home, the concept of a planetary atmosphere is one that is familiar to all, with the implications of the Earth's atmosphere so familiar that they are often taken for granted. The atmosphere provides the air we breathe; its presence is felt through the winds that drive it, and most have witnessed a blue sky during the day, which at turns to orange/red at sunset and sunrise - both direct fingerprints of the Earth's atmosphere on the light arriving from the Sun.

EChO communication and outreach activities will reach out to a wide audience that includes the Public at large as well as focused groups such as school students, amateur astronomers, politicians and artists. ESA will be responsible for planning and coordinating education, outreach and press release activities relating to the EChO mission, with the support of the instrument consortium. The plan will be developed and executed by ESA and the Instrument Consortium, with guidance from the EChO Science Team. ESA will coordinate the execution of all education and outreach activities within the data rights framework of the mission. For the purpose of public relations activities, the Instrument Consortium will provide ESA with unlimited access to all processed and analysed data, including data still within its proprietary period. Due credit will be given regarding scientific and technical results as applicable. Details of the communications, outreach and education activity plan will evolve with the mission, with an outline for responsibilities of the different EChO stakeholders detailed in the science management plan. In this chapter we describe some of the initiatives that are already under consideration, with activities intended to be member state-wide where possible.

The Instrument Consortium will work closely with space outreach and educational networks, including Europlanet RI (EU-funded), and its successor networks, Hands-on Universe, networks that have formed as a result of the 2009 International Year of Astronomy, ESA's own European Space Education Resource Offices, as well as national and more local networks. An open approach will be adopted; except where commercial confidentiality is at stake, the instrument consortium teams will welcome media professionals into their institutions, laboratories and workshops during all phases of the mission. Broadcasters will be invited to follow the mission with a view to producing bespoke programmes and documentaries that cover scientific and engineering aspects of EChO from cradle to grave. These activities will build on the strong record that many EChO Instrument Consortium scientists have in public outreach, which include TV and radio interviews with European broadcasters such as the BBC and Euronews. Online media outlets such as YouTube and Twitter will be used to post interviews with EChO scientists and engineers. This will build on the rapid dissemination of mission news and updates possible through existing ESA channels. It will allow interested parties to follow many different aspects of the mission and to stay informed about mission progress, and performance during flight. Short, "Day in the life of..."-type films and vodcasts following EChO scientists and engineers will be made to illustrate the wide range of tasks that technical professionals engage in over the course of a space mission, not just for general interest but also targeting school and university students to highlight the very wide ranges of challenges that careers in science and engineering have to offer.

The excitement generated by the EChO mission and its discoveries will provide a topical platform on which to develop educational materials, with many of the core concepts behind the EChO science objectives and technologies covered in school syllabi at different levels. Topics such as the study of exoplanets and their formation, and exoplanet discovery techniques, will join spectroscopic signatures of atoms and molecules, and "the conditions necessary for life to form" that are already common on school syllabi. Discussion of spacecraft engineering and operation, through topics such as power generation and orbital mechanics, will allow case studies to be made to give context to a wide range of technical areas and disciplines, in parallel helping to maintain the high profile of both EChO and ESA in general, within schools. Material will be developed for school students Europe-wide, and will be supported by Continued Professional Development courses to inform school teachers of the science and engineering challenges of EChO.

Schools will be actively engaged in the selection of the EChO core sample. A competition will be run across ESA member states to choose a School's Target Exoplanet. Supporting material detailing potential EChO candidate targets will be developed to enable students to make a scientifically-informed vote. Students will be able to follow observations of the chosen planet via a dedicated website, and participate in the analysis and interpretation of the data.

An excellent way to engage and motivate the public is to provide access to data. The public will be invited to participate in the science exploitation of the EChO mission through access to EChO data sets for analysis and interpretation, taking advantage of the networks developed by very successful citizen science programmes such as the Zooniverse/Planet Hunters team using Kepler data [Zooniverse website, 2013], and Solar Stormwatch [Solar Stormwatch website, 2013].

