DOCUMENT

EChO - Science Requirements Document

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CHANGE LOG

Reason for change	Issue	Revision	Date
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Update to reflect further definition and consolidation of the science requirements	**3**	**1**	**30/09/2013**
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CHANGE RECORD

Reason for change	Issue	Revision	Date
Update of descriptive text in all sections of the document	**3**	**1**	
Addition of requirements (001 – 008) to capture definition of the EChO core survey/survey modes	**3**	**1**	
Update and augmentation of SNR requirements to reflect updated survey strategy (055-059)	**3**	**1**	
Inclusion of requirements to capture scheduling constraints (060 and 065)	**3**	**1**	
Inclusion of goal requirements to capture secondary science objectives (210 and 220)	**3**	**1**	
Update of baseline bandwidth for photometric stability requirement	**3**	1	
Update of definition of classes of exoplanet and mean values for mass and radius.	**3**	**1**	
Creation of the design reference mission document to capture possible EChO survey target lists.	**3**	**1**	
Explicit reference to model to be used for the zodiacal background (taken back from MRD) (200)	**3**	**1**	

Update of naming of descriptive text, including naming of core survey tiers; update of science management requirement 230	**3**	**2**	December 2013

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1 INTRODUCTION

1.1 Purpose

This document provides the top-level science requirements for the Exoplanet Characterisation Observatory (EChO), a dedicated mission to investigate exoplanetary atmospheres.

The EChO mission was proposed to ESA in response to the M3 call in ESA's Cosmic Vision programme, and was selected for assessment in February 2011. The mission in turn builds on a concept for an Exoplanet Spectroscopy Mission (ESM) that was recommended by the Exoplanetary RoadMap Team (EPRAT) in 2009/10 for study by ESA.

The science requirements were initially derived from the science objectives described in the EChO M3 proposal [RD1] and have been refined and updated following discussions between the EChO science team and the ESA internal study team. This document was first written as input to the CDF study starting in June 2011. It has been updated continuously since, and will continue to be refined over the course of the study.

1.2 Scope

The aim of this document is to detail the science requirements for all aspects of the mission. As such, the document provides a means by which to understand, trace and support a detailed analysis of the relationship between the science objectives of the mission and the specification of the mission and payload

1.3 Acronyms

CDF	Concurrent Design Facility
EChO	Exoplanet Characterisation Observatory
EPRAT	Exoplanet Roadmap Advisory Team
ESM	Exoplanet Spectroscopy Mission
PPM	Parts per million
NIR	Near Infrared
MIR	Mid Infrared
M_{planet}	Mass of planet
pc	parsec
r_{sol}	Radius of the Sun
r_{Earth}	Radius of the Earth
R	Resolving power $\lambda/\Delta\lambda$
RSS	Root Sum Square
SciRD	Science Requirements Document
SED	Spectral Energy Distribution
SNR	Signal-to-noise ratio
T_{eff}	Effective temperature (star)

T_{planet}	Temperature of planet
TBC	To be confirmed
TBD	To be decided

1.4 Definitions

The term planet is used interchangeably with exoplanet, and refers to planets outside our own Solar System, unless explicitly stated.

Unit	**Value**	**Comment**
M_{sol}	1.9891×10^{30} kg	Mass of the Sun
$M_{Jupiter}$	1.8987×10^{27} kg	Mass of Jupiter
M_{Earth}	5.9742×10^{24} kg	Mass of the Earth
r_{sol}	6.9551×10^{8} m	Radius (equatorial) of the Sun
$r_{Jupiter}$	7.1492×10^{7} m	Radius (equatorial) of Jupiter
r_{Earth}	6.3781×10^{6} m	Radius (equatorial) of Earth
Pc	3.0857×10^{16} m	Parsec

In subsequent sections of the document we refer to Jupiters, Neptunes, small Neptunes and Super Earths. For the purpose of this document we define the mean mass and mean radius for each type in the table below. A justification for the choice of mean values is given in [RD10].

Planet Class	Exoplanet Radius [r_{Earth}]	Exoplanet Mass [M_{Earth}]
Jupiters	10 r_{Earth}	300 M_{Earth}
Neptunes	4.0 r_{Earth}	15 M_{Earth}
Small Neptunes	2.6 r_{Earth}	6 M_{Earth}
Super-Earths	1.8 r_{Earth}	7 M_{Earth}

Stellar emission is modelled by spectral energy distributions (SEDs) that have been generated using the Phoenix atmosphere models [RD5] assuming a surface gravity/log g = 4.5 and solar metallicity. A library of the SEDs of potential EChO target host stars, specifically the radiation flux density at the surface of the star as a function of wavelength, can be provided on request.

1.5 Reference documentation

[RD1] EChO Exoplanet Characterisation Observatory: Exploring Atmospheres of Diverse Worlds Beyond our Solar System (proposal submitted to ESA on Dec. 3rd, 2010 in response to call to M3 missions)

[RD2] ESA Radiometric model description (SRE-PA/2011.040)

[RD3] EChO consortim radiometric models and end-to-end instrument simulator (EChOSIM) (EChO URD and SRD)

[RD4] Tessenyi et al., "Characterising the Atmospheres of Transiting Planets: from Hot Gas Giants to Terrestrial Habitable Planets", ApJ, 746, 45 (2012)

[RD5] Allard, F., Homeier, D., Freytag, B., "Models of Stars, Brown Dwarfs and Exoplanets" , 2011, arXiv:1112.3591

[RD6] Ciardi, D. et al., " Characterizing the Variability of Stars with Early-release Kepler Data" AJ, 141, 108 (2011)

[RD7] Winn, J. et al., "A Super-Earth Transiting a Naked-eye Star", ApJL, 737, L18 (2011)

[RD8] Bouchy, F. et al. ,"ELODIE metallicity-biased search for transiting Hot Jupiters. II. A very hot Jupiter transiting the bright K star HD 189733" A&A, 444, L15 (2005)

[RD9] Webpage for evaluation of the pointing–specific contribution of the Zodiacal background:
http://lambda.gsfc.nasa.gov/product/cobe/dirbe_zodi_sw.cfm

[RD10] Ribas et al., "EChO targets: the Mission Reference Sample and Beyond" (EChO-SRE-SA-PhaseA-001)

[RD11] Glasse, A. et al. " The Throughput and Sensitivity of MIRI", Proc. SPIE (2010), 7731, p11

[RD12] The EChO Study Science Team, "The Design Reference Mission" (EChO-SRE-SA-PhaseA-010)

[RD13] Tessenyi, M. & Tinetti, G., "NH3 detectability: 11 micron vs. 10.6 micron cutoff" (ECHO-TN-0006-UCL)

[RD14] Barstow et al., "On the potential of the EChO mission to characterize gas giant atmospheres", MNRAS (2013), 430, 1188-1207-1188-1207

[RD15] Tessenyi et al., "Molecular detectability in exoplanetary emission spectra", Icarus(2013), 226, 1654

1.6 Document overview

In Section 2 we describe the fundamental science goals for the EChO mission, and proceed in Section 3 to detail the observing strategies and techniques that will be used to achieve these goals. In Section 4 we define the requirements for the EChO survey, identify the most demanding of the prospective targets and then derive the high-level science requirements for the mission. In Section 5 we tabulate these requirements.

2 SCIENCE GOALS

EChO is designed to measure the chemical composition and structure of hundred(s) of exoplanet atmospheres, with uninterrupted spectroscopic coverage from visible-to-infrared wavelengths. Targets will extend from gas giants (Jupiter- or Neptune-like) to super-Earths, in the very hot to temperate zones of F to M-type host stars, opening up the way to large-scale, comparative planetology that will firmly place our own solar system in the context of other planetary systems in the Milky Way.

2.1 Primary science goals

EChO will address the following fundamental questions:

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

EChO will provide spectroscopic information on the atmospheres of a large, select sample of exoplanets (> 100) allowing the compositions, temperature (profile), size and variability to be determined at a level never previously attempted. This information will be used to address a whole range of key scientific questions:

- Does the planet have an atmosphere?
- What are exoplanets made of?
- How were they formed?
- Did they migrate and if so how?
- How do (exo-)planet evolve?
- How are they affected by starlight, stellar winds and other time-dependent processes?
- Weather: how do conditions vary with time?
- What is the energy budget for the planet?

And of course:

- Do any of the planets observed have habitable conditions?

These objectives, tailored for gaseous and terrestrial planets, are summarized in Table 1.

Planet type	Scientific question	Observable	Observational strategy	Comments
Gaseous planets	Energy budget	Incoming and outgoing radiation	Stellar flux + planetary albedo and thermal	Chemical Census

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

	atmosphere?		particular) to constrain the scale height	
	Main atmospheric component	Scale height	Transit spectra at multiple wwavelengths (IR in particular) to constrain the scale height	Chemical Census
	Planetary interior	a. Density b. Hints from atmospheric composition?	a. Transit + mass from Radial Velocity b. Transit and eclipse spectra	Chemical Census
	Formation: Formed in situ? Migrated? Core of a giant planet? Frequency of Venus-like, Mercury-like, Ocean planets.	a. Density b. Is there an atmosphere? c. Primary (H2-rich) or secondary atmosphere? d. Atmospheric composition?	a. Transit + mass from Radial Velocity b. c. d. Transit and eclipse spectra	Chemical Census
Temperate terrestrial planets	Habitability	a. Temperature b. Chemical composition (H2O? CO2? O3?)	a. Eclipse measurements b. Transit or eclipse measurements at low R.	Challenging, need a late M star, bright in the IR

Table 1: A summary of the science objectives of the EChO mission. The specific tier of the EChO core survey , or specific target type, in/with which the science objective will be addressed is indicated in the comments column – further details on the different tiers of the core survey are given in Table 2 and Section 4.1.

2.2 EChO science beyond exoplanets

Several science objectives are achievable with EChO beyond the primary science objectives of exoplanets characterization. Some will be included in the main list of target, but others can also be left available for open time for the science community.

- **Observation of young stellar objects**
  Classical T Tauri stars with circumstellar disks can be observed with EChO in order to determine the physical properties of stars and disks and their variability.
- **Direct observation of solar system objects**
  Solar system objects will serve as calibration reference for EChO. Moreover, in terms of outreach, obtaining spectra of many objects from the same spectrometer will also valuable for textbooks references.
- **Stellar occultations by Solar System Kuiper Belt objects**

Occultation by Kuiper Belt objects of the Solar System (including Pluto) are expected at an occurrence of ~1/year : they can provide valuable information on the atmospheric composition and structure of these poorly known objects.

