# Assessing passive radar for LEO SSA

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**ABSTRACT**

In this paper we provide an overview of the passive radar concept before covering capabilities and opportunities for low Earth orbit (LEO) Space Situational Awareness (SSA). Using a unique selection of data obtained from Silentium Defence's MAVERICK-S radar, this work will demonstrate the benefits that passive radar offers for SSA and how it may form part of a complementary suite of SSA sensors.

## 1. PASSIVE RADAR CONCEPT

Passive radar is a form of radar that instead of using a dedicated transmitter, as is the case for traditional radar, utilises radio frequency (RF) energy already in the environment. The transmitter exploited in a passive radar system is typically non-cooperative (and hence known as an illuminator of opportunity) and can be located at a considerable distance from the receiver. This places the passive radar into a bistatic configuration and requires the passive radar system obtain a reference copy of the transmitted signal, in addition to the reflected signal from the target, for processing.

There is an abundance of existing energy available from geographically diverse sources that may be exploited by a passive radar system to suit the desired application and surveillance region. These sources range from fixed site terrestrial broadcasts (e.g., television and radio) through to rapidly moving spaceborne communications systems. Further, compared to a traditional pulsed-Doppler radar which transmits bursts of energy over a narrow sector, some of these sources may transmit continuously and can simultaneously illuminate a very broad area.

A representation of a passive radar system for space surveillance is shown in Fig. 1. Energy from the transmitter propagates along the paths shown in red, illuminating multiple RSOs over a broad angular extent as well as providing a reference signal at the radar site. The reflected energy from the RSOs, shown in white, is then received by the passive radar surveillance array for processing with the reference signal.

Passive radar employs signal processing and beamforming techniques that enable coherent integration periods of the order of several seconds to be achieved. This integration period is selected to strike a balance between the target's relative motion, and the energy required to achieve a sufficient signal-to-noise ratio (SNR) for detection.

The native measurement space for a passive radar is frequency difference of arrival (FDOA), time difference of arrival (TDOA), and 2D angle. This measurement space allows location and velocity to be calculated on each measurement frame.

Without the need to operate the transmit infrastructure, and with the broad illumination afforded by the illuminators, passive radar offers wide field of view coverage, long observation times, and lower operational costs. Passive radar can also operate continuously, regardless of the time of day or weather conditions, to enable observations to be conducted uninterrupted. Furthermore, unlike passive RF systems that operate by detecting signals transmitted by the RSO, passive radar detects both active and passive RSOs.

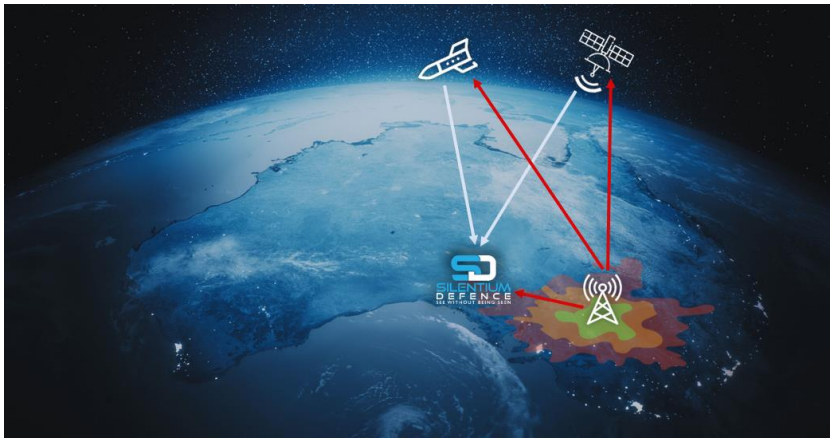

Fig. 1 Passive radar concept

The abundance of illuminators opens opportunities to exploit multiple sources simultaneously, placing the passive radar into a multi-static configuration. This provides three significant benefits to the passive radar system. It:

- increases the spatial coverage which, depending on the scenario, may allow additional RSOs to be simultaneously tracked, and RSOs to be tracked for longer periods
- increases detection opportunities by affording different incident angles on to the target, and hence radar cross section
- improves the track accuracy as a result of the additional measurement information available.

Passive radar has made significant inroads as a disruptive technology across multiple markets and surveillance applications over the last decade. Silentium Defence was founded with the purpose of providing passive radar for Australian and international markets across defence, space and commercial applications.