Amateur astronomers play a crucial role in leveraging the outreach efforts of professional scientists, providing both a link with the broader general public and key scientific input. EChO scientists will work to engage the amateur astronomer community - giving lectures, making available presentation material that can be used widely, and encouraging the community to undertake a programme of observations to support EChO in particular, and the science of exoplanets, in general. Since most of the targets of EChO are relatively bright stars, follow-up observations will be feasible, profitable and exciting to both scientists directly involved in the mission and to the public at large. Some robotic telescope networks are in the process of deploying spectrographs which will be available to amateur astronomers and school groups. School students in particular will be encouraged to link into such programmes (eg. [LCOGT website, 2013]), thus enhancing educational curricula as well as inspiring young people to take up the physical sciences in later studies and in their careers.

The Instrument Consortium will execute an active programme to brief and inform policy makers at national and European levels on scientific and technological developments of EChO. One-on-one meetings, seminars for politicians and stakeholders, exhibitions at venues such as the European Parliament, and public events that will involve political figures as keynote speakers will be organized to keep policy makers abreast of developments which, although in the "blue-skies" field of space exploration, create indirect economic benefits to society.

The fascinating new worlds that will be revealed by EChO will need visual support to capture the imagination of the public. EChO scientists will work together with ESA to produce images, animations, and 3-D simulations suitable for a wide range of online and broadcast media formats. A fine art program will be set up, to realise images that have high impact and at the same time are fully consistent with our best knowledge about these planets and the findings of EChO. This continues and expands the tradition of the "Space Art" movement that was initiated in Europe a century ago (most notably by L. Rudaux, [IAAA website, 2013]). Sponsorship from the scientific and artistic community, and from industry and commerce, will be sought to support this imaginative arts-science programme. Cultural and visual arts programmes will be developed at school level also, facilitating cross-curriculum discussion and interpretation of the scientific, historical and philosophical contexts of EChO. Links will also be established with performing arts organisations to explore the interpretation of exoplanet characterization through dance.

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All ESA documents, EChO Science Study Team technical notes and Consortium technical notes that are referred to in the text can be found by following the links on the webpage of the ESA EChO website: http://sci.esa.int/echo/EChODocuments-YellowBook2013, or directly from ESA on request.

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11 List of Acronyms

ACS	Active Cooling System
AIV	Assembly, Integration and Verification
AO	Announcement of Opportunity
AO	Announcement of Opportunity
AOCS	Attitude and Orbit Control System
AOR	Astronomical Observation Request
APE	Absolute Pointing Error
ASISC	Application-Specific Integrated Circuit
AU	Astronomical Units
AVM	Avionics Model
CAD	Computer-Aided Design
CCE	Cooler Control Electronics
CDMS	Command and Data Management System
cFEE	Cold Front End Electronics
CHEOPS	Characterizing Exoplanets Satellite
CQM	Cryogenic Qualification Model
CTE	Coefficient of Thermal Expansion
DM	Development Model
DPU	Data Processing Unit
DRM	Design Reference Mission (document)
EChO	Exoplanet Characterisation Observatory
ECSS	European Cooperation for Space Standardization
ECTA	EChO Telescope Assembly
(E)-ELT	(European) Extremely Large Telescope
EID-A	Experiment Interface Document-A
EM	Engineering Model
ESA	European Space Agency
ESAC	European Space Astronomy Centre
ESOC	European Space Operations Centre
EST	EChO Science Team
ETLOS	EChO Target List Observation Simulator
FCE	FGS Cold Control Electronics
FGS	Fine Guidance Sensor
FoV	Field of View
(p)FM	(proto-)Flight Model
FPA	Focal Plane Array
FPU	Focal Plane Unit
FWHM	Full Width Half Maximum
GFRP	Glass Fibre Reinforced Polymer
GMM	Geometrical Mathematical Model
GS	Ground Segment
HARPS	High Accuracy Radial-velocity Planet Searcher
HCU	Housekeeping and Calibration Source Unit
HGA	High Gain Antenna
HK	Housekeeping
HX	Heat eXchanger
ICU	Instrument Control Unit
IOB	Instrument Optical Bench
IOSDC	Instrument Operations and Science Data Centre
ITAR	International Traffic in Arms Regulations
ITT	Invitation to Tender
JPL	Jet Propulsion Lab
JT	Joule Thompson
JT	Joule-Thomson
JWST	James Webb Space Telescope
KBO	Kuiper Belt Object
L2	Second Lagrangian Point
LEO	Low Earth Orbit
LEOP	Launch and Early Operations Phase
LFSA	Large-Format Sensor Array
LGA	Low Gain Antenna
LoS	Line of Sight
LV	Launch Vehicle
LWIR	Long Wave InfraRed
MCT	Mercury Cadmium Telluride
MICD	Mechanical Interface Control Drawing
MIR	Mid-InfaRed
MLI	Multi-Layer Insulation
MOC	Mission Operations Centre
MPE	Mean Pointing Error
MRD	Mission Requirements Document
MRS	Mission Reference Sample
MRS	Medium Resolution Spectrometer (JWST-MIRI)
MWIR	MidWave InfraRed
NEOCam	Near Earth Object Camera
NGTS	Next Generation Transit Survey
NGTS	Next Generation Transit Survey
NIR	Near InfraRed
OBC	On-Board Computer

