Sensor Network for Global Monitoring of Spacecraft Situational Awareness

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ABSTRACT

The continued proliferation of new technologies, operators, and capabilities in the space domain has created a challenge in providing space situational awareness (SSA) intelligence and services. Specifically, the evolution of small satellite technologies over the last ten years from conceptual demonstrations to operational mega constellations has dramatically increased the complexity of the SSA mission. 2018 alone saw more than 100 successful launches with 450+ known payloads deployed, including over 60 payloads on the December 2018 SSO A mission. Launches in 2019, and beyond, are expected to exceed these numbers as multiple commercial "mega constellations" come online and become operational. New capabilities and approaches to space surveillance must be employed to not only handle the increasing volume of space based objects, but to also provide timely and accurate intelligence to stakeholders. Raytheon proposes to use a variety of low cost, geographically dispersed, ground based sensors and commercial ground networks to augment the Space Surveillance Network (SSN). Leveraging the efficiencies and capabilities of low cost sensor hardware combined with near global data networking options, the SSN can provide broader monitoring services of the space domain, better prioritization tasking of larger assets, and more data backed intelligence of the space operational picture.

To help address this problem, Raytheon proposes a low cost sensor network that employs scalable, distributed architectures along with cloud services to monitor space based phenomena. This concept considers the use of edge processing devices to process data at the sensor and reduce network burden across many disperse geographic locations. Network connectivity from a site location can also allow the system to move raw sensor data back to centralized cloud storage for more advanced processing into concise intelligence data products for analyst and operator consumption. Edge devices can be further leveraged to perform selective machine learning services on both raw and processed data to further reduce network load or produce intelligence products at the collection source.

Data fusion of various sensing data with other sources such as more traditional optical and radar products would provide additional secondary validation of spacecraft behavior against predicted or expected behaviors, for example expected orbit parameters or transmission frequencies. Cloud based storage of collected sensor data could be used for either real time, as available, or as needed cloud processing algorithms for more specialized analyses. Real time understanding of the operational space RF environment can provide invaluable intelligence to SSA and ultimately be utilized for the security of important space based assets. Building out and understanding a more complete space operational picture will be key to the long term safety and protection of the space domain. This paper will present and detail Raytheon's approach and recent efforts to implement this new sensor based SSA solution.

1. INTRODUCTION AND BACKGROUND

The accelerating proliferation of space with man-made objects creates an exponentially more complex mission for Space Situational Awareness. With no fewer than 100 launch vehicles actively being developed or sustained [1] the number of satellites placed into Earth orbit – especially low Earth orbit (LEO) – will, with near certainty, increase substantially. Multiple well-publicized launches such as the 2017 ISRO launch of 104 vehicles, the 2018 SpaceX/Spaceflight SSO-A launch of 64 vehicles, and the 2019 SpaceX launch of 60 Starlink vehicles have publicly underscored the need for improvements to the overall SSA mission. This trend will accelerate with future launches of mega-constellations planned by a myriad of commercial and government entities. These active satellites in particular will be critically important to track and monitor over time. New technologies are needed to upgrade today's SSA systems not designed to handle the volume of objects in orbit.

Historically, the SSA mission has been performed by specialized sensors and networks designed to observe and track the locations of space objects. As of 2019 the SSN falls under the responsibility of the Joint Functional Component Command for Space (JFCC Space) and is an organizational arm of United States Strategic Command (USSTRATCOM). This network assets consists of approximately 30 radar and optical sensors that are tasked to observe space objects. The SSN has become very effective over the past few decades at providing SSA information but has some limitations, including challenges for incorporating new sensors or intelligence sources. Vast amounts of vetted open-source information about objects are also not considered.

In order to address this difficult problem, Raytheon began development of a framework to enhance SSA with an initial focus on radio frequency (RF) collection sensors and techniques. RF in particular promises unique ways to cost effectively monitor active objects from a multitude of sources that can simultaneously augment and reduce the load on existing radar and optical assets. In this paper we discuss our applied approach to using RF for SSA as well as the benefits and challenges of using this technology to provide situational awareness intelligence and services.

