The Impact of Light Pollution from Low-Earth Orbital Space on Astronomical Observation in Antarctica

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Abstract. Quantitative assessment of satellite proliferation impacts on Antarctic astronomy reveals that 14.5% (14.14–14.86%) of images from Kunlun station are contaminated, exceeding Hubble's design tolerance over four times and ACS/WFC baselines (10.0%) by 45% and threatening humanity’s ultimate pristine window to the universe, immediate space traffic control is needed to improve the space environment. Using Kunlun Station images (05/2008, n=11477) and Space-Track.org satellite catalogues, we annotated satellite trails using LabelImg and modeled orbital mechanics to quantify contamination risks. We estimate the errors and uncertainties via Poisson Noise. Consistent with the contamination metrics, orbital density model visually demonstrates that polar-orbiting satellites over Antarctic (70°-90°S) have an areal density four times higher than equatorial orbits due to sun-synchronous orbits. This degradation poses a unique challenge because Antarctica offers unparalleled conditions for cosmic discovery. Its stable atmosphere, minimal light pollution and the world’s lowest atmospheric interference make Antarctic is the only capable of high-precision studies of the cosmic microwave background (CMB) and dark matter exploration. Without immediate action, these critical observations may be impossible in the future. Urgent mitigation strategies, such as satellites orbit regulations, must be implemented to preserve this vital window into the universe.

Keywords: Space Environment; Optical Astronomy; Antarctica; Contamination; Observations.

1. Introduction

1.1. The development of Space Exploration and Utilization

The first artificial satellite has been launched by Soviet Union on 4th, 10, 1957. From that time, human exploration and utilization (especially the space in LEO) has been developed rapidly. How did these aspects be developed over human’s history? Before, which was about five centuries ago, human used their naked eyes to observe the space. After that, in 17th century, the first telescope was invented by Galileo, he created a new era of surface observation. Later on, after the first artificial was launched, human started using rockets and spaceships instead of using telescopes to observe the space. When the first astronaut entered space and the first person landed on the moon, human explored the space more deeply. From 1980, many countries were starting to build International Space Stations and more mature space telescopes such as Hubble Space Telescope. In modern century, people are using satellites for navigating, forecasting weathers and satellite Internet, which has been developed a lot by star chains. In the future, some private companies are planning to build bases in the moon or even settlement to the Mars.

1.2. The pollution on Space Environment

The first artificial satellite was launched by Soviet Union in 4th, 10,1957, called Space Launch-1 Rocket Body. It did not have a specific role comparing with other rocket body, it only existed in space for about 1 month, which decayed on 1st, 12 in the same year as it launched. As shown in the Figure 1, the annual increase of space objects has reached its peak until 1997. The reason of that is that because artificial satellites became more and more mature, and more countries were able to do that over that period. In 1997, Russia and countries surrounding launched a lot of satellites that Soviet Union remained, and countries such as China, the USA and France also launched their satellites for navigating and military used. That is the reason why 1997 had the largest number of launching. However, after that, Iridium Project by the USA became bankrupt and the number of launching satellites has suddenly decreased. In 21st century, SpaceX, CNSA and ESA were able to launch variety of satellites, so the number increased again.

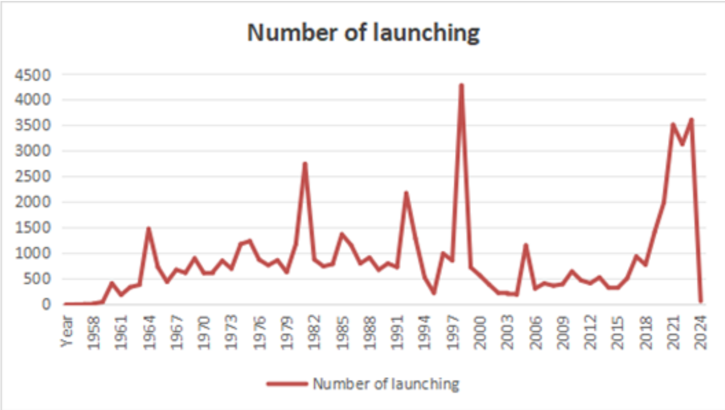


Figure 1. Illustration for the annual increase of space objects between 1957 and 2024

Figure 2 shows the tendency of the number of satellites in orbit between 1957 and 2024. If we check Figure 2 clearly, we can see that the overall number of space objects in orbit proliferated from 2 in 1957 to almost 30000 in 2024. Between 1997 and 2000 the number of satellites in orbit increased the most, which I have mentioned the reason above.

