# ERROR ASSESSMENT AND TARGET ACCURACY OF A MULTI-SPECTRAL IMAGING SENSOR ONBOARD THE INTERNATIONAL SPACE STATION (ISS)

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## ABSTRACT

ISSAC™ - International Space Station Agricultural Camera is a multi-spectral imaging system currently onboard the ISS capable of taking high temporal images (multi-days to multi-week) of Earth's vegetation. ISSAC's Science Operations Center (SOC) uses Satellite Tool Kit (STK), a software tool from Analytical Graphics Inc., for its mission planning to compute its ground target's access time and pointing angles. Reliable and sufficiently accurate trajectory information of the ISS is therefore essential to compute the target's access time and pointing angles. We describe multiple source of available ISS trajectory information and perform a detailed comparison and analysis of ground target's access time and pointing angle using each source of ISS trajectory information. A recommended approach potentially applicable to other remote sensing payloads onboard the ISS will be presented.

**KEYWORDS:** ISS Trajectory, Target Accuracy, Precision Remote Sensing, Ephemeris, TLE, STK

## INTRODUCTION

The International Space Station (ISS), a multi-national human-occupied spacecraft, assembled and operated in low earth orbit serves as a microgravity and space environment research laboratory to pursue research and development in bio-technology, biology, human physiology, physics, materials, and Earth and space sciences. ISS (shown in Figure 1) is the largest spacecraft ever built at a combined mass of over 360 metric tons, the external dimensions of about 109x51x20 meters, including deployed solar arrays. The ISS programme is a joint project between five participating space agencies, the American NASA, the Russian RKA, the Japanese JAXA, the European ESA, and the Canadian CSA. The station is divided into two sections, the Russian orbital segment (ROS) and the United States orbital segment (USOS), which is shared by many nations.

The ISS orbits at 51.6 degrees inclination, nearly circular, at a mean altitude of a little over 350 km; orbital period is thus typically about 91 minutes. ISS altitude degrades relatively quickly, necessitating several re-boosts per year. From an Earth remote sensing perspective, this varying altitude does cause the achievable spatial resolution of a given system to also vary, which needs to be taken into account when analyzing resultant imagery.

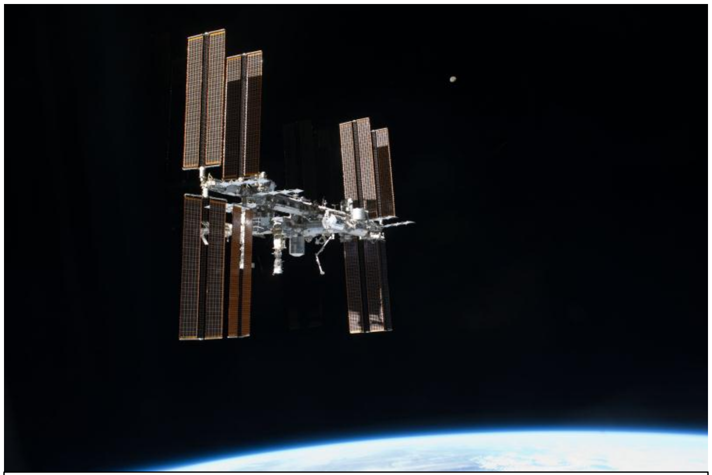
**Figure 1.** International Space Station taken from Space Shuttle Atlantis on July 2011 (Photo credit NASA, S135-E-011814).

With construction of the ISS now complete (shown in Figure 1), the spacecraft is maintained in a relatively stable earth-oriented attitude. Since the ISS orbit is not sun-synchronous, it cannot offer a remote sensing payload the advantages of sun synchronous operations – chiefly a repeating ground track with overflights over any specific point on the Earth occurring at the same local time for each over flight pass. For observing the Earth's surface, such an orbit is typically synchronized with a morning pass, to statistically reduce the chance of cloud cover. For example, with the Landsat 7 system, ground track repeatability is tightly controlled such that image products are provided in the familiar Worldwide Reference System (WRS) Path-Row location matrix; overflights occur every 16 days, with each descending node Equator crossing occurring at about 10:00 local time.