2. RF FOR SSA AUGMENTATION

Of the various phenomenologies, RF-based SSA poses a significant opportunity for augmenting existing SSA techniques such as radar and optical tracking. Individual RF techniques have been previously demonstrated to enhance SSA, such as maneuver detection [2]. Several recent technological advances further enable RF for SSA including low-cost software-defined radios (SDRs), a renaissance in machine learning (ML) techniques, software containerization, an abundance of commercial ground networks, and increasingly powerful edge-computing devices. All of these together create the opportunity to approach RF-based SSA from a new perspective where low-cost, ubiquitous, and even automated crowd-sourcing of RF collections are possible around nearly the entire surface of the Earth and even from space itself. Multiple private entities are currently operating or building global commercial ground networks. For example, from the KSAT [3], Kratos [4], and ATLAS [5] ground networks alone, there are over 63 ground stations operating in the VHF to Ku band and tracking from LEO to GEO. For the 4,987 active satellites in orbit at the start of 2019 [6], that is approximately 80 satellites per ground station to be tracked if just these three networks were unified under a single SSA mission.

Additionally, low-cost SDRs such as the RTL-SDR ($30), LimeSDR Mini ($190), and HackRF One ($295) significantly reduce the hardware expense of adding additional, fixed antenna (no azimuth/elevation tracking) locations and can support collections from 1-6 GHz at up to 20 MSPS. The frequency range can be increased even further by using downconverters which can handle any variety of input frequencies of interest. With appropriate spatial distribution (see Figure 1), these sensors could ensure collection of transmissions even with small half power beam width (HPBW) from LEO and above. For example, to capture all transmissions that land in the metropolitan Denver area (400 km^2) from 400 km orbits and above and with a HPBW of 1 degree or higher, it would take 3 SDRs each separated by about 14 km. For reference, a 3 GHz transmitter with a 1 m dish has an HPBW of about 3 degrees while an 8 GHz transmitter with a 1 m dish has a HPBW of about 1 degree. Traditionally, collecting these types of LEO signals would require a relatively expensive fast-tracking antenna system that was likely purpose-built for communicating with a limited number of small satellites as opposed to any LEO transmitter overhead and would also require a spectrum license for each ground location. From a purely passive RF monitoring standpoint, this type of system can be replaced with many cheaper, smaller, and fixed antenna SDR systems distributed over a wide area to increase the number of LEO signals that can be tracked for SSA purposes. As a result, today's SDRs offer a low-cost means for scaling RF SSA collections in addition to the utilization of existing commercial ground network infrastructure.

