Passive RF Sensing in support of SSA

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Abstract

In the Space Situational Awareness (SSA) mission area, and in particular, with Geosynchronous orbits, there are primarily two technologies in surveillance architectures used to observe, measure, and characterize Resident Space Objects (RSOs); ground-based radar; and optical telescopes. Both of these technologies are well known to the AMOS community and are available as commercial products. This abstract proposes that a third technology, passive RF sensing, can add an additional dimension to the SSA domain and is worthy of architectural inclusion as a fundamental sensor type.

Enhancing Space Situational Awareness with Passive RF Data

Radio Frequency (RF) data— the electro-magnetic spectrum used by space systems to communicate—can be used to enhance traditional SSA, offering a wealth of information absent from other sensors. For example, a satellite maneuvering in geostationary orbit is typically beyond the detection of radar and goes unseen by telescopes in the bright light of day. However, its RF signature can be used to detect maneuvers and anomalies, day or night and in all weather conditions. Further, RF can characterize behaviors, attributing whether an unexpected maneuver represents the patterns of adversarial intent, or the drift caused by an onboard malfunction. These RF capabilities fill the blind spots of existing sensors, while providing additional knowledge to enrich SSA.

RF data has been in use for years to support space operations, from monitoring payload performance and usage, to detecting and geo-locating interference, and to supplement government monitoring networks. In theory, this data always held significant value for SSA, but in practice was not available at scale due to limited sensor coverage and spotty infrastructure. Now, with global monitoring available, RF data can be collected for the complete geostationary arc at all times, 24/7/365, providing unique insights that elude detection or characterization by traditional sensors.

RF data improves current SSA capabilities by:

- Detecting satellite maneuvers in real-time and identifying their accurate location for conjunction assessment, collision avoidance, and safety of flight. In the SSA domain today, detection of a maneuvering satellite is complicated as the primary means of doing so is from ground based radars or optical telescopes. Often these resources are not available to support persistent monitoring, are unavailable during daytime, are not able to react quickly, or are not geographically located where they can apply their capabilities. Passive RF sensors provide an excellent, augmentation capability in that they are 24/7 capable and not affected by adverse weather. Furthermore, in addition to detection of a maneuver event, with multiple RF sensors the direction of the maneuver can be determined and ephemeris for the spacecraft post maneuver can be generated.
- Identifying anomalies in payload system performance and assessing their impact as well as characterizing satellite patterns and behaviors and identifying aberrations that can be alarmed and acted upon. Characterization through RF sensing of SATCOM transponder, payload and telemetry signals can be used to determine nominal behavior of an active RSO and provide an indication when the satellite has deviated from its defined norm. This characterization can be collected over extended periods, stored and then used as a reference for comparison purposes. This collection of RF information becomes the satellites established "pattern of life". An example of where RF sensing detected an anomaly based upon a deviation from expected behavior was clearly observed with the AMC-9 anomaly that happened in June 2017.
- Finally, passive ranging and ephemeris generation can be accomplished by collecting and cross correlating RF signals at multiple ground antenna locations. The process is similar to the method GPS receivers utilize but in reverse. With each collection system calculating delay times from the transmitter, and using surveyed collection sites, the range and angles to the satellite can be determined thus providing the ability to generate state vectors and accurate ephemeris on the RSO.

These capabilities, when fused with traditional SSA data, provide a combination that offers a more complete and accurate real-time picture of satellites, their activities, and the impact to users of these systems.

SSA Capabilities Provided by Passive RF

Maneuver Detection

Real-time identification of a maneuver event from a passive collection system that is actively monitoring a geosynchronous vehicle is important in informing the SSA and STM mission areas. Satellites typically maneuver for small adjustments in station keeping or larger adjustments when changing orbital planes or other orbital parameters. These changes in station keeping require a delta-V or acceleration to be applied to the satellite. As such, this acceleration imparts a dynamic change to the ballistic orbit of the RSO, taking it out of ballistic motion for a short period of time.

Kratos RT Logic first observed maneuvering satellites in the RF domain from our transponder monitoring equipment in support of Electromagnetic Interference (EMI) detection. During an experiment where our systems were processing differential frequency measurements from multiple antenna sources on a single satellite, a shift in center frequency was observed (Doppler) from all four of the collecting sensors at the same time. The data plot in Figure 1 captures the discontinuity in the Differential Frequency Offset (DFO) measurements which was attributed to a maneuvering satellite.