- **Planetary Seismology**
  Planetary interiors can be observed by the means of continuous observations of a planet (Uranus and Neptune being the best candidates), to detect coherent acoustic waves influencing the planetary flux.
- **Brown dwarfs**
  By monitoring brown dwarfs over at least one rotation cycle (typically 10 hours), we will characterize their spectral variability typically due to the presence of clouds on their atmosphere. The physics at play in the atmosphere of brown dwarfs is close to the hot Jupiters. Such targets will provide a calibrator to the codes use to decipher the properties of hot Jupiters.

3 OBSERVATIONAL STRATEGY

Variations in the measured signal from spatially unresolved observations of an exoplanet at different points in its orbit around its host star will be used to determine the spectrum of the planetary atmosphere (see Figure 1).

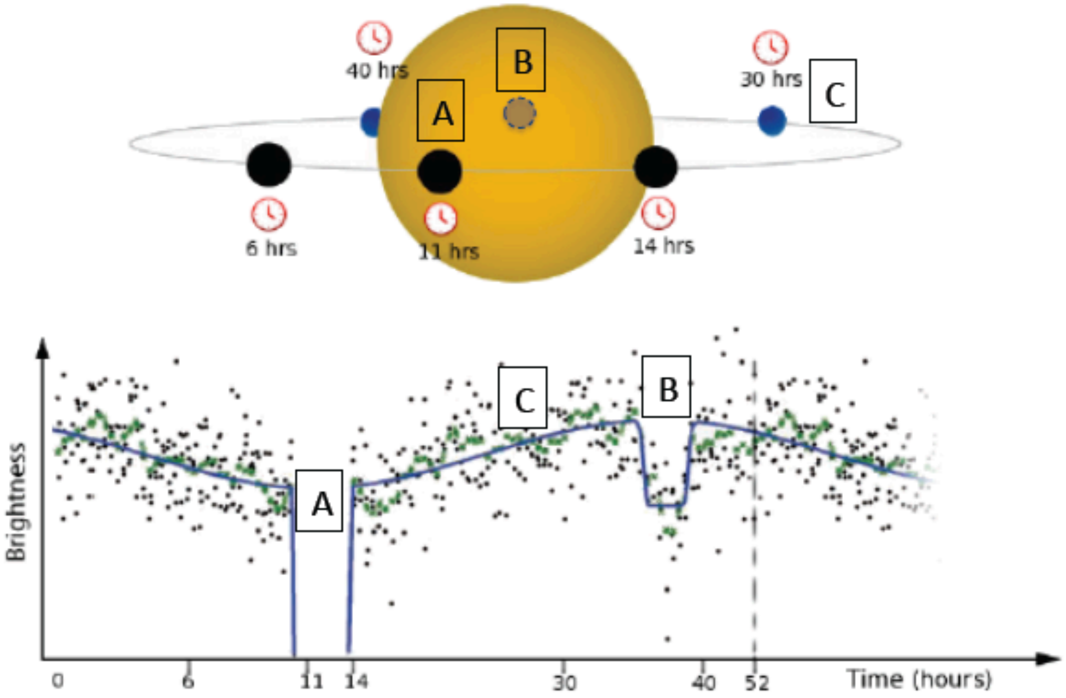


Figure 1: A schematic cartoon illustrating the orbit of an exoplanet around its host star and the resulting light curve measured from the combined star-exoplanet as a function of time, based on observations by Borucki et al (Science 2009, 325, 709) of HAT-P-7b with Kepler. Event A is referred to as a primary transit; B as occultation or a secondary eclipse and C as the orbital phase.

The signal from both the star and exoplanet are collected simultaneously. The signal from the exoplanet – a very small fraction of the total – can be isolated by differencing observations made at various points of the exoplanet's orbit. Each of the three sets of observations detailed below enable different characteristics of the exoplanetary atmosphere to be probed.

3.1 Secondary eclipse/occultation spectroscopy

During an eclipse, or occultation, a planet moves behind its host star (Figure 1, event B). The planet is temporarily blocked from view, and the observed signal is that from the star alone. On either side of occultation the observed signal is the combination of stellar light, light reflected by the planet and a component due to emission from the planet itself. By differencing the in- and out-of-occultation observations one can determine the dayside planetary spectrum.

In the near and mid-IR, the planetary signal is dominated by a thermal continuum that is modulated by molecular features. At these wavelengths emission is dominated by thermal emission modulated by molecular absorption/emission features. These are highly dependent on the thermal structure of the atmosphere and thus such spectra provide sensitive probes of the physical conditions at different heights within the planetary atmospheres. To be able to disentangle the molecular contribution from the vertical thermal structure, broad wavelength coverage is essential. The ability to detect key molecules in multiple spectral bands reduces sources of error and degeneracy in the interpretation of the observations.

In the optical the planetary signal is dominated by Rayleigh and/or Mie scattering of the stellar radiation. The exoplanet spectrum can therefore be used to establish the potential presence of clouds/weather systems.

Measurement of the planetary albedo (% of stellar light reflected by the planet) and thermal emission from the planet provide valuable constraints to the planetary energy balance.

Out-of-occultation: $F_*(\lambda) + F_p(\lambda)$
During occultation:$F_*(\lambda)$

Where: F_* = stellar flux; F_p = planetary flux;

3.2 Transmission spectroscopy – primary transits

During a transit, an exoplanet passes in front of its host star (Figure 1, event A). Stellar light passes through the limb of the planetary atmosphere as the planet transits. Part of the stellar light is absorbed: light passing through the planetary atmosphere bears absorption features that are characteristic of the atmospheric. The stellar light that passes through the atmosphere is a small fraction of the total signal measured in the telescope, which will be dominated by the light from the star itself, with a small additional component due to the emission from the night side of the planet. By differencing the in- and out-of-transit measurements one can isolate the fingerprint signal from the exoplanetary atmosphere.

Transmission spectroscopy probes the atmosphere at the terminator region of a planet. The atmospheric absorption features typically scale with the scale-height of the atmosphere, which in turn depends on temperature, molecular composition (mean molecular weight) and gravity. For this reason, this technique is more powerful for hot and “fluffy” types of atmosphere compared to very compact atmospheres (e.g. a Venus-like planet).

An advantage of transmission spectroscopy over emission spectroscopy, is that it is much less sensitive to atmospheric thermal gradients: molecular features always appear in absorption, so the interpretation of the spectra is less degenerate.

Out-of-transit: $F_*(\lambda) + F_p(\lambda)$
In-transit: $F_p(\lambda) + F_*(\lambda)\ [1 - (R_p(\lambda)/R_*)^2]$

Where: F_* = stellar flux; F_p = planetary night-side flux; R_p = planetary radius; R_* = stellar radius;

3.3 Phase variation

The fraction of the exoplanet dayside hemisphere visible to the observer changes with orbital phase: from a maximum at eclipse to a minimum at transit. If we assume that the stellar emission is constant, then the combined signal from the star + exoplanet measured at different points around the planet's orbit is made up of this constant stellar component and a slowly varying contribution from the exoplanet (**Figure 1**, C) due to changes in reflected starlight (at optical wavelengths) and in planet thermal emission. Such phase variation can be recovered by measuring the minute differences between observations made at different points in the planetary orbit and the background frame measured during secondary eclipse, revealing the longitudinal brightness distribution of the planet. This provides insights not only into the redistribution of absorbed stellar energy, but also into the dynamics of the exoplanetary atmosphere, which in turn is intimately linked to the chemistry.

3.4 Systematics

A tacit assumption of the EChO observing model is that any temporal variation in the calibrated signal from the (unresolved) host star/exoplanet can be attributed to changes in the (small) signal from the exoplanet, and is not a result of variation in either the stellar signal or instrument response. G, K and M stars are known to be variable to some extent. The most up-to-date and comprehensive information on stellar variability comes from the studies with Kepler (stability of 200/40 ppm in a 6.5 hr period on a 11/7 mag (V) star) that are based on the observation and analysis of ~150,000 stars taken from the first Kepler data release. Ciardi et al (2011) [RD6] have found that 80% of M dwarfs have dispersion less than 500 ppm over a period of 12 hours, while G dwarfs are the most stable group down to 40 ppm. Kepler operates in the visible (430 – 890 nanometer) where stellar photometric variability is a factor of more than 2 higher than in the "sweet spot" of EChO – the near and thermal IR – due to increasing contrast between spots and the stellar photosphere with decreasing wavelength. Timescales for stellar activity are mostly very different from those associated with single transit observations (a few hours) and so removal of this spectral variability is possible. As a case in point, photometric modulations in the host of CoRoT-7 b are of the order of 2% and yet a transit with a depth of 0.03% was identified. Analyses of observations from Kepler have yielded comparable results. Note that the timescale for phase variation and stellar variability is more similar.

The effects of stellar activity on EChO are very different in the case of transit and occultation observations. Alterations in the spot distribution across the stellar surface may modify the transit depth (because of the changing ratio of photosphere and spotted areas on the face of the star) when multiple transit observations are considered, potentially giving rise to spurious planetary radius variations. Correction of this effect requires the use of very quiet stars or precise modelling of the stellar surface using external constraints. The situation is much simpler for occultations, where the planetary emission follows directly from the depth measurement. In this case, only activity-induced variations on the timescale of the duration of the occultation need to be corrected for to ensure that the proper stellar flux baseline is used. In the particular case of EChO, photometric monitoring in the visible will aid in the correction of activity effects in the near and thermal IR.

A potentially significant source of variability will come from the detectors. Systematic variations of flux measurements of the host star/exoplanet system will arise from temporal or spatial variations of detector parameters such as the temperature dependence of detector responsivity, spectral response and linearity; spatial variation of detector inter- and intra-pixel variations (in combination with spacecraft pointing jitter); detector illumination history via persistence effects; cosmic ray effects and annealing history; variations of detector bias and electrical and optical crosstalk. Many of the limitations can in principle be calibrated out through extensive calibration and evaluation undertaken on-ground prior to launch.