## 2. APPLICATION TO LEO SSA

Low earth orbit (LEO) is becoming an increasingly congested and contested region with more than 450 emergency reportable public conjunction data messages issued daily. The dramatic increase in commercial space traffic over the last 5 years requires operators to routinely assess and negotiate manoeuvres to avoid any loss of capability. This makes LEO a highly dynamic environment, increasing the need for custody of all RSOs to minimise the uncertainty of their state. Current SSA data is incomplete and monitoring these objects is a resource intensive and time-consuming operation, especially for a narrow field-of-view sensor. The inability to track many of the objects currently detected, and forces other than gravity altering an object's orbit, highlight issues with maintaining custody of objects in LEO.

The application of passive radar to space surveillance has been investigated in several forms with a particular focus on the reuse of radio astronomy systems such as the Murchison Widefield Array [1-4]. Silentium Defence's MAVERICK-S system however is the first purpose-built SSA sensor utilising this technology.

Silentium Defence has recently opened its first observatory hosting the MAVERICK-S sensor. Developed with the support of the Australian Space Agency, and called 'Oculus', the observatory is positioned within a 180-ha parcel of land located in a rural area north east of the city of Adelaide in South Australia. Offering a near unimpeded horizon-to-horizon view and located on the outer edge of a dark-sky reserve, this site is also well positioned to host complementary SSA sensors. Two views of the observatory are shown Fig. 2 with the MAVERICK surveillance array on the right and the operations compound to the left.

Exploiting FM radio broadcasts and constructed as two orthogonal arms, each currently operated with 32 elements, the MAVERICK surveillance array affords a steerable beam with beamwidth of 4 degrees. Transmissions from up to 24 radio stations from 7 broadcast sites extending up to 490 km from Oculus are exploited for SSA. This is shown in Fig. 3 and provides access to approximately 3 MW of continuous radiated power across much of the south east of Australia.

Fig. 2 Silentium Defence's Oculus observatory and the MAVERICK-S passive radar


Fig. 3 Transmitter sites exploited for SSA from Oculus

## 3. SENSOR CAPABILITIES AND OPPORTUNITIES

Silentium Defence has been operating the MAVERICK SSA sensor at the Oculus observatory as part of a continual capability development and test program since late 2021. Over that period data has been collected on a variety of RSOs including operational satellites and debris. Analysis on aspects of this data is presented in this section focusing on instantaneous measurement, particularly bias and residuals in three measurement dimensions, field of regard, and ability to resolve objects in the Doppler dimension. Analysis drawing on the benefits afforded by the multi-static capability will be presented in a later work..

### 3.1 Measurement Assessment

Test data on two calibration quality RSOs – SWARM-C (NORAD ID 39453) and ICESAT-2 (NORAD ID 43613) was collected from late February to early March, 2022, as seen in Fig. 4. The goal was to investigate the measurement accuracy and system performance. High accuracy reference ephemeris for these was obtained from the International Laser Ranging Service, and following the procedures outlined in [6] a series of calibration runs were performed using Ansys' Orbit Determination Tool Kit (ODTK) [7]. The measurements consisted of azimuth and elevation angles (relative to the receiver) and bistatic time difference of arrival (TDOA) between each transmitter and the receiver. There is not currently a measurement model for this bistatic configuration of FDOA in the ODTK, and analysis of this measurement space will be reported later.

