Daytime resolved imaging of space objects from ground station

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ABSTRACT

Besides Space Situational Awareness, space object characterization is a strategic issue to improve our knowledge of space situation. Amongst characterization techniques, resolved imaging is very powerful, since it can provide direct information on object's size, shape and attitude. The observability of those characteristics can allow precious interpretation on object's status.

Resolved imaging from ground is strongly limited by atmospheric turbulences, but lucky imaging techniques can compensate part of them, allowing the production of resolved images of LEO objects at cheap cost. This has already been demonstrated in the visible spectrum. However, both resolved and unresolved observations of orbital objects are usually limited to nighttime. Consequently, favorable spans of time for observations are limited, especially for objects on low Earth orbits. Therefore, the ability to observe at daytime would allow the extension of the observing periods and multiply the observation opportunities. ArianeGroup is currently investigating the possibility of using resolved imaging techniques in daytime, by switching detection wavelength from visible to short wave infrared (SWIR).

In this paper, we will describe the setup that was used for the tests, the results obtained as well as the expected performances and limitations of a future operational system.

1. INTRODUCTION

Optical instruments are commonly used for Space Surveillance to provide position data for objects on any orbits with good accuracy. In most cases, the images taken from ground are unresolved, which means that the object size is smaller than the instrument resolution. Stars and objects appear as plots (or streaks in case of relative motion during the exposure time). The shape of the satellite is not visible in the image.
The instruments resolution is limited either by their intrinsic resolution (limited by diffraction or optical quality) or by the atmospheric turbulences. In order to obtain resolved images of space objects, we have to make sure that:

- The theoretical resolution of the instrument allows it, given the size and distance of the object you want to observe,
- The atmospheric turbulences do not damage the resolution.

The impact of atmospheric turbulences can be compensated by adaptive optics, but this method requires expensive elements and is quite difficult to implement on satellites. Lucky imaging techniques allow resolved imaging of targets at cheap cost: images of the target are acquired at high frequency and short exposures. An algorithm selects the best images of the target (where turbulences are light) and reconstructs a high-resolution image from the images selected ([4], [5], [6]). If these techniques can produce interesting images with moderate effort, the availability of the sensors is drastically reduced by the physical observability of the objects. Indeed, a successful observation requires clear sky conditions, observation station at nighttime, and object illuminated by the Sun. The accumulation of these criteria reduces the observation opportunities for LEO (Low Earth Orbit) objects, which are often located in Earth shadow at nighttime.

ArianeGroup is investigating the feasibility of lucky imaging techniques at daytime, based on experimental results obtained with its own observation station.

2. ACRONYMS

COTS	Commercial Off-The-Shelf
CSS	Chinese Space Station
DC	Dark Current
FOV	Field-Of-View
GEO	Geostationary Earth Orbit
iFOV	Instantaneous Field-Of-View
ISS	International Space Station
LEO	Low Earth Orbit
PSF	Point Spread Function
RON	Read-Out Noise
SNR	Signal to Noise Ratio
SWIR	Short-Wave InfraRed
VIS	Visible

3. BACKGROUND INFORMATION

Since 2014, ArianeGroup has been working on the deployment of an optical Space Surveillance network called GEOTracker®. ArianeGroup GEOTracker® network currently includes 14 telescopes deployed around the world providing a 360° GEO orbit coverage (as of July 2022) and is expected to reach more than 30 telescopes by 2025.
ArianeGroup operates both survey and tracking sensors covering orbits from LEO to GEO in order to be able to deliver a full set of services to its customers. GEOTracker® is able to provide support for a variety of customer needs such as anti-collision, automated manoeuver detection, conjunction alerts or reactive tasking. GEOTracker® special combination of sensors also allows the fast detection of objects when injected in GEO orbit by the launch vehicle.

