In-situ observations of resident space objects with the CHEOPS space telescope

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Abstract

The CHaracterising ExOPlanet Satellite (CHEOPS) is a partnership between the European Space Agency and Switzerland with important contributions by 10 additional ESA member States. It is the first S-class mission in the ESA Science Programme. CHEOPS has been flying on a Sun-synchronous low Earth orbit since December 2019, collecting millions of short-exposure images in the visible domain to study exoplanet properties.

A small yet increasing fraction of CHEOPS images show linear trails caused by resident space objects crossing the instrument field of view. CHEOPS' orbit is indeed particularly favourable to serendipitously detect objects in its vicinity as the spacecraft rarely enters the Earth's shadow, sits at an altitude of 700 km, and observes with moderate phase angles relative to the Sun. This observing configuration is quite powerful, and it is complementary to optical observations from the ground.

To characterize the population of satellites and orbital debris observed by CHEOPS, all and every science images acquired over the past 3 years have been scanned with a Hough transform algorithm to identify the characteristic linear features that these objects cause on the images. Thousands of trails have been detected. This statistically significant sample shows interesting trends and features such as an increased occurrence rate over the past years as well as the fingerprint of the Starlink constellation. The cross-matching of individual trails with catalogued objects is underway as we aim to measure their distance at the time of observation and deduce the apparent magnitude of the detected objects.

As space agencies and private companies are developing new space-based surveillance and tracking activities to catalogue and characterize the distribution of small debris, the CHEOPS experience is timely and relevant. With the first CHEOPS mission extension currently running until the end of 2026, and a possible second extension until the end of 2029, the longer time coverage will make our dataset even more valuable to the community, especially for characterizing objects with recurrent crossings.

1 The CHaracterising ExOPlanet Satellite (CHEOPS) mission

The European Space Agency (ESA) and the CHEOPS Consortium have partnered up to build and operate the first S-class mission of the ESA Science program. The CHEOPS Consortium is composed of 11 European countries, led by the University of Bern, Switzerland. CHEOPS was launched from the European Space Port in Kourou, French Guyana, by a Soyouz rocket on 18th December 2019. CHEOPS was successfully injected into its nominal Sun-synchronous orbit at 700 km altitude with a Local Time of Ascending Node of 6 a.m..

CHEOPS was designed to observe and characterize exoplanets with an exquisite precision of 10 parts-per-million (ppm) on targets brighter than GAIA magnitude 9. CHEOPS is equipped with a telescope of effective aperture 30 cm, operating in the visible range between 400 and 800 nm. CHEOPS' observing mode is to stare at one star at a time, for periods typically ranging from hours to days, to acquire a series of short-exposure images from which the target flux is measured precisely. Resulting light curves are exploited to detect variations that are primarily caused by planet(s) orbiting the host star. Planetary parameters such as radius, refined ephemeris, atmospheric properties can then be extracted from such light curves.

A complete description of the CHEOPS mission, including its platform, payload, ground-segment organization as well as its science program is given in [1].

2 Resident space objects crossing CHEOPS' field-of-view

In early January 2020, only a few hours after having opened the telescope tube cover, still during the commissioning phase, we observed for the first time a bright object that had crossed the field-of-view of the instrument at high velocity leaving behind a trail across the entire image. Since then, we have observed thousands of those, several per day, affecting the science images of CHEOPS. Figure 1 shows a gallery of such trails that we have collected.

