OPTIMIZING VISUAL DAYTIME SATELLITE OBSERVATIONS

Krzysztof Kamiński(1), Michał Żołnowski(2), Monika K. Kamińska(1), Mikołaj Krużyński(1), Dorota Krużyńska(1), Edwin Wnuk(1)

(1) *Astronomical Observatory Institute, Faculty of Physics, Adam Mickiewicz University, ul. Słoneczna 36, 60-286 Poznań, Poland, Email: chrisk@amu.edu.pl*
(2) *6ROADS Sp z o.o., ul. Godebskiego 55a, Kraków, Poland, Email: michal.zolnowski@6roads.com.pl*

ABSTRACT

With the increasing number of Space Resident Objects (SRO) there is a growing interest in their optical monitoring, partly as an augmentation to expensive radar facilities. One of the disadvantages of VIR satellite tracking is the difficulty to provide meaningful astrometric data during daytime. In recent years several authors provided simulations and experimental results of detecting up to 8-10 mag targets during the day using visual or near IR systems [3]. In order to optimize visual systems for daytime observations the use of a long-pass filter seems advisable as the way to lower the background level and noise in images. At the same time Earthshine, which is an important contributor to satellite brightness, is dominated by blue light. It is therefore unclear whether, and to what degree, the use of a filter would actually improve the SNR of satellite images. Using two identical 12.5 inch telescopes from PST3 telescope cluster, we compared the performance of several long-pass filters (with cut-off wavelengths from 400nm to 780nm) to a non-filtered system both on stars and satellites in different illumination conditions.

We investigated the possibility to improve SNR also for stellar images in an attempt to increase the chance to use them as reference for astrometric measurements. We also compared the slow and fast focal ratio configurations in order to establish the optimum optical system for daytime observations with a fast CMOS camera.

1 INTRODUCTION

Daytime observations of Space Resident Objects (SRO) have been demonstrated by several teams since the 1980s [5]. Most of them have been carried out in IR (see for example [4] or [6]), but some work has also been carried out in the visual domain (for example [2] or [7]).

Recent advancements in direct-drive technology for small telescopes, as well as high frame per second (FPS) electronic global shutter CMOS cameras, open new possibilities in daytime LEO tracking. The former allows high accuracy tracking and probably also sufficiently accurate astrometric measurements without reference stars. The latter allows for increased pixel full well and higher SNR for sky background dominated images. In this paper we present the results of a simulation that aims at evaluating what gains are realistically possible when daytime observations would be added to nighttime satellite tracking. Then we present an observational evaluation of potential improvements in detection of tracked stars and satellites by using long-pass filters or by increasing the focal ratio.

2 DAYTIME OBSERVATION GAIN

In order to evaluate a potential profit of daytime observations we used our Poznań Satellite Software Tools (PSST) to calculate satellite visibility from a single observatory. Our software has the capability of roughly estimating observed magnitude for all satellites in the Space Track Satellite Catalog based on their range, phase angle and size (Fig. 1).

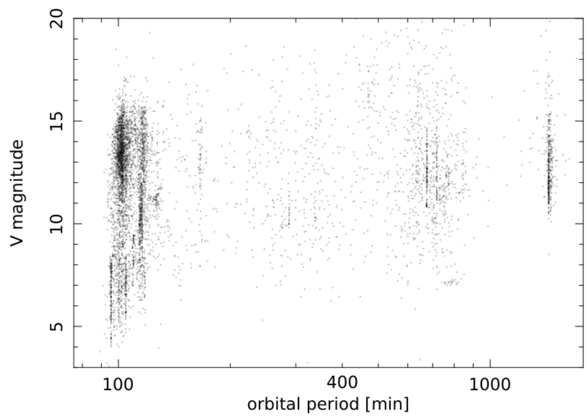

Figure 1. Magnitudes of all satellites from the NORAD catalog observable from a single site during a single night.

