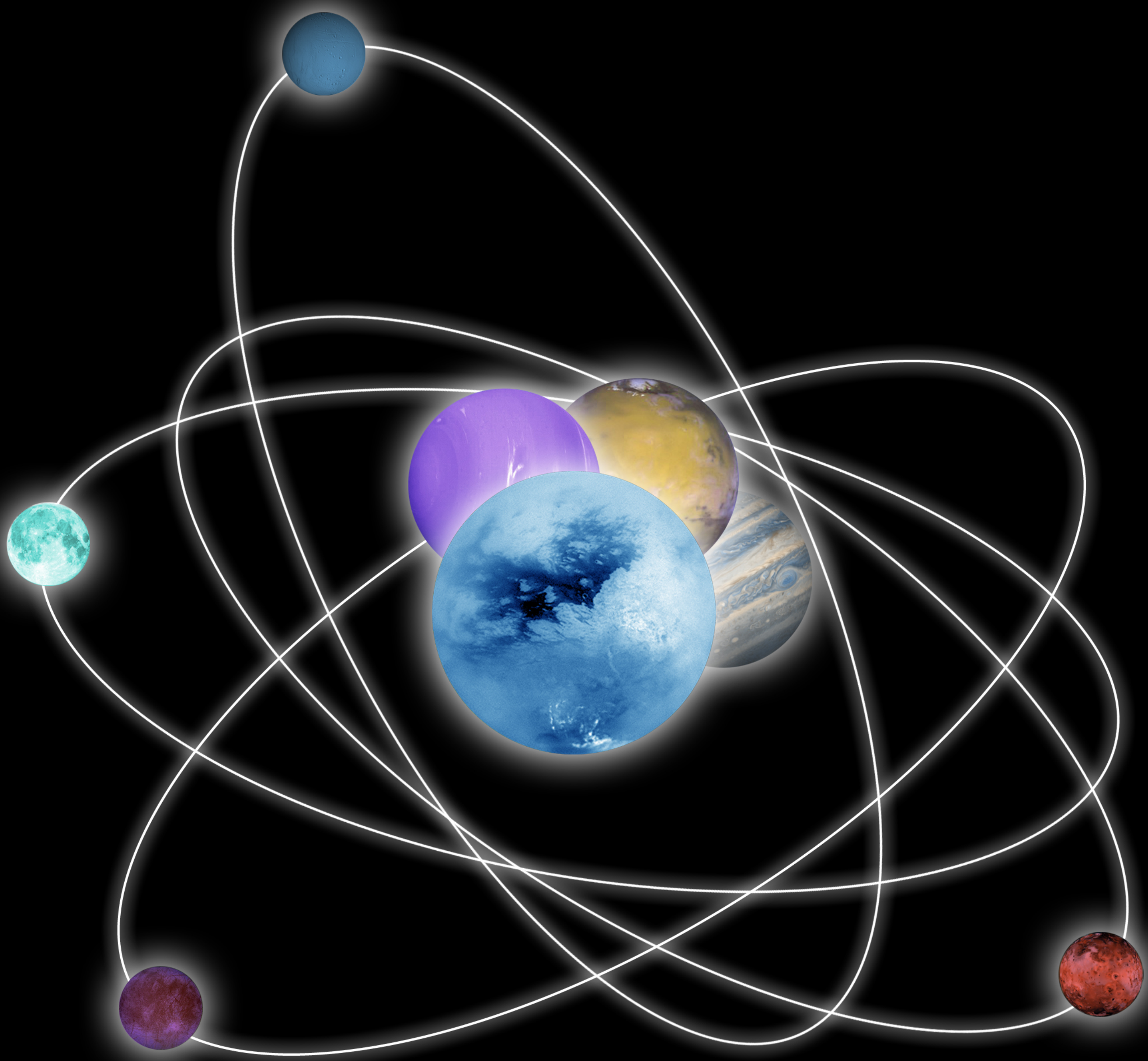
ECHO

Exoplanet Characterisation Observatory



Exploring Atmospheres of Diverse Worlds
Beyond our Solar System

EChO
Exoplanet Characterisation Observatory

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1 Executive Summary

EChO: *What are exoplanets made of?*

The Exoplanet Characterisation Observatory, EChO, will be the first dedicated mission to investigate the physics and chemistry of Exoplanetary Atmospheres. It will place our Solar System in context and by addressing the suitability of planets for life will allow us to address some of the fundamental questions of the Cosmic Visions programme:

- *What are the conditions for planet formation and the emergence of life?*
- *Are systems like our Solar System rare or very common? How does the Solar System work?*

EChO will provide high resolution, simultaneous multi-wavelength spectroscopic observations on a stable platform that will allow very long exposures. The use of passive cooling, few moving parts and well established technology gives a low-risk and potentially long-lived mission.

During a primary transit, when a planet passes in front of its star, the star's light passes through the limb of the planet's atmosphere, effectively providing an atmospheric transmission spectrum. During a secondary eclipse the planet passes behind its star; the dip in the flux reveals the emission, and at optical wavelengths, the reflection, spectrum of the planet. An orbital light-curve can be used to obtain the horizontal gradients of the temperature and composition of exoplanets. These combined approaches provide complementary information, including the temperature and composition profiles over ∼3 decades of pressure, the planet's cloud opacity and composition, and disk-wide temperature and composition variations. In all cases, instead of spatially separating the light of the planet from that of the star, EChO exploits temporal variations to extract the planet's signal. The mission will study a large range of processes that shape the structure of planets, a few of which we highlight here.

EChO will provide constraints on the formation of the exoplanets. Primary and secondary observations will readily indicate (through the CH_4, CO, CO_2 and H_2O features) the carbon and oxygen elemental abundance of the atmospheres which point to the formation mechanism of the planet: whether by the accretion of solids (as did our planets) or by gas collapse (as do stars). The planet's C and O abundance can be compared to measurements of C and O in the primary star to determine whether the atmosphere's abundance matches that of the star. A significant overabundance of heavy elements in the planet indicates formation by core accretion. A mild enrichment of heavy elements indicates formation by gas collapse.

EChO will characterise an exoplanet's climate. The composition and thermal structure of the planet's atmosphere will be compared to the primary star's incident light and measured reflection to determine the partitioning of stellar radiation. Such measurements probe the greenhouse effect, which shapes planetary atmospheres and renders them habitable (as on Earth) or uninhabitable (as on Venus). Planetary climates are also affected by atmospheric dynamics: Earth's circulation redistributes heat from equator to pole. EChO will study the dynamics of exoplanetary atmospheres through the derived vertical and horizontal temperature and compositional gradients.

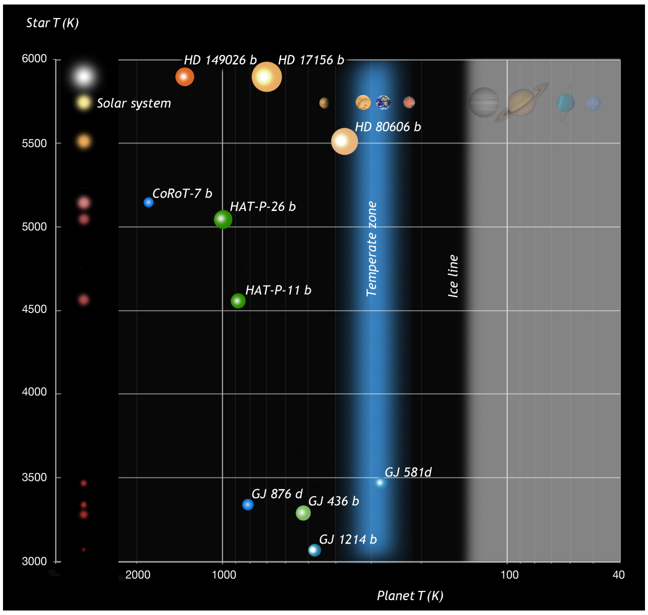

Figure 1: EChO will expand the playground of planetary science beyond our solar system, by providing a portfolio of exoplanet spectra under a wide gamut of physical and chemical conditions. The observed chemical composition largely depends on the planet's thermal structure, which in turn depends on the planet's orbital distance and metallicity, and the host star's luminosity and stellar type. The planetary mass determines the planet's ability to retain an atmosphere. The range of planets and stellar environments explored by EChO extends to the temperate zone and includes gas-giants, Neptunes and Super-Earths. It is already populated by ∼100 known transiting objects, and the number of sources is expected to increase exponentially until the launch date thanks to the current exoplanet discovery programs.

EChO will study exoplanetary chemistry. Thermal equilibrium models will indicate if an exoplanet's atmosphere is in equilibrium. With the exception of the deep atmospheres of the Giant Planets, atmospheric equilibrium is rare in the Solar System, so we expect to find atmospheres that are out of equilibrium. We plan to study photochemistry, the most important non-equilibrium chemical process which on Earth is responsible for O_3 production, through the identification and measured abundances of principal photochemical products.

Monitoring stellar variability simultaneously with exoplanet atmospheric data is a key aspect of the mission. The best available indicator of chromospheric flux in the wavelength ranges accessible to EChO is the H Balmer α line at 0.66 µm. Emission in the core of the line can be used to determine how variations in the stellar chromosphere affect planetary atmospheres, and to distinguish stellar variability from planetary variability. In addition, EChO will search for H_3^+, which indicates if a Jovian-type planet has a magnetosphere and is an indicator of the effects that stars of different types have on planetary atmospheres.

The investigation of exoplanetary atmospheres requires a dedicated space mission that is fine-tuned to this purpose. Such a mission must be capable of capturing a snapshot of the planet's atmosphere and separating time variable characteristics from steady state conditions. It must be able to observe many systems, including the dimmer planets that approach the size of Earth and be optimised to eliminate systematic errors. Lastly, it must have a spectrometer with sufficient resolution to capture the spectral characteristics of the constituents that reveal the chemical and dynamical processes of the atmosphere. EChO fulfils all of these requirements.

EChO will build on observations by Hubble, Spitzer and ground-based telescopes, which discovered the first molecules and atoms in exoplanetary atmospheres. However EChO's configuration and specifications are designed to study a number of systems in a consistent manner that will eliminate the ambiguities affecting prior observations. EChO will simultaneously observe a broad enough spectral region to constrain from one spectrum the temperature structure of the atmosphere, the abundances of the major carbon and oxygen molecules, the expected photochemically-produced species and magnetospheric signatures. The spectral range and resolution of the 4 channels are tailored to separate bands belonging to up to 30 molecules and retrieve the composition and temperature structure of planetary atmospheres.

The target list for EChO includes planets ranging from Jupiter-sized, with an orbital semi-major axis one tenth that of Mercury and equilibrium temperatures, T_{eq} up to 2000 K, to those of a few Earth masses, with T_{eq} ~300 K. The list will include planets with no Solar System analog, such a as the recently discovered planet GJ1214b, whose density lies between that of terrestrial and gaseous planets. As the number of detected exoplanets grows exponentially each year, and the mass of those detected steadily decreases, the target list will be constantly adjusted to include the most interesting systems.

Payload instrument

We have baselined a dispersive spectrograph design covering continuously the 0.4–16 μm spectral range in 6 channels (1 VIS, 5 IR) which allows the spectral resolution to be adapted to the target brightness from several tens ($\lambda \geq 11$ m) to several hundreds ($\lambda \leq 11$ m). Thus optimising for the scientific objectives over the observation spectral range. The instrument is mounted behind a 1.5 m class telescope passively cooled to 50 K with the instrument structure and optics passively cooled to ~45 K. The infrared channels will use HgCdTe detectors, with performance optimised precisely to each wavelength range, actively cooled to 30 K in order to reduce the dark current to the required level. Stability and accuracy of the photometry is critical to the success of EChO and the design of the whole detection chain and satellite will be dedicated to achieving a high degree of photometric stability and repeatability. For instance the stabilisation of the line of sight at the instrument level will be achieved through a combination of the satellite AOCS and a tip-tilt mirror in the instrument optical path controlled by the imaging of the target star onto a focal plane fine guidance sensor. Calibration is also critical and requires detailed monitoring of the detector performance using both internal and external calibration sources.

EChO will be placed in a grand halo orbit around L2 with a baseline of a ±30 deg roll ability about the normal to the Sun-Earth line. This orbit, in combination with a nested thermal shield design, provides a highly stable thermal environment for the passive cooling of the instrument and telescope. The orbit and thermal shield design will also provide a high degree of visibility of the sky over the year and an ability to repeatedly observe several tens of targets whatever the epoch in the year.

A trade-off analysis has been carried out under the auspices of the Estec Concurrent Design Facility in the context of the ExoPlanet Roadmap Advisory Team mandate. The study showed that no challenging technological developments are required for an immediate implementation of the mission[1]. We have undertaken a set of delta studies with experienced scientific institutes and European industrial partners to assess again the readiness of EChO for an M3 mission and the optimum design for the payload. Both the baseline and alternative designs have been evaluated and no critical items with TRL less than 4 to 5 have been identified. We have also undertaken a first-order cost and development plan analysis and find that EChO is easily compatible with the M-class mission framework.

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[1] http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=47037

2 Introduction

A dedicated mission to investigate Exoplanetary Atmospheres is a major milestone in our quest to understand our place in the Universe by placing our Solar System in context and by addressing the suitability of planets for the presence of life. These are major questions of arguable scientific and social interest and prominently identified as key themes in ESA's Cosmic Vision programme.

The idea is clearly not new: back in the eighties Bracewell (Nature, 1978) and Angel et al. (Nature, 1986) proposed that exoplanets around nearby stars could be detected in the IR (6-17 µm) and their spectra analysed, searching for CO_2 , H_2O, O_3 , CH_4 , and NH_3 spectral features. The implementation of this idea under the form of an IR nulling interferometer in space came almost ten years later (Léger et al, 1996). The concept, named DARWIN, was first proposed to ESA in 1993, when the only known planets were the nine in our Solar System (+ three around a neutron star). Its principal objectives were to both detect Earth-like planets around nearby stars, to analyse the composition of their atmospheres and assess their ability to sustain life as we know it. Two years later, the discovery of 51 Pegb – the first extrasolar planet orbiting a main-sequence star– with doppler techniques (Mayor and Queloz, Nature, 1995) would be a turning point. The DARWIN mission concept was a child of its time: the working hypothesis of an Earth-twin + Sun-twin as the only cradle for life, was too geocentric to survive the "exoplanet revolution".

More than fifteen years of Extrasolar Planets discoveries have taught us that the pathways to Habitable Planets are multiple, but the most interesting are the ones able to cast light on a plethora of physical and chemical processes not entirely understood or missing in our Solar System (Blue Dots Team report and Coudé du Foresto et al. 2010).

Among the 500+ exoplanets detected with various techniques to date, there is actually little resemblance with the Solar System paradigm. Planets with orbital properties far beyond our imagination, ranging from close-in hot-Jupiters, to planets on extremely eccentric orbits and resonant systems have been detected. A new class of planets with masses between the Earth mass and the 10 Earth masses –so called "Super-Earths"– seem to be quite common but absent from our Solar System, where the terrestrial planets are Earth mass or lighter. This diversity is certainly connected to the variety of initial conditions for planet formation provided by the range of protoplanetary disk properties and stellar environment, which plays a key role in the life and evolution of a planet. The climates of planets around late type stars, for instance, are expected to be altered by the red-shifted stellar spectra. Stellar flares might increase atmospheric erosion, with consequences which are still poorly understood.

And if 500 exoplanets, as a number, were not impressive enough, the Kepler mission alone, has announced 400 new transit candidates, while GAIA promises to bring this number to several thousands in the next 5 years. Now the key challenge is moving from simple discovery to characterisation:

What are these planets actually like, and –most importantly– why are they as they are?

In the past ten years, we have also learned how to obtain the first spectra of exoplanets using transit transmission and emission spectroscopy. With the high stability of Spitzer, Hubble, and large ground-based telescopes the spectra of bright close-in massive planets can be obtained and species like water vapour, methane, carbon monoxide and dioxide have been detected. With transit science came the first tangible remote sensing of these planetary bodies and so one can start to extrapolate from what has been learnt from Solar System probes to what one might plan to learn about their faraway siblings. Just as knowledge of Solar System planetary science expanded exponentially as planets went from dots in ground-based telescopes to clear images and extensive high-resolution remote-sensing data, so will our knowledge of exoplanets depend not only on simple statistics of masses and radii, but on what we can learn from transits and differential photometry and spectrometry. As we learn more about the atmospheres, surfaces and near-surfaces of these remote bodies, we will begin to build up a clearer picture of their construction, history and suitability for life. Even while limited to the larger, hotter and closer-in bodies we have made significant discoveries.

By characterising spectroscopically more bodies in different environments we will take detailed planetology out of the Solar System and into the Galaxy as a whole.

Here we propose the Exoplanet Characterisation Observatory –EChO, which will provide an unprecedented view of the atmospheres of planets around nearby stars. Those planets will span a range of masses (from gas giants to Super-Earths), stellar companions (F, G, K and M) and temperatures (from hot to habitable). In EChO, we revisit the original idea of Bracewell and Angel et al., that the atmospheres of exoplanets around nearby stars should be characterised spectroscopically in the IR, searching for molecular features. The scientific wisdom of increasing the wavelength coverage to include the optical (0.4 to 16 µm) comes from nearly 50 years of remote sensing observations of planets in our Solar System combined with the more recent experience of (very) remote sensing of exoplanetary atmospheres. EChO will inherit the technique and exquisite photometric precision of CoRoT and Kepler, aiming at the $10^{-4} - 10^{-5}$ level of precision in the observation of the target-star at multiple wavelengths. *EChO will observe the atmosphere of planets already discovered by other surveys and facilities.* If launched today, EChO would select ∼50 targets for atmospheric characterisation out of the 100+ confirmed transiting exoplanets. Most of these targets were discovered by dedicated ground-based transit/radial velocity search programmes, which are presently delivering a flood of new discoveries. And the future will bring with a new generation of transit/radial velocity surveys (MEarth, APACHE, ESPRESSO etc.) and provide new access to the population of Earth-mass planets orbiting bright late type-stars, e.g. GJ 1214b. Finally, in the quest for habitable worlds outside our Solar System, EChO will be able to observe, among other targets, Super-Earths in the temperate zone of M dwarfs: these are clearly not the Earth's and Sun's *twins*, but rather their *cousins*. Will they present equal opportunities for habitability ?

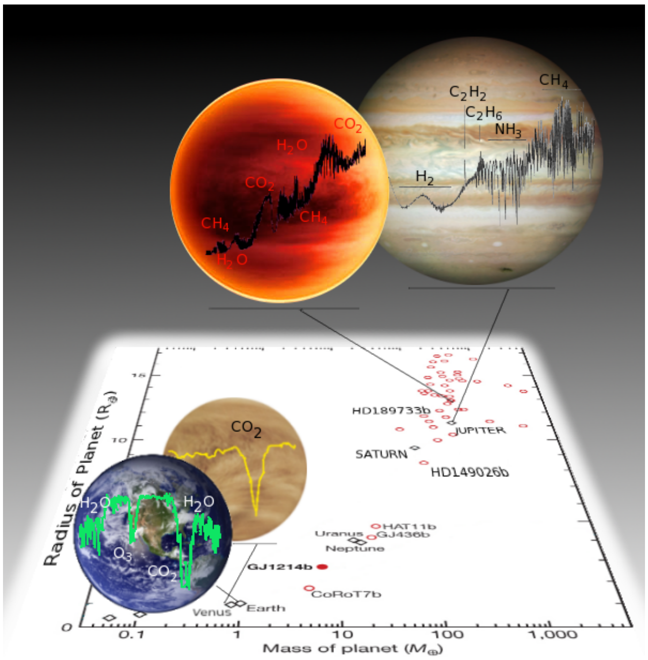


Figure 2: Planets can be very similar in mass and radius and yet be very different worlds, as demonstrated by these two pairs of examples. A spectroscopic analysis of the atmospheres is needed to reveal their physical and chemical identities.

3 Scientific objectives

The scientific objectives of EChO are to:

1. Measure the ***atmospheric composition, temperature and albedo*** of a highly representative sample of known extrasolar planets, orbiting different stellar types (F, G, K and M). The sample will include hot, warm, and habitable-zone exoplanets, down to the Super-Earth size (∼ 1.5 Earth radii). Table 2 shows the molecular, atomic and ionic species detectable by EChO between 0.4 and 16 µm at the baseline spectral resolving power (∼ 300)
   The climate of a planet depends on the amount of solar radiation that is reflected out to space and the amount that is absorbed. Measuring the reflected light from the planet will provide information about the albedo of the planet and the possible presence of condensates and hazes. The combination of visible albedo and infrared temperature will be key to understanding how the energy is redistributed. In the Solar System albedo can range from ∼ 0.05 for the asteroids belt to a maximum of 0.99 for Enceladus, with an average of ∼ 0.3, like the case of the Earth. Photometric observations with MOST seem to indicate that the albedo of the Hot-Jupiters HD 209458b and HD 189733b is very low[67], suggesting the presence of highly absorbing hazes or clouds.
2. Measure the spatial (vertical & horizontal) and temporal variability of the thermal/chemical atmospheric structure of giants, Neptunes and hot Super-Earths. The photometric accuracy of EChO at multiple wavelengths will be sufficient to observe the planet not merely as day/night hemispheres or terminator, but to divide the planet into longitudinal slices, hence producing coarse maps of exoplanets (see §5.1 and 5.2). Repeated ingress/egress measurements and phase light-curves for bright eclipsing hot exoplanets will inform atmospheric modelling efforts. This spatial/temporal differentiation is necessary to:
   - Understand the relative importance of ***thermochemical equilibrium, photochemistry***, and transport- induced quenching in controlling the observed composition. These factors largely depend on the planet's thermal structure, which in turn depends on the planet's orbital distance and metallicity, and the host star's luminosity and stellar type. The host star's chromospheric activity level and the overall UV flux incident on the planet can also affect the photochemistry, but properties like planetary mass or radius play less of a role (see §6.1).
   - Provide much needed constraints for ***atmospheric dynamics and circulation models***. General arguments suggest that planets with orbital periods on the order of a few days are tidally locked[53,61,63], so that their permanent day-sides are continuously subjected to intense stellar irradiation, while their night-sides may be heated only by a more modest internal energy flux. In the presence of such an uneven energetic forcing, leading to significant (horizontal) temperature gradients, the efficiency of the horizontal heat redistribution is an important open question, as it largely determines their observational properties. Several attempts have been made to address this general circulation problems. Longitudinal brightness maps from the light curve of phase variations, observed by EChO, promise to be powerful diagnostic tools

for simulations of hot planets' atmospheric dynamics.

Vortices and waves are structures in exoplanet atmospheres that can produce observable temporal variability: these are usually long-lived and evolve with characteristic periodicities[19,85] which can be captured by EChO's observations (see §6.2).