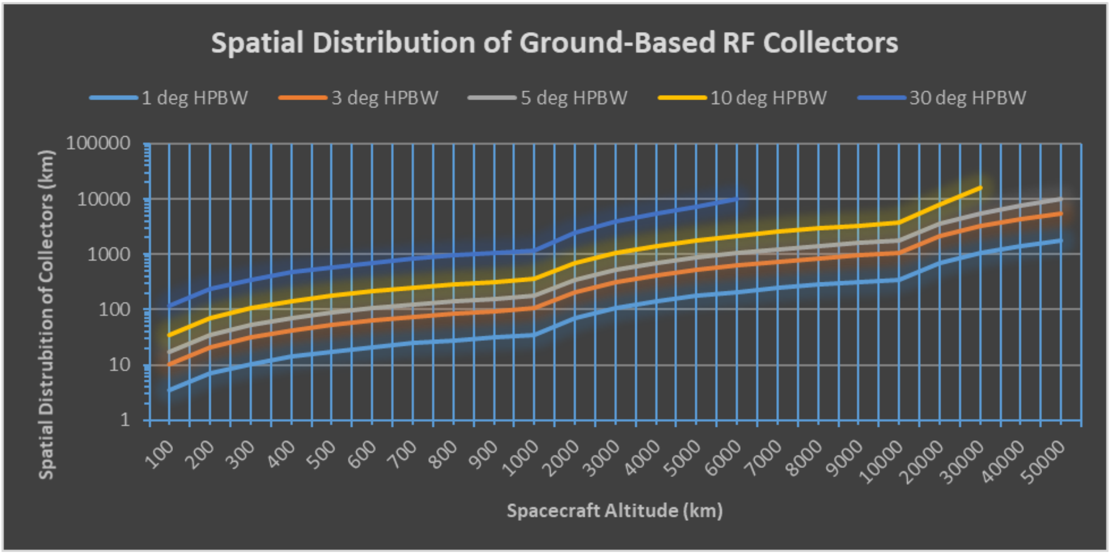

Figure 1: Spatial Distribution of Collectors

Advances in machine-learning provide another critical piece to RF-based SSA by enabling processing of the very large quantity of RF signals being generated from the nearly 5000 active satellites in orbit. If a system were in place to listen to every spacecraft at all times, it would generate approximately 1.8 Tbps of in-phase quadrature (IQ) data (assuming one LimeSDR Mini dedicated to each of the 4,987 currently active satellites and using the SDR's 12 bit A/D and 30.72 MSPS sample rate). For a day of collections, that would be approximately 20 petabytes of IQ data. Obviously, spacecraft are not always transmitting and there are likely some preprocessing steps that could be done to significantly reduce this value. However, the point remains that there would be enormous amounts of data generated that would have to be sifted through in order to realize any useful SSA insights. For the moment neglecting how much of this data would need to be transferred across a network before being processed, machine learning algorithms pose a candidate solution for performing SSA analytics on such a large data volume. Approaches to process RF signals using convolution neural networks (CNNs) and image-processing of waterfall plots, constellation plots, etc. are possible and have the benefit of being able to leverage a history of non-RF applications such as image recognition, video analysis, and natural language processing. Recurrent neural networks (RNNs) are another approach and are especially appealing due to their ability to interpret information with a time-series nature such as IQ data. RNNs have already seen use in performing RF fingerprinting of WiFi devices by processing IQ data directly (with no conversion to an intermediary image product) [7]. A similar approach could be used to passively identify and characterize spacecraft transmitters. In general, ML provides an opportunity for converting the vast amounts of potential RF signal data into insights for spacecraft identification, maneuver detection, communication behaviors, and more.

3. FRAMEWORK OVERVIEW

Innovative approaches to space surveillance are needed to handle the increasing volume of space-based objects and to provide timely, accurate intelligence to stakeholders. RF, as briefly discussed in the previous section, could provide a new approach to augment the SSA mission. Raytheon began investigating the development of such a framework to monitor space objects and characterize space events based on globally collected spacecraft radio frequency (RF) data. The framework includes the orchestration, scheduling, and tasking of heterogeneous collectors, collection of data, and processing into SSA intelligence. Raytheon has extensive domain knowledge of both ground and space services and has made multi-year investments in SSA and space protection technology, including analytics using ML, statistical, heuristic, and generic algorithms.

Figure 2 shows a Concept of Operations for the proposed system, demonstrating:

- tasking and use of a complex commercial ground network to passively collect space-originating RF of interest
- Intelligent edge-processing with minimized transfer of RF data over data networks
- processing of RF data using advanced analytics to provide SSA intelligence