4 SCIENCE REQUIREMENTS

EChO will measure the reflected/emitted/transmitted spectra of a sample of exoplanetary atmospheres over the visible to thermal IR wavelength range. The planets under study will range from hot Jupiters (T_{planet} >700K, M_{planet} >100M_{Earth}) to temperate super-Earths (T_{planet}~ 250-350K, M_p ~ 5M_{Earth}). Measurements of phase-variations will be made primarily on a subset of short period exoplanets orbiting a bright host star, which are the most favourable to be observed with such technique.

We have identified key science performance parameters that will drive the specifications of the EChO mission. These include:

i. wavelength coverage
ii. spectral resolving power
iii. signal-to-noise ratio and noise requirements
iv. photometric stability
v. sky visibility/source accessibility
vi. temporal resolution
vii. limiting targets
viii. calibration
ix. zodiacal light and backgrounds

In section 4.1 we discuss the EChO sample. In the sections 4.2 –4.10 we take each of the parameters listed above and detail the requirements that the EChO science objectives place on that parameter. In addition, in section 4.11 – 4.12 we consider the goal requirements that EChO science beyond exoplanets (section 2.2) place on the mission, as well as requirements on the division of observing time between survey, observatory and director's time.

4.1 The EChO sample

Many of the primary science objectives summarised in Section 2 call for atmospheric spectra of a large and diverse sample of known exoplanets covering a wide range of masses, densities, equilibrium temperatures, orbital properties and host-stars. Other science objectives require, by contrast, the very deep knowledge of a select sub-sample of objects. To maximize the science return of EChO and take full advantage of its unique characteristics, a three-tiered approach, has been considered, where three different samples are observed at optimised spectral resolutions, wavelength intervals and signal-to-noise ratios.

- Chemical Census - a shallow tier comprising the largest number of targets that will be used to establish the major chemical constituents of exoplanetary atmospheres, exploring the existing chemical diversity. Measurements of albedo and thermal emission will also determine/constrain the energy budget of those planets.

- Origin – a deeper tier which will provide the means with which to determine the molecular abundances of key atmospheric components as well as trace gases (e.g. H_2O, CO, CO_2, CH_4, NH_3 etc).
- Rosetta Stones – a third ultra-deep tier which will survey a small and select number of the brightest and most favourable targets to determine very accurate molecular abundances, horizontal and vertical thermal profiles and chemical gradients as well as temporal variability.

A summary of the survey tiers is given in **Table 2**.

The EChO Core Sample		
Name of survey	Characteristics	Description
Chemical Census	Survey	Exploring the chemical diversity of exoplanets. Either primary or secondary eclipse spectra. Average SNR~5: R=50 for λ<5 micron; R=30 for λ >5 micron.
Origin	Deep survey	Understanding the origin of exoplanet diversity. Both primary and secondary eclipse spectra. Average SNR~10: R=100 for λ <5 micron; R=30 for λ >5 micron.
Rosetta Stone (Exo-meteo/mapping)	Ultra-deep survey	A small sample of the most interesting targets spanning a range of exoplanet/host star classes, used as benchmark cases. Average SNR~20: R=300 for λ <5 micron; R=30 for λ >5 micron. (For a subset, weather through repeated observations, 2D-3D mapping, phase curves will be studied).

Table 2: A summary of the three tiers of the EChO core survey.

Examples of the possible target lists for the core survey based on currently known and potential future targets are described in the design reference mission [RD12]. Note that the Exo-meteo/mapping and Rosetta Stone are used interchangeably to refer to the ultra-deep tier of the survey.

R-SCI-001: EChO shall observe a core sample of > 100 exoplanet targets, known as the EChO core survey.

G-SCI-002: EChO should observe a core sample of > 200 exoplanet targets, known as the EChO core survey.

R-SCI-003: The mission design shall allow observations to be carried out of a wide range of planetary sizes from gas giants to super-Earths. These will have a range of temperatures from hot (up to 3000K) to temperate (350 K) and are found orbiting a range of stellar types and magnitudes from cool M-dwarfs to hot F-stars. The mission design shall encompass both the faintest and brightest expected targets. Nominally these are exemplified by the systems GJ1214 (faint cold dwarf star) and 55Cnc (bright G star).

R-SCI-004: The survey will be divided into three survey tiers: the names, characteristics and description of the each of the tiers are given in Table 2.

R-SCI-005: More than 25 (TBC) of the planets observed in the Chemical Census tier shall be observed in the Origin tier.

G-SCI-006: More than 50 (TBC) of the planets observed in the Chemical Census tier should be observed in the Origin tier.

R-SCI-007: More than 10 (TBC) of the planets observed in the Chemical Census tier shall be observed in the Rosetta Stone tier.

G-SCI-008: More than 20 (TBC) of the planets observed in the Chemical Census tier should be observed in the Rosetta Stone tier.

Note: The EChO Project Scientist shall ensure that a list of targets is defined that meets the requirements expressed in this document and which can be observed within the mission lifetime. The list shall be based on the design reference mission document [RD12] that shall, in turn, be derived in consultation with the Community and Advisory Structure.

EChO will measure the physical and chemical properties of a broad and diverse sample of exoplanets, spanning a wide range of masses, densities, equilibrium temperatures, orbital properties, host star parameters. It is expected that the numerous ongoing and future transit search experiments will keep on discovering new targets of EChO interest and improve on those presently available.

4.2 Wavelength coverage

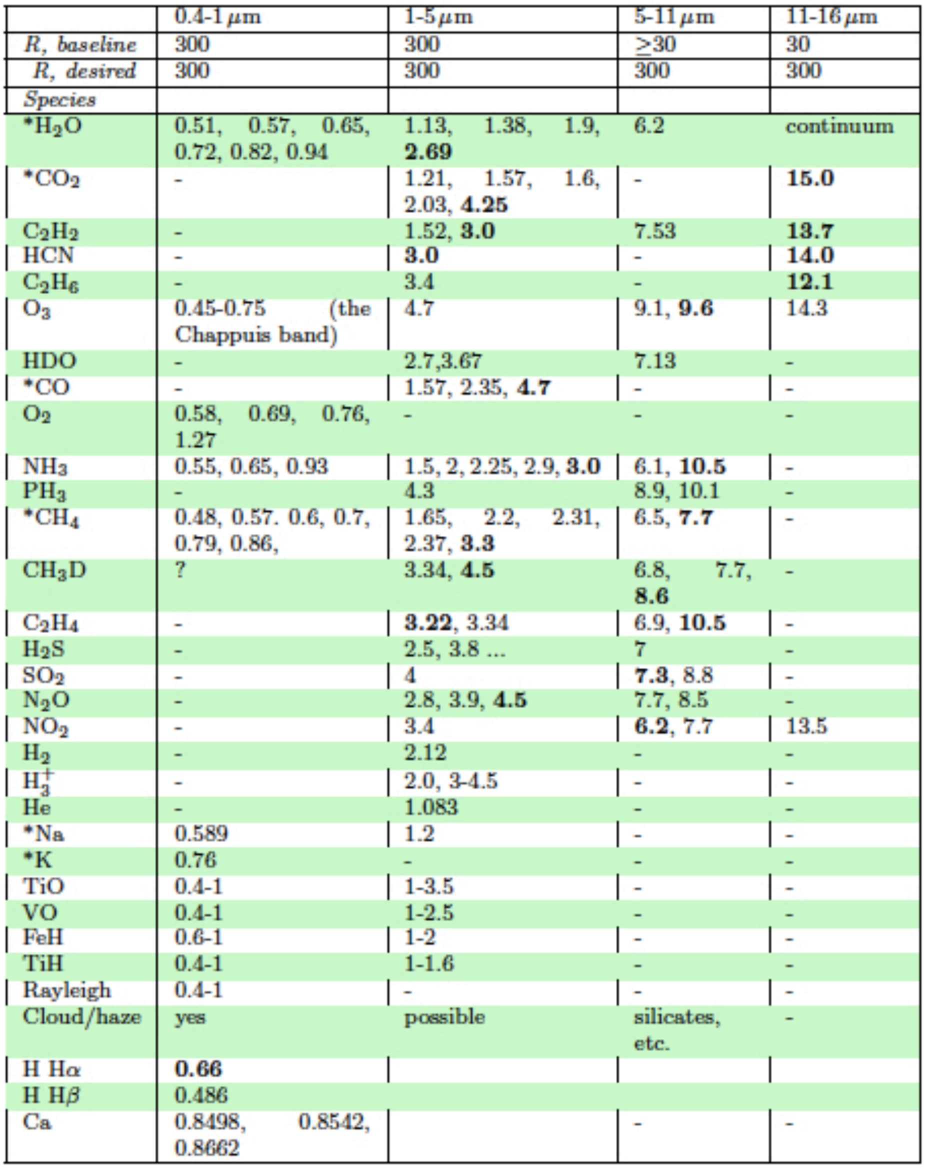
Spectral coverage over a broad wavelength range (~0.55 – 11 micron, goal 0.4 – 16 micron) is required in order to cover the wide range of spectroscopic emission and absorption features that will be used to probe the exoplanetary atmospheres of the EChO sample.

The key molecules that will be targeted by EChO are H_2O, CO, CO_2, CH_4 and NH_3: spectral features from these species are listed in Table 3 along with those of other important molecular, ionic and atomic species.

The role of the visible channel (VIS; ~ 0.4 -- 0.8 micron) is two-fold: (a) to monitor stellar activity by following the variation of a number of metallic spectral features, which in turn can be used to provide a measure of the global flux variations (photometric light curve of the star) (b) to provide an estimation of the planetary albedo (to estimate correctly the energy balance) and Rayleigh scattering/cloud contribution through transit observations.

The 1-5 micron waveband is essential to characterise hot/warm planets, as the peak of the Planckian for those temperatures occurs in this waveband. It can be seen from Table 3 that almost all proposed tracers – molecular, atomic and ionic - have spectroscopic features in this wavelength region.

The 5-11 micron waveband is essential to characterise temperate planets as the peak of the Planckian for those temperatures falls in this waveband (note: almost no photons are emitted at $\lambda < 5$ micron by a source at 300 K).
O_3 (biomarker), NH_3, CH_3D, C_2H_4, SO_2, NO_2 can all be detected at these wavelengths.
Additionally, even for hot planets this waveband is key to improving the retrieval of the atmospheric thermal structure. Note that 11 micron should not be considered a too rigid boundary: the impact on the detection of ammonia of a long wavelength cutoff that is slightly shorter is discussed in [RD15].