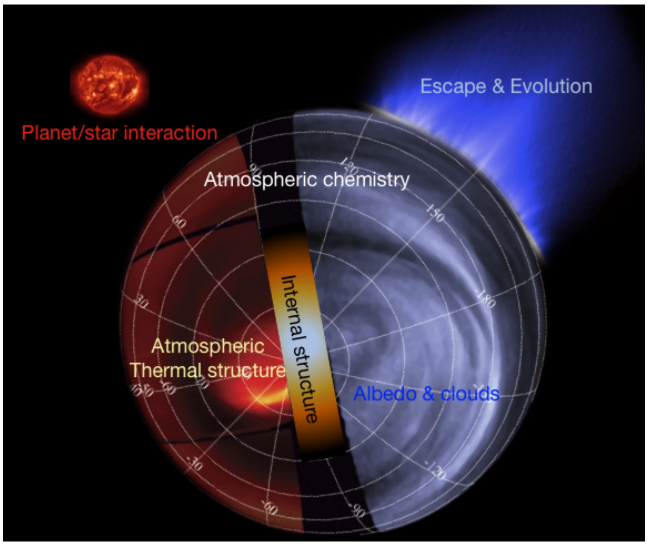


Figure 3: Scientific objectives of EChO.

3. Investigate the complex ***planet-star interaction***. Proper characterisation of a planet's host star is key to the interpretation and to the understanding of planetary data. The star has an impact on two major aspects, i) our ability to measure and interpret the data because of potential sources of systematic errors, and also ii) the modification of the structure and evolution of the planet atmosphere by being the overwhelmingly largest source of energy. Monitoring stellar variability simultaneously with the acquiring of data from which the exoplanet atmosphere will be measured is a key aspect of the EChO mission. Depending on the contrast temperature, our simulations indicate that the visible continuum variations can be a factor of 3-10 times larger than those of the near-IR and mid-IR, thus allowing for proper modelling and subsequent correction of the exoplanet data.
4. Constrain the models of ***internal structure***. Although EChO will by definition measure the characteristics of planetary atmospheres it will be also crucial in improving our knowledge of planetary interiors. 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 its ability to fully characterise the atmosphere in its composition, dynamics and structure. We give here a couple of examples (see §6.5).
   - Giant planets are mostly made of hydrogen and helium and are expected to always be in gaseous form[28]. Because they play an essential role in shaping planetary systems[89] determining precisely their internal structure and composition is essential to understanding how planets form. A large fraction of the known transiting planets are larger than expected, even when considering that they could be coreless hydrogen-helium planets[5,10,13,29,31,32]. There is thus missing physics that needs to be identified.
   - Neptune-like planets possess a thick atmosphere mostly composed of hydrogen and helium (several Earth masses). Mass and radius measurements obtained from radial velocities and transit observations, respectively, will not be sufficient to distinguish between this intermediate family and terrestrial planets with a significant amount of water[2]. This degeneracy can be easily removed by sounding the atmosphere through primary transit spectroscopy. EChO's observed spectra will allow the atmospheric scale height to be determined, hence the main atmospheric component (i.e. molecular hydrogen or water vapour in this case) and the gravity –the atmospheric temperature is estimated independently by eclipse measurements (see §6.5).
5. Improve our understanding of ***planetary formation/ evolution*** mechanisms. High resolution spectroscopy will provide important information about the chemical constituents of planetary atmospheres, and this is expected to be related to both the formation location, and the chemical state of the protoplanetary disk.
   Atmospheric escape is an important factor in the evolution of exoplanet atmospheres, and may define the boundary between Neptune-like planets and Super Earths. H_3^+ is a key component for the thermal stability of exoplanets: there is a sharp inner limit to the distance a gas giant can be from its star and retain thermal stability. Inside this distance (which is about 0.16 AU for a Jovian sized body around a Sun-like star) the H_2 from which the H_3^+ is made begins to dissociate, inhibiting the molecular ion's formation, thus reducing the cooling effect. The planet responds by heating up enormously with its thermosphere expanding to many times its normal size[40]. Our simulations show that EChO's spectral resolving power of $\sim$300 is sufficient to detect H_3^+ (see §6.4).
6. explore the thermal/chemical variability along the orbit of ***non transiting exoplanets*****, especially in high-eccentric orbit.** This work was pioneered by Harrington *et al.*[33] phase curve measurements of non transiting Ups And b. Despite the fact that all planets in our Solar System have a circular orbit, more than 60% of the exoplanets discovered have a high eccentricity, e.g. HD 80606b[42].

While non-transiting planets will not be a primary goal, EChO will give us the unique opportunity of studying the chemistry and thermal properties of very exotic objects.

On top of that, EChO could:

- ***search for Exomoons.*** We estimate that moons down to 0.33$R_\oplus$ would be detectable with EChO for our target stars. Whilst *Kepler* may also be able to detect exomoons, EChO has numerous advantages in that: 1) we target brighter stars so higher SNRs 2) EChO works from 0.4-2.5 µm and can thus obtain NIR light curves which exhibit highly reduced distortion from limb darkening and stellar activity e.g. spots (*Kepler* is 0.4-0.9 µm) and 3) multi-colour light curves significantly attenuates degeneracy of fitted limb darkening parameters across all wavelengths (see §6.5).
- identify ***potential biosignatures*** in the atmospheres Super-Earths in the habitable zones of late type stars. In addition to the basic parameters described above, which are common to all planets with atmospheres, a planet which harbours life may also exhibit astronomical biosignatures, i.e. the presence of chemically based life on a planet would change the composition of its atmosphere away from the a-biological steady state[51]. The study of Super-Earths in the habitable zone of stars cooler than the sun, will challenge the paradigm of the Earth-twin orbiting a Sun-twin as the only possible cradle for life.

3.1 Targets observed by EChO: which, how many, why?

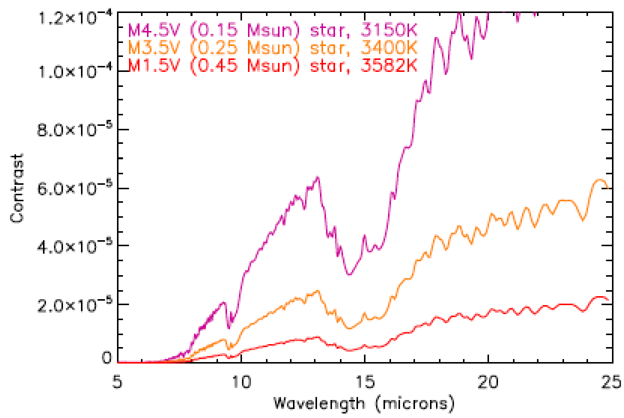
Table 1 lists the combinations of exoplanets/parent stars which will be observed by EChO. The planetary classification is done in terms of size and temperature: these two parameters combined with the stellar type, give the star-planet contrast at different wavelengths. The contrast, multiplied by the stellar luminosity, determines the feasibility and the integration time of the eclipse observations. For primary transit observations, the parameter to consider is the atmospheric scale height: the hotter is the atmosphere and the lighter is the main atmospheric component and the planetary mass, the easier is the primary transit observation. While EChO will be able to observe the secondary eclipse for all types of planets listed in Table 1, primary transit observations will be guaranteed only for exoplanets with a light main atmospheric component and/or relatively high temperature, nominally gas-giants, Neptunes and a sub-sample of Super-Earths with those characteristics (see §5.4). *EChO will observe as many Super-Earths as possible.* We expect, in fact, that the terrestrial planets' atmospheres will show a great diversity, well beyond the limited number of cases represented in our Solar System (Earth, Mars, Venus, Titan). On top of that, EChO will easily observe a large number of Gas giants and

Temperature / Size	Jupiters	Neptunes	Super-Earths
Hot > 700 K	F, G, K, M	G, K, M	M
Warm: 400-700	F, G, K, M	G, K, M	M
Temperate: 250-350	F, G, K, M	G, K, M	M2, M3, M4, M5 ...

Table 1: Type of planets and corresponding type of star observable by EChO. See §5.5 and 9 for additional information.

Neptunes orbiting different types of stars, with a variety of masses, radii and temperatures. A highly significant subset of those will be observed at high spectral resolution and with multiple visits, to monitor spatially and temporally resolved patterns due to photochemistry and dynamics.

Today, EChO would observe ∼50 known gas and icy giants transiting stars brighter than Mag V=12 (www.exoplanet.eu[69]), two transiting Super-Earths - CoRot 7b (hot[44]) and GJ 1214b (warm,[18])-, a non-transiting hot Gas-giant, ups And b[56]) and a non transiting hot Super-Earth, GJ 876d[66]. GJ 581, is a nearby star with at least 3 Super Earths orbiting in the vicinity of its habitable zone[57]. These Super-Earths would be ideal for EChO if they transited. Although today the available target sample is still biased towards more massive planets, from the preliminary analysis of HARPS data, more than 40% of stars have planets with masses below 50 Earth masses and 30% of stars with planets below 30 Earth masses[52,57]. Statistical estimates from microlensing surveys[14] indicate that 55% of late K and M dwarfs have Super-Earths. See §9 for further discussion on the targets available in 2020.



Brightness	Kmag ≤ 6	Kmag ≤ 7	Kmag ≤ 8	Kmag ≤ 9
total number	1506	5285	13680	35374

Figure 4: Good reasons for considering Super-Earths around M-dwarfs. Top: the cooler the star, the better the contrast star-planet, as this simulation shows (Tessenyi et al., 2010). Bottom: number of existing M-dwarfs as a function of stellar brightness (mag in K band (Afer and Micela, 2010)

The most favourable star-planet contrast in the case of the smallest targets, is obtained by observing planets around stars smaller and colder than our Sun, typically M-dwarfs. There are several advantages in selecting this star-planet combination. Cool stars of spectral type M, comprise about 70% to 75% of all stars, both in the

Solar neighbourhood and in the Milky Way as a whole 4. They range in mass from about 0.5 $M_\odot$ to less than 0.1 $M_\odot$, with associated reductions in heat and brightness. The sheer abundance of M dwarfs throughout our Galaxy ensures that a large fraction of exoplanetary systems will be centred on red suns. To date, radial velocity searches have detected 17 planetary systems around M stars. As a group, these systems harbour lower-mass planets orbiting at smaller semi-major axes than those around Sun-like stars, supporting the premise that system architecture scales roughly with stellar mass and thus with spectral type.

Given their meagre energy output, the habitable zones of M dwarfs, like their ice lines, are located much closer to the primary than those of more massive stars (Fig. 1). While 0.10 AU and 0.19 AU are reasonable numbers for the inner and outer boundaries of the habitable zones of larger M dwarfs, with masses of about 0.4 $M_\odot$ (e.g., GJ 436), the corresponding boundaries shrink to about 0.024-0.045 AU for the smallest members of the class, with masses of about 0.1 $M_\odot$[55]. This works in EChO's favour, as the short orbital period (ranging from one week to one month depending on the M type) will allow the observation of several tens (or even hundreds for late M) of transits during the life-time of the mission. The observation of the atmosphere of a terrestrial planet in the habitable zone of F, G, K type of star would, by contrast, be impractical with the transit technique. E.g. one could only afford to observe 3 to 5 transits in the lifetime of the mission for a terrestrial planet in the habitable zone of a Sun type star (one transit every calendar year!), way too little time to retrieve a useful spectrum with appropriate S/N.

4 Observational strategy & requirements

4.1 Observational techniques used by EChO

EChO will probe the atmospheres of extrasolar planets combining three techniques, making use of a) planet transits, b) secondary eclipses, and c) planet phase-variations, of which the latter will also be used for non-transiting planets. In all cases, instead of spatially separating the light of the planet from that of the star, EChO uses temporal variations to extract the planet signal.

a) Transmission spectroscopy When a planet partially eclipses its host star, star-light filters through the planet's atmosphere, adopting a spectral imprint of the atmospheric constituents. By comparison of in-transit with out-of-transit observations, this planet absorption is distilled from the absorption spectrum of the host star[12,70,86]. Transmission spectroscopy probes the high-altitude atmosphere at the day/night terminator region of the planet. Typically, absorption features scale with the atmospheric scale-height, which mainly depends on the temperature and mean molecular weight of the atmosphere. The first successes of exoplanet transmission spectroscopy were in the UV and optical[16,65,76,92], and have recently been extended to the near- and mid-infrared[3,7–9,38,80,87,88].

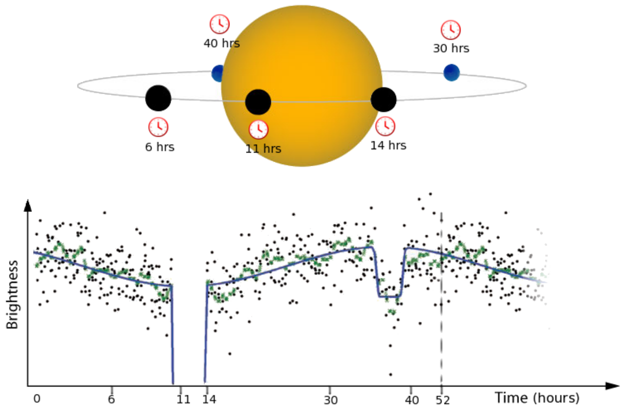


Figure 5: Optical phase curve of the planet HAT-P-7b observed by Kepler[11] showing primary and secondary transit measurements.

b) Secondary eclipse spectroscopy When a planet moves behind its host star (the secondary eclipse), the planet is temporarily blocked from our view, and the difference between in-eclipse and out-of-eclipse observations provides the planet's dayside spectrum. In the near- and mid-infrared, the radiation is dominated by thermal emission, modulated by molecular features[17,23,79–82,84]. This is highly dependent on the vertical temperature structure of the atmosphere, and probes the atmosphere at much higher pressure-levels than transmission spectroscopy. In the optical the planet spectrum is dominated by Rayleigh and/or Mie scattering of stellar radiation. For the latter, clouds can play an important role.

c) 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. Since the typical time scale of these phase-variations largely exceeds that of one observing night, these observations can only be conducted from space. However, they can also be performed on non-transiting planets[22]. Phase-variations are important in understanding a planet's atmospheric dynamics and the redistribution of absorbed stellar energy from their irradiated day-side to the night-side. Ground-breaking infrared 8μm Spitzer observations of exoplanet HD189733b have shown the night-side of this hot Jupiter to be only ∼300 K cooler than its day-side[38], implying an efficient redistribution of the absorbed stellar energy. 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. Towards the optical wavelength regime, an increasing contribution from reflected light is expected (as with

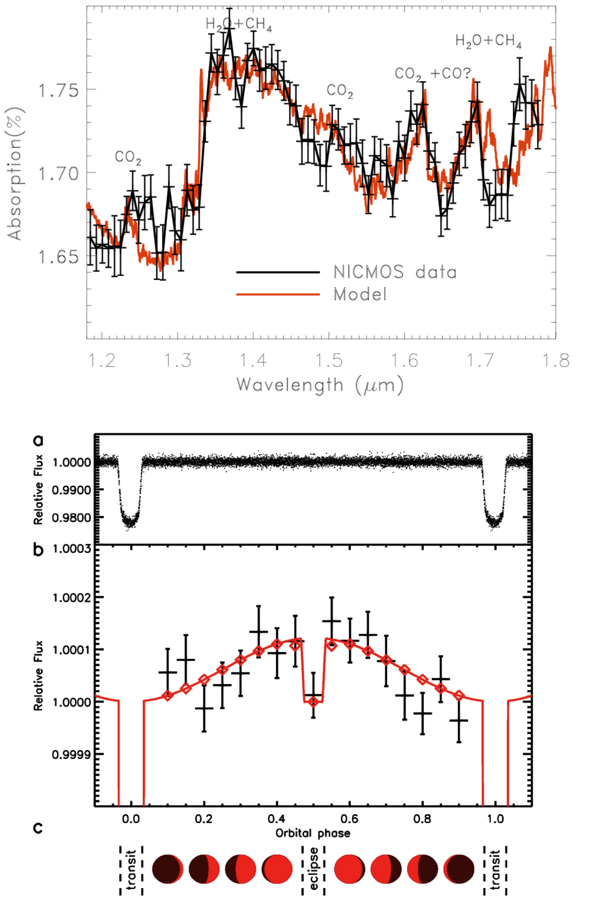


Figure 6: Atmospheric signatures of the planet XO-1b obtained with primary transit (Hubble)[88] and phase-curve of the planet CoRot-1b[77].

secondary eclipses), as is likely the case in CoRoT[77] and Kepler[11] light-curves.

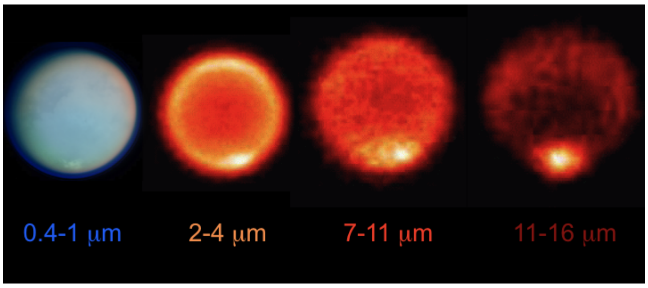


Figure 7: Exo-cartography of a planet at multiple photometric bands. For hot giant planets orbiting a bright star, this can be achieved by EChO with ~ 100 transits. For instance HD 189733b, can be mapped in 10 longitudinal slices with a spectral resolving power R~20 in the IR and a S/N~ 100. By binning more spectral channels we can improve the spatial resolution. .

d) Spatial and temporal resolution During a primary transit we probe the planetary limb at the terminator, whereas during secondary eclipse we sound the planetary hemisphere exposed to stellar radiation (day-side). If we have transit, eclipse and phase-curve measurements, we can extract the spectrum of the unilluminated (night-side) hemisphere[37]. Eclipses can be used as powerful tools to spatially resolve the photospheric emission properties of astronomical objects. During ingress and egress (Fig. 7), the partial occultation effectively maps the photospheric emission region of the object being eclipsed[21,64]. Note that the different system geometries affect the orientation and shape of the eclipsing stellar limb and consequently the detailed shape of the ingress/egress curves. The regime of atmospheric circulation present on hot, close-in exoplanets may be unlike any of the familiar cases encountered in the Solar System. Key constraints will be placed by EChO on these models through repeated infrared measurements.

4.2 Interpreting exoplanet spectra

Key species which should be observable by EChO are given in Table 2. Their complexity, together with the potential for overlapping molecular bands, means that the spectra can only be interpreted by comparing them to detailed atmospheric models.

Available retrieval models will be developed to explore the following questions:

- What information on atmospheric physical parameters and chemical composition can we derive from these spectra?
- Was this feature ever seen in any planets in our solar system?
- Is the interpretation of the planet derived from the observed spectrum plausible and realistic from a physical/chemical point of view?
- Is the interpretation unique or is there a degeneracy due to the insufficient spectral resolution and signal to noise[54,82]?
- Can further observations remove the degeneracy?

In an emission spectrum, measured through secondary eclipse observations in the IR, molecular signatures can appear either in absorption, emission, or both, depending on the shape of the pressure-temperature profile and the molecular vertical mixing ratio (Fig. 8)

Spectral retrieval methods and forward models are used to infer the presence and abundance of specific molecules and, in the case of an emission spectrum, the pressure-temperature profile; this can lead to a natural ambiguity between composition and temperature. Once the composition and temperature structure has been determined, knowledge of the atmospheric chemistry is inferred from the abundance estimates and vertical mixing ratios of individual molecules; for example, if the mixing ratio of CO_2 is higher than would be expected from purely equilibrium chemistry, a non-equilibrium chemistry mechanism (such as photochemistry) may be needed to explain the additional CO_2.

4.3 Justification of wavelength coverage and spectral resolution

For secondary transit measurements in the thermal regime (emission spectroscopy), retrieving abundances will require the simultaneous retrieval of the thermal profile (i.e. which features are in emission, which ones are in absorption?). This will be made easier

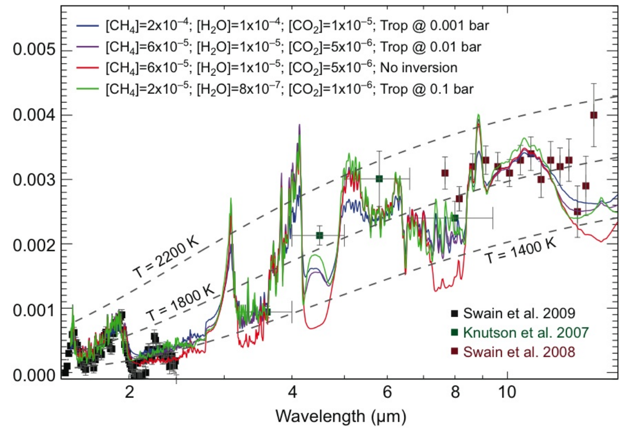


Figure 8: Emission photometry and spectroscopy the hot-Jupiter HD 209458 b[82]. The near-infrared and mid-infrared observations are compared to synthetic spectra for four models that illustrate the range of temperature/composition possibilities consistent with the data. For each model case, the molecular abundance of CH_4, H_2O, & CO_2 and the location of the tropopause is given, these serve to illustrate how the combination of molecular opacities and the temperature structure cause significant departures from a purely single-temperature thermal emission spectrum. Note that the current mid-infrared data shown here 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. This will not be an issue for EChO.

when bands of different intensities are used for a given molecule. EChO will perform broad, instantaneous spectral coverage from the visible (0.4 μm) to the mid-infrared (16 μm) where the data are obtained simultaneously. *Broad wavelength coverage enables resolving the temperature/composition ambiguity in an emission spectrum; simultaneous measurement of VIS-IR wavelengths allows planetary and stellar variability to be characterised and understood.*

Having signatures in both the reflected and thermal regions will greatly help the abundance and temperature structure retrieval. Moreover, monitoring stellar variability simultaneously with the acquisition of data from which the exoplanet atmosphere will be measured is a key aspect of the EChO mission: the light variations caused by magnetic activity can hamper the extraction of the exoplanet atmosphere signal and a need arises to diagnose stellar variability mostly in the near-IR and mid-IR continuum. Such variations are associated to active regions (star spots and bright spots or faculae) coming on and off view as the star rotates and also from intrinsic variability of such active regions. Both variations can happen at relatively short timescales, comparable to those of the planet's orbital period, and thus impact directly on the combination of different epochs of eclipse data. The best available indicator of chromospheric flux in the wavelength ranges accessible to EChO is the hydrogen Balmer α line at 0.66 μm. Emission in the core of the line appears as a consequence of chromospheric activity and thus can be used to monitor variations in the stellar chromosphere[93]. Observations in the visible range are thus essential to provide the stellar data needed for the measurement and

	0.4-1 μm	1-5 μm	5-11 μm	11-16 μm
R, baseline	500	300	300	20
R, desired	500	300	300	300
Species				
*H_2O	0.51, 0.57, 0.65, 0.72, 0.82, 0.94	1.13, 1.38, 1.9, **2.69**	6.2	continuum
*CO_2	-	1.21, 1.57, 1.6, 2.03, **4.25**	-	**15.0**
C_2H_2	-	1.52, **3.0**	7.53	**13.7**
HCN	-	**3.0**	-	**14.0**
C_2H_6	-	3.4	-	**12.1**
O_3	0.45-0.75 (the Chappuis band)	4.7	9.1, **9.6**	14.3
HDO	-	2.7,3.67	7.13	-
*CO	-	1.57, 2.35, **4.7**	-	-
O_2	0.58, 0.69, 0.76, 1.27	-	-	-
NH_3	0.55, 0.65, 0.93	1.5, 2, 2.25, 2.9, **3.0**	6.1, **10.5**	-
PH_3	-	4.3	8.9, 10.1	-
*CH_4	0.48, 0.57. 0.6, 0.7, 0.79, 0.86,	1.65, 2.2, 2.31, 2.37, **3.3**	6.5, **7.7**	-
CH_3D	?	3.34, **4.5**	6.8, 7.7, **8.6**	-
C_2H_4	-	**3.22**, 3.34	6.9, **10.5**	-
H_2S	-	2.5, 3.8 ...	7	-
SO_2	-	4	**7.3**, 8.8	-
N_2O	-	2.8, 3.9, **4.5**	7.7, 8.5	-
NO_2	-	3.4	**6.2**, 7.7	13.5
H_2	-	2.12	-	-
H_3^+	-	2.0, 3-4.5	-	-
He	-	1.083	-	-
*Na	0.589	1.2	-	-
*K	0.76	-	-	-
TiO	0.4-1	1-3.5	-	-
VO	0.4-1	1-2.5	-	-
FeH	0.6-1	1-2	-	-
TiH	0.4-1	1-1.6	-	-
Rayleigh	0.4-1	-	-	-
Cloud/haze	yes	possible	silicates, etc.	-
H α	**0.66**			
H β	0.486			
Ca	0.8498, 0.8542, 0.8662		-	-

Table 2: Main spectral features between 0.4 and 16 μm. The asterisk indicates the molecular/atomic species already detected in the atmospheres of exoplanets. At wavelengths shorter than 2 μm spectroscopic data are often not complete, so that the use of this region is much more difficult for band identification and analysis.

interpretation of exoplanet atmospheres. The ability to reach 0.4 μm is very important for observing the contribution of Rayleigh scattering. For a cloud/haze free atmosphere this additional information is key to removing the degeneracy embedded in the measurements of the planetary radius at wavelengths where molecules absorb.

