Collaborative Commercial Space Situational Awareness with ESpOC-Empowered Telescopes

David Sibert
ExoAnalytic Solutions, Inc.
T.S. Kelso
Center for Space Standards & Innovation
Bill Therien, Doug Hendrix, Clint Clark, Mark Jeffries
ExoAnalytic Solutions, Inc.
Robert A. Hall
Analytical Graphics, Inc.

ABSTRACT

This paper will demonstrate that by leveraging advanced photometric processing algorithms developed for the Ballistic Missile Defense (BMD) mission, ExoAnalytic and AGI have proven the capability to provide actionable SSA intelligence for satellite operators from small telescopes in less than optimal viewing conditions. Space has become an increasingly cluttered environment requiring satellite operators to remain forever vigilant in order to prevent collisions with their assets and prevent further cluttering of the space environment. The Joint Space Operations Center (JSpOC), which tracks all objects in earth orbit, reports possible upcoming conjunctions to operators by providing Conjunction Summary Messages (CSMs). However due to large positional uncertainties in the propagated position of space objects at the time closest approach, the volume of CSMs is excessive to the point that maneuvers in response to CSMs without additional screening is cost prohibitive. CSSI and the Space Data Center have been able to screen most CSMs by using more accurate operator ephemeris. By screening with operator ephemeris alone they have been able to demonstrate that safety limits will not be exceeded in a good number of these close encounters and that extra delta-V need to not be expended in performing a Collision Avoidance (COLA) maneuver. However there remains a decent portion of alerts that may warrant action especially when the secondary object is an uncontrolled space object without accurate ephemeris data such as a dead satellite or rocket body. By dynamically tasking the ExoAnalytic Space Operations Center (ESpOC) observatories to provide real-time tracking and photometric characterization of the secondary objects in response to these CSMs satellite operators stand to benefit significantly from an additional method of conjunction screening. The refined tracks and conjunction assessments obtained by ESpOC screening allow operators to safely reduce the number of COLAs performed in response to safe close approaches and provide optimized COLA maneuver planning in response to validated threats.

1. LEVERAGING ADVANCED MISSILE DEFENSE ALGORTIHMS FOR SSA

In response to the identified capability gap that remains for SSA at geostationary orbits, ExoAnalytic Solutions has created a software suite and network of telescopes to provide real-time tracking, photometry, and indications and warnings. This system was rapidly developed by leveraging algorithms and software developed over 10+ years in support of the ballistic missile defense mission and other internal research and development efforts. The innovative use of missile defense technology has enabled the ExoAnalytic Team to advance the state of the art in SSA—namely real-time processing, data fusion, and decision-making. For missile defense, data must be processed, exploited, and disseminated in a few minutes. This urgency requires real-time processing of optical images from multiple locations in multiple spectral bands with limited processing power and bandwidth. The speed and flexibility of our algorithms enable real-time decision support for commercial satellite operators.

This paper describes key aspects of the ExoAnalytic Space Operations Center (ESpOC) software suite and describes its planned use to support satellite operators through integration with System Tool Kit's (STK) Orbit Determination Toolkit (ODTK) through collaboration with the Space Data Center. First, we describe the workings of ESpOC software, algorithms, COP (common operating picture), and sample results. Then we discuss its planned use to support satellite operators after validating its operation and data accuracy with astrodynamicists within CSSI.

2. ESPOC OVERVIEW

The ESpOC software suite provides distributed command and control of a network of telescopes and performs real-time processing of the focal plane data. Data feeds from all operating ESpOC telescope sites are sent simultaneously to any number of operations centers or data subscribers. The software performs real-time space object detection, tracking, and association. Associated observations from multiple sites are fused and used in real-time to refine the orbits of space objects. These refined orbits are used to update real-time conjunction screening. The refined orbits are displayed along with any associated indications and warnings and real-time photometric light curves on a full sky augmented reality operational display. Through the ESpOC software remote operators can command long baseline stereo tracking of objects when there is a need for rapid orbit determination such as in response to Conjunction Summary Messages (CSMs), in response to detected maneuvers, or for initial orbit determination on Uncorrelated Tracks (UCTs).

Fig. 1. ExoAnalytic Solutions Manhattan Beach ESpOC Installation

ESpOC processing begins by ingesting raw focal plane data from astrophotography cameras. These data can be:

- Real-time data from a locally connected sensor,
- Real-time data from a remote observatory that is pushing the time registered images over the ESpOC network, and
- Archived focal plane data from past observations that can be reloaded for forensic analysis.