In contrast, the ISS orbit ground track has no fixed repeating pattern, and for a given location on the ground, can occur at any 24-hour local time instance. Considering only those overpasses that occur in sunlight (herein referred to as a revisit, or access), remote sensing from the ISS produces revisits which vary both seasonally and with latitude; more frequent revisits occur with greater latitude and the longer days of seasonal summer. A cross-track sensor pointing capability can significantly shorten times between revisits.

ISS Agricultural Camera (ISSAC™, shown in Figure 2) is the first science payload to make extensive use of the WORF and the US Laboratory Window onboard the ISS, and offers the opportunity to perform multi-spectral medium-resolution remote sensing investigations using the unique characteristics of the ISS.

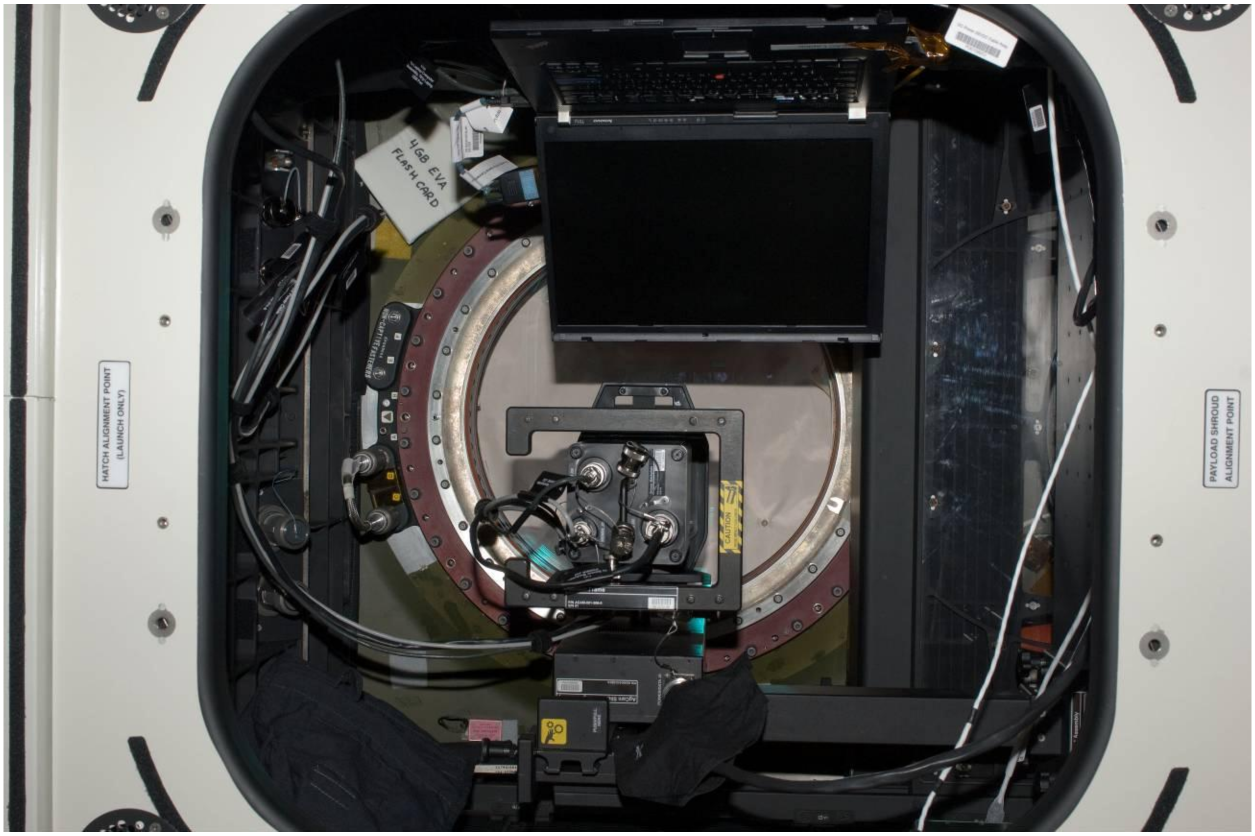

**Figure 2.** ISSAC installed on orbit inside WORF (Photo credit NASA, ISS027E023675).

ISSAC radiometric (Green, Red, NIR) and spatial (estimated 18-20m) resolution requirements were primarily defined to deliver images for applications pertaining to vegetation such as applications in precision farming, crop and grassland monitoring, grassland ecosystem, or land use land change study. In addition, the sensor off-nadir capability (±30 deg) from the ISS orbit enables ISSAC to deliver multidirectional data at different sun and viewing angles and at higher temporal resolution than sun-synchronous imagers; at higher latitudes, even several days in a row, or several times a day. This provides additional capabilities for scientific projects that profit from acquiring target reflectance as a function of illumination geometry and viewing geometry, such as scientific applications using BRDF or Digital Elevation Models (DEMs). ISSAC repetitiveness and targeting capability make it also a sensor adequate and potentially quite useful for evaluating and/or monitoring hazardous events.

