Developing and Demonstrating the IBEX Fused Satellite Tracker

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ABSTRACT

To have a better estimate of satellite orbits than Two Line Elements (TLE) can provide, work was started on a toolkit that can estimate more accurate satellite orbits using multiple measurements from various abstracted data sources.

The toolkit is structured in a modular fashion, to allow for various data sources and various data outputs. A new input format only needs an elementary abstraction layer to be coupled into the estimation tool. Because one of the first inputs provided were telescope images, the toolkit was named IBEX, for Image Based Ephemeris eXtractor.

IBEX currently has several different applications. The toolkit is used for the generation of satellite tracking files for telescopes (using data from various sources) and for the refinement of orbital estimations after a telescope has tracked a satellite. Additionally, IBEX is used to generate accurate orbits from aggregated TLE data and to generate precise tracks from radar plots for the application of generating inverse synthetic-aperture radar images.

Future applications include processing of generated laser ranging data, processing wide field of view optical measurements and fusing heterogeneous data sources for SSA purposes.

1 INTRODUCTION

Accurate orbit estimation is an enabling factor for many applications in the domain of space situational awareness (SSA). SSA is becoming an ever greater priority for many organisations and institutes that operate within NATO, TNO being no exception. Projects from various departments within our organisation had a key requirement for accurate orbit estimation.

Work on an estimator first started in the context of an Inverse Synthetic-Aperture Radar (ISAR) project. This project needed accurate positional information on a satellite to allow for coherent imaging of it. An estimator was made that could add positional information to a dataset of radar measurements.

Another project soon followed, where it was found that Two Line Elements (TLE) did not provide sufficient accuracy for tracking satellites with a narrow field of view telescope. When a TLE was used, the satellite would only briefly come in to the field of view of the telescope, exiting when the satellite came closer to the local zenith, where inaccuracies manifested. The goal of this project was to slew a telescope such that it could be used as a ground station for a satellite based laser communication terminal, so the satellite had to remain in the field of view during the entire pass. Similarities between the requirements of these projects were noted and work was started to adjust the estimator to this application. Adding in the option to refine estimates based on acquired optical tracks was the final action that lead to the creation of IBEX, the Image Based Ephemeris eXtractor. Even though there are many more input forms the toolkit can handle currently, it was decided to keep the name.

This article will describe the structure of the IBEX toolkit, the techniques used therein and the applied validation method.

2 PROBLEM STATEMENT

The projects mentioned in the introduction and some aspects of SSA have a need for accurately estimated orbits of Earth orbiting satellites. For example: a task like manoeuvre detection would require a very precisely determined orbit to determine the effect of a low-thrust electrical propulsion system.

In the field of SSA, it is possible that a tracked satellite has properties that affect its orbit that are unknown to the observer, e.g. weight, size, geometry, behaviour or the presence of a propulsion system. Therefore, detailed modelling of a satellite is not always possible or too labour intensive to be feasible. Without a detailed satellite model, a generic model has to be devised that sacrifices the smallest amount of accuracy in orbit estimation.

To properly integrate into a future SSA network, the software also has to be able to handle data from various sensors. These could be active sensors like radar or laser ranging stations, passive sensors like telescopes or multispectral cameras. The parameters needed for orbit estimation need to be identified and distilled from these various sensors.

In addition to accurately determining orbits, for some sensors an initial estimate of the orbit is also needed. An orbit can be coarsely determined from instantaneous position and velocity or another set of observed orbital elements, but not every sensor can provide this. For example, data from a sensor that only reports azimuth and elevation would need a good initial estimate to converge on the estimated orbit.

Summarizing, the problem IBEX intends to solve is: determine the orbits of satellites with unknown properties as precisely as possible from observations by heterogenous sensors without a-priori knowledge.

3 SOLUTION APPROACH

To tackle the complex task of estimating consistent orbits while having heterogeneous sensor inputs, a sensor abstraction was devised. This section will describe the different kinds of abstract observations IBEX can use and will illustrate the process of sensor abstraction, initial orbit determination and accurate orbit determination for image based data.

3.1 Abstracted Sensor Inputs

To allow for sensor fusion, all relevant observations have to be converted into a common format. This format has to allow for the estimator to generate an observation model, such that actual observations can be matched with the modelled observations. The following abstracted inputs are currently used by the tool:

- Cartesian Position in either ECEF or ECI frame
- Cartesian Velocity in either ECEF or ECI frame
- Azimuth / Elevation in sensor-local ENU frame
- Range to observer
- Rate (Instantaneous change of range)
- Right Ascension / Declination

All inputs should come with time and reference frame information. For some observations, like GNSS (Global Navigation Satellite System) data, the abstraction can be trivial: checks have to be made as to the reference frame and time datums of the measurements, but they can otherwise be utilized directly. Observations such as images will be more involved: the 2D pixel data and instrument settings have to be distilled into a useful Azimuth / Elevation or Right Ascension / Declination observation.