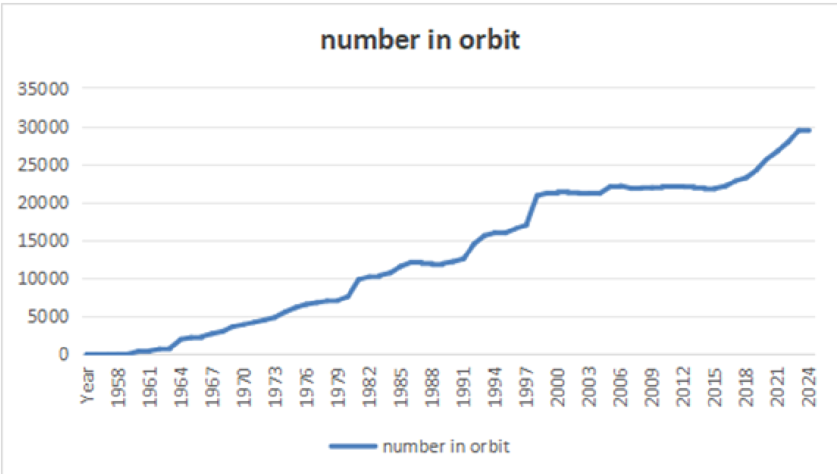


Figure 2. The number of space objects in orbits for the year from 1957 to 2024

Space becomes crowded year by year. Basically, debris caused by crashing is the main faction of the pollution. A famous example of it, in 2024, CZ-6A payloads has launched and the “Thousand Sails Constellation” satellites were successfully sent into designed orbit. Ideally, it would leave the orbit immediately and became a “harmless litter”, however it got some problems when evacuated gases, then it exploded. A military bureau in the USA found at least 700 pieces of debris. SpaceX criticized it because they said these debris may affect their Falcons. Ironically, satellites or rockets in SpaceX produced the most number of debris in space. For example, from 2019 to 2024, there are about 1% to 2% of Starlink satellites became defunct due to propulsion systems failures. Also, Falcon 9 made a lot of debris because SpaceX could no longer control it after it sent satellites into the designed orbits. In other words, what are the hazards made by debris in space? A term called “Kessler Syndrome” describes this phenomenon perfectly. This syndrome describes that when the density of debris reaches the critical value, so the debris made by crashes of satellites or spacecrafts makes more collisions happen. Finally, the number of debris will increase exponentially. Making more serious light pollution and interrupting the observation in polar areas.

