DOCUMENT

EChO - Science Requirements Document

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APPROVAL

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CHANGE LOG

Reason for change	Issue	Revision	Date
Updates in preparation for document re-issue at the start/kick-off of instrument and industrial studies	**2**	**0**	
Update following 3/4 September SST meeting and in preparation to instrument AO.	**3**	**0**	**14/09/2012**

CHANGE RECORD

Reason for change	Issue	Revision	Date
Inclusion of informational table defining range of exoplanet radii, masses and temperature appropriate to different classes of exoplanet (p6)	**2.3**		**23 February 2012**
Update of reference documents (deletion and replacement)			
Clarification of terminology - replacement of science/background frames with in-/out-of transit (section 3)			
Update of observational strategy, replacing secondary eclipse with occultation (section 3)			
Update of Table 3 – mission reference sample (p14)			
Revision of R-SCI-030 - addition of Figure 3 and Table 4 (TBC) to summarise restrictions on wavelengths at which EChO waveband subdivision may be made (p18)			
New goal G-SCI-031 to reflect additional constraints on waveband subdivision (p18)			
New quantitative requirement R-SCI-032 on channel overlap (previously included in R-SCI-030) (p18)			
Update of R/G-SCI-080/085 to specify that the stability requirement refers to post-processing (p20/21)			
Addition of a goal to cover long-term photometric stability (R-SCI-086) (p21)			

Minor rewording of R/G-SCI-100/110 (p22)			
Minor rewording of R-SCI-120 – 135 (p23)			
Update of R/G-SCI-160—170 to reflect current mission reference sample (p23)			
Addition of preliminary requirements for calibration (R-SCI-190 – 193) (p24)			
Update of summary table of requirements (p25)			
Inclusion of Table A6 (appendix A3) of physical parameters to match all stellar/exoplanet systems in the mission reference sample			
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Modification of R-SCI-010			
Revision of specifications on where cuts in the EChO waveband may be made (R/G-SCI-030, 031, 031a).			
R-SCI-032 – TBC has been confirmed			
Definition of the specification on uniformity of spectral response provided in the update to R-SCI-033			
Comprehensive revision of R-SCI-060			
Further elaboration of the requirement on sky visibility			
Comprehensive revision of limiting cases (R/G-SCI-120 – 150)			
Requirement on faintest target in the visible channel deleted as included in the new sizing requirements			
Requirement for photon noise limited performance deleted (R-SCI-180)			
R-SCI-190 – calibration accuracy of 5% adopted			
R-SCI-191 and 192 deleted			
Modification of R-SCI-193			
Modification of R-SCI-080, 085 and 086			

Table of contents

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 be refined over the course of the assessment 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 and definitions

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	Resolving power
RSS	Root Sum Square
SNR	Signal-to-noise ratio
T_{eff}	Effective temperature (star)
T_{planet}	Temperature of planet
TBC	To be confirmed
TBD	To be decided

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
$r_{Jupiter}$	7.1492×10^{7} m	Radius (equatorial) of Jupiter
r_{Earth}	6.3781×10^{6} m	Radius (equatorial) of Earth
r_{sol}	6.9551×10^{8} m	Radius (equatorial) of the Sun
pc	3.0857×10^{16} m	Parsec

In subsequent sections of the document we refer to Jupiters, Neptunes and super Earths: the range of radii and masses that are typically implied by these names are indicated in the table elow. It should be noted, that the same exoplanet can fall under two different categories eg. Neptune or super Earth depending on whether its mass or radius is used for classification: the values given below are therefore for illustration only.

Planet Class	Exoplanet Radius [r_{Earth}]	Exoplanet Mass [M_{Earth}]
Jupiters/gas giants	*7 – 18* r_{Earth}	30 – 4000 M_{Earth}
Neptunes	*2 – 7* r_{Earth}	10 – 30 M_{Earth}
Super-Earths	*1 – 2* r_{Earth}	1 – 10 M_{Earth}

1.4 Reference documentation

[RD1] EChO Exoplanet Characterisation Observatory: Exploring Atmospheres of Diverse Worlds Beyond our Solar System (November, 2010)

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

[RD3] EChO Consortia radiometric models (reference TBC)

[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)

1.5 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 present the EChO reference sample, 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. Lists of targets known today from which a mission reference sample could be drawn are given in the appendices.

2 SCIENCE GOALS

2.1 Primary science goals

The primary objective of the EChO mission is to study the physics and chemistry of the atmospheres of a representative sample of known exoplanetary systems found around nearby stars. The differential technique of transit spectroscopy will be used over the optical to thermal IR wavebands (~0.4 – 16 micron) to determine the physical and chemical conditions of the atmospheres of a sample ~ 100 known exoplanets, with masses ranging from Jupiter-like to a ~few Earths, and equilibrium temperatures of 2000- to 300 K. Through detailed measurement of the spectral energy distribution and spectral features of exoplanetary atmospheres, it will be possible to establish the:

(a) chemical composition
(b) energy budget
(c) chemical abundances
(d) thermal structure
(e) optical albedo
(f) spatial and temporal variability of the atmospheric structure
(g) in the most favourable cases, determine all of the above, as a function of orbital phase

in a statistically significant sample of exoplanets, including those closest in mass and temperature to our own Earth. By considering these goals across the sample as a whole, we will be able to start to determine the mechanisms driving the formation of exoplanets, including the role of the host star. For the most favorable sources, 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.

2.2 Secondary science goals

To be completed.

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).