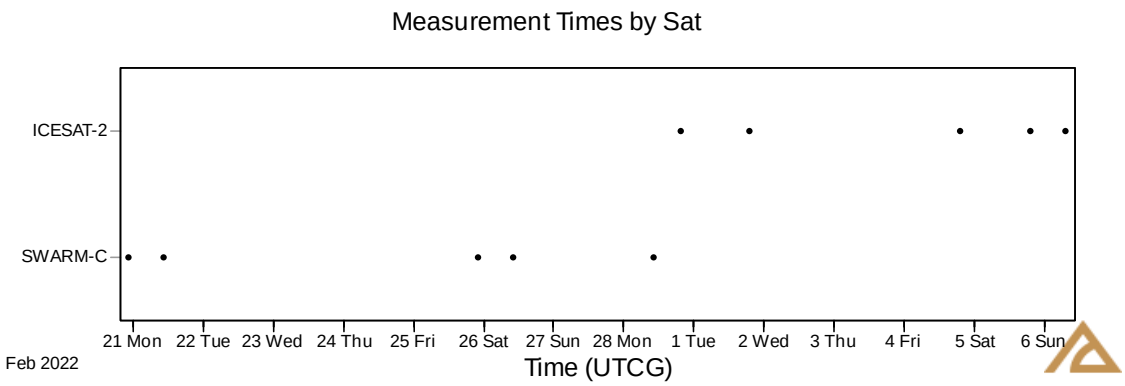


Fig. 4 Data collection times

The measurement residuals were calculated relative to the reference ILRS ephemeris to establish an initial first guess at the measurement white noise sigma and to identify any biases. The angle residuals in Fig. 5 and 6 show some variability in the white noise sigma and biases from pass to pass. The TDOA residuals in Fig. 7 appear unbiased with some variability in the white noise sigma from pass to pass.