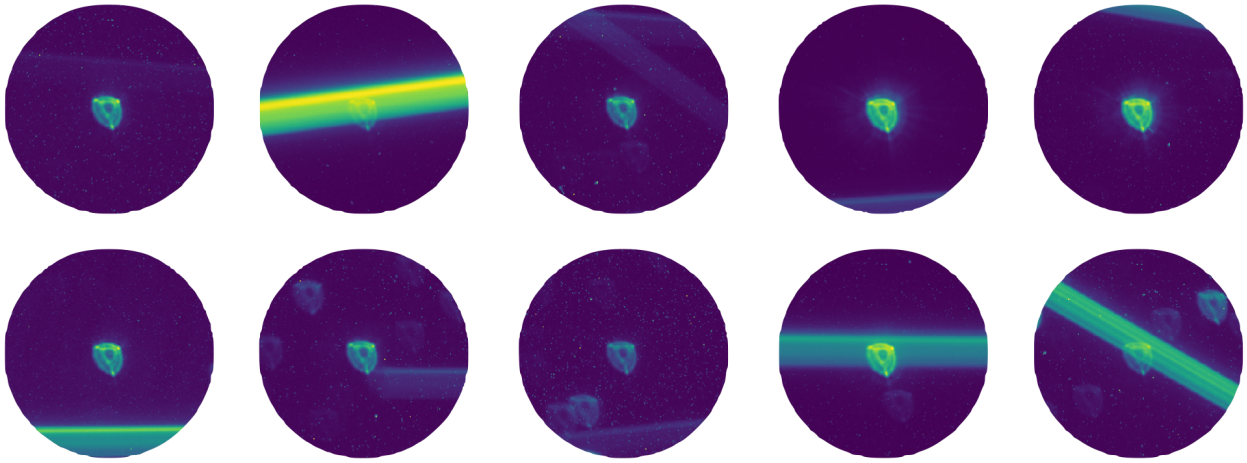


Fig. 1. Gallery of satellite/debris trails observed in CHEOPS science images showing bright, faint, grazing, partial and multiple trails.

The feature at the center of each image in Fig. 1 is the target star that was being observed at the time of the object crossing. As the CHEOPS instrument has been intentionally defocused by design to enhance its sensitivity, the Point Spread Function (PSF) spreads over 16 arcsec in radius and it has a complex structure, with a roundish halo and three bright spots due to the 3-legged structure that holds the secondary mirror. Details of the CHEOPS PSF and the overall instrument performances can be found in [2].

3 Automatic detection algorithm

In the present analysis, we are considering all and every CHEOPS science observation carried out over a period of over 3 years covering March 2020 until May 2023. This represents over 1.25 million images

collected over this period as part of the science program. These images are 200 arcsec across. They have been acquired with exposure times ranging from 1 millisecond for the brightest target stars to 60 seconds for the faintest ones, with a typical value around 30 seconds.

To cope with the large number of images, we have set up an automatic pipeline that scans each individual image and searches for linear features characteristic of satellite/debris trails.

Some pre-processing steps are required to ease and make the trail detection process more robust:

- Apply a median filter to the image to remove hot pixels
- Normalise the image to increase its contrast
- Apply a Canny edge detection to further increase the contrast. This step requires the fine tuning of thresholds to detect appropriate intensity gradients in the CHEOPS images and obtain the expected results.

We finally execute a Hough transform on the pre-processed images to detect and characterize trails (extract position angle and location on the image).

A dedicated completeness analysis of the trail detection process is underway. We have nevertheless already identified the root cause of most false positive detections:

- Excessive straylight from the Earth dayside may generate structures in the image background, e.g. linear ripples. Those images are excluded from the analysis.
- Edge-on cosmic ray hits lead to linear features in images. Those features can easily be filtered out as they are about 1-pixel wide, significantly thinner than a trail caused by a crossing debris.
- Crowded stellar fields, in combination with the extended structure of the CHEOPS PSF, may lead to false detections. These erroneous trail detections occur solely at 45 and 135 degrees, they are thus straightforward to filter out.
- Rare cases of saturation lead to vertical features that can be mis-identified for debris trails. Filtering out trails with position angles equal to zero solves this issue.
- CHEOPS' camera being shutterless, images containing very bright stars suffer from vertical smearing features. We can remedy this issue as above, filtering out images with 0 degree position angles.

The last caveat we have identified in our detection process concerns multiple trails. Those are currently considered as single trails with erroneous position/angle. Note that those represent only a small fraction of all trails seen in CHEOPS' field-of-view, estimated to a few percent at most, thus not biasing the statistical analysis presented below.

Out of the 1.25 million images scanned with our pipeline, and after filtering out false positives, we have identified a total of 3200 images that contain a trail due to a satellite or space debris crossing the field-of-view. This represents a mere 0.26% of the whole dataset, and this confirms that the CHEOPS Science program is not currently at risk due to these unwanted trails.

This relatively low value, compared to the few percent quoted in e.g. [3] for the Hubble Space Telescope, can be explained by the very small field-of-view of CHEOPS as well as the relatively short exposure times compared to those typically used with Hubble.

4 Dataset analysis

With thousands of trail detections, we have a large enough sample to explore possible trends on these crossing events. In the following sub-sections, we use the metadata available from CHEOPS images, like the line-of-sight (LOS) relative to the Earth horizon, to enrich our dataset and highlight statistically significant features.

4.1 Shell of debris in low Earth orbit

Along its revolution around the Earth, CHEOPS' attitude (i.e. telescope line-of-sight) remains constant for the duration of an observation, typically for a few hours/days. CHEOPS therefore probes various angles above the Earth horizon during the course of an observation. Figure 2 shows the distribution of the angular distance between the line-of-sight and the Earth horizon.