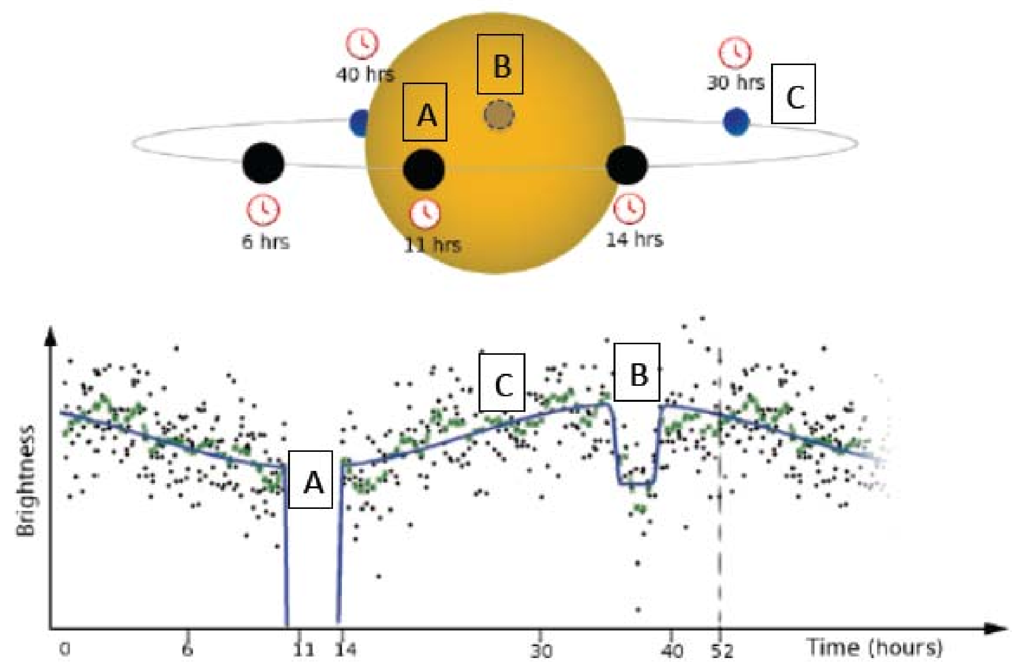


Figure 1: A schematic cartoon illustrating the orbit of an exoplanet around its host star and the resulting light curve measured from the combined star-exoplanet as a function of time, based on observations by Borucki et al (Science 2009, 325, 709) of HAT-P-7b with Kepler. Event **A** is referred to 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 a secondary 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. In the near and mid-IR, the planetary signal is dominated by a thermal

continuum that is modulated by molecular features; in the optical the planetary signal is dominated by Rayleigh and/or Mie scattering of the stellar radiation. By differencing the in- and out-of-occultation observations one can determine the dayside emission spectrum of the planetary atmosphere in the near- and mid-infrared. 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.
The optical part of the exoplanet spectrum can be used to establish the potential presence of clouds/weather systems. Measurement of the planetary albedo (% of stellar light reflected by the planet) provides a valuable constraint 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 primary 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 constituents of the atmosphere. 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. On either side of transit, the observed signal is dominated by light from the star itself plus 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 high-altitude atmosphere at the day/night 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 its emission counterpart, is that it is much less sensitive to atmospheric thermal gradients: molecular features always appear in absorption. In addition, the interpretation of the molecular contribution from low-(spectral) resolution spectra is less degenerate than is the case for emission spectra.

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 illuminated by its host star, and so visible to the observer, changes with orbital phase: from a maximum at secondary eclipse to a minimum at primary transit. Varying fractions of the day- and night-side of the planet are visible during periods between. 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 a constant stellar component and a slowly varying contribution from the exoplanet (Figure 1, C) which will depend on the exact phase/nature of the orbit, and the dynamics of the exoplanetary atmosphere. This periodic variation can be recovered by taking the differences between observations made at different points in the planetary orbit and the background frame measured during secondary eclipse and/or primary transit. By measuring minute changes in the brightness of the exoplanetary atmosphere as a function of orbital phase it is possible to determine the longitudinal brightness distribution of the planet, providing insight not only into the dynamics of the exoplanetary atmosphere but also into the redistribution of absorbed stellar energy, which in turn is intimately linked to the chemical and physical properties of the atmosphere.

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 primary (transit) and occultation observations. Alterations in the spot distribution across the stellar surface can modify the transit depth (because of the changing ratio of photosphere and spotted areas on the face of the star) when multiple transit observations are 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 through secondary eclipse spectroscopy will range from hot Jupiters (T_{planet} >700K, M_{planet} >100M_{Earth}) to temperate super-Earths (T_{planet}~ 250-350K, M_p ~ 5M_{Earth}). Transmission spectra will be measured using primary transit spectroscopy primarily in a subset of the sample that have light, or hot atmospheres. 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:

(a) wavelength coverage
(b) spectral resolving power
(c) signal-to-noise ratio and noise requirements
(d) photometric stability
(e) sky visibility/source accessibility
(f) temporal resolution
(g) limiting targets
(h) calibration

In Subsection 4.1 we define the EChO mission reference. In the subsections 4.2 – 4.9 we take each of the parameters listed above and detail the requirements that the EChO science objectives place on that parameter.

4.1 The EChO sample

EChO will observe a sample of exoplanets spanning a wide range of exoplanet/host star combinations. More than 280 transiting planets have been discovered to date and, among those, a relatively large fraction of hot Jupiters with bright host stars, as shown in the histogram in Fig. 1. Table 1 presents an illustrative list of currently known transiting planets for which EChO would yield measurements of sufficient SNR to fulfil the mission objectives. The target list comprises super-Earth, Neptune and Jupiter type planets, mostly with hot and warm temperatures.

It is expected that the numerous ongoing and future transit search experiments will go on discovering new targets of EChO interest, improving on those presently available. Note that, in the context of EChO being launched ten years from now, all but one of the targets in the list in Table 1 have been discovered in the last ten years, of which 75% over the last five years. One of the key aspects of the EChO mission is the need to cover a broad parameter space in terms of exoplanet and host star configurations. A statistical analysis has been carried out to estimate the future available parameter space for EChO together with the number of transiting planets expected. Two different approaches based on direct star counts and a projection of an available volume-limited and complete stellar census yield essentially compatible results on the estimated number of bright transiting planets of different types. A simple model [RD1, 2, 3 and 4] has been used to evaluate the parameters of the exoplanet/host star combination that could eventually be observed by a 1 m-class telescope operating in the vis-thermal IR waveband with state-of-the-art detectors. Conservative values for instrument parameters such as throughput have been adopted as appropriate to this early phase of the mission. The radiometric model was used to calculate the number of events needed to reach the required SNR for different kinds of host star/planet combinations with brightnesses compatible with the estimated population of transiting planets. A trade-off exercise was then run to optimize a sample of objects. This procedure considered factors such as the breadth of the parameter space probed, time spent observing the different object classes, total mission lifetime and number of required events.

The resulting hypothetical so-called Mission Reference Sample (MRS), listed in Table 2, covers the full range of exoplanetary host systems that EChO can potentially observe according to current SNR requirements and conservative assumptions on instrument performance. The MRS illustrates the “maximal” parameter space available to EChO while providing “minimal” target count estimates to reach the scientific objectives. The MRS includes a significant number of gaseous planets and a smaller, but non-negligible, number of rocky planets. The table also includes information on the technique best used to observe the planet (i.e., transit/transmission or occultation/emission) for optimal results. Such choice of whether to observe in occultation or transit was made based on integration time, i.e., the observational mode requiring the shortest integration time to reach the specified SNR was picked and the integration time carried forward to the total time required to observe the sample.