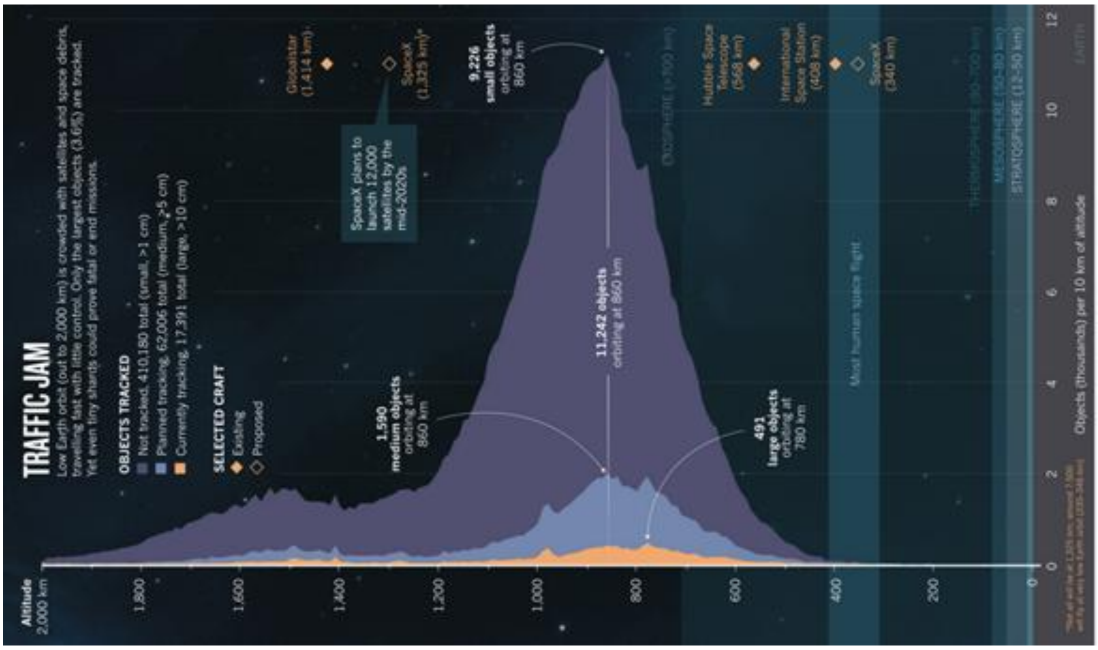


Figure 3. The distribution of orbital altitudes for tracked Space objected (in orange), the main population occupied the orbits with altitude from 400 km to 1,000 km. With global distributed sensor network, more space debris are in the tracking plan (in blue). More small-sized space debris are not trackable (in purple). (Jamie Morin, 2019)

1.3. Severe Light Pollution over Antarctica

Our orbital stimulation (Figure 4. a) shows obvious latitudinal disparities in density of satellites: For polar regions (80°S-90°S and 80°N-90°N), more than 3.8 million of satellites transit per year, which is represented by the red zones. For temperate zones and tropics (66.5°N-66.5°S), less than one million of satellites transit per year. According to Figure 4.b, we can deduce that the sky over Antarctic (same as the North Pole) has the most crowded converage.

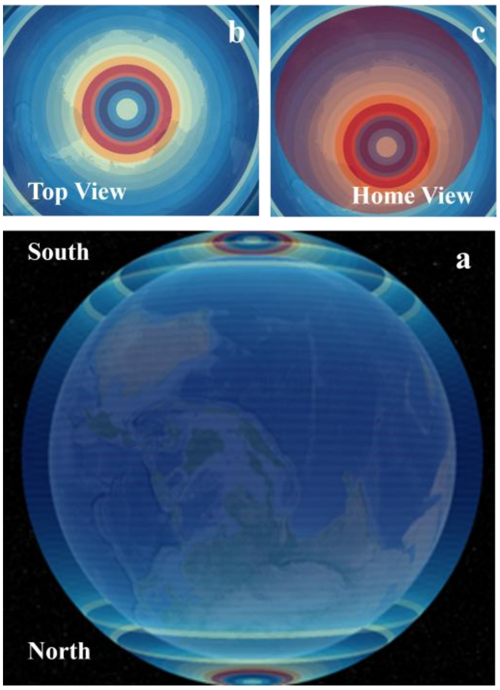


Figure 4. a. The spatial distribution of the number of satellites passing over the outer space of Earth for a simulation. The regions with the least satellite passing-by are in dark blue, the regions with the most are in red. b. A top view from Antarctica. c. A home view from Antarctic Dome A with its horizon

As shown in the figures, there are much more satellites pass overhead the Antarctic circle. But in the more southern area, the number of satellites is unexpected less. Figure 4 is the tangent plane that we observe the space in Kunlun observation station. (Kunlun station is a Chinese observation station in Antarctic, which is located at about southern latitude 80 degrees, eastern longitude 77 degrees). Despite reduced the density directly over the South Pole (Figure 4.b), Kunlun station's observational plane still intersects with the most crowded space zone (Figure 4.c). So, less satellites in the most southern area does not reduce the light pollution significantly. In addition to the increasing number of satellites in LEO, the distinctive atmospheric environment significantly amplifies the light pollution due to scattering properties and cosmic effects.

