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DETECTION VIA PERSISTENCE: LEVERAGING COMMERCIAL IMAGERY FROM SMALL SATELLITES

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Abstract: Detection via Persistence: Leveraging Commercial Imagery from Small Satellites

Sandia National Laboratories and BlackSky Geospatial Solutions Inc. are engaged in an exploratory effort to examine how the capabilities emerging in the small satellite industry, combined with the unique remote sensing and analytical capabilities at a U.S. national laboratory, can improve remote proliferation detection (PD) and other fields such as safeguards. The effort seeks to leverage capabilities such as adaptable, automated, high-sampling over surrogate sites with increased frequency and rapid revisit rates based on events unfolding on the ground. Such capabilities could be utilized for pattern-of-life analysis or to detect key remotely observable signatures such as the construction of facilities not included in an onsite inspection or a safeguards design information questionnaire. Companies such as BlackSky are developing the next generation of small satellite systems capable of collecting those signatures. Distinguishing factors of BlackSky include their rapid revisit rates (up to 30 imaging opportunities/day by 2020), individual satellite tasking, and publicly accessible, low cost images, delivering 1-m resolution shots at $400/image or less. The increased revisit rates will allow constellations to conduct near real-time activity monitoring of specific geolocations. BlackSky and Sandia also have unique data fusion capabilities. BlackSky can collect large numbers of images, produce correlating reports with photos, create custom alerts, and allow customers to task their satellites if an image is not archived. Sandia maintains strong nonproliferation and data analytics expertise, particularly in nuclear safeguards, pattern of life analysis, change detection, remote sensing data acquisition, and modeling and simulation. The paper explores a public-private partnership that leverages these unique capabilities to provide access to mature, deployed technology that, if successful, could expand the tools and techniques for safeguards at a fraction of the cost of current government-sponsored systems for a fixed period of time, freeing governments from long-term, costly and oversubscribed programs.

1. INTRODUCTION

Commercial satellite imagery has long been an important resource for nuclear non-proliferation and international safeguards. Such images from commercial earth observation (EO) satellites provide relevant open source data for the increasingly information-driven IAEA safeguards regime. The main applications of satellite imagery are to verify the correctness and completeness of the member states' declarations, and to provide preparatory information for inspections, complimentary access and other technical visits [1]. Between the late 1990s and mid-2000s, large commercial satellite companies dominating the market such as GeoEye and

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DigitalGlobe provided EO satellites in sun-synchronous orbits. Sun-synchronous orbits maximize the satellites' time spent in daylight, but results in low-revisit over specific sites at a rate of approximately one image per week. A critical reason for the lower revisit rate, as compared to higher projected revisit rates such as four to 30 images per day, is to take advantage of available light in mid-morning and mid-afternoon hours when shadows and light variations can be minimized. Between 2010 and today, however, several commercial start-ups have emerged with a charter to develop smaller, cheaper EO satellites capable of more rapid, persistent imaging combined with varying pass over times and the potential to deliver multiple images per day. The increased revisit rate is the result of larger mid-latitude constellations operating in low-earth orbit which are capable of making passes over target locations multiple times per day. One such start-up, BlackSky Geospatial Solutions [2], a subsidiary of SpaceFlight Industries, is playing a key role in bringing rapid, persistent imagery as well as unique open source analytical tools to the market at a fraction of the cost of current government-sponsored systems. The public-private partnership between BlackSky and Sandia National Laboratories (Sandia) is an effort to explore how some of these emerging capabilities will impact the non-proliferation mission space today and in the near future.