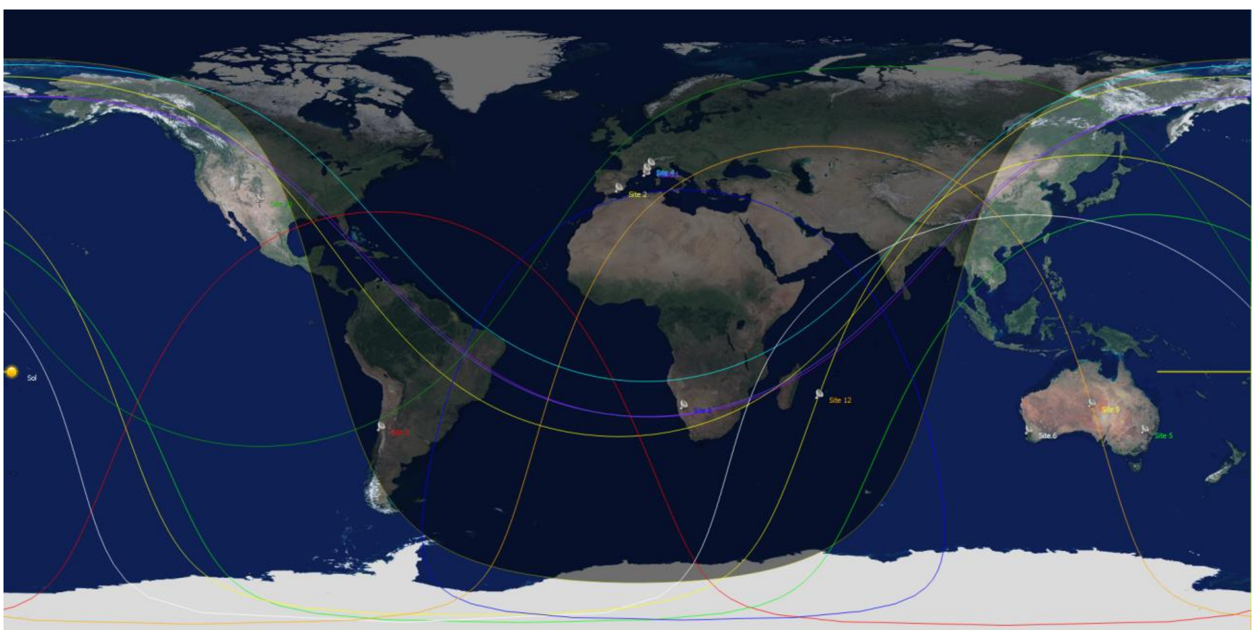

Fig 1 GEOTracker® network by November 2022 providing 360° capability

In order to improve the service delivered to its customers, ArianeGroup is constantly working on the evolution of its observation stations to extend the overall capacities of the network.

4. TECHNICAL CHALLENGE AND METHOD

Observing at daytime with the same techniques as nighttime observations is usually impossible due to sensor saturation. The signal coming from the sky background fills the pixels and the signal coming from the target is flooded in background signal. One way of reducing background signal is to change the wavelength of observation. Indeed, background signal is composed of sun emitted light, which spectrum is lower in SWIR (Short-Wave InfraRed) than in visible. Indeed, background signal is composed of sun emitted light, which level is lower in SWIR than in visible. Moreover, atmospheric scattering is stronger in visible wavelengths. Thus, observing in SWIR results in higher SNR. At daytime, it is more favorable to observe in SWIR than in visible wavelengths.

However, resolved imaging is more challenging in SWIR because the diffraction limit is less favorable, the theoretical limit being proportional to the wavelength. The Fried parameter r0, which is a commonly used parameter to quantify the astronomical seeing [1], varies as $\lambda^{6/5}$ [2]. This means that it is bigger at larger wavelengths. Thus, the impact of atmospheric turbulences will be less damageable in SWIR than in VIS. The following table gives a typical comparison of limitations between visible and short infrared wavelengths, for a 14” telescope.

Table 1: Typical comparison of limitations between SWIR and IR 14” telescope

Wavelength	Diffraction limit (arcsec)	Typical r0 (cm)	Turbulent resolution (arcsec)
VIS (700nm)	0,49	15	1,17
SWIR (1.3μm)	0,91	31	1,04

Moreover, the effect of atmospheric turbulences is stronger at daytime. Indeed, r0 parameter tends to be higher at night by a factor 2 [3], which makes resolved imaging more challenging at daytime.

The different phenomena at stake are difficult to anticipate and even more difficult to model realistically. ArianeGroup decided to experiment daytime imaging of low altitude satellites at high frequency with an existing observation station and available COTS equipment in order to assess the imaging performances in real conditions in both SWIR and VIS wavelengths.

The choice of the cameras has been performed with respect to their characteristics and performances, especially in terms of resolution and image frequency. SWIR (Short-Wave InfraRed) detectors available on the markets are less mature than VIS detectors. Thus, the camera trade-off is more difficult in SWIR than in VIS. In particular, lucky imaging technique needs high frequency imager, and high frequency SWIR cameras are not very common. Moreover, small pixel pitches are not easily available in COTS SWIR detectors. The characteristics of the chosen cameras are given in the next chapter.

ArianeGroup observation station had already been used for lucky imaging in visible wavelengths before [5] [6], but the SWIR setup has been specifically added for this observation campaign.

5. DESCRIPTION OF THE EXPERIMENT

Based on the existing observation station, ArianeGroup made a dedicated observation campaign using 2 cameras:

- One SWIR camera, with cooled InGaAs sensor.
- One VIS camera, with CMOS sensor.