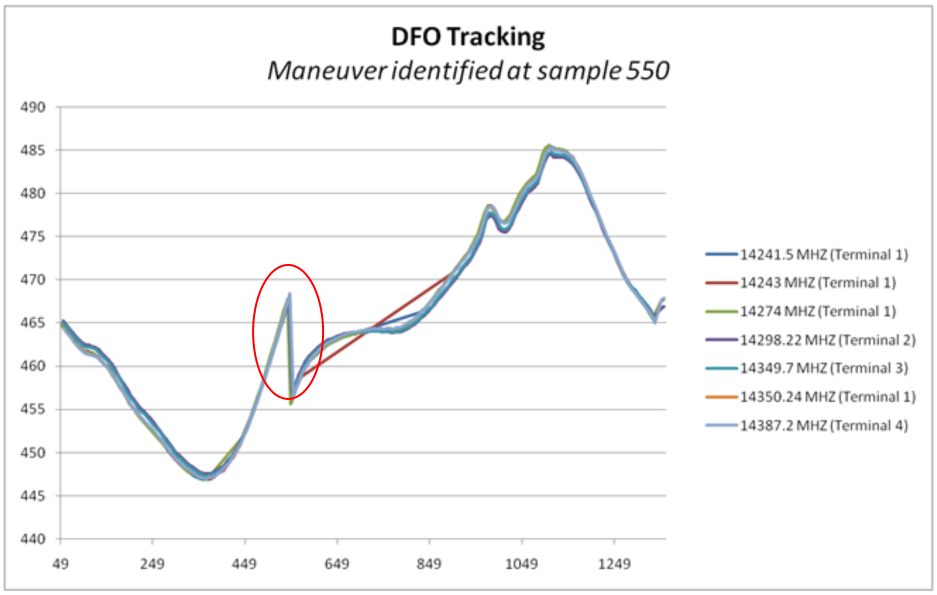

Figure 1. Maneuver Detection using DFO Processing

In late 2017, the experiment was repeated with the intent of seeing whether the event was reproducible from observations collected from single antenna measurements. While multiple antennas were used, differential processing was not employed. Figure 2 contains the normalized center frequency observations for six individual carriers within a transponder plus a ranging signal (dark blue). The ranging signal (a spread spectrum transmitted signal over the observed satellite's payload channel) also indicates a change in the measured range.

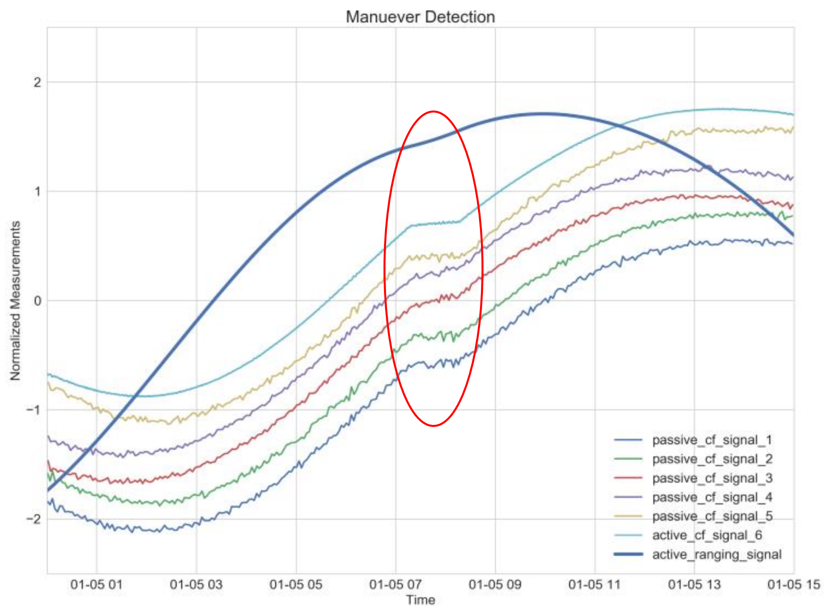

Figure 2. Visual Indications of a Maneuver on AMC 21

The observations in this chart reinforced that maneuvers are visible by a single antenna to which additional processing is applied to provide indications of a maneuvering satellite. Note that while these charts are based on wideband satellite payload signals, similar frequency shifts have been observed on L-band command and control signals.

Automatic detection of these subtle changes in center frequency is accomplished by smoothing the time series data to remove the gradual diurnal motion of the frequency shift from normal satellite motion and amplifying any sudden changes that deviate from expected motion. Figure 3 contains several charts that graphically depict this approach. The top chart (Figure 3– Chart 1) in the sequence of four charts is the observed center frequency of the satellite (AMC-21) transmitted signal. The center frequency varies in frequency due to Doppler shift associated with the satellite's movement over its diurnal cycle.

