USAF Academy Center for Space Situational Awareness

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ABSTRACT

Since the days of Sputnik, the Air Force has maintained the surveillance of space and a position catalog of objects that can be tracked by primarily ground-based radars and optical systems. Recent events in space such as the test of the Chinese anti-satellite weapon in 2007 and the collision between an Iridium and Russian Cosmo satellite have demonstrated the great need to have a more comprehensive awareness of the situation in space. Hence space situational awareness (SSA) has become an increasingly important mission to the Air Force and to the security of the United States. To help meet the need for future leaders knowledgeable about SSA, the Air Force Academy formally stood up the Center for Space Situational Awareness (CSSAR). The goal of the CSSAR is to provide a unique combination of educational operational experience as well as a world-class research capability for hands-on education in SSA. In order to meet this goal, the CSSAR is implementing an array of sensors, operations center, and associated software, and analysis tools. For example we have radar receivers for bi-static returns from the VHF space fence, a network of small aperture telescopes, AFSPC astro standards software, and Joint Mission System software. This paper focuses on the observational capabilities of our telescopes. In general, the preferable method for characterizing a satellite is to obtain a high-resolution image. However, high-resolution images from ground-based telescopes are only achievable if the satellite is large and close in range. Thus small satellites in low-earth orbits and large satellites in geosynchronous orbits are essentially unresolved in the focal plane of a ground-based telescope. Building ever larger telescopes capable of tracking fast enough for satellites at high resolution requires tremendous resources and funding. Cost is one of the reasons we decided to develop a network of small, commercially available telescopes spatially diverse and networked together. We call this the Falcon Telescope Network (FTN) and it provides the Air Force Academy, Air Force and Department of Defense with a unique capability that is essentially non-existent in today's research and operational environment. With the FTN we will have the eventual capability to conduct simultaneous observations of satellites for non-resolved space object identification (NRSOI). We present preliminary photometric and spectroscopic observations from LEO to GEO satellites. The Air Force Academy has a unique mission to educate future leaders in the science, technology, and operations in missions critical to the Air Force and the CSSAR is stepping up to meet these requirements for the SSA mission.

1. INTRODUCTION

The United States Air Force Academy (USAFA) in Colorado Springs, Colorado is a four-year undergraduate school of approximately 4000 cadets with the mission to educate, train, and inspire men and women to become officers of character motivated to lead the United States Air Force in service to our nation. Upon graduation, cadets receive both a Bachelor of Science degree and a commission in the United States Air Force. The academic requirements for all cadets involve a heavy core curriculum including two semesters of physics as well as a disciplinary major. The science and engineering major curriculums have achieved high-impact research opportunities by establishing research centers embedded within the culture of academic departments to provide opportunities for all.

These research centers form a foundation to implement a physics capstone research experience with the goal that students learn to contribute to the physics body of knowledge through research & become more confident independent thinkers, capable of forming/defending scientific viewpoints, as well as gaining enthusiasm for conquering unknown in science. Students "do what physicists do"—conduct original inquiry/ research to understand a physical phenomenon and generate new knowledge. Projects are directly relevant to Air Force and Department of Defense interests and each student team must produce publication quality paper & a poster presentation. For physics majors, a research requirement is formally implemented with the following required courses: Physics 490, Capstone Physics Research: (5 contact hours/week); with concurrent enrollment in Physics 405, Physics Seminar (1 contact hour/week.)

In addition to the courses above, other research opportunities exist and are supported by the research centers, through independent research courses. The infrastructure of the research centers is also leveraged to enhance the learning in courses that have a laboratory component. Examples are Physics 371-Astronomy, Physics 375-Space Situational Awareness, and Physics 482-Laser and Optics.

One area of research that is of importance to the nation is known as space situational awareness (SSA). More and more nations are finding the advantages of owning and controlling satellites customized to their needs. At the same time miniaturization in electronics has brought both satellite cost and accessibility within the reach of most nations. Characterization of these satellites (inferring fundamental properties via scientific methods) is a discipline actively under development. In light the importance of SSA to the nation, through the physics department, USAFA has chartered the Center for Space Situational Awareness Research (CSSAR). CSSAR is a centerpiece for developing a program to further develop SSA and improve the quality of science and engineering education at USAFA. This paper discusses the capabilities and initiatives we currently have and the ones we are developing for SSA education.

