CHEOPS Science Requirements Document

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CHANGE LOG

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Update of the requirements on photometric precision, simplification of the requirement document	2	0	2013-05-27

CHANGE RECORD

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Reason for change	**Date**	**Pages**	**Paragraph(s)**
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Correction of section title from Photometric Accuracy to Photometric precision	2015-03-19	16	Section 6.1
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Update of explanatory text of scireq 5.2	2015-03-19	23	Section 6.5
Inclusion of definition of scheduling efficiency	2015-04-8	24	Section 6.5
Update of effective temperatures for sizing stars	2015-04-16	15	Table 1

Table of contents:

1 PURPOSE AND SCOPE

This document provides the top-level science requirements for CHEOPS (CHaracterizing ExOPlanet Satellite). On 19 October 2012, CHEOPS was selected for study as the first S-class mission in Cosmic Vision 2015-2025 with a launch planned for 2017. Following the completion of the definition study, CHEOPS was adopted by the Science Programme Committee (SPC) on 19 February 2014, thus authorised to proceed with the implementation phase. The CHEOPS mission is a joint ESA-Switzerland project, with important contributions from a number of Member States, cooperating within a dedicated Mission Consortium.

This document describes the mission science objectives, the required measurements, and the associated science requirements with their justification, and shows the links between these elements. The science requirements are divided in two levels, Level 1 (L1) and Level 2 (L2), and the flow down from L1 to L2 requirements is indicated in each case. L1 and L2 are defined as follows:

- L1 - Top level science requirements directly linked to the science objectives. These should be met by the L2 requirements.
- L2 – Derived science requirements that specify the system scientific capabilities to enable the mission to meet the L1 requirements. These requirements provide the link between L1 requirements and the system engineering requirements.

The science requirements document will be used as a reference for the CHEOPS System Requirements document, which is the basis for the industrial activities.

2 MISSION SUMMARY

CHEOPS will be the first mission dedicated to search for exoplanetary transits on bright stars already known to host planets. The instrument will be able to point towards almost any locations on the sky and perform ultrahigh precision photometry. It will provide the unique capability of determining accurate radii for a subset of those planets in the super-Earth to Neptune mass range, for which the mass has already been estimated from ground-based spectroscopic surveys. It will also provide precision radii for new planets discovered by the next generation of ground-based transits surveys (Neptune-size and smaller). By unveiling transiting exoplanets with high potential for in-depth characterization, CHEOPS will also provide prime targets for future instruments suited to the spectroscopic characterisation of exoplanetary atmospheres.

The CHEOPS mission is envisaged as a partnership between Switzerland and ESA's Science Programme, with important contributions by a number of Member States.

3 SCIENTIFIC BACKGROUND

The discovery in 1995 (Mayor & Queloz, Nature 1995) of the first giant planet outside of the solar system sparked a real revolution in astronomy. The completely unexpected characteristics of this first planet captured the imagination and interest of the scientific community and the general public alike. Ten years later, ESA defined the conditions for planet formation and the emergence of life as one of its top scientific priorities for the period 2015-2025 (Cosmic Vision 2015-2025, 2005). Today, over 1500 exoplanets are confirmed. We have learned that planets are quite common, and that their properties are much more diverse than originally predicted (Udry et al. 2007). We have even witnessed the first few direct detections and analysis of their atmospheres in recent years. These pioneering measurements, previously restricted to planets within our solar system, are opening the door to actual characterization of exoplanets not only in terms of physical parameters but also in terms of understanding their diversity by better constraining their formation mechanisms and their evolutions.

In our solar system, giant planets (Jupiter, Saturn, Uranus, Neptune) are located relatively far from the Sun. This has been explained by the fact that, in order to grow large fast enough, these bodies require ices in condensed form, which are only available in cold and hence distant regions of the protoplanetary disc. Contrariwise, most detected giant exoplanets are located in regions much too close to their star for ices to have been present at any time. Furthermore, planetary orbits were thought to be well aligned with the star's equator (Fabrycky & Winn 2009), resulting from the notion of disc-driven migration (Lin et al. 1996; Ward 1997). Surprisingly, hot-Jupiter planets on non-coplanar orbits appear to be more common than previously thought, including some on retrograde orbits (see Triaud 2011 and references therein). The origin of such configurations is still a matter of debate but they are usually interpreted as resulting from dynamical interactions in multi-planet systems after the gas disc is dissipated. In summary, it is indeed striking that the bulk of the exoplanets discovered so far have distinctly different characteristics than was expected from solar system studies.

A significant fraction of known exoplanets is found transiting their host star. The special geometry of these systems makes them particularly interesting since for these planets the orbital inclination as well as the radius can be derived. In practice, a thorough analysis of the light curve and follow-up observations are needed to get a clear understanding of the nature of the transiting object. Usually, these follow-up observations consist of spectroscopic observations and precise radial velocity measurements (Doppler follow-up). The improvements and intensive efforts made during the last decade by teams carrying out Doppler surveys have led to the identification of numerous planetary systems hosting Neptune-mass planets and super-Earths. This clearly indicates that low-mass planets orbiting solar-type stars must be very common (Mayor et al. 2011). A similar conclusion has been reached analysing results from the Kepler mission (Howard et al. 2012), furthermore revealing a large population of "packed" planetary systems (Borucki et al. 2011; Lissauer et al. 2011) with about 17% of the stars hosting multi-planet systems. While their existence has been demonstrated, the exact nature of super-Earth planets remains a matter of fierce debate. From the handful of small planets with both mass and size estimates, characterising their structure remains challenging.

On the ground, transit surveys have been successful in detecting planets amongst which WASP and HAT stand as the most prolific, with an average rate of more than one planet discovered every 3 weeks. The main advantage of ground-based surveys is their ability to search the whole sky and hence to find planets orbiting bright stars. Current surveys have, within their design limitations, mapped almost the whole sky and found hundreds of short period giant planets.

The first dedicated space transit mission, CoRoT, was successfully launched in December 2006. It was a pioneer in its use of ultra-precision photometry with high sampling rate and long duration observations. The satellite primarily observed two fields of view each 4 square degrees – once per year. Each field counted typically 5–6 thousand dwarf stars with magnitudes ranging from roughly 11 to 16. After 5 years of operations, CoRoT has discovered dozens of exoplanets, among them the first super-Earth planet at very short orbital period, identified as having a rocky core: CoRoT-7-b (Léger et al. 2009).

Two years after CoRoT, the launch of the Kepler mission has turned out to be a landmark in transiting planet searches. Kepler has measured continuously for 4 years brightness variations of about 100,000 solar-like stars to an accuracy of order 10 ppm in a single field of view of approximately 100-square degrees. Kepler found many thousands of transiting planetary candidates, some of them with radii as small as the Earth radius ($R_\oplus$) and many multiple transiting systems. With these discoveries, Kepler has provided the community with a large uniform database of potential planetary systems enabling the derivation of distribution functions for planetary orbits, radii and hierarchical structure of systems (Borucki et al. 2011).

Both CoRoT and Kepler have been successful in reaching their design goals. However, it is revealing that despite this, only two rocky planets have been identified for certain (CoRoT-7 and Kepler-10). This paucity of the most interesting targets is related to the faintness of the target stars. The need to stare at a given field for a long time (in order not to miss a transit) as well as to have large numbers of targets in a given field of view (to maximize the chance of detection) dictated that both CoRoT and Kepler would search for transits toward stars typically between $V \sim 11$–16 magnitude. Measuring sufficiently precise radial velocities for stars this faint in order to obtain a reliable detection from an Earth-mass planet is virtually impossible. The example of CoRoT-7 shows that with the HARPS spectrograph it is possible to measure the mass of small planets in the super-Earth domain (Queloz et al. 2009; Hatzes et al. 2011), located on short period orbit for stars brighter than $V \sim 11$ magnitude. Similar measurements for planets with longer orbital periods on fainter stars, typical of Kepler candidates, would however, require a prohibitive amount of telescope time. In total Kepler has found a dozen of the smallest transiting planetary candidates orbiting stars brighter than 11th magnitude, with only a fraction of them offering hope for an accurate planet mass determination with the recently installed HARPS-North facility.