OBS	On-Board Software
OGSE	On-ground Support Equipment
OSV	Optical State Vector
PCDU	Power Control and Distribution Unit
PDE	Pointing Drift Error
PDR	Preliminary Design Review
PFM	ProtoFlight Model
PI	Principal Investigator
PLM	Payload Module
PM	Project Manager
POS	Planned Observation Sequence
PPM	Parts Per Million
PS	Project Scientist
PSF	Point Spread Function
PVM	Performance and Verification Model
QLA	Quick Look Analysis
QM	Qualification Model
R	Resolving power
ROIC	Read-Out Integrated Circuits
RPE	Relative Pointing Error
S/C	Spacecraft
S/W	SoftWare
SciRD	Science Requirements Document
SED	Spectral Energy Distribution
SNR	Signal-to-Noise Ratio

SOC	Science Operations Centre
SPC	Science Programme Committee
SRP	Solar Radiation Pressure
SRR	System Requirements Review
STM	Structural and Thermal Model
SVM	SerVice Module
SWIR	Short-Wave InfraRed
SYLDA	SYstème de Lancement Double Ariane
TAC	Time Allocation Committee
TBC	To Be Confirmed
TBD	To be Determined
TDA	Technology Development Activity
TESS	Transiting Exoplanet Survey Satellite
TM/TC	TeleMetry/TeleCommand
TMM	Thermal Mass Model
TN	Technical Note
TOB	Telescope Optical Bench
TRL	Technology Readiness Level
TRP	Technology Research Programme
TT&C	Tracking, Telemetry and Commanding
VLT	Very Large Telescope
VNIR	Very Near InfraRed
WFE	WaveFront Error

12 Appendix A: EChO Instrument Consortium

The members of the EChO Instrument Consortium who have contributed to the EChO proposal and study phase are:

12.1 Co-PI's

Jean-Philippe Beaulieu, Institut d'Astrophysique de Paris, France; Denis Grodent, Université de Liège, Belgium; Manuel Guedel, University of Vienna, Austria; Paul Hartogh, Max Planck Sonnnensystem, Germany; David Luz, Universidade de Lisboa, Portugal; Giusi Micela, INAF – Osservatorio Astronomico di Palermo, Italy; Hans Ulrik Nørgaard-Nielsen, DSRI, Denmark; Tom Ray, Dublin Institute for Advanced Studies, Ireland; Ignasi Ribas, CSIC – ICE, Spain; Hans Rickman, Space Research Centre, Polish Academy of Science, Poland / Department of Physics and Astronomy at Uppsala University; Avri Selig, SRON Netherlands Institute for Space Research, Netherlands; Mark Swain, NASA Jet Propulsion Laboratory, USA; Bruce Swinyard, RAL Space / University College London, UK.