2. PROJECT OVERVIEW

Sponsored by the U.S. Department of Energy's National Nuclear Security Administration (DOE/NNSA), the public-private partnership between Sandia and BlackSky consists of three phases over a three-year period (U.S. fiscal year (FY) 2018-2020). The plans for each year are designed to build upon each other and leverage the experience from prior phases as well as capability growth that will occur over time. The overall research objective is to explore how emerging capabilities in the small satellite industry such as rapid persistence, combined with unique non-proliferation and analytical capabilities of a national laboratory, can improve remote proliferation detection (PD) or other fields, such as international nuclear safeguards. Additional research questions will explore how rapid revisit rates from small commercial satellites can help achieve near real-time monitoring, and what proliferation-indicating patterns can be detected by low-resolution, high-revisit rates that cannot be seen with high-resolution, low-revisit rates. The project also seeks to better understand how the relatively arbitrary time-of-day imaging of high-revisit rates might affect data analysis such as change or anomaly detection, or pattern of life (PoL). Operational demonstrations I, II and III will provide important opportunities to address these questions through access to rich data sets, imagery and information analysis, and unique collaboration between public and private industry.

2.1 Phases I - III

Phase I of the effort (FY18) consists of project and demonstration planning, site selection, open source event feed development, an operational demonstration, imagery analysis, and an evaluation of how low-cost, 1 meter (m) resolution (or <1 m) imagery can contribute to PD mission needs. Through a subcontract, BlackSky and Sandia are collaborating in Phase I on an initial effort involving a familiarization period with the BlackSky platform and an operational demonstration to observe and analyse activity at a surrogate site over a fixed period of time. The BlackSky platform currently offers access to a "virtual constellation" of satellites by accessing imagery from other commercial satellites through its 'BlackSky Spectra' capability. Users can acquire both archived and tasked images of a specific location from third-party satellites and combine the imagery with other data sources such as news reports through a custom event feed, 'BlackSky Events.' [3]. The long-term goal of BlackSky is to operate its own satellite constellation using a series of satellites that can provide high-resolution (1 m or better) imagery at low costs [3]. Though only one prototype, the Pathfinder, is currently in orbit (as of July 2018), BlackSky's projection is to launch a 20-satellite constellation by 2020. Thus, in Phase I, the project relied exclusively on imagery from third party providers using BlackSky Spectra and achieved an average revisit of two images per day with one significant six-image burst in a 25-hour period (see section 3 for further discussion). Sandia, BlackSky, and Armillary Services LLC (BlackSky subcontractor) are now collaborating on imagery analysis.

Phase II of the effort will build on Phase I with plans to achieve a higher revisit rate (4-10 imaging opportunities per day), a longer monitoring period, and a second refined event feed using BlackSky Spectra. The team will again collaborate on imagery and information analysis to better understand how the capability growth between Phases I and II in areas such as increased persistence and a more finely-tuned custom event feed can further impact the PD mission space. Similarly, Phase III will build on lessons learned from Phases I and II, but will leverage an even higher revisit rate with a goal of 10-20 imaging opportunities per day and an even longer monitoring period. Phase III will also explore the impact of low-cost, high-cadence, increasingly accessible commercial imagery on areas such as societal verification whereby individuals or groups are mobilized to detect and verify activities such as changes to nuclear facilities, movement of vehicles, rapid clean-up efforts, or missile launch operations. Phase III will also include a cost-benefit analysis of low-cost, high resolution, high-cadence commercial imagery for the PD mission space.