	0.4-1 μm	1-5 μm	5-11 μm	11-16 μm
R, baseline	300	300	≥30	30
R, desired	300	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 Hα	**0.66**			
H Hβ	0.486			
Ca	0.8498, 0.8542, 0.8662		-	-

Table 3: A table of key spectral features that will be used to study the physical and chemical characteristics of exoplanetary atmospheres. Wavelengths given in bold are the fundamental vibrational modes of the particular molecules. *indicates that the molecule/atom/ion has already been detected in an exoplanetary

The 11-16 micron waveband plays host to a number of molecular species that can be used to recover of thermal profile of the atmosphere. These include the CO_2 band at 15 micron (especially for temperate planets), the C_2H_2 and HCN bands at 13.7 and 14 micron and C_2H_6 at ~12 micron which at these wavelengths do not overlap.

R-SCI-010: The instantaneous wavelength coverage of EChO shall span 0.55 to 11 micron.

G-SCI-020: The instantaneous wavelength coverage of EChO should span 0.4 to 16 micron.

R-SCI-030: For wavelengths greater than 3 micron, division of the EChO waveband shall be made such that no cut falls between the following wavelength intervals (inclusive):

3.00 - 3.60 micron, 4.10 - 5.00 micron, 5.70 - 8.30 micron, 9.20 - 11.00 micron

For wavelengths less than 3 micron, division of the EChO waveband shall respect each of the following constraints:

(1) No cuts are permitted between the following intervals ($CO+CO_2$ features):
1.55 - 1.67 micron, 1.91 - 2.10 micron, 2.30- 2.39 micron, 2.65 - 2.82 micron

(2) Cuts may fall in not more than one of the four intervals listed for each of the two groupings below:
Group A (H_2O features): 1.10 – 1.20 micron, 1.31 - 1.50 micron, 1.75 - 2.02 micron, 2.38 - 3.00 micron

Group B (CH_4 features): 1.10 - 1.20 micron, 1.31 - 1.50 micron, 1.60 - 1.85 micron, 2.11 - 2.52 micron

(3) No cuts are permitted between the following intervals:
0.55 – 0.61 micron (Sodium "D" lines doublet), 0.645 – 0.665 micron (H-alpha), 0.69 – 0.72 micron (CaH/TiO), 0.74 -- 0.80 micron (Potassium "D" lines doublet)

In-band (where in-band refers to a wavelength interval in which cuts cannot be made) performances should meet all other SciRD requirements. In the transition region between two adjacent bands, relaxation of in-band performance to 50% is allowed taking into account both adjacent channels i.e. at any wavelength in the transition band at least one of the two adjacent channels or the combination of signals from these channels has to have at least 50% performance. This is shown graphically in Figure 3a: it is assumed that the point at which the performance falls to 50% for both channels is located at the centre wavelength of the transition band. The wavelengths of spectral features associated with key and goal species, as well as the corresponding intervals in which cuts should not be made, are tabulated in Table 4. These are also shown in Figures 3b and c, in which normalized, representative model spectra from these same species as seen in occultation are plotted over the 1 – 5 and 1 – 16 micron intervals respectively.

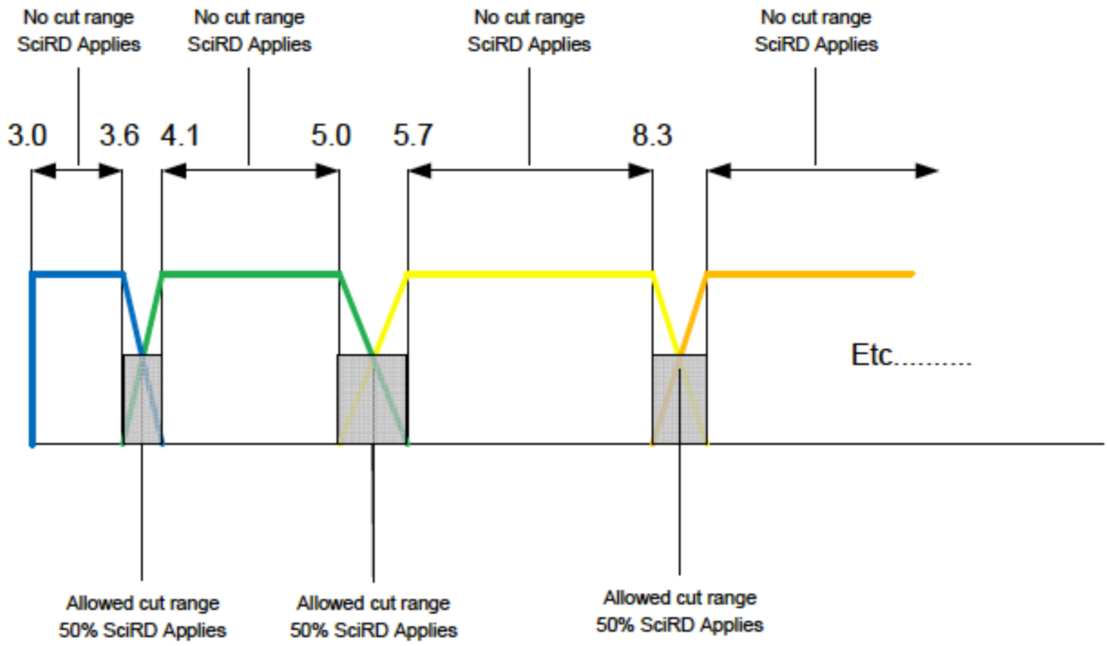


Figure 2a: A pictorial illustration of how cuts in the EChO waveband should be made. Wavelengths are given in microns

G-SCI-031: Division of the EChO band should be made such that no cut falls in the following intervals (inclusive):

1.95 - 2.10 micron (H_3+); 2.50 - 2.70 micron (H_2S); 2.90 - 3.10 micron (HCN+C_2H_6);

3.30 - 3.50 micron (C_2H_6); 3.85 - 4.10 micron (H_3+); 4.10 - 4.40 micron (PH_3+H_2S)

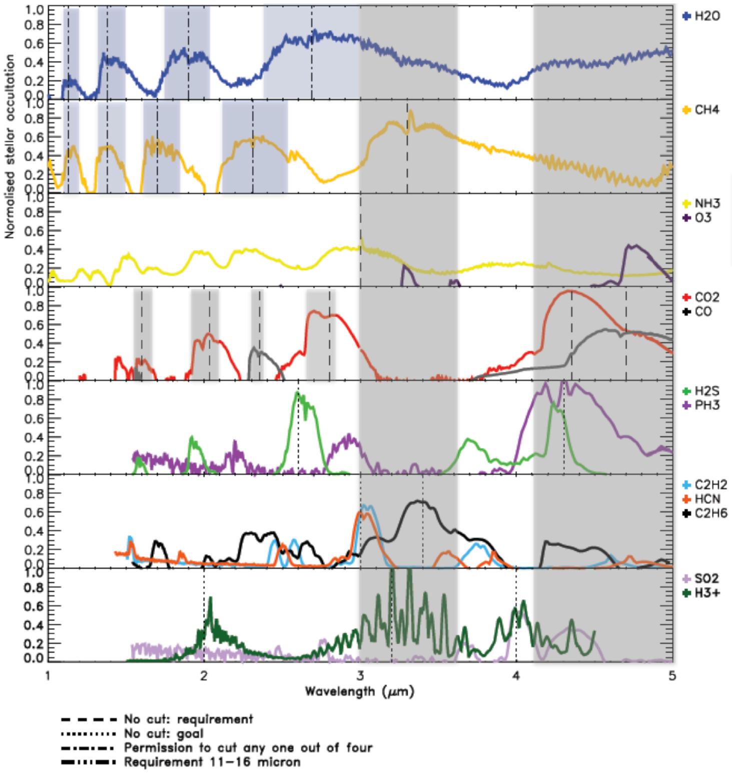
G-SCI-031a: Division of the EChO waveband should be made such that no cut falls in the wavelength interval 13.50 - 16.00 micron

The notes specifying the performance requirements in-band as well as in the transition band as detailed in R-SCI-30 hold for G-SCI-031 and G-SCI-031a also. It is recognised that there are large number of features associated with goal species and that it may not be possible to avoid placing a cut within the corresponding intervals for features that fall at wavelengths outside the interval given in G-SCI-031a. Wavelengths of these goal species features, along with their intervals, have been included in Table 4 for completeness.

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

H_2S	**2.6 (2.50, 2.70)**	**4.30 (4.10, 4.40 to include PH_3 @ 4.30), 8.00 (7.50-8.50)**
SO_2		**7.30 (7.00-7.50), 8.80 (8.20-9.00)**

Table 4: A table of wavelengths of sectral features in the EChO waveband at which subdivision of the waveband should not be made. Associated with each wavelength is an interval (lower bound, upper bound) in which the cut should not fall.



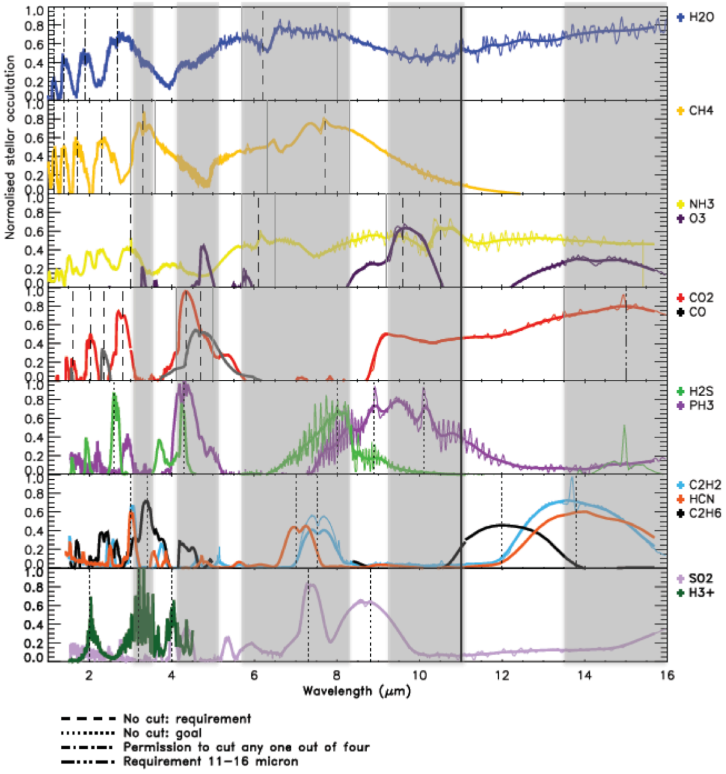


Figure 3b (upper): Plots of the normalised expected signal from a model exoplanet atmosphere observed during stellar occultation, as a function of wavelength for key and goal species. Vertical lines indicate the centres of spectral features (see legend for further detail). Lightly shaded bands indicate the intervals around a spectra feature in which a cut must not fall, as specified in R-SCI-030. In the case of H_2O and CH_4 where necessary a cut can be made in any one of the four shaded (light blue) intervals indicated for each molecule.