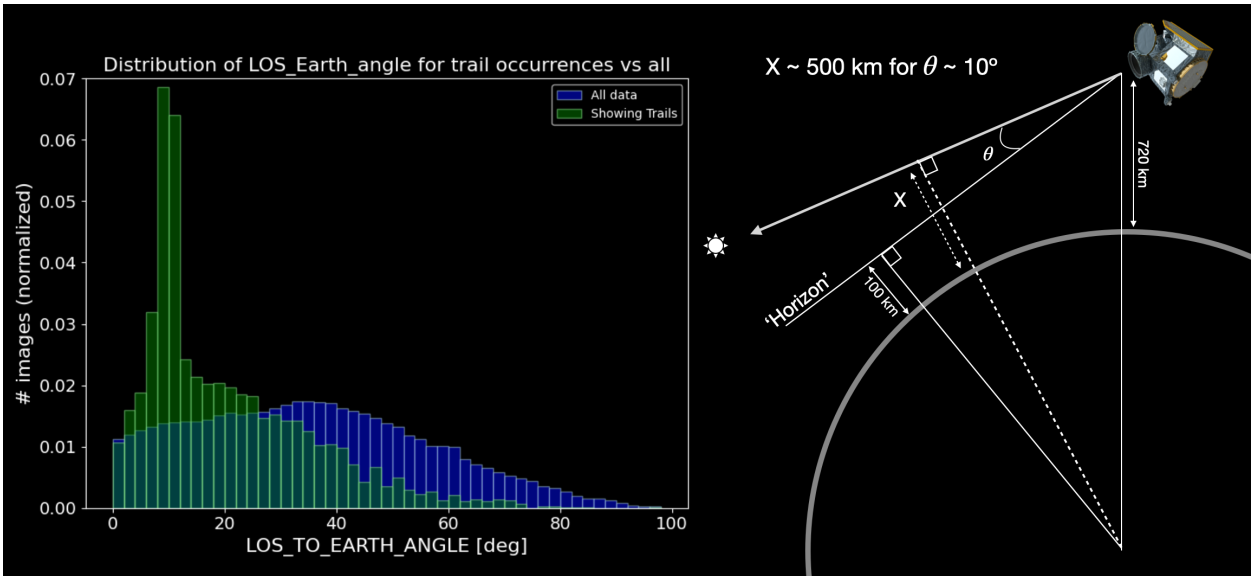


Fig. 2. Distribution of angular distances between line-of-sight (LOS) and Earth horizon.

The blue histogram shows the distribution for the entire dataset of 1.25 million images. The green histogram shows the distribution exclusively for images affected by trails. Both distributions are strikingly different, which means that trails occur preferentially at some specific angles above the horizon. In particular, the green histogram of figure 2 shows a peak at around 10 degrees above the horizon which denotes an excess detection rate at a specific '*angular altitude*' above the horizon. Depending on where along the line-of-sight the object is crossing, as depicted in figure 2, an elevation of 10 degrees corresponds to an object orbiting at 500 km or above, typically between 500 and 700 km. This peak in the green histogram traces a high-density shell of satellites and debris, the so-called Low Earth Orbit, that has been nicely probed by the CHEOPS line-of-sight over the past 3 years.

4.2 Higher detection rates for small phase angles

CHEOPS' orbit is Sun-synchronous such that the Sun always shines on the backside of the spacecraft to minimize straylight contamination (and power up solar arrays). Figure 3 shows the distribution of the

angular distance between the line-of-sight and the Sun direction. Allowed values range from 120 to 180 degrees, meaning that we only observe within 60 degrees of the anti-Sun direction.