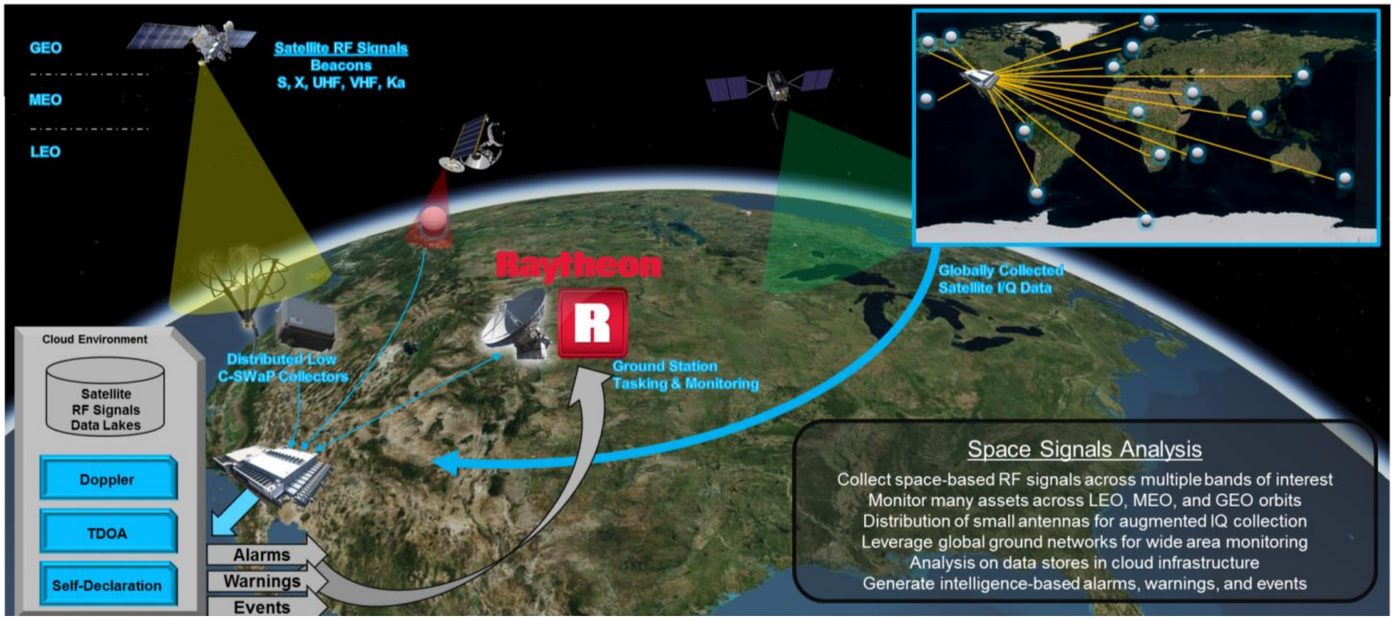

Figure 2: Concept of Operations

Collection Platforms

Our framework seeks to utilize the emergence of new, non-traditional sensor sources deployed globally and combine them into a single framework for tasking into the SSA mission. A wealth of new collection sensors such as commercial ground networks allow for passive RF collection around the world. Scalability and cost-efficiencies are gained by using only what is needed from the commercial networks, automatically increasing or decreasing usage as required with tunable levels of priority for antenna tasking. Additionally, any number of low fidelity, small C-SWAP sensors could be deployed and tasked to provide additional sensors in a hybrid RF SSA architecture. The Raytheon proposed system would passively collect space-based RF data and demonstrates storage, analytic processing, and intelligence-making for the purpose of SSA.

Web-based User Interface Framework

Just as innovative approaches are needed for collecting and analyzing SSA data, innovative approaches are needed for visualizing and controlling an increasingly complex system. Optimal performance depends not only on the ability to view and understand complex information, but on the ability of the user interface to be accessed from anywhere. Raytheon has developed a proprietary web-enabled framework that is highly configurable with broad applicability across domains. The framework gives the user the ability to have multiple roles and views in a single unified display and rapidly switch between them. This opens the door to tasking, viewing and analyzing data from anywhere.

The current implementation has leveraged three different views to support global monitoring of RF signals and their application to SSA. Figure 3 shows the SSA dashboard view where RF SSA data can be viewed and analyzed. In addition, it has the ability to manage multiple configurations of RF sensors and the vehicles they are tracking. Figure 4 shows task management, collection schedules, and resource status of all available sensors. Finally, Figure 5, shows the ability to switch to a view that has access to a specific collection resource where fine monitoring and control are possible, including spectrum, Doppler shift and constellation plots.

With a highly configurable framework, and multiple views, greater control and efficiency are possible, and remove obstacles to SSA data collection and analysis.