2. CURRENT CAPABILITIES

The U.S. Air Force Academy has two operational telescopes on campus, an f/15 24-inch (61-cm) and an f/8 16-inch (41-cm) Cassegrain reflector telescope (Figure 1). Both telescopes are over 20 years old and were acquired primarily to support cadet education and research in astronomy. Although the telescopes have primarily been used in the past to support cadet classes in astronomy, in recent years, cadets have begun using them for SSA research. Within the past year, we have upgraded the 16-inch telescope to allow it to track low-earth orbiting satellites. We are using an Apogee U47 camera and Johnson filters to make photometric measurements. We have also begun slitless spectroscopic observations using a 300 lines/mm diffraction grating. The plan is to make the 16-inch telescope remotely operable and to this end, it has a radio controlled dome. This telescope will allow us to develop procedures applicable for operating a network of telescopes.

Fig. 1. A 24-inch (left) and 16-inch (right) telescope at USAFA.

3. CAPABILITIES IN DEVELOPMENT

USAFA is in the process of acquiring five 20-inch telescopes with identical instrumentation. Four would be located in the state of Colorado at Ft. Lewis College in Durango, Colorado Mesa University in Grand Junction, Northeast Junior College in Sterling, and Otero Junior College in La Junta. The fifth telescope will be located at the municipal Mamalluca Observatory in Vicuna, Chile. Figure 2 depicts the location of, and baselines between, the Colorado telescopes. These telescopes are funded by the Defense University Research Instrumentation Program administered by the AF Office of Scientific Research. These five telescopes, along with the current 16 inch telescope at USAFA will form the Falcon Telescope Network (FTN). The FTN will be ideally suited for research in techniques leading to the identification and characterization of unresolved space objects. The 5 locations allows for 10 different baselines at 10 different and unique orientations providing opportunities to observe a wide range of satellite orbits simultaneously. With only a pair of telescopes, one will overly constrain the illumination and observation geometries and run the risk of both telescopes being weathered out at the same time.

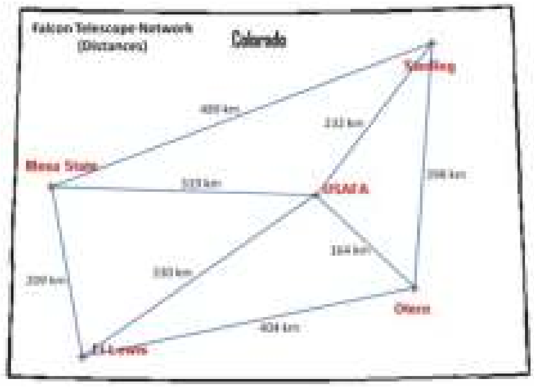

Fig. 2. Location of proposed telescopes in Colorado and corresponding baselines.

Locating a telescope in Chile provides opportunities to perform cue and hand-off operations as well as simultaneous observations. As an example, Colorado and Chile align fairly well along the terminator during the solstices as seen in Figure 3. During June, the dawn terminator aligns with Colorado and Chile, while in December the evening terminator aligns with the two locations. Analysis shows that under the right lighting condition, telescopes in Colorado and Chile will be able to simultaneously observe the same satellite (assuming a 20° elevation angle at the telescope site) with an altitude greater than 6,500 kilometers (see Figure 3). Thus it will not be possible to conduct simultaneous observations of low-earth orbiting satellites.