The list of EChO observable planets will evolve over the coming years by expanding into the variety of star/planet configurations as defined by the MRS. The current fainter targets will be replaced by brighter counterparts and objects covering new parameter space will be added.

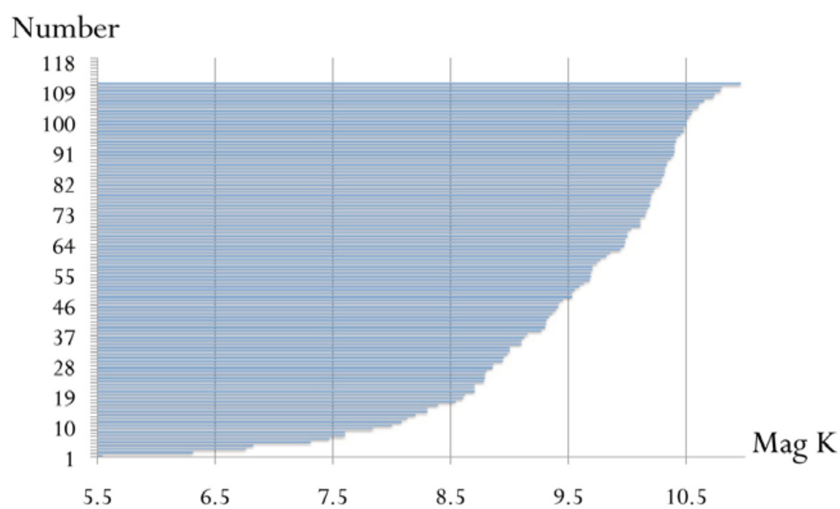


Figure 1: Number of known transiting hot Jupiters as a function of the Ks magnitude of the host star.

Planet Name	Type	M_p (M_J)	R_p (R_J)	P(d)	SPTyp	$M_\star$ ($M_\odot$)	$R_\star$ ($R_\odot$)	V	K_s
55 Cnc e	HSE	0.027	0.194	0.737	K0V	0.905	0.943	5.95	4.01
HD 189733 b	HJ	1.138	1.178	2.219	K2V	0.80	0.788	7.67	5.54
GJ 436 b	HN	0.0737	0.365	2.644	M2.5V	0.452	0.464	10.68	6.07
HD 209458 b	HJ	0.714	1.38	3.525	G0V	1.148	1.146	7.65	6.31
HD 17156 b	WJ	3.191	1.095	21.216	G0V	1.275	1.508	8.17	6.76
HD 149026 b	HJ	0.356	0.718	2.876	G0IV	1.3	1.497	8.15	6.82
HAT-P-11 b	HN	0.081	0.452	4.888	K4V	0.81	0.75	9.59	7.01
HD 80606 b	WJ	3.94	0.921	111.436	G5V	0.98	0.98	8.93	7.31
KELT-2A b	HJ	1.486	1.306	4.114	F7V	1.31	1.842	8.71	7.35
WASP-33 b	HJ	4.59	1.438	1.220	A5V	1.495	1.444	8.13	7.47
HAT-P-2 b	HJ	8.74	0.951	5.633	F8V	1.36	1.64	8.71	7.60
HAT-P-22 b	HJ	2.147	1.08	3.212	G5V	0.916	1.04	9.73	7.84
GJ 3470 b	WN	0.044	0.375	3.337	M1.5V	0.541	0.503	12.3	7.99
WASP-38 b	HJ	2.712	1.079	6.872	F8V	1.216	1.365	9.42	8.00
WASP-8 b	HJ	2.244	1.038	8.159	G6V	1.033	0.953	9.9	8.08
WASP-18 b	HJ	10.43	1.165	0.941	F6V	1.24	1.23	9.3	8.13
WASP-7 b	HJ	0.96	1.33	4.955	F5V	1.276	1.432	9.51	8.39
HAT-P-17 b	WJ	0.53	1.01	10.339	K2V	0.857	0.837	10.54	8.54
HAT-P-20 b	HJ	7.246	0.867	2.875	K7V	0.756	0.694	11.34	8.60
WASP-14 b	HJ	7.725	1.259	2.244	F5V	1.319	1.297	9.75	8.62
WASP-29 b	HJ	0.244	0.792	3.923	K4V	0.825	0.846	11.3	8.78
GJ 1214 b	WSE	0.02	0.245	1.580	M4.5V	0.153	0.21	14.67	8.78
WASP-34 b	HJ	0.59	1.22	4.318	G5V	1.01	0.93	10.4	8.79
HAT-P-1 b	HJ	0.524	1.217	4.465	GOV	1.133	1.115	10.4	8.86
WASP-43 b	HJ	1.78	0.93	0.813	K7V	0.58	0.667	12.4	9.27
XO-2 b	HJ	0.57	0.973	2.616	K0V	0.98	0.964	11.18	9.31
WASP-11/ HAT-P-10 b	HJ	0.46	1.045	3.722	K3V	0.82	0.81	11.89	9.42
HAT-P-3 b	HJ	0.591	0.827	2.900	K0V	0.917	0.799	11.86	9.45
WASP-35 b	HJ	0.72	1.32	3.162	G0V	1.07	1.09	10.95	9.53
XO-1 b	HJ	0.9	1.184	3.942	G1V	1.0	0.928	11.3	9.53
WASP-16 b	HJ	0.855	1.008	3.119	G3V	1.022	0.946	11.3	9.59
WASP-2 b	HJ	0.847	1.079	2.152	K1V	0.84	0.834	11.98	9.63
TrES-1	HJ	0.761	1.099	3.030	K0V	0.88	0.85	11.79	9.82
WASP-50 b	HJ	1.47	1.15	1.955	G9V	0.89	0.84	11.45	9.97
WASP-10 b	HJ	3.06	1.08	3.093	K5V	0.71	0.783	12.7	9.98
HAT-P-12 b	HJ	0.211	0.959	3.213	K5V	0.73	0.7	12.84	10.11
HAT-P-18 b	HJ	0.197	0.995	5.508	K3V	0.77	0.749	12.76	10.23
Qatar-1 b	HJ	1.09	1.164	1.420	K1V	0.85	0.823	12.84	10.41
WASP-23 b	HJ	0.884	0.962	2.944	K1V	0.78	0.765	12.7	10.45
HAT-P-19 b	HJ	0.292	1.132	4.009	K2V	0.842	0.82	12.9	10.55
TrES-3	HJ	1.91	1.305	1.306	G8V	0.924	0.813	12.4	10.61

Table 1: List of targets that, if to be observed by EChO today, would produce data of sufficient quality to attain the scientific objectives over the course of the mission duration. These objects have been selected from the brightest available transiting planets and cover different types of planet/star combinations, including hot and warm super-Earths, Neptunes and Jupiters (see column labeled Type).

