ANALYSIS OF ITALIAN SITES FOR NEO AND SPACE DEBRIS OBSERVATIONS WITH THE ESA FLYEYE TELESCOPE

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ABSTRACT

The benefits of the so-called “Flyeye” optics in designing a wide-field high-sensitivity instrument for NEO and space debris detection have long been recognized [1] [2]. They led to the development of an innovative 1-meter class telescope characterized by an extremely large Field of View (6.7°x6.7° FoV) with a 1.5”/pixel resolution and a limiting magnitude of 21.5. This telescope will allow to scan the entire observable sky three times per night, being equivalent to 16 1-m class telescopes where each single telescope – optical channel – exploits the full one-meter-equivalent aperture of the common primary mirror. The first “Flyeye” telescope is being developed by ESA within the framework of the SSA (Space Situational Awareness) Programme. When operational, NEOSTEL (NEO Survey TELescope) is expected to significantly contribute to NEO discoveries. Because of the many “firsts” involved in the deployment of the NEOSTEL prototype, avoiding a remote site appears desirable in order to ease managing the commissioning, science verification and early operational phases. Several Italian candidate observational sites have been therefore taken into consideration. We present the results of a trade-off study where each site is characterized in terms of both, annual cloud coverage and sky brightness. We also present an analysis of the astronomical seeing campaigns carried out on Mt. Mufara, in Sicily, eventually chosen as the nominal location for the NEOSTEL deployment.

1. INTRODUCTION

The choice of an astronomical site depends on many factors, which involve political, logistic and technical considerations. Yet even if one limits the analysis to the technical ground, the selection of a site results from the interrelations among its environmental properties for astronomical observations (e.g. seeing, sky brightness, cloud coverage), the instrumental characteristics of the telescope (e.g. aperture, photometric filters, pixel scale), and the scientific goal (e.g. galactic/extragalactic pointing, transients survey, solar system moving objects detection/characterization). When dealing with NEOSTEL this means to address the issue of deploying a newly conceived telescope in an accessible site for routinely performing faint moving object detection aimed at NEO discovery. Within this framework, ASI (the Italian Space Agency) has proposed to deploy the ESA NEOSTEL prototype in Italy. In order to evaluate the feasibility of this scenario, a collaboration between ASI and INAF (the National Institute for Astrophysics) has been set-up for jointly reviewing and characterizing potential candidate locations in Italy.

Focus is then given to Mt. Mufara, within the protected area of “Parco delle Madonie” in Sicily. This site is well known to possess an excellent sky quality, having been taken into consideration in the past for hosting TNG (Telescopio Nazionale Galileo), the Italian 4-m class telescope eventually installed in La Palma (Canary Islands). An extended seeing-monitoring campaign has been therefore carried out by means of an ad-hoc instrumentation installed on top of Mt. Mufara.

In what follows the NEOSTEL site selection and characterization activity is described and the outcome is discussed within the framework of the future NEO discovery and space surveillance scenario.

2. ITALIAN SITES TRADE-OFF

Seven Italian sites have been taken into consideration for their overall logistic, technical and astronomical features. They include five INAF observatories, the ASI Center for Space Geodesy (CGS), located nearby the town of

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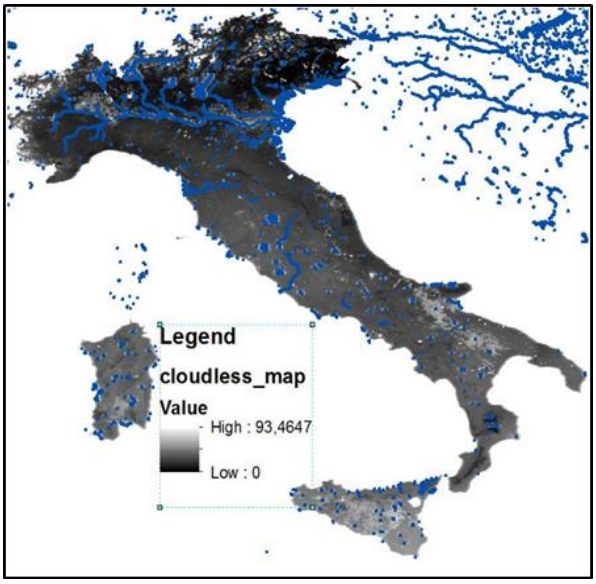


Figure 1. Cloudless map of Italy: a southward trend of increasing better weather conditions is evident.