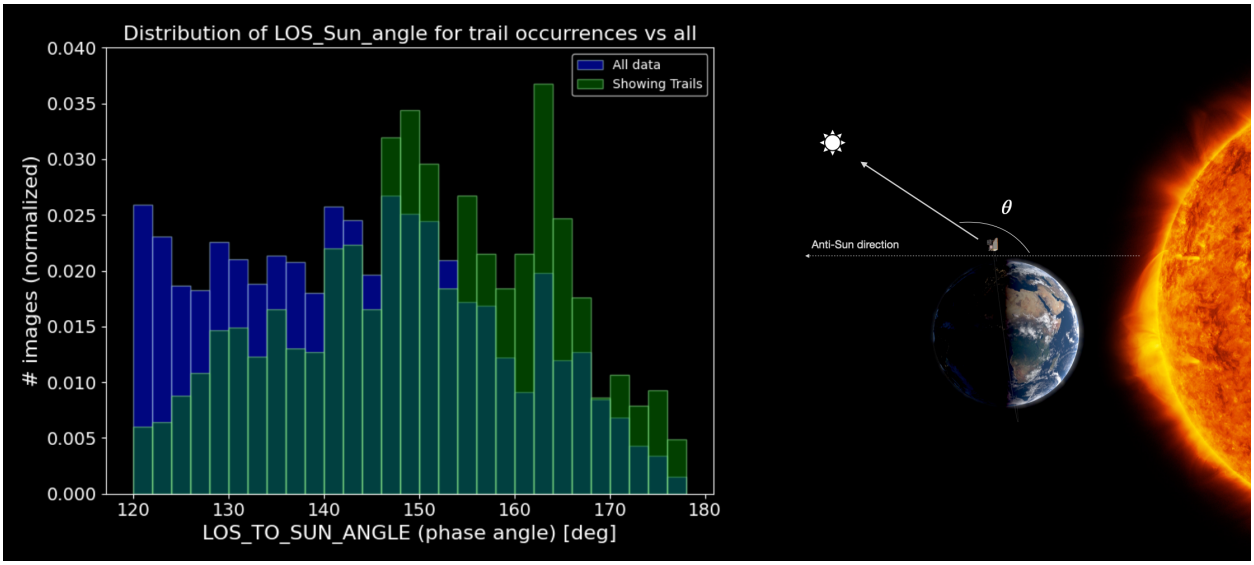


Fig. 3. Distribution of angular distances between line-of-sight (LOS) and Sun direction.

The blue histogram shows the distribution for the entire dataset of 1.25 million images. The green histogram shows the distribution exclusively for images affected by trails. Both distributions are different, with an excess detection rate at low phase angles, i.e. when the crossing object is illuminated from a direction close to the line-of-sight. We interpret this feature as meaning that crossing objects look globally brighter when the Sun shines on them from straight behind the observer. This is consistent with most phase functions that describe the dependence of scattered light versus the incident radiation phase angle.

4.3 Starlink imprint in geographic coordinates

We now consider the geographic position of CHEOPS at the time of observation to search for trends and features. Figure 4 shows the distribution of latitudes at which CHEOPS was located when it was observing.

The blue histogram shows the distribution for the entire dataset of 1.25 million images. Note that, with an orbital inclination of 98.7 degrees, CHEOPS always remains below a latitude of 81.3 degrees. The asymmetry close to the poles is also due to the inclination of CHEOPS' orbit as the spacecraft spends on average more time on the day side of the Earth when close to the South pole than close to the North pole. As CHEOPS is very sensitive to straylight, images acquired close to the South pole are often affected by straylight and therefore rejected on-board, thus leading to a deficit of images at very low latitudes. In addition, the dip in the blue distribution between latitudes 0 and -50 degrees is due to the South Atlantic Anomaly (SAA). When CHEOPS crosses the SAA, data are not recorded on-board because of a too high level of cosmic ray hits on the detector.

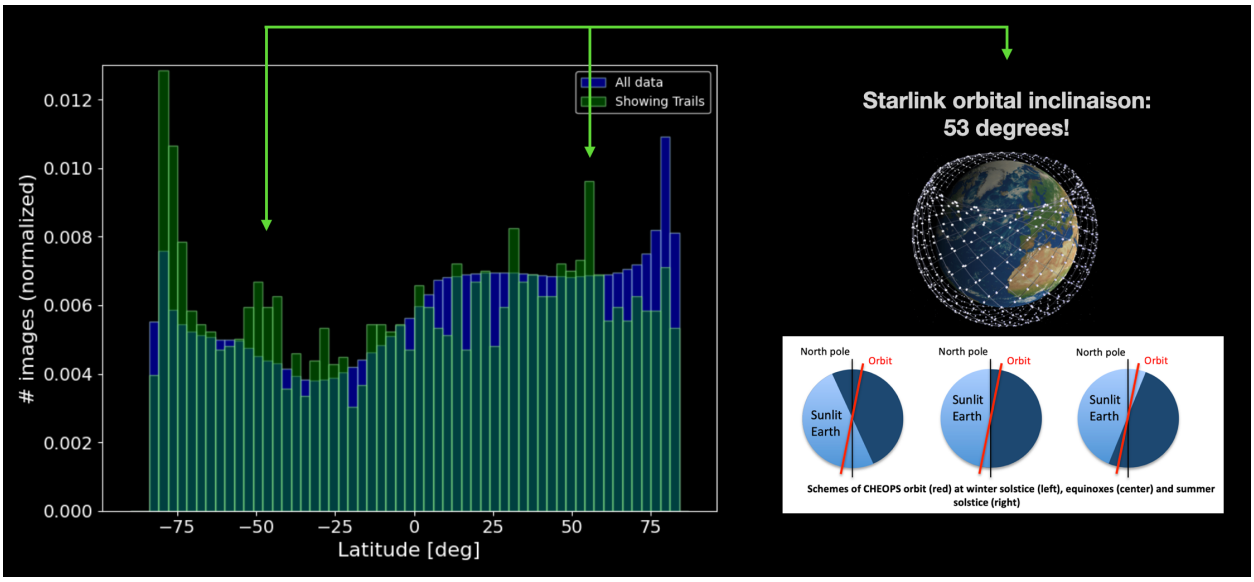


Fig. 4. Distribution of latitudes at time of observations.

