Reconstructing from Extended Imagery of Space Objects

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ABSTRACT

Large resident space objects may be imaged using optical telescopes but as they traverse the sky in a matter of minutes their range from the telescope and associated size and aspect on the sensor change drastically. Traditional image stacking of images is not possible, so we address a volumetric reconstruction of the 3D object from the diverse observations. We report on this algorithm using observations of the ISS from the Canberra node of the Falcon Telescope Network.

1. INTRODUCTION

Photometric and Astrometric observations using optical telescopes of Resident Space Object (RSO), whether illuminated actively in ranging experiments, or by the Sun, are routine methods for monitoring the well-being of existing RSO and identifying new objects. Global distribution of these telescopes aids in refinement of their location and orbit, feeds the Space Surveillance Networks (SSN), and allows for better detection through more observations when the optical signal is poor. For Geosynchronous orbits, the use of Sun illumination is predominant, as ranging lasers systems cannot deliver the same power to the object, where the large range diminishes the return light. For Low Earth Orbit (LEO) objects, the ranging system is more the precision instrument because it can gain a signal regardless of the solar phase angle, which limits the window of opportunity for a passive (Sun illuminated) observation. However the passive observation of larger objects allows for a spatially resolved image of the object.

Observation of LEO objects is made difficult due to their interaction with the (rarified) atmosphere, which affects their ballistic solution, and reduces their predictability of their orbit. The lower they are in altitude, and the larger their cross-section, the less predictable they are in position relative the small field of view of tracking telescopes. The International Space Station (ISS) is one such RSO that presents an image, and is worthy of tracking and imaging to perfect algorithms that might seek to super-resolve the imagery using multiple observations. This study presents our work imaging the ISS over many orbits, ranges, and solar phase angles, in an attempt to use the observations to determine a partial three-dimensional tomographic reconstruction of the ISS.

2. THE FALCON TELESCOPE NETWORK

The observations of the ISS presented here are taken using the UNSW Canberra node of the USAFA's Falcon Telescope Network (FTN)[1]. The 0.5 m f8.1 semi-autonomous optical telescope uses commercial-off-the-shelf components to drive the pointing, and capture the image. One megapixel, 16 bit per pixel images are acquired using an Apogee (now Andor) AltaF47D camera, with mechanical shutter. The light is imaged through a choice of optical filters. Exposures as short as 1ms are used on the bright signal from the ISS. Any shorter exposures are hindered by the mechanical shutter speed, and while they would allow for reduction in the bloomed parts of the image that are caused by specular reflections of the varied facets of the ISS structure, they would lose the fainter reflections from the rest of the structure. Hence a balance must be obtained between exposure time, dynamic range, and the spatial structure that is visible.

An added complication in the observation of the ISS is whether it is in fact within the 15 arc minute field of view of the telescope. The ISS is a large, changing, object in LEO, whose interaction with the rarified atmosphere, and despite good and up to date predictions delivered by the SSN in Two Line Element (TLE) form, its exact location is difficult to rely on. A significant effort is required to find it low to the horizon on a pass within the field of view, and adjust telescope angular rate to follow it for a significant part of its path. A poor estimate of angular rate at acquisition will mean the mechatronics of the mount can't adjust at the rates required, and the RSO eventually lost. This also happens when the observation is close to the meridian, as the mount used is a German Equatorial type and re-positioning on the other side of the meridian and re-acquisition is required. This must all happen in roughly the five minutes of the traverse. The same requirements, but without a reliable photometry signature are imposed on the cubesats launched from the ISS from time to time, so this is worth refining, as a "direct reckoning" solution.

Of course an active loop tracking the RSO over a wider field of view is a solution, and we are investigating this, but at the moment the FTN is operated using COTS solutions, and it is a tribute to the software and hardware already in use that we are able to compensate and present the images herein. The authors are grateful to the USAFA for the donation and access to the FTN telescope for this work.