Using Mini-MegaTORTORA and ESA DISCOS databases, as well as our own observational data, we collected information about satellite sizes for over 90% of targets from the Space Track Satellite Catalog and calculated an average albedo. In our simulation we assumed that only targets above 30° altitude, outside the Earth's shadow and at elongation over 60° are observable. With these assumptions we tested several

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scenarios of daytime observations from a single location (0° E, +30° N) at a single date of 2021-03-20.

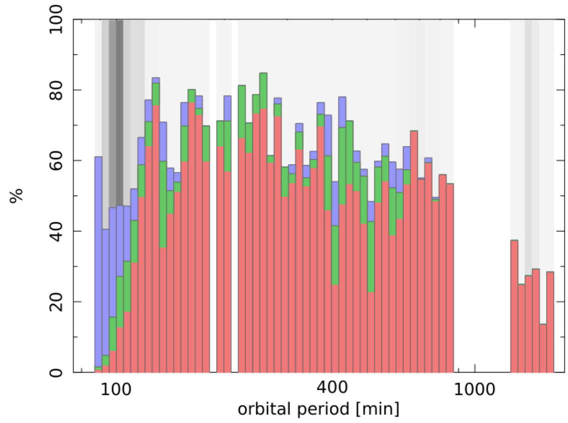

Figure 2. The percentage of satellites from Space Track Satellite Catalog observable from a single site during one day and night. Red - satellites visible only at night, blue - only during day, green - during day and at night. Only satellites brighter than $V=10^m$ are considered at daytime. The gray columns in the background represent the relative number of satellites at a particular orbital regime.

Table 1. The number of satellites visible 30° above horizon from one site during one day and night. The numbers in brackets are representing satellites visible twice or more - at day and at night during the same 24h.

	LEO	other
no of objects in catalog	16230	4596
only nighttime objects	4110	2284
only daytime objects	6275	937
night and day objects	2946	1782
only daytime $V<10^m$	3728 (1805)	84 (147)
only daytime $V<8^m$	639 (81)	13 (27)
only daytime $V<6^m$	4 (1)	0 (0)
only daytime $V<10^m$, Sun alt < 5°	1322 (351)	42 (29)

In Fig. 2 we present a percentage increase in the number of observable satellite passages from a single site assuming that we combine nighttime observations with daytime observations of $V<10^m$ targets. An overall increase in the number of observable satellites is at the level of 46% with 63% increase in LEO and 3% in other orbital regimes.

In Tab. 1 we present several scenarios of daytime observations. Assuming that all known satellites are detectable, the overall gain in the number of observable satellites is significant - at the level of 65%. Restricting ourselves to more realistic assumptions of limiting magnitude at the level of 10^m, 8^m and 6^m we derived the following percentages: 46%, 10%, 0.1%, respectively. It seems that daytime observations become sufficiently profitable only after reaching a limiting magnitude of about 8^m. Although it is important to mention that our calculations were taking into account only solar illumination. It is possible that taking Earthshine into consideration would improve the results for low orbit targets. The last line in Tab. 1 presents the number of satellites visible when the Sun is between -12° and +5°. It is clear that even extension of LEO observations to the time between nautical night and low solat altitudes can be useful.

3 OBSERVATIONS

In order to test two methods of improving SNR of point-like sources during daytime observations we used three different facilities. The first is Poznań SST Telescope 3 (PST3) owned by the Astronomical Observatory Institute of Adam Mickiewicz University (Fig. 4). It was used for comparing satellite and stellar observations made with different filters using two identical telescopes. Each of these is composed of Planewave CDK12.5 f/8 OTA, Planewave L500 direct-drive mount capable of tracking LEO satellites using orbital elements in TLE format and Andor Zyla 5.5 sCMOS camera (pixel scale: 1.06 arcsec/pix). One of these telescopes was additionally equipped with 5 long-pass filters with cut-off frequencies of: 400nm, 495nm, 590nm, 695nm and 780nm (Fig. 3). The second telescope was used without any filter and they both observed at the same time almost simultaneously (± 2 min).