Figure 3c (lower): As for Figure 3b, covering the 1 – 16 micron wavelength interval. Note, only those intervals above 3 micron are indicated.

R-SCI-032: The overlap between spectral channels shall be ≥ 5 resolution elements for λ <5 micron (assuming R≥300) and ≥ 1 resolution element for λ>5 micron (assuming R≥30).

R-SCI-033: A minimum of 80% of the in-channel average performance is required for each resolution element.

4.3 Resolving power.

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

At wavelengths shortward of 5 micron, a resolving power of R~300 is sufficient to separate molecular and atomic features (see Figure 2).

At wavelengths longward of 5 micron, the spectral features are broader, especially at hot temperatures, thus a spectral resolving power of R ~ 30 is sufficient to detect the molecules (See Figure 2). A goal would be to separate the rotational components, for which a resolving power R~60 is needed for the H_2O band at 6.2 micron (ν_2), R~170 for CH_4 at 7.7 micron (ν_4) and for NH_3 R~50 at 10.5 micron (ν_2).

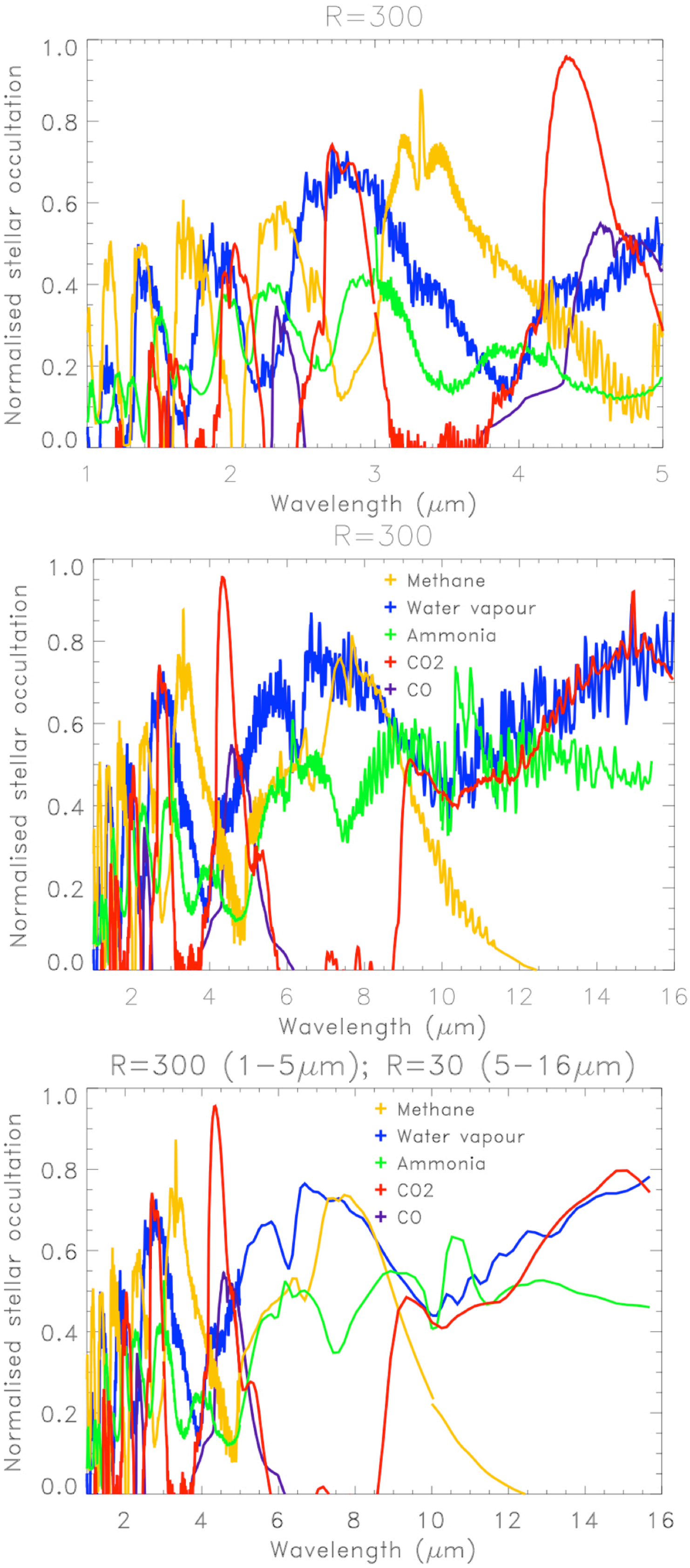


Figure 3: A simulation of typical exoplanet transmission spectra for a hot Jupiter as would be produced from primary transit observations, showing the wealth of spectral features from a selection of key diagnostic molecules that fall into the 1 – 16 micron wavelength range. Spectra have been normalised to the maximum atmospheric contribution in the 1 – 16 micron band. Upper panel: simulated spectra at a resolving power of ~ 300 - absorption features increase in strength and width as one moves to longer wavelengths; Central panel: a zoom-in of the 1 – 5 micron waveband – features are closely packed and a resolution of a few hundred is needed to separate the different components; Lower panel: simulated spectra smoothed to a resolving power of a few tens (~30) at $\lambda > 5$ micron (~300 below), illustrating that many features can still be resolved with quite modest resolution. Note: R is used to denote resolving power in the figures.

R-SCI-040: EChO shall have a resolving power of R ≥ 300 for λ<5 micron and R≥ 30 for λ>5 micron.

Note: R=λ/Δλ where Δλ ≥FWHM of the monochromatic system PSF.

G-SCI-050: EChO should have a resolving power of R ≥ 300 over the wavelength range specified in G-SCI-020.

4.4 Signal-to-noise ratio (SNR) and noise requirements

The EChO three tier survey has been conceived to maximise the science return of the mission. This will be achieved by tailoring the SNR and spectral resolving power, to address well defined scientific questions for well defined classes of planets and stars.
Retrieval studies and simulations of molecular detectability in a variety of exoplanet atmospheres have been extensively performed to refine the requirements reported below ([RD14], [RD15]).

R-SCI-055: The average SNR achieved per spectral element for targets defined in the Chemical Census tier shall either be ≥5 at R=50 averaged over the 2 micron ≤ λ ≤ 5 micron wavelength interval, or shall be ≥5 at R=30 over the 5 micron < λ ≤ 11 micron wavelength: whichever is less demanding. The planet shall be observed in primary transit or occultation/eclipse, whichever is less demanding.

R-SCI-056: The average SNR achieved per spectral element for targets defined in the Origin tier shall be either ≥10 at R=100 averaged over the 2 micron ≤ λ ≤ 5 micron wavelength interval, or ≥10 at R=30 over the 5 micron < λ ≤ 11 micron wavelength interval: whichever is less demanding. The planet shall be observed in primary transit and occultation/eclipse.

R-SCI-057: The average SNR achieved per spectral element for targets defined in the Rosetta Stone tier shall either be ≥20 at R=300 averaged over the 1 micron ≤ λ ≤ 5 micron wavelength interval, or shall be ≥20 at R=30 over the 5 micron < λ ≤ 11 micron wavelength: whichever is less demanding. The planet shall be observed in primary transit or occultation/eclipse, which ever is less demanding.

G-SCI-058: The average SNR achieved per spectral element for targets defined in the Rosetta Stone tier shall either be ≥20 at R=300 averaged over the 1 micron ≤ λ ≤ 5 micron wavelength interval, or shall be ≥20 at R=30 over the 5 micron < λ ≤ 11 micron wavelength: whichever is less demanding. The planet shall be observed in primary transit and occultation/eclipse.

R-SCI-059: For all targets observed in primary transit the average SNR on the stellar signal per spectral resolution element at R=300 in the 0.55 – 1.0 micron waveband shall be ≥ 200 per transit event.

R-SCI-060: All targets in the target list shall be observed with at least 90% of the SNR defined in R-SCI-055 and R-SCI-056

G-SCI-065: All targets in the target list should be observed with at least 95% of the SNR defined in R-SCI-055 and R-SCI-056

R-SCI-070: Neighbouring sources that fall within the field of view of target stars shall make a negligible contribution to the noise budget. Observation of stars with neighbouring sources that make a larger contribution is TBD.

The differential techniques proposed in Section 3 assume that the difference between the in- and out of transit/occultation observations is the signal from the exoplanet itself. Measurements of the stellar emission are required that are both accurate and precise. Measurements of the continuum stellar flux in the optical band (0.55 – 1.0 micron) will be used to monitor and correct for stellar variability across the full EChO waveband. Such monitoring/correcting will be particularly important when combining multiple primary transits, since any redistribution of stellar spots over the stellar surface could potentially alter the measured depth of the transit. Late-type stars are, on average, quite active and so this effect could be significant. K and M stars, however, will be primarily observed in occultation mode that is less sensitive to such effects (only to those with a timescale comparable to the duration of the eclipse) since the planetary signal relates directly to the depth of the occultation, without the need to model the stellar surface.

R-SCI-075: Stellar variability (post-processing) shall make a negligible contribution to the noise budget (< 10% in RSS). Observation of stars with a higher residual variability is TBD.