12.2 Co-I's

Marek Banaszkiewicz, Space Research Centre, Polish Academy of Science, Poland; Mike Barlow, UCL, UK; Neil Bowles, University of Oxford, UK; Graziella Branduardi-Raymont, MSSL, UK;Vincent Coudé du Foresto, LESIA-Astro, France; Pierre Drossart, LESIA-Planeto, France; Pieter Deroo, JPL, USA; Jean-Claude Gerard, Université de Liège, Belgium; Laurent Gizon, MPS-Heliosism. Germany; Allan Hornstrup, DTU Space, Denmark; Christopher Jarchow, MPS-Planeto, Germany; Franz Kerschbaum, University of Vienna, Austria; Géza Kovacs, Konkoly Observatory, Hungary; Pierre-Olivier Lagage, CEA – Saclay, France; Tanya Lim, RAL Space, UK; Mercedes Lopez-Morales, CSIC – ICE, Spain; Giuseppe Malaguti, INAF – IASF – Bologna, Italy; Marc Ollivier, IAS Paris, France; Emanuele Pace, Università di Firenze, Italy; Enric Pallé, IAC, Spain; Enzo Pascale, Cardiff University, UK; Giuseppe Piccioni, INAF - IASF – Roma, Italy; Alessandro Sozzetti, INAF – Osservatorio Astrofisico di Torino, Italy; Bart Vandenbussche, Leuven University, Belgium; Gillian Wright, UK ATC, UK; Gonzalo Ramos Zapata, INTA, Spain; Maria Rosa Zapatero Osorio, CAB, Spain.

12.3 Consortium Technical Team Coordinators

Consortium Project Manager – Paul Eccleston, RAL Space, UK. **Instrument Scientist –** Marc Ollivier, IAS Paris, France. **Payload Scientists –** Giuseppe Malaguti, INAF, Italy; Giorgio Savini, UCL, UK**. Consortium PA Manager –** Richard Stamper, RAL Space, UK**. Consortium SGS Lead –** Tanya Lim, RAL Space, UK. **Systems Engineering Working Group Coordinators –** Ana Balado, INTA, Spain; Ian Bryson, UK ATC, UK; Raymond Burston, MPS, Germany;Vincent Coudé du Foresto, LESIA-Astro, France; Martin Crook, RAL, UK; Anna Di Giorgio, Italy; Kevin Middleton, RAL Space, UK; Frederic Pinsard, CEA – Saclay, France; Gianluca Morgante, INAF – IASF Bologna, Italy; Emanuele Pace, Università di Firenze, Italy; Pep Colomé, ICE – CSIC, Spain; Ranah Irshad, RAL, UK; Bruce Swinyard, RAL Space / UCL UK; Berend Winter, MSSL, UCL, UK**. Consortium Management Advisor –** Matt Griffin, Cardiff University, UK**. Module Design Leads –** Alberto Adriani, IAPS-IAPS, Italy; Neil Bowles, University of Oxford, UK; Kevin Middleton, RAL Space, UK; Roland Ottensamer, University of Vienna, Austria; Gonzalo Ramos Zapata, INTA – LINES, Spain; Jean-Michel Reess, LESIA-Planeto, France**. National Project Managers –** Ruymán Azzollini, DIAS, Ireland; Raymond Burston, MPS, Germany; Josep Columé, CSIC-ICE, Spain; Ruud Hoogeveen, SRON Netherlands Institute for Space Science, Netherlands; Roland Ottensamer, University of Vienna, Austria; Emanuele Pace, Università di Firenze, Italy; Mirek Rataj, Space Research Centre, Polish Academy of Science, Poland; Jean-Michel Reess, LESIA-Astro, France; Jan-Rutger Schrader, SRON Netherlands Institute for Space Science, Netherlands.