Focal plane registration and calibration. Each frame is instantly processed (< 0.1 s) by our TRL 9 streak-detection algorithm to identify any streaks on the focal plane that are detectable above the noise. The *STARS* star registration algorithm then "learns" which objects are stars by calculating the most common streak length and direction. Each streak identified as a star by this smart filter has its centroid calculated and correlated against a star catalog with full-sky coverage down to magnitude 21 (>900,000,000 stars). Each frame is independently registered with a theoretically achievable uncertainty of 2 μrad, and pixel brightness is calibrated to within 0.1 visual magnitude.

The frame shown in Fig. 2 was registered and calibrated in <0.1 s and each star streak on the focal plane has been identified (white box). Simulated stars (white dots) are aligned with the centroid of each star streak. A Delta 4 rocket body was easily detected despite the streak resembling a star due to differences in its streak characteristics versus the stars. The software has automatically highlighted the object (orange box).

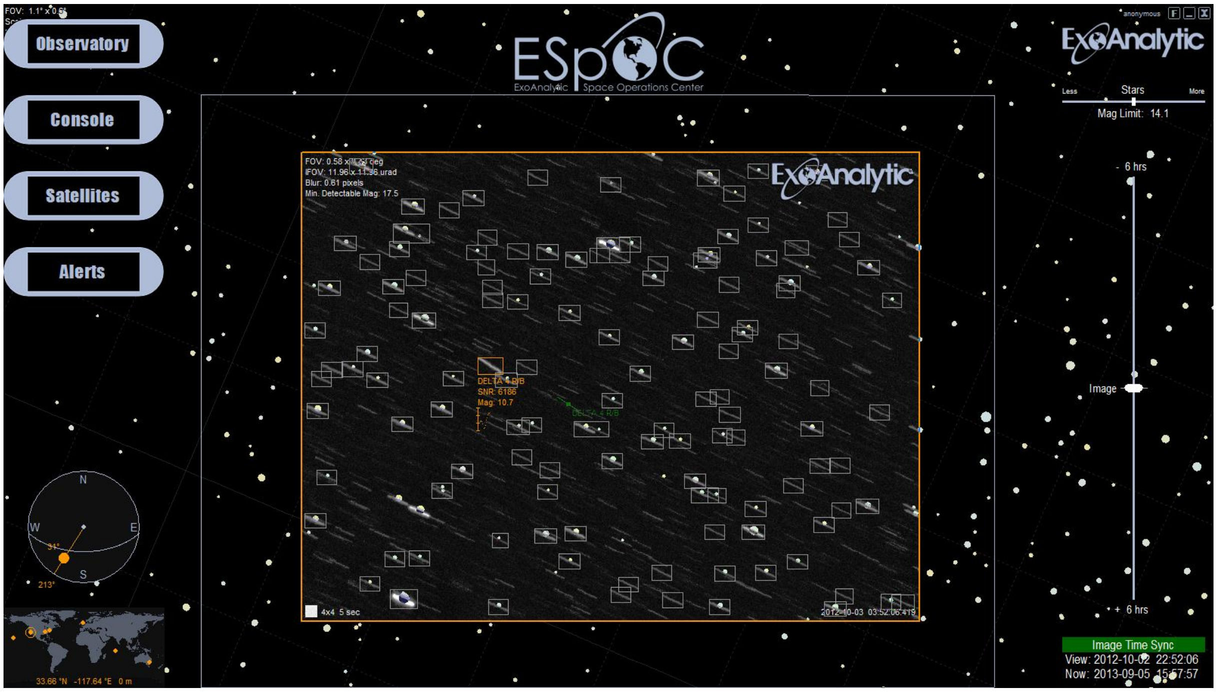

Fig. 2. A single processed focal plane image in ESpOC overlaid on the simulated sky background

Uncued object detection and dim Closely Spaced Object (CSO) detection. Any remaining streaks in the frame not matching a star are identified as Uncorrelated Detections (UCDs) by the software and their centroids are calculated. The RA/Dec to the object and its visual magnitude is recorded to the obs file and the object is visually highlighted for the operator by drawing a colored box around the streak. All streaks, including stars, are then further analyzed for closely spaced objects. The closely spaced objects algorithm is highly optimized and can detect object pairs within the Rayleigh limit with substantial intensity contrast ratios and can support frame rates of over 1000 Hz. Fig. 3 shows an example of the ESpOC CSO algorithm processing an image with a dim simulated object added right next to GOES 15 in a real observation data of GOES 15 and AMC 10.