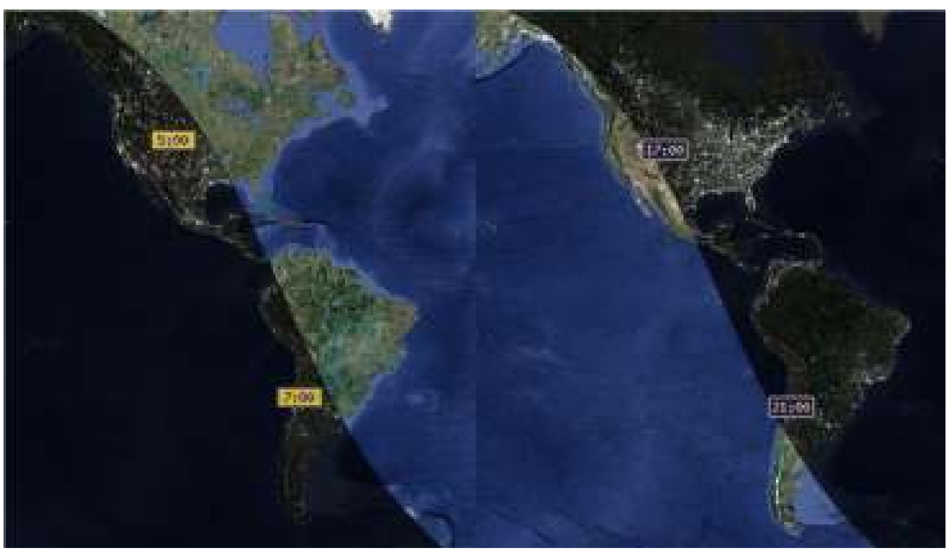

Fig. 3. Terminator on June 21, 2010 at 5:00 am MDT (left panel) and Dec 21, 2010 at 5:00 pm MST (right panel.)

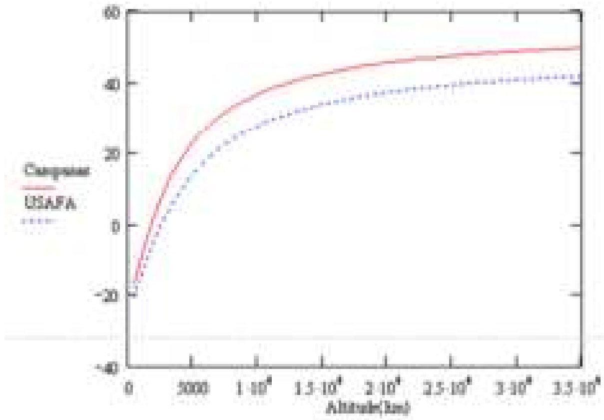

Fig. 4. Analysis of the elevation angle from Las Campanas, Chile and USAFA. At 20° elevation, any satellite above 6,500 kilometers is visible from both sites.

Details of the telescopes we plan to acquire would be 20-inch (51-cm) f/8.1 RC Optical Systems telescopes. The optics would be zero expansion Astro-Sitall tested and certified to at least 1/25th wave RMS with enhanced aluminum (SiO_2/TiO_2) overcoat and a 96.9% reflectivity. The mechanical features include low expansion, light weight carbon fiber truss, and 6061 aluminum components that are all CNC machined. There will be a precision secondary mirror focuser (to 1/40,000 of an inch per count), multi-stage primary mirror baffle with internal knife-edge light stops, conical secondary light baffle, 6061 aluminum mounting rings, active cooling, focus and forget technology, and adaptable to Paramounts. Each telescope will have a Losmandy RDF-90 finder scope 3-point mounting bracket to support a Takahashi - FSQ-106 New "Q" wide field refractor. We propose Paramount MEs from Software Bisque which can typically achieve one arcsecond peak-to-peak or less tracking performance after periodic error correction is applied. Additionally, the Paramount ME can achieve repeatable, quantifiable pointing accuracies from 10 to 30 arcseconds RMS. These pointing accuracies, in our experience, are sufficient to acquire and track satellites using Celestrak ELSETS. The telescopes will be housed in an observatory with a 12-foot clam-shell dome and will have identical cameras and control systems to mitigate and reduce operations and calibration. This collection of equipment (to include a weather station, cloud monitor, UPS, and an iBoot device) is specifically designed for remote robotic telescope operations. All of the proposed components and software of the Falcon Telescope Network are commercially available.

In addition to the fixed sites we have also in the process of setting up two mobile fast-tracking telescopes. This effort is in partnership with the Arnold Engineering and Development Center.

Fig. 5. USAFA 20 inch fast-tracking mobile telescope.

We have one trailer that has been delivered with a second trailer planned for purchase when funds become available. In Figure 5, one can see how the walls of the trailer can be lowered for observing. The mount for the telescope can be decoupled from the trailer by lowering legs from the mount to the ground and then using built-in hydraulic lifts to isolate the trailer from the mount. Instrumentation for the mobile telescopes includes a two channel polarimeter, photometric filters and back illuminated cameras. Planned concepts of operations are to take simultaneous polarimetric/spectral measurements from at least two telescopes at the same location or relocating the mobile telescope for simultaneous measurements from different locations. The telescopes are the same telescopes as those proposed for the fixed sites and discussed above. However, instead of Paramounts controlled by The Sky software, these mobile telescopes have alt-az mounts operated with proprietary RC Optical control software.