12.4 Consortium Science Team Coordinators

Science Team Co-leads – Giovanna Tinetti, UCL, UK and Pierre Drossart, LESIA-Planeto, France. **Science Team Working Group Leads –** France Allard, ENS, France; Joanna Barstow, Oxford University, UK; James Cho, QMUL, UK; Athena Coustenis, LESIA, France. Charles Cockell, ROE, UK; Alexandre Correia, IN, Portugal; Leen Decin, University of Leuven, Belgium; Pieter Deroo, JPL, USA; Therese Encrenaz, LESIA, France; Francois Forget, LMD, France; Alistair Glasse, UK ATC; Caitlin Griffith, UoA, US; Tristan Guillot, Nice Obs. France; Paul Hartogh, MPS Germany; Tommi Koskinen, UoA, US; Helmut Lammer, IWF, Austria; Jeremy Leconte, LMD, France; Pierre Maxted, Keele University, UK; Giusi Micela, INAF, Palermo, Italy; Ingo Mueller-Wodarg, Imperial College, UK; Richard Nelson, QMUL, UK; Chris North, Cardiff, UK; Enric Pallé, IAC, Spain; Isabella Pagano, OAT, Italy; Guseppe Piccioni, INAF/IASF, Italy; David Pinfield, UH, UK; Remco de Kok, SRON, Netherlands; Ignasi Ribas, CSIC-ICE, Spain; Franck Selsis, Université de Bordeaux, France; Ignas Snellen, Leiden University; Alessandro Sozzetti, INAF

Torino, Italy; Lars Stixrude, UCL, UK; Jonathan Tennyson, UCL, UK; Diego Turrini, INAF-IASF, Italy; Mariarosa Zapatero-Osorio, CAB, Spain.

12.5 Consortium Contributing Scientists & Engineers

Austria – W. Magnes, IWF Graz; E. Dorfi, University of Vienna; M. Güdel, University of Vienna; F. Kerschbaum, University of Vienna; A. Luntzer, University of Vienna; E. Pilat-Lohinger, University of Vienna; T. Rank-Lüftinger, University of Vienna; **Belgium –** B. Bonfond, Université de Liège; J.-C. Gerard, Université de Liège; M. Gillon, Université de Liège; J. Gustin, Université de Liège; B. Hubert, Université de Liège; A. Radioti, Université de Liège; L. Soret, Université de Liège; A. Stiepen, Université de Liège;

Czech Republic – D. Heyrovsky, Charles University;

Denmark – A. Andersen, DARK Cosmology Center; L. Buchhave, DARK Cosmology Center; D. Watson, DARK Cosmology Center; N. Christian Jessen, DTU Space; I. Lundgaard Rasmussen, DTU Space;

France – C. Cavarroc, CEA; S. Charnoz, CEA; E. Pantin, CEA; C. Alard, IAP; V. Batista, IAP; A. Cassan, IAP; J.-P. Maillard, IAP; J.-B. Marquette, IAP; P. Bordé, IAS; O. Demangeon, IAS; P. Gaulme, IAS; P. Lognonné, IPGP; C. Michaut, IPGP; S. Jacquemoud, IPGP; P. Fouqué, LATT; B. Bézard, LESIA; P. Kervella, LESIA; E. Lellouch, LESIA; B. Sicardy, LESIA; S. Vinatier, LESIA; T. Widemann, LESIA; D. Cordier, Obs. Besancon; M. Agundez, Obs. Bordeaux; M. Dobrijévic, Obs. Bordeaux; V. Eymet, Obs. Bordeaux; I. Gomez-Leal, Obs. Bordeaux; E. Hébrard, Obs. Bordeaux; F. Hersant, Obs. Bordeaux; A.-S. Maurin, Obs. Bordeaux; O. Venot, Obs. Bordeaux; P. Tanga, Obs. Cote d'Azur; F. Vakili, Obs. Cote d'Azur; L. Abe, Obs. Nice; V. Parmentier, Obs. Nice; R. Petrov, Obs. Nice; F.-X. Schmider, Obs. Nice;