## ISSAC MISSION PLANNING

ISSAC uses Satellite Tool Kit (STK), software from Analytical Graphics Inc. (AGI) for its mission planning to compute the target access time and pointing angle using the ISS trajectory information. STK offers a variety of analytic and numerical orbit propagators to input the trajectory information, some of which are Two Body, J2 Perturbation, J4 Perturbation, Simplified General Perturbations (SGP4), and StkExternal.

Two-Body, J2Perturbation and J4Perturbation are analytical propagators that generate ephemeris by evaluating a formula. Two-Body's formula is exact (i.e. the formula generates the known solution for a vehicle moving about a central body considering only the effect of the body viewed as a point mass) but is not an accurate model of a vehicle's actual force environment. J2Perturbation includes the point mass effect as well as the dominant effect of the asymmetry in the gravitational field (i.e. the J2 term in the gravity field, representing North/South hemisphere oblateness); J4 additionally considers the next most important oblateness effects (i.e., the J2^2 and J4 terms in addition to J2). None of these propagators model atmospheric drag, solar radiation pressure or third body gravity; they only account for a few terms of a full gravity field model. These propagators are often used in early studies (where vehicle data is usually unavailable for producing more accurate ephemeris) to perform trending analysis. The solutions produced by the J2Perturbation and J4Perturbation propagators are approximate, based upon Keplerian mean elements.

The SGP4 propagator is used with two-line mean element (TLE) sets. It considers secular and periodic variations due to Earth oblateness, solar and lunar gravitational effects, gravitational resonance effects, and orbital decay using a drag model. ISS trajectory information are widely used, readily available and frequently updated in TLE format and therefore ISSAC uses TLE sets for its mission planning. TLE sets are specially formatted text files ending in a *.tce or *.tle extension. TLE sets contain information about position vectors for objects orbiting the Earth. A sample ISS-TLE data set with each term definition is shown in Figure 3.