4. CADET EDUCATION AND THE CADET SPACE OPERATIONS CENTER

We have developed a new physics course, Physics 375, Physics of Space Situational Awareness. The course is an overview course covering both optical and radar sensors. Using our two operational telescopes, we have developed laboratories on orbit determination and photometry. The course includes several guest lecturers adding relevancy and motivation to the course material. One guest lecture is from the National Reconnaissance Office which offered cadets a classified glimpse into the world of satellite reconnaissance. Other guest lecturers were from Air Force Space Command (AFSPC) which provided cadets an understanding of the natural space environment and its impact to satellite operations, and commander of AFSPC 21st Operations Group to discuss the space surveillance network.

The Cadet Space Operations Center (CSpOC) is envisioned to be a central control room from which cadets will be able to remotely task USAFA sensors, perform data analysis, and maintain a space catalog of a limited number of known objects. In the CSpOC cadet space operators will be able to maintain a SSA catalog and manage a SSA sensor network for both an education/research purpose and a training purpose. The cadet SSA catalog will go beyond the operational catalog and include satellite characterization and capability information instead of just orbital information. Cadets will have the opportunity to develop algorithms and write software that can be used to analyze collected data. The CSpOC will be used as a SSA test bed for CSSAR and its partners, and will have an operational software foundation.

Current government software tools available used by the CSpOC are the astrodynamics standards software developed and used by AFSPC/A3/A9 that includes routines to do initial orbit determination, orbit propagation, look angle calculations, and conjunction analysis among others. We also are running an unclassified version of the Web Integrated Space Situational Awareness (Web ISSA) tool developed by personnel at the Space Innovation and Development Center. Among other things, this tool provides excellent visualization tools.

In addition to the government software, we are using a multitude of commercial tools in the CSpOC for image analysis, programming, control of hardware such as the telescopes and cameras. For example, these include STK, CCD Soft, and The Sky. Finally, using Matlab, we also have also developed in-house software for data analysis.

Software and data are hosted on a server and accessed via remote terminals. The server hardware is on permanent loan to the CSSAR by MITRE.

5. PLANNED OBSERVATIONS/ANALYSIS

With our 16 inch telescope, we are able to track LEO satellites and are now collecting photometric data and producing absolute magnitude light curves. A typical image is shown in Figure 6. The satellite is the point of light in the middle of the image. The light streak to the left of the satellite is a star streak (since we are operating in satellite track mode.) All photometric data collected to this point has been done with Johnson filters. Future work will include measurements with Sloan filters.

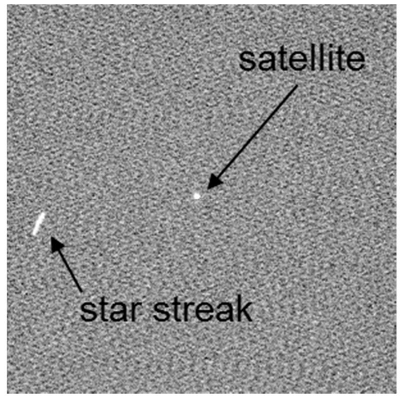

Fig. 6. FITS file image of SL-8 made by CSSAR using 16 in telescope on August 11, 2011.

In analyzing the image, one must take care to characterize the instrument's sensitivity over time as well as changes in the atmospheric extinction through which the object is observed. We collect reference stars throughout an observation night to determine the extinction as a function of airmass, and hence elevation angle. An example curve is shown in Figure 7. This was a "good" photometric night for which the linear fit line covariance for the slope and y-intercept were 0.001 and 0.003 magnitudes respectively. For comparisons sake, a poor night (due to intermittent wispy clouds) had uncertainties of 1.2 and 2.5 magnitudes.