The green histogram shows the distribution of the same quantity but exclusively for images affected by trails. Both distributions are again quite different. The asymmetry between South and North poles, also caused by CHEOPS' orbital inclination, goes in the opposite direction now. Close to the North pole, CHEOPS spends a fraction of its time in the shadow of the Earth during winter months, in the so-called eclipse season. During this period, a fraction of the objects crossing the field-of-view of CHEOPS will go unnoticed as they would also be in the shadow of the Earth during observations. This explains the deficit of trail detections close to the North pole. Conversely, close to the South pole, objects crossing the field-of-view spend comparatively more time illuminated by the Sun, thus increasing the number of detections at those low latitudes.

The green distribution also shows a couple of peaks at around -50 and +50 degrees latitude. Coincidentally a large fraction of the Starlink constellation have an inclination of 53 degrees, which means that Starlink satellites spends comparatively more time at latitudes $\pm$ 53 degrees than at other latitudes thus increasing the likelihood of being observed by CHEOPS at those latitudes. We therefore interpret the couple of features at $\pm$ 53 degrees latitude as being the imprint of Starlink.

4.4 Increased trail occurrence rate

With the injection of thousands of Starlink satellites in low Earth orbit over the past couple of years, we expect to see an increase in the number of trails detected with CHEOPS. This is indeed what is observed and presented in figure 5 where we plot the bi-weekly number count of trail detections.

The histogram shows strong modulations due to seasonal effects, with a severe deficit of detections during winter months. This is related to CHEOPS entering the eclipse season, as mentioned in section 4.3, where the spacecraft spends a fraction of its time in the Earth's shadow. During these winter months, many objects crossing the CHEOPS field-of-view will also be in the shadow of the Earth thus making them too faint to be detected in the images, and consequently reducing the number of detections. Summer months suffer from a similar effect, but to a lesser extent.

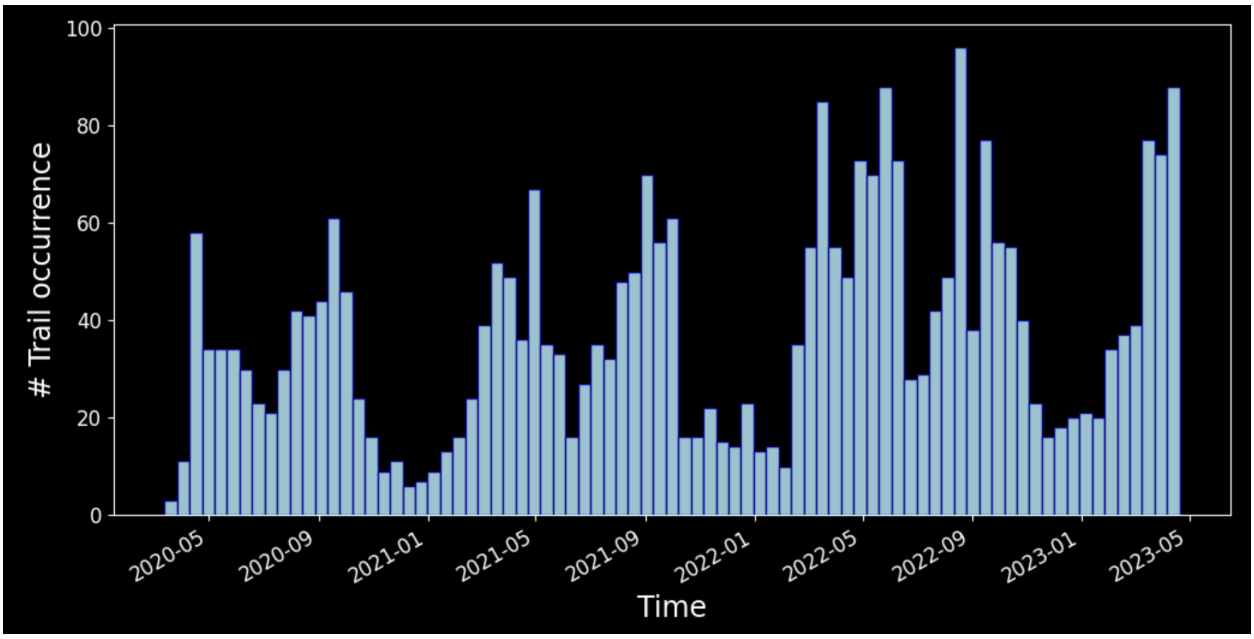


Fig. 5. Trail detection number count in bi-weekly bins.