4.5 Photometric stability

EChO will observe exoplanets for which the contrast between exoplanet and host star can be as low as 10^{-5}, and will be typically of order 10^{-4}. Achieving this contrast ratio with sufficient signal-to-noise will require co-addition of a number of transits/occultations in many cases. To ensure that the co-addition itself doesn't add systematic noise to the data, an overall stability of 10^{-4} or better is required over an individual transit/occultation measurement. The nature of the time series data produced during a transit/occultation, and the fact that we have accurate knowledge of the timing of the events, is very helpful in restricting the frequency range over which this stability is required. **Figure 4** shows the situation for an idealised transiting source in the time domain. For stability purposes we need to know how this time signature appears in the frequency domain – **Figure 5** shows the Fourier transform of the time signature for a number of different planet orbital durations. From the figure it can immediately be seen that for a given source the signal is confined to a number of harmonics covering a defined frequency space. This then allows us to confine the required system stability requirements to be within the same, or for safety a slightly larger, frequency domain as the nature of the measurement and subsequent data processing effectively filters out instabilities at higher or lower frequencies. The requirements are set to cover a typical single transit/occultation observation period -- we will not "stare" constantly at a source over many transit/occultation events, but rather "revisit" the source at the appropriate time intervals. Based on likely targets, the longest interval over which systematic stability is required is set to 10 hours. The minimum time interval needed is less easy to define, however the typical ingress/egress of exoplanets is no faster than 10's of minutes and the extreme end of the frequency range in **Figure 5** is 1.7 mHz. Taking these into account, we set the minimum time interval over which the requirements apply to 3 x the baseline sampling requirement (see section 4.7): conversing these numbers into equivalent frequencies we require the stability requirements to be met within 2.8×10^{-5} Hz and 3.7 mHz. As a goal we set the longest and shortest time intervals to 72 hours (3 days) and 1 minute respectively.

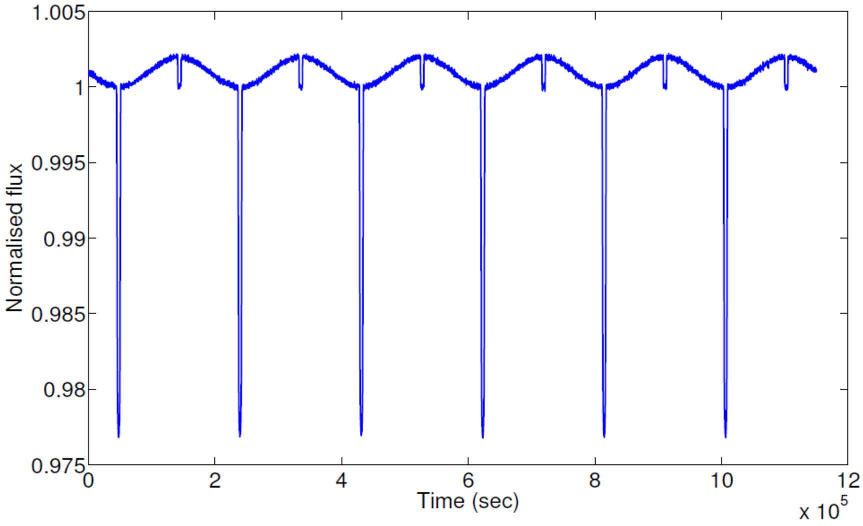


Figure 4: A simulation of the time series of 6 orbits of a HD189733b-like planet. The deep troughs are limb-darkened primary transits, the smaller troughs are the secondary eclipse/occultation, whilst the sinusoidal variation is the planetary phase curve due to the planetary day-side rotating in and out of view. White noise at the 10^{-4} level has been added.

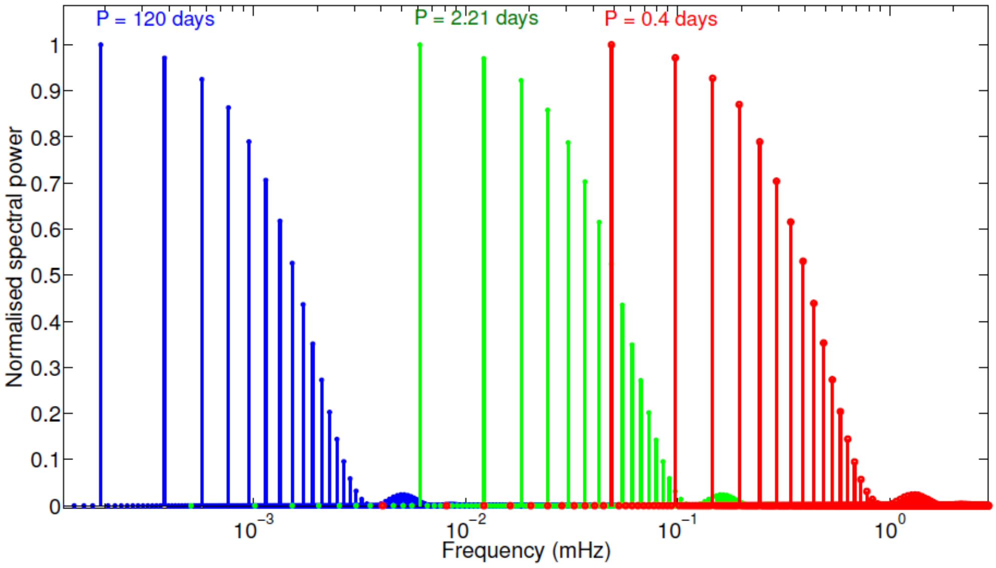


Figure 5: Power spectra of the time series shown in Figure 4 for different orbital periods covering the full range of expected targets for EChO. Blue: Period = 120 days, Green = 2.21 days (akin to HD189733b), Red = 0.4 days.

R-SCI-080: Only photometric variations within the frequency band of 2.8×10^{-5} Hz to 3.7 mHz shall be included in the overall

noise budget which is set by requirements R-SCI-055, R-SCI-056, R-SCI-057 and R-SCI-059

Note: R-SCI-080 shall apply post-processing, and needs to take into account intrinsic stellar variability in the corresponding frequency band

G-SCI-085: Only photometric variations within the frequency band of 3.8×10^{-6} Hz to 16mHz should be included in the overall noise budget which is set by requirements R-SCI-055, R-SCI-056, R-SCI-057 and R-SCI-059

Note: Achieving G-SCI-085 after post-processing needs to take into account intrinsic stellar variability in the corresponding frequency band.

4.6 Sky visibility

EChO will visit a large and well-defined set of targets (see Section 4.1) in order to catch the exoplanet at different phases of the exoplanet's orbit. Repeated visits may be required to build up the SNR of individual target spectra. The typical duration of a visit to a target system will be 6-8 hours, interspersed by periods of a few days, up to a few tens of days. In principle, the targets may be in any part of the sky, and as such the satellite will need to have a large field of regard, with minimal constraints (due to Earth/Sun) on the direction in which it can be pointed.

The most challenging targets for EChO will be habitable super-Earths. Given the orbital period to achieve the appropriate (temperate, T_p~300K) thermal conditions, a maximum number of a couple of hundred transits, depending on the host star, would be obtainable assuming mission lifetime of 4years. Without access to significant fraction (TBD) of these transits it will not be possible to achieve the required SNR.

R-SCI-90: 40% of the sky shall be accessible at any one time. The same 40% shall be accessible over a period of ~10 hrs. The complete sky shall be accessible within a year (TBC). A source at the ecliptic shall be observable for 40% of the mission lifetime.

4.7 Temporal resolution

The accuracy and reliability with which atmospheric parameters can be derived and models constrained by EChO will depend not only on the photometric precision and stability of the measurements, but also in temporal sampling. The cadence of sampling should allow accurate recovery of the shape of the ingress and egress, which in turn will requires of order of 10 measurements across ingress/egress. One of the shortest-durations of ingress known to-date is that of GJ 436b, which is ~15 minutes: this sets a maximum sample interval of 90 seconds

R-SCI-100: The interval between consecutive measurements of the host star/exoplanet system taken during a single transit/occultation shall be ≤90 seconds.

G-SCI-110: The interval between consecutive measurements of the host star/exoplanet system taken during a single transit/occultation should be ≤30 seconds.

4.8 Limiting cases – the brightest and faintest targets

The required (goal) waveband for EChO operation is defined in Section 4.2. It is clear from the science goals given in Section 2.1 and the mission reference sample defined in Section 4.1, that it will not be possible to obtain high SNR spectra for all exoplanetary systems across the full goal waveband. This places different requirements across the band on the minimum signal levels that the EChO payload must be able to accommodate.

R-SCI-120: The faintest target shortward of 3 micron that the spacecraft will be designed to observe shall be a M5V star with Ks-band magnitude of 8.8 (equivalent to GJ 1214).

Note: The flux from GJ1214 can be evaluated using the appropriate SED from the library provided - based on an effective temperature of Teff = 3200 K - and a stellar radius of $R = 0.19\ r_{sol}$ *. The distance to GJ 1214 is 13 pc.*

The integrated flux from such a star in the 0.4 – 0.8 micron /0.55 – 1 micron waveband is $6.4 \times 10^{-14}\ Wm^{-2}$ */ is* $1.46 \times 10^{-13}\ Wm^{-2}$ *respectively.*

G-SCI-125: The faintest target shortward of 3 micron that the spacecraft will be designed to observe should be an M5V star with Ks-band magnitude of 9.8.

Note: The flux from such a target can be evaluated using the appropriate SED from the library provided - based on an effective temperature of Teff = 3200 K - and a stellar radius of $R = 0.19\ r_{sol}$*. The distance an M5V star with Ks-band magnitude 9.8 is 20.6 pc*

The integrated flux from such a star in the 0.4 – 0.8 micron/0.55 – 1 micron band is $2.1 \times 10^{-14}\ Wm^{-2}$ */*$4.8 \times 10^{-15}\ Wm^{-2}$ *respectively.*

R-SCI-130: The faintest target between 3 and 8 micron that the spacecraft will be designed to observe shall be a G0V star with Ks-band magnitude of 9.0 (no known equivalent yet).

Note: The flux from a G0V can be evaluated using the appropriate SED from the library provided - based on an effective temperature of Teff = 6030 K - and a stellar radius of R = 1.05 r_{sol}*. The distance to such a target with a Ks-band magnitude of 9.0 is 150 pc.*

G-SCI-135: The faintest target between 3 and 8 micron that the spacecraft will be designed to observe should be a G0V star with Ks-band magnitude of 10.0.