The telescope used is a standard COTS 14” telescope. Note that this telescope is not optimized for SWIR applications, neither in terms of transmission nor in terms of optical quality. This means that the PSF of the telescope is unlikely to be diffraction limited in SWIR. A beam splitter is used in order to split the optical path between SWIR and VIS, so that both cameras can be used simultaneously on each observation (see *Fig 2*).
Due to the pixel size of the cameras, the geometrical resolution is finest on the visible path than on the SWIR path. However, the geometrical resolution on both paths is finer than the diffraction limit, meaning that the observation configuration is a little oversampled with respect to the theoretical maximum reachable resolution.

The observation characteristics of both paths are given in the table below:

Table 2: Characteristics of SWIR and VIS optical paths

	COTS SWIR camera	COTS VIS camera
Resolution (pixels)	640x512	2048x1536
Pixel pitch (µm)	15	3,45
RON (e-)	<30	N/A
DC (e/p/s)	<600	N/A
Max framerate (fps) (full frame)	600	121
Exposure time (ms)	0,5	1
FOV (°)	0,14x0,11	0,10x0,08
iFOV (arcsec)	0,79	0,18
Collection diameter (cm)	35,5	35,5

Fig 2 Double path optical train for simultaneous SWIR and VIS observations

6. RESULTS

Several targets have been tracked and acquired with the experimental setup described above. In each case, the acquired images have been processed with a classical Shift-and-Add algorithm. Note that the evaluation of the gain provided by the reconstruction algorithm is not in the scope of this paper.
The ISS (International Space Station) being the biggest and closest object in orbit is the ideal test case to evaluate the performances. We also managed to acquire resolved images of CSS (Chinese Space Station). The results are presented and analyzed below.

6.1 Results obtained on ISS

The best images of the ISS were obtained during a morning pass around its culmination at elevation 64° for a range of about 460km. Note that it was 10h34 local time, meaning full daytime conditions. Unfortunately, no seeing measurement was available.

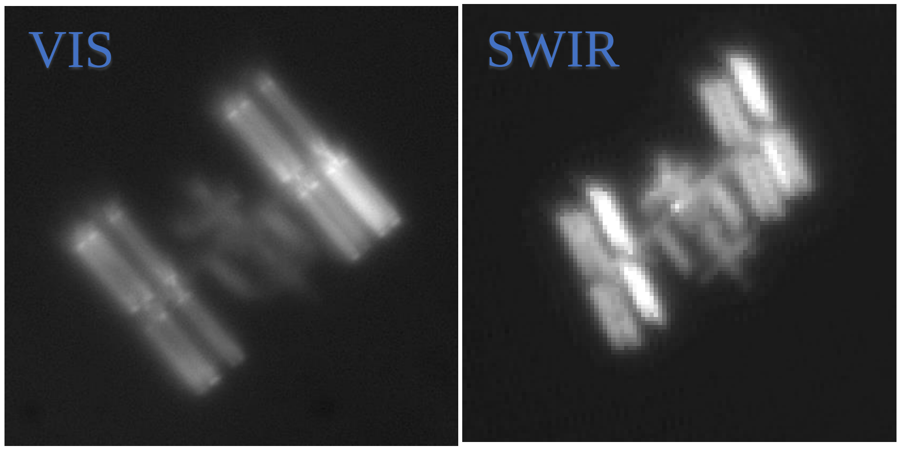

Fig 3 Resolved images of ISS obtained at daytime, shift and add post processing (left = visible image, right = SWIR image), 10h34 (local time) (full daylight)

For scale reference, on those images, the ISS is about 240 pixels wide in VIS and 60 pixels wide in SWIR.

Diffraction limited resolution at this distance is 1m for VIS, and 2m for SWIR. For scale reference, each solar panel is 35 meters long and 12 meters large. We can roughly estimate that the resolution limit on both images is close to the distance between two individual panels, which is about 2,5m. Note that this shall be considered as a rough estimation, since it is likely that the panels are inclined with respect to the station. However, we can see that the resolution reached here is close to the diffraction limit in SWIR, but more degraded in VIS. Although it has not been rigorously checked, the performance here is probably limited by the PSF of the instrument. However, we can make a comparative analysis of the two images:

- The ISS being particularly bright, imaging at daytime is feasible in visible wavelengths (with short exposure time). However, the contrast is better in SWIR even if the exposure time is twice shorter. From a photometric point of view, imaging of smaller and fainter targets shall be easier in SWIR.
- The resolution on the panels seems a little better in VIS than in SWIR. But on the central core, it looks that more details are visible in the SWIR image. It is most probably due to the highest contrast obtained in this zone. The resolution seems similar.