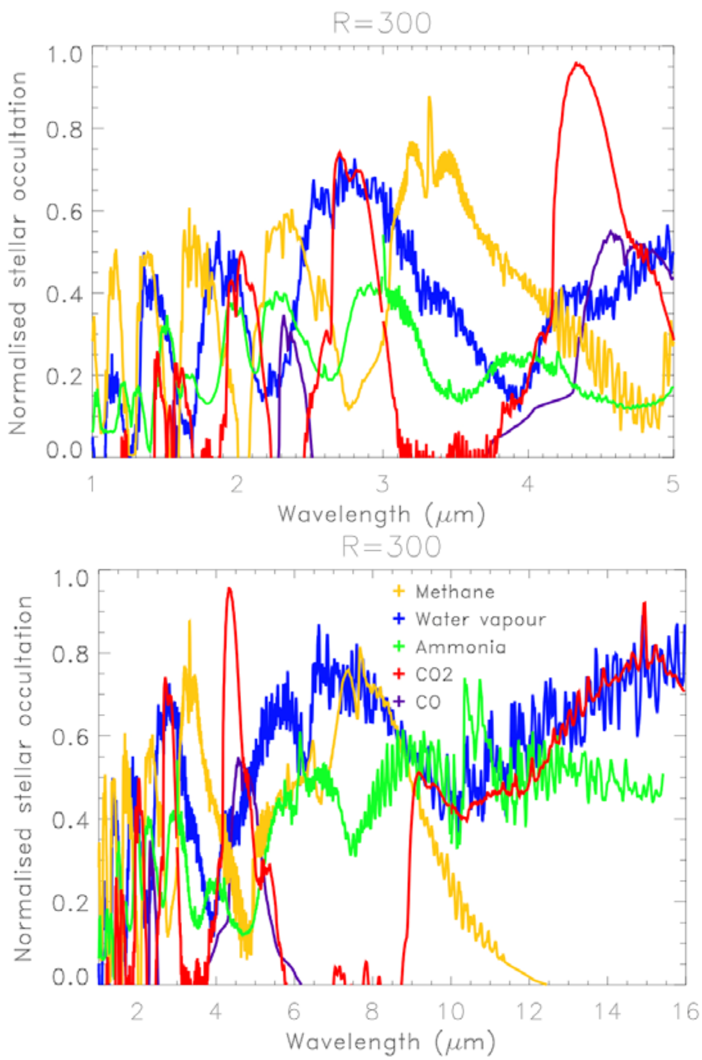
Planet type/temperature	Transit/Occultation	Minimum no. targets
Super Earths :		
Hot (T_{eq} > 700 K)	Occultation Occultation Occultation Occultation Occultation	2 M4-... @K_s<9 3 M2-M3 @K_s<8 2 K7-M1 @K_s<7 2 K0-K6 @K_s<6 1 G0-G8 @K_s<4
Warm (350 < T_{eq} < 700 K)	Occultation Occultation	3 M4-... @K_s<9 2 M2-M3 @K_s<8
Temperate (T_{eq}~250-350 K)	Transit	2 M4-... @K_s<7.5
Neptunes:		
Hot (T_{eq} > 700 K)	Transit Transit Transit	2 K7-M3 @K_s<8 5 K0-K6 @K_s<7 4 G0-G8 @K_s<6
Warm (350 < T_{eq} < 700 K)	Transit Transit	4 K7-M1 @K_s<8 2 K0-K6 @K_s<8
Hot (T_{eq} > 700 K)	Occultation Occultation Occultation	15 K0-K7 @K_s<9 12 G0-G8 @K_s<8 4 F7-F9 @K_s<7
Warm (350 < T_{eq} < 700 K)	Transit	2 G0-G8 @K_s<8 2 K0-K7 @K_s<8
Temperate (T_{eq}~250-350 K)	Transit	1 K5-K7 @K_s<7

Table 2: The EChO mission reference sample: a target list as a function of planetary type, temperature and stellar type to be observed in transit or occultation. The effective temperatures, radii and distances for different stellar types listed, as well as representative physical parameters for the different classes of exoplanet, are given in Table A2 in Appendix A2: these have been derived assuming the definitions/assumptions given in Table A3 and using the mapping between spectral type, effective temperature and stellar radius given in Table A4. The calculations are given for spectral type intervals but the calculations were run, generally, for the hot end of such interval. Also given in the table is the most favourable type of event (i.e., transit or occultation) for each planet class. Missing from the table is a list non-transiting exoplanets with bright (V= 3-4) hosts, on which orbital phase studies will be made. These will be included in a future revision of this document.

4.2 Wavelength coverage

Spectral coverage over a broad wavelength range (~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 shown in Figure 2 and the wavelengths listed in Table 3 along with those of other important molecular, ionic and atomic species.



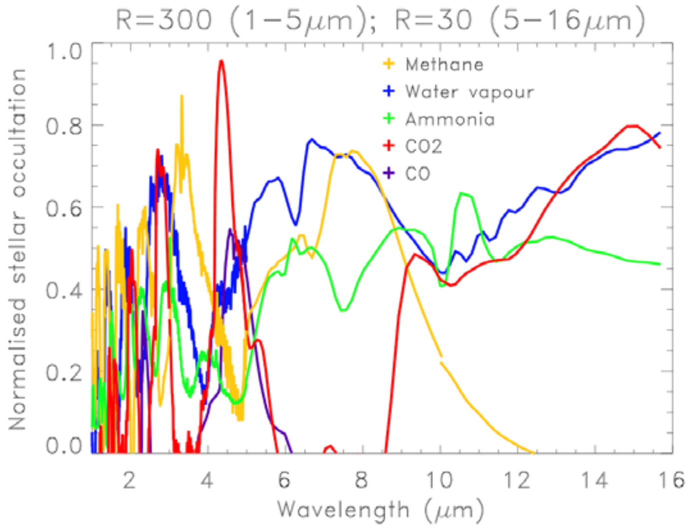


Figure 2: A simulation of typical exoplanet transmission spectra for a hot Jupiter as would be produced from primary transit observations, showing the wealth of spectral features from a selection of key diagnostic molecules that fall into the 1 – 16 micron wavelength range. Spectra have been normalised to the maximum atmospheric contribution in the 1 – 16 micron band. Upper panel: simulated spectra at a resolution 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 resolution 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 resolution in the figures.