The resolving power given for the EChO base line will be sufficient not only to separate the bands but go to the next step, i.e. detect the molecular features, retrieve abundances, disentangle the contribution of different molecules if they overlap etc. In table 2 we give the most important molecular, atomic and ionic species which are present in planetary atmospheres and have a spectral signature in the wavelength region covered by EChO. We also indicate the spectral resolving power obtainable by EChO, in its baseline configuration, and the goal.

The 11-16 μm band is crucial, particularly for the CO_2 band at 15 μm: this is a key band for retrieving the thermal profile in terrestrial atmospheres and in many cases (especially exoplanets in the habitable zone), see Fig. 4.3. For giant planets/Neptunes, increasing the resolution to R =300 in that channel instead of the cur-

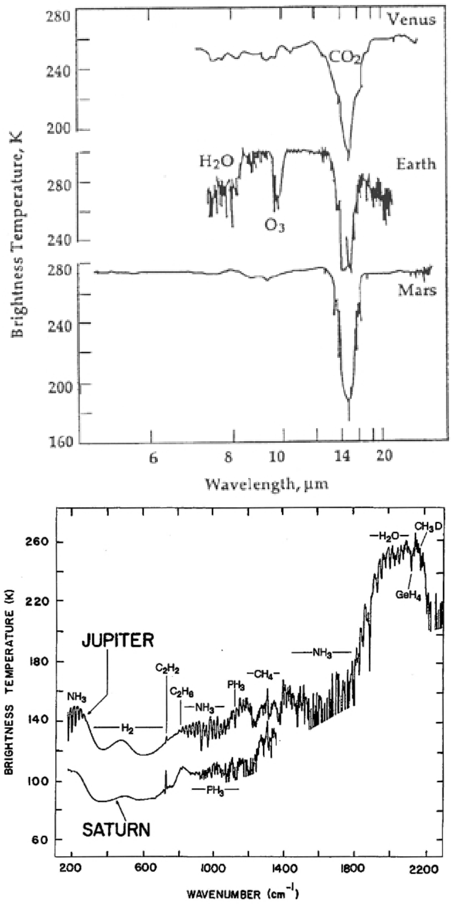


Figure 9: The 11-16 μm band is a key band for retrieving the thermal profile in planetary atmospheres (especially exoplanets in the habitable zone). From a chemical point of view, the main loss would be the CO_2 band at 15 μm for terrestrial planets and the Q-branches of hydrocarbon species for hydrogen-rich atmospheres.

rently proposed 20, would make it possibility to separate C_2H_2 from HCN and greatly improve the temperature structure retrieval.

4.4 Justification S/N, timing, calibration, observational strategy

The integration time needed to observe specific targets is based on the time length required to obtain spectra of transiting exoplanet atmospheres, given a defined spectral resolution and signal-to-noise ratio. The estimated time is based on the contrast ratio of the flux from the planet over the flux from the star in a selected wavelength region and on the instrument parameters. EChO's characteristics were planned to guarantee the required performances. The fluxes were obtained from synthetic spectra and blackbody curves. We show here a few key examples (Tables 4, 5, Fig. 10, 11).

According to our simulations, for spectroscopic observations (i.e. R$\geq$ 10) we need stellar targets brighter than V=12 for F, G and K stars, and brighter than K=9 for M dwarfs (see Tables 3 4 and 5). For giants orbiting fainter stellar companions (mag. $\leq$ V=15, e.g. typical CoRoT and Kepler targets), EChO will be able to observe them in 2 or 3 large photometric bands (VIS, NIR and MIR). There are currently 48 known transiting sources which are within the sensitivity range of EChO's spectroscopic capabilities (Fig. 12).

We will perform high-precision in-flight calibration and monitoring of the responsivity of the observatory, in short the "transfer function (TF)", by observing cali-

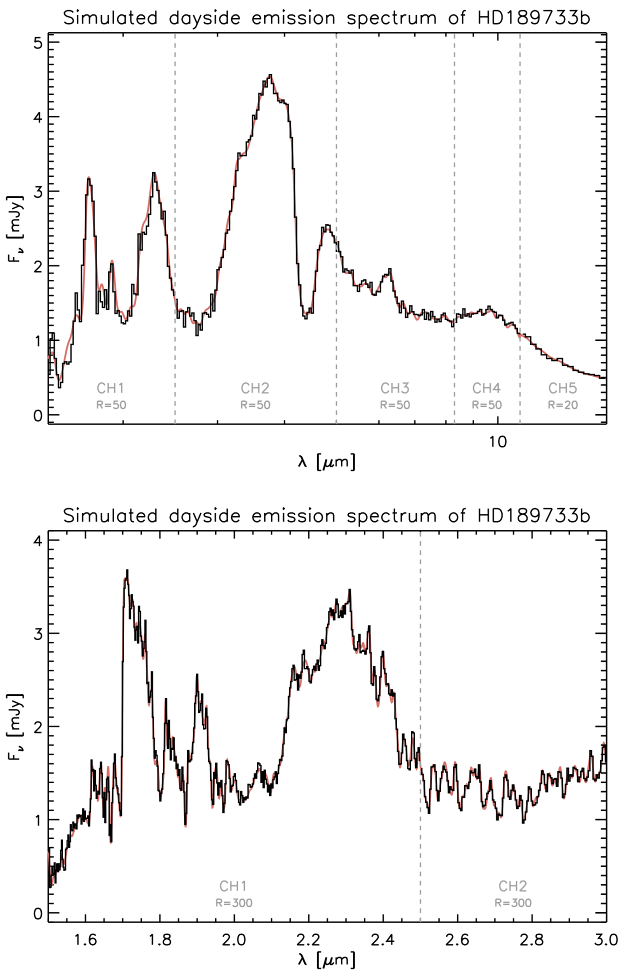


Figure 10: Simulations of EChO observations of the hot-Jupiter HD189733b. Top: dayside emission spectrum at resolution R=50, single eclipse. Bottom: NIR zoom of dayside emission spectrum at resolution R=300, averaged over 50 eclipses. Total observing time 8 days, can be done over 3.5 months.

Star-type	T (K)	R ($R_\odot$)	contrast ($*10^{-3}$)	Magnitudes in V band 5	6	7	8	9
Secondary eclipse, Resolution 300, SNR 50, averaged over 5-16 μm								
F3	6908	1.56	2	1.5	4	11	34	-
G2	5800	1	3	0.5	1.3	3.3	10	33
K1	4746	0.8	5	0.2	0.6	1.1	3.3	9
Primary eclipse, Resolution 100, SNR 50, averaged over 5-16 μm								
F3	6908	1.56	0.35	15	38	99	270	
G0	6030	1.15	0.65	3.7	9	24	63	
K1	4746	0.8	1.32	0.8	2.2	5	14	

Table 3: Integration times (**in number of transits**) for a hot-Jupiter in primary transit (top) and in secondary eclipse (bottom)

With Resolution 40, SNR 10, 5-16 μm

M-type	T (K)	R ($R_\odot$)	contrast (10^{-4})	Magnitudes in K band 5	6	7	8	9
M1.5V	3582	0.42	1.4	14	36	95	258	-
M3V	3436	0.30	2.8	6	13	34	93	277
M4V	3230	0.19	7.7	1	2	6	18	52
M5V	3055	0.15	13.2	0.5	1	3	8	23

Table 4: Integration times (in number of transits) for a hot (850 K) Super-Earth (1.6 R_{earth}) in secondary transit

bration stars. Our goal is to monitor the spectral shape of the TF as well as its absolute level to a precision better than a few times 10^{-5}, such that uncertainties in the TF do not significantly affect the final quality of the obtained science spectra. Detailed modeling of optical light curves measured by the Kepler satellite using stellar model atmospheres shows that the vast majority of G-dwarfs and selected A-dwarfs have an intrinsic stability of their infrared spectra of better than

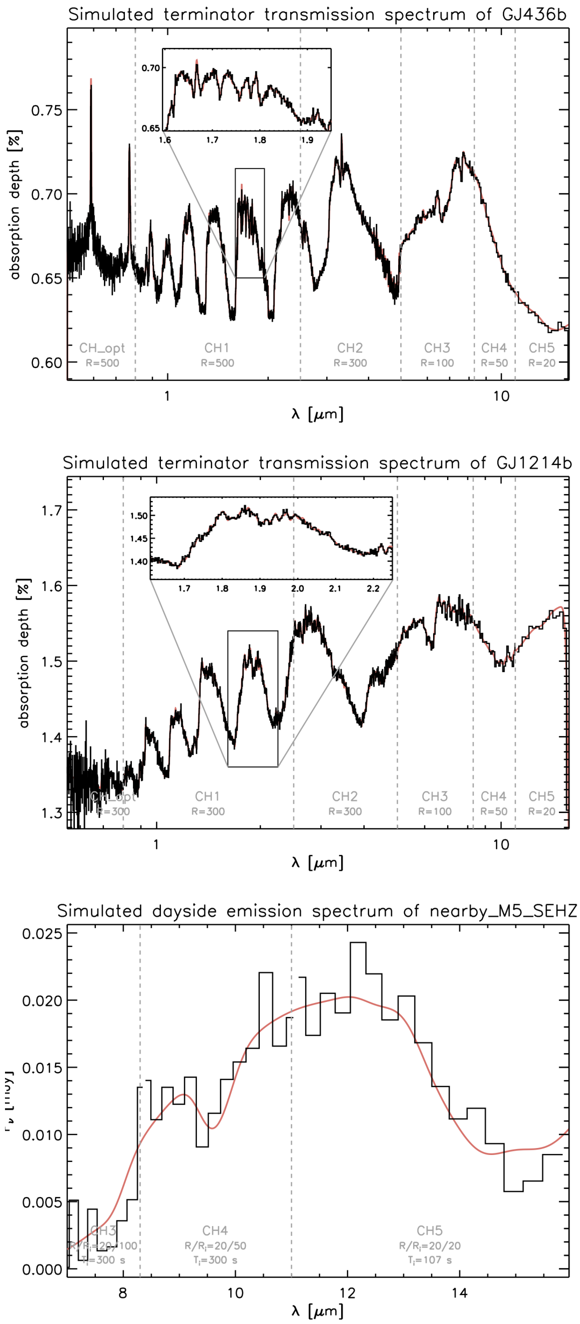


Figure 11: Simulations of EChO's performances. 1) Transmission spectrum of warm-Neptune GJ 436b (top) at intrinsic instrumental resolution, averaged over 50 eclipses. Total observing time 6 days, can be done over 4 months. 2) High resolution (R=300) transmission spectrum of warm Super-Earth GJ1214b, averaged over 300 transits. Total observing time 3 weeks, can be done over 1.3 years. 3) Emission spectrum of a favourable case of a temperate Super-Earth with an Earth-like atmosphere orbiting a bright late M. (bottom).

$3{\cdot}10^{-5}$ in level and better than 10^{-5} in shape, where the former offer the highest precision in absolute level and the latter in shape. While the actual stars used to calibrate EChO will not be those observed by Kepler –rather a sample of nearby main sequence stars distributed over the sky– we have demonstrated the feasibility of reaching a calibration precision of order 10^{-5} using stars. We will build up a calibration network and perform pre-flight characterisation of the potential calibrators using ground-based high-accuracy (relative) photometry in order to ensure sufficient stability of the stars in the network. This is possible because the Kepler data show that the photometric variability of stars shows a bi-modal distribution: they are either variable on the level of 1 mmag or more which is well measurable from the ground, or they are stable to better than $5{\cdot}10^{-5}$ in the optical which makes stable to the levels quoted above in the infrared.

With Resolution 10, SNR 5, 5-16 μm

Star type	T (K)	R ($R_\odot$)	Period (days)	contrast (10^{-5})	Magnitudes in K 5	6	7	8	9
M2V	3522	0.38	30.6	0.9	72				
	3475	0.34	26.6	1.2	45	113			
M3V	3436	0.30	23	1.5	32	81			
	3380	0.25	19.3	2	20	52	132		
M4V	3230	0.19	12.7	4		18	46	117	
	3150	0.17	10.7	5.2		12	32	80	208
M5V	3055	0.15	8.7	6.9			19	49	128
	2920	0.13	6.7	9.8			12	29	76

Table 5: Integration times (number of transits) for a habitable-zone (320 K) Super-Earth (1.6 $R_\odot$) in secondary transit

HD 189733		GJ 1214	
albedo=0.05	$\sim 4\sigma$	albedo=0.3	$\sim$0.3 σ
albedo=0.1	$\sim 8\sigma$	albedo=0.3, hot	$\sim$26 σ
albedo=0.2	$\sim 15\sigma$		

Table 6: Measurement of planetary albedo with one eclipse in the optical for key examples of hot-Jupiters and Super-earths. The results strongly depend on the type of planet/star, distance to the star and albedo value.

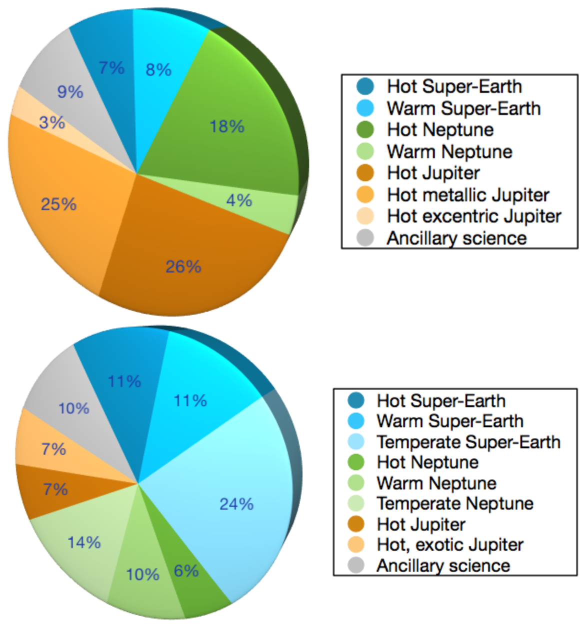


Figure 12: Top: partition of observing time on available sources for EChO today. Bottom: partition of observing time for EChO in 2020.

5 Science return

5.1 The chemistry of Jupiters and Neptunes

Although it is likely that thermochemical equilibrium prevails in the deeper, hotter regions of the atmospheres of extrasolar giant planets, two main processes can drive the atmosphere out of equilibrium: 1) *transport-induced quenching* and 2) *photochemistry*.

1. In the first process, temperatures in the radiative portion of the exoplanet atmosphere may be cool

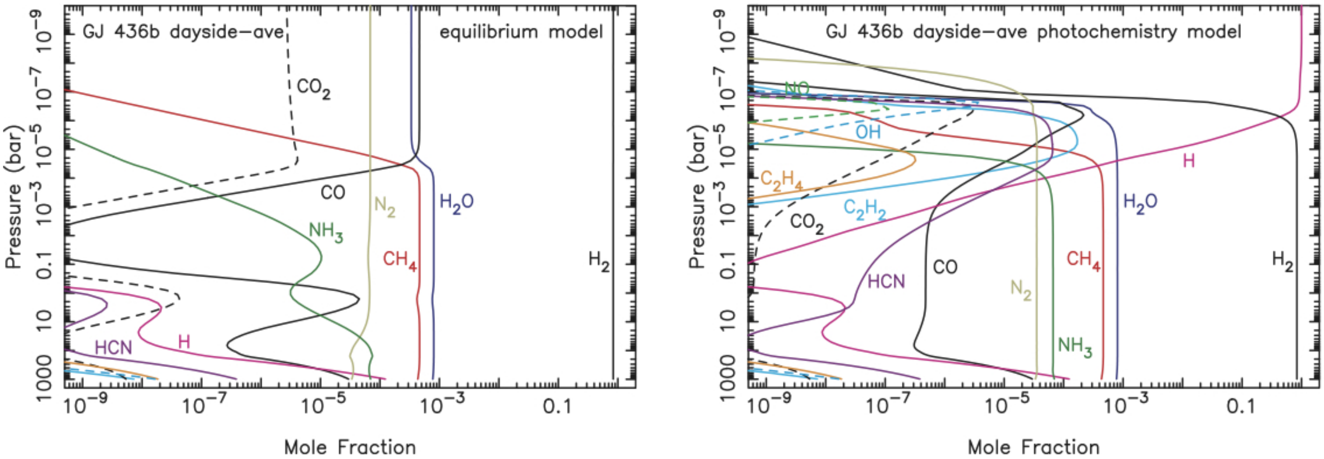


Figure 13: Predicted mole fractions for major H, C, O, N species on GJ 436b, assuming thermochemical equilibrium (left) or considering thermochemical and photochemical kinetics and transport (right) from 1-D models[59]. The models assume a solar composition, a dayside-average thermal structure and an eddy diffusion coefficient of 10^9 cm^2 s^{-1}. Differences in the results for the kinetics/transport models are then due largely to the thermal structures of the planets, with secondary effects resulting from different ultraviolet fluxes from the parent stars. Results will also be sensitive to the assumed metallicity of the planet and to the eddy diffusion coefficient profiles. In general, the cooler the exoplanet, the more important disequilibrium processes are likely to be. This trend is especially true for planets like GJ 436b that orbit close to weaker M stars such that the temperature structure lies within the CH_4 stability field rather than the CO stability field. The carbon-hydrogen bond in CH_4 is much weaker than the carbon-oxygen bond in CO, helping to free up carbon for disequilibrium processes. Complex hydrocarbons and nitriles may be produced on such planets (see Moses *et al.*[59], Zahnle *et al.*[98])

enough that energy barriers to kinetic reactions are difficult to overcome, so that chemical kinetic time scales can become large. If the vertical transport time scales drop below the chemical kinetic time scales, the mole fractions of some spectroscopically important species may be "quenched" or frozen in at abundances representative of deeper pressure levels[62], leading to disequilibrium compositions in the observable regions of the exoplanet atmosphere.

2. In the second process, the energy delivered from the absorption of stellar ultraviolet radiation can excite atmospheric molecules or break chemical bonds, setting off a series of chemical reactions that lead to the production of disequilibrium constituents[96]. For giant planets close to their host stars, this disequilibrium photochemical mechanism is a particularly effective process[46–48,97,98], as long as atmospheric temperatures are not so high as to drive the composition back to equilibrium.

The relative importance of thermochemical equilibrium, photochemistry, and transport-induced quenching in controlling the observed composition largely depends on the planet's thermal structure, which in turn depends on the planet's orbital distance and metallicity and the host star's luminosity and stellar type. The host star's chromospheric activity level and the overall UV flux incident on the planet can also affect the photochemistry, but properties like planetary mass or radius play less of a role. The importance of the thermal structure in controlling chemistry is illustrated in Figs. 14, 13, which show that the thermal structures of different Jupiter- or Neptune-mass planets can lie within very different thermochemical equilibrium regimes, effecting not only the equilibrium composition but the effectiveness of disequilibrium processes like photochemistry.

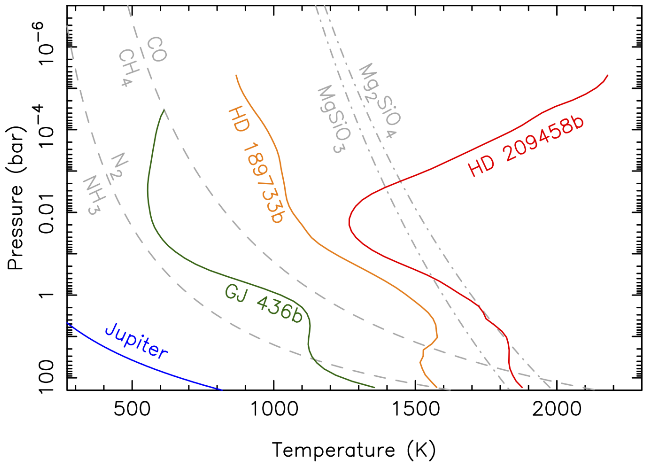


Figure 14: The possible presence of a strong thermal inversion on the dayside[13] may drive the chemistry back to equilibrium despite the strong UV flux incident on the planet. Disequilibrium processes on cooler planets like HD 189733b that orbit a fainter K2V star are expected to be more important[48,59], due to the more sluggish rates of the chemical processes driving the composition back toward equilibrium. Some key molecules like CO, H_2O, and CO_2 may have vertical profiles that remain close to equilibrium predictions on on these cooler "hot Jupiters" like HD 189733b, but transport-induced quenching may allow CH_4 and NH_3 to be much more abundant in the few bar to few mbar region than is expected based on equilibrium, and photochemistry might lead to the production of nitriles like HCN and unsaturated hydrocarbons like C_2H_2 that can affect spectral behaviour at visible and infrared wavelengths[59]..

5.2 Upper Atmosphere

Within our own solar system, the upper atmospheres of Gas Giants Jupiter and Saturn, both of which have been explored over recent decades both from Earth and from in-situ orbiting satellites, have been found to form regimes of complex interaction between the atmospheric gases, solar radiation, magnetospheres and their plasma population as well as the solar wind. These are regions of particular importance to investigate as they constrain the relative roles of external energy sources, including the magnetosphere/plasma environment, as well as constraining rates of atmospheric gas escape as well as other dynamical processes driven from the deeper atmosphere. In many cases upper atmospheres also feature auroral regions, where energetic particle precipitation deposit energy locally and generate optical emissions which can be observed from Earth, constraining atmospheric gases as well as the magnetic and plasma environments.

EChO offers an unprecedented opportunity of expanding this exploration to solar systems outside of our own. We intend with EChO to explore the upper atmospheres of exoplanets, with the aim of addressing the following key science questions:

- What is the thermal structure and energy balance of exoplanet atmospheres? What are the characteristics of stellar forcing? What are the radiative time scales of atmosphere and how important are processes in Local Thermodynamic Equilibrium (LTE) versus those who are in non-LTE.
- What is the composition and vertical distribution of constituents, what chemical processes are active?
- What are the characteristics of the magnetic and plasma environments of exoplanets and how do these interact with the atmospheres?
- What are the rotation rates of exoplanet upper atmospheres?