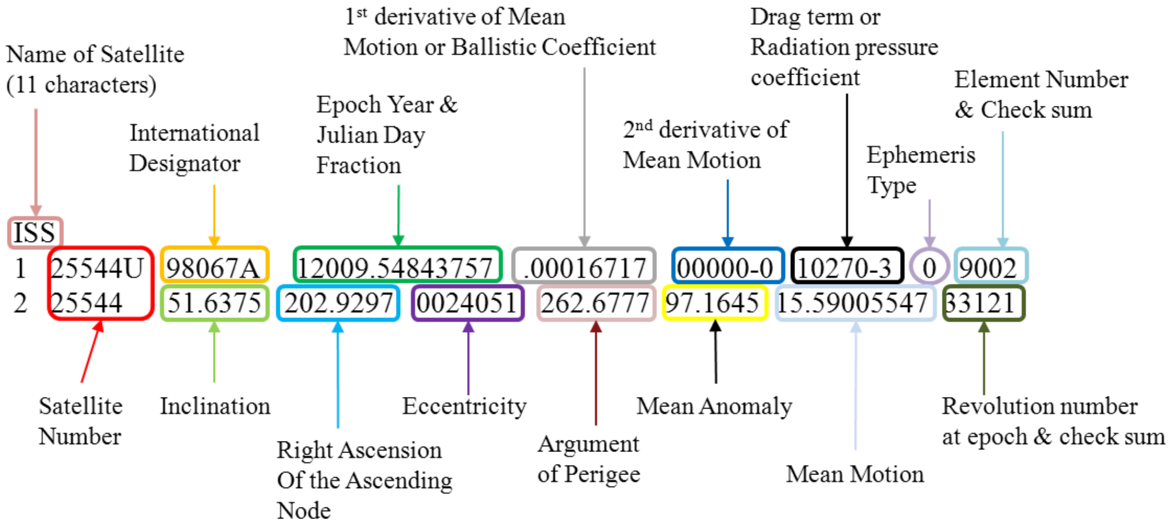

**Figure 3.** Example - Two Line Element (TLE).

The individual components of TLE set is briefly defined below

**Name of Satellite**: (ISS) This is simply the name associated with the satellite. In our case, it's "ISS"-International Space Station.

**International Designator**: (98067A) The 98 indicates launch year was in 1998, while the 067 tallies the 67th launch of the year, and "A" shows it was the first object resulting from this launch.

**Epoch Date and Julian Date Fraction**: The Julian day fraction is just the number of days passed in the particular year. For example, the date above shows "12" as the epoch year (2012) and 009.54843757 as the Julian day fraction meaning a little over 9 days after January 1, 2012. The resulting time of the vector would be 2012/009:13:09:45.01.
This was computed as follows:
Start with 009.54843757 days (Days = 9)
009.54843757 days - 9 = 0.54843757 days

0.54843757 days x 24 hours/day = 13.16250168 hours (Hours = 13)
13.16250168 hours - 13 = 0.16250168 hours
0.16250168 hours x 60 minutes/hour = 9.7501008 minutes (Minutes = 9)
9.7501008- 9 = 0.7501008 minutes
0.7501008 minutes x 60 seconds/minute = 45.01 seconds (Seconds = 45.01)

**Ballistic Coefficient**: (0.00016717) Also called the first derivative of mean motion, the ballistic coefficient is the daily rate of change in the number of revs the object completes each day, divided by 2. Units are revs/day. This is "catch all" drag term used in the Simplified General Perturbations (SGP4) USSPACECOM predictor.

**Second Derivative of Mean Motion**: (00000-0 = 0.00000) The second derivative of mean motion is a second order drag term in the SGP4 predictor used to model terminal orbit decay. It measures the second time derivative in daily mean motion, divided by 6. Units are revs/day^3. A leading decimal must be applied to this value. The last two characters define an applicable power of 10. (12345-5 = 0.0000012345).

**Drag Term**: (10270-3 = 0.00010270) Also called the radiation pressure coefficient (or BSTAR), the parameter is another drag term in the SGP4 predictor. Units are earth radii^-1. The last two characters define an applicable power of 10.

**Element Set Number and Check Sum**: (9002) The element set number is a running count of all 2 line element sets generated by USSPACECOM for this object (in this example, 900). Since multiple agencies perform this function, numbers are skipped on occasion to avoid ambiguities. The counter should always increase with time until it exceeds 999, when it reverts to 1. The last number of the line is the check sum of line 1.