2. Data analysis

2.1. Data collection

From the images taken between 29th May in 2008 and 31st May in 2008, there are 1664 images have trails among 11477 photos. As we all know, every data we measure must includes some error. How can we calculate the errors? We need to know a concept in probability, which is called Poisson's Distribution. In order to calculate the errors, we use Poisson's Noise instead of Poisson's Distribution. There are two parameters are required, the first one is variance, can be calculated by square root of λ, where λ is the average quantity. Relative error can be calculated by reciprocal of SNR (Signal-to-Noise Ratio), which is variance divided by λ, with simplifying, it can be written as $\sqrt{\lambda}$. According to this formula, we can find that more measurements deserved higher precision.

Back to our own issue, what are the errors we have in our images. The errors of the images containing trails can be calculated as:1664 (square root of the photos containing 1 trail only) divided by 11477 (total amount of samples), which equals to 14.50%±0.36%. For the errors of the images containing 2 or more trails, the errors can be calculated like: 193 (square root of the photos with trails more than 1) divided by 11477 (total amount of samples), which the result is1.68%±0.12%.

2.2. Recognizing the satellite trails in images

As mentioned above, we have 11477 images in total. Firstly, we need to extract the images that contain satellites trails. Most of the images do not have any trails at all. But some images have trails up to four. How can we label these images contain trails, we have two methods: Firstly, we can write programming codes, it is very effective but sometimes it could be unreliable, so after we use these codes, we need to check it and waste much time. Secondly, we can label them manually using an annotation tool (i.e. LabelImg), which enables us to highlight the images containing trails. Although it also takes a lot of time, luckily, we do not need to check it after we use this software.

So how can we use it? Firstly, Anaconda is necessary, because it is an internal software in Anaconda. Once we download it, we should open Anaconda Prompt and type LabelImg in it. Now we can start label the images contain trails. Firstly, we should open our files, we only need to find a choice called "Open Dir" and select the files we want to label. Secondly, we can view our photos and click "Next Image" and "Previous Image" to access all images in our file. Thirdly, if we see trails contained, we need to click Verify images to highlight them. Then we can see there are some highlighted parts around the image, shown in Figure 5 below.

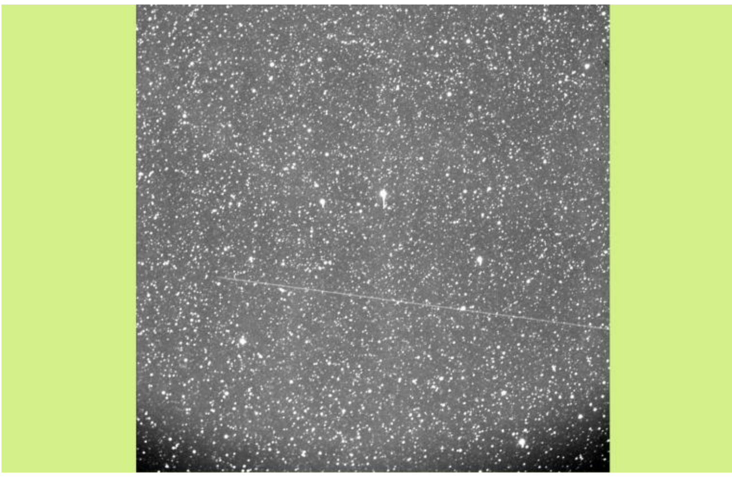


Figure 5. The interface of LabelImg annotation tool

After we label all images containing trails, we need to save them. The original format is xml, if there are any trails contained in an image, we can see <object> in xml document. According to that, we can make a python code for it to count how many <object>s included in the files. We got the images containing trails right now, but we have not done our work yet. We should find how many trails in every image, it is much easier because where are only 1665 images contain trails. Finally, we find that 1471 images contain only one trail, 176 images contain two trails, 16 images contain three trails and only one image contain four trails. Figure 6 is the pie chart that shows a clear result of number of trails. After using LableIMG to help me annotate, Python code is also programmed and used to assist us to check. With a view to make the result more accurate, only the "trails" brighter than the background and the length longer than 15 pixels can be considered to be "real trails". As the result, the final value is within the range of 14.50±0.36%.