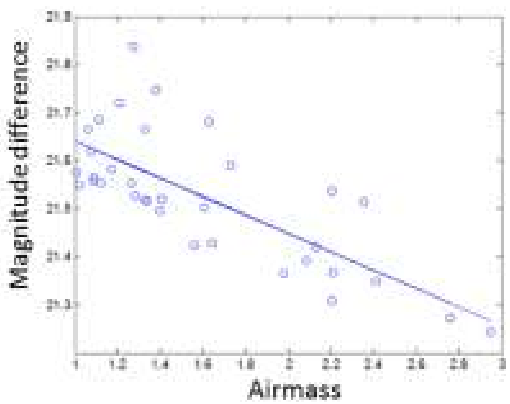

Fig. 7: Magnitude difference between star catalog value and instrument value versus airmass (taken on August 23, 2011.)

Cadets involved with the CSSAR performing research will investigate how to get information from a photometric signature. On way is by using forward modeling of signatures and the inversion of an observed signature. In general, a satellite's photometric signature is a function of its body parameters and its attitude parameters [1]:

$$F_j = F\left(t_j, p_{body}, p_{attitude}\right) \tag{3}$$

Where p_{body} are all the parameters needed to calculate the flux reflected from the satellite body from within the body frame and $p_{attitude}$ are all the parameters needed to describe the satellite attitude with respect to the Earth-centered inertial frame for all observation times. Inverting a satellite's light curve could involve a tremendous amount of computation. Some assumptions have to be made in order to minimize the parameter space to search in order to replicate the observed light curve. Cadets will use a priori information or assumptions about the satellite shape and attitude when performing their analysis. Examples of two light curves of an SL-8 rocket body, collected on two consecutive nights, are shown in Figure 8. These Figures are very similar, but that is not necessarily the case for the same space object on different passes. The light curve will depend on viewing geometry as well as the space object attitude and this will be an area of research for the cadets. In the Figure error bars are shown. This error is the quadratically added error of the extinction curve fit and the single measurement error in the observed satellite. The observed error is taken to be,

$$\sigma_{se} = 2.5log\left(\frac{1}{SNR} + 1\right)$$

where SNR is the signal-to-noise ratio taken to be,

$$SNR = \frac{signal}{\sqrt{signal + pixnoise^2}}$$

Collection of satellite light curves over a wide range of observation parameters will form a "photometric" catalog.

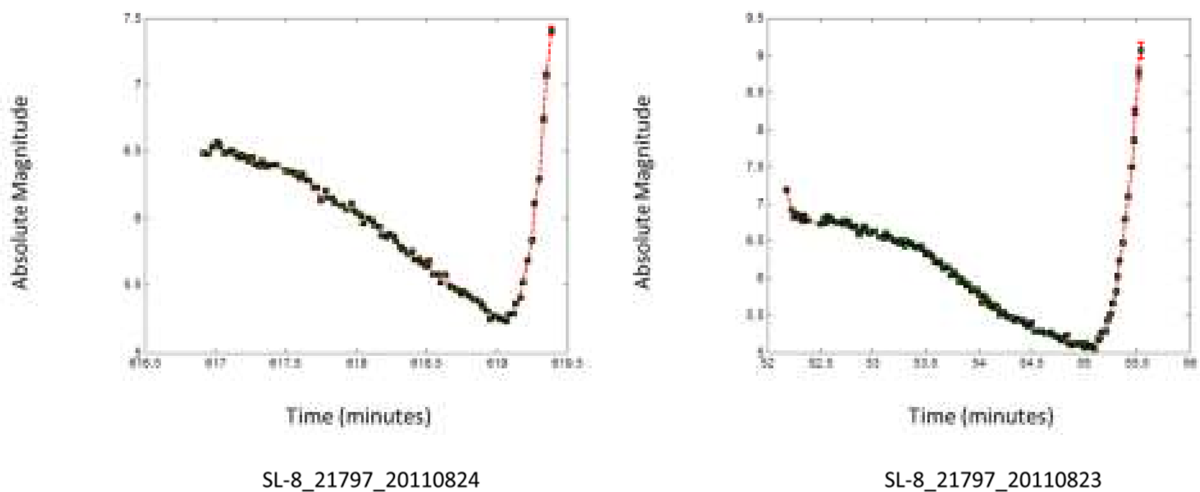

Fig. 8: Consecutive nights of photometric observations of SL-8 R/B (SSN 21797).

Observational data is stored in text files and stored on a CSpOC server.