**Satellite Number**: (25544) Also known as NORAD Catalog Number, NASA catalog number, USSPACECOM object number or simply Catalog number and similar variants, is a sequential 5-digit number assigned by USSPACECOM to all Earth orbiting satellites in order of identification. Before USSPACECOM, the catalog was maintained by NORAD. The first catalogued object, catalog number 00001, is the Sputnik 1 launch vehicle. Catalog number 25544 represents ISS and "U" indicates an unclassified object.

**Inclination (degrees)**: The angle between the equator and the orbit plane. The value provided is the TEME mean inclination.

**Right Ascension of the Ascending Node (degrees):** The angle between vernal equinox and the point where the orbit crosses the equatorial plane (going north). The value provided is the TEME mean right ascension of the ascending node.

**Eccentricity:** (0024051) A constant defining the shape of the orbit (0=circular, Less than 1=elliptical). The value provided is the mean eccentricity. A leading decimal must be applied to this value.

**Argument of Perigee (degrees):** The angle between the ascending node and the orbit's point of closest approach to the earth (perigee). The value provided is the TEME mean argument of perigee.

**Mean Anomaly (degrees):** The angle, measured from perigee, of the satellite location in the orbit referenced to a circular orbit with radius equal to the semi-major axis.

**Mean Motion**: (15.59005547) The value is the mean number of orbits per day the object completes. There are 8 digits after the decimal, leaving no trailing space(s) when the following element exceeds 9999.

**Revolution Number and Check Sum**: (33121) The orbit number at Epoch Time. This time is chosen very near the time of true ascending node passage as a matter of routine. The last digit is the check sum for line 2.

## Sources of ISS Trajectory in TLE Format

Even though ISS trajectory information could be obtained in multiple formats, ISSAC uses TLE format due to its availability, and ease of use. ISS trajectory information in TLE format could be obtained via multiple sources, some of which are AGI satellite database server, Space Track Database, NASA Human Space Flight, and NASA-TOPO.

STK by default allows the satellite’s TLEs to be automatically updated by querying the AGI server which finds the appropriate set of TLEs during the propagation interval. STK also offers methods to upload an external .tce/.tle files obtained from other sources. Spacetrack database provide TLE data to authorized users for free, the advantage of using spacetrack database is that it allows users to upload past TLE data. Another source of getting TLE data is from NASA – human space flight and it lists TLE data for the current date to the next 14 days. NASA-HSF updates TLE data three times a week (Monday, Wednesday, and Friday). ISS trajectory information could also be obtained from NASA-TOPO (Trajectory Operations Officer) in multiple formats and requires users to have appropriate security clearance in order to access the data. Only NASA employee and ISS payload developers with NDC access could access TOPO website.

A small uncertainty in ISS trajectory and attitude information may cause significant issue for any payloads especially remote sensing payload such as ISSAC, as it may result in missing the target completely from its field of view (FOV) by few kilometers given the altitude of the space station. For this reason, ISSAC relies on more accurate and precise ISS trajectory and attitude information, as these inputs could significantly alter the target access time and pointing angle determination. For example, ISS travels at a speed of ~7.7 kilometers per second and if the calculated target access time is off by few seconds, it will result in capturing an image off by several kilometers on the ground. ISSAC being an area scan camera is capable of taking multiple images at a given frame rate and this helps the target acquisition process, simply by taking more number of frames. Meaning, in an ideal situation, if you want to take a point target (say 15x20km area) – only one frame count of an image is all it takes to capture the intended target provided if we have accurate ISS trajectory and attitude information. But in reality, it's not possible to obtain a 100% accurate data, and therefore require an uncertainty to be added into the calculation. For this reason, adding few seconds before and after the calculated target access time allows to compute the required number of frame count (also depends on the target size) which will result in capturing the intended target image on the ground. Higher the uncertainty in the ISS trajectory information, more the number of frame counts will be required and this is critical to ISSAC operations because it will result in higher downlinking time as more number of frames is to be downloaded.