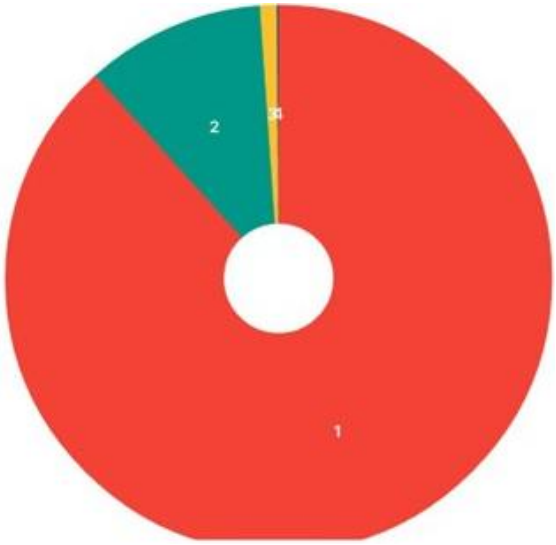
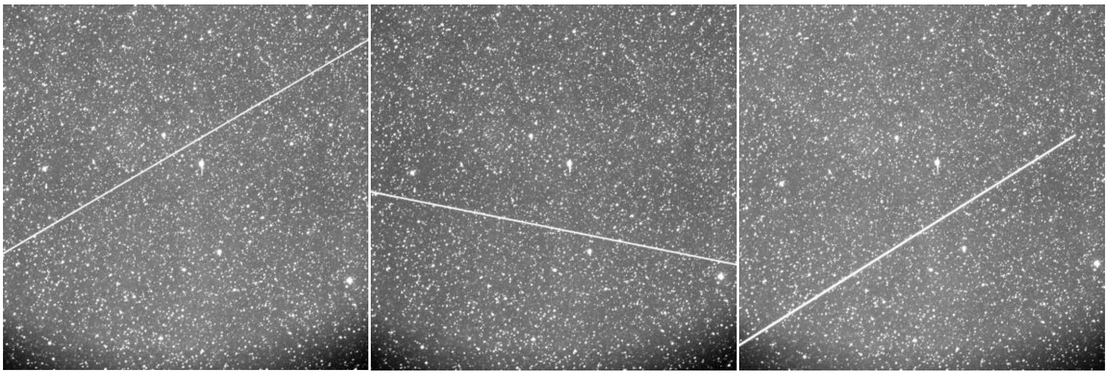


Figure 6. The fraction of images containing one trail, two trails, three and four trails

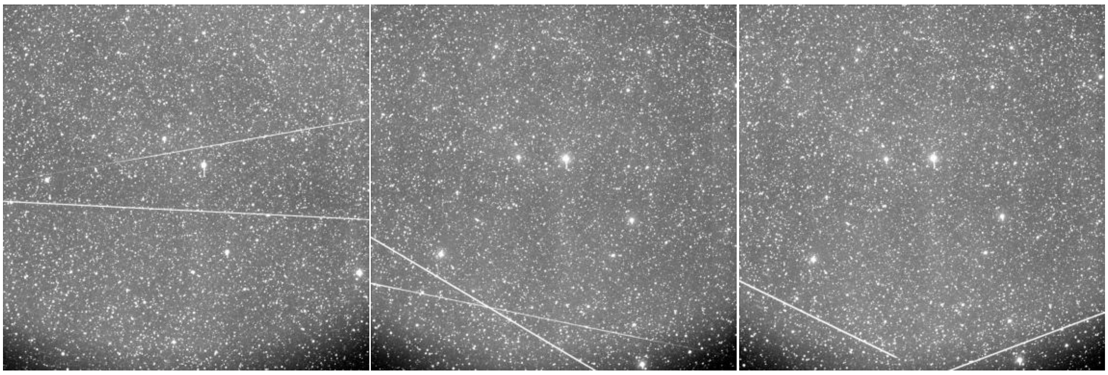
2.3. Results

Let's calculate the ratio of trails that account for the whole images. In order to make the task more easily, we need to make three groups. The first group only contain one trail and luminous, long and trails is located in the middle of the images. Figure 7. a, b, c are three typical examples.