4 SCIENCE OBJECTIVES

The main science goal of the CHEOPS mission will be to study the structure of exoplanets smaller than Saturn orbiting bright stars with revolution periods below 50 days. With an accurate measure of masses and radii for an unprecedented sample of planets, CHEOPS will set new constraints on the structure and hence on the formation and evolution of planets in the sub-Saturn mass range. In addition, CHEOPS will also follow a handful of hot giant planets.

4.1 Mass-radius relation determination

The knowledge of the radius of the planet by transit measurements combined with the determination of its mass through radial velocity techniques allows the determination of the bulk density of the planet. Technically, this quantity provides direct insights into the global structure (e.g., presence of a gaseous envelope) and/or composition of the body (see Figure 1). Although it is well known that the determination of planetary structure from bulk density is a highly degenerate problem, the knowledge of the planet mass and radius provides enough information to derive a number of basic quantities relevant to planet structure (by comparison to models as illustrated in Figure 1) and hence to formation and evolution to make them vital measurements for further progress.

Large ground-based high-precision Doppler spectroscopic surveys carried out during the last years have identified nearly a hundred stars hosting planets in the super-Earth to Neptune mass range ($1 < M_{planet}/M_{\oplus} < 20$). As search programs continue the number is called to increase, likely double, in the coming years. The characteristics of these stars (brightness, low activity levels, etc.) and the knowledge of the planet ephemerids make them ideal targets for precision photometric measurements from space.

The new generation of ground-based transit surveys (e.g. NGTS), capable of reaching 1 mmag precision on V < 12.5 magnitude stars, provide yet another source of targets. By the end of 2017, NGTS will provide a minimum of 50 targets in the sub-Saturn size range. As with previous or on-going ground-based transit surveys, the precision of NGTS measurements will be inherently limited by correlated noise induced by the presence of Earth's atmosphere.

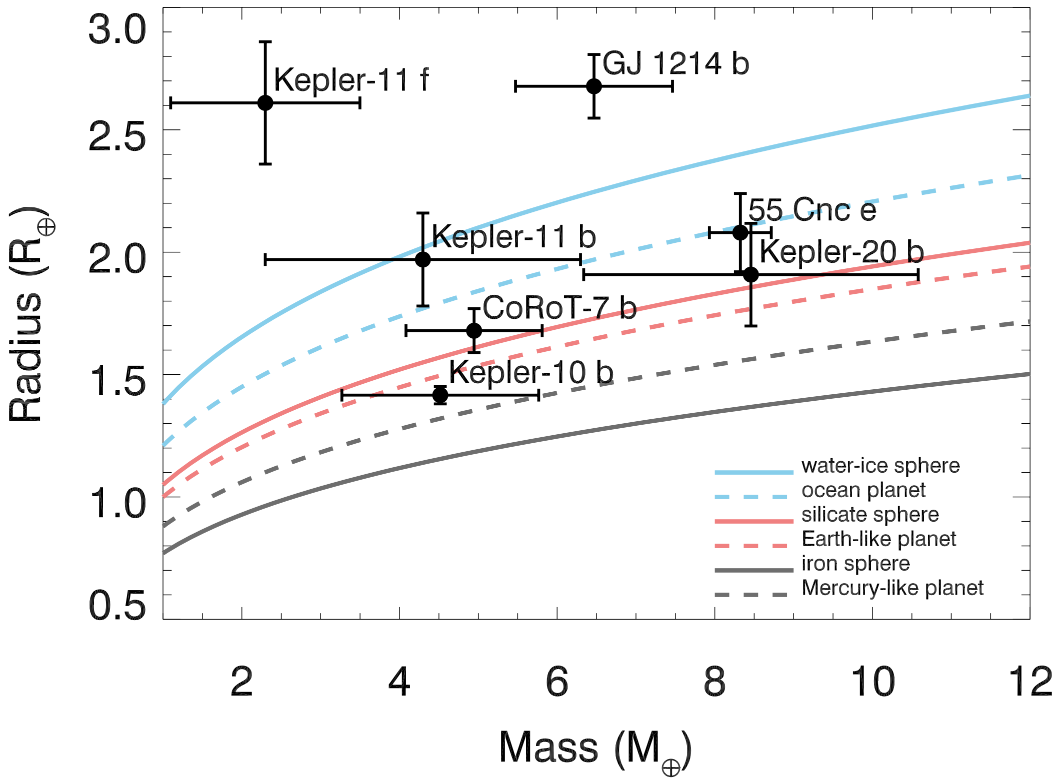

Figure 1: Mass-radius relationship for different bulk composition of the planet (adapted from Wagner et al. 2011) with superimposed known transiting planets where both the mass and the radius of the planet have been measured (with the 1-σ errors on these parameters). So far, in most cases the error bars are too large to obtain an unambiguous insight on the bulk structure of the planets.

CHEOPS will determine the mass-radius relation in the planetary mass range from 20 $M_\oplus$ down to 1 $M_\oplus$ to a precision not achieved before. In particular, CHEOPS will be able to measure radii to a precision of 10%.

By targeting stars located anywhere on the sky (some biases exist towards southern hemisphere, where HARPS has operated since 2003), which are bright enough for precise radial velocity follow-up – CHEOPS will not suffer from the limitations in the planet mass determination associated with fainter stars. CHEOPS will provide a uniquely large sample of small planets with well-measured radii, enabling robust bulk density estimates needed to test theories of planet formation and evolution.

4.2 Identification of planets with atmospheres

In the core accretion scenario, the core of a planet must reach a critical mass before it is able to accrete gas in a runaway fashion. This critical mass depends upon many physical variables, among the most important of which is the rate of planetesimals accretion. To date, there are no observational constraints on the critical mass of the cores. Estimations of core masses will shed light on the process of solids accretion. The determination of the mean planetary density can provide a lower limit for the mass of the gaseous envelope. For example, a 5-$M_{\oplus}$ planet composed of 50% solid terrestrial composition and 50% water vapour has a radius roughly twice as large as the same-mass planet with purely terrestrial composition. In light of recent studies indicating that low density super-Earths with large rocky cores and hydrogen envelopes may survive outgassing, it seems the presence of a significant H/He envelope would have an even more dramatic effect on the radius due to the reduced molecular weight compared to water. Similar conclusions can be reached assuming that the planetary core is composed of pure water ice. Indeed, for a given mass, the radius of a pure water planet (see Figure 1) represents an upper limit for the radius of a planet without an envelope. Therefore, a lower limit to the envelope mass can be derived (as a function of assumed envelope composition) by matching the observed radius and mass, assuming a pure water ice core, a composition of the envelope, and a temperature (corresponding to the equilibrium temperature with the stellar flux, an adequate assumption if the planet is not located too close to its star).

CHEOPS will identify planets with significant atmospheres in a range of masses, distances from the host star, and stellar parameters. Using observations of a sample of planets with and without significant gaseous envelopes, CHEOPS will be able to constrain the critical core mass (in the case of runaway gas accretion) or the loss of primordial H/He atmospheres as a function of the distance to the star and possibly stellar parameters (mass, metallicity). This will be especially true for planets not located extremely close to their stars: if the planet is too close, evaporation could be an issue.

4.3 Constraints on planet migration paths

It is generally accepted that the envelope masses and compositions of Uranus and Neptune are directly related to their formation in our own solar system. Although forming large cores fast enough is a challenge beyond 10 au, it is not entirely clear why these two planets did not succeed in accreting larger amounts of gas. Constraining the gas fraction for a large sample of Neptune-like planets, but at various distances to the central star, will shed light on the physical processes that could produce these types of planetary bodies. Yet even observations of planets for which it will be impossible to infer unambiguously the presence of a thick atmosphere (those located below the blue line in Figure 1) provide strong constraints on formation models in a statistical sense. There is ample evidence that planets are not born where they are observed today but that they have migrated during their formation possibly over large orbital distances. The present day observed location could therefore have been reached following different paths depending upon the growth history of the planet, as well as interactions with the gaseous disc or with other planets. Each of these paths samples different regions of the proto-nebula in varying proportions leading to unique combinations corresponding to the growth history and chemistry appropriate for the amount of time spent at a given orbital radius. As a result, the bulk composition, and hence the mean density, will depend upon which track was followed.

CHEOPS will provide a sufficiently large sample of planets with accurate densities to allow discriminating between common groups of migration paths. In particular, CHEOPS will place constraints on possible planet migration paths followed during the formation and evolution of planets where the clear presence of a massive gaseous envelope cannot be discerned.