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 for planets orbiting close-in (to estimate correctly the energy balance) and Rayleigh scattering/cloud contribution through primary 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. A resolving power of R~300 is sufficient at these wavelengths to separate molecular features and retrieve the abundances.

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. Spectral features in this region are broader than those in the 1-5 micron waveband, thus a spectral resolving power of R ~ 30 is needed just to detect the molecules. A goal is 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). For hot/warm planets, NH_3

and CH_4 can be detected also at wavelengths < 5 micron, however given that in the NIR molecular features are very closely spaced, observations at longer wavelengths provide very useful confirmation of the feature identification. Additionally, this waveband is key to improving the retrieval of the atmospheric thermal structure.

	0.4-1 μm	1-5 μm	5-11 μm	11-16 μm
R, baseline	300	300	$\geq$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 atmosphere.

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, 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. For terrestrial temperate planets, the detection of the CO_2 band at 15 micron is critical, as CO_2 cannot be detected at shorter wavelengths.

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 shall 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 Fig. 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.*

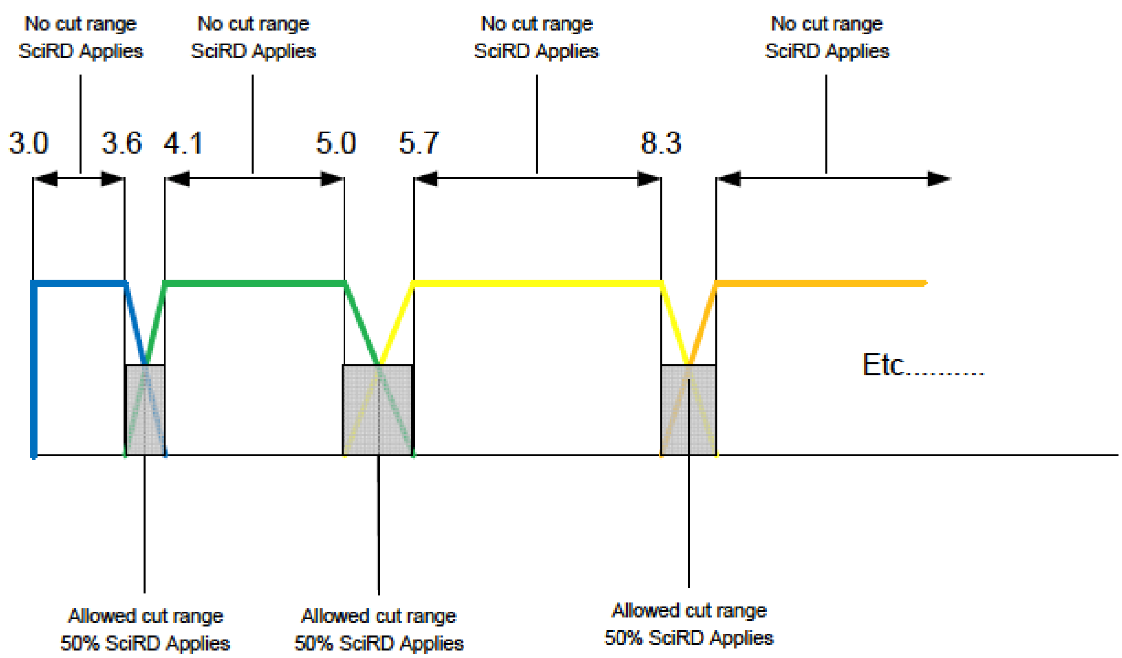


Figure 3a: A pictorial illustration of how cuts in the EChO waveband should be made. Wavelengths are given in microns

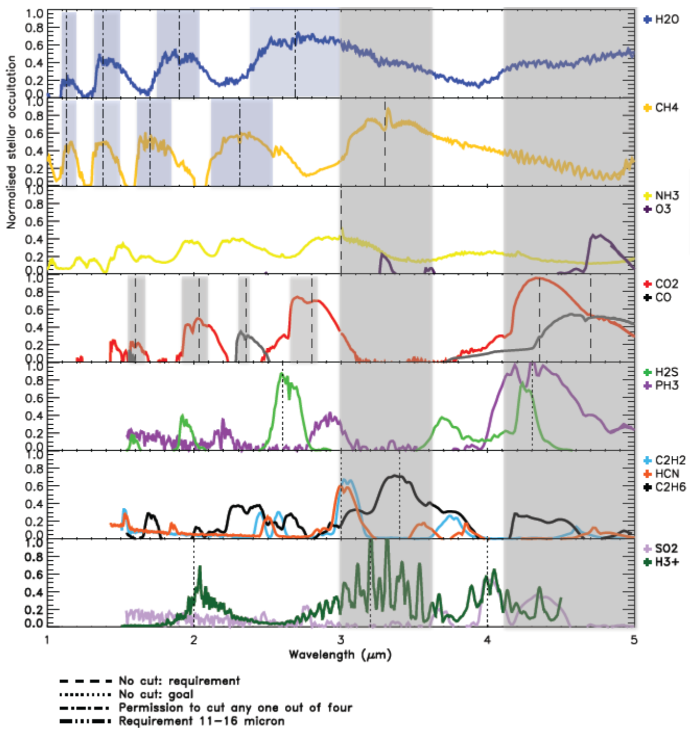
G-SCI-031: Division of the EChO band shall be made such that no cut falls in the following intervals (inclusive):
1.95 - 2.10 micron (H_3+); 2.50 - 2.70 micron (H_2S); 2.90 - 3.10 micron (HCN+C_2H_6);
3.30 - 3.50 micron (C_2H_6); 3.85 - 4.10 micron (H_3+); 4.10 - 4.40 micron (PH_3+H_2S)

G-SCI-031a: Division of the EChO waveband shall 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 spectral 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.