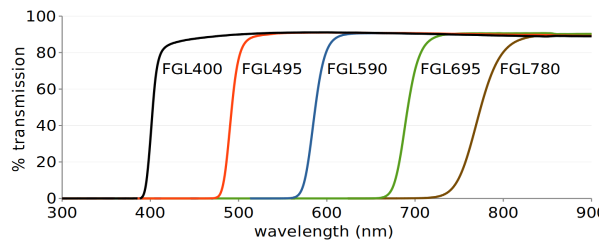

Figure 3. Transmission curves of longpass filters used for daytime observations with PST3 telescopes.

Two other observatories, owned by 6ROADS company, were used for comparison of stellar observations made with different focal ratios (Fig. 5). One is Rantiga Observatory with a 40cm Newtonian telescope and QHY600 16-bit BSI sCMOS camera (pixel scale: 1.0 arcsec/pix). Its native focal ratio is f/3.8 and it was also used with a diaphragm increasing its focal ratio to f/10.4. The other one is Solaris Observatory with a 30cm Newtonian telescope and QHY174GPS 12-bit FSI CMOS camera (pixel scale: 1.0 arcsec/pix). Its focal ratios were f/4.0 without and f/10.9 with a diaphragm.

Figure 4. Poznań SST Telescope 3 with two of its 5 telescopes used in this experiment marked with red circles.

Figure 5. Rantiga Observatory to the left and Solaris Observatory to the right. Diaphragm with straylight reducing tubes visible in the right image.

3.1 Using long-pass filters

The first result from comparison of daytime observations using long-pass filters on 2021-03-22 is presented in Fig. 6. It shows the difference in sky background per pixel normalized to the same exposure time, starting when the Sun was at the altitude of -11.5° up to about +10°. The elongation was nearly constant 85° and altitude above the horizon changed from 65° to 74°. Overall, we observed similar sky background signal increase in all filters by about 4 orders of magnitude, with the fastest change occurring between about -5° and 0°. The brightening in NIR is faster than in other bands, which slightly hampers the performance of these filters at that time. This reflects the change in sky background color during sunrise. Starting from about +5° the relative differences in sky background are nearly identical as during the nautical night.

In order to investigate the limiting magnitude change during the transition between night and day we observed a type B2 star HIP 92728 (V=5.6, B-V=-0.15) for about 2 hours periodically. The exposure time for unfiltered observations varied from 0.01s at nautical night (a typical exposure time for optical tracking of LEO satellites) to 0.002s at daytime to prevent overexposure. Observations with filters were carried out with longer exposure times in order to record roughly the same sky background level. Any remaining variations were corrected during analysis, so each SNR presented in this paper is normalized to 30000 ADU/pix sky background level. The result for a single image is presented in Fig. 7 and the result for stacking 100 images is presented in Fig. 8. In both cases when the Sun was below 5° observations with short wavelength cut-off filters (or no filter) achieved the best results, while observations with long wavelength cut-off filters remained significantly worse. Afterwards the situation reversed and observations with filter passing only NIR produced the best SNR. Since the target star is bluer than most other bright stars in the sky, we expect that on average the NIR filter will be even more effective. It is also an indication that this filter can be successfully applied for satellites whose spectrum is a mixture of yellow sunlight and blue Earthshine.

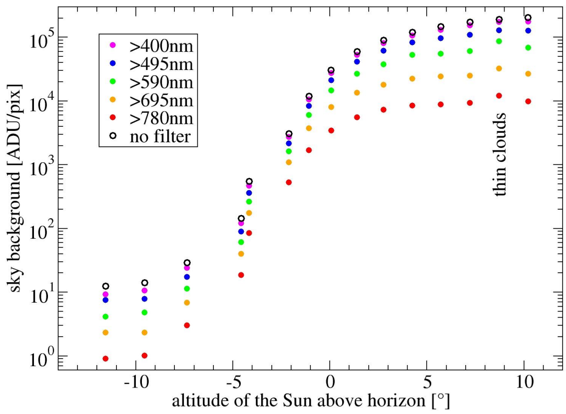

Figure 6. Sky background changes during sunrise at single R.A., Dec location, elongation 85°, altitude from 65° to 74° above horizon. *Nearly simultaneous observations using different longpass filters and no filter for comparison.*

Examples of daytime stellar images are presented in Fig. 9. These are images reduced with flat field and bias correction using Starlink package [1]. It is worth noting that some residual patterns in sky background became prominent after stacking. At a very low background level horizontal lines are visible across images with all filters. At medium sky background level vertical lines become prominent. At a very high sky background level they are barely visible, probably because flat fields were taken shortly afterwards, when sky background had similar spectral composition. The dark sky lines are most likely associated with dark signal non-uniformity, while the bright sky lines results from photo response non-uniformity wavelength dependence.