4.4 Energy transport in hot Jupiter atmospheres

The detection of the phase curve provides information on planet albedos. These have been well measured for CoRoT-1b (Snellen et al. 2009) and HAT-P-7b (Borucki et al. 2010) with the CoRoT and Kepler missions, respectively. The detailed shape and amplitude of the phase curves represent a powerful tool to study the thermal distribution in the atmosphere (e.g., HD189733b, Knutson at al. 2007) and therefore the physical mechanisms and efficiencies of the energy transport from the dayside to the night side of the planet. Since this effect can be seen on any hot Jupiter, including non-transiting geometrical configurations, the number of potential targets amongst hot Jupiters detected orbiting bright stars is significant.

CHEOPS will have the capability to detect the phase curve of hot Jupiters in the optical regime, which will provide information on planet albedos. CHEOPS will bring new constraints on the atmospheric properties of known hot Jupiters that will help studying the physical mechanisms and efficiency of the energy transport from the dayside to the night side of the planet.

4.5 Targets for future spectroscopic facilities

Understanding the true nature of super-Earth planets requires not only precise measurements of their mass and radius, but also a study of their atmospheric properties. This is only possible for planets orbiting bright enough stars to permit high signal-to-noise spectro-photometric observations. This last condition is drastically more stringent for low-mass planets than for gas giants leading to the conclusion that only the few dozens of super-Earths that statistically transit the brightest stars within the solar neighbourhood will ever be suitable for a thorough characterization with future instruments (e.g., Seager et al. 2009). This has been nicely demonstrated in the case of the planet 55 Cnc e. This 8-$M_\oplus$ planet is the only one transiting a star visible to the naked eye. First detected by Doppler measurements, transits were later detected by the Spitzer and MOST space telescopes (Demory et al. 2011, Winn et al. 2011), revealing a planet with a size of ~2.1 $R_\oplus$. Owing to the brightness of its host star (V=6, K=4), very high signal-to-noise occultation photometry was possible with Spitzer, leading to the detection of the thermal emission of this super-Earth planet (Demory et al. 2012).

Earth-like planets are not expected to bear massive atmospheres. Since the presence of a gaseous envelope (only a few per cent in mass) or icy mantle (above 10% in mass) has a large effect on the planet radius and mean density, CHEOPS will be able to discriminate between telluric, Earth-like planets where life as we know it could blossom, and other kinds of Earth-mass planets (hydrogen-rich Earths, ocean-planets) which challenge our understanding of habitability.

CHEOPS will provide unique targets for future ground- (e.g., E-ELT) and space-based (e.g., JWST) facilities with spectroscopic capabilities. For example, CHEOPS will be able to identify planets that are more likely to have a thin envelope, which are prime targets for future habitability studies.

4.6 Astronomical sources variability studies

CHEOPS will have the capability to provide, on timescales < 2 days, precise time-differential photometric measurements (photometric time series) of a large number of variable light sources in the Universe. This is regarded as ancillary science for which observing time will be allocated (as open time) to guest observers.

5 MEASUREMENTS

CHEOPS' science objectives will be achieved by measuring high precision photometric sequences to detect a variation in the stellar brightness induced by a transiting planet.

5.1 Measurement principle

The contrast (or transit depth), the timing sequence of the event, and the detailed shape of the transit light curve provide (see Figure 8): (1) the geometry of the eclipse and the ratio of the planetary radius to that of the star, (2) the period of the orbit and (3) the density of the star (direct outcome of Kepler's law from the ingress/egress timing of the transit). These parameters, together with the effective temperature of the stellar atmosphere and an evolutionary model, allow retrieving the mass and the radius of the star and finally the determination of the radius of the planet (Mazeh et al. 2000; Hebb et al. 2009). The precision of this determination is therefore directly affected by the precision to which the stellar parameters are known.

The ratio of the depth of the light curve during a transit to the noise (rms) averaged over the duration of the transit defines the transit signal-to-noise ($S/N_{transit}$). In the case of a hot Neptune, the transit duration is typically 3 hours (see Figure 2), for a "warm" super-Earth (4 $M_{\oplus}$, 1.5 $R_{\oplus}$) it is about 6 hours. In both cases one considers that $S/N_{transit}$ = 5 allows for a reliable detection, while smaller planets, down to 1 $R_{\oplus}$ and below, can be detected through multiple transit observations at the same S/N ratio. On the other hand, $S/N_{transit}$=30 is required to obtain the radius of the planet with good precision.

A precise measurement of the mean density of exoplanets is necessary to constrain the bulk compositions and discriminate between families of planets: telluric (rocky) super-Earths, volatile-rich super-Earths, and Neptunes. Useful compositional constraints require a precision of ~20–30% on the density. This precision requirement on the density measurement translates into the need for CHEOPS to measure the mass and radius of the planet to better than 10%. Such precision will be achievable for all the planets that will be probed by CHEOPS orbiting stars brighter than V = 9 mag. In this magnitude range, the

10%-precision mass measurements will be possible with precision Doppler measurements obtained by instruments like HARPS, HARPS-North, Espresso, etc., while CHEOPS will provide the needed 10%-precision on the radii. This key specification defines the photometric precision required by the mission.

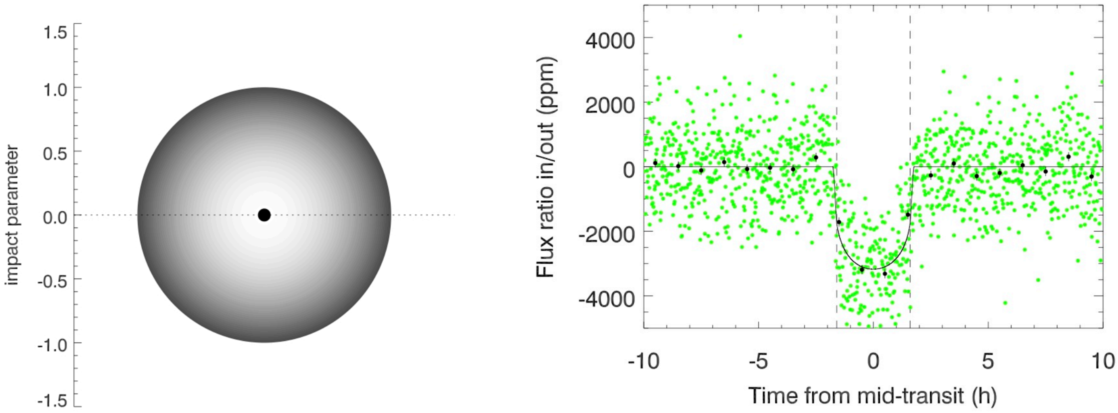

Figure 2: Simulation of a transiting Neptune-size planet with a 13-day revolution period orbiting a K dwarf star of the 12th magnitude in the *V* band, as observed by CHEOPS. The transit is sketched to the left and the simulated CHEOPS light curve is shown to the right. Sampling time is 1 minute and noise 1100 ppm/minute. The black dots indicate 1h-averaged photometry. This light curve illustrates a transit detection with a $S/N_{transit}$=30.

5.2 Measurements description

CHEOPS shall observe one star at a time. An example of observing sequence (hereafter, a "visit") is represented in Figure 3. A visit consists of observations acquired during consecutive spacecraft orbits and typically includes the acquisition of the science target and on-target exposures. Both Earth occultations –during which the target is not visible– and passages through the South Atlantic anomaly –during which the target is visible, but the increased noise due to high particle flux compromises the photometric precision that can be achieved– can occur during a visit. These are considered to be interruptions and calibration or instrument monitoring observations may be done during these periods[1]. Note that the types of calibration observations that can be done are restricted to those for which no change of pointing is required.

[1] No observations might be collected when the particle level flux reaches its highest value in the core of the SAA.