Independently of these seasonal effects, the overall trend seen in figure 5 is indeed an increase in the detection rate. This trend becomes even clearer when considering specific 'angular altitudes' above the Earth horizon.

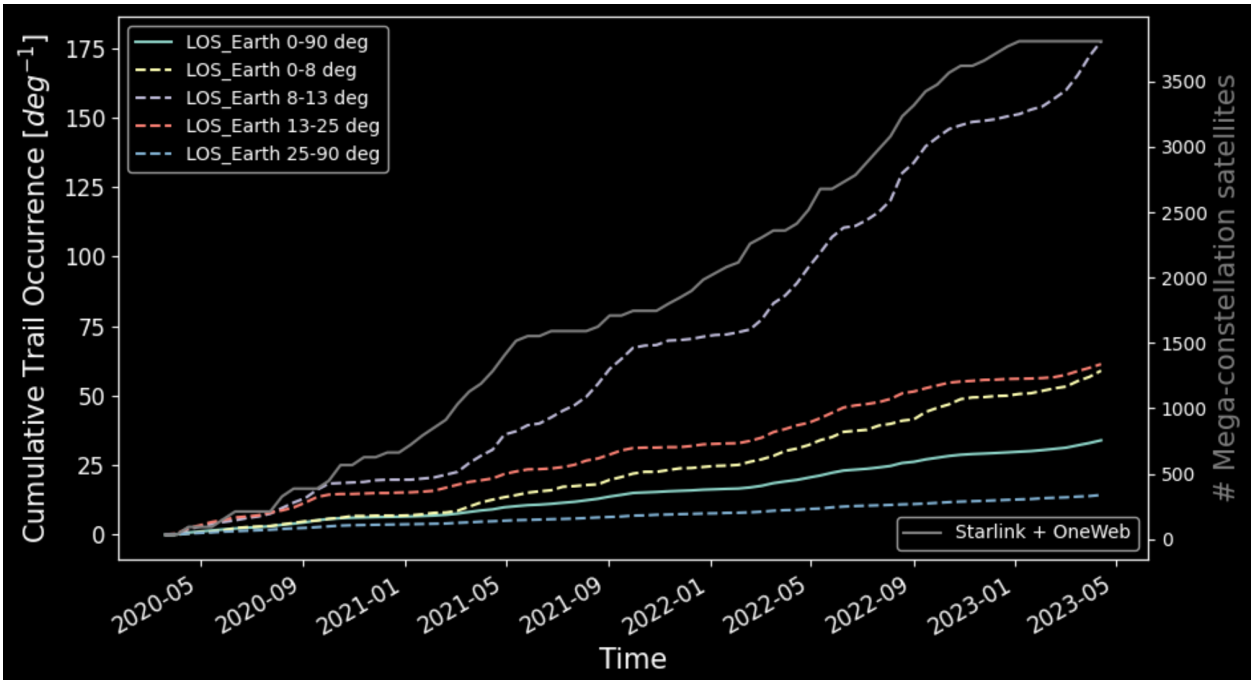


Fig. 6. Cumulative distribution of trail occurrences for various angular distances between line-of-sight and Earth horizon, along with the number of Starlink and OneWeb satellites injected into low Earth orbit over the same period.

Figure 6 presents the cumulative distribution of trail occurrences for various bins of angular distances between the line-of-sight and the Earth horizon, as described in section 4.1. The distribution is normalized by the bin size to represent a proxy of the debris/satellite density in each bin.

When considering only trails detected far above the horizon, e.g. between 25 and 90 degrees, figure 6 shows that the cumulative distribution is nearly linear. This means that the number of detections, per degree above the horizon, remains relatively constant, i.e. the population of objects detected in this zone has changed very little, if at all, over the monitored period.

Conversely, the densest zone probed between 8 and 13 degrees above the horizon, corresponding to the peak in figure 2, shows the strongest increase in the number of trail detections. As this zone traces mostly the population of resident space objects in low Earth orbit, we interpret this steep rise as a significant increase in the number of objects now populating this zone. This is consistent with the fact that Starlink and OneWeb have launched thousands of satellites into low Earth orbit over the past couple of years, as shown in figure 6.