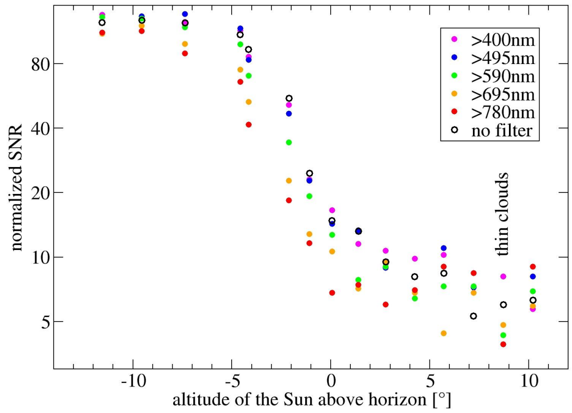

Figure 7. Changes in SNR of V=5.6^m star (normalized to the same background level of 30000 ADU/pix and same exposure time of 0.002s) on a single image during sunrise. Nearly simultaneous observations using different longpass filters and no filter for comparison, at elongation of 85° and altitude from 65° to 74°.

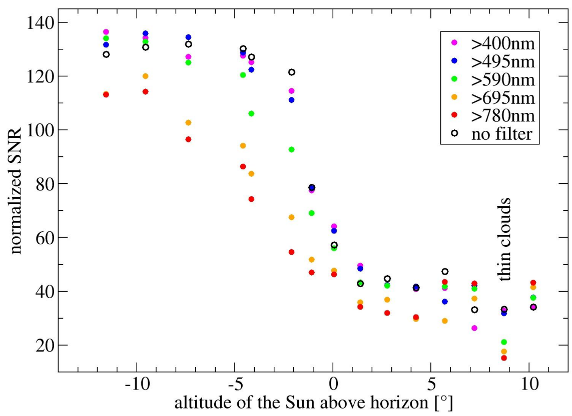

Figure 8. Changes in SNR of V=5.6^m star (normalized to the same background level of 30000 ADU/pix and the same exposure time of 100 x 0.002s) on stacked 100 images during sunrise. Nearly simultaneous observations using different longpass filters and no filter for comparison, at elongation of 85° and altitude from 65° to 74°.

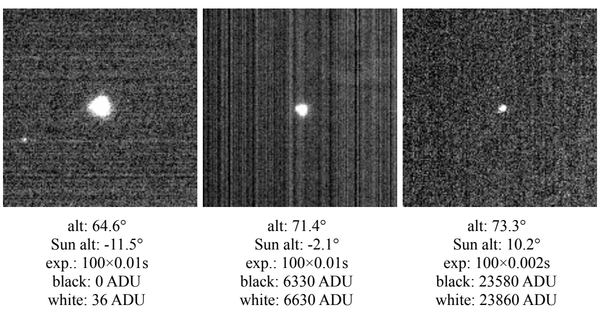

Figure 9. Stacked images of HIP 92728 (V=5.6^m) in the center and V=12^m star near the edge (only in the left image), using longpass filter >780nm.

Table 2. SNR values for satellites listed in Tab. 3 observed with different longpass filters. These numbers were derived using 100 stacked images and different exposure times for each filter. SNR values are normalized to the same sky background level.