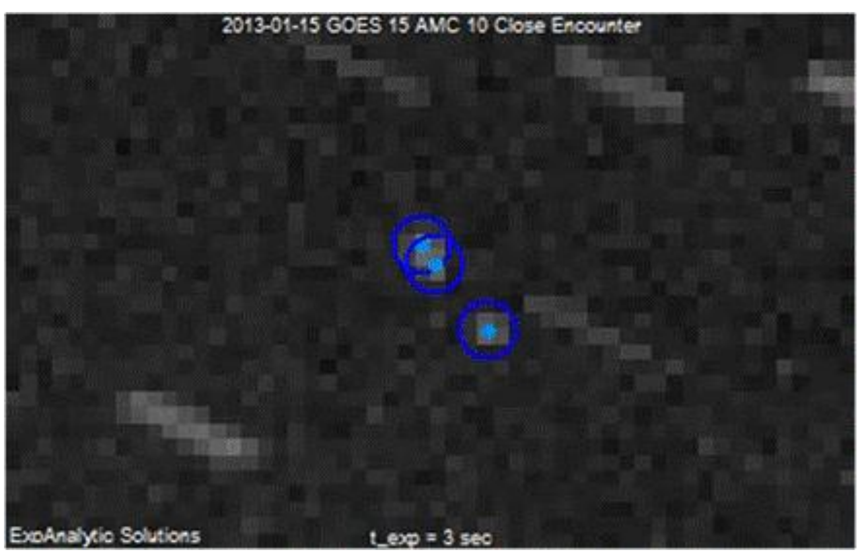

Fig. 3. The ESpOC CSO algorithm processing a simulated object and two satellites

When debris threats or other objects are too dim to be detected in the first frame, the operator has the ability to make real-time adjustments to ensure good collections. First the operator may adjust the integration time for each frame with the software and also has the option of "binning" or combining light from neighboring pixels into a lower resolution image with greater sensitivity. Another option is rerun the recorded image sequence through the Exo *STARE* algorithm. *STARE* utilizes frame-stacking and GPU processing power to discover dim "dots" or "streaks" in a series of images. ExoAnalytic has demonstrated *STARE* through offline processing of ExoAnalytic focal plane data to verify its ability to detect 18th magnitude resident space objects (RSOs) with COTS hardware.

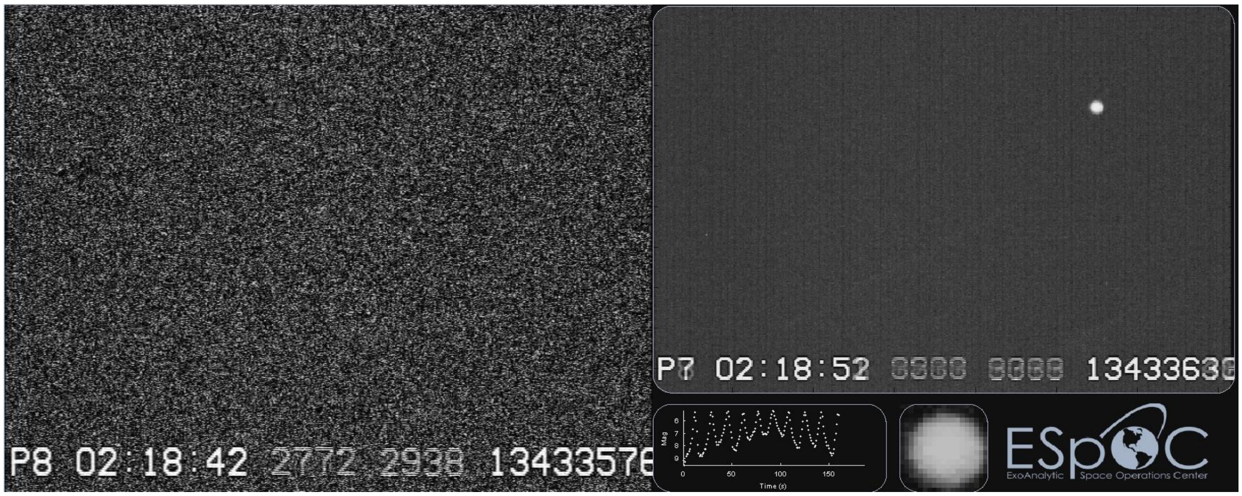

Fig. 4. A single frame next to a STARE produced 60-frame stacked image and light curve of a dim RSO