Over recent years first direct spectroscopic observations have been made of atmospheres of extrasolar planets. Spectra observed during the transit have identified the NaI D lines, the H Ly line and ionised species (CII, SiI) in absorption[15,49,92]. These observations placed first constraints on the structure of extrasolar planet upper-atmosphere. Simulations by Yelle[95] have shown these observations to be consistent with thermospheric temperatures near 10,000 K, which in turn drive hydrodynamic escape and cooling of the thermosphere by adiabatic expansion. While allowing for detection of unexpected spectral signatures, we intend to specifically investigate amongst other the following lines:

- 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 Gas Giant emissions between 3 and 4 µm. As shown by Miller et al. (2006), H_3^+ is a powerful indicator of energy inputs into the upper atmosphere of Jupiter, suggesting a possible significance in exoplanet atmospheres as well. Simulations by Yelle[95] and Koskinen *et al.*[40] have among other investigated the possible importance of H_3^+ as a constituent and infrared emitter in exoplanet atmospheres. One particular finding of these calculations and those of[95] is the fact that close-orbiting extrasolar planets (R≤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. Fig. 15 shows an example of a simulated emission spectrum of H_3^+ for HD209458b at resolution of R=300, which matches the anticipated EChO resolution in this spectral range.

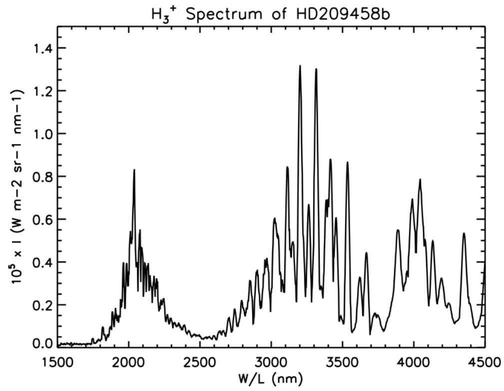


Figure 15: H_3^+ simulated spectrum for hot-Jupiter HD209458b[41]. A model of the planet's upper atmosphere[39] was used to calculate the substellar column density of H_3^+ . This model is based on solving the one-dimensional equations of motion for dynamic expansion together with realistic heating rates and photochemistry for an atmosphere composed of hydrogen and helium. The results agree roughly with those of[24,95] for the same planet.

- CH_4 emission Observations of the auroral regions of Jupiter have given positive detections of CH_4 in emission, which are thought to be generated by energetic particle precipitation which penetrates below the homopause level, reaching stratospheric methane. Therefore, CH_4 can be regarded as a powerful constraint for processes of magnetosphere-atmosphere coupling. Swain et al. (2009a) identified an unexpected spectral feature near 3.25 µm in the atmosphere of the hot-Jupiter HD 189733 b which was found to be inconsistent with LTE conditions holding at pressures typically sampled by infrared measurements. They proposed this feature to result from non-LTE emissions by CH_4, indicating that non-LTE effects may need to be considered, as is also the case in our solar system for planets Jupiter and Saturn as well as Titan. We intend to specifically address this question with EChO, making use of the improved observing conditions from orbit.

5.3 Atmospheric Dynamics of Hot-Jupiters and Hot-Neptunes

EChO will provide much needed constraints on atmospheric dynamics and circulation models. This is done via careful, repeated observations. The following are the various types of observations that EChO can provide:

- Primary and secondary transits, leading to day and night side information
- Ingress and egress measurements, leading to hori-

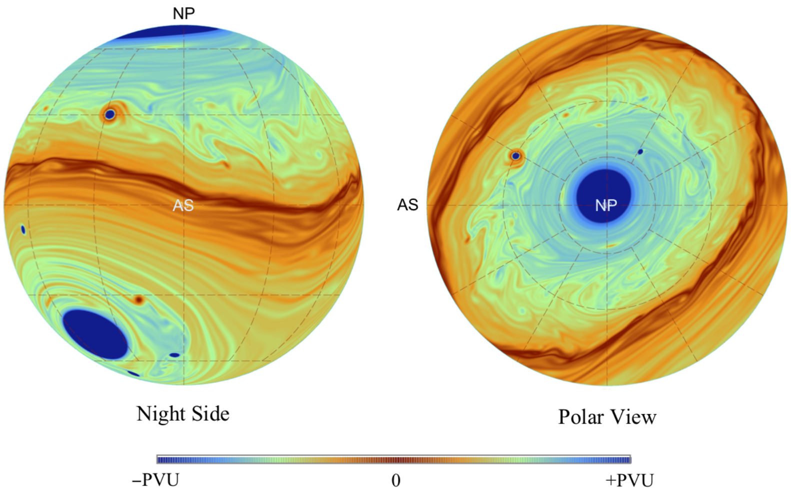


Figure 16: Maps of vorticity in the inertial reference frame and the rotating reference frame from 2-D and 3-D high-resolutions simulations of tidally locked hot Jupiters [19]. We can appreciate the complexity of the flow with structures on an large range of scales.

zontal/vertical structure information

- Non-transiting planet observations, providing information about the extra-tropics on the planet
- Host stars, providing information about the background and ionisation

Currently, what is lacking is good statistics and times series of observations to assess variability, which is expected to occur on a wide range of scales [85]

An iterative approach will be used. First, using plausible vertical temperature profiles from full three-dimensional (3-D) general circulation models, spectra models can give information about the composition and its vertical distribution. The latter will then be inserted as input back into the 3-D models as either initial condition or self-consistently evolved distribution to obtain global temperature and flow distributions. When very high resolution calculations are needed to capture detailed physical or chemical effects, they can be carried out using vertically- or zonally-averaged two-dimensional (2-D) models, as appropriate.

At the cutting edge of the field is whether transient phenomena exist in the light curves and spectra obtained from hot Jupiters, as well as the implications of variability if it exists. Vortices and waves are long-lived, coherent features which should contribute heavily to variability on hot gaseous planets. The variability is expected to be slow and occurs on a large scale, as indicated by three-dimensional simulations. The resulting, computed power spectrum of the temperature field shows that the bulk of the energy is contained in the channel corresponding to a period of about 15 planetary days. The baroclinic instability may also contribute to variability; its basic mechanism is well understood, at least from a terrestrial standpoint. In the case of the hot Jupiter HD 209458b, the gravest (most unstable) mode has a wavenumber of between 2 and 3, while its growth period is about 10 planetary days. By comparison, the gravest mode in the terrestrial atmosphere has a wavenumber of 6 and a growth period of about 2 Earth days. The detection of variability in the atmospheres of hot Jupiters allows us to judge which are the dominant fluid instabilities at work and consequently determine their influence on the observed spectra.

In general, general circulation simulations are dealing with a three-dimensional, non-linear problem involving multiple parameters. For example, the outcome of these simulations depend significantly on the initial conditions of the surface flow [85], which are presently unknown in the case of hot Jupiters. Furthermore, the predictions for the surface wind speeds carry an intrinsic range of uncertainty (Heng, et al., 2010) which can only be calibrated out via direct measurements. The key point is that a pragmatic approach which couples transit observations with a hierarchy of theoretical models and simulations is the way forward towards increasing the predictive power of the general circulation simulations of hot Jupiter atmospheres.

5.4 Super-Earths around M-dwarfs: what should we expect?

As previously discussed in §4, EChO will have the capability to perform transit spectroscopy of Super-Earths near or in the habitable zones of M-dwarf stars. These planets will be of immense scientific interest, as their climates may be comparable to those of the terrestrial planets in our own system. In particular, if they are rich in H_2O and have surface temperatures and pressures compatible with liquid water, they may potentially support Earth-like life. In general, the atmospheres of terrestrial exoplanets are expected to depend strongly on details of their formation and subsequent evolution, which means they are more difficult to predict theoretically than gas giants. However, M- dwarfs have some unique features that have already been predicted to make the climates of planets in their habitable zones very different from those in our own Solar System. First, they are relatively faint, so planets must be close in to receive Earth-like amounts of insolation

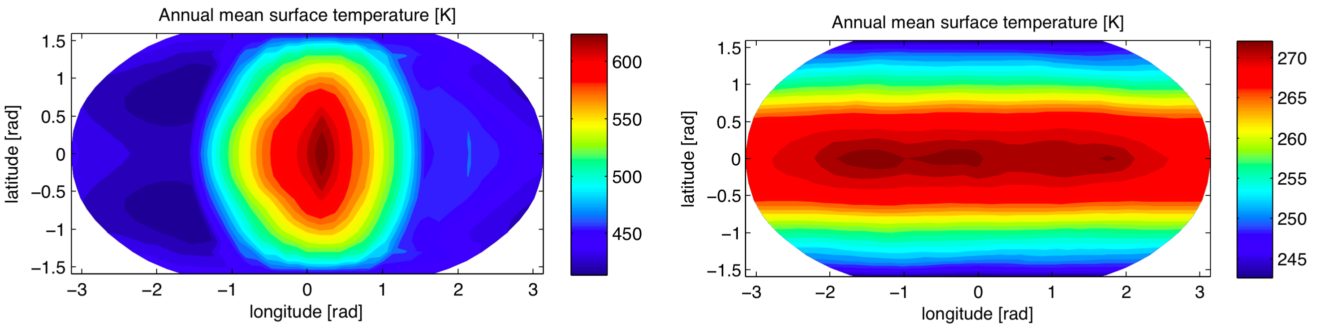


Figure 17: Simulations of the climate of a $R = 1.8R_E$ rocky planet with CO_2-dominated atmosphere around an M-class star of luminosity 0.013 L_s (Wordsworth et al.,). Two cases: hot (orbit 0.05 AU, $T_p \sim 400$ to 650 K) resonance 1:1, cold (orbit 0.22 AU, $T_p \sim 230$ to 280 K) resonance 1:10.

from them. This means that terrestrial exoplanets in M-dwarf habitable zones might be in tidally resonant or locked orbits (see Fig. 17). As in the hot Jupiter case (§6.2), tidal locking can cause super-rotation in the planet's upper atmosphere, with potentially observable consequences. Tidal locking may also have serious consequences for habitability, as volatiles such as H_2O will tend to evaporate on the light side and freeze on the dark side of the planet. In the most extreme cases, the entire atmosphere can even condense out on the dark side. However, modelling has indicated that there are also many scenarios in which locked planets can sustain atmospheres and water cycles. For example, a Super-Earth with a dense atmosphere and a global ocean could efficiently transport heat across its surface and hence maintain a stable climate. One alternative to the scenario of tidal locking is spin-orbit alignment. A planet in a relatively eccentric orbit may escape synchronisation and establish a rotational spin that is some multiple of its orbital period, as happened to the planet Mercury[20]. The climates of terrestrial planets around M-stars will also be altered due to the red-shifted stellar spectra. Red-shifting of the spectrum decreases Rayleigh scattering, so the bond albedos of M-class terrestrial exoplanets should generically be lower than those of planets in the Solar System. This theoretical prediction will be directly testable by EChO through secondary transit measurements in the optical. One side effect of this difference is that greenhouse warming by dense atmospheres becomes more effective than on Earth[94], which alters the range of orbits for which habitable conditions are possible. Another unusual feature of M-class stars is their increased magnetic activity, which leads to a stronger stellar wind and more stellar flares[74]. Increased stellar wind means increased atmospheric erosion, the consequences of which are still poorly understood for terrestrial exoplanets. The problem of H_2/He escape is a particularly critical one for planets intermediate in mass between the Earth and Neptune, as it ultimately determines the boundary between rocky and ice/gas giants. By studying the atmospheric composition (secondary transit) and probing the scale height through primary transit measurements (the scale height would be noticeably larger for a hydrogen-rich type of atmosphere), EChO will be able to investigate this vital scientific question directly.

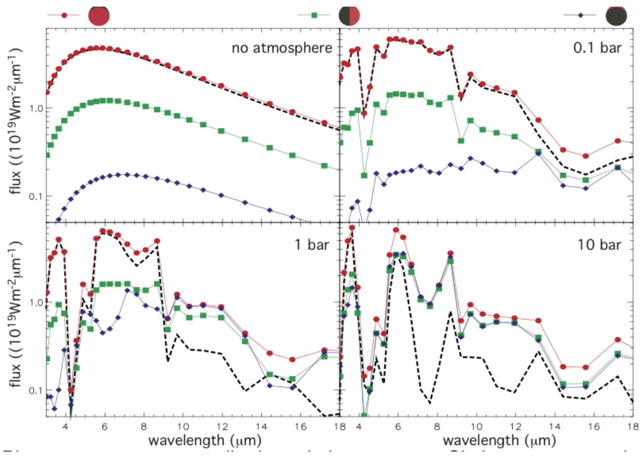


Figure 18: Planetary spectra vs amplitude-variations spectra (Selsis, Wordsworth, Forget, in prep.). Circles, squares and diamonds correspond the planetary spectrum at 3 different phases indicated at the top of the graph. The dashed line shows the amplitude of the phase-curve that can measured with a 7 points orbit. In the case with no atmosphere, the surface temperature is simply in equilibrium with the stellar irradiation (the surface thermal inertia has no effect on a synchronised planet). For the 3 cases with an atmosphere, a GCM (Global Climate Model) to model the 3D structure of the atmosphere. For simplicity, modelled atmospheres are made of a single atmospheric constituent (CO_2).

In addition to the basic parameters described above, a planet which harbours life may also exhibit astronomical biosignatures The Earth's atmosphere contains an imprint of life from so-called biomarker molecules such as molecular oxygen (O_2), ozone (O_3) and nitrous oxide (N_2O). Theoretical studies[27,73] have begun to explore the extensive parameter range of potential biomarker spectral signals, assuming a similar development as the Earth and varying e.g. planetary and atmospheric mass, star class, position in the HZ, biosphere etc. Results suggest a strong dependency of the biomarker responses depending upon the class of the central M-star. Care is needed to distinguish true biomarker signals from so-called “false- positives” i.e. cases where planetary atmospheres “mimic” life[75] due to inorganic chemical processes producing biomarkers – for example, strong CO_2 photolysis eventually leading to molecular oxygen production. Ozone features

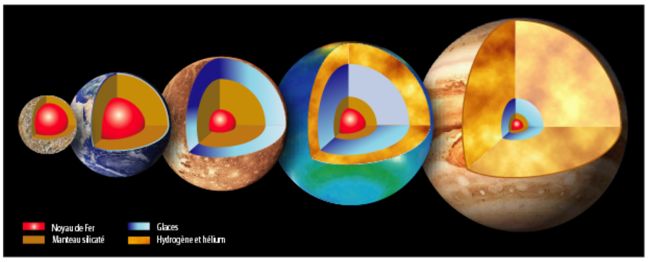


Figure 19: Internal structures of planets (not at scale). The three sub-families on the left are part of the terrestrial family (see text for detail). Giant planets (Jupiter-like) are on the right. Neptune – like planets, are on the fourth position from the left.

a strong infra-red absorption band at 9.6 µm, easily measurable by EChO, and it may be present in large amounts over a wide range of oxygen concentrations [72]. In this sense, ozone is a good biomarker. However, its photochemistry is complex (WMO, 1998) and is influenced by trace amounts of nitrogen-, chlorine-, and hydrogen-oxides whose abundances are difficult to constrain. Sources of nitrous oxide (N_2O) into Earth's atmosphere (IPCC TAR) are almost exclusively associated with microbial activity. It absorbs mostly in the troposphere with bands at e.g. at 7.8 and 3.9 µm. It is an excellent biomarker from the point of view that inorganic (non-life) production identified so far on the Earth is negligible, implying that false-positives are unlikely. However, its absorption features are weak for typical modern Earth abundances and measurements are extremely challenging. Atmospheres with weak UV-B could favour the build-up of large atmospheric N_2O abundances because its photolytic sink is weak in such cases.

Planets with no atmosphere We expect that Super-Earths with no or negligible atmosphere would show large variations in intensity as a function of planetary phase. The MIR variability is driven by the difference in day-night surface temperatures. This variability in surface temperature should be relatively high, as a thin atmosphere has a very limited heat capacity to buffer its climate and even out day/night variations (Fig. 18).

5.5 Linking atmospheres and interiors

The ability of EChO to fully characterise an exoplanetary atmosphere in its composition and thermal structure will provide major improvements for interior models as well. Except for the Earth and the Moon, there is no direct measurements of the deep structure of the planets, as this investigation requires a network of seismometers for terrestrial planets, or techniques similar to the asterosismology for gaseous giants. Nonetheless, the internal structure of planetary bodies in the solar system is, even if not precisely, relatively well understood. Planetary bodies can be split into three main families (Fig. 19) which are: i) the terrestrial planets (or solid planets), ii) the giant planets (or gaseous), and iii) the intermediate planets which are in between the two extreme cases.

The giant planet family Giant planets are mostly made of hydrogen and helium and are expected to always be in gaseous form [28]. Because they play a tremendous role in shaping planetary systems [89] determining precisely their internal structure and composition is essential to understand how planets form. Contrary to solid planets, they are relatively compressible and the progressive loss of heat acquired during their formation is accompanied with a global contraction. Inferring their internal composition thus amounts to understanding how they cool. Fortunately, 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 and all elements other than hydrogen and helium, i.e. heavy elements, that are present.

The determination of sizes from primary transit measurements and masses from radial measurements have yielded in some cases a constraint on the mass of heavy elements present in the interior that is relatively independent of model hypotheses [34,68] and otherwise global tendencies showing that this mass is correlated with the metallicity of the parent star [13,29,32]. However, several problems arise. First a large fraction of the known transiting planets are larger than expected, even when considering that they could be coreless hydrogen-helium planets [5,10,13,29,31,32]. There is thus missing physics that is to be identified. Second, we do not know whether these heavy elements are kept inside a central core or distributed inside the planet. This influences how they cool [6,28] and is crucial in the context of formation scenarios [50]. Third, the complex dynamics of the atmosphere of heavily irradiated planets that constitutes the outer boundary condition of evolution models is poorly understood. This has direct consequences for our ability to accurately predict the evolution of these planets [30,31].

The terrestrial family Three different sub-families of planets can be considered from left to right in Fig. 19: Mercury-like planets mostly composed of an iron core and a thin layer of silicates, Super-Earth made of an iron core and a thick silicate mantle (such as Venus, Mars and the Earth) and Ocean-planets made of iron, silicates, and water (similar to icy moons of Jupiter and Saturn). Super-Earths are composed of an internal iron-rich core and a thick silicate mantle (lower mantle) covered by a thin layer of low-pressure silicates similar to the upper mantle on Earth, and a very thin liquid layer (like Earth-oceans). Ocean-planets are composed of an iron core, a silicate mantle, and a thick icy layer surrounded by a thin ocean or icy crust at the surface.

For a given mass, one would expect Ocean-like planets have a smaller metallic core and silicate mantles, but also a larger radius than for Earth-like planets because icy materials are lighter than silicates. On the contrary, the radius of a much denser Mercury-like planets is about 80% that of an Earth-like planets[26,91]. Mass - Radius measurements, though, do not give unique solutions. For example, a silicate-rich planet surrounded by a very thick atmosphere could provide the same mass and radius of an ice-rich planet with no atmosphere![2]. EChO will unravel the ambiguity through primary transit spectroscopic observations in the optical and IR, providing the bulk composition of the atmospheres when they are present. If EChO detects an atmosphere which is not primarily made of helium and hydrogen, thus the planet is most certainly from the terrestrial family, which means that the thickness of the atmosphere is expected to be negligible with respect to the planetary radius. If this is the case, an extensive literature[2,26,43,71,78,90,91] can be fully exploited to characterise the inner structure of the new planet.

The intermediate family Planets in between the gas giants and the small solid terrestrial planets are key to understand the formation of planetary systems. The existence of these intermediate planets close to their star, as found by radial velocity surveys, is already crucial to highlight the shortcomings of theoretical models[58]. (i) Standard planet formation scenarios predict that embryos of sufficient mass (typically above 5 Earth masses) should retain some of the primordial hydrogen and helium from the protoplanetary disc. With EChO measurements, we will probe which planets indeed possess a hydrogen helium atmosphere and directly test the conditions of planet formation. (ii) The two only intermediate planets that we can characterise, Uranus and Neptune, are significantly enriched in heavy elements, in the form of methane[28]. 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 these models. (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 determine whether its interior is solid, partially liquid or gaseous.

6 Ancillary science

While the vast majority of the EChO mission will be dedicated to exoplanet spectroscopy and its design will be fine-tuned for that cause, the ability to do spectroscopy with broad simultaneous wavelength coverage and high sensitivity makes EChO a superb tool to address a host of science cases. Particular foci of the EChO ancillary science programme should be observations: a) of targets not accessible with other facilities (e.g. too bright for JWST, wavelength range not accessible from the ground); b) where superb precision and long-term stability are required (e.g. asteroseismology); c) where synoptic monitoring over a broad wavelength range is critical for the science (variable young stellar objects; evolved stars; novae); and d) "filler" survey programmes providing legacy atlases for future ground- and space-based programmes. For reasons of brevity we here highlight science cases that are highly synergistic to the exoplanet case but EChO would find excellent use in many other areas of observational astrophysics. Ancillary observing programmes that EChO could enable include:

- Direct spectroscopic characterisation of free-floating (and perhaps in rare cases resolved companion) brown dwarfs and planetary mass objects, with particular focus on constraining surface gravity and composition to compare free-floating planets to models of planets formed through core accretion. In particular, spectroscopic follow-up of L, T, and particularly Y dwarfs from the WISE mission allows confronting models of these very cool objects with observations. The superb stability of EChO allows monitoring of atmospheric variability and dust condensation.
- We are already in the era of population synthesis where sophisticated models of planet formation can be compared to the ensemble of data accumulated from radial velocity, transit, microlensing, and soon direct imaging surveys[58]. The next frontier will be to understand how the elemental abundances of planets follow from the composition and chemistry of the disks in which they formed. Spectroscopy of circumstellar disks from the optical to $\sim$16 micron allows measuring many emission and absorption features of solid state and gaseous species, revealing the composition and evolution of the disk material. In particular, the ability to obtain simultaneous visible to mid-IR spectra for variable young stellar objects could make profound contributions to our understanding of how changes in disk accretion and dust attenuation affect disk structure and the evolution of gas and dust composition in planet-forming disks[1,4].
- Search for extrasolar moons. Exomoons are likely to be rocky bodies and thus offer the same potential of Earths/Super-Earths as possible havens for life. Their discovery would also reap immense new understanding of planet/moon formation. For transiting planet systems, exomoons can be detected through two principal methods i) transit timing effects ii) exomoon transits[35,36].
- Rocky transiting planets found with Kepler are unlikely to induce detectable radial velocity signals and thus the only way to confirm their planetary nature is to rule out the probable sources of astrophysical false positives, most pertinently blends (e.g. background eclipsing binaries) that mimic an exoplanet signature in the Kepler bandpass. By measuring the transit depth at multiple wavelengths, such scenarios

can be easily excluded.