Another class of satellites which can be observed by either of our current telescopes is the geosynchronous satellites. Geosynchronous satellites are ideal candidates for unresolved signature analysis because they are simply too far away for any ground-based telescope to produce resolved imagery. Many of the geosynchronous satellites are large with very large solar array panels, and under certain lighting conditions, will glint brightly. Part of the CSpOC catalog will include geosynchronous satellites and cadets will be asked to plot brightness as a function of solar phase angle. One benefit of observing a satellite's brightness as a function of phase angle is identifying potential anomalies. Satellite operators usually keep their solar panels pointed toward the sun. Therefore, at zero phase angle, one would expect to see the maximum brightness. However, it has been reported by others that from these curves it is possible to determine that the solar panels are offset in pointing relative to zero phase angle [2].

The time-varying photometric signature or light curve can also be used to determine if a space object is rotating. For example, Figure 9 shows an SL-8 rocket body and periodic fluctuations in the light curve are clearly evident. A simple analysis of this light curve indicates a periodic fluctuation of 1.5 minutes.

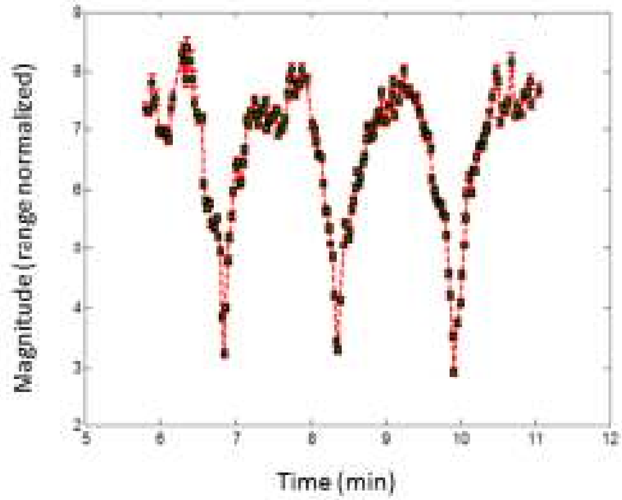

Fig. 9: Periodic fluctuations in SL-8-36520 light curve observed August 8, 2011.

Cadets will analyze this type of data more thoroughly to determine synodic periodicities. Others have shown that knowing these periodicities, one can determine the objects spin axis orientation and sidereal angular rate.[3] In addition to photometric measurements, we will collect spectral measurements as well.

If one shifts his view from the time or frequency domain to the spectral domain, the potential of extracting information spectrally which may be very useful in deciphering signature content of an unresolved source becomes available. Signature decomposition uses measurements at discrete wavelengths and in principle are not time constrained.

Radiation from unresolved multiple sources is simply the linear superposition of the signatures of its component sources. The expected value of the measurements can be expressed in the form

$$E(\lambda_i) = \sum_{j=1}^{m} K(\lambda_i)_j N_j \qquad (i=1,2..,k)$$

where

$E(\lambda_i)$	is the expected value at wavelength λ_i
$K(\lambda_i)$	is the intensity of model j at wavelength λ_i
N	is the number density of class j
m	is the number of models available
k	is the number of measurements
i	is the measurement counter (1..k)
j	is the model counter (1..m)

In this application the kernel $K(\lambda_i)$ constitutes a reference or design matrix containing spectral signatures as a function of wavelength and component class for a predetermined set of components. The matrix is constructed such that all possible combinations of classes with the predetermined set are considered. Since the component classes of all the models are implicitly referenced in the design matrix, the only unknowns are the *N* terms which can be interpreted as the number density. The spectral resolution problem is described in matrix form as

$$\overleftrightarrow{A}\vec{x} = \vec{b}$$

where $\overleftrightarrow{A}$ is the design matrix

$$\overleftrightarrow{A} = \begin{pmatrix} K(\lambda_i)\ _{1;j=1} & \cdots & K(\lambda_i)\ _{1;j=m} \\ \vdots & \ddots & \vdots \\ K(\lambda_i)\ _{k;j=1} & \cdots & K(\lambda_i)\ _{k;j=m} \end{pmatrix}$$

and $\vec{x}$ is the solution vector and $\vec{b}$ is the data array. In principle, inversion of this matrix will contain number densities at vector locations where the presence of that class is indicated. Using this analysis, similarly to a "photometric" catalog, cadets will maintain a "spectral" catalog on a limited set of objects for satellite characterization.