Accurate angles only measurements. The ESpOC generates angles-only metric observations from focal plane data which has been accurately time resolved using a GPS receiver. Look angles to detected objects are calculated from relative sub-pixel distance on the focal plane from detected stars which have been accurately matched to a high-accuracy star catalog. In this way every single image is self-calibrating and the errors associated with each angles-only measurement and magnitude measurement are estimated based on variations observed on the focal plane.

Raw observations can be output in multiple formats. The basic B3 format records only the time and right ascension and declination from a known sensor site but allows for easy integration with other tools and services and could allow the ESpOC to provide data directly into the existing JSpOC processes in circumstances when JSpOC is open to accept observations from other contributing sensors. More data is recorded in the default ESpOC specific obs file format which records a dynamic position data for mobile observatories and also includes photometric visible magnitudes and error estimates for pointing accuracy and magnitude based on variations observed in each frame relative to the simulated data. This format allows for rapid automated filtering of bad observations that are degraded due to jitter induced by wind gusts or other vibrations and also allows for rapid filtering of photometric values to ignore magnitude measurements from frames that contain irregular cloud cover across the frame. Acceptable observations are archived in the ExoAnalytic observation database and aids in the maintenance of our feature aided object catalog.

Real-time photometry and stability assessments. One of the more powerful features of the ESpOC is the ability to not only record the photometry for a satellite but to perform real-time analysis of the photometry and display real-time stability assessments of objects and display photometric light curves for all detected objects within the frame during a collection. Any anomalous photometry is highlighted in red on the screen and may alert the operator of the need to take more measurements of the object in question or to task other network sensors to look at the object to get multi-aspect photometry.

Object association and catalog maintenance. The ESpOC maintains a combined space object catalog that combines various data sources to calculate expected satellite states based on past track data and orbital perturbations. These data sources include TLEs obtained from Space-Track.org, CelesTrak supplemental TLEs, shared operator ephemeris and telemetry, ESpOC generated data (TLEs, state vectors, vector covariance tracks from ExoAnalytic independent observations), amateur astronomer TLEs, and high fidelity state vectors and TLEs produced by ODTK real-time processing of ESpOC observations. The ExoAnalytic catalog aids in reacquiring RSOs and is an initial input into our autonomous track association algorithm. Any object that has been successfully detected in a registered frame is checked against this combined space object catalog and is automatically tagged with NORAD Catalog Number associated with the best candidate orbit from the dataset. Improper association can be readily detected by an operator with the augmented reality display within the ESpOC which automatically tags detected satellites with their association and metadata. Photometric discrepancies with past observations can often reveal when satellites have been cross-tagged in the space-track data.

Uncued object detection and UCTs. We routinely observe resident space objects that cannot be associated to any object in the combined catalog. ESpOC logs these objects as Uncorrelated Tracks (UCTs) and maintains the UCTs in its internal database of historical observations. Manual processing is required to match UCTs to a lost object in from the satellite database or to associate the objects to a new launch.

3. RESULTS

In this section, we discuss key results that highlight ESpOC capabilities to enable commercial SSA. The results discussed in this section were produced using the ESpOC software suite and images collected using commercial off the shelf (COTS) small-aperture telescopes and astronomical cameras. The COTS telescopes used range from 16” to 4.5” in aperture. The COTS cameras used were an ATIK 383L+ and an ATIK 314L+. With this modest hardware, we have demonstrated ESpOC’s ability to detect anomalous photometry indicative of an attitude change, identification of cross-tags in space-track data for satellites in cluster orbits, and to maintain track of maneuvering uncatalogued objects. Figure 5 below shows three of our COTS hardware configurations, our 16” Dobsonian on the balcony of our Mission Viejo, CA office and two of our portable 4.5” Orion Starblasts which have been deployed and utilized in remote multi-site collection demonstrations in Dayton, OH, Albuquerque, NM, and Maui, HI.