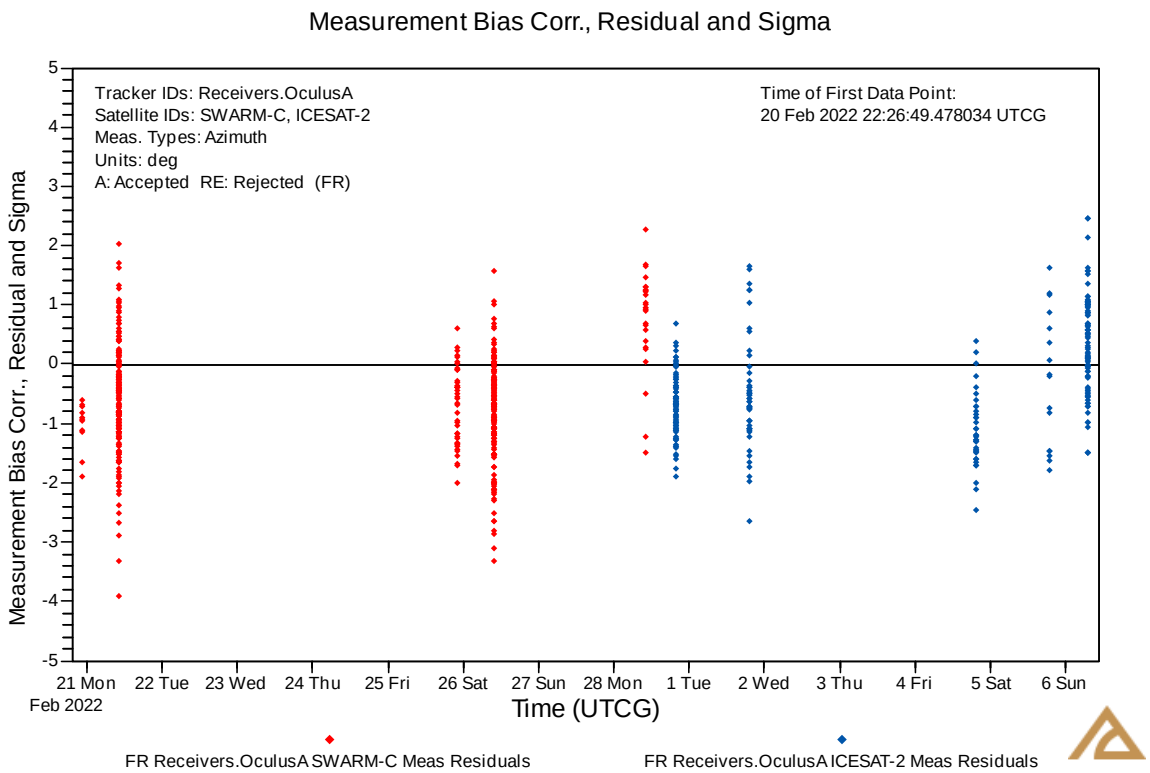


Fig. 5 Azimuth residuals using the reference ephemeris

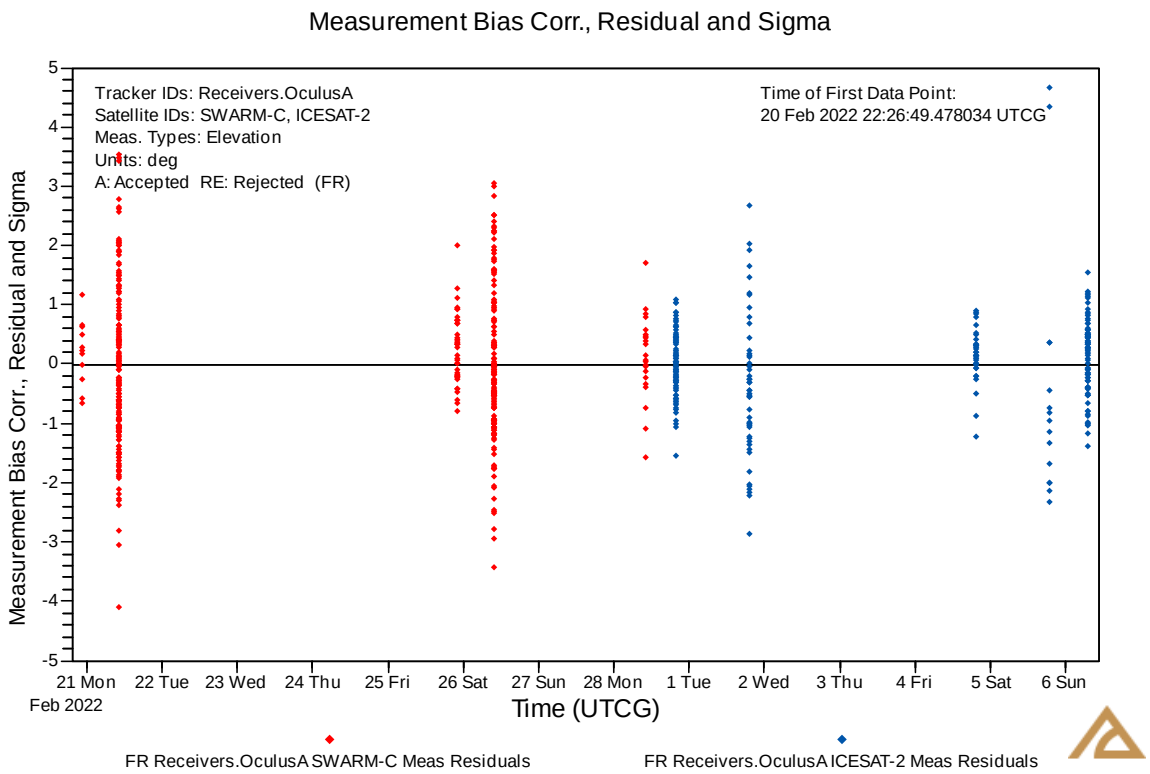


Fig. 6 Elevation residuals using the reference ephemeris

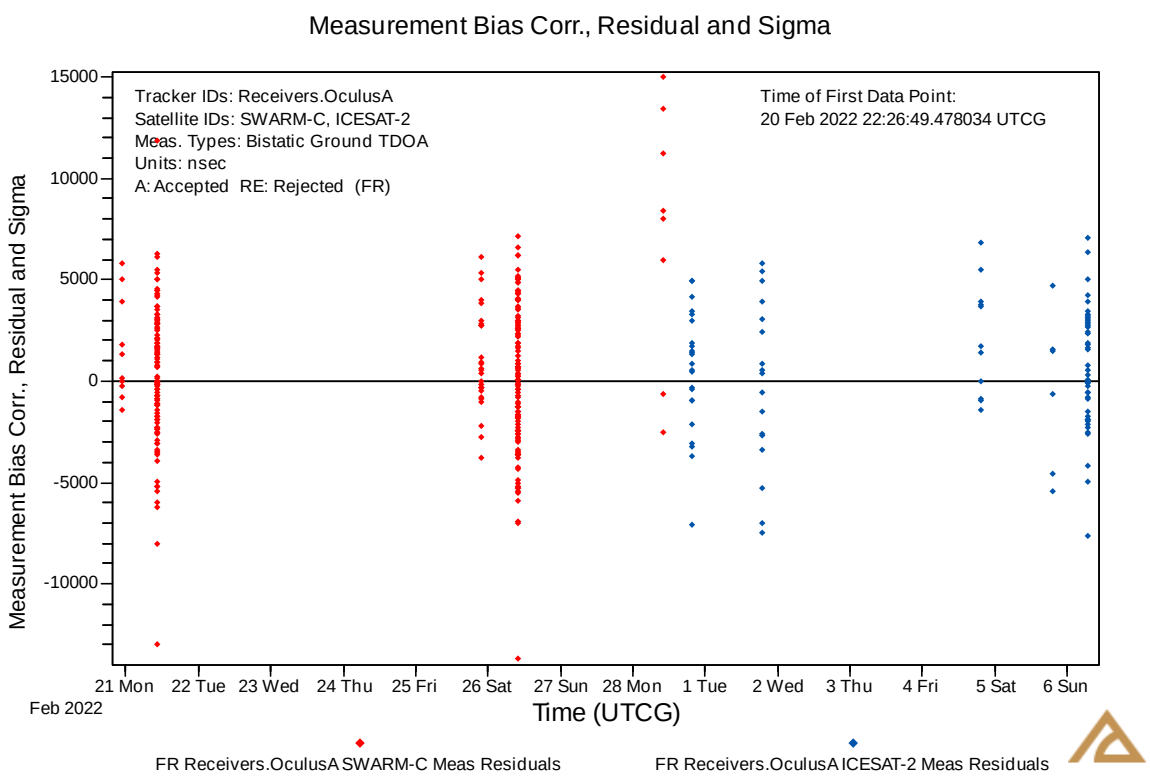


Fig. 7 Bistatic Ground TDOA residuals using the reference ephemeris

The next set of runs estimated the measurement biases and fine tune the white noise sigma. The RSO position and velocity states were obtained from the reference ephemeris, but we let the filter and smoother estimate the measurement biases. The resulting calibrated measurement statistics are shown in Table 1. The TDOA measurement accuracy is fundamentally driven by the bandwidth of the RF signal used for correlation (a relatively narrow FM radio station in our case).

Table 1. Measurement Statistics

| Measurement | White Noise Sigma | Bias | Bias Sigma | Bias Half Life |
|---|---|---|---|---|
| Azimuth | 0.85 deg | -1 deg | 0.75 deg | 5 days |
| Elevation | 1 deg | 0 deg | 0.5 deg | 5 days |
| Bistatic Ground TDOA | 3100 ns | -2900 ns | 200 ns | 10 days |

Finally, we directly estimated the SWARM-C orbit state, ballistic coefficient, and solar radiation pressure coefficients using the five passes of data. The state and covariance were initialized using a least squares fit, then the filter and smoother were used to estimate the parameters. The resulting residual ratios, and filter and smoother position uncertainty (1-sigma) are shown in Figs. 8-10. The large growth in the intrack uncertainty after the second pass is caused by the filter not having fully converged and sorted out all the cross correlations yet, combined with a 4.5 day data gap. The subsequent passes show significantly better performance as the filter solution improves. The smoother uncertainty shows a definitive orbit accuracy of less than 1 km intrack, even at the end of the run. Increasing the bandwidth of the RF signal will improve the measurement accuracy and ephemeris uncertainty. The tracking data passes used for this analysis were less than a minute long. Longer passes are easily obtained and will also improve the observability. FDOA offers the highest resolution of the measurements dimensions and looks very promising. We are continuing to test including those measurements into the overall solution as well and anticipate significant improvements in performance.