Note: The flux from a G0V can be evaluated using the appropriate SED from the library provided - based on an effective temperature of Teff = 6030 K - and a stellar radius of R = 1.05 Rsol . The distance to such a target with a Ks-band magnitude of 10.0 is 238 pc.

R-SCI-140: The faintest target longward of 8 micron that the spacecraft will be designed to observe shall be a G0V star with Ks-band magnitude of 8.0 (no known equivalent yet).

Note: The flux from a G0V can be evaluated using the appropriate SED from the library provided - based on an effective temperature of Teff = 6030 K - and a stellar radius of R = 1.05 Rsol . The distance to such a target with a Ks-band magnitude of 8.0 is 94.6 pc.

G-SCI-145: The faintest target longward of 8 micron that the spacecraft will be designed to observe should be a G0V star with Ks-band magnitude of 9.0.

Note: The flux from a G0V can be evaluated using the appropriate SED from the library provided - based on an effective temperature of Teff = 6030 K - and a stellar radius of R =1.05 Rsol . The distance to such a target with a Ks-band magnitude of 9.0 is 150 pc.

R-SCI-150: The brightest target that the spacecraft will be designed to observe shall be a K0V star with Ks-band magnitude 4.0 (equivalent to 55 Cnc).

Note: The flux from 55 Cnc can be evaluated using the appropriate SED from the library provided - based on an effective temperature of Teff = 5250 K - and a stellar radius of R = 0.80 Rsol. The distance to 55 Cnc is 12.3 pc.

G-SCI-155: The brightest target that the spacecraft will be designed to observe should be an F9V star with Ks-band magnitude 2.9 (equivalent to υ And).

Note: The flux from υ And *can be evaluated using the appropriate SED from the library provided - based on an effective temperature of Teff = 6115 K - and a stellar radius of R =1.10 Rsol . The distance to* υ And *is 13.5 pc.*

G-SCI-170: TBC source to set pointing requirement, determined by secondary science cases

4.9 Calibration

Calibration of spectral covers both amplitude and wavelength, and can be both relative and absolute. We define absolute calibration as the conversion of the recorded signals from the instrument into physical units and comparison to some standard system. In the case of EChO, absolute knowledge of the flux from a target is not necessary for the discovery of spectral features or, for the most part, recovery of the planetary atmosphere models. This is because the models generally rely on line/continuum ratios and knowledge of the relative variation of the continuum as a function of wavelength. Relative calibration between the various channels of the instrument is therefore much more critical to the scientific outcome than absolute knowledge of the flux. If, however, one wishes to compare measurements from different facilities one needs to be able to reference the fluxes to some accepted standard. For this reason we place a requirement on the absolute knowledge of the flux measured by EChO. Given the wavelength range and the ability to observe many stars with well-calibrated spectra we believe that 5% absolute knowledge of the flux is readily obtainable. This figure is similar to that quoted for *Spitzer*/IRAC for instance.

In order to build up the signal to noise in the EChO measurements we require that each recorded spectrum is accurately aligned in wavelength. This requires accurate relative wavelength calibration, i.e. each spectrum must have the same relationship between pixel position and wavelength, with high stability over time. Absolute calibration of the wavelength -- knowledge of the actual wavelength -- of the detected spectral features is important to allow identification of molecular species and, again, to allow comparison of spectra taken with different facilities. Given the relatively low spectral resolution of EChO even this requirement is rather relaxed and we set a modest requirement to know the wavelength within 1/3 of the spectral element width. This will be easily achieved using high signal to noise measurements on stars with known spectral features.

R-SCI-190: An absolute photometric calibration accuracy of 5% (TBC) shall be achieved for all targets across the full waveband of EChO using celestial objects.

R-SCI-193: Absolute wavelength calibration, after post-processing including calibration observations, shall be accurate to within 1/3 of the required spectral resolution element at all wavelengths and for all targets.

4.10 Backgrounds and straylight

EChO will operate from visible to “thermal infrared” wavelengths. At the long wavelength end, this implies that any objects or structures at a few 100 K seen by the instrument will emit strongly in the EChO band and may add unwanted noise and photometric instability into the measurement. Whilst most sources of emission -- the telescope, the instrument and associated structures -- can be reduced to negligible levels by cooling them, there are possible astrophysical sources that must be taken into account in any assessment of the mission performance. The brightest of these sources is the Solar system Zodiacal dust cloud, which both reflects/scatters sunlight in the visible/near infrared and emits directly in the thermal infrared band. In order to take this source into account we parameterise the overall visible to infrared spectrum in a manner used by previous missions. In practice the Zodiacal cloud is not smooth/uniform, and sophisticated pointing direction models exist [RD9] which can be used to verify the impact on any particular observation. The initial assessment of performance is based on the simplified assumptions given below which in turn is based on the approach used for the JWST time estimator [RD11].

R-SCI-200: The zodiacal background model which shall be used to model the performance of EChO is defined by:
$\mathrm{Zodi}(\lambda) = B\lambda\ (5500\ \mathrm{K}) \times 3.5.10^{-14} + B\lambda\ (270\ \mathrm{K}) \times 3.58.10^{-8}$ in units of [W/m2/sr/m], where $B\lambda(X)$ is Planck’s law written in terms of wavelength at a temperature of X [K].

The zodiacal background is a strong function of viewing direction, and 3 cases shall therefore be considered and defined as below:

- Minimum zodi = 0.9 x expression above (value at ecliptic poles).

- Maximum zodi = 8 x expression above (Solar elongation angle of 55 degrees at an ecliptic latitude of 0 degrees).
- Average value = 2.5 x expression above.

Note: The zodi model on which parameterisation has been evaluated is based on the Hubble model out to 2.5 micron, and the DIRBE model at wavelengths beyond: the parameterisation is the same as that used by JWST.

4.11 EChO science beyond exoplanets

In this section we note additional requirements that are driven by the science objectives outlined in section 2.2: specifically, by science that it will be possible to address with a mission that meets the science requirements detailed in sections 4.1 – 4.10, but that is beyond the core science objectives of the EChO mission. These are goals, not baseline requirements, and shall not drive the design of the spacecraft or payload. The observations outlined will help to resolve questions concerning the origin of planetary systems by (a) improving our knowledge of objects in the Solar System, (b) through the study of stellar disks and thus of stellar environments, and (c) by addressing the key issue of the differences/similarities between brown dwarfs and planets: are they different in structure or composition, due to a different origin?

G-SCI-210: It should be possible to observe the following objects/classes of objects with the same performance as for the primary exoplanet targets:

- **Uranus and Neptune**
- **Brown dwarfs**
- **Comets**

G-SCI-220: It should be possible to track Solar System objects that move at nonsidereal rates of up to 10 arcseconds/minute

4.12 Observing time

R-SCI-230: No less than 85% (TBC) of the total available observing time shall be reserved for the EChO core survey.

R-SCI-240: A percentage, TBC but less than 5%, of the observing time that is not specified in R-SCI-230 shall be allocated by the Director at his discretion (discretionary time).

5 SUMMARY OF REQUIREMENTS

Index R - Requirement G- goal	Parameter	Descriptor
R-SCI-001	EChO core survey definition	EChO shall observe a core sample of > 100 exoplanet targets, known as the EChO core survey.
G-SCI-002	EChO core survey definition	EChO should observe a core sample of > 200 exoplanet targets, known as the EChO core survey.
R-SCI-003	EChO core survey definition	The mission design shall allow observations to be carried out of a wide range of planetary sizes from gas giants to super-Earths. These will have a range of temperatures from hot (up to 3000K) to temperate (350 K) and are found orbiting a range of stellar types and magnitudes from cool M-dwarfs to hot F-stars. The mission design shall encompass both the faintest and brightest expected targets. Nominally these are exemplified by the systems GJ1214 (faint cold dwarf star) and 55Cnc (bright G star).
R-SCI-004	EChO core survey definition	The survey will be divided into three survey tiers: the names, characteristics and description of the each of the tiers are given in Table 2.
R-SCI-005	EChO core survey definition	More than 25 (TBC) of the planets observed in the Chemical Census tier shall be observed in the Origin tier.
G-SCI-006	EChO core survey	More than 50 (TBC) of the planets observed in the

	definition	Chemical Census tier should be observed in the Origin tier.
R-SCI-007	EChO core survey definition	More than 10 (TBC) of the planets observed in the Chemical Census tier shall be observed in the Rosetta Stone tier.
G-SCI-008	EChO core survey definition	More than 20 (TBC) of the planets observed in the Chemical Census tier should be observed in the Rosetta Stone tier.
Note to requirements 001 -- 008		*Note: The EChO Project Scientist shall ensure that a list of targets is defined that meets the requirements expressed in this document and which can be observed within the mission lifetime. The list shall be based on the design reference mission document that shall, in turn, be derived in consultation with the Community and Advisory Structure.*
R-SCI-010	Wavelength coverage (requirement)	The instantaneous wavelength coverage of EChO shall span 0.55 to 11 micron.
G-SCI-020	Wavelength coverage (goal)	The instantaneous wavelength coverage of EChO should span 0.4 to 16 micron.
R-SCI-030	Waveband subdivision	For wavelengths greater than 3 micron, division of the EChO waveband shall be made such that no cut falls between the following wavelength intervals (inclusive): 3.00 - 3.60 micron, 4.10 - 5.00 micron, 5.70 - 8.30 micron, 9.20 - 11.00 micron For wavelengths less than 3 micron, division of the EChO waveband shall respect each of the following constraints:

		(1) No cuts are permitted between the following intervals ($CO+CO_2$ features): 1.55 - 1.67 micron, 1.91 - 2.10 micron, 2.30- 2.39 micron, 2.65 - 2.82 micron (2) Cuts may fall in not more than one of the four intervals listed for each of the two groupings below: Group A (H_2O features): 1.10 – 1.20 micron, 1.31 - 1.50 micron, 1.75 - 2.02 micron, 2.38 - 3.00 micron Group B (CH_4 features): 1.10 - 1.20 micron, 1.31 - 1.50 micron, 1.60 - 1.85 micron, 2.11 - 2.52 micron (3) No cuts are permitted in the following intervals: 0.56 – 0.62 micron (Sodium “D” lines doublet), 0.645 – 0.665 micron, (H-alpha), 0.70 – 0.72 micron (CaH/TiO), 0.74 -- 0.80 micron (Potassium “D” lines doublet)
G-SCI-031	Waveband subdivision	Division of the EChO band should be made such that no cut falls in the following intervals (inclusive): 1.95 - 2.10 micron (H_3+); 2.50 - 2.70 micron (H_2S); 2.90 - 3.10 micron ($HCN+C_2H_6$); 3.30 - 3.50 micron (C_2H_6); 3.85 - 4.10 micron (H_3+); 4.10 - 4.40 micron (PH_3+H_2S)
G-SCI-031a	Waveband subdivision	Division of the EChO waveband should be made such that no cut falls in the wavelength interval 13.50 - 16.00 micron
R-SCI-032	Channel overlap	The overlap between spectral channels shall be ≥ 5 resolution elements for λ <5 micron (assuming $R \geq 300$) and ≥ 1 resolution element for $\lambda>5$ micron (assuming $R \geq 30$) TBC.