This abstraction approach allows for new sensors to be added to the sensor fusion application by writing a translation layer between the raw sensor output and one or more of the abstracted observation inputs.

3.2 Image Based Angle Extraction

After an optical telescope has tracked a satellite, the output of the telescope can be used to further refine the orbital estimation of the satellite. This is accomplished by extracting the satellite's angular coordinates over time from a time series of 2D pixel data of observations and then using these coordinates to estimate an improved orbit. In the case of the TNO telescope (shown in Figure 3-1), the 2D images were stored using the Flexible Image Transport System (FITS). This image format comes with attached metadata from the telescope and its tracking system.

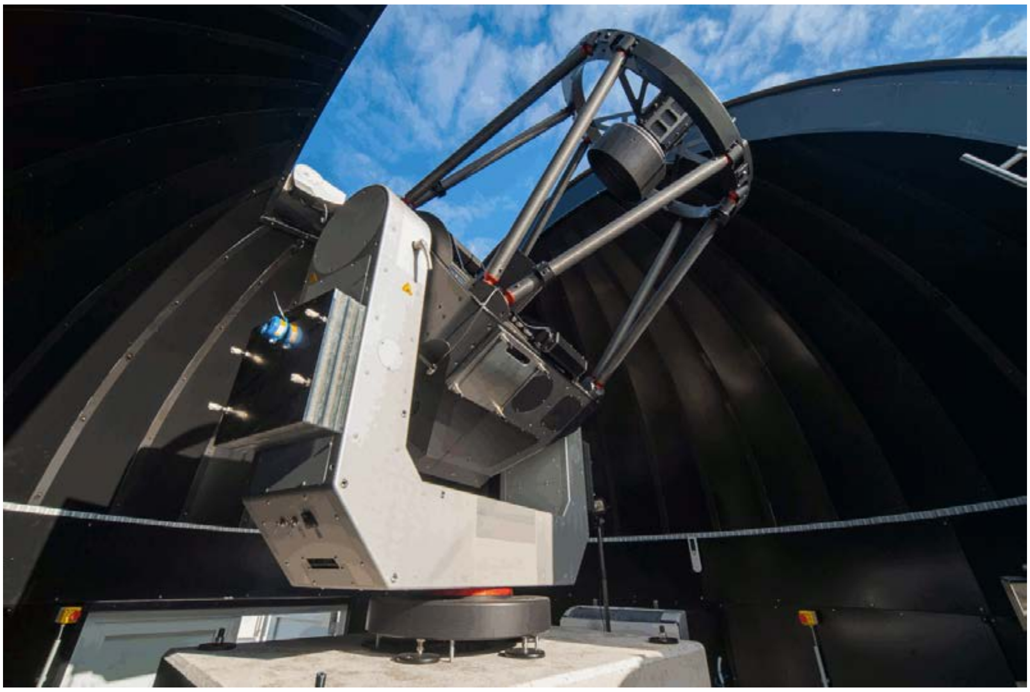

Figure 3-1: The telescope at the TNO Optical Ground Station.

In ideal circumstances the satellite would be right at the centre of the telescope's viewfinder as it is following the satellites orbit. In this case, the angular coordinates would simply be equal to the Right Ascension and Declination as reported by telescope's tracking system in the image metadata. However, as illustrated in Figure 3-2, this is typically not the case as inaccuracies in the tracked orbit will cause the satellite to deviate from the viewfinder.

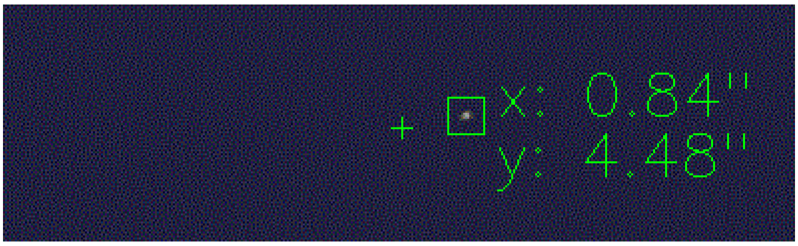

Figure 3-2: The satellite Starlette as seen through a TNO telescope. The green reticule indicates the centre of the viewfinder (boresight). The green box contains the satellite. The x and y coordinates indicate the angular distance to the centre in arc seconds.