2.2 Unique Partnership to Leverage Emerging Technology

While commercial imagery has long been an important source of information for governmental, non-governmental and international organizations, research partnerships between these entities are not as common. By engaging in unique, collaborative efforts that leverage both organization's strengths, significant benefits such as improved capability and lower cost has the potential to make a significant impact on multiple areas including non-proliferation, international nuclear safeguards, trade analysis, disease tracking, environmental monitoring, emergency response and human trafficking, to name a few. For example, the U.S. government has traditionally relied on one or two large commercial satellite imagery providers for very high resolution imagery. Due to high demand, number of facilities to monitor and geographic dispersion of the target locations, these providers are often over-subscribed and products come with a high cost and slow order-to-delivery period. Moreover, developing, testing and launching a government-owned satellite can cost on the order of hundreds of millions or billions of dollars in research and development (R&D) and operations and management (O&M) costs. In 2013, the U.S. Government Accountability Office (GAO) estimated that more than $25 billion was appropriated to agencies for developing space systems. The U.S. Department of Defense (DoD) estimated that its total program costs for the Evolved Expendable Launch Vehicle would approach $70 billion between 2013 and 2030 [4]. While perhaps lower in resolution, other commercial satellite entities are now able to offer dramatic cost savings, improved responsiveness, and added features such as significant increases to revisit rates. A unique partnership between a U.S. national laboratory and a commercial small satellite company offers the opportunity for the U.S. government and others to shift away from the huge, high-cost burden of developing, launching, operating and building satellites. As costs continue to consolidate for commercial satellite operators, governments and other user communities will have the option to augment their systems with commercial satellite constellations that offer a low-cost, low-risk, high technology readiness level (TRL) system.

2.3 Small Satellite Industry: Current State of Play

Since 2010, several EO start-ups have emerged with a charter to develop smaller, less costly imaging satellites. The systems emerging now have a significant impact across multiple domains including private industry (finance, energy and agriculture), government (national security and intelligence), and R&D (academia and think-tanks). The so-called 'revolution' occurring in the space industry is driven by technological advancements and innovations in areas such as launch and satellite manufacturing capabilities. For example, the industry has moved from a satellite launch mass of 20,000 kg to less than 4 kg in a span of 60 years. This industry is not only defined by rapid inventions, lower costs, and rideshare opportunities, but also commercially available parts and incremental developments [5]. For example, rather than building redundant systems into a single satellite, which requires a larger team and more materials, small-satellite constellations build redundancy into the overall constellation. This puts the cost burden on production rather than R&D, which is proportionately less expensive.

Over the past decade, important developments have driven the current satellite industry. These drivers include improved launch systems and sensors, lower costs due to smaller size and commercially available components, more sensors, and a greater diversity of new sensor types. The combination of decreased costs and increased capabilities e.g., greater spatial resolution, higher temporal cadence, and richer spectral coverage, has made commercial satellite imagery accessible to more than just government and big, multinational industries. Some of the emerging capabilities include: rapid persistence (multiple revisits per day); sensor integration (the integration of sensory data from disparate sources, such as imagery and multivariate spatial data fusion); high definition video; high resolution hyperspectral imagery (imagery that can help detect specific objects by resolving more detailed spectral features allowing identification); thermal infrared (TIR) (detect heat signatures emanating from buildings/structures); advanced data analytics (imagery plus machine learning (ML)-based information analysis); and stratollites (balloons launched with payload platforms that can remain virtually “on-station” for a period of months). As many of these capabilities become available to a larger user community, the impact on multiple mission spaces, including non-proliferation and safeguards, are extraordinary. The research being conducted for this project seeks primarily to explore how to leverage the rapid persistence capability, though it also examines areas such as advanced data analytics and sensor integration.

3. OPERATIONAL DEMONSTRATION-1: CHALLENGES, SUCCESSES AND OPPORTUNITIES

Upon completion of project planning and site selection, Sandia and BlackSky coordinated with DOE/NNSA to execute the Phase I operational demonstration. This effort consisted of three core elements: 1) identification and purchase of archived imagery; 2) imagery taskings over a two-week period; and 3) imagery collection. Sandia and BlackSky identified archived images of the target location, an industrial plant under construction (Site A), and tasked seven third-party commercial providers to collect as much imagery as possible over a two-week period (15-29 May). During the collection period, BlackSky tasked seven partner providers with a total of 33 image collections, of which 26 were delivered successfully representing an 83% success rate, including one significant six-image burst in a 25-hour period. The average collection-to-delivery time was 1.875 days and the average revisit rate was approximately two images per day. While the revisit rate was about the same as those commercially available today, the one six-image burst between 28 and 29 May represents an extraordinary demonstration of the persistence capability, including intraday imagery collection, one that has rarely, if ever, been seen in the commercial satellite industry before (see Figure 1).