5 Object identification

5.1 TLE projection

For a detailed analysis of each individual detection, the observational circumstances, such as observer-target distance, phase angle and angular velocity are required. To obtain this information, we linked each observed trail to the catalog of known space objects provided by the US 18th Space Defense Squadron, published on the space-track website[1]. Orbital information on space objects is usually provided by Two-Line Element sets (TLEs), that correspond to the mean keplerian orbital elements at a given epoch. This results in the accuracy of positions computed from propagating the TLEs to decrease with increasing distance from the TLE epoch. Since the CHEOPS data was acquired over the past 3 years, historic TLEs are required to identify the detected trails with cataloged space objects. The space-track API provides access to historic orbital information but only limited functionality to constrain the search. Further, the number of requests is limited which made it impractical to use the space-track API since we needed to link thousands of trails. This forced us to download the entire catalog of TLEs over the period of CHEOPS operations (March 2020 to June 2023), which contained 49,280,118 individual TLEs in total.

5.2 Identification process

For each CHEOPS image that contains a trail, we selected the TLE of CHEOPS that was closest to the observation time to compute the observer location, and for every cataloged space object, we selected its TLE closest to the observation time from an interval of 2 days around the observation epoch. This resulted in about 18,000 to 25,000 TLEs for each observation. Using the precise observation time and the astrometric solution stored along with the CHEOPS data, we were able to compute which of those objects were crossing the observed field during the exposure and projected their track into the image. This projection is of limited precision due to several reasons. Firstly, because the observer location and the positions of the cataloged space objects were computed from TLEs which are inherently imprecise, and the uncertainty of positions, computed by propagating the orbit, grows with increasing distance to the TLE epoch. Secondly because CHEOPS is nearly nadir-locked, i.e. slowly rotates in order keep its radiators always away from Earth, and this rotation is not accounted for in the astrometric solution

[1] https://www.space-track.org/

stored along with the data. However, by defining margins for the identification, it was still possible to assign the majority of the trails to cataloged objects.

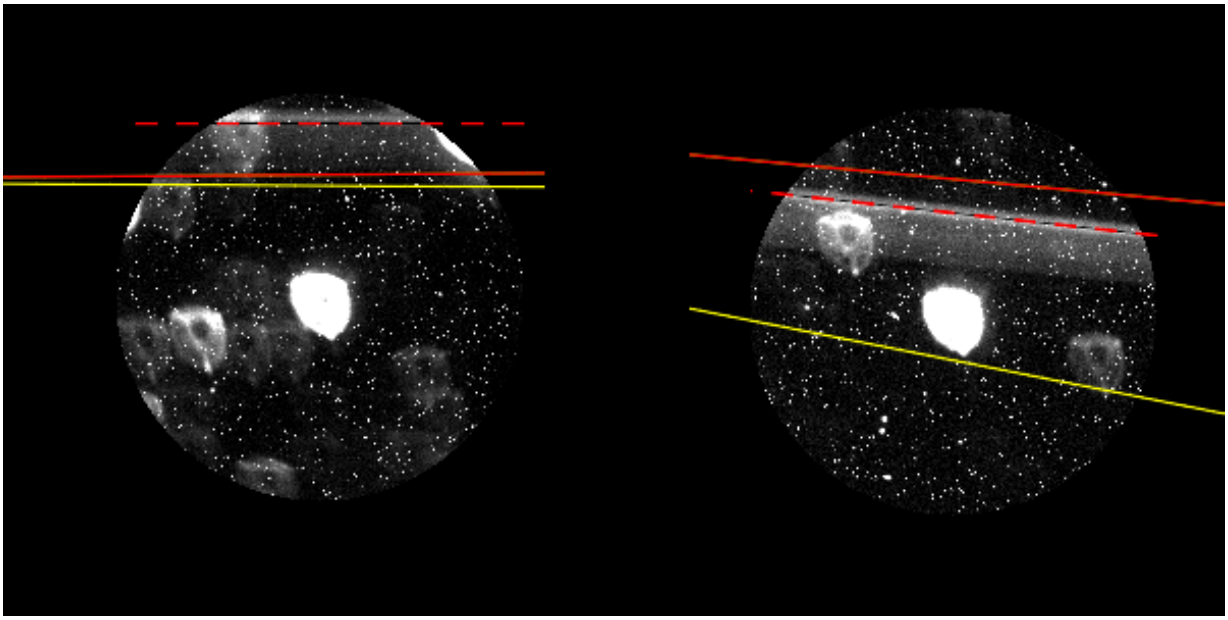


Fig. 7. Trail detections (dashed red lines), projections of all cataloged objects that cross the field of view (solid lines) and the assigned known object (solid red line).