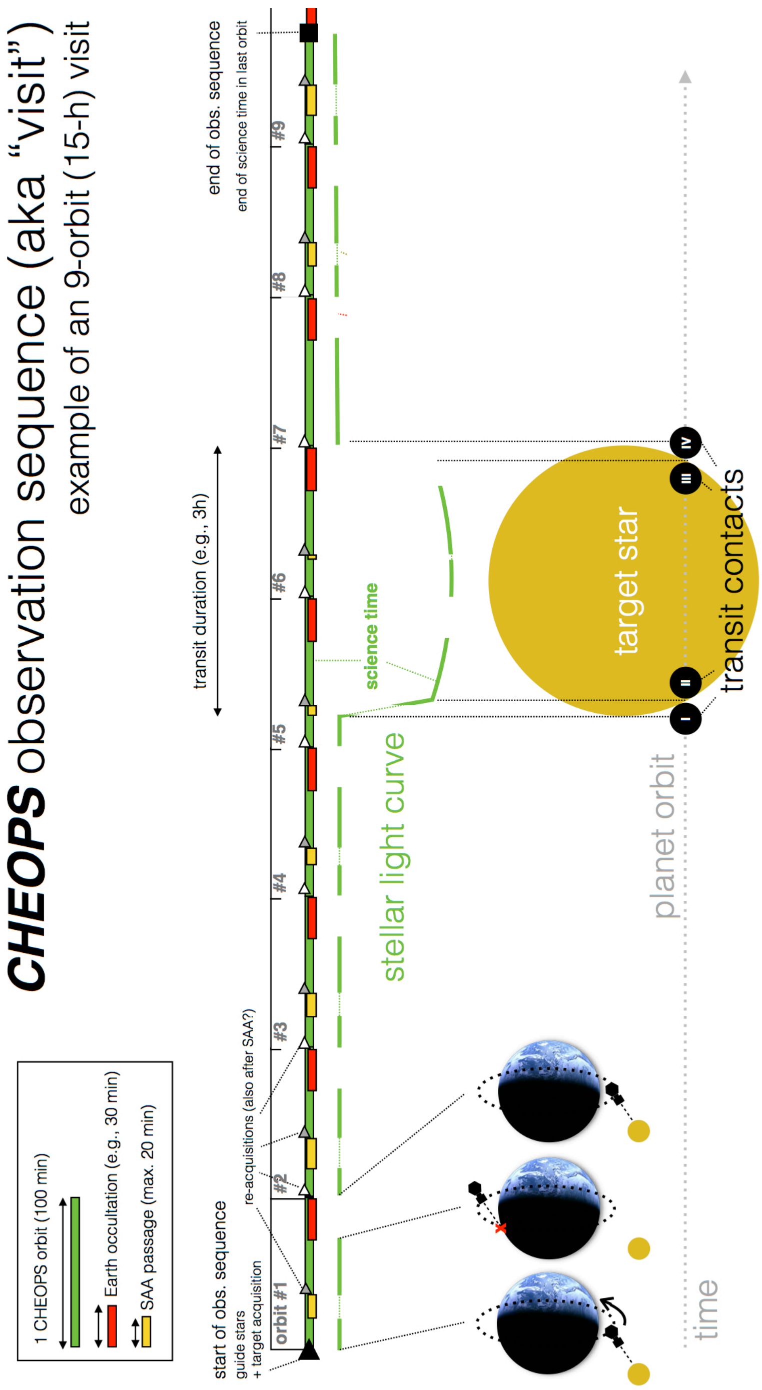

Figure 3: Example of a CHEOPS observing sequence or "visit". A stellar light curve before, during, and after planetary transit is shown for reference. The duration of the transit is roughly to scale with the visit. The arrows represent initial acquisition (filled) and (optional) re-acquisitions (open) after interruptions. Interruptions of the science time (time spent on-target and integrating; in green) can be caused by Earth occultations (red) and passages through the South Atlantic anomaly (yellow). A visit shall last for up to 48 hours, allowing to conservatively bracket the uncertainty in the predicted mid-transit time of an exoplanet detected with velocimetry.

The CHEOPS target list will consist of stars with: 1) small exoplanets previously detected by accurate Doppler surveys; 2) known transiting Neptune-size planets detected by ground-based surveys; and 3) hot Jupiters (short-period –≤2-day period– gas giants with temperatures in the range 1000–2000 K and beyond). Target stars can also be of different types. The stellar parameter with the strongest impact on transit measurements is the stellar radius (R_*), simply because the transit depth is proportional to R_*^{-2}. For each spectral type, we associate a stellar radius following Table 1.

The measurements required for these target types are, respectively:

1. Observation of transits on stars already known to host planets, by obtaining a transit signal-to-noise ratio of 5 for an Earth-size planet with a period up to 50 days on G5 dwarf stars (stellar radius R=0.9 $R_\odot$; stellar mass M=0.9 $M_\odot$) with a V magnitude brighter than 9th. Note that planets with longer periods will not be discarded from the CHEOPS target list, however they are less likely to transit their host star. This signal-to-noise ratio is sufficient to establish the transit detection and determine the presence or absence of a significant atmosphere for planets with masses ranging from Neptune to Earth. It may be achieved in one visit, however in the case of long interruptions of the observations (up to 50%) multiple transits from different visits will be required to built up the signal-to-noise ratio. For planets with revolution periods of ≤ few days, the duration of the transit will be a few hours only, and it may also be necessary to combine the observations from several visits.

   This measurement addresses science objectives 4.1, 4.2, 4.3 and 4.5.

2. Observation of transits for a number of hot and warm Neptune planets orbiting stars brighter than 12th V magnitude. Observing such known transiting planets with a higher precision than that possible from ground will not only grant us the possibility to accurately determine the transit parameters of the system but also search for yet unknown inner, smaller planets co-aligned with the known outer transiting Neptune. The new generation of ground-based transit searches in the southern hemisphere (e.g. NGTS or HAT-S) will detect a significant number of Neptune-sized planets orbiting late K dwarfs and early M stars. CHEOPS will detect the transit of these planets with signal-to-noise ratios above 30, with an observation cadence allowing the measurement of the transit egresses. This will enable the characterisation of the transit light curve, i.e. the possibility to accurately derive the transit parameters of the system: the impact parameter, the transit duration, and the stellar limb-darkening coefficients (cf. Figure 8). This information will then be used to obtain the accurate radius ratio between the planet and its host star. Similarly to the previous point, multiple visits may be necessary to obtain the required signal-to-noise ratio, in particular for the shortest-period planets, which have the shortest transit durations. In some cases it is foreseen that up to 10 visits could be obtained.

   This measurement addresses science objectives 4.1, 4.2, 4.3, and 4.5.

3. Observations of light curves of transiting and non-transiting hot Jupiters over a full orbital period, in order to measure phase modulation due to varying contribution of the

planet dayside. In some cases observations around planetary eclipse will also be made (cf. Figure 7).

This measurement addresses science objective 4.4.

Table 1: Types of target (dwarf) stars considered for transit measurements with CHEOPS. The stellar radii are expressed in solar radii, and the corresponding transit depths $(R_p/R_*)^2$ are indicated for Earth- and Neptune-size planets. The rounded values of 100 and 2500 ppm are used for SciReq 1.1 and SciReq 1.2, respectively. The stellar parameters considered here are those used in the CHEOPS Noise Budget.

	Stellar properties			Transit depth (ppm)	
Spectral type (dwarfs)	Radius ($R_\odot$)	Mass ($M_\odot$)	Temperature (K)	"Earth" (1 $R_\oplus$)	"Neptune" (4 $R_\oplus$)
G2 (Sun)	1	1	5780	84	1341
G5	0.9	0.9	5500	103 (~100)	1655
K	0.7	0.7	4500	171	2736 (~2500)

Since the transit measurement is differential, obtaining a "good quality" out-of-transit baseline, before and after the transit event, is essential. In the case of a photon-noise-limited observation, the signal-to-noise on the transit depth is driven by the measurements obtained during the transit. To secure this, if Δt represents the transit duration, the star shall be observed for a time Δt before the transit ingress and for a time Δt after the transit outgress, for a total observation time equivalent to 3×Δt. Transit observations are often dominated by time-correlated noise (aka "red noise"), however, and a good assessment of the time correlations in the light curve, which would allow the light curve detrending, depends on the characteristic time scales of the induced variations. Therefore, the 3×Δt observation time shall represent a *minimum* time scale.

A second key reason to observe a planetary system for a significantly longer time than the expected transit duration is because of the drift of the transit ephemeris, which will be particularly important in the case of search for transiting planets in systems that are already known to host planets. The uncertainty in the transit ephemeris comes (i) from the error in the mid-transit time T_o (usually a few percent of the orbital period) and in the period P ($\sim 10^{-4}$, which is multiplied by the number of transits that have elapsed since T_o), and (ii) from the error in the orbital eccentricity, which typically is known to ~10%. The combination of the two sources of error push towards maximising the observation windows for exoplanets detected by radial velocity.