Fig. 5. Example COTS hardware configurations

UCT Events. The next two sections address separate uncorrelated track events that were resolved through analysis using ESpOC.

Successful Data Gathering on a New Foreign Launch. On 15 Jul 2013 at 03:40 local time in Mission Viejo, CA, ESpOC was able to collect on objects launched from China just 1 hour and 13 minutes earlier that were not in any published TLE sets. Fig. 6 shows one of the collections soon after launch. In addition to angles measurements the photometric analysis of the streaks in the frames revealed the objects rotation rate.

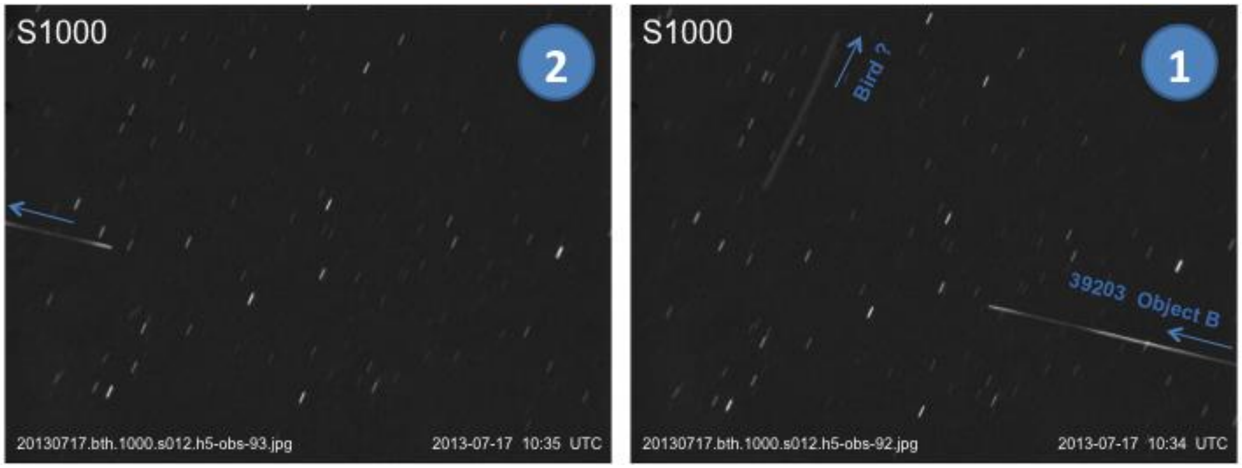

Fig. 6. ESpOC collection of Shijian 11-05

Multiple Asteroids Detected in One Night During Search for Dim Objects. ESpOC is currently optimized to observe and collect information on man-made satellites in near-Earth orbits. NEAs, however, provide unique opportunities to test and verify our uncued dim object detection capabilities. On 24 April 2013 at between 20:45 and 23:00 local time in Mission Viejo, CA, ESpOC detected multiple near-Earth asteroids (NEAs). During the test observations, ESpOC detected 1 Ceres, 9 Metis, and 192 Nausikaa. Telescopes were intentionally pointed to the expected locations of the three known NEAs to test our algorithms. Fig. 7 provides a screenshot from our detection of 1 Ceres.