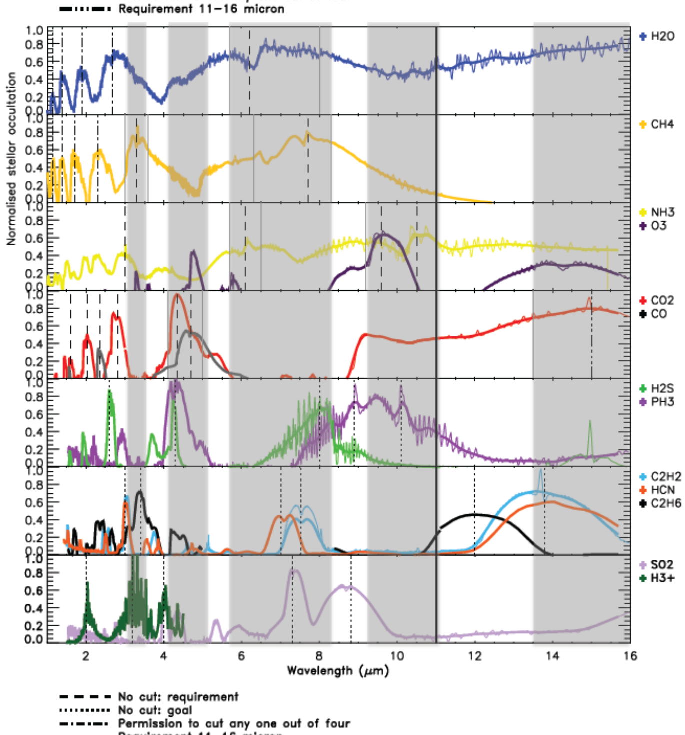


Figure 3b (upper): Plots of the normalised expected signal from a model exoplanet atmosphere observed during stellar occultation, as a function of wavelength for key and goal species. Vertical lines indicate the centres of spectral features (see legend for further detail). Lightly shaded bands indicate 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 MIR wavelengths a resolving power of R ≥ 30 is required in the MIR waveband to separate and detect individual molecular bands. Detecting molecular features, retrieve abundances and resolve blended features will require R>100. We note that NIR spectrometers with R~300 were used in recent the exploration of the giant planets of our Solar System (e.g. Galileo/NIMS, Cassini/VIMS) to retrieve not only atmospheric composition, but also the abundances and atmospheric structure.

In the case of hot-Jupiters and Neptunes, a resolving power of R~ 300 in the NIR will be sufficient to detect and separate molecules, and constrain the abundances and the thermal profile. We expect to be able to obtain spectra with R~300 + SNR ~ 50 in a relatively short time (from between 1 to 50 transits). The MIR spectral region will be used to confirm the presence of specific molecules and refine the thermal profile. For this task a resolving power of R~ 30 in the MIR is enough.
Temperate planets emit particularly strongly at the longer infrared wavelengths, at λ > 5 micron, so the contribution from the NIR is negligible. In the case of habitable-zone super-Earths, a spectrum with a R of few tens and a SNR of 5 to 10/micron should be realisable in between 1 to 100 transits ([RD4]).

Spectroscopy of Jupiters/Neptunes orbiting host stars that are fainter than V = 12 mag, or K=9 mag in the case of Super-Earths will be very challenging, however VIS, NIR and MIR photometry (R~few) of the planets will still be feasible and of scientific merit: confirmation of Kepler's smallest candidate planets that could be very difficult using radial velocity techniques will be possible using multi-band photometry.

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

Note: $R=\lambda/\Delta\lambda$ where $\Delta\lambda \geq$FWHM of the monochromatic system PSF.

G-SCI-050: EChO shall 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

Discussion/justification to be added in future updates.

R-SCI-060: The SNRs specified in Table 5 shall be achieved within the mission lifetime

Note: all SNRs with exception to that specified in the visible are to be achieved on the exoplanet signal The SNR in the visible is to be achieved on the stellar signal, and is the unweighted average in the wavelength interval 0.55 – 0.85 micron.

Spectral Type	Kmag	SNR on the star in the 0.55 - 0.85 micron band unweighted (average)	SNR @ 2.5 micron	SNR in 7 - 9 micron band	SNR in 11 - 16 micron band	Observational mode
Hot Super Earths						
M4	9	200	(10 @ R=50) 4.1 @ R=300	10 @ R=30		occultation
M2	8	200	(10 @ R=50) 4.1 @ R=300	10 @ R=30		occultation
K7	7	200	(10 @ R=50) 4.1 @ R=300	10 @ R=30		occultation
K0	6	200	(10 @ R=50) 4.1 @ R=300	10 @ R=30		occultation
G0	4	200	(10 @ R=50) 4.1 @ R=300	10 @ R=30		occultation
Warm Super Earths						
M4	9	200		(5 @ R=10) 2.9 @ R=30		occultation

M2	8	200		(5 @ R=10) 2.9 @ R=30		occultation
Temperate Super Earths						
M4	7	200		(2.5 @ R=10) 1.45 @ R=30		transit
Hot Neptunes						
K7	8	200	10 @ R=300	10 @ R=30		transit
K0	7	200	10 @ R=300	10 @ R=30		transit
G0	6	200	10 @ R=300	10 @ R=30		transit
Warm Neptunes						
K7	8	200	(10 @ R=50) 4.1 @ R=300	10 @ R=30		transit
K0	8	200	(10 @ R=50) 4.1 @ R=300	(10 @ R=10) 5.7 @ R=30		transit
Hot Jupiters						
K0	9	200	15@R=100 8.67@R=300	10 @ R=30		occultation
G0	8	200	15@R=100 8.67@R=300	10 @ R=30		occultation
F8	7	200	(15@R=100) 8.67@R=300	20 @ R=30		occultation
Warm Jupiters						
G5	8	200	(10 @ R=50) 4.1 @ R=300	(5 @ R=10) 2.88 @ R=30		transit
K5	8	200	(10 @ R=50) 4.1 @ R=300	(10 @ R=15) 7.07 @ R=30		transit
Temperate Jupiters						
K5	7	200		5 @ R=15		transit

				3.53 @ R=30		

Table 5: signal-to-noise ratios to be achieved over the mission lifetime for the individual targets in the mission reference sample. Note that the astronomical parameters for the sources are provided in Appendix A3, table A6.

R-SCI-070: Neighbouring sources which 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: 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}. This contrast ratio needs to be reached in order to detect the exoplanetary atmospheric signal, but can be achieved over a large number of transits/occultations. An overall stability of 10^{-4} (3σ) or better is therefore required over an interval equivalent to the time taken to observe both the science and background frames during a single transit/occultation. Based on likely targets, this interval is set to 10 hours (i.e., transit/occultation duration interval either side). 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 (0.4 – 0.8 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-080:-The EChO instrument and satellite systems shall not induce noise or disturbance in the frequency band of 2.8×10^{-5} Hz to 4mHz that raises the fundamental white noise floor in this band by more than 10% following post processing and extraction of the wavelength dependent transit signal.