6 SCIENCE REQUIREMENTS

The science requirements are numbered following the convention: SciReq n.m, with n indicating the section of this chapter (e.g., n=1 → section 6.1 Photometric accuracy) and m a consecutive number. Explanatory comments are provided in italics under each requirement. The level corresponding to each requirement is indicated as (L1/2).

An *explanatory note* in italic is appended to each requirement. The term "observation efficiency" used several times is defined as the ratio of the time spent when the instrument is acquiring scientifically valid data to the available time (including interruptions). For instance, an observation efficiency of 50% means that half of the time available in the visit (including interruptions) is spent obtaining scientifically valid data. As also explained in §6.3, "scientifically valid data" means that the photometric precision reached on these data complies with the following requirements on the photometric accuracy.

6.1 Photometric precision

SciReq 1.1 **Photometric precision for transit detection (L1)**

CHEOPS shall be able to detect Earth-size planets transiting G5 dwarf stars (stellar radius of 0.9 $R_\odot$) with *V*-band magnitudes in the range $6 \leq V \leq 9$ mag. Since the depth of such transits is 100 parts-per-million (ppm), this requires achieving a photometric precision of 20 ppm (goal: 10 ppm) in 6 hours of integration time. This time corresponds to the transit duration of a planet with a revolution period of 50 days.

The duration of the transit by a planet with a 50-day revolution period around a G5 dwarf is 6 hours. Interruptions during a visit will make the time spent on-target and integrating effectively lower than 6 hours. SciReq 2.1 defines the efficiency of such observations to be ≥50%. In case of minimum efficiency (50%), the required precision shall be reached by accumulating several transits during different visits (typically, two visits). More visits may also be necessary to reach the required $S/N_{transit}$ ratio for planets with much shorter revolution periods, as they will have correspondingly shorter transit durations.

SciReq 1.2 **Photometric precision for transit characterization (L1)**

CHEOPS shall be able to detect Neptune-size planets transiting K-type dwarf stars (stellar radius of 0.7 $R_\odot$) with *V*-band magnitudes as faint as *V*=12 mag (goal: *V*=13 mag) with a signal-to-noise ratio of 30. Such transits have depths of 2500 ppm and last for nearly 3 hours, for planets with a revolution period of 13 days. Hence, a photometric precision of 85 ppm is to be obtained in 3 hours of integration time. This time corresponds to the transit duration of a planet with a revolution period of 13 days.

This duration of the transit by a planet with a 13-day revolution period around a K dwarf is 3 hours. For a Neptune-size planet, the egress times (cf. Figure 8*) is approximately 20 min. An observation efficiency of ≥80% is required in SciReq 2.2 to allow building-up the signal-to-noise ratio and observing either one of the egresses of the transit light curve. This will enable light curve characterisation, i.e. the accurate determination of the transit parameters (cf.* Figure 8*). Several transit observations might* *be necessary to reach the requested signal-to-noise ratio for shortest-period planets with shorter transit durations or in case of minimum observing efficiency (80%).*

SciReq 1.3 Point spread function (L2 ← SciReq 1.1, SciReq 1.2)

The point spread function (PSF) of CHEOPS shall be adjusted (e.g., defocused) pre-flight as a function of the flat-field precision (SciReq 1.4) and the pointing accuracy (SciReq 1.6) to reach the required photometric precision (SciReq 1.1, SciReq 1.2).

This shall ensure that the PSF shape and surface area will result from a compromise between the expected spacecraft jitter (which implies a wider PSF to reduce error contributions from the flat-field) and the need to minimize the PSF because of (i) potential stray light contamination of the signal, (ii) a possible contamination from background stars, (iii) the possibility to obtain light curves from close binaries, and (iv) the amount of cosmic rays hitting the area covered by the PSF.

SciReq 1.4 Pixel-to-pixel flat-field precision (L2 ← SciReq 1.1, SciReq 1.2)

The pixel-to-pixel flat field (or p-flat) shall be measured down to a pixel-to-pixel precision of σ_{ff}=0.1%.

This precision results from a compromise between the size and shape of the PSF (SciReq 1.3) and the pointing accuracy (SciReq 1.6), and is necessary to reach the required photometric precision (SciReq 1.1, SciReq 1.2). As the PSF wanders on a set of adjacent pixels due to the pointing jitter, the amplitude of which shall be consistent with SciReq 1.6, the pixel response non-uniformity (PRNU), or interpixel sensitivity variation, is a major source of noise. The local, high-spatial-frequency flat field (or pixel-to-pixel flat field; p-flat) is representative of this PRNU. On the contrary, the low-spatial-frequency flat field (or L-flat, e.g., sensitivity gradients across the detector array) is not relevant to the photometric precision of CHEOPS observations.

SciReq 1.5 Flat-field stability (L2 ← SciReq 1.1, SciReq 1.2, SciReq 1.7)

The pixel-to-pixel flat-field precision (SciReq 1.4) shall be stable during a visit.

SciReq 1.6 Pointing accuracy (L2 ← SciReq 1.1, SciReq 1.2, SciReq 1.7)

The pointing accuracy during a visit (out of the interruptions) shall be better than 8 arcsec rms.

The 8-arcsec standard deviation of the jitter results from a trade-off between the size of the PSF and the flat field, necessary to reach the *required photometric precision (SciReq 1.1, SciReq 1.2). This formulation is compatible with the system requirement formulation that during observations, the half cone angle between the actual and desired payload line of sight (LoS) directions shall have an absolute performance error (APE) less than 8 arcsec at 68% confidence, using the temporal statistical interpretation.*

These four last L2 requirements (SciReq 1.3, SciReq 1.4, SciReq 1.5, SciReq 1.6) are tied together. The effect of the spacecraft jitter causes a displacement of the PSF onto different detector pixels, introducing extra noise due to pixel-to-pixel variations. This extra noise depends on the flat-fielding accuracy and can be mitigated by obtaining a flat PSF without a central peak very sensitive to inter-pixel variations. Trades are therefore possible between the flat-field precision, the extent of the PSF, and the pointing accuracy, provided the overall precision is maintained.

SciReq 1.7 Time scale for photometric performance (L1)

CHEOPS shall maintain its photometric performances (SciReqs 1.1 and 1.2) during a visit (out of interruptions), with duration of up to 48 hours (including interruptions).

A visit is defined as the scheduling and data product unit that is associated with a particular target (see Figure 3*). The 48-h observation duration results from the need to encompass the uncertainties on (i) the transit time ephemeris for radial velocity targets (typically ~1h/yr for a planet with an orbital period of 10 days and an uncertainty of 10^{-4} on the period measurement), (ii) the error on the orbital eccentricity, which can dominate the ephemeris uncertainty in particular for planets with longer periods, and (iii) to allow observing phase curves for hot and short-period giant planets. For longer observations, there is no requirement on the stability after the first 48 hours.*

6.2 Sky coverage

CHEOPS is a follow-up mission and in order to be able to access the most scientifically interesting targets it is critical that it is able to observe host systems in the largest possible fraction of the sky. The requirements on sky coverage for the two principle categories of CHEOPS targets are driven by their distribution on the sky and by the characteristics of their orbit. The choice of the operational orbit of CHEOPS has an impact on the sky coverage that can be achieved. CHEOPS will be a passenger on a shared launch opportunity, and as such the characteristics of the final orbit of CHEOPS will to some extent be driven by the needs of the primary launch payload.

SciReq 2.1 Stars with planets detected via Doppler velocimetry (L1)

50% of the whole sky shall be accessible for 50 (goal:60) cumulative (goal: consecutive) days per year and per target with time spent on-target and integrating the target flux longer than 50% of the spacecraft orbit duration (e.g., >50 min for a 100-min spacecraft orbital period).