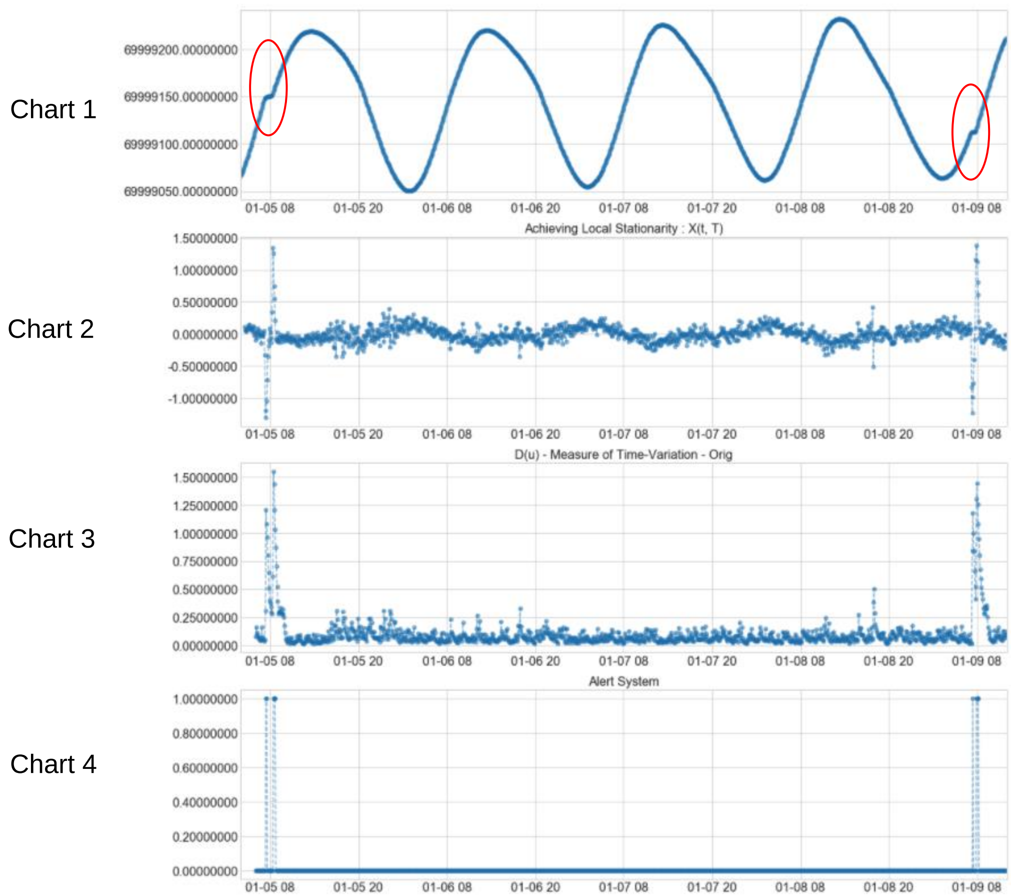

Figure 3. Maneuver Detection Processing Applied

In this test, the satellite's signal characteristics change slowly rather than abruptly over time. Therefore, solely relying on threshold parameters to detect changes does not result in an accurate detection. These types of signals are considered to be smooth time series varying signals.

For the detection of the frequency shift, the smooth time-series signal is processed through a 2-step process to arrive at an alert system. The first step is to achieve local stationarity (Figure 3– Chart 2). In this case, a set of transformations is applied to the smooth time-series data to remove any seasonality or other repetitive time-dependent patterns. Ideally, a smooth signal would be transformed to the point where the mean of the time-series is 0 over a specific/local window of time. The next step is to acquire a measure of time-variation within the locally stationary signal (Figure 3– Chart 3). This measure acquires the maximum difference between a subset of data within the local stationary signal and the entire local stationary mean. Thus, over a specific period of time, the maximum time-variance of the smooth signal is tracked. This process helps diminish local noise versus the presence of a gradual change that keeps presenting itself over time. From testing, smooth gradual changes in the time-series data becomes detectable, which allows tailoring of an alert system (Figure 3– Chart 4). In this last chart, a threshold parameter is applied to the data for automatic detection purposes. While this approach has worked well for detection of these frequency shifts, additional research is being performed to apply a multi-hypothesis approach that leverages this test as well as Kalman filtering techniques.

RF Event Detection

Just as RF methods have been honed over the years to support satellite mission performance and interference detection, new RF techniques are being developed to exploit its value for SSA and RF situational awareness. With the right tools in the hands of skilled scientists and professionals, analytics, machine learning, and artificial intelligence can characterize RF data to identify the attributes of satellites, predict maneuvers or actions they may undertake, and discern intentions.

Using machine learning and pattern recognition algorithms, large amounts of RF data can establish the normal expected behaviors of space objects, such as routine station-keeping and the frequency of maneuvers. By monitoring and detecting deviations in these patterns, those that are atypical and unexpected can be alerted for more pre-emptive threat awareness and space traffic management.

RF based analytics support:

- Machine learning applied to payload, usage, and maneuver data to detect anomalous conditions and patterns of interest.
- Long-term trending and characterizing of RF signals to establish patterns and changes in satellite and interference locations, including the terminal types, waveforms, and recurring violators involved.
- Analyzing payload performance baselines and systems status to identify the capabilities and status of friendly and adversary satellites.
- Automated classification of bandwidth use, transmission type, and timing can help identify satellite modems, payload activities, and attribute behavior.
- Integrating these event feeds with other sensor, open source, and intelligence data provides real time situational awareness of space system assets and events.

This type of machine-speed data collection and analysis supports more predictive warning, extending lead times and knowledge for appropriate response. For example, early patterns of satellite interference detected from RF SSA can be correlated with other events, such as cyber disruptions and upticks in social media activity, as precursors of hostile actions by rogue nation-states. Synthesizing RF-inclusive analytics with other data sources can provide decision-makers the information needed to get ahead of threats to missions, whether to trigger maneuvers to avert satellite collisions or to deploy waveforms to counter an expected RF attack.