To determine the offset of satellite with respect to the viewfinder, the 2D-pixel coordinates of the satellite, relative to the viewfinder centre, must first be identified. This is achieved by first finding the brightest pixel in the image and ensuring that the intensity of the pixel is not within five standard deviations of the average pixel intensity of the frame. The pixel with the highest intensity will likely be a part of a cluster of bright pixels, representing the satellite. The centre of the cluster of brightest pixels is then determined using the 2D-Gaussian function in combination with a non-linear least squares curve fit function.

Once the 2D-pixel coordinates of the satellite have been identified, they must first be corrected for the sideways reflection of the light in TNO's Nasmyth telescope. A rotation matrix with an angle derived from the camera mount orientation angle and telescope's Altitude angle is used to rotate the coordinates.

Finally, the rotated 2D-pixel coordinates are converted to Azimuth and Elevation offsets. The offsets are then added to the telescope's Azimuth and Elevation to determine the satellites angular coordinates. To collect as many measurements as possible, this process is repeated for each observation frame.

The results of image based angle extraction are promising, with basic track initiation solely on optical tracks being possible. For single station passes, accuracies close to TLE level are possible. For better estimation of long term orbital effects, like the drag coefficient, multiple passes are needed. Tracks from various spatially separated sensors are also beneficial to accuracy, as a single earth-fixed sensor will sample the satellite at approximately the same point in an orbit. This leads to inaccuracies in the parameters determining the eccentricity of the orbit.

More research into the various offsets and error sources is needed to produce accurate tracks using this method alone. The arc second level of azimuth and elevation determination possible with the telescope is not reflected in the accuracy of orbital solutions currently attained.

3.3 Initial Orbit Determination

In order for IBEX to accurately estimate the satellites orbit, an initial orbit must be set. This initial orbit must have a reasonably high accuracy to allow for the accurate orbit estimation algorithm to converge. Several options of determining the initial orbit were determined and implemented in IBEX:

- One position and velocity observation in cartesian coordinates;
- Two position observations in cartesian coordinates. The initial orbit is determined using Lambert's method of initial orbit determination [1];
- Two Range-Azimuth-Elevation observations. Similar to the two cartesian positions, Lambert's method is used here;
- Three angular observations according to Gauss's iterative method as described by [2, *Algorithm 5.5*

and 5.6]; and

- Two-line elements (TLE). The cartesian position-velocity state is extracted from the TLE using a TLE propagator based on the SGP4 and SDP4 models.

A two angular observation initial orbit determination method was also considered. The two angles method is based on Kepler's second law and assumes a near-circular orbit. However, this method was not found to produce accurate enough initial orbit estimates to allow for the accurate orbit estimation algorithm to converge.

3.4 Accurate orbit estimation

Accurate orbit determination primarily depends on an accurate model of both the satellite and the orbital environment. Since the goal is to be able to estimate generic satellite orbits, there is some loss of accuracy compared to models that use specific satellite models. For this tool, the choice was made to model the satellite as a point mass with a ballistic coefficient. The ballistic coefficient is estimated with the orbit, so if external information on the satellite frontal cross section and attitude behaviour is known, the satellite mass can be determined and vice versa.

Since IBEX is meant to estimate orbits of satellites in Earth orbits, a force / acceleration model for the near Earth environment is needed. The following effects are currently modelled:

- Gravity Field including spherical harmonics
- Atmospheric Drag
- Relativity
- Lunar Attraction
- Solar Attraction

Effects like solar radiation pressure are not modelled, as this would require an estimate of the sun-facing surface of the satellite. This would make the model too dependent on satellite specific properties, like attitude behaviour and geometry. Adding such effects would negate the generic characteristic of the estimator.

Accounting for these effects, a least squares estimator is used in conjunction with a Levenberg–Marquardt optimizer. Once the optimizer has converged to within pre-set bounds, the resulting solution will be presented and forwarded to the output stage of the application.

4 APPLICATION STRUCTURE

The primary parts of the application are illustrated in Figure 4-1. Here the various inputs (left) and outputs (right) can be seen. When a new input or output is desired, this can be facilitated by adding a new parser or processing core.

Figure 4-1: The Structure of the IBEX Application. Boxes indicate modular code bases.

The separation of the estimator core from the end-user application allows for the core to be implemented in different application, while maintaining a single codebase. This feature has been used to create a different application that generates tracking files for a telescope from automatically updated data sources, ensuring accurate tracking is always available without any human effort. Accurate tracking files are needed because of the very narrow field of view of this telescope.