7 Differences and Synergies between EChO and future missions and facilities

In the upcoming decade, two important new facilities are planned to come on line 1) the space-borne James Webb Space Telescope (JWST) due to be launched in 2015, and 2) the next generation of extremely large telescopes, such as the European Extremely Large Telescope (E-ELT) with first light foreseen in 2018. A significant advantage of EChO as a dedicated instrument is its ability to provide the observations to fully test models: this requires observations of a large sample of objects, generally on long timescales, and cannot be efficiently pursued with a multi-purpose facility such as JWST or the ELT. Such a comprehensive approach holds out the possibility of discovering unexpected, "Rosetta Stone" objects, i.e. objects that definitively confirm or disprove theories.

Compared to EChO, a 42 m telescope such as the **E-ELT** could be perceived with two major advantages: a much larger collecting area and a superior spatial resolution. Yet the E-ELT will have the obvious limits of every ground-based facility: namely much lower observing efficiency (e.g weather conditions, day/night cycles, observability of the target) and, more critically, more limited spectral coverage. A large fraction of the spectral range observed with EChO, in fact, is inaccessible from the ground (e.g. H_2O bands between 1-5 μm, and the region between 5-8 μm where there are key molecular lines). Finally, the long term photometric stability –a key requirement to achieve the science goals of EChO– will never be reached from the ground.

EChO's 1.4m telescope might appear also "small" compared to **JWST**. Yet to reach our science objectives, other parameters are as critical: stability, spectral coverage, optimised detectors and high degree of visibility of the sky. The key areas where EChO will excel compared to JWST are:

- *Dedicated mission*: The main advantage of a dedicated mission such as EChO will be the design of an optimal scientific program. In the Design Reference Mission for JWST, at least 80-85% of its time will be dedicated to non-exoplanet science. This brings critical constraints on target observability and mission planning, especially for the planned EChO sample of time-critical observations of transiting exoplanets. It will be impossible to perform large systematic surveys with many repeated observations of targets within the mission lifetime of JWST.
- *Instantaneous wavelength coverage*. Contrary to JWST, EChO can simultaneously sample wavelengths between 0.4-16 μm. This is essential to study atmospheric variability and weather pattern. JWST will need to observe at least four separate transit/secondary eclipse events to get similar, but still inferior, wavelength coverage. Important spectroscopic features like the CO_2 band at 15 μm (see e.g. Figure 9), will have to be observed over more than one transit. This has the potential to introduce fatal systematic errors in these most sensitive measurements, especially for a planet orbiting an active star. We believe EChO can achieve this while JWST will not.
- Long term photon-noise-limited stability of 10^{-5}. Although the thermal stability of JWST and its instruments will be very high, there are several factors which will limit its achievable precision: 1) The JWST instruments are optimised for background-limited observations and not for photon-limited observations, the latter case being appropriate for most of the nearest exciting targets; 2) The (generic) instruments on JWST contain many moving parts which will be a source of calibration uncertainty; 3) The segmented mirrors of JWST will exhibit low level deformations over time causing temporal variations of the psf. EChO will not suffer from any of these problems. As the long term high level of stability is essential for atmospheric variability and weather pattern studies, EChO will be superior in this respect.

EChO, specifically designed to reach 10^{-5} long-term, photon noise limited stability and detectors optimised for observing bright sources, will provide a critical scientific yield as a stand-alone observatory, yet the synergy between EChO, JWST and the ELTs could be particularly powerful. EChO will garantee a synoptic view over a wide variety of extrasolar planets by simultaneously measuring their emission/transmission spectrum between 0.4-16 μm. A sub sample could be observed at higher resolution over a limited spectral window with JWST, or very high resolution with an ELT in complement with EChO.

8 Targets for EChO

The main objective of EChO is to characterise spectroscopically the atmospheres of exoplanets already discovered by other facilities at the time EChO flies. To detect the chemical and thermal signatures of these remote worlds, the typical signal to aim at is between 10^{-5} and 10^{-3} times the flux of the parent star, for this reason, the brighter the star in the wavelength range selected, the better. Our simulations (validated against current observations of exoplanet atmospheres with Hubble, Spitzer and ground-based observatories) indicate that the brightness thresholds for EChO's observations are: Mag. V=12 for a G-K star, with an orbiting Jupiter or Neptune, and Mag. K=9-10 for "Habitable-zone" Super-Earths around dM stars, respectively (see §5.4).

Currently, about 50 of the 500+ currently identified exoplanets, are transiting planets with a stellar companion satisfying those criteria[69]. At present, the available sample for EChO includes few Super-Earths and Neptunes, but it is still biased on more massive planets. Thanks to ongoing and planned new surveys and facilities (the ESA-GAIA mission alone is expected to discover several thousands new exoplanets), a more complete reservoir of potential targets will become available in the next decade. The redundancy of observable targets will allow to refine the selection criteria for the EChO targets.

We list below some approved projects and surveys that will likely provide additional exciting targets for EChO in the next 10 years:

- Concerning the solar-like stars (G and K) ,EChO will observe stars up to a distance of 330, and 170 pc for a G0 and a K0, respectively, essentially the same volume explored by ground-based surveys. Ongoing and planned **HAT-S, NG-WASP, LCOGT, XO** etc. surveys will significantly increase this number by expanding the parameter space (e.g. the surveyed spectral types, metallicity, sky coverage, etc.).
- Most recently several ground-based surveys completely devoted to the detection of planets around M stars have been planned and implemented, In particular programmes aiming detecting Habitable-Zone Super-Earths around dM stars are already ongoing and other are planned for the next future. All these projects will deliver good targets for EChO in addition to those already known (e.g. the Neptune GL 436b[25] and the SuperEarth, GJ1214b[18].
  - The most relevant ongoing survey, **MEarth**[60], aims at monitoring about 2000 late M dwarfs (R $\leq$ 0.33 R_{sun}) taken from the Lepine-Shara Proper Motion Catalog of northern stars[45] to search for Super-Earths, as small as twice the radius of the Earth, in the Habitable Zone. About two dozen of stars in the EChO magnitude range are included in the monitored target sample. GJ1214b, the first transiting Super-Earth around a M star, has been identified as part of this survey.
  - Another planned ground-based survey expected to provide suitable targets for EChO, is **APACHE** (expected to start in 2010). This project is dedicated to the long-term photometric monitoring of thousands of nearby M dwarfs in the Northern hemisphere, providing the first-ever, longitudinally distributed network of telescopes dedicated to the search for transits of small-size planets. We foresee the discovery of few tens of Super-Earths around M in the next few years.
  - HARPS-S (La Silla) and HARPS-N (La Palma), dedicated survey for exoplanets orbiting bright stars. The preliminary analysis of HARPS data, more than 40% of stars have planets with masses below 50 Earth masses and 30% of stars with planets below 30 Earth masses[52,57].
  - Further ground-based resources for EChO targets will be radial velocity instruments such as **CARMENES** (Calar Alto), specifically built to search for Exo-earths in Near-Infrared and Optical around stars later than dM4, with an average distance of 15 pc. Depending on the abundance of low-mass planets around low- mass stars, 4-5 transiting Super-Earths may be detected.
  - Analogously, **ESPRESSO** (Paranal) on VLT will achieve a radial velocity precision of about 40 cm s^{-1} for M stars with V $\leq$12, which is enough to detect rocky planets in the Habitable Zones of these stars.
- While most of the exoplanets discovered by **CoRot & Kepler** orbit stars too faint for allowing detailed spectroscopic studies, broad band photometric observations in the optical and IR with EChO will be feasible for target stars as faint as mag. V=15.
- As mentioned in previous sections, EChO could consider few non-transiting planets in its target sample (combined-light observations[33]), with a view for non-transiting eccentric systems, to study the seasonal changes in atmospheric composition/thermal properties due the significantly variable irradiation conditions (for an e=0.6 orbit, the stellar flux varies by a factor of 16 along the planet's orbit!). For non-transiting eccentric Neptunes and Giants, **GAIA** will certainly deliver high-quality orbit reconstructions and mass determinations, independently of the existence of RV measurements. If the full orbit and actual companion mass are available, it is then possible to predict where and when one will find the planet around the star.

Finally, a number of space mission concepts, currently proposed to ESA and NASA, promise to detect additional transiting planets: PLATO, TESS, ASTRO. These missions and EChO are fully independent experiments: while EChO might benefit of an even more enticing selection of bodies to choose from, in the case these missions are launched, EChO does not require PLATO/TESS/ASTRO discoveries to achieve the scientific objectives described in the previous sections.

8.1 Baseline mission requirements, configuration and orbit choice

We present in the next sections the basic requirements on the payload configuration needed to achieve the science goals. The major driver on the overall system configuration is the need to provide a 1.2-1.5 m telescope cooled to at least $\sim$ 50 K with an instrument optical bench cooled down to less than 45 K with detectors at 30 K. These requirements come from an estimation of every contribution to the final noise in the SNR analysis. Achieving these goals requires a satellite with significant thermal shielding to provide a passively cooled telescope and instrument optical bench similar to the systems employed for the PLANCK satellite and proposed for the JAXA SPICA satellite. To provide the lower temperature for the detector will almost certainly require active closed cycle coolers. The options for this are discussed in the next section.

Given the need to cool the payload passively and maintain a stable thermal environment the choice of orbit is limited to the Earth trailing type such as used by Spitzer or the L2 Lissajous (PLANCK and Herschel) or the L2 halo orbits. The Sun synchronous low Earth orbit, which may have the benefit of allowing a larger mass and therefore larger mirror, has many drawbacks in terms of observing modes. Given that the Earth trailing orbit has a disadvantage in terms of a decreasing data rate capability as the satellite drifts away from the Earth, we are assuming that the satellite will be placed into a halo orbit at L2 with a large radius (800 000 km). The large radius halo orbit is preferred as it reduces the sun-satellite distance variation speed along the terrestrial revolution and avoids eclipse over the complete mission with no significant ΔV requirements, greatly simplifying the thermal design and spacecraft operations. In addition, it allows a greater mass for the satellite. We estimate that the overall mass of the system presented here will be less than 2.1 T allowed for a Soyuz Fregat launcher.

8.2 Baseline operational scenario

The typical mission duration is 5 years. The nature of the scientific mission that EChO will carry out is to visit a restricted set of stellar targets (some 10's) at prescribed times to match the orbital phase of the exoplanet. Typical visits per target will be of the order of an hour to a few hours interspersed by periods of a few to up to 20 days. Given that target stars may be in any part of the sky and will have a range of orbital periods it is essential that the satellite has a large "field of regard", i.e. as little restriction as possible on the direction the satellite can be pointed due to Solar and terrestrial viewing constraints. This requirement will, in turn, drive the basic direction of spacecraft pointing and the arrangement and size of the thermal shields, antennae and Solar arrays. A typical angle of $\pm$ 30 degrees with the Sun-Earth normal appears to be a good trade-off (cf. observation strategy section). It allows a full visibility of the sky (all the targets) over one year, and an instantaneous visibility of more than 40% of the targets. The observation plan can thus permanently adapted according to scientific interest of the targets.

Given the predictable nature of the observing plan we envisage that the satellite will be able to carry out semi-autonomous operations for reasonably long periods of time with minimal ground contact required (typically 2 per week). During the observing periods we anticipate that the instruments/CDMU will store the majority of the science data on board (suitably compressed). This is possible because of the relatively low data volume provided by the instrument. During this "Observe Mode" period only low data rate housekeeping will be required to be sent to the ground for health monitoring and we assume a rate compatible with continuous LGA operation. The high rate transfer of the science data to the ground will be achieved during dedicated "Data Transfer and Commanding Periods" (DTCP) using an MGA or HGA depending on the final rate required. This would be similar to the Herschel and PLANCK operations but with a rather lower duty cycle. In the basic operational scenario updates to the observing plan and any adjustments to the instrument and satellite operations can be uploaded during DTCP. In addition to this basic scenario we will study whether EChO can be made truly autonomous (i.e. with no active ground intervention) and the costs and benefits of this approach. In any event operations and data transfer and distribution will follow a conventional pattern for ESA astronomical satellites with a combined ESA/instrument team providing safety and operational input and data processed and archived as described in §11.

9 Proposed model payload to achieve the science objectives

9.1 Payload requirements and preliminary studies

The EChO instrument has to perform the spectrophotometric measurements of the brightest transiting planet hosting stars in the 0.4-16 μm spectral range, with a photometric stability of up to 10^{-5} over several hours to tens of hours. It should also permit regular visits to targets according to the transits timetable in order to enable multi-transit observations. A SNR analysis including all the instrumental and background noise sources leads to define an instrument working at 45 K at the focus of a telescope at 50 K, with a pointing stability of a few tens of mas within a FOV smaller than 1 arcmin. All the spacecraft and payload design will be driven by these requirements.

A preliminary concept study of an infrared observatory dedicated to the spectroscopy of transiting planets has been realised internally by ESA in 2009 - 2010. This study named "Exoplanet Spectroscopy Mission (ESM) had several key points but no show-stopper. EChO's concept is similar to ESM. To address these key points, we have conducted additional studies within the proposers' consortium and with significant contributions of industry. We performed detailed studies of the instrument and in this section, we show the solutions we propose for EChO to these identified key points. We present a baseline concept for the mission that can be implemented without any strong additional

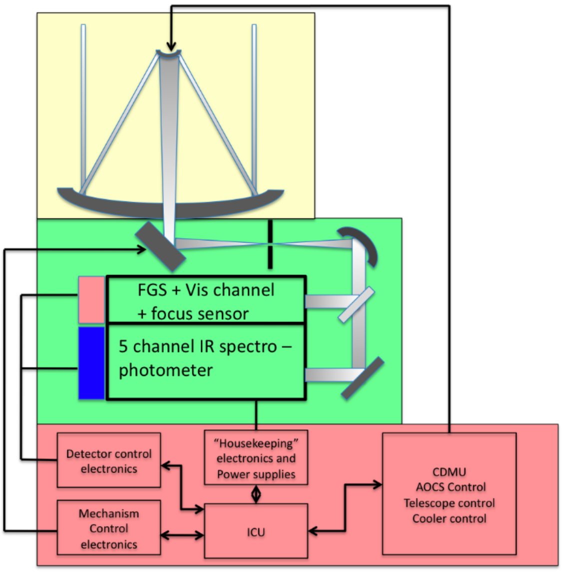


Figure 20: Scheme of the payload. Temperature colour code is : yellow ∼ 50 K, green ∼ 45 K, blue ∼ 30 K, red ∼ 300 K.

R&D requirements and present possible optimizations to achieve the instrument performance in key areas. In this instrument concept, we choosed on a robust and simple implementation to improve its reliability, reduce its cost and allow a fast development.

Our studies indicate clearly that EChO falls within the envelope of an"M-Class" mission and that it can be launched within the Cosmic Vision timeframe.

9.2 Overview of the payload

The payload (Fig. 20) consists of a single instrument, a multi-channel spectrograph, at the focus of a 1.5 m effective aperture telescope.

The spectrograph covers the spectral range from 0.4 to 16 μm with 1 vis/NIR and 5 IR channels with a spectral resolution varying from a few tens in the thermal infrared to a few hundreds in the near infrared. The vis/NIR channel is used for stellar activity monitoring and combines also fine guiding sensor (FGS) and focus sensor (FS) functions. The telescope temperature should not exceed 50 K, while the instrument is working at 45 K with detectors at 30 K. Thermal constraints are reached only by passive techniques except for the infrared detectors where small cryo-coolers are used. The instrument electronics includes a DPU, which performs on board data processing and compression before passing the data to the spacecraft CDMU for on-board storage and subsequent transmission to the ground.The requirements for the on-board storage capabilities are discussed in §9.3.5.

9.3 Summary of instrument key resources and characteristics

9.3.1 Description of the measurement technique

The instrument is a spectro-photometer used in 3 observational scenarios:

- Primary transit : this occurs when a planet transits front of its parent star. The spectral features seen in the stellar spectrum due to absorption in the planetary atmosphere can be deduced by differential spectrophotometry out of transit and during the transit.
- Secondary transit : this occurs when a planet transits behind its parent star. Here the emission spectrum of the day side planet itself is deduced directly from differential spectro-photometry outside (star + planet) and during the transit (only the star).
- Phase curve: in this scenario it is not necessary to observe a transiting system. The reflected, diffused or emitted light from the planet is seen as a modulation superimposed on the stellar flux as the planet orbits the star. Several visits during the orbit are necessary to observe different phases.

In all these 3 techniques, the instrumental considerations are the same: one must extract a weak planetary component super imposed to stellar signal. In the case of brightest stars, the observation quality is limited by the photon noise of the star itself. The instrument drivers are :

- Fast photometry operations (1 point every 1 or 2 minute),
- Photometric stability over the total transit observation duration or orbital period (several tens of hours) at a level of 10^{-5},
- Adaptability to huge dynamic range between star and planet within the whole, spectral range for each target (contrast planet/star from several 10^{-2} to 10^{-5}).

Observation strategy, calibration procedure and spectrum extraction technique are developed in §4.

9.3.2 Instrument baseline conceptual design and key characteristics

Following the successful ESA/ESM study, a classical on-axis Cassegrain telescope with a 1.5 m class primary mirror diameter (1.2 m in the ESA/ESM study) would meet the main requirements of EChO such as cooling to 50 K by passive techniques and reaching the PSF quality requirements within a central small field of view (several arcmin) around the target star. The design and development of such a telescope shown on Fig. 21 does not present any particular difficulty.

A dispersive/diffractive spectrograph has been investigated as baseline concept. We propose to split EChO observation spectral range (0.4 to 16 μm) in 6 channels (1 vis/NIR + 5 IR) for which optical design and observation parameters (elementary and overall integration times, spectral resolution thanks to binning of the spectrum...) can be adjusted individually. The Vis/NIR channel is also used as FGS and FS as mentioned above. The spectrograph is fed directly by the telescope image through an entrance aperture whose size is slightly bigger than the PSF size at 16 μm. As a consequence, the entire flux of the star is used in the different channel and no slit are used.

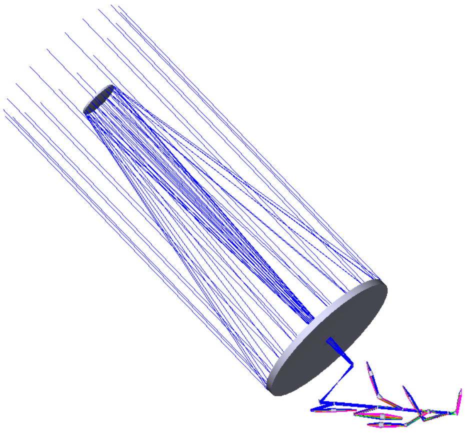


Figure 21: Top: **Baseline optical concept** with on-axis telescope and full diffractive/dispersive spectrograph as proposed in the ESA ESM study.

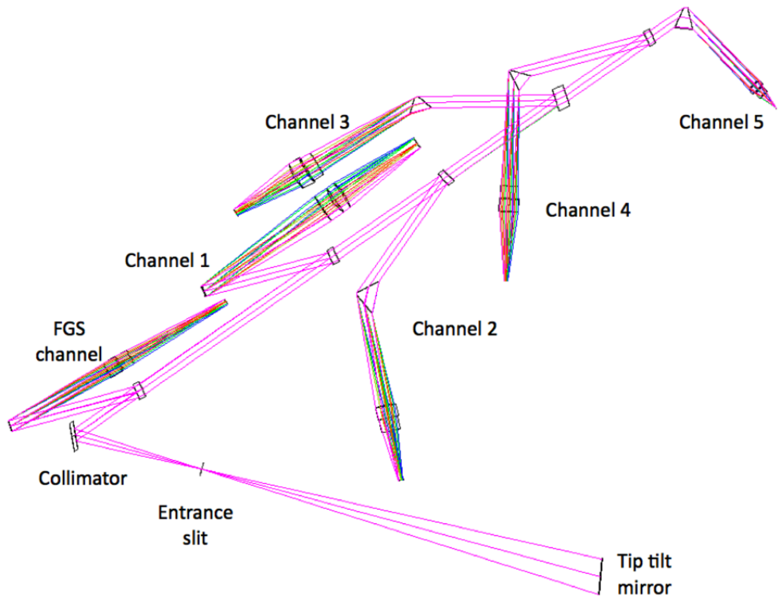


Figure 22: Right: **Baseline optical design** of a dispersive implementation of the instrument. The FGS channel is also a FS channel and a 0.4-1 micron spectrograph, with a spectral resolution of about 600, to monitor the stellar activity.

A preliminary design of this concept has been done and is presented on Fig. 22). The characteristics of each spectral channel is presented in table 7 assuming the requirements on spectral channels (spectral range, spectral resolution) and the characteristics of available detectors (size, pixel size and number).

One of the key-points of the instrument, which drives its development, is the choice of the detectors. This choice is strongly constrained by the availability in Europe of very few detectors in the 0.8-16 µm spectral range. The best European detectors in this spectral range are based on InSb (NIR) and HgCdTe technologies. For homogeneity of the focal plane and readout electronics, we based the pre-design exclusively on HgCdTe (also called "MCT") detectors, available under the form of 350x250 or 500x500 pixel matrices, whose performances are already acceptable with current products until about 11 µm. These detectors are based on "n on p" technology or similar, which is mastered by several company in Europe (SOFRADIR, AIM, SELEX, VIGO). Technological improvements are necessary for the 11-16 µm spectral range to reduce the level of dark current but development already started through CNES R&T program (see §12.1.1) and through development programs at AIM and improved detectors should be available in the timeframe of the project. All the detectors will be optimised in terms of cutoff wavelength to exhibit the best response and lowest dark current level with respect to the required spectral range. The main advantage of this solution is that it is based on full European products.

At wavelengths greater than 5 µm, MCT detectors will need to operate at 30 K in order to minimise the level of dark current. A preliminary study to confirm the performance of the detectors and readout circuits at 30 K will be undertaken during the early development phase of the mission. This point is detailed in §12.1.1.

An alternative suggested in the ESM study could be the use of SiAs (BIB) technology, leading to virtually "noiseless" detectors (e.g. Raytheon). However, present products work at 7 K, require long readout time to keep the noise level very low and exhibit low full well capacity, which leads to frequent readout at low rate to keep the performance and reduction of the overall duty cycle of the instrument. They would need to be adapted to EChO (detectors and readout circuits). In addition the durability of the development chain after JWST is very hypothetical. These detectors are thus not considered in the baseline concept but at least as backup or at best as options in case of collaboration with American partners. Some of these detectors are also ruled by ITAR considerations and are not considered at present as a "safe" option for the project.

The detector for the Vis/NIR channel (0.4-1 µm), FGS and FS is a classical CCD, commercially available in Europe (e.g. EEV).

The instrument is designed to work at 45 (+/- 70 mK), with detectors at 30 K (+/-10 mK). Assuming a telescope at 50 K (+/- 100 mK), the thermal equilibrium of the whole payload is obtained by passive cooling, except for the detectors themselves where the 30 K environment is obtained thanks to small cryo coolers such as Joule Thomson devices (R&D Darwin, MIRI/JWST, Planck heritage), or Turbo Brayton coolers (NICMOS/HST heritage).