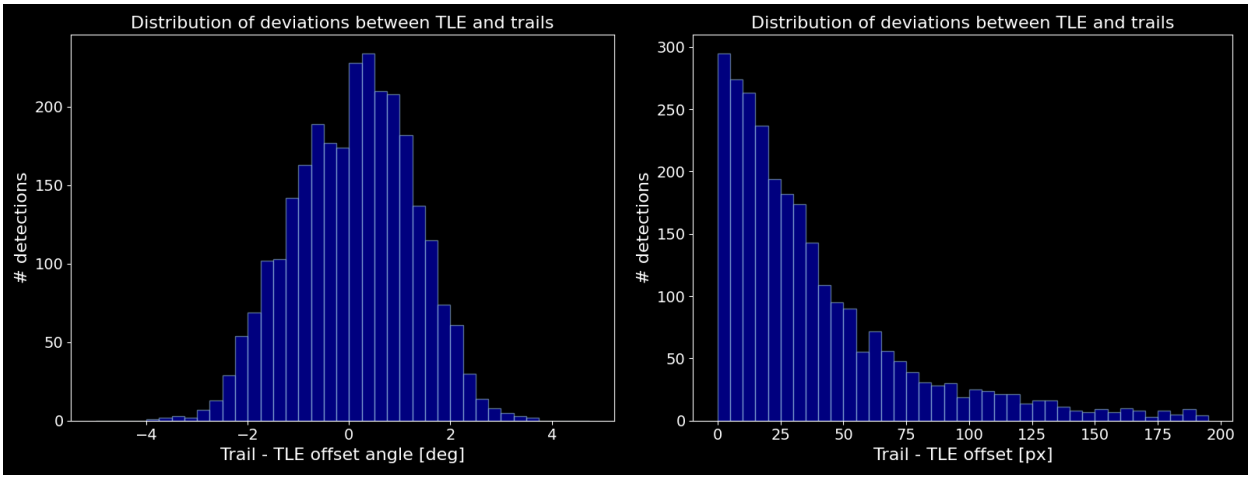


Fig. 8. Distributions of the offset in position angle (left) and the distance between trail and projected trajectory (right) of the identified trails.

Figure 7 shows two examples of the trail identification. The dashed red line corresponds to the detected trail and the solid lines to cataloged objects crossing the field during the exposure. The red solid line corresponds to the cataloged object that was identified with the detected trail. In order to account for the inaccuracy of the projection, we used margins of 350 px for the distance and 4 degrees for position angle between trail and projected object for the assignment. The margins were chosen to account for an expected uncertainty in the positions computed from propagating the TLEs of about 1 km at 600 km distance and a rotation rate of CHEOPS of 6 degrees/minute on average. In case there were multiple

known objects within these margins, the one closest to the detected trail was selected. The distribution of pixel offset and difference of the position angles of the identified objects is shown in Figure 8. The majority of identifications are actually much closer to the detected track than the accepted limits, suggesting that the TLEs selected for identification generally have good accuracy.

As already explained in section 4.4, we expect that a significant number of trails were caused by satellites from the Starlink constellation. Indeed, out of the 2742 trails that could be identified with known objects, 805 were caused by Starlinks, making the Starlink constellation responsible for about one third of the detected trails. Considering only trails caused by payloads (1799), Starlink satellites are responsible for almost 50% of the detected trails. We further identified 785 trails belonging to rocket bodies and 140 to orbital debris.

6 Conclusions

Astronomical observations have been increasingly affected by resident space objects over the past few years. Even sending telescopes into low Earth orbit does not make them immune to intruding objects crossing their field-of-view. The current projection for the next decade, including all planned private and governmental mega-constellations, is that the low Earth orbit could host hundreds of thousands of satellites. This is two orders of magnitude larger than it is today. If CHEOPS were to still be in operations then, the fraction of affected images would go from a fraction of a percent to nearly a quarter of the collected images, which would seriously impair the science case of CHEOPS.

Despite its detrimental impact on observational astronomy, serendipitous observations of space debris by astronomical facilities can be turned into useful information. The dataset presented in this article is indeed very valuable for the Space Situational Awareness community because it provides in-situ observations of satellites and other space debris over a period of 3 years that covers the start of the mega-constellations era. Besides, the CHEOPS dataset is complementary to ground observations, and in a sense ahead of its time when we consider that several projects dedicated to in-situ observations of space debris are currently in development [4, 5]. We aim at making our dataset public via the International Astronomical Union's CPS[2] (Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference). This dataset could be used to refine observing strategies and mission concepts for these future endeavors.

7 References

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[2] https://cps.iau.org