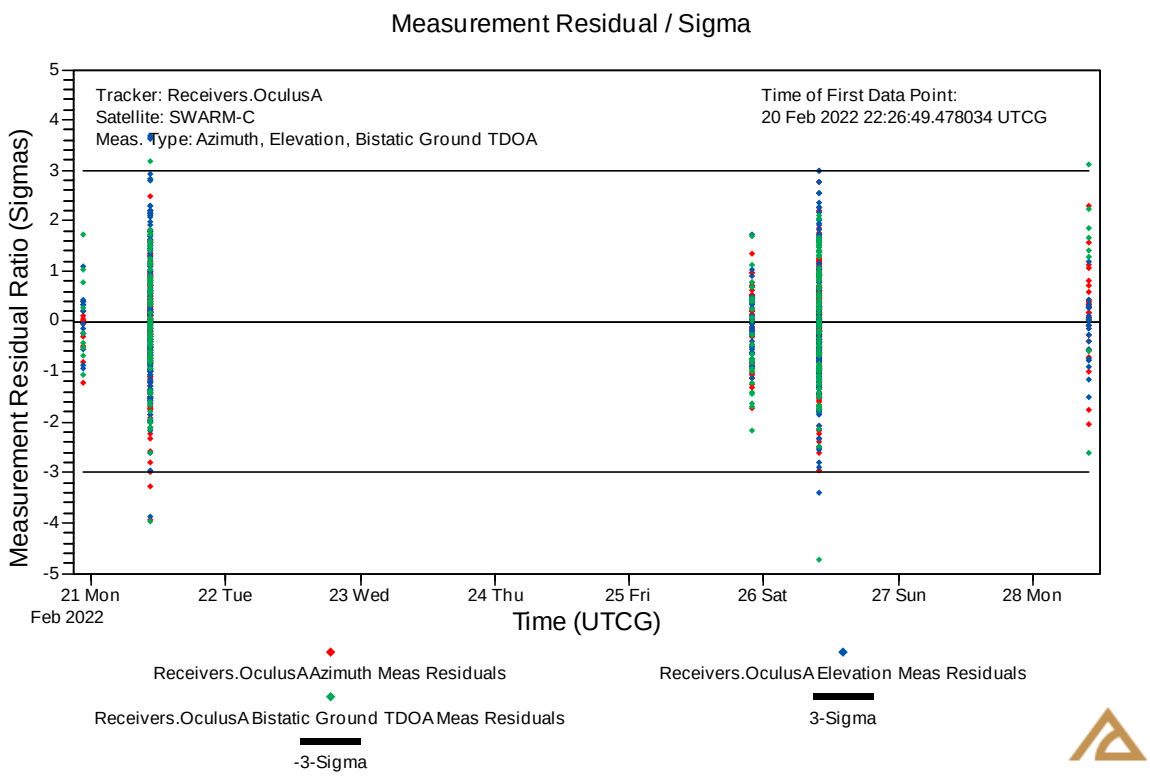


Fig. 8 SWARM-C residual ratios

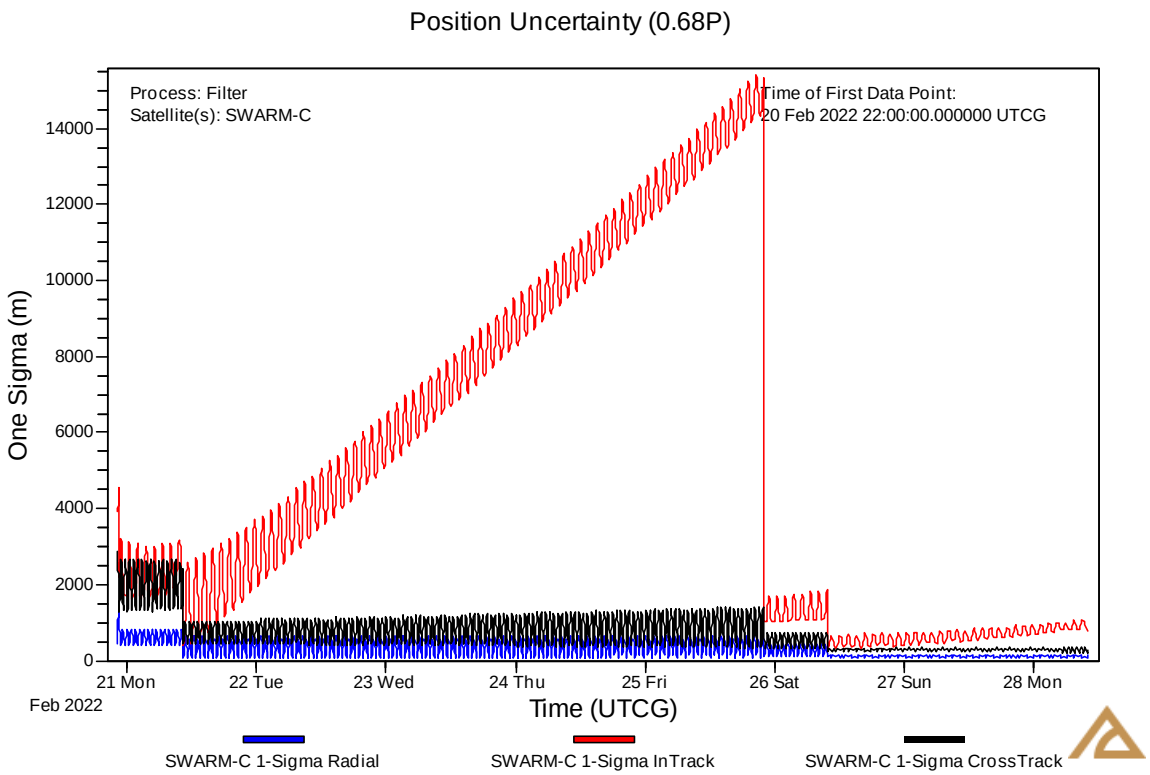


Fig. 9 SWARM-C filter position uncertainty

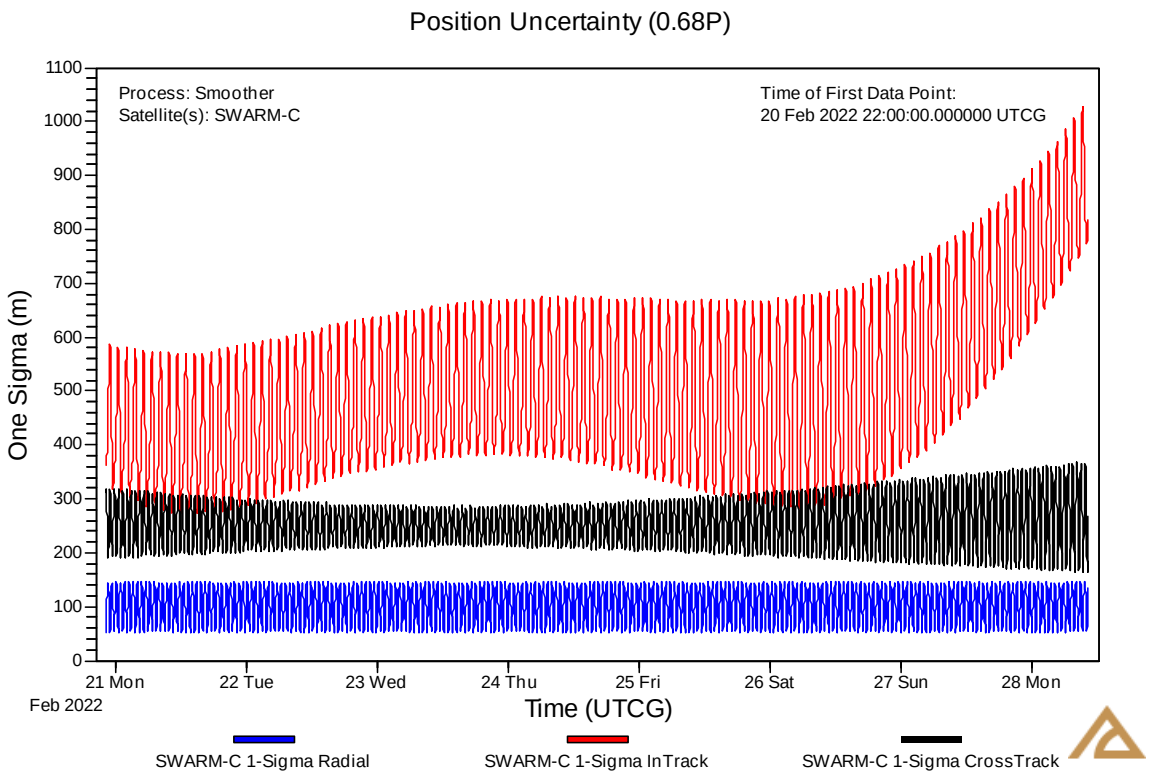


Fig. 10 SWARM-C Smoother position uncertainty

### 3.2 Field of View and Track Duration

The MAVERICK-S sensor located at the Oculus observatory has a wide field of regard (FOR), allowing RSOs to be detected and tracked at large offsets in two angular dimensions. Fig. 11 shows a heatmap of data collected on a selection of 225 Starlink passes (all between 540 km and 580 km altitude) over an extended duration during system testing. This image also represents the field of view (FOV) for objects at this altitude and size, as the FOR is identical to the FOV for the MAVERICK-S sensor. The coverage area represented in the figure is limited by the selection of passes and is approx. 260,000 km$^2$. Larger RSOs have been observed at elevation angles less than 30$^o$ and more than 1,500 km from the observatory.