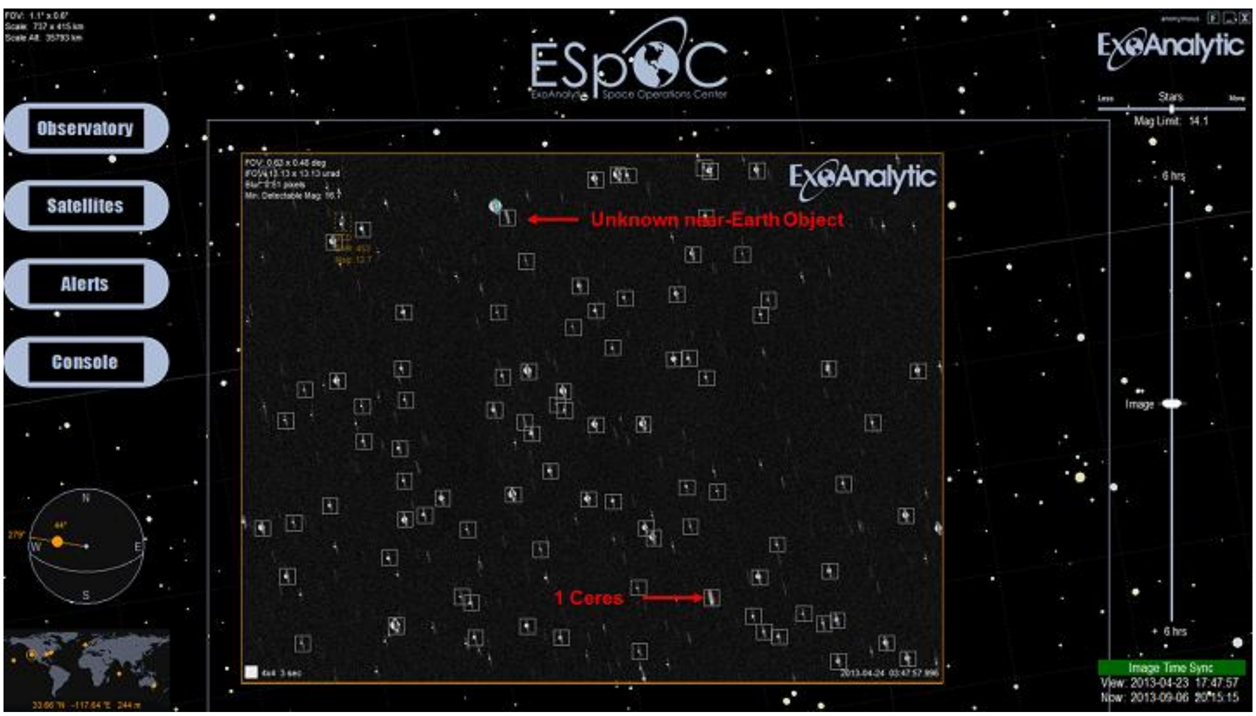

Fig. 7. One asteroid and a star that was initially mis-identified as an unknown NEO in one field of view

Observation accuracy and consistency. The frame registration, pointing angles, object association, and magnitude are calculated independently for each object in each frame based on different star backgrounds. Our output and analysis show remarkable consistency and accuracy beyond what one would expect from such modest telescopes. This is due in part to the high accuracy of our timing which we get directly from a GPS receiver and the accuracy of our star catalog (900 million stars with ~1 μrad error). Fig. 8 below shows an analysis of residual from obs collected on our first prototype ESpOC system in February 2013. The residuals for three different satellites which were tracked in 5 separate observation periods over a one night 7-hour span. The residuals were well clustered within 5–10 μrad but systemic biases were revealed in the consistent offset pattern observed between intervals which were traced to issues in our first attempt at automated orbit determination. Analysis of outliers also revealed issues caused by edge cases with our early method of star registration. As a result of this analysis we adapted our algorithms to use all suitable stars within the frame for registration initiated collaboration with AGI to create an ODTK module which can run in-line with the ESpOC. Initial analysis indicates that these algorithmic improvements may yield residual variances closer to 2 μrad which approaches the limits of our current star catalog. While this has shown that our measurements are internally consistent there is still potential for bias. The ESpOC team is working closely with both CSSI and AFRL/RV to identify remaining errors and bias in our obs measurements and validate the angles only measurements that are generated by the ESpOC by comparing observations with known "truth" ephemeris for some satellites.

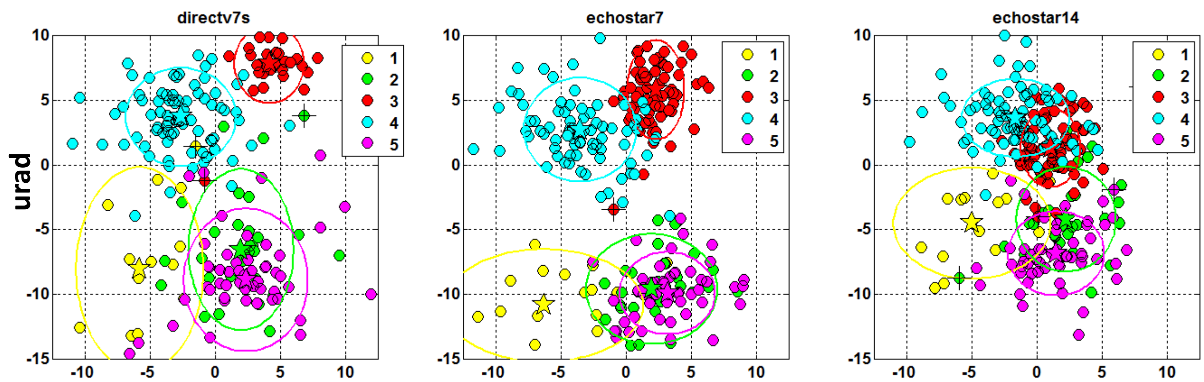

Fig. 8. Plots of residuals for 3 satellites in the same FOV. Color coded by observation interval (five separate tracking periods during a 7-hour span