This requirement is associated with the detection of Earth-size planets (SciReq 1.1). CHEOPS is a follow-up mission; therefore it is absolutely critical that it is able to observe stars with Doppler-detected planets in the largest possible fraction of the sky. The 50% of the whole sky results from a trade-off with the maximum revolution period of the planets we want to observe: a period of 50 days corresponds to a planetary orbit at the inner edge of the habitable zone of K stars. The transit of an Earth-size planet with a revolution period of 50 days across a G5 (0.9-$R_{\odot}$) star has a depth of 100 ppm and lasts for 6h. Since the transit measurement is essentially differential, it is necessary to monitor the star before, during, and after the transit, which for such transit duration requires visits typically comprising 9 to 12 consecutive spacecraft orbits. A CHEOPS visit on a target could be extended up to 48 h (29 orbits) depending on the transit ephemeris precision for this given target. A CHEOPS visit is usually not strictly continuous but contains interruptions (Earth occultations, SAA). Given the photon noise (~150 ppm/min) expected for a V=9 magnitude star, and the current noise budget, which is dominated by systematics, the required rms (SciReq 1.1) may be achieved if 50% of the visit is spent on-target and integrating the target flux and if the transit is properly sampled by the observations, i.e. if the on-target observing time is evenly dispatched among all spacecraft orbits. To favour this circumstance, it shall be possible to observe the star during at least 50% of each spacecraft orbit. The 50 days of visibility with >50% of the spacecraft orbit shall be as consecutive as possible to allow for uncertainties in the time of the transit and thus transit coverage at any time during the window.

Note that the transits of Earth-size planets with shorter revolution periods will also be shorter, e.g. 4-hour transits for revolution periods of 15 days; for such planets multiple transits will be needed to obtain the required signal-to-noise ratio. Note also that for small-size transiting objects, the time of the egresses is too short to be of any use to constrain the planet size through comparison with the precise measurement of the contrast. Missing egresses (occurring during interruptions) would not affect the performance of the mission to detect the transit and measure the size of small planets.

SciReq 2.2 **Stars with planets detected via ground-based transit surveys(L1)**
25% of the whole sky, with 2/3 in the southern hemisphere, shall be accessible for 13 days (cumulative; goal: 15 days) per year and per target, with time spent on-target and integrating the target flux longer than 80% of the spacecraft orbit duration (>80 min for 100-min spacecraft orbit).

This requirement is associated with the observation of transiting Neptunes on stars with V magnitudes < 12 (goal: 13) (SciReq 1.2). The revolution period of 13 days (goal: 15 days) is linked to the window function of the Next Generation Transit Survey (NGTS), which will be effective in detecting Neptune-size planets with revolution periods up to 15 days. The transit of such a planet across a 0.7-$R_\odot$ K-type star has a depth of 2500 ppm and lasts for 3 hours, which is short enough for a non-negligible fraction of the transit to be missed in the event of long interruptions during spacecraft orbits. The duration of all transits of K-type stars by Neptune-like planets with revolution periods <13 days fits within two spacecraft orbits. These transits can be measured with the required $S/N_{transit}$=30 (SciReq 1.2) provided that the time spent on-target and integrating the target flux represents at least 80% of each spacecraft orbit (<20% of interruptions). The sky coverage need not be as complete for these targets as for the Doppler targets, since for example NGTS will target only a fraction (10%) of the southern sky.

6.3 Target observability

The conditions for a target to be observable are defined below. When the target is observable and the instrument is pointing the target ("on-target"), data are obtained when the instrument is integrating the target flux. These data is referred to as "scientifically valid" when the photometry extracted from them meets the precision required in SciReq 1.1 and SciReq 1.2.

SciReq 3.1 Earth occultation (L2 ← SciReq 2.1, SciReq 2.2)

For the observing time to be scientifically valid, the target shall have a projected altitude from the surface of the Earth equal or higher than 100 km.

The margin of 100 km is taken to avoid atmospheric glow.

SciReq 3.2 Earth stray light exclusion angle (L2 ← SciReq 1.2, SciReq 2.1, SciReq 2.2, SciReq 4.1)

For the observing time to be scientifically valid, and in order to limit stray light contamination, the minimum angle allowed between the line-of-sight and any (visible) illuminated part of the Earth limb, the so-called *Earth stray light exclusion angle* shall be 35° (goal: 28°).

*This angle value is driven by the faint magnitude limit (*SciReq 4.1*) but could be adapted (lowered) as a function of the target magnitude.*

*The minimum value of the angle is set by the faint magnitude limit (*SciReq 4.1*). The assumption is that for angles above this the performance of the telescope is ideal and the stray light rejection infinite. The value could be adapted (lowered) in the case of brighter targets, for which the straylight requirements will be less stringent. The minimum value can* *also be lowered in the case of a non-ideal telescope, for which the off-axis/out-of-field-of-view straylight rejection is non-zero.*

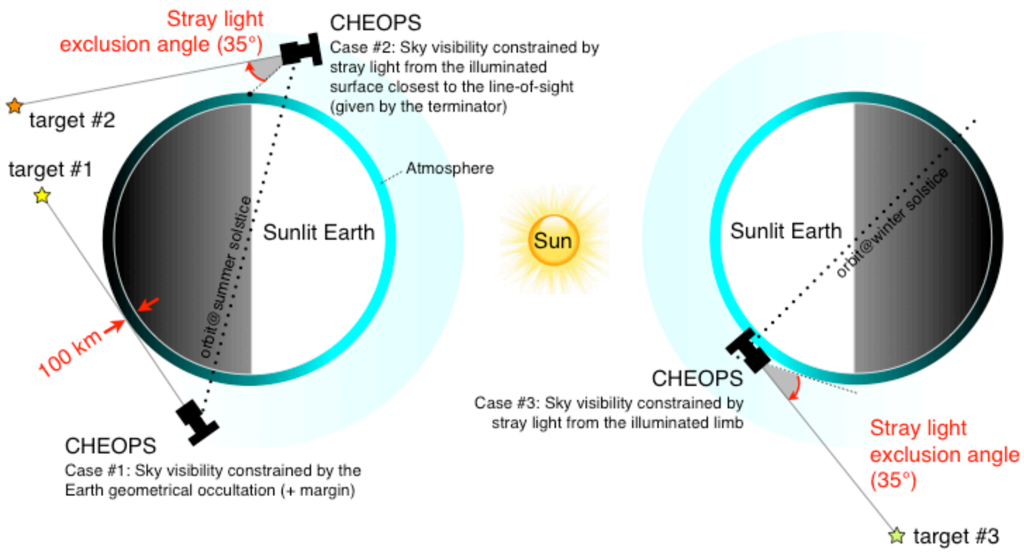

Figure 4: Illustration of the pointing constraints introduced by SciReq 3.1 and SciReq 3.2.

SciReq 3.3 Sun exclusion angle (L2 ← SciReq 2.1, SciReq 2.2)

During science observations, the Sun must be outside the cone around the line-of-sight (LOS) of the telescope having a half-angle, the so-called *sun exclusion angle*, of 120°.

This angle will in particular ensure that the radiators are never illuminated by the Sun. A Sun exclusion angle < 120° (goal) would enable better sky coverage capabilities.

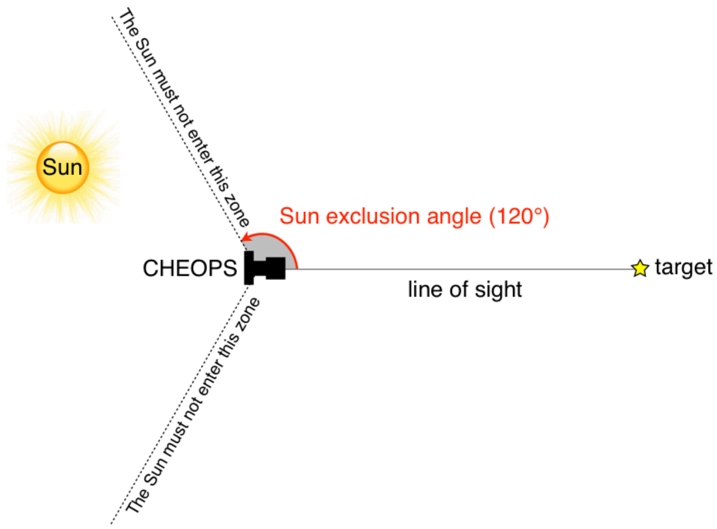

Figure 5: Illustration of the pointing constraint introduced by SciReq 3.3.

SciReq 3.4 Moon exclusion angle (L2 ← SciReq 2.1, SciReq 2.2)

For the observing time to be scientifically valid, the bright Moon must not be inside a cone around the line-of-sight of the telescope having a half-angle, the so-called *moon exclusion angle*, of 5°.