Figure 2. Sky brightness map of Italy; pinpointed is Mt. Mufara.

Matera, and Mt. Mufara, in Sicily. For each of them the most relevant parameters defining the efficiency of an all-sky survey have been evaluated: the percentage of cloudless nights for maximizing operations, the background luminosity and the average seeing for satisfying the telescope performance requirements. In doing so it has been found that these quantities are often difficult to find and, when available, harmonize, especially for long-established astronomical sites (where the seeing is estimated directly upon reducing observations) and/or where the sky quality is quickly changing in time (e.g. due to the increasing light pollution of anthropic origin). Therefore the weather conditions and the sky brightness of each site have been derived from a common source: the former from the annual cloud coverage measured by Earth Observation satellites [3], the latter by using the last updated sky brightness world catalogue [4].

2.1. Weather considerations

In order to evaluate the number of clear nights per year, the cloud coverage over Italy has been investigated relying on the NASA Earth Observation System. The data acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) on board of the Aqua and Terra polar satellites [3] were used to this end. They cover the entire Earth's surface every 1 to 2 days, collecting data in 36 spectral bands. For Italy, the night time range covered by Terra is 20:00-22:30 UTC, while for Aqua is 00:00-02:30 UTC. The dataset used in this investigation consists of more than 20,000 images acquired over ten years (2007-2016) with spatial resolution of 1 km x 1 km. Data analysis was performed using the MOD35/MY35 data products and the Land Data Operational Product Evaluation (LDOPE) suite (both available at https://ladsweb.modaps.eosdis.nasa.gov/). The result is a map of Italy displaying the clear sky probability (expressed as cloudless percentage) at 1 km square resolution (Fig.1). Owing to the low spatial resolution, these data provide a conservative estimate of the actual clear sky conditions, especially for high altitudes sites, such as Mt. Mufara, which may rise above the cloud layer.

2.2. Sky brightness

The sky brightness has been evaluated by using data from The New World Atlas of Artificial Night Sky Brightness (WA2015, [4]), obtained by the Visible Infrared Imaging Radiometer Suite of the Suomi National Polar-Orbiting Partnership (VIIRS-NPP). The spatial resolution is 0.5-1 km and the corresponding map of Italy, displayed by means of the application available at www.lightpollutionmap.info is shown in Fig. 2 (colour scale varies from blue to red as the brightness increases). By zooming the on-line map it is possible to obtain the local value of the sky brightness for any given geographical coordinates. As an example, the Mt. Mufara sky brightness resulted as 21.53 mag/arcsec^2, which is among the lowest values in Italy.

2.3. Results and sites comparison

By using the tools described in Sections 2.1 and 2.2, for each site we evaluated the annual clear sky probability and the night sky brightness. The results are summarized in Tab.1. Among the four high altitude sites Mt. Mufara exhibits the lowest sky brightness and one of the highest clear sky probability. Also the INAF Cagliari site, where the 64 m dish of the Sardinia Radio Telescope is located, is characterized by a remarkably dark sky. Yet the local topography favors the frequent occurrence of humidity levels which prevent the execution of optical observations. The ASI center near Matera, although having an excellent cloudless score, pays a higher background luminosity due to the proximity to the city lights.

Site	Height above sea level (m)	Clear sky probability (% nights/year)	Sky brightness (mag/arcsec^2)
INAF Asiago Mt Ekar	1376	48	20.94
INAF Cagliari	588	60	21.51
INAF Campo Imperatore	2170	48	21.31
INAF Loiano	785	54	20.96
ASI Matera	485	64	20.91
Mt Mufara	1865	58	21.53
INAF Serra La Nave	1735	N.A.*	20.85

Table 1 - Italian sites comparison
** data biased due to the frequent presence of snow*

Thus, from an astronomical point of view the data listed in Tab.1 support the choice of Mt. Mufara, because of the lowest sky brightness among all sites and the remarkable value of clear nights. Although Mt. Mufara does not host an observational infrastructure, the logistics is supported by the recently established International Astronomical Park by the Fondazione Gal Hassin [5] in the nearby town of Isnello. There, in addition to a state-of-the-art planetarium and an array of commercial telescopes for public outreach, a 1-m telescope (WFMT – Wide Field Mufara Telescope) is being realized on top of the mountain as well, with the obvious operational synergies and sharing of facilities that this implies.