5 VALIDATION TEST SET-UP

To determine the accuracy of IBEX's orbital estimator using sensor fusion, a testing methodology was devised. The main concept is using sensor data to estimate an orbit and generate a CPF (Consolidated Prediction Format) file that can be used by a telescope to track the satellite. As mentioned in the introduction, this was needed as TLE based tracking would quickly result in the satellite being out of the narrow field of view of the telescope.

This testing method can be summarized as follows:

1. Gather tabulated positional data for a satellite.
2. Estimate an orbit based on this data.
3. Propagate the orbit to the time of tracking.
4. Generate a CPF file for tracking the satellite with a telescope.
5. Track the satellite based on the CPF file.
6. Determine deviation of satellite from computed track with telescope images gathered during tracking.

Tracking of the Aerocube 14A satellite (COSPAR ID 2019-071D) was planned and executed at the 21st of September 2021 at 03:58Z at the telescope facility in The Hague. This satellite had a laser transmitter on board which was active during later passes. Successful reception of this signal during the entire pass is considered the validation criterion.

6 VALIDATION RESULTS

A validation of IBEXs capabilities was performed using the test set-up described in Section 5.

Tabulated GNSS data from the satellite's internal receiver was used to prime the satellite tracker. At the time of the satellite pass this data was around a week old. No manoeuvring of the satellite was done in the time between sensor readout and tracking.

An orbit was estimated and a CPF file with entries close to the time of the overpass was generated. Using this file, tracking was done with an accuracy of around 30 arc seconds, as can be seen from Figure 6-1.

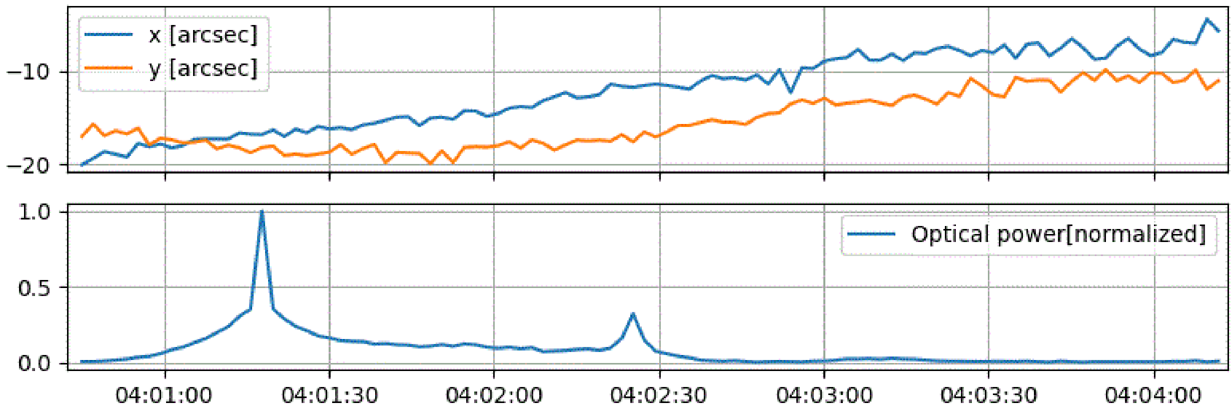

Figure 6-1: The location of the tracked satellite from the telescope boresight and normalized received optical feature signal power.

The method described in Section 3.2 was used to gather satellite track deviation information from FITS files generated by the telescope system.

These results do also have the reporting inaccuracies of the telescope built in. However, pointing tests have indicated that these to be well under a single arc second, leaving the attained worst case better than 30 arc seconds. These accuracies were sufficient to achieve a lock on the laser signal and demodulate the received waveform with a receiver without a closed loop tracking system.

After this experiment several other satellites have been successfully tracked with the telescope system and an automated track generation system based on IBEX has been installed.

7 CONCLUSION

The IBEX fused satellite tracker has been shown to be accurate on real-world GNSS data. The generated tracking file was accurate enough to perform optical tracking of a satellite to within 30 arc seconds with week-old input data.

IBEX has proven to be flexible enough to have already been used in multiple projects with very different input and output requirements. Key projects are ISAR image generation, tracking of satellites operating a laser based telecommunication terminal and sensor fusion experiments.

Estimating orbits based purely on azimuth and elevation measurements from a ground based telescope have been shown to be viable, although more research is needed to get to the expected levels of accuracy. Future experiments are planned using wider field of view optical heads and multiple sensors to create an automated satellite orbit determination system.

REFERENCES

[1] E. R. Lancaster and R. C. Blanchard, A Unified Form of Lambert's Theorem, NASA Technical Report, 1969.

[2] H. D. Curtis, Orbital Mechanics for Engineering Students., 4th ed. Butterworth-Heinemann, 2019.