This approach to characterization has the potential of providing additional satellite morphology for unresolved objects. When considering morphology, the issues becomes more convolved as the number of classes increase. However, satellites by design have a minimum set of components that are visible (e.g., solar panels, communication antennas, and Kapton/gold foil) thus the problem should be contained with a small number of potential components. This is a rich area of research which cadets will pursue.

For example, consider geostationary satellites—since a geosynchronous satellite stays over a given location on the earth, the solar phase angle changes with time as the earth rotates. As mentioned before, most (if not all) geosynchronous are powered by solar panels so the satellite must constantly change the solar panel angle to the sun to maintain proper power. A proper decomposition would isolate the solar panel contribution to the signature, thus as a function of phase angle the solar panel signature would vary from a minimum phase angle of 90 degrees to a maximum. At maximum phase angle the contribution of the solar panels to the signature should indicate their relative size. Comparison of satellites with similar structures that differ in solar panel size (power) may provide a means to calibrate solar panel size with available power. This would provide a means to estimate available power on unresolved satellites where little is known. Additionally, once the solar panel vs. phase angle contributions are well known for a given satellite only sparse observations are needed to verify that the satellite has sufficient power. Since the spectral measurements can be simultaneous or in high frequency, temporal cadence glints should not be an issue as they can be omitted from the final measurements.

We will examine if the data collected by slitless spectroscopy is sufficient for this methodology. This method uses a diffraction grating to disperse the light onto a CCD camera. Examples of slitless spectroscopic observations are shown in Figure 10. There are two geosynchronous satellites in each image. The arrows label the satellite and point to the zero-order grating lobe which can be used as a reference point. The lines directly below the zeroth order is the first order diffraction pattern which contains the spectral signature. The streaks in each image are spectral signatures of stars.

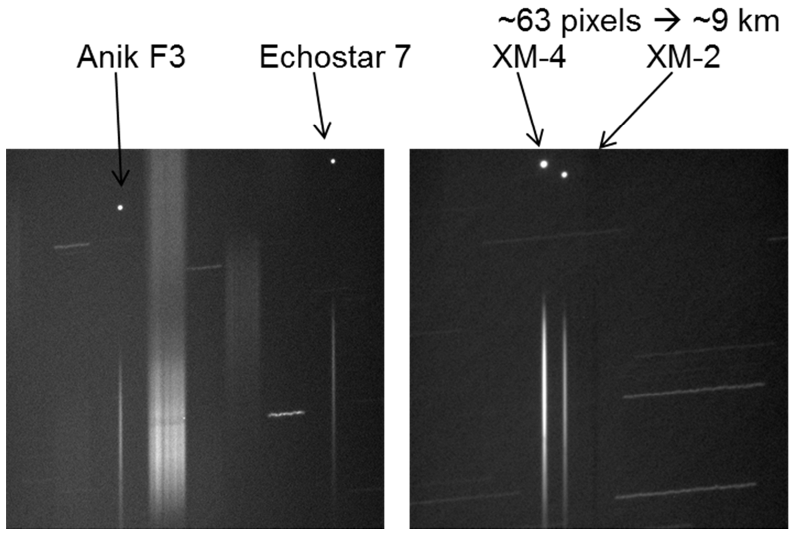

Fig. 10: Two examples of slitless spectroscopy images of four geo-satellites.

6. CONCLUSIONS

The Academy and CSSAR have invested in three areas for SSA education: 1) the development of a network of small, robotic telescopes called the Falcon Telescope Network, planned to be shared with both U.S. and international university partners, 2) the implementation of a Cadet Space Operations Center where cadets will maintain a catalog of satellites for education purposes, and 3) development of a new academic course in space situational awareness available to all cadets who have completed their core physics courses. These three investment areas form the core of a unique SSA learning environment that to our knowledge currently does not exist at any undergraduate school in the world.

7. ACKNOWLEDGEMENTS

We would like to thank our partners, Space Innovation and Development Center, ESC, MITRE, Arnold Engineering and Development Center, AF Space Command/A9, AFOSR, AFRL/RV (MESSA) and the Defense Advanced Research Projects Agency.

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