(a) (b) (c)

Figure 7. Three examples of CSTAR image containing one long bright trail



(a) (b) (c)

Figure 8. Three examples of image containing two bright trails

For contaminated images as in Figure 7, 0.75% pixels in image a are affected by bright trails, 0.55% in image b and 0.73% in image c. The mean value is 0.67%, which is a little much higher than the result (0.3%) from Hubble telescope in 2023, (Sandor Kruk, Pablo Garcia-Martin, Marcel Popescu et al. 2023) because we pick the images with a extreme long bright trail (All values of the Images containing two trails, some of them intersect with each other and some of them are parallel. Here are three typical examples. As the results, proportion of trails is 1.02%, in the left panel, proportion of trails is 0.88% in the middle panel and the proportion of trails is 0.90% in the right panel. The mean value is 0.93%, which is also higher than the result (0.7%) from Hubble telescope in 2023.

(a) (b) (c)

Figure 9. Three examples of image containing three or more bright trails

And let's start researching on group three. Obviously, group three os the images which contain more than two (three or more). There are only a little of images satisfying, according to Hubble Telescope's investigation, fewer than 1% of images contain three trails or more (Sandor Kruk, Pablo Garcia-Martin, Marcel Popescu et al. 2023). Our result is also reliable because 0.148% of images contain trails three or more. Image shown below are three examples.

The results of trials' proportion, 1.79% of image in the left panel is polluted, 1.34% of image in the middle panel is polluted and 1.50% of image in the right panel is polluted. The mean value is 1.54%, which is still higher than the result from Hubble Telescope.

2.4. Statistics

The proportion of images containing trails is different from other telescopes. Hubble telescope's tolerance is 2.7%±0.2% (Sandor Kruk, Pablo Garcia-Martin, Marcel Popescu et al. 2023. Average exposure time is 11 min) from 2002 to 2021, our result is 437.0% more than the Hubble's tolerance! The proportion is proliferating much faster in recent year because the increasing number of mega constellations (Mega constellations refer to a large-scale satellites networks comprising hundreds to tens of thousands of LEO satellites, primarily deployed for global communication, Earth observations, and military applications). Result of recombinational images from Advanced Camera for Surveys (ACS) and Wide Filed Camera (WFC) is 8.9%±1.1%. The proportion of our images contain trails is 14.5%, which is 31.8% more than the upper bound of the result provides by ACS and WFC.

Our 2008 consequence reveals that in pre-megaconstellation satellites populations (around 15000, far less than 30000 in 2025) already caused 14.5% of contamination, which exceeds the baseline given by Hubble Telescope, 2.7%. This proves that deterrent policy needs to be initiated as a matter of priority, otherwise human will lose the final vantage point to observe the space.

3. Discussion

3.1. Identification of Satellite in Images

We have so many images containing trails right now, although we have known the proportion of images that contain trails, more further investigations are still required. We should figure out what are the specific satellites that included in the images. We should do several preparation steps. Firstly, we should know where these images are taken. As shown above in 1.3, these images are taken by a telescope at Kunlun Station, which is located in -80.4169, +77.1161 in Antarctica, with elevation of 4087 meters. Secondly, we should use a tool called nova.astrometry to calibrate the fields of view in sky for images (see Figure 10). We should save the results as WCS coordinators. After these steps, we can start identifying the satellite producing the bright trails in images.

We have a python code to help us do that; we just need to input the name of satellites (serial number) and the address of the astrometry result that we save. According to the hints provided, we can get the result as shown in Figure 11. We can see three obvious trails (blue light rails) and one red light trail. We need to search the serial number in satellite catalogue; the matched results are the satellites included in images.

3.2. Properties of Detections

Let's talk about the images included in Fig. 10. First one is 27430, which is the upper trail in the image. According to our satellites catalogue, this is the rocket body called Delta IV launched by the USA in 2006. It was launched by United launch Alliance (ULA) not NASA. Delta IV is a heavy lift carrier rocket for helping tasks from the USA Military and NASA. Delta rocket is the rocket launch mission of Boeing Company, and it has a super powerful engine using hydrogen-oxygen fuel. It can carry up yo 28 tons to LEO and 14 tons geostationary transfer orbit (35786 km from the surface, satellites used for communicating, weather forecasting is in GTO). Delta IV also did a famous task in 2018; it carried Parker Solar Probe to the space successfully.