Note: Achieving R-SCI-080 after post-processing needs to take into account intrinsic stellar variability in the corresponding frequency band.

G-SCI-085: The EChO instrument and satellite systems shall not induce noise or disturbance in the frequency band of 3.8x10^{-6} Hz to 16 mHz that raises the fundamental white noise floor in this band by more than 10% following post processing and extraction of the wavelength dependent transit signal

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 small but 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 will 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 few hundred transits, depending on the host star, would be obtainable assuming mission lifetime of 5 years. 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 should be accessible at any one time. The same 40% should be accessible over a period of ~10 hrs. The complete sky should be accessible within a year (TBC). A source at the ecliptic should 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 $\leq$90 seconds.

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

4.8 Limiting cases – the brightest and faintest targets

The required (goal) waveband for EChO operation is defined in Section 4.3. It is clear from the science goals given in Section 1.2, 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 to be observed by EChO shall be an 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 Rsol . The distance to GJ 1214 is 13 pc.

The total flux from such a star in the 0.4 – 0.8 micron band is 6.4 x 10^{-14} Wm^{-2}.

G-SCI-125: The faintest target shortward of 3 micron to be observed by EChO shall 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 Rsol. The distance an M5V star with Ks-band magnitude 9.8 is 20.6 pc

The total flux from such a star in the 0.4 – 0.8 micron band is 2.1 x 10^{-14} Wm^{-2}.

R-SCI-130: The faintest target between 3 and 8 micron to be observed by EChO shall be a G0V star with Ks-band magnitude of 9.0 (no equivalence 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 9.0 is 150 pc.

G-SCI-135: The faintest target between 3 and 8 micron to be observed by EChO shall 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 to be observed by EChO shall be a G0V star with Ks-band magnitude of 8.0 (no equivalence 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 to be observed by EChO shall 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 for which science data will be collected will 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 for which science data will be collected will 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

Descriptive text will be included in a future issue.

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.

R-SCI-194: The EChO satellite and focal plane instrument shall together provide TBD housekeeping monitoring, calibration sources and reference detector data to allow the co□addition of more than one light curves without increasing the fundamental white noise floor of the measurement by more than 10% in order to obtain the total signal-to-noise ratio required through R-SCI-060. This shall be achieved following frequency dependent signal extraction.

5 SUMMARY OF REQUIREMENTS

Index R - Requirement G- goal	Parameter	Descriptor
R-SCI-010	Wavelength coverage (requirement)	The instantaneous wavelength coverage of EChO will span ~0.55 to 11 micron.
G-SCI-020	Wavelength coverage (goal)	The instantaneous wavelength coverage of EChO will 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 shall 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 shall 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≥300) and ≥ 1 resolution element for λ>5 micron (assuming R≥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-20.
R-SCI-060	Signal-to-noise	The SNRs specified in Table 5 shall be achieved

	ratio	within the mission lifetime
G-SCI-065	Signal-to-noise ratio	TBC
R-SCI-070	Noise contributors	Neighbouring sources which 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	The EChO instrument and satellite systems shall not induce noise or disturbance in the frequency band of $2.8x10^{-5}$ Hz to 4 mHz that raises the fundamental white noise floor (i.e. photon noise from the target and zodiacal background) in this band by more than 10% following post processing and extraction of the wavelength dependent transit signal.
G-SCI-085	Photometric stability	The EChO instrument and satellite systems shall not induce noise or disturbance in the frequency band of $3.8x10^{-6}$ Hz to 16 mHz that raises the fundamental white noise floor (i.e. photon noise from the target and zodiacal background) in this band by more than 10% following post processing and extraction of the wavelength dependent transit signal.
R-SCI-090	Sky visibility	40% of the sky should be accessible at any one time. The same 40% should be accessible over a period of ~10 hrs. The complete sky should be accessible within a year (TBC). A source at the ecliptic should 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 shall be ≤ 30 seconds.
R-SCI-120	Limiting target	The faintest target shortward of 3 micron to be observed by EChO shall be an M5V star with Ks-band magnitude of 8.8 (equivalent to GJ 1214).
R-SCI-125	Limiting target	The faintest target shortward of 3 micron to be observed by EChO shall be an M5V star with Ks-band magnitude of 9.8.
R-SCI-130	Limiting target	The faintest target between 3 and 8 micron to be observed by EChO shall be a G0V star with Ks-band magnitude of 9.0 (no equivalence yet).
R-SCI-135	Limiting target	The faintest target between 3 and 8 micron to be observed by EChO shall be a G0V star with Ks-band magnitude of 10.0.
R-SCI-140	Limiting target	The faintest target longward of 8 micron to be observed by EChO shall be a G0V star with Ks-band magnitude of 8.0 (no equivalence yet).
G-SCI-145	Limiting target	The faintest target longward of 8 micron to be observed by EChO shall be a G0V star with Ks-band magnitude of 9.0.
R-SCI-150	Limiting target	The brightest target for which science data will be collected will be a K0V star with Ks-band magnitude 4.0 (equivalent to 55 Cnc).
R-SCI-155	Limiting target	The brightest target for which science data will be collected will be an F9V star with Ks-band

		magnitude 2.9 (equivalent to υ And).
G-SCI-170	Limiting target	TBC
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-194	Calibration requirement	The EChO satellite and focal plane instrument shall together provide TBD housekeeping monitoring, calibration sources and reference detector data to allow the co□addition of more than one light curves without increasing the fundamental white noise floor of the measurement by more than 10% in order to obtain the total signal-to-noise ratio required through R-SCI-060. This shall be achieved following frequency dependent signal extraction

APPENDICES

Appendix A1

Shown below in Table A1 is an overview of the type of exoplanet/stellar type in which the primary science objectives of the EChO mission will be studied (see Section 2.1). Note that hot refers to T_{planet} > 700K; warm refers to 350 K < T_{planet} < 700 K and temperate to 250 K < T_{planet} < 350 K. This table should be considered as indicative, as results will change depending on the exact parameters chosen (brightness, planetary radius and temperature etc.)