Germany – P. Börner, MPS; M. de Val-Borro, MPS; N. Krupp, MPS; U. Mall, MPS; A. Medvedev, MPS; M. Rengel, MPS; L. Rezac, MPS; J. Sethenadh, MPS; N. Iro, Hamburg University;

Ireland – A. Scholz, DIAS;

Italy – L. Testi, ESO; A. Bulgarelli, IASF-Bologna; F. Gianotti, IASF-Bologna; G. Malaguti, IASF-Bologna; L. Terenzi, IASF-Bologna; M. Trifoglio, IASF-Bologna; F. Altieri, IAPS-Roma; G. Bellucci, IAPS-Roma; D. Biondi, IAPS-Roma; M.T. Capria, IAPS-Roma; R. Cerulli, IAPS-Roma; A.M. Di Giorgio, IAPS-Roma; N. Fabrizio, IAPS-Roma; G. Filacchione, IAPS-Roma; M. Giuranna, IAPS-Roma; D. Grassi, IAPS-Roma; S.J. Liu, IAPS-Roma; S. Pezzuto, IAPS-Roma; D. Turrini, IAPS-Roma; C. Baffa, OA-Arcetri; C. Del Vecchio, OA-Arcetri; E. Giani, OA-Arcetri; L. Gambicorti, OA-Arcetri; F. Massi, OA-Arcetri; E. Oliva, OA-Arcetri; F. Palla, OA-Arcetri; K. Readorn, OA-Arcetri; A. Tozzi, OA-Arcetri; E. Poretti, OA-Brera; C. Cecchi Pestellini, OA-Cagliari; J. Alcala, OA-Capodimonte; E. Covino, OA-Capodimonte; P. Ballerini, OA-Catania; N. Lanza, OA-Catania; G. Leto, OA-Catania; S. Scuderi, OA-Catania; G. Strazzulla, OA-Catania; R. Claudi, OA-Padova; E. Giro, OA-Padova; L. Affer, OA-Palermo; A. Ciaravella, OA-Palermo; A. Collura, OA-Palermo; U. Lo Cicero, OA-Palermo; A. Maggio, OA-Palermo; L. Prisinzano, OA-Palermo; G. Scandariato, OA-Palermo; A. De Sio, UniFirenze; M. Focardi, UniFirenze; M. Pancrazzi, UniFirenze; S. Shore, UniPi;

The Netherlands – C. Dominic, University of Amsterdam; I. Snellen, Leiden University; R. Waters, SRON;

Poland – H. Rickman, SRC-PAS; M. Banaszkiewicz, SRC-PAS; M. Błęcka, SRC-PAS; A. Wawrzaszk, SRC-PAS; T. Wiśniowski, SRC-PAS; M. Rataj, SRC-PAS; P. Sitek , SRC-PAS ; R. Graczyk, SRC-PAS; M. Stolarski, SRC-PAS; P. Wawer, SRC-PAS; R. Pietrzak, SRC-PAS; W. Winek, SRC-PAS;

Portugal – M. Montalto, CAUP; V. Adybekian, CAUP ; I. Boisse, CAUP ; E. Delgado-Mena, CAUP ; P. Figueira, CAUP ; M. Monteiro, CAUP; N. Santos, CAUP ; S. Sousa, CAUP; T. Kehoe, I3N; H. Morais, I3N ; M. Abreu, CAAUL; D. Berry, CAAUL; A. Cabral, CAAUL; S. Chamberlain, CAAUL; R. Herdero, CAAUL; P. Machado, CAAUL; J. Peralta, CAAUL; J. Rebordão, CAAUL;

Slovakia – J. Budaj, Slovak Academy of Sciences;