While the Phase I operational demonstration was a success, it was not without some challenges. For example, the BlackSky constellation is not yet available due to launch delays. Without this capability, the Phase I demonstration was restricted to purchasing and tasking imagery from third-party providers. While the collected imagery is of relatively high spatial resolution (<1 m), the project was restricted to a limited number of satellites at a higher price point than will be available once more satellites are launched through the BlackSky constellation (anticipated end of 2018). Another technical challenge was that the collected images were from multiple providers with differing sensors and spatial resolution as well as varying registrations, degrees of light and levels of obliquity. While some of these challenges were addressed in Phase I, they will be further resolved in Phases II and III as the BlackSky constellation comes online delivering more frequent, less expensive imagery from satellites with similar sensors and levels of spatial resolution.

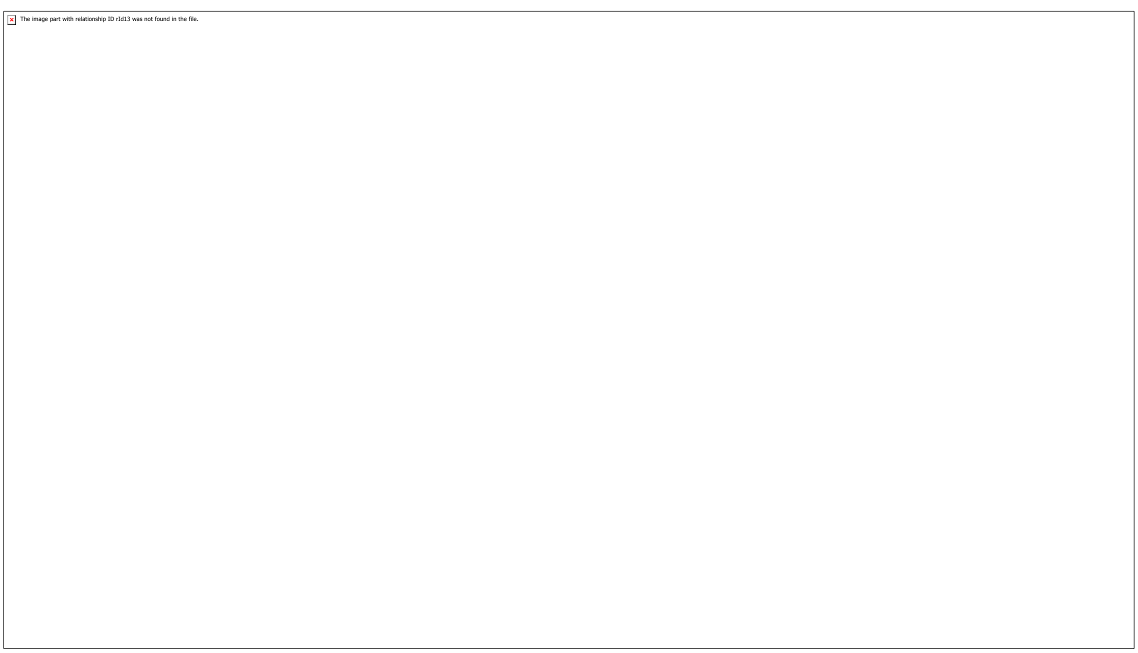

FIG. 1. Six-image burst of Site A between 28 and 29 May 2018.

4. IMAGERY ANALYSIS

Following collection of archived and tasked imagery during Operational Demonstration-1, BlackSky and Sandia conducted analysis both independently and collaboratively to better understand the on-the-ground activity at Site A. Archived imagery from the early years of construction were used as a baseline to see large changes over time, while tasked imagery was analysed to understand more detailed, nuanced activities occurring on a day-to-day basis.