3. IMAGING FORMULATION

Assuming instrument parameters have been successfully applied it is possible to gain a sequence of short, rate-tracked, images $g_i(x,y)$ of the RSO. However there are a number of geometry factors, illumination geometry factors, and atmospheric turbulence related effects to consider. We therefore give a simplified imaging construct,

$$g_i\left(x,y\right) = D.H_i\left(t,R\right).S_i\left(R\right).M_{\theta_i}\left(t\right).M_{\phi_i}\left(t\right).P\left(\theta_i,\phi_i,\gamma\right).f\left(x_0,y_0,z_0\right) + N_i \quad (1)$$

where $f(x_o,y_o,z_o)$ is the RSO in its orbit coordinate set. It is assumed here that the z_o coordinate is along the orbit (positive in the forward direction), and hence y_o is directed towards the Earth's centre.
H denotes the atmospheric turbulence related blur, which can incorporate tracking variability, chromatic effects, and atmospheric absorption, as a function of slant-range, *R*.
S denotes the apparent scale change between the object and the sensor as a function of range, R. This effect can be explicitly determined and corrected for, from true range data and angular position, if known of trusted, or it can be estimated given metrics such as encircled energy and the like.
The *M* operators are affine transformations from the object orientation with respect to its orbit, and the angle to the sensor at a given part of that orbit.
The optional *P* operator may be used to determine the Sun illumination effects based on Solar Phase Angle, Υ, and object orientation at each exposure.
It is assumed the object *f* is a rigid body for this investigation, however this may not realistically be the case when observations are taken over many dates, and when the ISS in this case, feathers its solar panels to face the Sun as it orbits to maximise power consumption.
Many observations may be taken, with variant parameters such as which spectral filters are used, what exposure time is used. The latter, coupled with the Sun's position, may cause blooming in the sensor, around the location of specular reflections. Such need to be identified and removed or reduced, leaving the remaining observations or image content with sufficient dynamic range to contribute to the reconstruction process.

4. TYPICAL OBSERVATIONS

The acquisition of significant images of the ISS involved a campaign over multiple days, and resulted in a range of images, with their own associated problems. The campaign is illustrated in Figure 1 as a range of observations with differing elevations, and hence ranges, with a range of camera exposure times, and filter spectral bandwidths — largely in the "V" or green centred spectrum, but with some with Red "R" or Near Infrared "I" filters. The airmass is included to show the inverse relationship with elevation.

Typical sequences of images are shown in Figure 2, after automatic detection and extraction of the ISS within the megapixel imagery. The reduction in size with range is evident intra-sequence, and also between sequences were the pixelation of the sampling matrix changes when we attempt to compare similarly scaled objects. Also evident is the blooming from the regions of high specular reflection. These regions must be automatically determined and their effect reduced before reconstruction, but keeping these images is important since surrounding regions have image data with high dynamic range for the non-specular reflections.

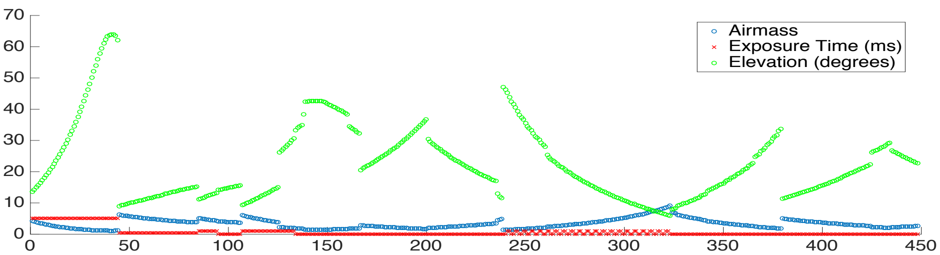

Figure 1: A campaign of observations of the ISS, showing varying elevation, exposure time and the amounts of atmosphere (in units of airmass) the light must traverse.