3. THE MT. MUFARA SITE

The Mt. Mufara astronomical site is located at 1865 m altitude, at Long=14.0166 °E and Lat=37.9375 °N, and is characterized by two distinct hill-shaped mountain tops which can in principle host telescope in-frastructures (Fig.3). The two locations are separated by about 300m. On one of them (Site 1 in Fig. 3) the basement of the afore mentioned WFMT is already in place. The other (Site 2 in Fig.3) is candidate for the NEOSTEL

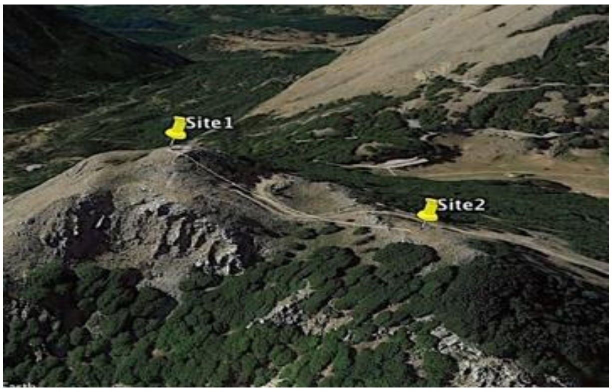


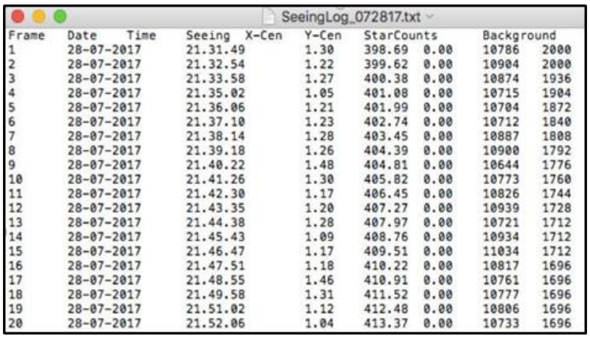
Figure 3. The two sites of Mt. Mufara (credit: Google Earth).

telescope. For Site 1 and Site 2, see also respectively top and bottom panel of Fig 4.

Figure 4. The NEOSTEL location as seen from the WFMT site (up) and viceversa (down)

3.1 The Mt. Mufara seeing campaign

In June 2017, profiting of the electrical power line connecting the already existing infrastructure, a seeing measurement equipment (SBIG Seeing Monitor ST-402) owned by ASI has been installed on the WFMT site (Site1). The equipment was remotely accessible and its functioning was regularly monitored over more than three months, until an electricity shortage has terminated the campaign. The campaign was resumed in 2018 using a new-generation SBIG solar-powered equipment, this time placed directly on the NEOSTEL site (Site2). In the next sections, the data collected by both instruments and the strategy adopted to evaluate the quality of the seeing in relation to the technical characteristics of the telescope are discussed.



SeeingLog_072817.txt

Frame	Date	Time	Seeing	X-Cen	Y-Cen	StarCounts	Background
1	28-07-2017	21.31.49	1.30	398.69	0.00	10786	2000
2	28-07-2017	21.32.54	1.22	399.62	0.00	10904	2000
3	28-07-2017	21.33.58	1.27	400.38	0.00	10874	1936
4	28-07-2017	21.35.02	1.05	401.08	0.00	10715	1904
5	28-07-2017	21.36.06	1.21	401.99	0.00	10704	1872
6	28-07-2017	21.37.10	1.23	402.74	0.00	10712	1840
7	28-07-2017	21.38.14	1.28	403.45	0.00	10887	1808
8	28-07-2017	21.39.18	1.26	404.39	0.00	10900	1792
9	28-07-2017	21.40.22	1.48	404.81	0.00	10644	1776
10	28-07-2017	21.41.26	1.30	405.82	0.00	10773	1760
11	28-07-2017	21.42.30	1.17	406.45	0.00	10826	1744
12	28-07-2017	21.43.35	1.20	407.27	0.00	10939	1728
13	28-07-2017	21.44.38	1.28	407.97	0.00	10721	1712
14	28-07-2017	21.45.43	1.09	408.76	0.00	10934	1712
15	28-07-2017	21.46.47	1.17	409.51	0.00	11034	1712
16	28-07-2017	21.47.51	1.18	410.22	0.00	10817	1696
17	28-07-2017	21.48.55	1.46	410.91	0.00	10761	1696
18	28-07-2017	21.49.58	1.31	411.52	0.00	10777	1696
19	28-07-2017	21.51.02	1.12	412.48	0.00	10806	1696
20	28-07-2017	21.52.06	1.04	413.37	0.00	10733	1696