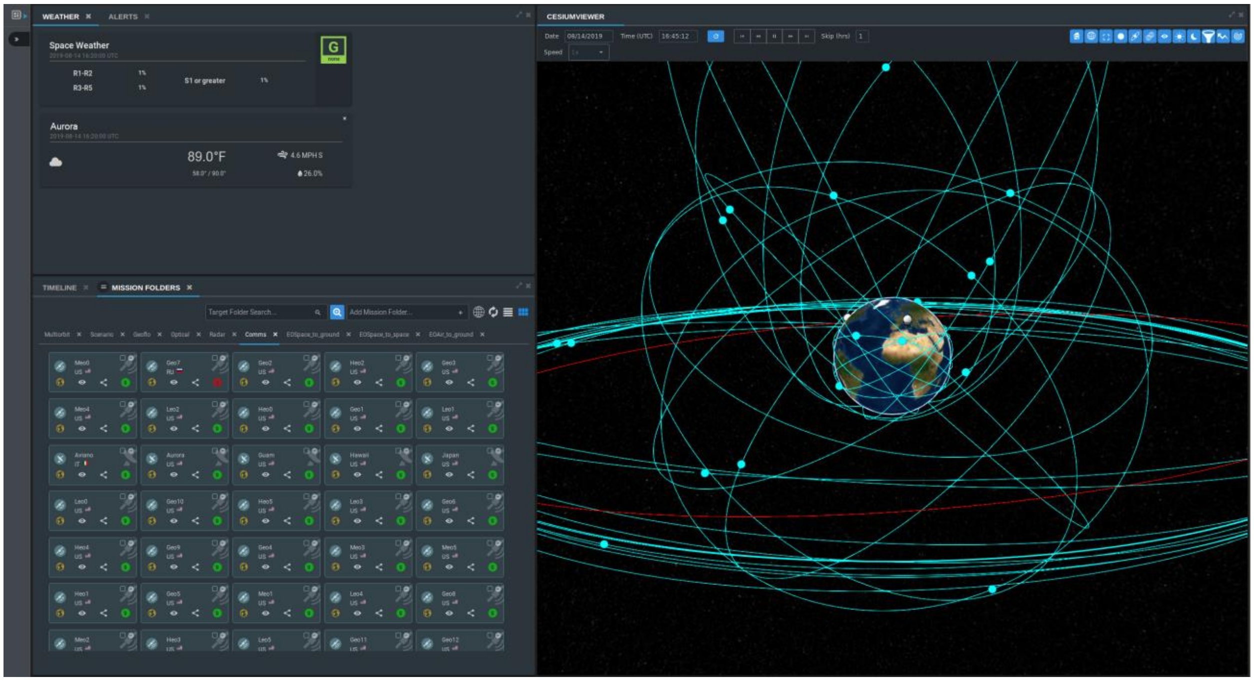

Figure 3 – Space Situational Awareness Dashboard View

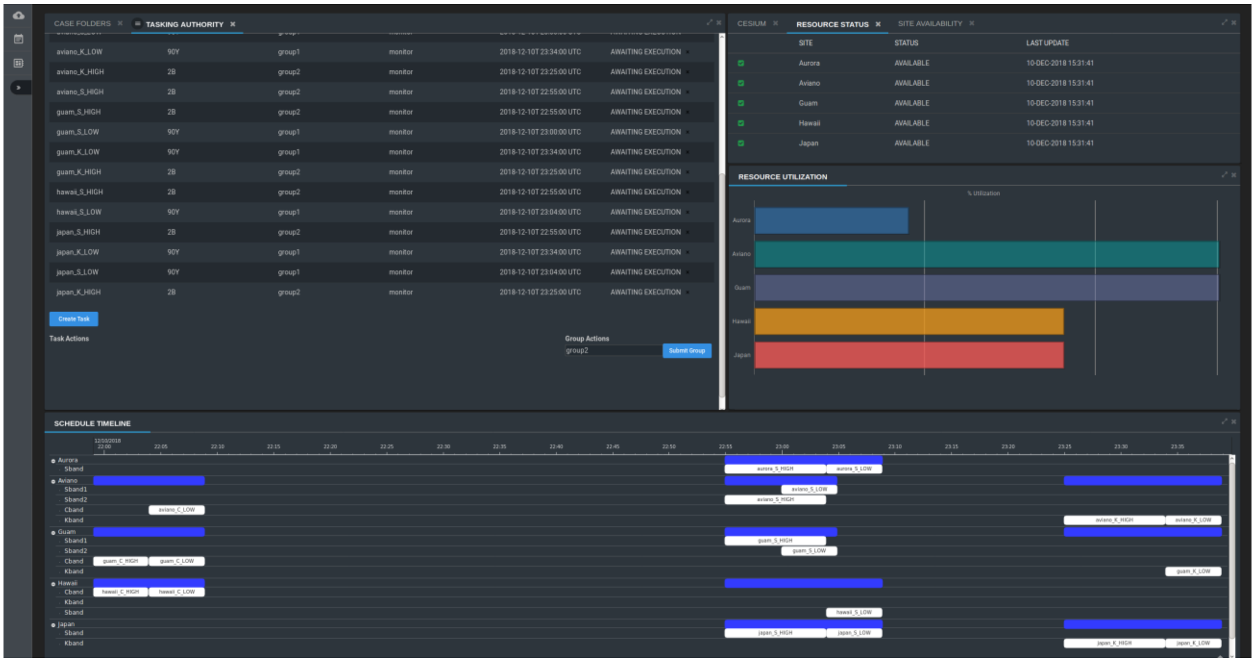

Figure 4 – Task Management of RF Resources View

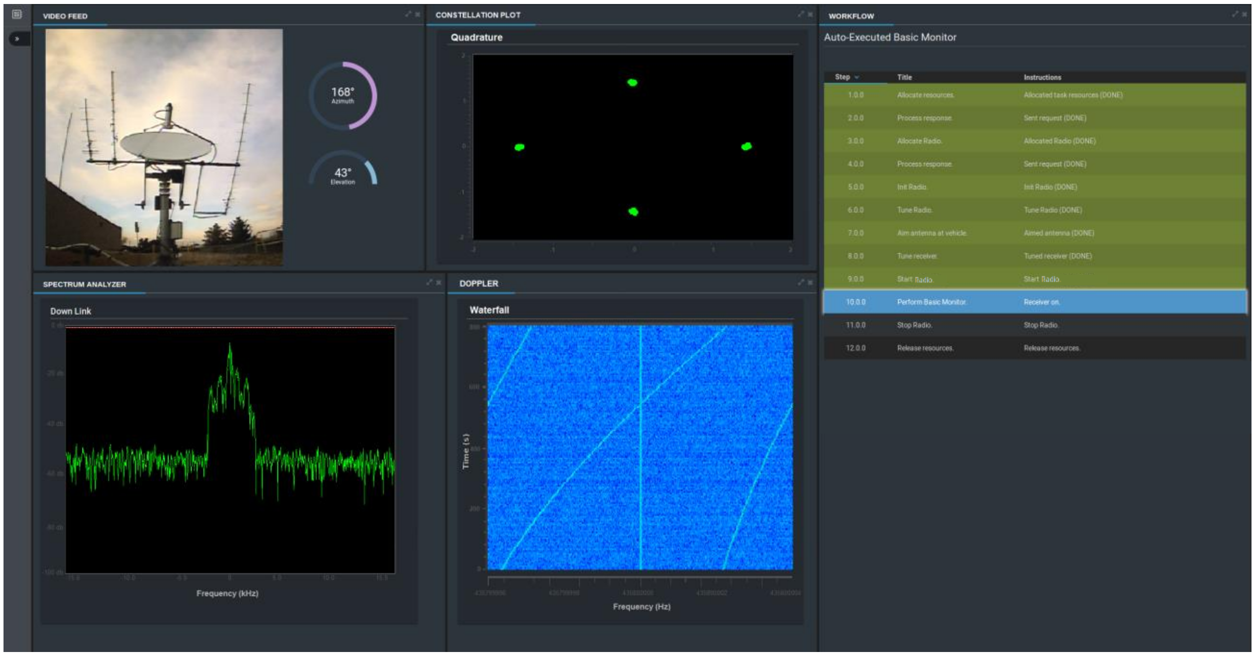

Figure 5 – RF Resource Monitoring

Scheduling and Tasking

The ability to task, schedule, and command and control (C2) individual assets networked together is important to the collection of data at scale. The proposed RF SSA framework uses proprietary Raytheon scheduling and C2 capabilities to bring any number of disaggregate collection sensors under one framework, task against them during pass opportunities, implement command and control when needed, collect and processes data automatically, and provide tip/cue capabilities to other assets – possibly non-RF collection sensors – to further collect valuable intelligence. Robust and truly heterogeneous scheduling and tasking capability prevents collection systems from ending up in stovepipe architectures and allow a robust network of SSA augmenting sensors to be created.