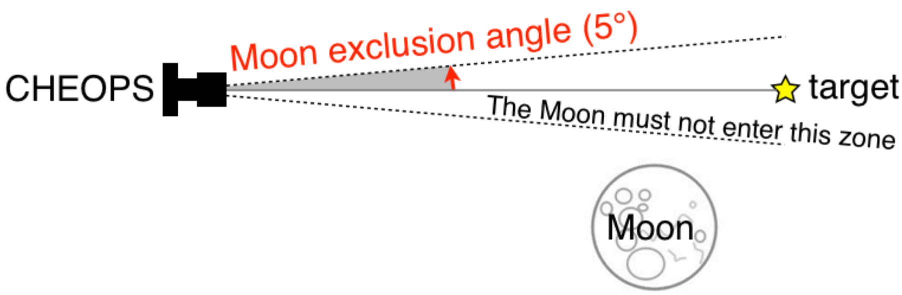

Figure 6: Illustration of the pointing constraint introduced by SciReq 3.4.

SciReq 3.5 South Atlantic Anomaly (L2 ← SciReq 2.1, SciReq 2.2)

For the observing time to be scientifically valid, the maximum total energetic particle flux due to the passage of the spacecraft through the South Atlantic Anomaly at the detector shall be 2 particles/s/cm^2.

6.4 Magnitude range of targets and exposure times

SciReq 4.1 Bright-to-faint target magnitudes (L1)

CHEOPS shall be able to observe bright to faint stars with *V*-band magnitudes in the range $6 \le V \le 12$ with the photometric precisions given in SciReqs 1.1 & 1.2.

SciReq 4.2 **Very bright target magnitudes (L1)**
CHEOPS shall be able to obtain light curves from very bright stars down to a V-band magnitude of V=0.

There is no requirement on the photometric precision for such targets.

SciReq 4.3 **Exposure times (L2 ← SciReq 4.1, SciReq 5.1)**
The exposure times for targets in the magnitude range defined in SciReq 4.1 shall range from 1 to 60 seconds.

The shortest exposure times would prevent saturation of the 6th-magnitude targets, while the longest exposure times are set by the temporal sampling of the measurements (SciReq 5.1).

6.5 Time sampling & precision of the light curves

SciReq 5.1 **Temporal resolution of the measurements (L1)**
CHEOPS shall be able to provide one photometric measurement per minute (goal: one per 30 seconds) in order to characterise the transit light curves of Neptune-size planets (SciReq 1.2).

In particular, this requirement will enable the ingress and egress phases to be temporally resolved, which will in turn lift the degeneracy between the impact parameter and the transit duration.

SciReq 5.2 **Time stamp uncertainty (L1)**
CHEOPS shall be able to provide photometric measurements with time stamp (UTC) uncertainties of 1 second (goal: < 0.01 second) for transit light curves. The goal value is set to provide a better time stamp precision for ancillary science.

Given the expected durations of the transits (from one to several hours), this time stamp uncertainty is sufficient to determine the central time of the transit to a precision that will enable light curves to be used in the analysis of transit timing variations.

6.6 Lifetime

SciReq 6.1 **Mission duration (L1)**
The nominal duration of the mission science operations shall be 3.5 years (goal: 5 years).

Table 2 *shows an example of mission duration budget broken down in terms of the type of targets in the CHEOPS core science programme. The allocation of the mission time to the different themes in the CHEOPS core* *science programme is indicative only, and will evolve until 6 months before launch.*

An average visit duration is assumed for each type of targets: visits of 48 hours are assumed for the detection of transits (SciReq 1.1) of planets discovered via velocimetry, while visits of 12 hours are assumed for the transit characterisation (SciReq 1.2) of planets previously discovered in transit. For the latter case, the transit ephemeris is obviously more accurate compared to the former case where the exact timing and occurrence of transit are unknown. A best engineering estimate of the observation overheads is also assumed. Searching for transits on 150 bright stars identified by Doppler surveys will need a minimum total of ~600 days, under the assumption of 50% observation efficiency (SciReq 2.1), 48-h visits, and two visits (on average) per target.

Characterising transits of 105 bright to faint targets from previous transit surveys will require a total of 150 days of mission, based on the assumption of 80% observation efficiency (SciReq 2.2), 12-h visits, and one, four, or ten visits (on average) for different subsamples of targets :transits shorter than 3 hours will require multiple visits, here 4 in average, and a handful of targets could require a large number of visits, here 10 on average, e.g. in the case of the search for transit timing variations.

Phase curve measurements for a handful of hot Jupiters will be made. These planets have typical orbital periods of a couple of days or less. Given the time scale for photometric performance (SciReq 1.7), CHEOPS could cover full orbits of planets with revolution periods of ≤2 days. Following-up e.g. 5 such planets with periods of 2 days and assuming that 7 visits are necessary to detect their phase curves requires a total of 70 days of the mission.

In total, these programmes combined require ~685 visits and a corresponding number of target pointings. Assuming 0.3 hours per visit for observation set-up (e.g., pointing for acquisition), and a tentative activity plan fill factor of 0.8[2]*, the allocation for the core programme is estimated at ~1032 days or 2.8 years. Adding to this duration the required open time allocation (20% of the science time), the required duration of the CHEOPS science operations mission is estimated to be 3.5 years. Finally, a small fraction of the remaining available time (e.g., 5%) will be dedicated to instrument monitoring and characterisation observation programmes.*

An extended mission (5 years) would allow the follow-up of more targets (e.g., following-up candidate planets detected by TESS to

[2] The fraction of time in the Activity Plan during the nominal science operations phase in which time-critical science observations can be scheduled for visit durations set on a per-target basis. This fraction of time excludes that used to execute the monitoring and characterisation programme, time taken for slewing as well as platform/instrument-related maintenance activities. Currently visits are set to 12h for know transiting reoplanets and 48hr for potentially transiting exoplanets – these durations can evolve in the future.

confirm/characterise their transits), the collection of more transit observations for objects discovered during the later phases of the mission, either with CHEOPS or other instruments (space-borne and ground-based surveys), and further monitoring for transit timing variations or exomoons.

Table 2: Mission core science operations duration budget example (time allocation between different core science sub-programmes will evolve)

#Targets	Time/visit (days)	#Visits		Total time (days)
Example of core science prg #1: Search for transits of known exoplanets				
150	2	2	600	600
Example of core science prg #2: Characterisation of known transits				
50	0.5	1	25	150
50	0.5	4	100	
5	0.5	10	25	
Example of core science prg #3: Phase curves of hot Jupiters in reflected light				
5	2	7	70	70
Overheads for observation set-up (pointing, etc. for 0.3 h/visit)				7
Guaranteed time dedicated to core science programmes (allowing for scheduling efficiency of 0.8)				**1032**
Open time dedicated to science programmes (20% of science time, including overheads)				**206**
Time dedicated to instrument monitoring & characterisation (e.g., ~5%)				61
Total mission science operations				**~1300**

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ACRONYMS

AU	Astronomical Unit
CCD	Charge-Coupled Device
CHEOPS	CHaracterizing ExOPlanet Satellite
CoRoT	COnvection, ROtation & planetary Transits
EChO	Exoplanet Characterisation Observatory
E-ELT	European Extremely Large Telescope
ESA	European Space Agency
HARPS	High Accuracy Radial Velocity Planet Searcher
HAT	Hungarian-made Automated Telescope
JWST	James Webb Space Telescope
LOS	Line Of Sight
$M_{\oplus}$	Earth mass (5.97×10^{24} kg)
MOST	Microvariability and Oscillations of STars telescope
NGTS	Next Generation Transit Search
ppm	Parts-per-million
PSF	Point Spread Function
$S/N_{transit}$	Signal-to-noise ratio of the transit detection
SPC	Science Programme Committee
$R_{\oplus}$	Earth radius (6371 km)
$R_{\odot}$	Sun radius (6.96×10^{5} km)
UTC	Coordinated Universal Time
WASP	Wide Angle Search for Planets

APPENDICES

Exoplanetary transit nomenclature and parameters.

The following sketches are meant to explicit most of the notions used in the text of this document. For more details, the reader is referred to Winn (2010).