Real-time conjunction analysis—improved track accuracy prior to conjunction. The ESpOC can be responsively tasked to track secondary objects in CSMs but the ESpOC also performs automated all-on-all conjunction analysis based on its more complete combined space object catalog. Fig. 9 below shows observations during one such identified close approach that was internally flagged for investigation by the ESpOC. On 13 Jan 2013, Space Track TLEs indicated that there would be a 4.4-km close approach between GOES 15 and AMC 10. Our observations and refined orbits showed that there was indeed a close approach but that the TLEs were inaccurate. The ESpOC software calculated a miss distance of ~10.1 km using the ESpOC-refined orbits which were continually updated by a Kalman filter by using observations taken of the satellites during the time interval leading up to the conjunction. While the satellites were safe this time, the fact that the miss distance was within the errors observed relative to the Space Track TLEs for each object is worrisome. ESpOC now has the ability to also display and use operator ephemeris in addition to orbits derived from two line elements. When this data is overlaid with our observations bias and errors in various data sets can be immediately revealed.

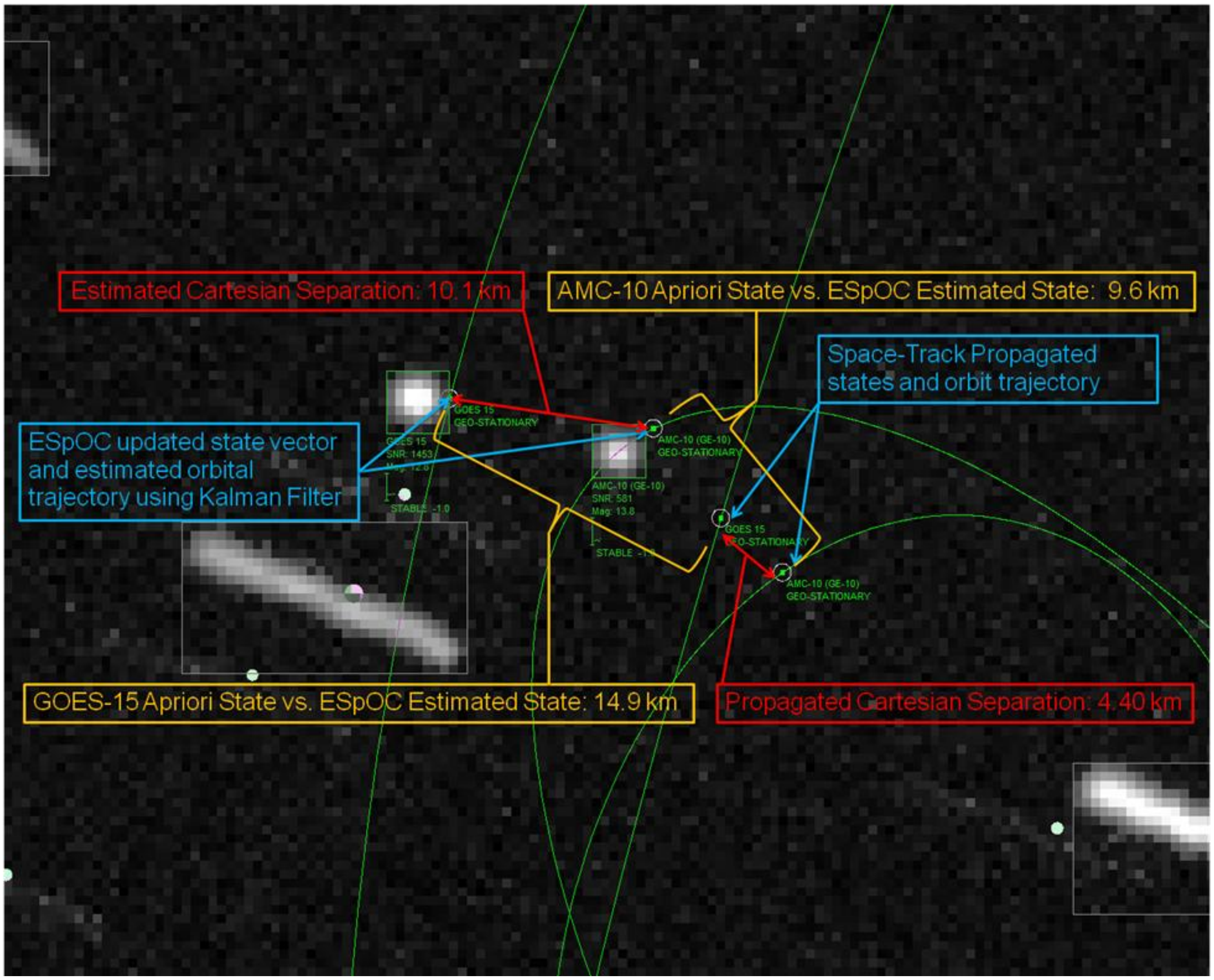

Fig. 9. A close up view of GOES 15 and AMC 10 as they were tracked during a close approach

4. CURRENT WORK

Validation of tracking accuracy against known ephemeris. Parallel work is being conducted with AFRL/RV and with select satellite operators in the Space Data Association to compare ESpOC+ODTK derived orbits with known ephemeris from satellite telemetry. This data will be used to identify and eliminate remaining sources of bias.

Integration with ODTK. The real-time refined orbits generated via a Kalman filter inside the ESpOC are useful to maintain track on an object that has maneuvered or had a bad TLE and to preventing cross tagging in cluster orbits. But higher accuracy determination of the satellite state vector is desired and possible for aiding conjunction assessment and collision avoidance planning. Working collaboratively with AGI and CSSI, a prototype real-time integration of ESpOC with AGI's Orbit Determination Toolkit (ODTK) has been attempted. ESpOC real-time observations are read by CSSI-developed middleware that ingests ESpOC observations directly and processes them into ODTK the second that they are generated. These observations are then run through initial orbit determination algorithms and batch differential correction processes to determine accurate refined orbits with covariance estimates. These resulting