Host star spectral type	Hot Jupiters	Warm Jupiters	Temp. Jupiters	Hot Neptunes	Warm Neptunes	Temp. Neptunes	Hot Super Earths	Warm Super Earths	Temp. Super Earths
G bright	(a)–(g)	(a)–(e)	(a)–(b)	(a)–(g)	(a)–(d)	(a)–(b)	(a)–(g) (excl. (f))	(a)–(b)	none
G faint	(a)–(b)	(a)–(b)	(a)–(b)	(a)–(b)	(a)–(b)	(a)–(b)	photomet ry	none	none
K bright	(a)–(g)	(a)–(e)	(a)–(b)	(a)–(g)	(a)–(d)	(a)–(b)	(a)–(g) (excl. (f))	(a)–(b)	none
K faint	(a)–(b)	(a)–(b)	(a)–(b)	(a)–(b)	(a)–(b)	(a)–(b)	(a)	?	none
M	(a)– (g)	(a)–(e)	(a)–(b)	(a)–(g)	(a)–(d)	(a)–(b)	(a)–(g) Excl f	(a)–(b)	(a)–(b) If late, bright M

Table A1: An overview of the types of target that are being considered for study with EChO and that will address the primary science goals of the EChO mission.

Appendix A2

Detailed in Table A2 are the physical parameters and characteristics for the all targets listed in the mission reference sample (Table 2). These have been derived using the assumptions given in Table A3 and Table A4 (tabulation of effective temperature stellar radius for the range of stellar spectral types that are possible EChO targets)

Spectral Type	M_{star} [M_{sol}]	T_{eff} [K]	R_{star} [r_{sol}]	Distance [pc]	Kmag	Vmag	T_{planet} [K]	R_{planet} [R_{earth}]	Orbital Period [days]	Semi-major axis [A.U]	Transit duration [s]
Hot Super Earths											
M4	0.25	3370	0.25	20.72	9	13.7	1500	1.8	0.1072	0.002783	1066.3
M2	0.41	3580	0.41	23.44	8	12.3	1500	1.8	0.2108	0.005150	1858.3
K7	0.59	4060	0.59	25.24	7	10.56	1500	1.8	0.4425	0.009532	3032.9
K0	0.8	5250	0.8	26.34	6	8.02	1500	1.8	1.2974	0.021611	5318.2
G0	1.05	6030	1.05	14.93	4	5.42	1500	1.8	2.5801	0.037420	8016.7
Warm Super Earths											
M4	0.25	3370	0.25	20.72	9	13.7	600	1.8	1.3877	0.015338	2504.6
M2	0.41	3580	0.41	23.44	8	12.3	600	1.8	2.7283	0.028388	4363.3
Temperate Super Earths											
M4	0.25	3370	0.25	10.39	7	12.2	320	1.8	9.1474	0.053924	4696.0
	Hot Neptunes										
K7	0.59	4060	0.59	40	8	11.56	1500	4	0.4425	0.009532	3032.9
K0	0.8	5250	0.8	41.74	7	9.02	1500	4	1.2974	0.021611	5318.2

G0	1.05	6030	1.05	37.5	6	7.42	1500	4	2.5801	0.037420	8016.7
	Warm Neptunes										
K7	0.59	4060	0.59	40	8	11.56	600	4	5.7266	0.052540	7120.8
K0	0.8	5250	0.8	66.15	8	10.02	600	4	16.7892	0.119122	12485.3
Hot Jupiters											
K0	0.8	5250	0.8	104.85	9	11.02	1500	10	1.2974	0.021611	5318.2
G0	1.05	6030	1.05	94.2	8	9.42	1500	10	2.5801	0.037420	8016.7
F8	1.14	6200	1.14	65.59	7	8.31	1500	10	3.045	0.042950	8949.6
Warm Jupiters											
G5	0.95	5770	0.95	82.9	8	9.6	600	10	26.4676	0.170867	16294.9
K5	0.66	4350	0.66	48.49	8	11.15	600	10	7.8791	0.067469	8534.7
Temperate Jupiters											
K5	0.66	4350	0.66	30.59	7	10.15	320	10	51.9372	0.237196	16002.5

Table A2: Stellar/exoplanet parameters for targets in the mission reference sample listed in Table 2. Parameters have been derived using assumptions, parameters and the library of stellar spectral energy distributions (SEDs) detailed in [RD2]. The SED library is available from ESA by request.

Parameter	**Value**
T_{hot}	1500 K
T_{warm}	600 K
$T_{temperate}$	320 K
Bond albedo α (≈optical albedo): Hot planets Warm and temperate planets	 0.1 0.3
Radius of "Jupiter"	10 R_{Earth}
Radius of "Neptune"	4 R_{Earth}
Radius of "Super Earth"	1.8 R_{Earth}
Mass of "Jupiter"	300 M_{Earth}
Mass of "Neptune"	15 M_{Earth}
Mass of "Super Earth"	5 M_{Earth}
Mean molecular weight (to determine scale heights of atmospheres): Jupiters and Neptunes Super Earths	 2 g/mole 18 g/mole
Number of scale heights to be used	5
Impact parameter	0.5
Eccentricity e	0
Heat re-distribution factor f	1

Table A3: Stellar/exoplanet parameters for targets in the mission reference sample listed in Table 2. Parameters have been derived using assumptions and parameters detailed in [RD2].

Spectral Type	T_{eff} [K]	Radius [R_{sol}]
F0V	7200	1.7
F1V	7050	1.6
F2V	6890	1.5
F3V	6740	1.43
F4V	6590	1.36
F5V	6440	1.27
F6V	6360	1.22
F7V	6280	1.18
F8V	6200	1.14
F9V	6115	1.1
G0V	6030	1.05
G1V	5945	1.01
G2V	5860	0.98
G3V	5830	0.97
G4V	5800	0.96
G5V	5770	0.95
G6V	5700	0.93
G7V	5630	0.91
G8V	5520	0.87
G9V	5410	0.84
K0V	5250	0.8
K1V	5080	0.77
K2V	4900	0.74
K3V	4730	0.72

K4V	4590	0.69
K5V	4350	0.66
K6V	4205	0.63
K7V	4060	0.59
M0V	3850	0.55
M0.5V	3790	0.53
M1V	3720	0.49
M1.5V	3650	0.46
M2V	3580	0.41
M2.5V	3520	0.37
M3V	3470	0.32
M3.5V	3420	0.28
M4V	3370	0.25
M4.5V	3310	0.23
M5V	3200	0.19
M5.5V	3070	0.16

Table A4: Stellar/exoplanet parameters for targets in the mission reference sample listed in Table 2. Parameters have been derived using assumptions and parameters detailed in [RD2].

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.