R-SCI-033	Uniformity of spectral response	A minimum of 80% of the in-band channel average performance is required for each resolution element
R-SCI-040	Resolving power	EChO shall have a resolving power of R ≥ 300 for λ<5 micron and R≥ 30 for λ>5 micron.
G-SCI-050	Resolving power	EChO shall have a resolving power of R ≥ 300 over the wavelength range specified in G-SCI-020.
R-SCI-055	Signal-to-noise ratio	The average SNR achieved per spectral element for targets defined in the Chemical Census shall either be ≥5 at R=50 averaged over the 2 micron ≤ λ ≤ 5 micron wavelength interval, or shall be ≥5 at R=30 over the 5 micron < λ ≤ 11 micron wavelength: whichever is less demanding. The planet shall be observed in primary transit or occultation/eclipse, whichever is less demanding.
R-SCI-056	Signal-to-noise ratio	The average SNR achieved per spectral element for targets defined in the Origin tier shall be either ≥10 at R=100 averaged over the 2 micron ≤ λ ≤ 5 micron wavelength interval, or ≥10 at R=30 over the 5 micron < λ ≤ 11 micron wavelength interval: whichever is less demanding. The planet shall be observed in primary transit and occultation/eclipse.
R-SCI-057	Signal-to-noise ratio	The average SNR achieved per spectral element for targets defined in the Rosetta Stone tier shall either be ≥20 at R=300 averaged over the 1 micron ≤ λ ≤ 5 micron wavelength interval, or shall be ≥20 at R=30 over the 5 micron < λ ≤ 11 micron wavelength: whichever is less demanding. The planet shall be observed in primary transit or occultation/eclipse, whichever is less demanding.
G-SCI-058	Signal-to-noise	The average SNR achieved per spectral element

	ratio	for targets defined in the Rosetta Stone tier shall either be ≥20 at R=300 averaged over the 1 micron ≤ λ ≤ 5 micron wavelength interval, or shall be ≥20 at R=30 over the 5 micron < λ ≤ 11 micron wavelength: whichever is less demanding. The planet shall be observed in primary transit and occultation/eclipse**.**
R-SCI-059	Signal-to-noise ratio	For all targets observed in primary transit the average SNR on the stellar signal per spectral resolution element at R=300 in the 0.55 – 1.0 micron waveband shall be ≥ 200 per transit event.
R-SCI-060	Signal-to-noise ratio	All targets in the target list shall be observed with at least 90% of the SNR defined in R-SCI-055 and R-SCI-056.
G-SCI-065	Signal-to-noise	All targets in the target list should be observed with at least 95% of the SNR defined in R-SCI-055 and R-SCI-056.
R-SCI-070	Noise contributors	Neighbouring sources that fall within the field of view of target stars shall make a negligible contribution to the noise budget. Observation of stars with neighbouring sources that make a larger contribution is TBD.
R-SCI-075	Noise contributors	Stellar variability (post-processing) shall make a negligible contribution to the noise budget (< 10% in RSS). Observation of stars with a higher residual variability is TBD.
R-SCI-080	Photometric stability	Only photometric variations within the frequency band of 2.8x10^{-5} Hz to 3.7mHz shall be included in the overall noise budget, which is set by the MRS and SNR requirements defined in R-SCI-060 *Note: R-SCI-080 shall apply post-processing, and needs to take into account intrinsic stellar variability in the corresponding frequency band*

G-SCI-085	Photometric stability	Only photometric variations within the frequency band of 3.8×10^{-6} Hz to 16mHz should be included in the overall noise budget, which is set by the MRS and SNR requirements defined in R-SCI-060 *Note: Achieving G-SCI-085 after post-processing needs to take into account intrinsic stellar variability in the corresponding frequency band.*
R-SCI-090	Sky visibility	40% of the sky shall be accessible at any one time. The same 40% shall be accessible over a period of ~10 hrs. The complete sky shall be accessible within a year (TBC). A source at the ecliptic shall be observable for 40% of the mission lifetime.
R-SCI-100	Cadence	The interval between consecutive measurements of the host star/exoplanet system taken during a single transit/occultation shall be ≤90 seconds
G-SCI-110	Cadence	The interval between consecutive measurements of the host star/exoplanet system taken during a single transit/occultation should be ≤30 seconds.
R-SCI-120	Limiting target	The faintest target shortward of 3 micron that the spacecraft will be designed to observe shall be a M5V star with Ks-band magnitude of 8.8 (equivalent to GJ 1214).
G-SCI-125	Limiting target	The faintest target shortward of 3 micron that the spacecraft will be designed to observe should be an M5V star with Ks-band magnitude of 9.8.
R-SCI-130	Limiting target	The faintest target between 3 and 8 micron that the spacecraft will be designed to observe shall be a G0V star with Ks-band magnitude of 9.0 (no known equivalent yet).

G-SCI-135	Limiting target	The faintest target between 3 and 8 micron that the spacecraft will be designed to observe should be a G0V star with Ks-band magnitude of 10.0.
R-SCI-140	Limiting target	The faintest target longward of 8 micron that the spacecraft will be designed to observe shall be a G0V star with Ks-band magnitude of 8.0 (no known equivalent yet).
G-SCI-145	Limiting target	The faintest target longward of 8 micron that the spacecraft will be designed to observe should be a G0V star with Ks-band magnitude of 9.0.
R-SCI-150	Limiting target	The brightest target that the spacecraft will be designed to observe shall be a K0V star with Ks-band magnitude 4.0 (equivalent to 55 Cnc).
G-SCI-155	Limiting target	The brightest target that the spacecraft will be designed to observe should be an F9V star with Ks-band magnitude 2.9 (equivalent to ν And).
R-SCI-190	Absolute photometric calibration	An absolute photometric calibration accuracy of 5% (TBC) shall be achieved for all targets across the full waveband of EChO using celestial objects.
R-SCI-193	Absolute spectral calibration	Absolute wavelength calibration, after post-processing including calibration observations, shall be accurate to within 1/3 of the required spectral resolution element specified in R-SCI-040 at all wavelengths and for all targets.
R-SCI-200	Zodiacal background model	The zodiacal background model which shall be used to model the performance of EChO is defined by: $\mathrm{Zodi}(\lambda) = B_\lambda\ (5500\ \mathrm{K}) \times 3.5.10^{-14} + B_\lambda\ (270\ \mathrm{K}) \times 3.58.10^{-8}$ in units of [W/m2/sr/m], where $B_\lambda(X)$ is Planck's law written in terms of

		wavelength at a temperature of X [K]. The zodi is a strong function of viewing direction, and 3 cases shall therefore be considered and defined as below: - Minimum zodi = 0.9 x expression above (value at ecliptic poles). - Maximum zodi = 8 x expression above (Solar elongation angle of 55 degrees at an ecliptic latitude of 0 degrees). - Average value = 2.5 x expression above.
G-SCI-210	Secondary science	It should be possible to observe the following objects/classes of object with the same performance as for the primary exoplanet targets: - Uranus, Neptune - Brown dwarfs - Comets
G-SCI-220	Pointing /tracking	It should be possible to track Solar System objects that move at nonsidereal rates of up to 10 arcseconds/minute.
R-SCI-230	Allocation of observing time	No less than 85% (TBC) of the total available observing time shall be reserved for the EChO core survey.
R-SCI-240	Allocation of observing time	A percentage, TBC but less than 5%, of the total available observing time that is not specified in R-SCI-230 shall be allocated by the Director at his discretion (discretionary time).

6 APPENDIX

6.1 The relationship between spectral type, effective temperature and stellar radius

In the table below we provide the mapping between spectral type, effective temperature and stellar radius. The mapping between spectral type and effective temperature for all stars up to late Ms has been taken from Table A5 of Kenyon & Hartmann (1995, ApJ, 101, 117), connecting smoothly with Golimowski et al. (2004, AJ, 127, 3516) for the late-Ms, and using Baraffe et al. (1998, A&A, 337, 403) 1-Gyr isochrone for the radii.

Spectral Type	T_{eff} [K]	Radius [R_{sol}]		Spectral Type	T_{eff} [K]	Radius [R_{sol}]
F0V	7200	1.7		K1V	5080	0.77
F1V	7050	1.6		K2V	4900	0.74
F2V	6890	1.5		K3V	4730	0.72
F3V	6740	1.43		K4V	4590	0.69
F4V	6590	1.36		K5V	4350	0.66
F5V	6440	1.27		K6V	4205	0.63
F6V	6360	1.22		K7V	4060	0.59
F7V	6280	1.18		M0V	3850	0.55
F8V	6200	1.14		M0.5V	3790	0.53
F9V	6115	1.1		M1V	3720	0.49
G0V	6030	1.05		M1.5V	3650	0.46
G1V	5945	1.01		M2V	3580	0.41
G2V	5860	0.98		M2.5V	3520	0.37
G3V	5830	0.97		M3V	3470	0.32
G4V	5800	0.96		M3.5V	3420	0.28
G5V	5770	0.95		M4V	3370	0.25
G6V	5700	0.93		M4.5V	3310	0.23
G7V	5630	0.91		M5V	3200	0.19
G8V	5520	0.87		M5.5V	3070	0.16
G9V	5410	0.84				
K0V	5250	0.8				

Table A1: Stellar parameters for F – M spectral types. The corresponding spectral energy distribution (SED) library can be obtained from ESA on request.