9.3.3 Alternative design studies of key items

Alternative options to the baseline concept have been considered. The payload and mission requirements have been studied together with the industry (Astrium

	FGS + FS+ Vis/NIR channel	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5
Bandpass (µm)	0.4 - 1	0.8 – 2.7	2.3 – 5.2	4.8 – 8.5	8.3 – 11	11 - 16
	TELESCOPE					
Diameter	1.2 to1.5 m (larger size to be studied). 1.4 m telescope used in this proposal					
F#	10					
Transmission	98%					
	COLLIMATOR : off-axis parabola					
Focal length	200 mm					
Transmission	99%					
	OBJECTIVES					
Type	Doublet	Doublet	Doublet	Doublet	Doublet	Doublet
Material	PHH 71 LAH 54	F_Silica CaF2	ZnSe Germanium	Silicon AMTIR 1	Silicon AMTIR 1	CdTe CdSe
Focal length	200 mm	150 mm	100 mm	100 mm	100 mm	50 mm
Image F/#	10	7.5	5	5	5	2.5
Transmission	95 %	95 %	95 %	95 %	95 %	95 %
	DISPERSION SYSTEM					
Type	Grating	Grating	Prism	Prism	Prism	Prism
Grating density	111/ mm	64 /mm	N/A	N/A	N/A	N/A
Material	N/A	N/A	CaF2	CaF2	Cleartran	CdTe
Prism angle	N/A	N/A	62 °	47 °	59 °	59 °
Spectral resolution	600	600	600 or better (to be studied)	600	600	20
Transmission	60 %	40 %	90 %	90 %	90 %	90 %
	DETECTOR					
Type	CCD	HgCdTe SWIR	HgCdTe MWIR	HgCdTe LWIR	HgCdTe LWIR	HgCdTe VLWIR
Pixel size		30 µm	15 µm	30 µm	30 µm	30 µm
Needed pixels	600	650	460	330	182	40
Working temperature		< 110 K	< 80 K	<40 K	< 40 K	30 K
Quantum efficiency		0.5	0.7	0.7	0.7	0.7
Dark current (e-/s/px)		$< 10^{(1)}$	$< 10^{(1)}$	500	500	10000(2)
Readout noise (e-/px/ro)		150	400	1000	1000	1000

Table 7: Main characteristics of instrument and detectors. Objective and prism materials are detailed for the dispersive solution.

(1) maximum value performance not measured at this temperature

(2) expected performance after technology improvement see §j.1

GmbH, Germany, Astrium UK) and national agencies (CNES) to confirm technical feasibility of key items within the M-Class cost cap. As outlined in §14 such compliance is achieved and a trade-off for detailed design will to be performed during assessment study and phase A.

Telescope: The need for EChO's spectrophotometric stability of 10^{-5} over several hours requires a thermally stable telescope, i.e. a well baffled and shielded system with high mechanical stiffness and stability. These design drivers led to the possibility of a 1.5 m off-axis design (1.45 m effective diameter) which has been investigated in order to optimize the thermal shielding. It is illustrated on Fig. 23. The off-axis system with M2 location close to the thermal shields (see Fig. 28) allows implementation of an oversized shield which provides high thermal stability since mounting spiders of an on-axis secondary mirror can be avoided, minimising drifts in thermal emission due to temperature changes. This design also has no energy loss due to clipping from the central obscuration and also provides a cleaner pupil. This concept easily accommodates beamsplitting into a visual channel including the FGS (followed by a relay optics towards the star sensor chip) and into the scientific IR channels towards the spectrometers including a focus sensor (e.g. Shack-Hartmann or specific device). The positional tolerance of M2 is less stringent for this optical design than for a classical on-axis system, therefore lowering the requirements for an refocus mechanism. Due do its stability requirements at 50 K operating temperature SiC would be the material of choice for the telescope, given its largely increasing thermo-elastic stability as well as diffusivity with decreasing temperature with to Zerodur/CFRP or Zerodur/ceramic technology. Another advantage of SiC for EChO is the absence of moisture release associated with CFRP.

Instrument: In addition to the dispersive/diffractive design an implemention of the spectrometer channels based on Fourier transform schemes has been studied.

FTS come in a variety of designs including the use of gratings in the interferometer arms (so called Spatial Heterodyne Spectrometer - SHS) or using a beam shearing system. In the studied FTS implementation of the EChO instrument (see Fig.24) all channels are behind the collimator which reduces the beam size of the scientific path from 100 mm down to 25 mm. A series of dichroics separates the beam into the different spectrometer channels. Spectral bands 1, 2 and 3 are realized with fixed-mirror FTS. The interferogram will be generated by tilt of one mirror according to the required resolution. The image is focused by an anamorphic camera in reflective optics onto a $\sim$ 1024x10 detector array. The pupil image is reduced to the size of 20 mm in the afocal direction on which the spectrum is spread. The focal direction reduces the spot size form the star image onto a few pixels.Conservative assumptions on the dark current of currently available European detectors does not permit a fixed mirror FTS with a detector line in CMOS technology and were design drivers for favouring a scanning FTS for the two channels 4 and 5. A trade based on detector performance and spectrometer concept (dispersive/FTS) of each channel will be performed during later study phases. In any case, the modular concept of the instrument allows to use both FTS/dispersive channel for optimum instrument performance across the whole wavelength range. FTS solutions may particularly be considered for the 11-16 µm spectral range, if insufficient improvements in the VLWIR detector performances and infrared material performances prevent us from classical dispersive solutions.

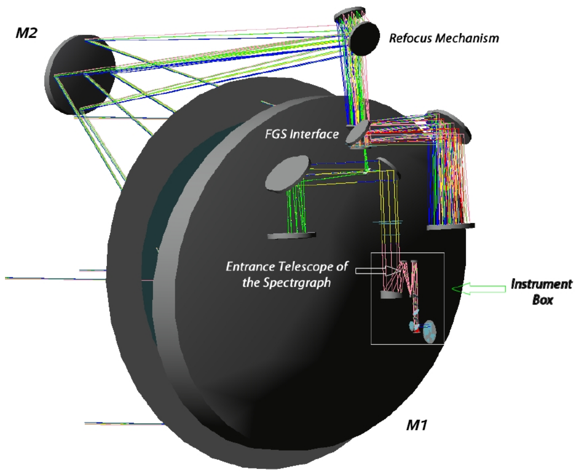


Figure 23: Alternative design proposed by Astrium Germany for a 1.5 m off-axis telescope: 3d view of the payload optical path. Refocus amd FGS units are also indicated.

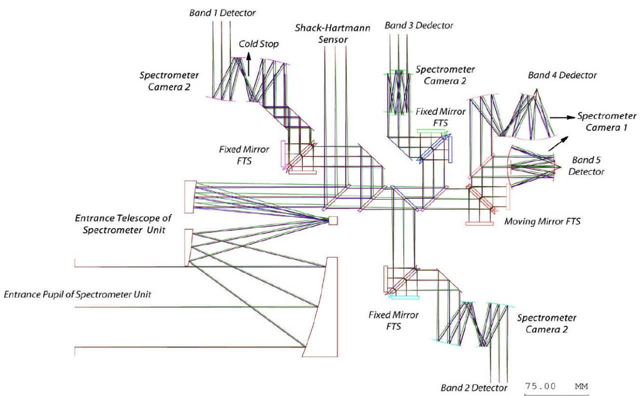


Figure 24: Alternative spectrograph proposed by Astrium Germany, using Fourier transform spectrometers (FTS) for all channels. A series of dichroics separates the beam into the different spectrometer channels. Band 1-3 are realised with fixed-mirror FTS using anamorphic cameras in reflective optics for imaging onto the detecors. The long-wavelength channels 4 and 5 are implemented as scanning FTS to mitigate dark-current constraints. A trade-off for EChO may lead to implementation of FTS in one or more channels of the baseline design.

9.3.4 Performance assessment with respect to science objectives

In order to evaluate the performance of the instrument, we developed a specific exposure time calculator (ETC). This ETC computes the effective and total integration time at a given spectral resolution and S/N per spectral element, in a given spectral range, taking into account the characteristics of the astrophysical object (spectral type and magnitude of the star, contrast between star and planet), the characteristics of the telescope (diameter, transmission, temperature), the instrument (transmission, temperature) and associated detectors (temperature, quantum efficiency, dark current, readout noise, full well capacity…). The ETC includes also tools to estimate the transit duration of hypothetical transiting object, and tools to estimate the effective temperature of planets and associated contrast to the star in the case of secondary transits (including reflected and thermal emission of the planet). The ETC has been applied to a target list made of the 50 brightest objects among the more then 100 known transiting objects. The detail of performance evaluation is summarised in the §4.4 of this proposal.

9.3.5 On board data handling and telemetry

The EChO payload will include an OBDH (On-Board Data Handling) Unit devoted to data, TM and TC management (Fig. 25). The main tasks this unit will perform can be split in two different functional blocks: a Digital Processing Unit (DPU) and an Instrument Control Unit (ICU).

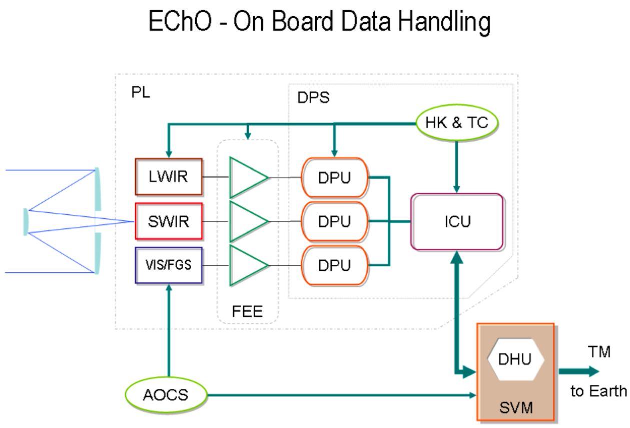


Figure 25: EChO on-board data handling

The output signal from the FPA detectors will be digitised by means of dedicated Front End Electronics (FEE) and handled by a DPU. DPU will be in charge of processing digital data coming from the ADC inside the FEEs as well as performing data serialisation in order to send them to the central unit through one or more SpaceWire link. This operation could be performed by means of a processor and a programmable logic device like an FPGA implementing an IP core dedicated to packet data in the SpW format and routing them. ESA standards already foresees integrating procedure and rad-hard devices dedicated to these operations, like the RTC (Remote Terminal Controller) AT7913E device and the SpW ASIC AT7910E router, using so consolidated technologies. Data from the DPU of each spectroscopic channel (VIS, SWIR, LWIR) will be collected by the Instrument Control Unit (ICU), compressed - if required - and then formatted and sent to the Data Handling Unit (DHU) of the Service Module (SVM) that will be in charge of buffering and storing data or transmitting them to ground. Image stacking and/or averaging will be performed at the ICU level. ICU will acquire housekeeping data of EChO subsystems and control their status to ensure proper instrument operation. ICU will be also in charge of receiving, validating and dispatching commands sent by the SVM. To perform these activities ICU will implement a processor, a control and communication programmable logic (like an FPGA), an SpW router and several types of memories like PROM, EEPROM, SDRAM for storing data and running the low-level drivers, the Operative System and the Application SW. The ICU mother-board will run on its processor the Operating System as well as higher level software applications in order to manage the EChO subsystems, allowing communication and control of the overall payload as well as executing the FDIR (Fault Detection, Isolation and Recovery) Application SW devoted to:

- detect, isolate and recover power input/output overcurrents, under- voltages and over-temperature conditions;
- detect the predefined alarms generated by FEEs and isolate by power switch-off the FEE and all the foreseen mechanisms;
- recover processor failures using watchdog timers;
- acquire and check periodically a set of parameters (voltage, current, temperature) against predefined thresholds;
- generate periodic diagnosis and FDIR data to report on the Payload behaviour to SVM via telemetry;
- acquire periodically ancillary and diagnostic data generated by the OBDP electronics;
- detect the PROM, RAM, EEPROM and Mass Memory data corruption by EDAC protection and scrubbing mechanism.

Taking into account the observation procedures we will accumulate 3.5 Gbits of data per day including housekeeping and margins (see §11.1 for detailed estimation). These data rate and volume can be easily managed by a standard SpaceWire link/network. An on-board SDRAM memory unit for data buffering will be available at the ICU level, while data storage collecting images for about 3 days (i.e. 12 Gbit memory unit, considering 20% contingency) will be included in the DHU. Several space industries produce rad-hard datastore systems that could be good candidates for implementing the memory unit. These memories are in facts data storage solutions which can be used as single board memory extension in data processing units and as multiple memory module board in a mass memory system. High capacity is achieved by state of the art memory and high density vertical packaging technologies. Memories could be configured, read and written by means of the standard RMAP (Remote Memory Access Protocol) SpW compliant protocol. Redundancy of critical elements will be foreseen and its level and characteristics (cold, warm or hot redundancy) will be fixed during phase A after requirement definition. The EChO Digital Processing System (DPS) design do not require new technologies development and all the electronics sub-systems are based on standard operations and data flows well within the capabilities of already-available technologies. A preliminary analysis of the elements constituting the EChO OBDH unit has shown the needed components are already available at a space or military qualification level and any element has not been identified as critical. So, concerning the technology aspects, we have a TRL greater or equal to 8 at components level for the OBDH electronics and a TRL greater or equal to 5 for the overall electronics system at the end of the Definition Phase, limiting thus the risk related to this system.

9.3.6 Pointing and alignment requirements

Another key point of the instrument is the stability of the line of sight, i.e. the stability of the stellar image at the entrance aperture of the spectrograph, in order to maintain the photometric stability over the spectra and avoid inter and intra pixel inhomogeneities. The spectrograph is designed so that the size of the PSF seen through the spectrograph is about one pixel on each spectral channel. A stability of the line of sight at a fraction of the PSF at the shortest wavelength is required. At 1 µm the required stability is about 20 mas. Because EChO is not an imaging mission, we do not need to stabilize the rotation of the field but only the line of sight (on-axis target). The stability of the line of sight is obtained thanks to the pointing of the orbital platform (absolute pointing of several arcsec, stability at the level of several hundreds of mas) and a fast steering mirror within the instrument that stabilises the position of the stellar image at the entrance aperture with an accuracy of several tens of mas).

The tip-tilt mirror is driven within the field of view of the telescope by a fine guiding sensor (FGS) included in one channel of the dispersive/diffractive spectrograph (see Fig. 22). The information of the FGS is also used to feed the AOCS which is described in §10.1.

The focusing of the telescope is obtained by the use of a focusing device adjusting the position of the telescope secondary mirror. This device is driven by a focus sensor within the Vis/FGS unit that analyses the size of the image at the entrance aperture of the spectrograph.

The stringent spectro-photometric stability requirements for EChO require a stable thermal and thermoelastic optical system. The alignment tolerances (M1-M2) are estimated to be of order 2 µm for a telescope compatible with visible light operation down to 500 nm wavelength (optical spectrograph, FGS). Alignment tolerances of order 1 µm have been recently demonstrated on comparable systems. The refocusing unit and the fine steering mirror will be controlled by a Shack-Hartman sensor after the beam splitter, or by a specific device included in the vis/FGS channel, measuring the photo-centre of the optical beam and the size of the image at the entrance aperture of the spectrograph. The current baseline foresees a silicon carbide design with CVD coating and brazing technology which has been demonstrated on prototypes.

The instrument is composed from individual spectral channels. The entrance optics for all of these channels are placed in the parallel beam, thus lowering alignment tolerances. The individual channel optics is based on an a-thermal aluminium concept made from synchronous diamond-turned mirror optics, which have intrinsically good performance on relative optical alignment. The alignment tolerances (M1-M2) for the optical subsystems are estimated to be of order 1 μ m and have been demonstrated. The modular design driven from the parallel optical beam allows independent AIV and cryotesting of these individual subsystems and therefore lowers the technical risk.

9.3.7 Operating modes

The basic operating modes for the mission are relatively straight forward and consist of the following:

- Target acquisition - modern AOCS provide the attitude of the platform using both information from star tracker (absolute position) and gyroscopes (fast relative moves). They will place the target within the field of view of the fine guidance sensor ($\sim$10's arcsec) and then target will be locked onto using the fine guidance sensor (FGS) in feed back with the the tip tilt mirror. The control sequence needs to be worked through in fine detail for this especially in light of the automatic nature of the proposed observing and operations programme.
- Data acquisition during transit - the FGS is in feedback with the fine positioning mirror and the detectors acquire data over the period of the visit ($\sim$ few hours). The data are reduced from their raw data rate (see table 8) by integration of the time series over as short a period as possible. This depends on the number of detectors employed but (again see table 8) $\sim$ 1 to 2 minutes appears to be sufficient to stay within the allowed data rate.

These then will form the overwhelming majority of the science observations and calibration observations using astronomical sources. There are also calibration and engineering tasks that will need to be carried which are relatively standard for a space mission. These include:

- Data Transfer and Commanding Periods (DTCP): These will occur every few days of the mission depending on the degree of autonomy that is finally decided upon. During this period we baseline that science observations will cease and the data from the on-board mass memory will be transferred via a high or medium gain antenna to the ground. Any engineering and new observational sequences will be uploaded during this period.
- Internal Calibration: Periodic calibration measurements (see §9.3.9) will be carried out. These will take data in exactly the same way as the targeted observations but with the on board calibration lamp activated and (probably) the spacecraft pointed at blank sky. Reference targets which stability has been measured by previous high precision photometry missions (e.g. CoRoT / Kepler) can also be an alternative to on board calibration lamp, assuming the stability of the stellar source can be confirmed at the level of 10^3.

Mode	Instrument activated	Data rate native/ telemetered (Kbits/s)
Target acquisition	FGS/ Tip-tilt	800 /1000
Science observation	All	3500 / 100
Internal calibration	IR channels / Calibration source	3500 / 100
DTCP	None	N/A

Table 8: Operating modes, required data rate into the on board processor (native) and ultimately sent to the ground (telemetered)

9.3.8 Specific interface requirements

The instrument is designed to be autonomous. The only interface requirements concern:

- power : the estimated instrument consumption is 75 W provided by the payload module (see Table 12).
- thermal disconnection of the payload and the payload module. The instrument is passively cooled, except the detectors, which are cooled down to 30 K thanks to small cryo-coolers. The mission design must include specific shielding and radiator in that purpose, according to the results of the thermal modelling of the payload that still should be done during the A-Phase study. At this level of the study, analogy to existing missions such as Planck / Herschel can only be done and do not let foresee any particular show stopper.

9.3.9 Calibration and other specific requirements

The basic measurement technique involves extracting spectrally separated signals in phase with the known period of our target planets (see §9.3.1). The difference between the stellar signal and the planet is very small (in the extreme $\sim$1 part in 10^5) and in some cases, many transits are required in order to build sufficient signal to noise to extract a high fidelity planetary only signal. Clearly accurate calibration and signal stability are going to be of the utmost importance both during and transit observation and in attempting to combine observations.

The general situation is illustrated in Fig. 26 and Fig. 27 indicating how the variations due to the

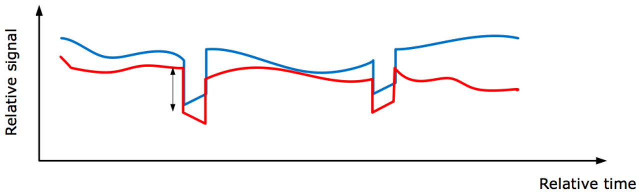


Figure 26: Measurement situation in the time domain. With (exaggerated) differences between two visits to a transiting planet. The period of the transit plus stellar flux measurement determines the lower bound of the instantaneous signal band - the upper bound is defined by the electronics low pass filter. The period between transits defines the frequency at which the primary signal is extracted and the time between visits defines the lower band of interest in Fourier decomposition and accurate calibration of all possible sources of disturbance are required to avoid systematic uncertainties at the extraction frequency.

Figure 27: Measurement situation rendered in frequency space. The shaded box illustrates the instantaneous frequency band of the measurement and all high frequency noise sources should be kept away from this band. The primary signal extraction frequency is at very low frequencies and the EChO calibration and observation stability must be such as to avoid allowing unknown systematic uncertainties into this frequency space.

(roughly) square wave transits are transformed into a pseudo monochromatic spectral feature in frequency space plus higher harmonics. The fluctuations due to variations in stellar flux, temperature drifts, detector drifts, miss pointing and jitter etc are super imposed in frequency space as some form of 1/f "pink" noise spectrum with (hopefully) a low frequency cut off somewhere above primary frequency band for the transits. Some sources of noise, such microphonics from reaction wheels or mechanical coolers, may lead to higher frequency disturbances which, if not removed, will add is as white noise. One way of combating these is to ensure that they are at frequencies above the low pass filter cut off in the detector signal chain.

We anticipate that most sources of uncertainty will either enter as white noise (accounted for in the sensitivity analysis) or at frequencies sufficiently removed from the signals of interest that they can be ignored or removed by correlation. Some disturbances will, however, be in phase with the measurements and we will need to calibrate certain aspects of the systems with extreme care. We need to consider the following in some detail:

- The ability to point the target at exactly the same location onto the instrument and any variation in instrument response across its field of view. Miss pointing when re-acquiring the target is in direct phase with the measurement frequency and will be difficult to deal with as it requires a stable astronomical source which cannot be guaranteed for our target stars (see below). This aspect can only be assessed and calibrated with multiple pointing at stable sources associated with highly accurate calibration measurements of the spatial response of the system.
- High frequency variation in signal response due to detector instabilities or satellite disturbances. These will not necessarily be removed by the phase detection and will add to white noise in the measurement. Unless these are correlated with other measurements on the spacecraft (temperature, reaction wheel frequency etc) they are difficult to remove. This means that careful attention should be made on where the frequencies of possible disturbing elements are placed and all possible correlating sensors (thermistors, position indicators, voltages etc) must be sampled with sufficient fidelity that they can be used to perform de-correlation of the signals if necessary in ground processing.
- Any stellar variation on timescales similar to the period of the transiting object that could mimic a transit signal. This may be unlikely but still needs to be monitored and considered in detail.
- Variation in the instrument response over a long timescale must be monitored as this will also lead to systematic variations in the signal at the frequency of interest.

In general attempting to provide absolute calibration of the system to the level of 1 part 10^5 is extremely difficult and ultimately limited by our lack of detailed knowledge of the characteristics of stellar variability at this level. Rather our strategy will be to eliminate as much of the systematic sources of uncertainty as possible following the discussion in this section and rely on the target stars themselves, in conjunction with an on board calibration source, to provide repeated measurements of the instrument behaviour over many timescales thus providing longitudinal calibration trends to remove all possible sources of systematic uncertainty. A highly stable and repeatable calibration source is an essential part of this scheme and our outline design envisages placing a source at the location of the telescope secondary where (in an on-axis design at least) the anti narcissus beam dump (hole) will be placed at the centre of the mirror. Placing the source here has the major advantage that the calibration source is viewed through as much of the optical chain as possible and therefore monitors the total degradation in performance over the course of the mission. Our initial goal for the calibration source is that it is stable to 1 part in 10^3 over at least one year of operation.

9.3.10 Current heritage and Technology Readiness Level (TRL)

Current heritage used for the instrument of EChO and Technology Readiness Level of subsystems are sum-

	TRL	Current heritage /development
European HgCdTe detectors SWIR/MWIR	8	Planetary missions : MEX, Phobos Grunt
European HgCdTe detectors LWIR/VLWIR with low dark current	3 at present, should be TRL 5 within the next 2 years	
American HgCdTe/SiAs detectors LWIR/VLWIR with low dark current	8	
Optimised readout circuits	3 (classical process of 24 to 36 months to reach TRL 6)	
Dispersive spectrograph / optics	8	Heritage IR spectrographs
FTS spectrograph knowledge / technology	5 (prototypes) to 9 (instruments already launched)	SPIRE(Herschel) / IASI (Metop) / MIPAS (Envisat)
Detectors electronics chains	5	
DPU and on board processing electronics	9	
Fine guiding system	5	

Table 9: TRL and current heritage for payload subsystems

marised in table 9.