>400nm	>495nm	>590nm	>695nm	>780nm	no filter
6	4	18	44	44	9
30	58	90	115	57	30
15	25	42	50	66	20
27	36	41	48	30	14
75	172	233	165	124	~26
126	157	211	299	313	126
49	37	61	~90	44	10

Table 3. Satellites and conditions at which they were observed during daytime observations with different longpass filters.

satellite	Sun alt [°]	alt [°]	elong [°]	V mag	cross section [m^2]
43153 EPS. R/B	7.8	20 - 46	99 - 122	5	~2.0
29507 CZ-4B R/B	20.8	35 - 43	114 - 116	4	17.4
18586 SL-8 R/B	26.7	35 - 44	104 - 109	5	14.6
9444 SL-8 R/B	29.9	32 - 38	112 - 114	6	10.2
39574 GPM	33.2	25 - 38	103 - 108	3	55.7
19120 SL-16 R/B	34.4	42 - 53	87 - 101	4	37.8
15772 SL-12 R/B	36.1	34 - 73	69 - 97	5	23.6

Using the observations of the V=5.6^m star we calculated an estimated limiting magnitude (at SNR=6) when stacking 100 x 0.002s images. The estimated limiting magnitude when the Sun is at +10° altitude is about 7.5^m. If this can be treated as an indication of daytime satellite detection limit, then according to our simulations from the previous chapter it seems that it should be possible to observe at least hundreds of LEO targets every day.

Daytime satellite observations are somewhat harder to interpret because the brightness of satellites is usually impossible to predict with high accuracy. Our estimations have an accuracy of only about 2^m and cannot be used to reliably determine limiting magnitude. Therefore we focused on comparing the performance with different filters. On 2021-03-22 we attempted 11 satellite tracking observations selecting most of the time the brightest (V<7^m) LEO targets. Two satellites were undetectable, 8 were detectable in at least one filter on single images, 9 were detectable in at least one image combined of 100 individual images. In 7 cases we were able to detect satellites in all filters and we used them as a test case for calculating normalized SNR for all filters. The results are presented in Tab. 2 and 3. An example of stacked images of the 29507 satellite CZ-4B R/B is presented in Fig. 10.

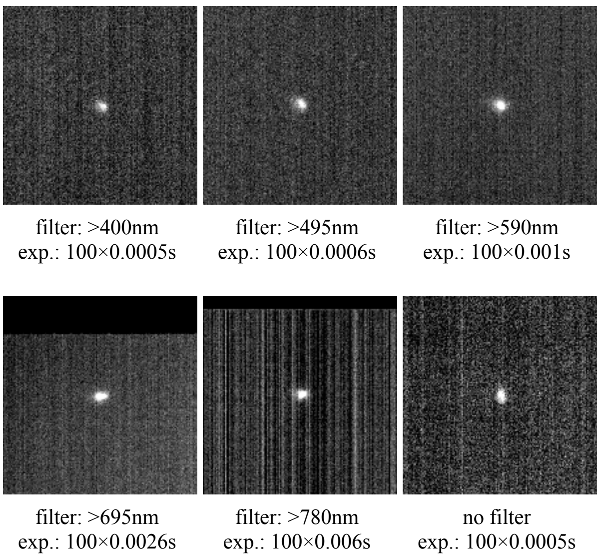

Figure 10. Stacked images of 29507 satellite CZ-4B R/B in different filters during daytime observations at altitude from 35° to 42°, solar altitude 21° and elongation from 114° to 116°.

3.2 Increasing focal ratios

In order to check the influence of changing focal ratio on daytime visibility of point-like targets MŻ performed two observing sessions in two different 6ROADS observatories (described in Section 2). In both cases two consecutive series of images of bright stars were made during daytime. First series was made with full aperture and shorter exposure time, second was made with aperture significantly reduced and exposure time extended to compensate for reduced pixel illumination. Any remaining differences in sky background were later normalized during analysis. Tab. 4 presents normalized SNR measurements obtained after stacking 10 images with lower quality QHY174 CMOS camera. Tab. 5 presents normalized SNR measurements obtained after stacking 10 images with a high quality QHY600 sCMOS camera.

Table 4. Comparison of SNR (corrected for different sky background level) for nearly simultaneous observations of Deneb with full aperture and with a diaphragm.