Figure 5. Sample data provided by the SBIG system (first 20 rows) on 28/07/2017.

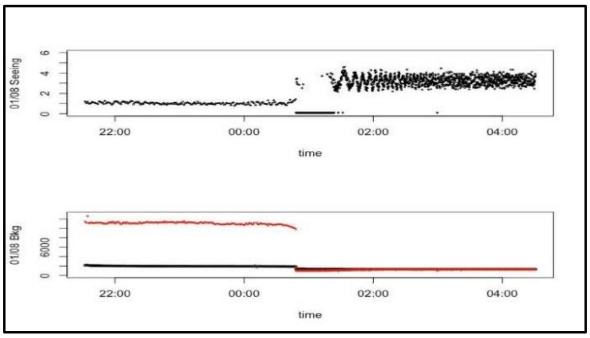


Figure 7. 01/8/2017: (top) seeing behaviour; (bottom) star counts (red) and background level (black).

3.2 Datasets

The seeing measurements belong to two distinct datasets, automatically acquired by pointing the North Star during the period between June and September 2017 (for 65 nights) and from September to November 2018 (for 79 nights). Each night, the system carried out from several hundreds up to two thousands seeing measurements, in time steps of 10-16 seconds. As output, the instrument produces a table that lists the following quantities: single frame identifier, date and time of the acquisition, seeing value in arcseconds, X and Y star coordinates, star counts and background level (Fig.5). For each night, the system software also produces an image file with a plot of the seeing during time. Selected examples are shown in Fig. 6, whose implications will be discussed in detail in the following section. Here it is important to draw some general considerations. The short amplitude oscillations indicate generally stable sky conditions throughout the night, with values that can reach down to less than 1 arcsec. When unsatisfactory results are achieved (e.g. Fig. 6, bottom right) additional information is needed in order to search for correlation with meteorological or environmental conditions (clouds, winds, humidity etc).

3.3 Data quality evaluation and analysis

In order to validate the seeing measurements collected by the automatic acquisitions, an analysis of the data reliability has been carried out. The quality of the measures has been studied by analyzing the signal-to-noise ratio (S/N) given by the ratio between the stellar counts and background level. As an example, in Fig.7 in the night of 1st August 2017, the seeing distribution (top