9.3.11 Proposed procurement approach

The instrument design, development, building, integration, calibration and funding and the data processing and archiving will be done by the contributors of this proposal, with the support of their national space agencies. In the baseline, the telescope is procured by ESA. The partners have expressed their interest and potential implication in the instrument as summarised in table 10.

Contributing country	Expressed interest
France (IAS, LESIA, IAP,CEA)	Instrument design and development, optics, detector procurement and test, AIV, instrument calibration and testing, ground segment
Germany (MPIA)	Instrument design & development, optics, 0.8-8.5 µm channels incl. detector procurement, instrument AIV & Calibration, software development, ground segment (commissioning, calibration, operations)
Italy (INAF)	Vis / FGS channel, on-board data processing, telescope (if not procured by ESA)
Netherlands (ESRON)	Detector procurement and characterisation, detector electronics development and production, development, testing, and calibration of (parts of) the spectrometer, e.g. gratings
Spain (CAB, IEEC, IAC)	Vis / FGS channel, On-board and ground segment data processing, calibration software, MIR optical design, optics procurement and testing, electronics, Optical, thermal, mechanical, and electromagnetic qualification of space equipment
Switzerland (ETH)	Cryogenic mechanisms, calibration unit, NIR optics procurement and testing
UK (UCL, RAL, Oxford, Cardiff)	System, thermal and optical design, calibration, reduction software, AIV, electronics, detector procurement and test

Table 10: Potential contributions of the National Space Agencies to the EChO payload.

9.3.12 Critical issues

Critical issues of the instrument development in its basic version are clearly identified:

- Detectors and readout circuits: Detectors with the expected performance exist until about 10 µm. Technology should be improved for the 10-16 µm spectral range. R&D started at CEA/LETI. This point is detailed in §12.1.1. Readout circuits exist, but must be optimised according to each detector specificity. This point requires a 24 to 36 month-study/development. In additions, a general study must be done do check the performance of all the detectors and readout electronics in an environment at 30 K.
- Cryo coolers for the detectors: Even id the telescope and instrument cooling is done passively (temperature between 45 and 60 K), the detectors at 30 K cannot be passively cooled. Small cryo-coolers, dissipating a few hundreds of mW should be considered for the focal plane arrays cooling. Three ways can be considered : Joule Thomson devices (heritage Planck/Herschel/R&D Darwin) but small devices are still at low TRL, Turbo Brayton coolers as used for the NICMOS/JWST camera, or sorption coolers which show best performance with respect to microphonics.
- Line of sight correction device: as mentioned before, it does not appear to us necessary to use a complex AOCS for the whole satellite, to stabilise the line of sight. Because EChO works in a very narrow field of view (the target is the guiding star), it is possible to use the target position given by the FGS to drive directly a tip-tilt mirror in the optical beam and stabilise the position of the stellar image at the entrance aperture centre. A fast tip-tilt mirror, driven by cryo-motors may be considered in that purpose (see §12.1.3).

10 System requirements and spacecraft key issues

The EChO system design is driven by the stability and sensitivity requirements of differential spectroscopy in the optical, near and thermal infrared. The spacecraft driving requirements are: (1) Provision of cooling for the telescope and the spectrograph to ∼50 K and ∼45 K (30 K for the detectors), respectively, (2) high photometric stability requirement which translates to line of sight (LOS) stability and payload thermoeleastic environment stability requirements; and (3) overall compatibility with cost and technology readiness criteria of M-class mission, i.e. launch on a Soyuz-Fregat rocket.

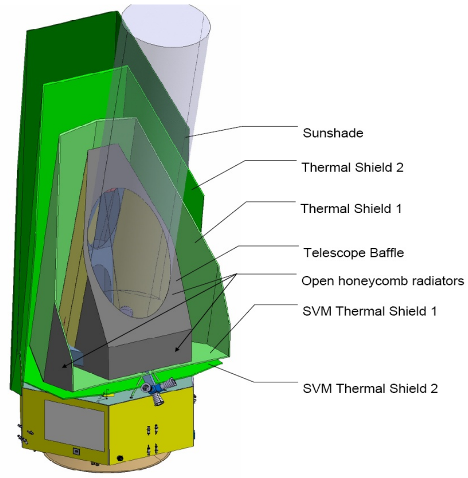


Figure 28: Baseline of EChO thermo-mechanical design concept. Startrackers are mounted on TOB.

The EChO spacecraft consists of three major modules (fig 28): (1) A payload module (PLM) including the instrument (telescope hardware, focal plane assemblies and on board science data management) containing all functionalities required for the scientific measurements. It is designed to guarantee the required performance by highest thermo-elastic stability. (2) A service module (SVM) containing all functionalities and equipment required to support the PLM for the scientific observations. The SVM accommodates all the spacecraft subsystems such as propulsion, communication, power, and the attitude and orbit control system (AOCS). (3) A multi-layer sunshield for protecting the PLM from solar, terrestrial and lunar irradiance. It thus guarantees the thermal stability for the telescope and the instruments.

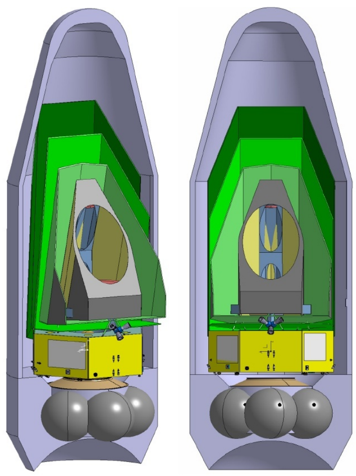


Figure 29: EChO spacecraft baseline configuration under the Soyuz-Fregat fairing.

The structural concept for the SVM takes benefit of heritage gained by industry (Astrium) from the design of the GAIA SVM structure, with which it shares many important similarities. The EChO SVM has 6 sides and a central cylinder, in contrast to the 12-sided GAIA SVM structure with its central, inverted cone structure. The smaller interface diameter of the EChO PLM drove these simplifications to the GAIA SVM. Common to both structures is the use of MLI to enclose the sides - rather than heavier panels - and the accommodation of equipment on the internal radial panels and the bottom floor, where necessary. This scenario has been arrived at after careful consideration of the main load paths (of the PLM in particular, but also of the tanks and equipment), along with the aim of minimising both the mass and size of the SVM. Both EChO and GAIA are to be launched with Soyuz, so it will be sensible to take advantage of the highly detailed analysis already performed on GAIA in order to identify those areas of the EChO structure which should first receive more detailed examination.

One area which shall be investigated in the forthcoming concept study by analysis is the diameter and shape of the central structure. This has direct impact on the interface loads at the PLM, on the tank accommodation, on the load flux at the launcher interface and potentially even the final size of the SVM. The primary structure of the SVM consists of an 1194mm diameter central cylinder which provides a load path from the corresponding 1194mm launcher interface to the interface points of the payload on an approximately 1700 mm diameter. Owing to this offset of the main interface points, the top floor of the SVM is suitably reinforced. Keeping the gap between the SVM and PLM to a minimum will help reduce the bending moments at the interface. To provide the best mechanical solution in this situation, the 6 PLM interface points are arranged so that they align with the mid-points of the six radial panels. The central cylinder is 1100 mm high. This was driven by the height of the cold gas tanks. The possibility of reducing this to around 900 mm shall be investigated in the concept study, following further assessments of both the central structure and the tank size. Its lower end holds the interface ring to the 1194 SF Launch Vehicle adapter. Around the central cylinder there are 6 radial equipment panels, arranged equidistantly around the circumference. As well as providing the mechanical interface to the PLM instrument, these radial panels stiffen the top and bottom floors and provide equipment mounting in the classical shearpanel-type configuration. The top and bottom floors have an outer diameter of 3130 mm and are attached to the central cylinder, thereby also stiffening this against lateral loads induced by the heavy PLM. The top floor also carries the sunshield, via a series of struts. The sunshade protects the PLM instruments from direct sun light and the resulting thermal loads. The panel construction proposed for the primary structure consists of alu skins with an aluminium honeycomb core, to minimise mass and thermoelastic distortions.

10.1 Attitude and orbit control

The EChO spacecraft needs to be 3-axis stabilized in order to be able to provide a high instrument line-of-sight pointing accuracy and stability of few tens of milli-arcsec (mas). The exact value depends on the measurement principle with a dispersive system being more sensitive than a fourier- transform implementation. As design criterium, the size of the PSF diffraction limited at the short-wavelength end of the infrared spectrograph of 0.8µm is 110 mas for a 1.5 m telescope and 35 mas is about 1/4th of its size. Using a dispersive spectrograph with entrance slit, successfully demonstrated on Hubble and Spitzer, as worst-case scenario requires an RPE of 30 mas over 500s while a fourier transform spectrograph operating in the pupil has lower requirements of 100 milli-arcsec.

To avoid stringent pointing requirements on the AOCS alone for LOS stabilisation we suggest to separate the overall satellite AOCS and instrument line of sight control by using a fast fine-steering/tip-tilt mirror within the instrument. This is possible since the main science objectives are related to the central stellar source and corrections for the central source can be performed by a movable pick-up mirror located after the beam splitter. Particularly, the field rotation in the focal plane due to AOCS fluctuations have no consequence on the performance of the instrument because the only requirement is the stability of the on-axis PSF at the spectrograph entrance aperture.

For the overall AOCS the requirement on RPE is 500 milli-arcsec over 500s and an absolute pointing error of a few arcsec can be achieved with classical reaction wheels. This system is controlled by star trackers which have to be mounted under optimised thermoelastic constraints onto the payload module. The RPE is dominated by wheel noise in the frequency domain up to 200 Hz. Since our target star are very bright in the optical, the bandwith of the control signal for the delta-movements of the fine-steering mirror can be sufficiently high and is provided by a FGS included in the visible channel that monitor the position of the star image at the spectrograph aperture entrance. An alternative to such device is the use of a Shack-Hartmanm wavefront sensor, which would also provide control information for the refocus mechanism. The FGS information (line of sight) may also be used by the global AOCS loop as in PLATO and Euclid concepts.

Recently, within the EUCLID study a performance compatible with the RPE requirement of 35 mas for EChO has been demonstrated in the laboratory using a cold gas micro-propulsion system. If TRL > 5 is confirmed such a system would meet the requirements for the EChO satellite and is consistent with the cost-cap outlined in §13.

10.2 Thermal aspects

Cooling the telescope and the instrument to cryogenic temperatures between 45 to 50 K requires an effective sunshade/sunshield system shading the payload from the sun and insulating it from the warm SVM. Furthermore the bipods supporting the telescope optical bench (TOB) have to be thermally low conductive and long conductive paths and low conductive materials (manganin, phosphor bronze, stainless steel) are mandatory for the harness between SVM and telescope and between telescope and instrument. Herewith the total parasitic heat flux has to be reduced to a level that can be balanced by the heat rejected from the payload radiating surfaces (T $<$ 50 K) towards deep space.

For the sunshade/sunshield system different concepts will be traded in the concept study taking into account the following major constraints:

- The sunshade/sunshield system has to be accommodated under the Soyuz-Fregat fairing.
- The sun-spacecraft-LOS angle shall be large enough. Goal is to achieve a solid angle of 1 to 2π steradiant at any time.
- The structural design of the sunshade/sunshield system shall be compatible with mass and mechanical requirements.
- The thermal design shall allow to passively cool the telescope to T $<$ 50 K.
- The use of structural material and MLI shall be compatible with outgassing requirements.

10.2.1 Thermal baseline design

Different design concepts have been considered. Herschel uses a single sunshade/sunshield system and a separate single SVM thermal shield to passively cool the LHe cryostat vessel to 70 - 80 K. This might be insufficient for EChO . For this reason a multiple system consisting of a sunshade and two separate thermal shields is suggested taking advantage of the V-groove effect as successfully applied to the Planck-spacecraft. Manufacturing of cylindrical shield structures however, is time and cost-consuming. For this reason flat sandwich panels (as for Herschel) are selected as baseline.

The large area of the shields are a source of significant quantities of water and other species if the sandwich faceskins are made of CFRP and if the panels are covered by MLI, creating a potential serious risk of contamination of the instrument and the telescope. For this reason the baseline uses aluminium faceskins and includes the instrument spectrometers in a sealed box that is only open at the aperture. The extent of MLI -usage will be thoroughly traded in the forthcoming concept study. To benefit from the V-groove effect it is important to achieve flat and high reflective surfaces which is difficult for MLI layers that tend to form a corrugated surface. The thinner the outermost layer the more corrugated the surface. The best results are achieved for 5 mil thick VDA/Kapton. As an alternative to MLI the thermal shield panels can be polished or taped with VDA/Kapton. In the baseline the sunshade is covered by MLI whereas the two thermal shields are VDA-coated on the sun-pointing side whereas the rear side is covered with MLI. This issue will be revisited in the forthcoming concept study and thoroughly be traded. All materials, in particular MLI-constituents (Mylar and Kapton foils) will be baked out before blanket manufacturing and integration (as done for Herschel) to minimize later outgassing of volatiles that could jeopardize optical performance. Outgassing of water can not be avoided by this method and therefore formation of water-ice on cold MLI surfaces can not be excluded. For this reason the water-ice thickness on the MLI has to be computed and an increased emissivity be assumed in the thermal analysis. An in-orbit bake-out of the MLI by electrical heating is not feasible due to the unacceptable high power demand and a "barbecue" in the sun is critical to low-emissive MLIlayers.

The sunshade/sunshield and the two thermal shields can be differently accommodated under the Soyuz-fairing as shown in Fig. 29. The vertical telescope-LOS configuration as shown on the left hand side allows for adjusting a minimum sun - S/C -LOS angle of 55°(56°with 1°safety margin). This angle can considerably be reduced to 39.5°(40°including 0.5°safety margin) when the telescope LOS is tilted w.r.t. the launcher longitudinal axis. In this way the conical part of the fairing envelope can be used to accommodate the top part of the sunshade/sunshield system as shown on the right hand side of Fig. 29. This configuration allows for observing a solid angle of 1.4 π steradiant at any time of the year. Note that any sun-S/C-LOS angle greater than 90°only allows to observe the same point only once a year since the S/C moves around the sun. Not taken into account are the position of earth and moon which restrict the solid angle range at some extreme earth/moon constellations.

Special attention has to be attended to the launch adapter ring that is sun-exposed when the S/C is adequately slewed. To minimize temperature variations of the SVM the launch adapter ring has to be SSM-taped as far as possible and the SVM bottom side has to be well insulated by MLI and completely covered by SSM-foil or OSRs.

The telescope and its baffle are passively cooled at T $<$ 50 K by an open honeycomb radiator on the deep-space viewing part.of the baffle. To achieve this the telescope has to be thoroughly decoupled from the SVM and from thermal shield 1. The latter is done by a high-efficient MLI (Herschel cryostat) on the baffle side viewing shield 1. Thermal isolation from the SVM is obtained by the same type of MLI on the TOB opposed to the SVM thermal shield 1 and by using low-conductive bipod struts for supporting the TOB on top of the SVM. The selection of the strut material has to result from a trade-off taking into account mechanical stiffness and strength requirements as well as thermal properties. Considering the Herschel heritage (70 K / 290 K for cryostat/SVM struts and 70 K / 420 K for cryostat/sunshield struts) and the temperature range of 270 K to 50 K for ECHO, glass-fibre struts are the preferred selection for the ECHO SVM/TOB-struts. Furthermore none-copper PLM/SVM harness (manganin, phosphor bronze, stainless steel) is mandatory.

In the baseline the whole instrument optical bench (IOB) shall be controlled at T $<$ 45 K and thus has to be isolated from the TOB by using high-efficient MLI and low conductive kinematic mounts. Struts made of T300-CFRP are first choice in the temperature range around 40 K. This is in line with the struts used inside the Herschel cryostat. The strut end-fittings at the interface to the TOB SiC-structure,must be made of Invar to compensate the CTE-missmatch whereas at the aluminium IOB I/F Ti6Al4V shall be preferred as end-fitting material. This issue will be traded in the concept study, i.e. total cryogenic heat load versus design complexity and mass.

10.2.2 Alternative thermal designs

Alternative thermal designs were considered (Astrium UK) to allow an increase of the roll angle with respect to the position of the satellite on its orbit in the antisolar direction and as a consequence, an increase of the sky fraction, which is instantaneously visible. Such concepts, circular or semi-circular sunshields, require the use of curved panels as illustrated on Fig.30.

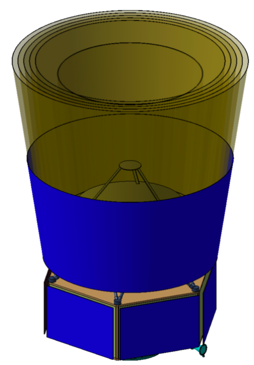


Figure 30: Alternative thermal design with curved shieldings proposed by Astrium UK to allow an increase of the observable sky fraction.

A preliminary study of these concepts showed that they are slightly more complex and that the mass increase is low compared to the baseline solution. Anyway, they keep comfortable margins with respect to Soyuz-Fregat launch capabilities. As for the payload, a complete trade-off at the system level, including scientific performance increase should be done during the assessment phase.

10.3 Mission operations concept (ground segment)

The ground segment foreseen for EChO is a very classical concept including:

- a Space Operation Center (SOC), in charge of all the operation of the satellite (post-launch control of the satellite, telemetry/ telecommands through the Deep Space network, survey of the satellite..). The SOC would be under the responsibility of ESA and can be located in existing facilities (i.e. ESOC)
- a Mission Operation Center (MOC), in charge of all

the operation concerning the operations of the instrument itself, including the definition of observation sequences, the configuration of the instrument, the survey of house keeping data...), and the production of scientific raw data to the SDPC (see below). The MOC would be under the responsibility of ESA and can be located in existing facilities (i.e. ESRIN)

- a Science and Data Processing Center (SDPC), in charge of the production of scientific data and its distribution to the co-Is and the astrophysical community. The SDPC may gather several pipelines, but is responsible for the qualification of scientific data and the validation of data processing algorithms. The SPDC would be under the responsibility of proposing partners.

10.4 Estimated overall resources (mass, power, communications)

Mass: The mass budget of the EChO satellite is compiled in Table 11. The mass budget for the SVM is based on a study for the EUCLID mission. The total launch mass of the EChO satellite is 1470 kg. With regard to the Soyuz-Fregat launch capacity of 2160 kg there is still a contigency of 32 %. Because to its superior thermoelastic properties SiC has been adopted as baseline material for the telescope and the instrument optical bench. If the mass contigencies are confirmed during phase A study, heavier baseline materials with higher TRL (Aluminium, Zerodur) might be alternatively reconsidered for performance/cost trade-off .

Power: The baseline assumption is to use a bus which is similar to the one envisaged in the EUCLID study. In this case the satellite-bus, including in particular the thermal subsystem and the data transmision, is in the order of 850 W, including 20 % system margin. Since the data rate of EChO is considerably smaller than for EUCLID this is considered as an stringent upper limit. The instrument electronics of ECHO, including an instrument internal mass memory, is expected to require approx. 75W plus approx. 7W for thermal control and mechanisms, leading to a total of about 932 W. The power budget of the instrument is compiled in Table 12.

The preferred solution is to restrict the solar array area to the central level of the satellite structure. This accomodates a maximum area of approx. 10 m^2 with an inclination of approx. 5°with respect to the sun. In case of power limitation, two additional panels could be envisaged with an incidence angle of approx. 30°.

At L2, the solar intensity is at 1340W/m2. Thus, the available power of the central structure is approximately: $1340\ W/m^2 \times 10 m^2 \times\ 17\%$ efficiency = 2278 W. Taking into account a a 30°solar aspect angle yields an available power of 1970 W. This is also compliant with a peak power demand of 1900 W identified in the ESA ESM study.

Communications: given a data rate of 3.5 GBits/ day (see §11.1) a medium-gain antenna (1.5 GB/s data rate) is sufficient assuming a DTCP scenario of two passes of 3 hours per week. Alternatively, a more autonomous mission operational scenario using a HGA system and fewer DTCPs is under investigation (see §8.2).

10.5 Specific environmental constraints (EMC, temperature, cleanliness) and specific requirements

There are no specific requirements on the environment for the operation of EChO apart from those already discussed in the text. Namely cryogenic temperatures and high temperature stability for the telescope and instrument and detectors. Several detectors to be employed have flown on many previous space missions ("n on p" detectors at least) and require only a standard low noise EMC environment combined with sound engineering design of the ground plane and Faraday cage associated with the instrument and read out electronics. The cleanliness requirements for the instrument and telescope will be similar to those required for any optical/infrared payload such as JWST-MIRI. Typical levels (in NASA terminology) will be 300B for instrument components on delivery with an overall budget on orbit of 500C. A detailed assessment will be required for the telescope and will depend on the amount of scattered light that is acceptable due to particulate contamination. We set an initial budget (in ESA terminology) of 2000 ppm for EOL.

10.6 Current heritage and Technology Readiness Level (TRL)

Current heritage used for the system of EChO and Technology Readiness Level are summarized in table 9 for the payload (p. 30) and table 13 for the spacecraft.

10.7 Proposed procurement approach

The EChO mission is proposed to be managed by ESA with an important contribution to the payload made by a consortium of institutes funded by various national agencies. Possible hardware contributions of the different consortium members have been outlined in table 10 (p. 30) and reflect the technological heritage of the respective institutes and associated industry partners.

10.8 Critical issues

The two most critical areas of the spacecraft with respect to the scientific performance of the mission are the AOCS and the thermal design. Both topics are discussed in §10.1 and 10.2.

11 Science Operations and Archiving

Members of the EChO team have and extended experience in operating processing and distributing space based survey observations (Corot, Huygens, Herschel). EChO will provide survey style observations with nu-

Subsystem	Material	Mass [kg]	Margin [%]	Nominal Mass [kg]
Service Module				
AOCS		72.0	7	76.0
Communications		34.0	12	39.0
Data handling		19.0	13	20.0
Harness		60.0	20	72.0
Power		50.0	12	55.0
CPS		22.0	9	23.0
Structure		300.0	20	360.0
Thermal H/W		25.0	20	30.0
SVM Dry Mass		582.0		675.0
Payload Module				666.8
M1	SiC	80.0		
M1 ISMs	Invar/Titanium	6.5		
Instrument Base Plate	SiC	58.5		
Instrument ISMs	Invar/GFRP	15.0		
M2	SiC	5 .0		
M2	Support SiC	40.0		
Refocus incl. 2 Mirrors	various	6.0		
M3-1	SiC	1.2		
M3-2	SiC	1.2		
Fold Mirrors FM1-6	SiC	3.6		
Camera incl. Mirrors	Al	2 .0		
Common Housing for Camera and Spectrometers	Al	6.0		
5 Spectrometers	various	3.5		
FGS (Star Camera)	various	3.0		
Optical Instrument and Structure		231.5	20	277.8
Shield 1	Al-Honeycomb	58.0		
Shield 2	Al-Honeycomb	67.0		
Shield 3	Al-Honeycomb	62.5		
Baffle	Al-Honeycomb	12.6		
2 Struts	GFRP/Al	6.0		
Struts and clamps	GFRP/Al	10.0		
MLI		49.8		
Cooler incl. Lines		10.0		
Thermal HW and Cooler		275.9	20	331.1
Solar Array		5.0		
PCDU		26.3		
Focal Plane Electronics		8.0		
Harness		9.0		
Electronics S/S		48.3	20	58.0
Propellant				127.0
Total Launch Mass				1468.8
Launch Vehicle Capacity				2160.0
Launch contingency [kg]				691.2
Launch contingency [%]				32.0

Table 11: Mass budget estimation of the ECHO spacecraft including payload.