This creates a requirement for obtaining more precise and accurate ISS trajectory information in order to accomplish ISSAC science objectives. A preliminary detailed analysis was carried out to access the accuracy of the ISS trajectory information obtained from various sources and compared to the real-time data.

## ERROR ASSESSMENT AND TARGET ACCURACY

During ISSAC initial imaging period (June – August 2011), we used automatic TLE updates (default) from AGI server, and assumed that the automatic TLE updates would be sufficient to compute an accurate target access time and pointing angle for our end-user targets in STK. But it was learned that to ensure target acquisition, we need to add a variable amount of seconds to the computed access time using the automatic TLE option in STK and resulted high number of frames to be taken for ISSAC's target. In spite of using high number of frame count to capture an image, on several instances – STK had automatically updated the ISS trajectory with extremely inaccurate TLE data. Meaning, sometimes whenever there is an update to the TLE data via the automatic method, the target access time computed using the new TLE data update differ by more than 10 minutes when compared to the last TLE data. Further analysis showed that the new TLE data update was incorrect and caused more than 10 minutes difference in the target access time. In order to correct this discrepancy, incorrect TLE data via the automatic update method should be replaced by the last TLE data which predicted the target access time quite reasonably. As previously mentioned, Spacetrack database provides ISS trajectory information in TLE format, especially all the past updates to the TLE data. Hence, we used the TLE data from space track database to compensate the occasional inaccurate TLE data in the automatic TLE update method via AGI server in STK. Even though, this resolve the issue by using the last accurate TLE data from the spacetrack database to compute the ISSAC target access time, it is not always possible to identify whether the automatic TLE update method in STK is accurate or not, because occasionally the TLE data may be inaccurate and result the target access time to be off by more than 10 minutes which is not acceptable from ISSAC science perspective. On the other hand, even though spacetrack database provide an option to use the past TLE information, both spacetrack database TLE and AGI server automatic TLE update get the ISS trajectory information from same source other than NASA and these TLE data are just a predicted values, not accurate enough to compute the required target access time to achieve ISSAC science objectives.

NASA have its own source portal (Human Space Flight, HSF) for getting ISS trajectory information and these data are from TOPO who update the ISS trajectory information more frequently based on real-time space station information and predicts the future ISS trajectory as accurate as possible. HSF updates the ISS trajectory information, thrice a week (Monday, Wednesday, and Friday) and provide data in multiple formats (M50, J2K, TDR, TLE, etc.) all available for free access to the public. After using the HSF TLE information in STK, the target access time was found to be reasonably accurate and consistent.

The most accurate target access time is possible by using the HSF TLE along with the ISS attitude (roll, pitch, and yaw) information directly from TOPO. Attitude timeline data from TOPO can be accessed only by NASA employee and NDC authorized users which require security clearance. With the ATL information, the target access time calculated based on HSF will be off by 3-5 seconds and the pointing angle will be accurate within 0.3 deg. During space station vehicle activity (Docking/Undocking, Reboost, Debris avoidance maneuver, etc.), ISS attitude is unpredictable, but TOPO provides regular updates to the ISS trajectory and attitude soon after such event accessible by authorized users.

Table 1 shows the comparison of ISSAC target access time and their deviation from the actual target acquisition time (target found/located in real-time) when using different sources of ISS trajectory information. The values shown below are computed in STK by using the appropriate TLE data sources which provides the ISS positional information along with TOPO's attitude timeline data which provides the attitude of the space station.