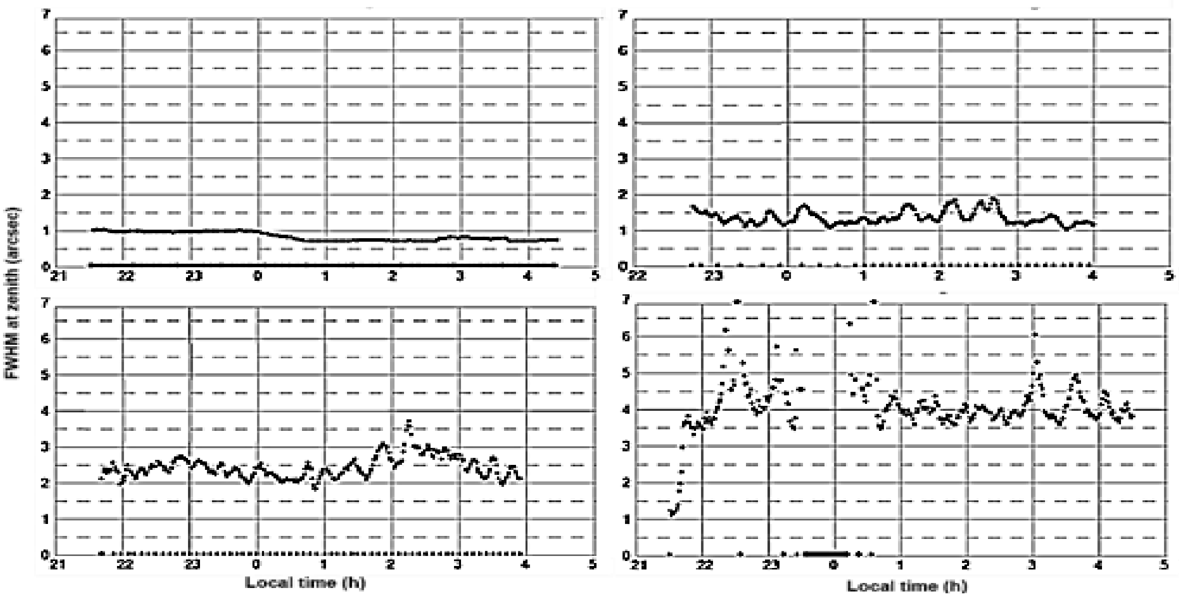


Figure 6. Representative seeing behaviour during four different nights: 29/08/2017 (upper left), 25/10/2018 (upper right), 24/10/2018 (lower left); 20/08/2017 (lower right).

panel) and the stellar and background counts (bottom panel) are shown. In this case, during the first part of the night (up to 01:00 am) the seeing value is ≈1.2 arcsec, while it rapidly increases to 3-4 arcsec during the second part. This behavior occurs in several nights and was studied in depth. It has been found that in the second part of the night the star counts are lower than the background level, also when considering the Poisson errors (S/N $\leq$ 1, Fig.8). This result suggests that the seeing values of the second part of the night are not reliable and likely related to software problems.

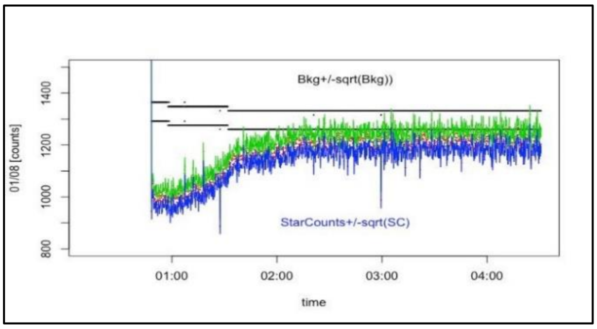


Figure 8. Second part of 1st August night. Upper and lower limits for the star counts (green and blue respectively) and for the background (horizontal black lines) as defined by the Poisson error.

Therefore, in order to provide a robust statistical analysis, hereinafter the data were selected in quality by considering S/N $\geq$ 10. As consequence, for the above night, only the seeing measurements corresponding to the first part of the night have been considered. Moreover, we excluded nights with less than 20 measurements. By taking into account the above quality selection, we ended up with 57 nights for 2017 and 45 nights for 2018. In the former case we have processed ≈6,000 measurements, while in the latter case ≈9,500. By using these datasets we computed the mean seeing for each night and the results are displayed in the histograms of Fig.9 and of Fig.10 corresponding to the two seeing campaigns.

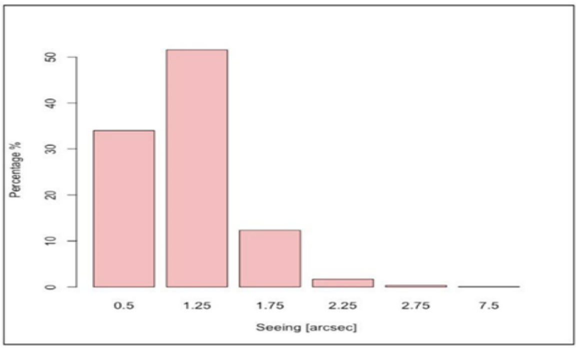


Figure 9. Histogram of the seeing values for 2017. Mean values are shown along X-axis.