Satellite Usage Classification

RF data signal characterization can help determine the nature of an asset's transmission, whether its mission supports video broadcast or UAV operations, for example, and whether a large spike in bandwidth and upload of certain traffic type is an indication or warning. This process of characterization falls into the category of spectrum classification. One approach at classification involves the clustering of similar signals into groups and then organizing them in such a way where their common features cluster them together. Figure 4 is a sample of satellite based RF spectrum waterfall collections along with preliminary clustering of the individual bursts of signal transmissions applied:

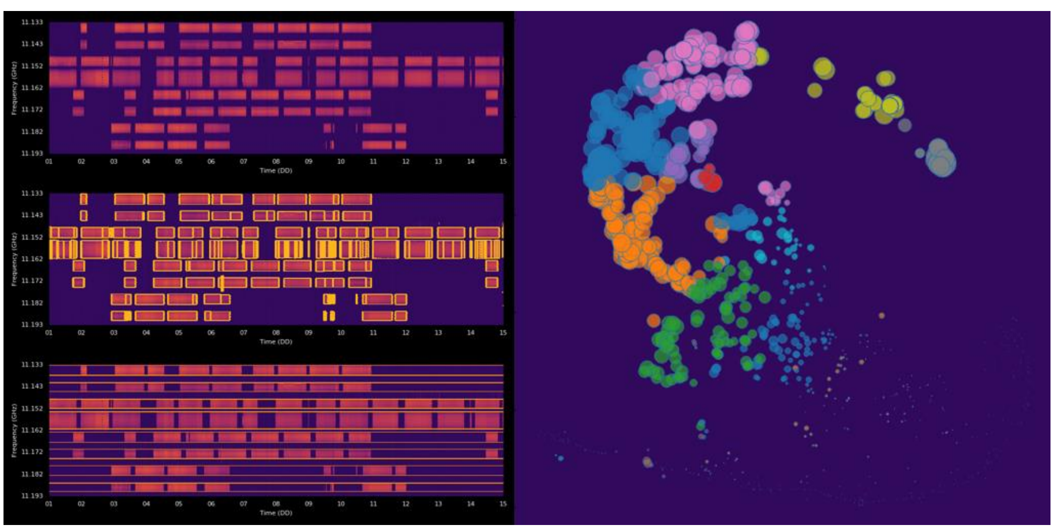

Figure 4. Machine Learning Applied to Channel Accesses

This clustering of the spectrum access uses machine learning algorithms and has the goal of being able to uniquely identify and label RF channel accesses that have the same sets of features. For example, if a particular type of unmanned aerial vehicle exhibits a particular RF signature, that signature can be decomposed into features (time, duration, center frequency, location, modulation type, etc.) and then labeled. Every occurrence of that label becomes searchable from a larger database of accesses and extractable for additional pattern recognition. The additional patterns may be correlated to operations tempo, troop deployments, global crisis, or predicators to missile test events. The end result is that the analytics and classification of spectrum give way to larger and broader understandings of global activities

Anomaly Cause & Attribution

RF performance metrics can detect and reveal the extent of an anomaly and its cause. Slow, gradual variations in normal baseline measures might indicate equipment wear or changes in user requirements. More sudden or severe RF signal deviations may uncover a polarity issue, adjacent satellite interference, payload system failure, jamming or a directed energy attack. The ability to detect payload irregularities and their origin accelerates response and resolution. For example, operators would know whether to re-route traffic to bypass an equipment issue, or to focus efforts on geo-locating an unauthorized broadcaster to mitigate interference.

One recent and highly relevant example of how RF supports anomaly detection was the June 2017 catastrophic event that befell SES's AMC-9 satellite. RF sensing systems detected a complete de-allocation of carriers near simultaneously across the satellites transponders. The waterfall plot in Figure 5 demonstrates this sudden departure from active carriers.