4.1 Imagery Analysis Defined

Satellite imagery analysis is a complex, evolving field that requires both human expertise and computer-based techniques. The automated, computer-based approaches include pre-processing to correct radiance differences caused by variations in solar illumination, atmospheric conditions, sensor performance and geometric distortion, respectively [1]. They also include object and feature extraction using very high-resolution optical data [7]; change detection and analysis based on multitemporal optical data [8]; 3D change detection using optical stereo images [9]; coherent change detection based on synthetic aperture radar (SAR) imagery [10]; supervised classification of surface materials using hyperspectral imagery [11]; the operational status of facilities based on thermal imagery [12]; and the detection of thermal anomalies [13] [1]. For non-proliferation, the human component of imagery analysis requires a unique combination of both technical skills and subject matter expertise in areas such as the nuclear fuel cycle. A human imagery analyst must be able to understand and, theoretically, recognize the 'who, what, when, where and why' of an image. Imagery analysts should also have the skills to recognize constituent features in an image such as size, shape, shadows, shade, surroundings, signatures, texture, time and perspective [6]. For non-proliferation and international nuclear safeguards, imagery analysis combines pixels with other open-source information (e.g., safeguards-relevant data or news reports) to derive information that may not have been previously understood or recognized. Imagery analysis is also critical to non-proliferation verification and monitoring, particularly as it applies to identifying possible undeclared activities and facilities [6]. In this area of work, it is crucial to have human imagery analysts who are both well-trained and cognizant of the nuclear fuel cycle and its infrastructure, equipment, operations, and who are able to correctly distinguish those features from those that can be associated with other non-nuclear industrial processes [6]. This will reduce the potential for erroneous identification of proliferation-related activities when, in fact, they may be innocuous events on the ground.

4.2 Summary of Phase I Imagery Analysis

4.2.1 Pattern of Life (PoL) and Change Detection

For this project, imagery analysis involves the process by which to extract meaningful information from images obtained from low-earth-orbiting commercial imaging satellites. In Phase I, human analysis and computer-based techniques were used to conduct pattern of life (PoL) analysis and change detection. As a method to document or understand habits or behaviours, PoL was used to better analyse activities such as construction, operations, and the behaviours and routines of staff and contractors at Site A. During the two-week collection period, a number of activities were observed, including the movement of cranes, trucks, buses, vehicles, and equipment. The computer-based change detection, which involved the development of a custom algorithm to identify changes between images captured at different times by different satellite sensors, provided insight into changes in activity such as the movement of vehicles, equipment and terrain (See Figure 2).

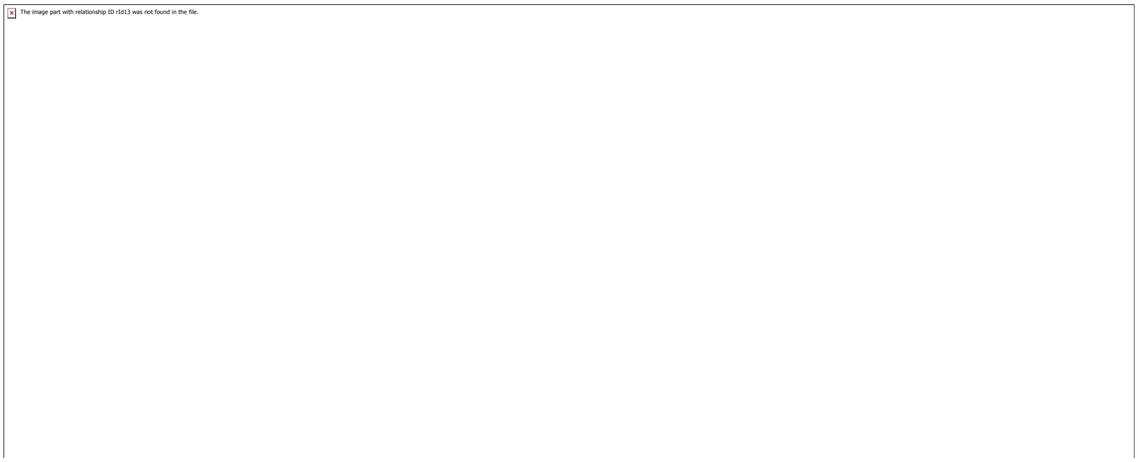

FIG. 2. Automated change detection of Site A.