Unit/Subfunction	Consumption [W]	Dissipation [W]	Remark
ICU core	6	5.5	
Instrument HK	5	4	
Digital Processing	8	8	For five spectrometer channels/detectors
Compression stage	2	2	
Encryption	2	2	Optional
Formatter	2	2	
Mass Memory	30	30	Depending on final memory size
Power Conditioning & Distribution	12	9	DC/DC losses, Supply of FEEs, w/o external loads for mechanisms and cal. elements w/o heater consumption
ICU total	67	63	
Front End Electronics	3.0	2.7	For five channels (secondary supply from ICU) including detectors
Fine Guidance Sensor	2.5	2.3	TBC, incl. DC/DC conversion losses
Cooling System	TBD	TBD	Depending on the cooler and the cooling system

Table 12: Power budget estimation of the instrument.

merous consecutive visits scheduled precisely to a limited numbers of scientific and calibration targets. It only requires the ESA standard service of operations as for the other planned L2 missions (Herschel, Plato, Euclid, SPICA) in terms of performance, availability and low risk requirements. It will minimize contact with the ground and systematically prefer to use standards developed for earlier missions. With an estimated data volume of few Gbits per day (11.1), it could be downloaded during 2 passes of 3 hours per week with a required downlink of 1 Mbit/sec, well within existing capabilities (Herschel and ESM study). The ground operation will be composed of the satellite and instrumentation operations controlled by the Mission Operation Center (MOC) of ESA, and likely sharing the control room with other L2 missions.

The Instrument Operation Team (IOT) will be responsible for the preparation of the scheduling of the science observations, controlling performance of the instrument, its calibration with the objective to maintain its optimal operation. EChO will operate autonomously, performing the pre defined sequence of observations for periods that could be up to a week to 10 days. Then, housekeeping and science telemetry will

	TRL	Current heritage /development
Thermal system (shields, radiators...)	8	Heritage Planck / Herschel (adaption needed)
Line of sight stabilization	5 to 7	Heritage laser comunication systems / Herschel
Telescope	5 to 9	see the text for discussion
AOCS	8	Classical system + correction at the instrument level
AOCS	5	EUCLID/GAIA cold gas
Refocusing mechanism	8	NIRSpec (adaption needed)

Table 13: TRL and current heritage for the system of EChO

be downlinked to the MOC while commands to control the satellite and the instruments will be uploaded.

The ESA Science Operation Center (SOC) will receive both the housekeeping and the scientific data. It will perform quicklook analysis of the instrument performance and quality control of the data and will interact with the MOC and the IOT for science planning and scheduling. Data will be distributed by the SOC to the Science Data Centers (SDC) managed by the consortium. The SDC will be in charge of the pipeline developments, the preparation of the Level 2 data, the archiving, distribution of data and of pipelines and analysis tools. SDC will be funded by the national agencies and institutes of the different partners. It will be decided once we will have endorsement documents when discussing the management plan in the next selection phase. Given expertise acquired on earlier missions we estimate that 5 FTE/years will be needed starting 4 years before launch.

11.1 Expected volume and format of the acquired data

We consider as a standard observation a 2 minute integration. For the six channels we are reading subframes leading to 5000×10 pixels, coded on 21 bits, therefore accounting for some housekeeping channels as well and assuming an an allowed average rate into the CDMU of 40 kbits/s we will accumulate 3.5 Gbits of data per day. For the "'housekeeping"' the major data volume will come from keeping the tracking information of the the tip-tilt mirror movements at a high rate (100 Hz) because of the importance of monitoring precisely the position of the spectra on the pixels. With the 3 year baseline mission, this will account for 1 Terabits of raw data, and 1.8 Terabits with the extended mission (3+2 years). We estimate that Level 1 data (dark current, flatfielded, non linearity corrected) will have a volume 4 times larger. The processing from Level 1 to Level 2 (correcting for systematic effects and optimal extraction of the scientific signal) will be the most crucial step. We intend to keep different data products such as state vectors for the instrument while performing deconvolution. We will have 8 10^5 spectra for the baseline mission, 1.3 10^6 spectra in total with the extended mission. Data will written into fits file containing all the house keeping and calibration informations. The final data product of extracted individual spectra will have a size of 10 Gb. Given the modest size of the archive, it could be replicated in the SDCs of the different partners.

11.2 Quick-look assessment of data

One of the key ingredient of the success of EChO is to have an instrument as stable as possible and monitor precisely all the characteristics of the instrument and the telescope. The IOT and the SOC will perform immediate quality control of the downloaded data.

11.3 Ground data processing structure (pipelines, etc.) and challenges

EChO data processing has two main component. First the usual dark corrections, flatfield and non linearities corrections and wavelength calibration to produce Level 1 data. The most challenging part of the data processing chain is the production of the pipeline to produce the Level 2 data. We are intending to provide the most stable possible instrument but the noise budget of our analysis will be dominated by systematics that have to be corrected. uilding on past experience in data analysis of space (HST NICMOS, SPITZER) and ground-based (eg. IRTF, VLT, TNG, WHT) data, the systematics correction will be comprised of a two step process. The temporally resolved spectra (a timeseries covering the eclipse event per spectral channel) will be decomposed into its individual components, using low-order statistic principal component analysis (PCA) or high-order statistic, independent component analysis (ICA). This will effectively separate statistically independent (in the case of ICA) signals in the data set and allow us to de-correlate the individual components with recorded instrumental state vectors recorded for the duration of the observation. These vectors include, but are not limited to, residual temperature variations of instrument-components, tip-tilt mirror position, angle of the thermal shield with respect to the sun, etc. Once de-correlated, the data-set is reconstructed. The second step is a normalised convolution in the frequency domain of wavelength similar timeseries (binning) and/or of several eclipse events (coadding). The advantage of this step is the very effective self-filtering of the signal, reducing all systematics but the common-to-all eclipse signal in the data.

11.4 Archive approach

We will develop the EChO data processing and archiving framework with the objective of offering the astronomy community comprehensive means to get the best scientific return. We will archive and distribute Levels

1 (raw) and 2 (scientific) data, pipelines to remove instrumental and satellite systematic effects and perform optimal extraction of scientific signal, all quality control informations and tools to calibrate the data. We will organize the Level 2 data the following way : Continuous observation sequence of one planet, called a visit, consisting of a time series of extracted spectra for each channel (out of transit and in transit). We will propose a variety of products ranging from individual spectra to mean spectra for the star and the planet. Different SDC will be in place in order to perform internally competitive analysis in order to maximize the quality control ultimately. We also stress that it be homogenous data and the structure straightforward that could built on COROT and other space missions. The challenge will be in the correction for systematics, calibration, extraction of scientific signal and quality control.

11.5 Proprietary data policy

We are planning an early release of a sample of the first six month of observations 18 month after beginning of scientific observations. This would consist of a portfolio of exoplanet spectra of different types to the community. Targets from the core science program will be available 12 months after the acquisition of the last image of the scheduled observations for a given target. From year 2 of the project, we will have a fraction of open time to the worldwide community as guests programs. Moreove, the consortium will explore with ESA and its advisory structure an optimum model for data release during the formulation of the Science Management Plan for EChO.

11.6 Community interfaces and interactions

EChO Science Data Centers will provide a well tested and documented data processing pipelines and data products to the community. This will include all the tools to generate level 2 products (corrected for instrumental response and satellite effects). The pipelines will be open source and developped to be platform independant coded in Java/Jython. The tools will be GUI oriented and EChO products will be made from start VO compliant. Members of the consortium and then the community will have access to the EChO data via interactive sessions with the same philosophy as developped for Herschel.

12 Technology development requirements

12.1 Payload technology challenges and technology development strategy

12.1.1 Detectors and readout circuits

European commercially available HgCdTe detectors (technology ”n on p” or similar) already reach the performance required by EChO until 11 µm, assuming they all can be used at 30 K (to be checked within the instrument development timeframe). For the 11-16 µm spectral range, the level of dark current, even at 30 K (about 10^6 e-/s/px), remains too high to allow sensitive observations. Alternative solutions should be considered. Among them, the use of HgCdTe ”p on on” technology seems to be very attractive and let foresee a decrease by a factor of several 100 of the dark current level (reaching several 10^4 e-/s/px for a detector at 30 K with a cutoff wavelength of 16 µm, value used to estimate the performance of the 11-16 µm in this proposal). These detectors are under development in Europe. CEA/LETI starts recently a 24 month-R&D study on that topic under a CNES contract. The first components should be available for testing by mid 2012. The goal of this R&D study is increase the working temperature of ”p on n” detectors compared to ”n on p” ones by at least 20 K with the same dark current level. This corresponds, at the same working temperature, to a decrease of the dark current by a factor of several 10 to 100. It is not unconceivable to consider this way for EChO. This supposes that the technology is transferred to the industry (e.g. SOFRADIR, AIM, SELEX. . .) within an acceptable timeframe. This also supposes heavy development and optimisation of the readout circuit (ROIC). A 36 to 48 month study is considered as necessary to be able to get ROIC adapted to specific detector. This activity needs to be assessed and included in the EChO development plan but is compatible with the mission schedule.

12.1.2 Cryo-coolers

As mentioned before, cryo-coolers are necessary to make the detector arrays reach 30 K. R&D and qualification effort should be maintained to bring Joule Thomson device at the sufficient TRL for EChO. This devices have no moving parts and are particularly vibration free. An alternative is the use of Turbo Brayton coolers used in the NICMOS/HST camera. This device exhibits a very low level of vibration and the advantage of in flight experience.

12.1.3 Tip-tilt mirror

The tip tilt mirror option for stabilising the pointing requires a low frequency two axis mirror system similar in character to that used for the Beam Steering Mirror (BSM) on the Herschel-SPIRE instrument. This mechanism employs a flex pivot plus linear motor system to give ± 2.5 degrees throw in one axis and ± 0.6 degrees in the other with first order response times of 2 and 0.5 Hz respectively and a maximum power dissipation of a few mW at 4.5 K. The position feedback is via linear magneto-resistive devices providing an estimated accuracy of 1 part in 10000 over the range. These devices are not available any longer but may be replaced by linear encoders. The device is mechanically robust (TRL

9) and the basic design is capable of adaptation to the needs of EChO (increase by a factor of 20 of the angular resolution but over a smaller range of 10 arcsec) with little change to the basic layout. Fast beam steering systems have been also used for laser communication terminals. Such systems are also capable of adaption to the EChO requirements and provide sufficient bandwith to be able to correct AOCS gyro noise.

12.2 Mission and Spacecraft technology challenges

Assuming that the the instrument itself maintains the stability of the line of sight, the main mission and spacecraft technology challenges are linked to the thermal specifications required by the telescope and the instrument. This point requires the use of well suited shields and radiators. A clever design of the spacecraft, coupled to an accurate thermal model of each part is necessary. The Planck / Herschel heritage may be used in that purpose as demonstrated in §10.2.

13 Preliminary programmatics/Costs

13.1 Overall proposed mission management structure

The proposed structure for the mission management is described on Fig. 31.

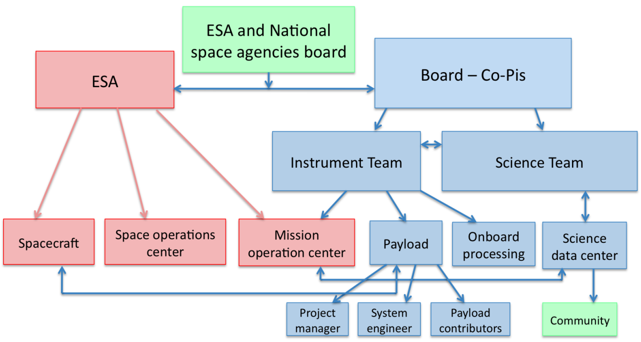


Figure 31: EChO project management structure

13.2 Mission schedule drivers

13.2.1 Development plan

The proposed implementation scheme of the selected proposal will follow the current practice of an ESA science programme under the present call for missions. Phase A and B organisation and time frame is detailed on Fig. 32.

During Phase C the EChO design will be finalised, analysed demonstrating compliance with the requirements and manufacturing files will be prepared for flight models. A Structural Thermal Model and an Engineering Model will be built and tested to support the evolution and qualification of the EChO design. Phase C is concluded by the EChO Critical Design Review.

In Phase D flight hardware manufacturing will be completed, and the EChO PFM will be integrated. The EChO Qualification Review (QR) will complete the incremental qualification and verification review process at lower level before the final instrument performance and qualification testing will commence. During Phase D mathematical models will be finally correlated with the test results of EChO PFM to accurately reproduce instrument performances with the actual test results. After the respective Preliminary Acceptance Review the EChO PFM payload will be delivered to satellite level AIV. Phase D ends with the Final Acceptance at EChO FAR.

13.2.2 AIV plan

The proposed AIV programme is based on an incremental model philosophy, which provides a thorough performances consolidation logic. The development approach is based on widely decoupled activities on a structural thermal model and on an engineering model before starting the protoflight model activities. It is assumed that on spacecraft level a classic STM-EM-PFM approach is followed and that payload models will be requested accordingly. The overall schedule is based on following EChO payload model philosophy:

- Structural / Thermal Model – STM to achieve structural and thermal qualification of the payload module, micro-vibration assessment and model correlation. An early STM qualification programme is planned to validate the thermo-mechanical design with passive cooling of the telescope. The early start is driven by the STM structure delivery and the need to freeze all interfaces by end of phase B2.
- Engineering Model – EM to achieve electrical and functional verification and EMC qualification. This model is essential for electrical and functional verification. The EM payload programme is planned in continuation of the Software Validation Facility (SVF) activities to develop and validate procedures for integration, functional testing and data evaluation. Further more EMC qualification will be achieved avoiding critical tests as arc/discharge on flight hardware. Optical performance verification and pre-validation of the calibration set-up shall be achieved by testing with actively cooled instruments by an adequate GSE.
- Protoflight Model - PFM will experience a full performance verification, calibration and characterisation, and environmental qualification program capitalising on pre-qualification results as far as possible.

As the overall thermo-mechanical design verification requires a complex test in a TV chamber with Helium cooled shrouds, it shall be checked in phase 0 whether a test of a scaled thermal model in one of the vacuum chambers with Helium cooled shrouds is a valid concept. In that case, the payload model philosophy would be changed to an Structural Model (S(T)M), scaled Thermal Model (TM), Engineering Model (EM) and Protoflight Model (PFM).

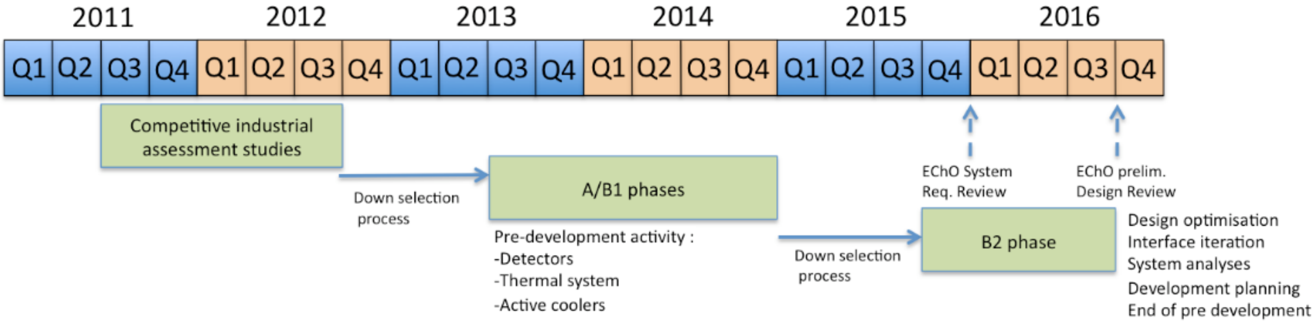


Figure 32: EChO Phase A and B plan.

13.3 Payload/Instrument schedule and cost

The schedule is developed on the basis of the following inter-connection logic between the various AIV campaigns conducted as part of the overall model philosophy:

- STM integration starts about 10 months after PDR assuming long lead item procurement in phase B2
- EM integration starts about 1 year after PDR assuming long lead item procurement in phase B2
- STM and EM AIV programmes have to be completed before PFM integration start
- STM and EM AIV can run in parallel because STM is focussing on mechanical and thermal aspects while EM concentrates mainly on electrical and optical performance

The Master Schedule was derived following the AIV approach given above. The 26 weeks contingency corresponds to 8.0% of duration from kick-off phase B2-C/D to the start of the launch campaign with respect to a launch on 29.03.2022. The contingency increases to 17.3% taking into account a launch by end of 2022 as requested in the Mission Call. A launch in 2020 can be achieved by advancing the pre-implementation phases, optimising payload and satellite test sequences and reducing the final contingency period. The nominal schedule is based on the reference implementation timeline given in table 2 of the annex to the mission call (AD3). Kick-off of phase B2-C/D can be advanced by 9 months. Phase C/D up to PSR can be reduced from 47 months to 42.5 months. The contingency period after PSR can be reduced from 6 months to 4.5 months. The contingency periods in phase C/D remain unchanged. The remaining 18 weeks contingency corresponds to 6.4% of duration from kick-off phase B2-C/D to the start of the launch campaign with respect to a launch on 17.12.2020.

13.3.1 Assumed share of payload costs to ESA

In the preliminary concept of the EChO mission detailed in this proposal, the only part of the payload cost that should be included in ESA's fundings is the telescope itself, including mirrors but neither re-focusing nor tip-tilt devices which are both included in the instrument package. The design and integration in the instrument of these sub-systems are namely strongly linked to the instrumental activities. According to previous experience (SPICA telescope cost estimation and Herschel telescope final cost), the estimated cost of the telescope is about 60 Meuros. Our overall financial contingency of 85 MEuros for the full ESA contribution includes a contigency of 10 MEuros for the telescope

Subsystem	Cost estimation (Meuros)	Fraction of overall funding
ESA contribution		
Spacecraft	130	30 %
Payload (telescope)	60	13 %
Launch service	75	16%
Ground segment (MOC and SOC)	70	15 %
ESA internal cost	47	10 %
ESA Contingency	85	18%
Total ESA contribution : 467 Meuros		
Consortium contribution		
Instrument (incl. OGSE)	80	64 %
Science data centre	25	20 %
Consortium contingency	20	16 %
Total consortium contribution : 125 Meuros		
Overall mission cost : 595 Meuros		

Table 14: Cost estimation of the EChO mission.

13.3.2 Estimated non-ESA payload costs

At this stage of the proposal, it is difficult to have an accurate estimation of the instrument cost without a detailed design and associated development plan. However, it is possible to get an estimation of the costs by analogy comparison with other previous realisations on ISO, Planck, Herschel, JWST. We have performed such an estimation together with industry and estimate the cost of the instrument to be 80 MEuros. Because of development uncertainties in the field of long-wavelength detectors and coolers we assume a conservative 25% contingency on this cost, i.e. 20 Meuros). This instrumental cost includes the required developments, particularly concerning the detectors, tip-tilt and refocusing mechanisms. The overall cost of the instrument will be shared between members of the proposing consortium and funded by their national agencies.

13.4 Overall mission cost analysis

The overall mission cost analysis is summarized in table 14. The ESA contribution fits in the M-class mission envelop. The cost estimation for the satellite has an uncertainty of about 20% at this stage as it is based on a preliminary assessment only. However the overall cost of the mission has also been assessed as part of the

Estec CDF study and found to be within the M-class mission cost cap. Contingency is spread over all the items of ESA contribution. All item cost estimations include technological development if required.

The fraction of the ground segment (15%) has been reduced compared to ESA's guidelines (20%), because the level of operations required by EChO will be reduced. Operations will happen only once per week. The overall volume of data is low and associated resources can be limited compared to other mission concepts, which require much bigger volume of data handling and processing.

14 Communication and Outreach

The discovery of $\sim$ 500 extrasolar planets in the last 15 years is probably the most exciting development of modern astronomy. It resonates enormously with a public that has already been shown to have high interest levels in the exploration of the diverse worlds of our own Solar System, and an insatiable hunger for news about space exploration. It directly addresses deep philosophical issues that concern our fellow citizens: what are other worlds like? how do they form and evolve? are we alone in the universe - Theme 1 of ESA's Cosmic Visions?

So that means that public outreach that aims to engage our fellow citizens with the excitement of EChO and its science objectives will be at the forefront of mission planning.

EChO's team will not re-invent the wheel. We will work closely with established space outreach and educational networks. These will include Europlanet RI (funded by the European Union), 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 local networks.

Openness will be a watchword of the project. Except where commercial confidentiality is at stake, EChO will welcome media professionals into its institutions, laboratories and key workshops. We will make use of new media outlets such as YouTube and Twitter, posting interviews with EChO scientists and engineers on the web, and developing a following amongst "tweeters" that will keep them posted on how the mission is developing, and how it is performing during flight.

Nowadays, amateur astronomers play a crucial role in multiplying the outreach efforts of professional scientists, as a link with the broader general public, as well as providing real input into cutting edge science. They help to embed the aspirations of the astronomical community into society. We will work to engage the amateur astronomer community, giving lectures, making available material that they can use, and encouraging them with a programme of observations to support EChO, in particular, and the science of extrasolar planets, in general. Since most of the targets of EChO are relatively bright stars, follow-up observations of its discoveries will be feasible, profitable and extremely exciting, both to those taking direct part and to the public at large. School students, in particular, can be linked into such a programme, enhancing educational curricula as well as inspiring young people to take up the (physical) sciences in later studies and in their careers.

The EChO team is also keenly aware of how important it is to keep policy makers abreast of scientific developments, particularly in the more "blue-skies" fields, such as space exploration, that create indirect economic benefits to society, whilst pursuing knowledge-based aims. EChO will have a pro-active programme of briefing and informing policy makers at a national and European level, through one-on-one meetings, seminars for politicians, exhibitions at venues such as the European Parliament, and public events that will involve political figures as keynote speakers.

The fascinating new worlds that will be revealed by EChO will need visual support to better capture the imagination of the public. We will produce images, animations, and 3-D simulations suitable for a wide range of online and new media formats. A fine art program will be set up, to translate into high impact images, but carefully consistent with our best knowledge about these planets, the findings of EChO. This will be continuing and expanding the tradition of the "Space Art" movement that was initiated in Europe a century ago (most notably by L. Rudaux). At the time, when people painted landscapes of the Solar System they could not even dream those would be revealed by spacecraft decades later — likewise, can we dream that those exoplanets studied by EChO will reveal the secrets of a very wide variety of other worlds, including habitable ones. There is no doubt that many sponsors, inside the scientific and artistic community, and from industry and commerce could be found to support this imaginative arts-science programme.

Each planet tells a tale, and all these tales help us put the story of our home planet, the Earth, into perspective. Popularizing EChO results will be done, too, in the context of Earth's own story – what can we learn about our Home Planet from these distant and thus far unfamiliar worlds?

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