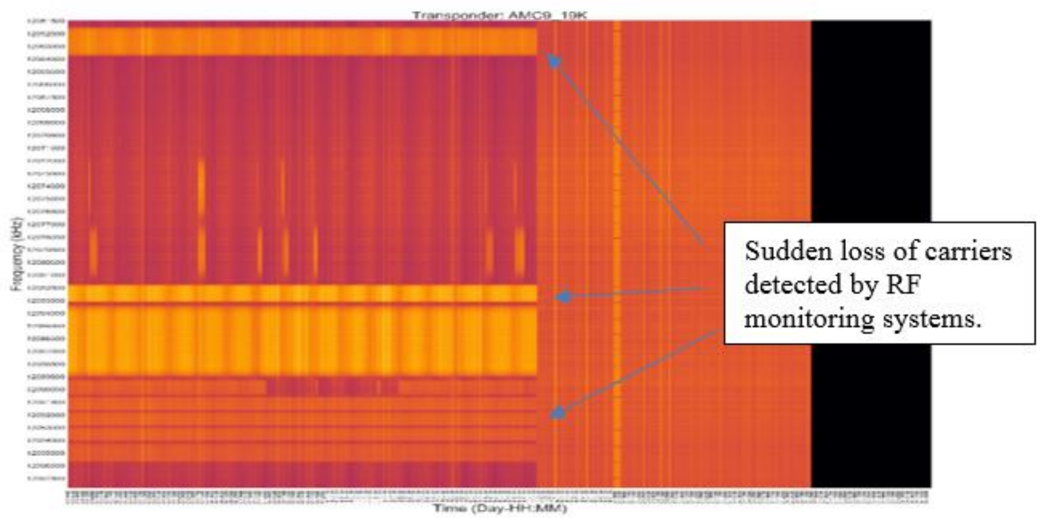

Figure 5. AMC-9 Sudden Loss of All Carriers

The event was later collaborated with optical telescope observations though the RF observations were the first indications of the satellite experiencing issues. In this case, the event occurred at nighttime which allowed telescopes to collect immediately. However, had this event occurred during sun exclusion times, hours would have passed before optical systems could report on the event. RF sensing, when combined with analytics provides an immediate notification of an anomaly.

RF Passive Ranging and Orbit Determination

Unless a sensor system can generate orbital elements and contribute to a space catalog, its utility is limited. Fortunately, RF sensing enables orbit determination when precise co-collects from multiple apertures are made over time. The process involves time synchronized short captures of the raw signal data. The raw data is precisely time stamped at a surveyed antenna location such that the capture time of each signal is known and time aligned from the same time reference across all antennas. From these signal captures, differential time offset (DTO) and differential frequency offset (DFO) measurements are made between all capture sites. Ideally three or more capture sites are needed to perform OD, however with measurements being made over time, OD can be made with just two locations. The concept behind DTO and DFO collection is shown in Figure 6 and Figure 7.

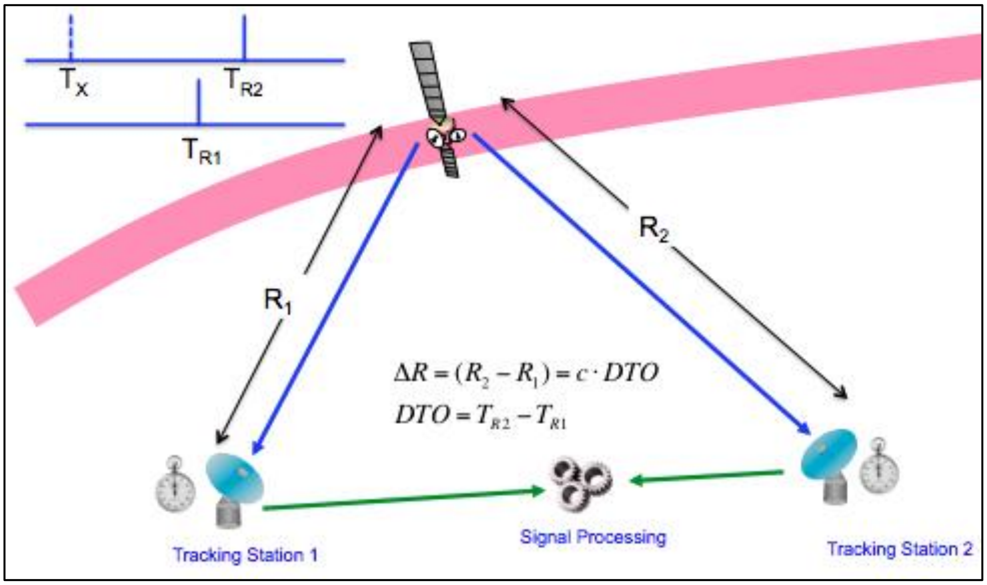

Figure 6. DTO Output Yields Range Information

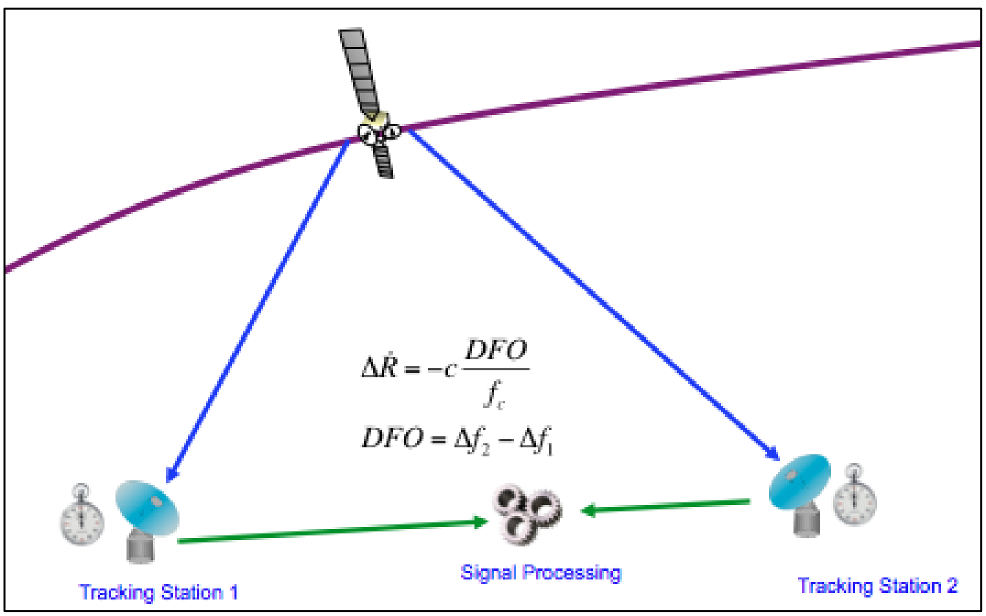

Figure 7. DFO Output Yields Range Rate Information

The normalized FDOA can be shown to be equivalent to the TDOA rate-of-change and as such is referenced as TDOT. Thus the two observable types to be used are TDOA and TDOT generated from the collection of satellite DTO and DFO measurements.