4. CHALLENGES

Multiple difficult technological challenges face the overall SSA mission as the space environment grows more crowded and complex. The use of RF signal collection in an operational framework shares many of these same challenges, such as:

- **Data storage and access** – the amount of data generated by raw RF IQ analysis across multiple sensors and targets quickly scales to extremely large volumes. Analysis, whether done locally or remotely, is used to identify, track and/or characterize radiating objects in space. Keeping track and appropriately managing this data is required for effective SSA.
- **Limitation in data transport bandwidth –** movement of raw data taxes the capability of existing data transfer methods and infrastructure. Judicious movement of information and ideally in some cases the processing of data locally at the sensor is necessary to avoid prohibitively expensive or difficult data transportation.
- **Exponential computation growth** – as the number of sensors collecting against the increasing number of space objects grows, the number of intensive computations grows exponentially.

Data Storage and Access

The generation of raw IQ data presents challenging data storage and access problems. Advances in cloud-computing have presented multiple solutions in this area and Raytheon continually investigates and utilizes multiple data repository technologies that have emerged to tackle large-scale and difficult data storage and access problems. Use of datacenter-grade technologies allows for efficient and cost effective storage of data. To simplify access to collected RF data, our framework further utilizes RESTful web service endpoints via our proprietary user interface framework to allow access to the underlying data from any client type (i.e. scripts, web applications, micro services) without requiring transport or direct access to data repositories while users who do need more direct access can use the API provided by the underlying technology.

Limitation in data transport bandwidth

Movement of raw IQ data collected by individual sensors proves an extremely difficult problem and is coupled closely to data storage and access challenges. As discussed earlier, data volumes increase exponentially as collection against active objects increases to non-trivial fractions of space objects. Movement of this data across existing terrestrial networks will quickly drive cost and complexity of an operational system. Judicious selection and movement of data can dramatically decrease the volume of data needed to be moved between edge collection sensors and central processing, storage, and /or consumption locations. Our framework will look to lower-cost edge-processing techniques that range from noise detection, channelization, and change detection to full edge processing of IQ data into SSA intelligence prior to movement of raw data over networks. This approach of leaning into edge-processing will enable large numbers of collection systems and the real-time processing of massive data volumes in ways that make RF an operational choice for SSA.

Exponential computation growth

Multiple new tools and technologies have become widely available that enable graceful solutions to exponentially difficult computing problems. Docker in particular has become a defacto solution to software container platforms and Raytheon has extensively used Docker along with supporting technologies such as Kubernettes and Rancher to create software solutions that scale as complexity grows. With this core suite of scalable data management technologies, it is possible to tackle the growth of computationally intensive operations presented by RF SSA.

5. CONCLUSION

The continually increasing complexity of SSA and its growing importance in the swiftly evolving space environment has driven Raytheon to develop new game-changing technologies to improve and adapt the SSA mission for future challenges. One method presented here has been a prototype framework for operationalizing the use of passive RF collection sensors for SSA augmentation. We have proposed a framework and set of tools that manage multiple RF collectors and ties into a signal capability to task, schedule, and collect data at global scales. Raw RF data collected and analyzed can be used to provide valuable SSA. The applications of cloud technologies and, especially, new AI/ML techniques allows scalable SSA from RF and a capability to interface and tie that SSA intelligence to the broader, more traditional SSA systems. Leveraging a framework such as the one proposed here can lead to tangible and valuable improvements to the SSA mission at a critically important time for the space domain.

6. REFERENCES

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