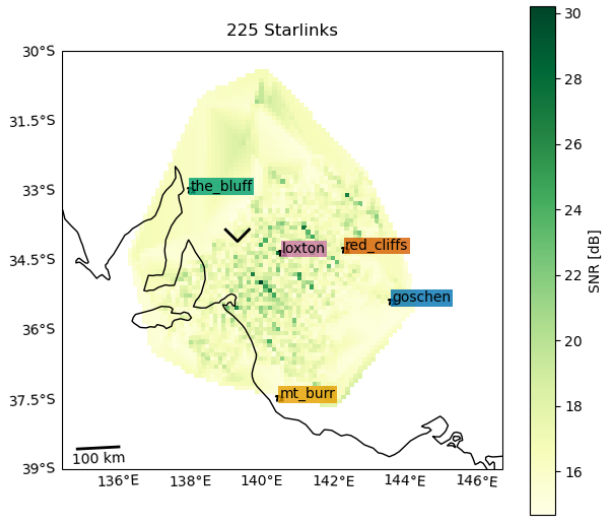


Fig. 11 Heat map of Starlink observations showing the FOR

### 3.3 Resolution in Doppler

The relatively long coherent integration times achievable with a passive radar afford the MAVERICK sensor a fine Doppler resolution not achieved with traditional radar systems. This allows RSOs that are spatially close to be resolved despite potentially falling within the same TDOA measurement bin. This capability is shown in Fig. 12 for the Tianhui 2-02 A/B pair of RSOs (NORAD ID 49071, 49072) which were sitting within 5 km of one another at the time of measurement. These measurements are plotted relative to the published TLE for 49072 and show a separation of approx. 6 Hz, equivalent to 30 Doppler bins.

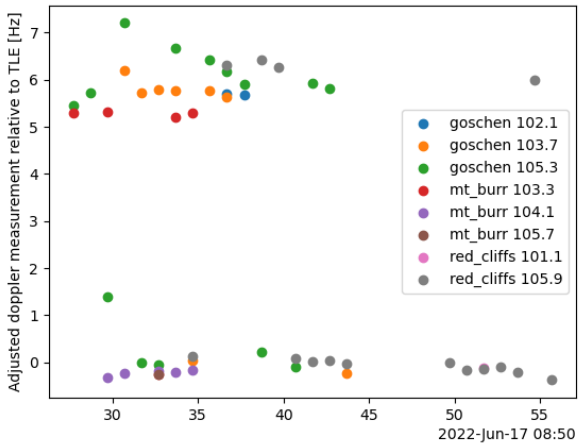


Fig. 12 Doppler measurements of two closely spaced RSOs

### 3.4 Role in Suite of Complementary Sensors

The MAVERICK-S sensor is an affordable, deployable, and scalable complement to the existing suite of sensors utilized by the COMSPOC. The combination of a wide field of regard, multi-object tracking, and immunity to weather and lighting constraints offers significant flexibility. Because the sensor takes advantage of existing in-situ transmitters, new sensors can be deployed without requiring RF licensing coordination. Deploying multiple MAVERICK-S sensors around the world will provide persistent, frequent coverage. Combining this with other LEO sensors such as active radars and optical tracking will significantly improve LEO SSA knowledge.

## 4. FUTURE WORK

Silentium Defence, in collaboration with COMSPOC, is engaging the market with SDA products from the Oculus observatory. Future work will seek to maximise value to customers and may include such elements as:

- reducing latency and simultaneously increasing capacity, potentially providing observations on several thousand RSO passes per day
- increasing the sensitivity of the system with the aim of providing observations beyond the current minisatellite (100-500kg) capability to the lower end of microsatellites (10-100kg)
- exploiting transmitters on longer baselines (with subsequent increase in coverage and observation duration)
- operating multiple surveillance locations, both in Australia and internationally
- exploitation of the multi-statics and fine Doppler resolution to provide RSO characterisation capabilities.

Forthcoming upgrades to the sensor will see the surveillance array double in aperture. This will increase the sensitivity, improve angular accuracy of the instantaneous measurements, and enlarge the FOV/FOR (and subsequently increase the track duration) referenced to RSO size and altitude.

In subsequent papers the role of multi-static measurements in improving the position accuracy will be explored.

## 5. CONCLUSION

In an increasingly congested LEO regime, the task of maintaining custody of objects cannot be filled by traditional sensors alone. The unique passive radar capability for SSA developed by Silentium Defence is well positioned to become the workhorse of catalogue update in a complementary sensor suite.

Silentium Defence in collaboration with COMSPOC have demonstrated the initial capability of the MAVERICK-S sensor at Oculus. The assessment of instantaneous passive radar measurements in the TDOA and 2D angle dimensions, together with the wide FOV/FOR and ability to resolve closely spaced objects, introduces this technology's capabilities in SSA applications.

## 6. REFERENCES

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