In all cases a minimum of six observations are needed to differentially correct the six state vector elements $(x, y, z, \dot{x}, \dot{y}, \dot{z})$. These observations can be any combination of TDOAs and TDOTs, but are normally paired TDOA/TDOTs. If there are exactly six independent (non-statistically connected) observables, the system is called exactly determined. In most cases, there needs to be more than six observations and such a system is referred to as overdetermined. To handle the overdetermined cases, the method of least squares is used and the process is referred to as the minimum variance estimation technique.

The algorithmic process takes an estimated satellite location and velocity together with the ground collection station locations and observables over a sequence of time and attempt to correct one of the satellite state vectors using a differential correction process. To reduce complexity, one of the central data collects will be used and its state vector will be corrected at the given time by using the TDOA/TDOT observables. Convergence is generally fast, but in selecting more iterations of the algorithm, all of the state vectors of the observables need to be corrected relative to the central state vector chosen to be correct. This requires that the state vectors be propagated from the corrected state vector using an accurate satellite propagator. Each iteration of the least squares, minimum variance estimator proceeds in the same manner with the propagator used between iterations. The partial derivatives that need to be computed for each iteration require the determination of $\frac{\partial x_S}{\partial x_0}$ where x_S is one of the state vector elements of the satellite at t_S and x_0 is the corresponding state vector element of the state vector being corrected at time t_0. Because the dynamic properties of an earth orbiting satellite are known, the process of determining $\frac{\partial x_S}{\partial x_0}$ is computed as $\frac{\partial x_S}{\partial (OE)}$ where OE is a chosen orbit element, times $\frac{\partial (OE)}{\partial x_0}$ and combined using the chain rule, $\frac{\partial x_S}{\partial x_0} = \frac{\partial x_S}{\partial (OE)} \frac{\partial (OE)}{\partial x_0}$. Computing the partial derivatives with respect to the orbit elements is messy and requires much bookkeeping. Sensitivity of the TDOA and TDOT observables to error is computed using gradient methods at the satellite. It is possible to give a distance error for each observable for a given unit of error and the locations of two ground stations and satellite. This represents the width of the line of constant TDOA (isochrone) and the line of constant TDOT (isodot) at the satellite relative to the two collection stations. The width of these two lines together with the intersection angle of the lines gives a relative intersection accuracy for the two observables.

Our approach to RF passive ranging and orbit determination supplies precision satellite location information without the need for transmissions from the ground to the satellite, satellite cooperation, specialized satellite payloads or detailed knowledge of ranging signal structures and definition. Together, these RF measurements can be useful in satellite detection, tracking, identification and characterization operations. This includes attribution, differentiating close objects, custody, and gleaning maneuver/operational prediction information when other sensor types cannot “see” the object of interest.

Commercial Space Situational Awareness

The USAF Space Surveillance Network (SSN) has been in existence for well over 50 years and currently consists of a network of optical telescopes and ground based radars. Over the last 50 years, the USAF operated SSN has been the primary system where SSA data is gathered, processed, and distilled into orbital elements through the Joint Space Operations Center (JSpOC). These orbital elements often are shared with the broader space community through public dissemination channels. The intent of this sharing was to make space a safer place to operate by maintaining track on the large number of objects in the various orbital regimes. However, this heritage of public SSA is changing.

In June of this year, President Trump established a series of space policy directives. These directives are an acknowledgement of the changing use of space as more and more commercial entities begin to operate in space, largely made possible by the drastically lower satellite manufacturing and space launch costs. These reductions in costs are a direct result of new entrants in the Aerospace Industry that seek to commercialize the process of getting to the “high ground”. Along with these financial changes, nation states have begun to operate with a greater presence in space. Countries such as China and Russia are now using space in much more significant roles for commercial and military purposes. The end result is an acknowledgement that, from a USAF perspective, space is a new theater where conflicts can take place. Given the US military’s high dependence on space for warfighting, the Administration has chosen to separate the peacetime needs from the military needs of space. In the future, the USAF will focus on the military mission, public SSA and Space Traffic Management (STM) is to be turned over to civil agencies. As part of this change, commercial SSA entities are being encouraged to lead - excerpt from Space Policy Directive 3, Section 4, Goals (c)

> *“Encourage and facilitate U.S. commercial leadership in S&T, SSA, and STM. Fostering continued growth and innovation in the U.S. commercial space sector, which includes S&T, SSA, and STM activities, is in the national interest of the United States. To achieve this goal, the U.S. Government should streamline processes and reduce regulatory burdens that could inhibit commercial sector growth and innovation, enabling the U.S. commercial sector to continue to lead the world in STM-related technologies, goods, data, and services on the international market.”*

This policy excerpt clearly states that the opportunity space is open for commercial companies to create business models around S&T, SSA, and STM with the expectations that the US government will foster such endeavors.