state vectors and covariance can readily be used by Systems Tool Kit (STK) Conjunction Analysis Toolkit to perform refined probability of collision calculations. In the event of high-probability of collision these data can be used directly within the STK model to analyze various courses of action an operator could take to minimize total delta-v usage by optimizing the maneuver to reduce the probability of collision while also reducing the future delta-v required for station keeping post maneuver.

Maneuver-detection testing. The ESpOC has already demonstrated the ability to make uncued detections maneuvering objects and correctly associate and maintain track of uncatalogued as they perform radical station change maneuvers, however we have not yet been able to verify the minimum-detectable threshold for maneuvers. The Intelsat supplemental TLEs distributed by CelesTrak include upcoming stationkeeping maneuvers for their fleet. We plan to observe these objects as they carry out small stationkeeping burns to determine if our algorithms can successfully perform maneuver detection and recovery.

5. CONCLUSIONS AND VISION OF POTENTIAL APPLICATIONS

By bringing together complementary key technologies that each company has mastered, ExoAnalytic Solutions and AGI have established a promising new SSA capability. The software suite described can be used to maximize the tracking accuracy, responsiveness and utility of any telescope running the software. We have demonstrated that an ESpOC-equipped low-end consumer telescope can generate data of sufficient quality to be a contributing sensor for SSA. A large network of such low-cost sites could remove many of the limiting factors that currently plague deep-space observation: lack of geographic diversity, local weather viewing restrictions, a limitation on the number of objects that can be tracked at any given time, and long revisit intervals required due to limited time available across tracking assets. When combined with the real-time ODTK module, these sites can provide real-time actionable data that can be used for course of action analysis and maneuver planning. Rather than having to wait hours for new TLEs to be published, anyone subscribing to the ODTK data feed would have instantaneous orbits for objects with the orbit fidelity that is possible from ODTK. It is the hope of the authors that telescope operators will consider integrating the software suite, that commercial satellite operators will task the network for SSA when needed, and that Space Command and other organizations will consider integrating a network of low-cost sites with this capability into their space surveillance architecture.