Sun alt [°]	alt [°]	elong [°]	V mag	exp. time. [ms]	SNR f/4.0	SNR f/10.9
37	70	65	1.3	0.1	35.1	23.1

The results seem inconsistent. Two of them indicate significant improvement in SNR while 3 others indicate slightly decreased SNR when using longer focal ratio. It seems that when a pixel scale reaches 0.5×$FWHM_{PSF}$ of stellar images (in this case typical seeing at both sites was indeed at the level of 2 arcsec), then no significant improvement can be gained in limiting magnitude by increasing focal ratio.

Table 5. Comparison of SNR (corrected for different sky background level) for nearly simultaneous observations of the same star with full aperture and with a diaphragm.

star	Sun alt [°]	alt [°]	elong [°]	V mag	exp. time. [ms]	SNR f/3.8	SNR f/10.4
γ Ori	9	50	67	1.6	3	433	954
η Tau	6	49	46	2.9	7	77	127
20 Tau	6	49	46	3.9	7	62	55
20 Tau	0	43	46	3.9	7	181	175

4 SUMMARY

In conclusion we can summarise that daytime observations, even limited to V<8^m and even when only low solar altitudes are considered have a potential to significantly increase the number of observations of LEO satellites. This will be especially important in the upcoming age of mega-constellations composed of relatively bright satellites at low orbits. Better simulations, which would include Earthshine contribution to the observed magnitude, would be desirable to more accurately evaluate daytime observations. It would also be beneficial for observation planning to have a simple formula for estimating satellite daytime magnitude.

Our satellite observations indicate that despite the Earthshine, which is significantly bluer than sunlight, it is beneficial to use a long-pass filter for daytime observations of satellites and stars, when the Sun is higher than 5° above horizon. Below that altitude unfiltered observations seem to produce better results because of the atmosphere's reddish tint near the sunrise and sunset.

Our results also indicate that it should be possible to plan satellite daytime tracking observations at the time when the target is passing by a relatively bright V<8^m star. Using a high frame rate camera it should be possible to collect multiple images of such a star even when tracking a LEO satellite. Then by using synthetic tracking it may be possible to detect this star on stacked images and use it as a single reference point. Although such a reference star alone can not be used for astrometric measurements, it may be valuable as a verification and even correction of measurements based on telescope's encoders.

5 REFERENCES

1. Currie, M. J., Berry, D. S., Jenness, T., Gibb, A. G., Bell, G. S., Draper, P. W. (2014), Starlink Software in 2013. *Proceedings of the 2013 Astronomical Data Analysis Software and Systems XXIII meeting* **485**, 391.

2. Estell, N., Ma, D. & Seitzer, P. (2019). Daylight imaging of LEO satellites using COTS hardware. *Proceedings of the 2019 Advanced Maui Optical and Space Surveillance Technologies Conference.*

3. Garanin, S. G., Zykov, L. I., Klimov, A. N., Kulikov, S. M., Smyshlyaev, S. P., Stepanov, V. V., Syundyukov, A. Yu. (2017). Daytime observation of low-brightness stars (7^m - 8^m) from level terrain. *Journal of Optical Technology* **84** (12), 816-821.

4. Jim, K. T. C., Gibson, B. N. & Pier E. A. (2012). Daytime Sky Brightness Modeling of Haleakala along the GEO Belt. *Proceedings of the 2012 Advanced Maui Optical and Space Surveillance Technologies Conference.*

5. Rork E. W., Lin S. S., and Yakutis A. J. (1982). Ground-based electro-optical detection of artificial satellites in daylight from reflected sunlight. *NASA STI/Recon Technical Report N* **83**.

6. Shaddix J., Brannum J., Ferris A., Hariri A., Larson A., Mancini T., Aristoff J. (2019). Daytime GEO tracking with "Aquila": approach and results from a new ground-based SWIR small telescope system. *Proceedings of the 2019 Advanced Maui Optical and Space Surveillance Technologies Conference.*

7. Zimmer P., McGraw J. T., Ackermann M. R. (2020) Optimizing Daylight Performance of Small Visible-NIR Optical Systems. *Proceedings of the 2019 Advanced Maui Optical and Space Surveillance Technologies Conference.*