Spain – D. Barrado, CAB-INTA; H. Bouy, CAB-INTA; N. Huelamo, CAB-INTA; J. Martín Torres, CAB-INTA; M. Morales-Calderón, CAB-INTA; A. Moro Martín, CAB-INTA; A. Moya Bedon, CAB-INTA; J. Sanz Forcada, CAB-INTA; E. García Melendo, FOED/ICE; P. Amado, IAA; A. Claret, IAA; M. Fernández, IAA; M. Lopez-Puertas, IAA; M.A. Lopez-Valverde, IAA; C. Allende Prieto, IAC; C.A. Alvarez Iglesias, IAC; J.A. Belmonte Avilés, IAC; H.J. Deeg, IAC; M. Espinoza Contreras, IAC; M. Esposito, IAC; B. Femenía Castella, IAC; R.J. García López, IAC; J. Gonzalez Hernandez, IAC; B. González Merino, IAC; G. Israelian, IAC; B. Laken, IAC; J. Licandro Goldaracena, IAC; N. Lodieu, IAC; P. Miles-Paez, IAC; P. Montañés Rodríguez, IAC; F. Murgas Alcaino, IAC; H. Parviainen, IAC; K.Y. Peña Ramírez, IAC; R. Rebolo López, IAC; V.J. Sánchez Béjar, IAC; E. Sanromá Ramos, IAC; B.W. Tingley, IAC; M.L. Valdivieso, IAC; J. C. Morales, ICE; J. Colomé, ICE; E. Garcia-Melendo, ICE; L. Gesa, ICE; J. Guardia, ICE; E. Herrero, ICE; F. Rodler, ICE; C. Eiroa, UAM; J. Maldonado, UAM; E. Villaver, UAM; F.J. Alonso Floriano, UCM; D. Montes, UCM; H.M, Tabernero, UCM; R. Hueso, UPV; S. Perez-Hoyos, UPV; A. Sanchez Lavega, UPV;

Sweden – N. Piskunov, Uppsala University; U. Heiter, Uppsala University; K. Justtanont, Onsala Space Observatory;

UK – E. Barton, UCL; C. MacTavish, Cambridge; P. Ade, Cardiff; S. Eales, Cardiff; W. Gear, Cardiff; H. Gomez, Cardiff; M. Griffin, Cardiff; P. Hargrave, Cardiff; M. Galand, IC; J. Haigh, IC; J. Harries, IC; A. Coates, MSSL; R. Cole, MSSL; G. Jones, MSSL; A. Smith, MSSL; C. A. Haswell, OU; G. White, OU; L. Fletcher, Oxford; P. Irwin, Oxford; M. Tecsa, Oxford; J. Temple, Oxford; P. Read, Oxford; C. Agnor, QMUL; I. Polichtchouk, QMUL; C. Watkins, QMUL; T. Lim, RAL; D. Waltham, RHUL; N. Achilleos, UCL; A. Aylward, UCL; R. J. Barber, UCL; C. Danielski, UCL; P. Doel, UCL; S. Fossey, UCL; P. Guio, UCL; M. Hollis, UCL; O. Lahav, UCL; C. Lithgow-Bertelloni, UCL; G. Morello, UCL; H. Osborne, UCL; R. Prinja, UCL; M. Rocchetto, UCL; G. Savini, UCL; M. Tessenyi, UCL; S. Thompson, UCL; S. Viti, UCL; R. Varley, UCL; I. Waldmann, UCL; S.N. Yurchenko, UCL; J. Frith, UH; H. Jones, UH; I. Bryson, UK ATC; A. Glasse, UK ATC; G. Wright, UK ATC; N. Iro, Un. Keele; P. Maxted, Un. Keele; M. Burleigh, Un. Leicester; E. Kerins, Un. Manchester; D. Ward-Thompson, Un Lancaster;

USA – H. Thrastarson, Caltech; Y. Yung, Caltech; D. Kipping, CfA; L. Brown, JPL; G. Orton, JPL; G. Bakos, Princeton; J. Moses, SSI; A. Showman, UoA; C. Griffith, UoA; T. Koskinen, UoA; R. Yelle, UoA; P. Mauskopf, UoA.