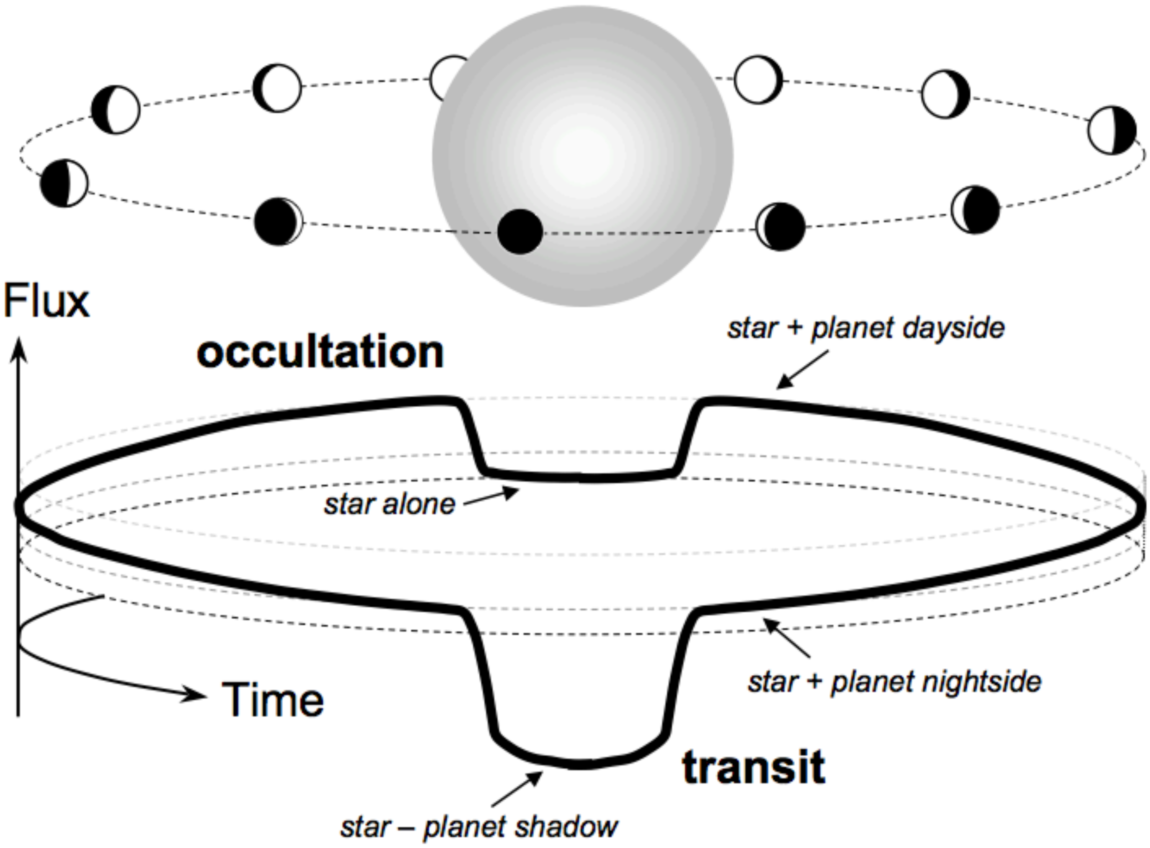

Figure 7: *Top*– Illustration of the transit and occultation of an exoplanet along its orbit around the host star. The phases of the planet are represented. *Bottom*– Sketch of the corresponding transit and occultation light curves. The transit light curve dip results from the fractional occultation of the star light by the planet (the "shadow"). The occultation light curve results from the total eclipse of the planet by the star, masking the light emitted (in the infrared) or reflected (in the visible) by the planet itself. The phase curve (which includes the transit and occultation) denotes the progressive phase change of the planet and provides information about the light emitted or reflected by the planet (in the infrared and visible, respectively). After Winn (2010).

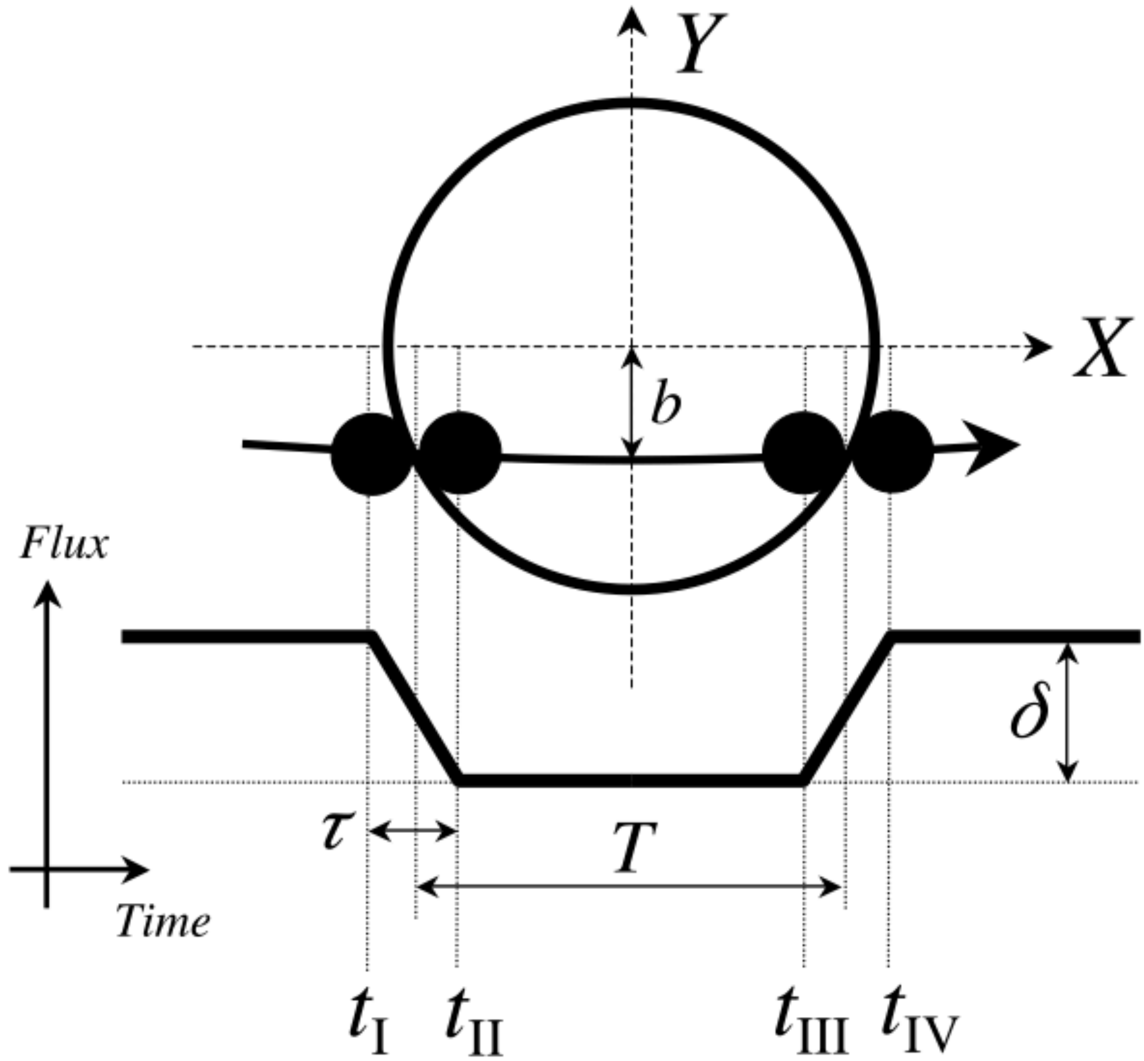

Figure 8: Sketch of a transit light curve showing the transit parameters. The transit depth is the squared ratio of the planetary to stellar radii, $\delta \approx (R_p/R_*)^2$. The impact parameter is the projected separation between the planet and the star centre, $b = a_p/R_* \cos i$, where a_p is the semi-major axis and i the inclination of the orbital plan. The quantity a_p/R_* is referred to as the system scale. The duration of the transit event is encompassed between the total transit duration –from the first contact t_{I} to the fourth contact t_{IV}– and the full transit duration – between the second contact t_{II} to the third contact t_{III}. The times between t_{I} and t_{II} and t_{III} and t_{IV} are referred to as the transit egresses (ingress and outgress, respectively). In reality, a transit light curve in the visible has no flat bottom but presents a curvature due to the stellar limb-darkening effect (the star is brighter at its centre than at its edges). If the star were a homogeneous disc, the transit depth would be exactly equal to $(R_p/R_\star)^2$. The transit light curve allows to quantify the limb-darkening profile of the star. After Winn (2010).