The automated change detection provided complementary insight to the PoL analysis regarding activity on the ground and could be used to alert a human analyst of changes not seen by the naked eye. Initial findings from Phase I illustrate that delivery of high-cadence imagery of these activities, such as those from the six-image burst, provides more insight into the daily activity of a target location and will likely paint a more detailed, nuanced picture of what is happening on the ground than the standard twice-per-day revisit rate. While Phase I involved fewer than 50 images, thousands of changes could be observed in areas such as parking lots, administrative buildings, storage areas, living quarters and operational facilities. Only a fraction of these activities were analysed, indicating that, with the increase in volume of imagery that will be achieved through a surge in persistence in Phases II and III, automated analytical capabilities will play a key role.

The six-image burst over Site A (Figure 1) includes imagery of one of several areas that provide support for construction and logistics. Human PoL analysis reveals that vehicle activity fluctuates here throughout the day, indicating laborers, construction officials, and auxiliary staff are "dropped off" and "picked up" here during the work hours. The small buildings and temporary structures in the imagery could serve a number of functions, including small-scale administration or logistics such as reception/administration, cantina, an auxiliary medical department, other emergency services, or storage. High-cadence imagery such as this might help an analyst better understand the human behaviour, industrial activities or schedules that could provide advantageous insight into the purpose or function of a specific target location. For example, tracking buses throughout the day will expand the understanding of the amount of construction staff within an industrial complex. An influx of laborers – even an increase of support staff – could directly signify an increase of activity at a particular location or even a nearby site. Gleaning such information from high-cadence imagery will allow analysts to draw more nuanced, possibly even more accurate, conclusions about activities on the ground.

4.2.2 Open Source Information Analysis

Open source information analysis was an important component of learning about and understanding activities at Site A. Publicly Available Information (PAI), such as local news, combined with ML methodologies provided additional insight into events occurring on the ground. For example, Sandia and BlackSky collaborated to develop a custom event monitoring 'channel' within 'BlackSky Events' that uses textual data to support Natural Language Processing (NLP) and Named Entity Resolution (NER) to provide both context and activity alerts. The ML algorithms underlying the custom BlackSky Events feed, based on keyword search terms, allowed channels to focus on activities and organizations that might be directly or tangentially involved in site construction or operation. Information gleaned from the channels, such as changes in operational schedules, construction design, or high-level visits, could be used to complement or confirm activity observed in the imagery. If accurately refined, the ML-based custom event feed capability could have significant implications for fields such as international nuclear safeguards and non-proliferation. For example, an information analyst at IAEA headquarters could leverage the combination of imagery and a custom open source event feed to support Safeguards Evaluation Groups (SEGs) and inspectors for State evaluations and onsite inspections.

5. CONCLUSION

Phase I of the Detection via Persistence project gleaned new insight into the benefits and challenges of leveraging commercial imagery from small satellites for areas such as PD, non-proliferation and international nuclear safeguards. The project seeks to apply higher-cadence imagery to the PD mission space and also explore and even develop the tools necessary to analyse high volumes of imagery collected on a daily basis, imagery that only a very small fraction of which could be processed by a human analyst. Within the next five years, high resolution imagery from multiple providers will become ubiquitous and prices will continue to fall, thereby increasing accessibility to user communities beyond just large government and industry customers. This has significant implications for the non-proliferation and international nuclear safeguards communities, among others. Access to more frequent high resolution imagery of specific locations will not only provide unique, distinct insight into activities on the ground, but will help analysts and inspectors draw more nuanced insight that may not have been previously detected with lower frequency imagery.

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