Now let's focus on the trail in green (the middle one). It is a communication satellite called Meridian1 launched by Russia in 2006. This is used for communicating in polar areas and on the oceans, also providing encrypted data for military applications. The trails included in this image is the first satellite in Meridian series, but unfortunately, this satellite decayed in 2021. The organization designed it and launched it is Roscosmos and Russian Ministry of Defense.

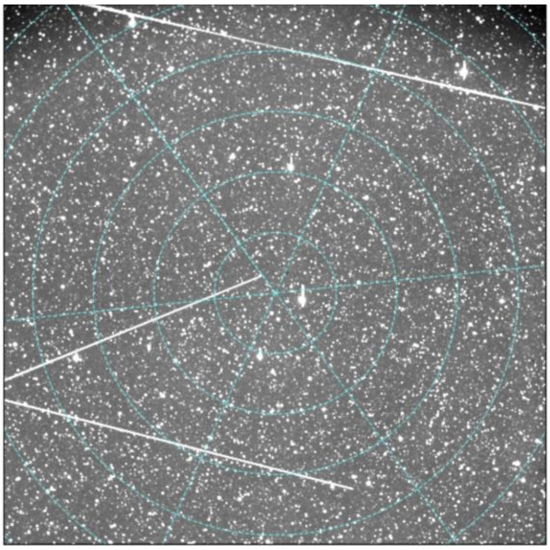


Figure 10. The example of astrometric calibration. The image is on the south pole of sky; the cyan curves are the celestial coordinates

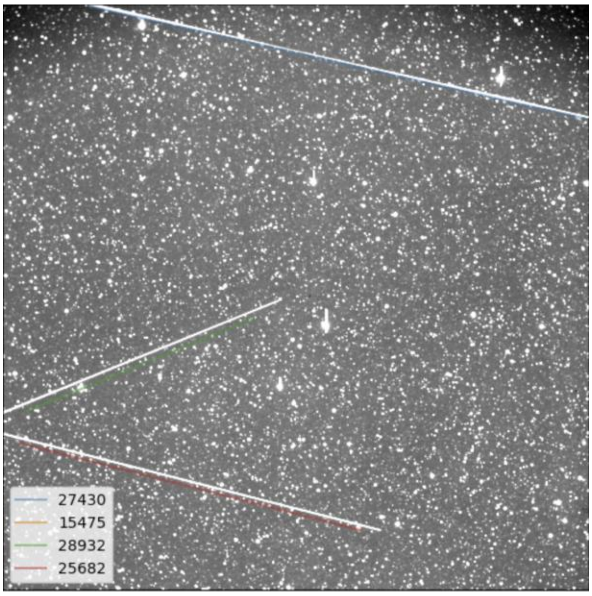


Figure 11. The example of satellite identification. The color lines are the calculated satellite trails from the catalog of Space-Track.org. Their orbital parameter in the observation time is used in the computation. There trails are successfully identified by comparing with the computed trails

Next one is the trail in red. This is a trail of debris, it used to be a piece of CZ-4 rocket body, which was a Chinese rocket body launched in 1999. This rocket body is used to carry CBRES-01, which is used to detect resources. But because of some unknown reasons, it did not become a harmless space object and escaped from LEO, it broke up into about 200 pieces of debris and polluted the space environment. After the breaking up, CNSA admitted and showed the details to the public. CNSA corrected the flaws and make the rockets and payloads better and better.

4. Summary

Our findings demonstrate significant light pollution degradation at Antarctic astronomical observatories. With 14.5% of images from Kunlun station is contaminated, a margin projected to widen beyond 30 percent by 2030 under current launch trajectories. This trajectory threatens the unique value of Antarctic (particularly 80。—90。S) for infrared astronomy, because of the low atmospheric emissivity and stable polar night. That will surpass 30% by 2030 under current launch rate. We propose two key interventions: Firstly, immediate establishment of an IAU-coordinated light pollution monitoring network across Antarctic. Secondly, International adoption of spacecraft reflectance standards (albedo ≤0.08 verified for freezing space environments), utilizing recent advances in biomimetic coatings (e.g., MIT 2024 research), with phased implementation prioritized for polar-orbit satellites. Preserving the Antarctic observing environment demands urgent international cooperation. As the only ground-based platform capable of deciphering the universe's origins, preserving Antarctic skies demands immediate global governance, before humanity loses its window into cosmos.

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