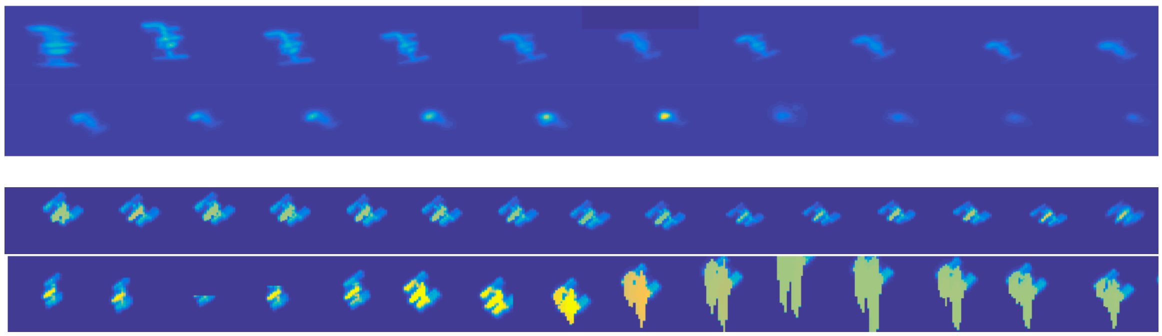

Figure 2: Two sequences of the ISS serve to illustrate the changing aspect within a sequence and between sequences, the scaling with range; they also illustrate the difficulty in tracking such a large, low orbiting object with frames cut-off as the tracking in not centred; and finally the blooming that accompanies high dynamic range observations.

5. TOMOGRAPHIC RECONSTRUCTION

Most tomographic reconstruction algorithms work on the fact that the projections are received through the scattering object, at defined an constant distances from the centre of the sample. This is clearly not the case here; firstly the object changes range between each exposure, so there is no equidistance assumption, and secondly the light is from reflection or scattering from the surface of the object, being very dependent on the illumination angles.

Thus a variation on tomographic reconstruction is required. We use this need to embrace the possibility of super-resolved imagery, by exploiting the sampling matrix, D, in eq (1), and the many observations. We could determine with reasonable accuracy the range to the RSO, using the Two Line Element (TLE) information, and hence determine the scaling operator in terms of angular geometry. Instead we propose to scale the object between observations, counteracting the S matrix. We also exploit the turbulence induced blurring H_i in each observation, realising this is also a function of range, but removing the explicit need to undertake spatial blurring the object prior to scaling and sampling the projection – a step usually adopted in standard tomography.

As a first step algorithm we adopt a method that has proved useful in Remote Sensing from satellite[2], to take multiple observations of the same scene, and exploiting sparsity priors, to aid the inverse problem to gain $f(x_o,y_o,z_o)$. In this process, the discrete wavelet transform is used on both sides or eq 1, and assumptions of scale dependence of the noise used to regularize the solution. Largely this algorithm seeks to evaluate the Bayesian probability of the three dimensional object, f, given all the observations.

$$P\left(f\left(x_0,y_0,z_0\right)|g_i\left(x,y\right),\ldots,g_k\left(x,y\right)\right) \tag{2}$$

The estimate f* seeks to maximize the probability

$$f^* = argmaxP\left(f|g_i,\ldots,g_k\right) \tag{3}$$

which may be shown to lead to a cost function that must be reduced by other means.

$$L(f) = \alpha \sum_{i=1}^{k} \|g_i - D.S_i.M_{\theta_i}.M_{\phi_i}.f\|^2 + f^T Q f \qquad (4)$$

The final regularization term involves estimating the co-variance matrix of the noise process, Q. The term α controls the rate of minimization. Readers are referred to [2] for details of an iterative algorithm that has performed well in satellite remote sensing to gain super-resolved imagery from multiple observations. This algorithm employs a wavelet transform on the images and allows for a regularization prior such as the statistics associated with edges in the image across scale. At this stage we are still refining the algorithm for this application.

6. CONCLUSION

We have begun an observation plan for the ISS as an exemplary RSO in LEO to explore algorithms to reconstruct the three dimensional structure from the many observations. Significant difficulties arise when observing such a large object with significant atmospheric drag, and with such a high dynamic range for the reflected light. We have shown here examples of the imagery that illustrate the problems that need to be overcome in such a reconstruction, ignoring the dynamic structure changes of the ISS over its orbit such as solar panel re-orientations. We have proposed an imaging model for the projection we obtain using the FTN telescope, and indicated a likely algorithm for reconstructing the structure from the observations. Testing of this algorithm is a work in progress.

7. REFERENCES

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