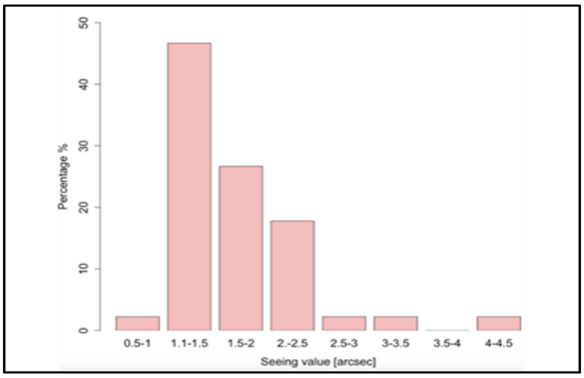


Figure 10. Histogram of the seeing values for 2018. Bin size is 0.5 arcsec, intervals are shown along X-axis.

The statistics shows that, for the time span considered covering almost 6 months during summer and autumn, more than 80% and about 50% of measurements, respectively, are lower than 1.5 arcsec.

This result must be discussed in the framework of the Nyquist theorem [6] which affirms that to efficiently sample a signal, the sampling frequency should be at least twice the highest frequency component of the signal. In terms of astronomical observations, this means that the choice of a pixel scale at least a factor of two smaller than the expected seeing is appropriate. In fact if the pixel scale is larger than the seeing, the pixel loses details (undersampling). On the other hand, if the pixel scale is too small with respect to the seeing, the pixel noise increases significantly without bringing any advantages (oversampling). This is why usually the pixel scale is 1/2 or 1/3 of the astronomical seeing of the hosting site (1/1.5 – 1/2 for astrometry). Known examples are the main optical telescopes in Chile (VLT, CTIO, future LSST) whose pixel scale ≈ 1/3 of the local seeing [7]. The Nyquist theorem is fundamental in case of star (or NEO) photometry, where light is integrated by considering discrete continuous pixel sampling. Concerning transients and/or moving objects, a seeing significantly lower that the pixel scale does not increase the detection rate, which is limited by the instrumental resolution. In some cases it could even increase the occurrence of false positives.

4. CONCLUSIONS AND DISCUSSION

We have analyzed the main issues related to the selection of an observational site, highlighting the need for an integrated approach. We have then applied this method to the characterization of seven Italian candidate sites for the future ESA-SSA NEOSTEL telescope devoted to NEO discovery. Comparison among the different sites has required a non trivial effort of data harmonization. In particular, Earth Observation Satellite data over a 10-

year time span have been used for estimating the cloud coverage of each site. Results have shown that, for the purpose of NEOSTEL, Mt. Mufara ensures an excellent sky quality in terms of both background luminosity and clear nights. These are two major requirements for carrying out a successful NEO survey, being tied to the achievable limiting magnitude (thus entering also in the computation of the exposure time) and to the continuity of the operations, respectively.

The in-situ seeing campaign carried out on Mt. Mufara has further strengthened this conclusion. A proper balance between the average seeing and the telescope pixel size is always desirable, ideally the former being 2 to three times the value of the latter. Since the NEOSTEL design has driven the telescope pixel size to its present 1.5" value, the high percentage of nights found with an average seeing equal or less this treshold fully satisfies this requirement.

An additional advantage of the Mt.Mufara site is that it is located eastward with respect the present/future US based surveys and this implies that "incidental" follow-up observations are likely to quickly confirm the NEOSTEL findings. This is particularly relevant for facing the imminent impactors problem, characterized by the rapid response times needed to assess the potential hazard of a newly discovered object.

In conclusion, our results shown that the Mufara site satisfies both, the technical requirements of the telescope and its utilization for moving objects detection. When considering both issues, the statistics on the occurrence of best sky conditions are comparable to those characterizing some of the best sites in the world [8]. Although a more extended seeing campaign is anyway needed in order to study the seasonal effects, the astronomical characterization of Mt. Mufara carried out so far provides enough technical ground for its selection, considered by ESA and ASI a pre-requisite for hosting the NEOSTEL prototype.

The experience gained and the tools developed for performing the site characterization analysis presented will be extremely useful within the framework of the possible utilization of the Flyeye design for detecting space debris. As described in [1] a network of such telescopes could complement the radar sensors in the high-LEO regime as well as being extremely effective for cataloguing objects in the MEO and GEO regions. In order to do so the NEOSTEL design would require minor HW adaptations (e.g. a shutter enabling short exposure times) and a customization of the data processing pipeline for the identification of space debris trails. In this respect the NEOSTEL commissioning and science verification phase represents a unique opportunity for optimizing the telescope performances for NEO and space debris observations.

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