Commercial RF Monitoring

Commercial based RF Monitoring adds to the growing list of companies that are performing commercial SSA in support of STM. One example of a commercial RF sensing network is the Kratos RT Logic network of EMI monitoring systems. This network is a collection of RF sensors that provide SATCOM monitoring and geolocation services to commercial and government users. The system is used to detect terrestrial interference on SATCOM transponders and when detected, geolocate the source of the interference using two satellite geolocation techniques. Interestingly enough, these same techniques are the foundation for the Passive Ranging and Orbit Determination approach referenced above. In order for a network to be useful for passive sensing, the network must be global in coverage with large geographic diversity between collection points. Each sensor site must have access to network connectivity back to either a main datacenter or a cloud based system and be capable of highly accurate timed captures of digitized signals.

Figure 8. Commercial Global RF Monitoring Sites

In Kratos RT Logic's solution each antenna location hosts multiple sensors connected to a suite of specialized signal processing equipment to create a standalone network that utilizes commercial leases for network communications over encrypted links. The current configuration includes 21 worldwide monitoring sites hosting 80+ antennas with visibility to the majority of the GEO belt, currently monitoring 60 satellites, 200+ beams and 300+ transponders. The system hosts a main datacenter in Colorado Springs, Colorado as well as high bandwidth pipes to Amazon Web Services EC2 instances where big data techniques and off-site data storage is managed.

System Architecture

The System Architecture for this global network relies on both local processing equipment and Amazon Web Services EC2 instances. The local processing equipment consists of carrier monitoring systems, local data buffer capture systems, narrow and wideband digital capture systems, as well as generic processing power for running software intensive algorithms. In fact the majority of the Passive RF SSA processing is performed in software using Virtual Machines. The Virtual Machines host a variety of software modems, data recorders, DSP algorithms for blind characterization, and TDOA/FDOA measurement logic. The local processing is intended to handle the raw signal data extracted from the digitizing systems where all downstream processing works off of the same Inphase and Quadrature (I&Q) data streams. The conceptual architecture is shown in Figure 9.

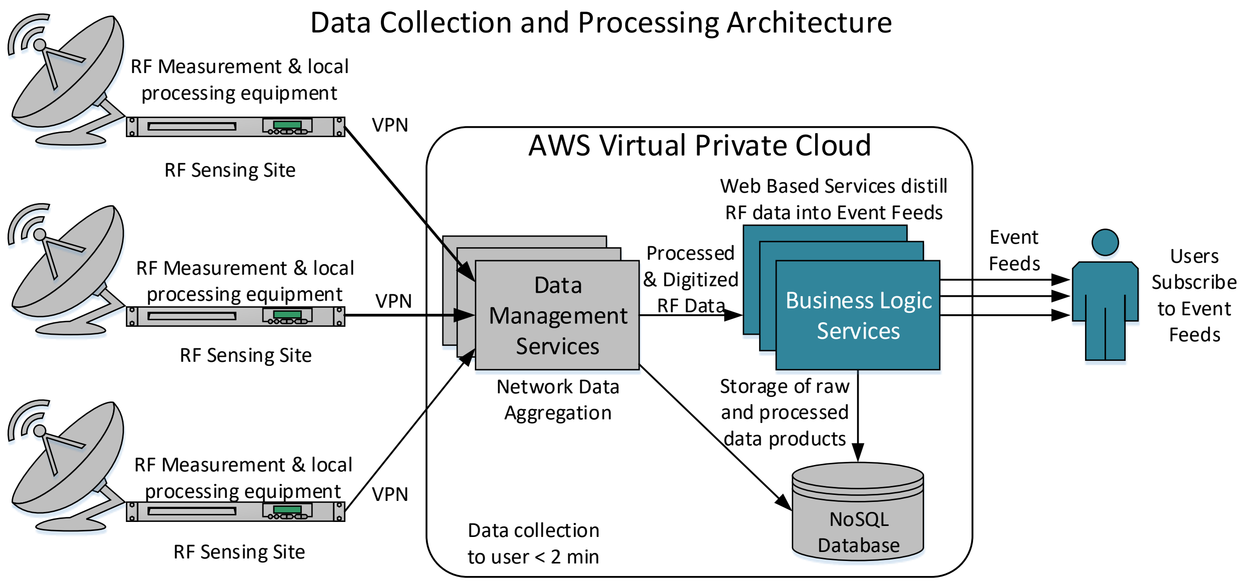

Figure 9. Data Collection and Processing

Data aggregation and SSA processing is performed in a series of services that hold the business logic of the system. These services are broken into a set of capabilities and infrastructural components for the processing data flows. The capability-based components are responsible for the major operations of the architecture, namely functions like maneuver detection, passive ranging, and EMI processing. The services are lightweight software components that interact using RESTful interfaces in a Service Oriented Architecture (SOA). Elaboration of the Data Collection and Business Logic Service Components is shown notionally in Figure 10.