**Table 1.** ISSAC target acquisition time using various TLE sources

| | | Difference between actual target acquisition time and STK calculated access time | | |
|---|---|---|---|---|
| Targets | Actual target acquisition time | NASA HSF TLE | STK automatic TLE updates | Spacetrack database |
| | hh:mm:ss | hh:mm:ss | hh:mm:ss | hh:mm:ss |
| 1 | 21:27:07 | 00:00:11 | 00:00:04 | 00:00:05 |
| 2 | 06:19:56 | 00:00:13 | 00:00:27 | 00:00:26 |
| 3 | 07:38:56 | 00:00:14 | 00:00:11 | 00:00:11 |
| 4 | 10:11:06 | 00:00:15 | 00:00:06 | 00:00:05 |
| 5 | 19:59:02 | 00:00:17 | 00:10:17 | 00:10:17 |
| 6 | 21:52:24 | 00:00:15 | 00:00:13 | 00:00:15 |
| 7 | 14:26:41 | 00:00:14 | 00:00:17 | 00:00:13 |
| 8 | 11:05:32 | 00:00:18 | 00:00:12 | 00:00:11 |
| 9 | 11:19:31 | 00:00:17 | 00:00:06 | 00:00:06 |
| 10 | 01:00:26 | 00:00:14 | 00:00:15 | 00:00:16 |
| 11 | 19:10:13 | 00:00:19 | 00:00:12 | 00:00:13 |
| 12 | 11:08:23 | 00:00:11 | 00:00:03 | 00:00:02 |
| 13 | 10:50:55 | 00:00:20 | 00:11:20 | 00:11:20 |
| 14 | 14:21:15 | 00:00:13 | 00:00:13 | 00:00:14 |
| 15 | 09:09:46 | 00:00:18 | 00:00:21 | 00:00:20 |
| 16 | 08:04:17 | 00:00:14 | 00:00:10 | 00:00:12 |

## Results and Conclusion

Table 1 clearly shows that the ISSAC target acquisition time varies significantly when different sources of TLE data are used along with the ISS attitude information from TOPO. The default automatic TLE updates method provides an inaccurate and unreliable target access time (occasionally) for ISSAC science and operations, due to the fact that the automatic TLE updates provide an incorrect ISS trajectory information (occasionally) compared to the last TLE updated data which creates offset in target acquisition time by more than 10 minutes on multiple instances that are unacceptable to ISSAC operations. Even though spacecraft database provides an option to download and use the previous version of TLE from the past, but it still contain the similar ISS trajectory data that AGI server uses for automatic TLE and this is also not acceptable for ISSAC operations. The target access time computed using the NASA-HSF TLE (ISS trajectory data) and the TOPO's ATL data (ISS attitude information) is more reliable and consistent. If carefully noted, the target acquisition time computed using HSF is off by a constant value (>10sec) from the actual target acquired time. By adding the 10 seconds offset to the calculated target access time (using HSF TLE) and taking 5-10 frame count will solve the uncertainty involved in target accuracy. ISSAC has been using the ISS trajectory information from NASA-HSF along with ISS attitude information (ATL) from TOPO to compute the access time and pointing angle for its ground targets; ISSAC was able to accomplish the required science by using NASA-HSF and TOPO data for its operations.

ISS Trajectory Operations and Planning Officer (TOPO) are responsible for the trajectory of the ISS including: Orbit determination, Ephemeris modeling, Maneuver planning (reboost), Conjunction evaluation, and Contingency planning. TOPO provide ISS trajectory and attitude information trice in a week, updates on Monday, Wednesday, and Friday. TOPO also provide additional updates whenever there is a significant change in the trajectory due to ISS vehicular activity such as reboost, Debrie Avoidance Maneuver, Docking, Undocking, etc., ISS Trajectory information predicted by TOPO is reasonable accurate for 2-3 days and consistent with real-time data. The accuracy of the trajectory data decreases beyond 3 days. Given the successful target acquisition (to date) using TOPO's ISS trajectory and attitude information, ISSAC recommends TOPO's predicted ISS trajectory data for any remote sensing payload operations onboard the ISS. Users who don't have access to TOPO could obtain the ISS trajectory information through NASA – HSF website where ISS positional information is provided in multiple formats and updated thrice in a week (Monday, Wednesday, and Friday).

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