6.2 **Results obtained on CSS**

The chinese space station (CSS) is much smaller than the ISS. At the time of the acquisition (April 2022), the station was composed of 3 modules [7]:

- Tianhe (core module – 17m length)
- Tianzhou 3 (~11m length)
- Shenzou 13 (~9m length)

The images hereafter were obtained during a morning pass around its culmination at elevation 53° for a range of about 470km.

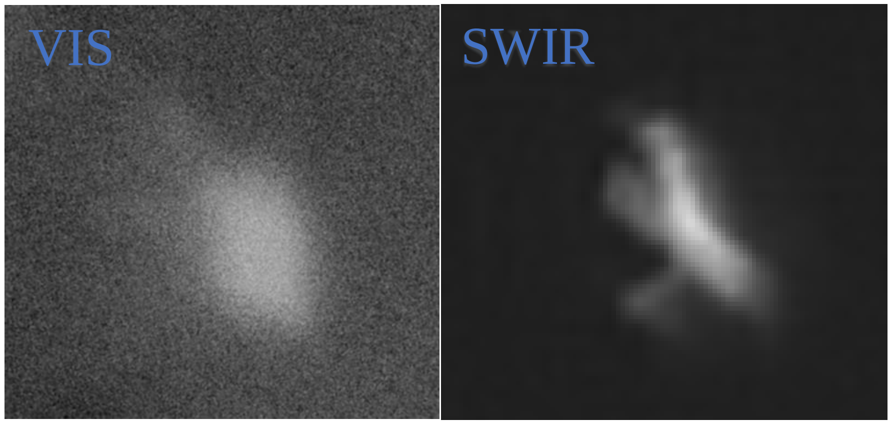

Fig 4 - Resolved image of CSS obtained at daytime, shift and add post processing (left = visible image, right = SWIR image) - 10h16 (local time) (full daylight)

In this case, the visible image is not exploitable. This can be explained by the fact that the individual images are too damaged by the turbulences to allow the reconstruction. Moreover, the signal level is low, which makes the reconstruction even harder. On the contrary, the shape of the station is visible on the SWIR reconstructed image. On the original SWIR images, the size of the station is about 15x13 pixels (it has been oversampled during the reconstruction process).
Our interpretation of the image is as follows:

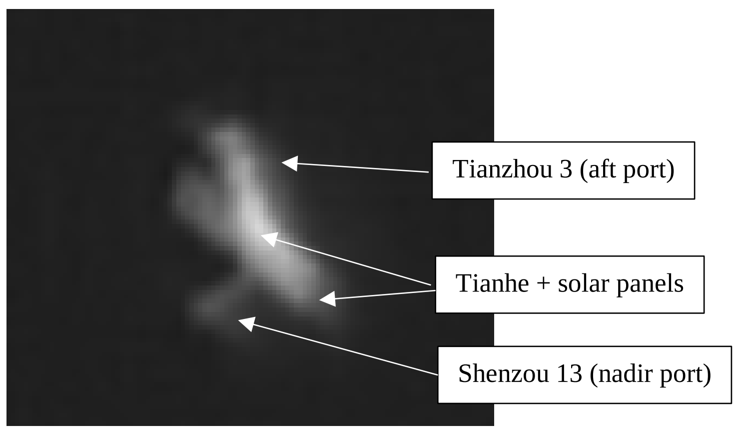

Fig 5 – Interpretation of the shape of Tiangong space station on SWIR image (april 2022)

As a scale reference, the solar panels of Tianhe are about 11m x 4m each.
Even if the image resolution is not very fine, we can still use the SWIR image to correlate the shape of the station with its constitution at the time of the observations.

7. CONCLUSION AND WAY FORWARD

These preliminary tests of satellite resolved imaging from the ground and at daytime gives interesting comparative results between visible and SWIR images. For targets that would be smaller and fainter than space stations, imaging in SWIR is more promising in terms of sensitivity, with no obvious loss in resolution with respect to visible.
In order to go further and obtain more interesting resolution, we would need to work on a dedicated station with larger collection diameter (to improve the theoretical resolution limit) and better optical performances in terms of PSF (optical design dedicated to SWIR imaging). With upgraded system and under good atmospheric conditions, we expect to reach sub-metric resolution at distance 500km.
The ability of imaging at daytime is especially interesting in terms of observation opportunities for LEO satellites, the latter being in Earth shadow most of the time when the station is at night. ArianeGroup plans to go further with this study in order to assess the interest of this technique for spatial object characterization.

8. REFERENCES

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