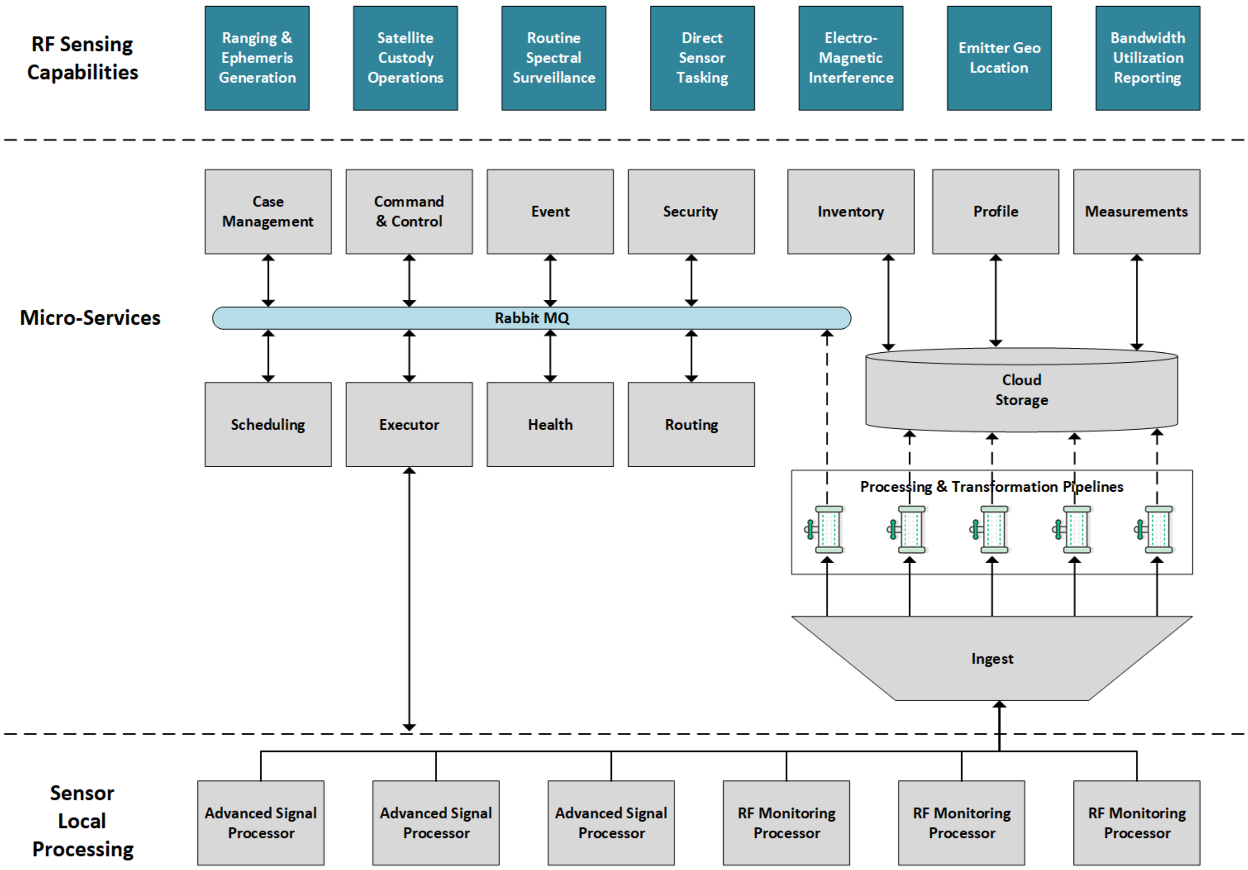

Figure 10. Service Oriented Architecture

This architecture uses primarily Java components for the standalone services, though Python components are used when necessary. For data ingest, Kinesis pipelines are used to move data from the local processing equipment into the AWS EC2 system. AWS Lambda functions are applied on the streams as necessary to massage the data into the necessary formats for processing and archival. The data archival currently uses PostgreSQL databases to host static data on satellites, antennas, site locations, etc. Dynamic data also uses PostgreSQL as the database currently though other solutions are being researched as the data grows. Currently this system holds well over 10 Terabytes of RF data.

Summary

This paper sought to bring to light the benefits of Passive RF sensing in support of Commercial SSA. First and foremost, the capabilities of Passive RF sensing stated above demonstrate how the phenomenology can support maneuver detection in real time, provide patterns of life and discern anomalies in satellite behavior, and is capable of providing ranging data necessary for orbit determination. Next an architecture for how a passive RF sensing network is assembled and the qualities necessary for such an architecture was explained. Finally, details of the changing roles of the US military and the SSA mission are creating opportunities for commercial companies to enter into this new and emerging marketplace. In conclusion, by connecting all of these elements, capabilities, architecture, and the move to commercial SSA operators, that Commercial Passive RF sensing is the new third leg to the triad of SSA sensors.