Earthfence: Global Expansion of an Unclassified Deep Space Radar Capability

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Abstract

We describe the global expansion of ThothX's (thothx.com) novel deep space radar technology called Earthfence. Earthfence is a software defined pulse compression radar technology that enables operators of large aperture antennas to repurpose them into GEO capable monostatic radars. Originally developed and now deployed on ThothX's 46 m parabolic antenna near Ottawa, Canada's largest full steerable antenna, Earthfence observes resident space objects up to one hundred million meters in range and provides meter scale range accuracy in near real time and with industry leading latency, cadence and automation. Operating in C-band, the solution is fully digital, the radar return pulses digitized in complex quadrature after low-noise amplification and forwarded for analysis by a supercomputer cluster that applies radar processing algorithms including pulse decompression. The system live streams results without human-in-the-loop intervention to repositories including the Unified Data Library where ThothX regularly contributes radar observations of GEO spacecraft during Sprint Advanced Concept Training (SACT) events, a joint initiative of Space Force and the Department of Commerce. Using novel hardware technology and very low amplifier power levels in comparison to traditional radars, Earthfence is virtually undetectable by the target under observation making it inherently resistant to jamming or interference. Earthfence's high accuracy results rely for calibration on a hydrogen maser frequency standard only.

In contrast to ground-based optical systems where sensor availability may be 20% or less, radar provides a methodology to observe RSOs at any time of day, under all weathers and with little or no solar exclusion and an availability exceeding 98%. We present results from recent work under a technology demonstration program for Defence Research Development Canada to demonstrate the radar's performance including a capability to continuously observe targets over periods exceeding days for applications including Rendezvous and Proximity operations (RPO) monitoring and to meet technology milestones such as an observation cadence less than 30 seconds. We will present results on Earthfence's ability to discriminate closely spaced objects. We outline our roadmap to increase detectivity to a capability that can detect objects the size of a football in GEO (Radar Cross Section of 0.16 meters squared) to meet at a fraction of the cost, a performance level similar to the United States Space Force's proposed Deep Space Advanced Radar Capability (DARC) program.

Recently, Thoth has partnered with MDA (mda.space), Canada's leading space technology company, to provide an operationalised solution for the Canadian government, and we present results from this collaboration including software and hardware upgrades and a program to apply Inverse Synthetic Aperture Radar (ISAR) to the imaging of GEO belt objects as well as other object characterization techniques that are under development. We describe various technology initiatives to extend Earthfence's radar capability to Low Earth Orbit (LEO) and to integrate Earthfence observations with NEOSSat, a space-based optical sensor. We report on a Directed Learning Objective to enhance Canada's response to on-orbit GEO events in an event simulating an operator-based emergency.

Lastly, we will describe our program to expand our existing America operations to Pacific and European theatres to provide global commercial coverage of the GEO belt where ThothX is refurbishing existing C-band antennas for radar service including a 30-meter antenna in Western Australia. Combined, these assets will provide near global coverage and a continuous, unclassified, radar-backed space situational awareness data service. Global deployment of Earthfence will enable 24/7 surveillance of critical GEO assets using a key sensor architecture that can underpin a robust civil space traffic management plan for GEO assts and provide the low latency, high revisit rate SSA data service that is needed to secure this crucial orbital regime.

2. Introduction

ThothX is a US company based in Colorado Springs that brings advanced radar sensing technologies to Space Domain Awareness and offers Deep Space Radar data as a service to qualified clients. It's Earthfence radar technology is proven to be capable of observing spacecraft in high Geostationary orbit.

Earthfence is a ground-based system that uses large aperture radio antennas to range and image spacecraft up to 100,000 kilometres from Earth. The primary application is the monitoring of Geostationary Orbit (GEO) where some of the most expensive assets are parked and provide services critical to the modern way of life. Developed entirely commercially, Earthfence is a proprietary software defined pulse compression radar system with a signal to noise that enables observation of space objects over ranges of millions of meters. ThothX's North America station, located near Ottawa in Canada is fully operational and has been demonstrated in operation during a series of validations of technical performance.

3. **Accuracy**

Earthfence DSR accuracy calibration was achieved in collaboration with Exa Research and COMSPOC. The Figure below shows measurement residual comparisons with three spacecraft, SES-15, Galaxy 30 and Eutelsat 117 WEST B each which carry a payload that includes a GNS sensor system.

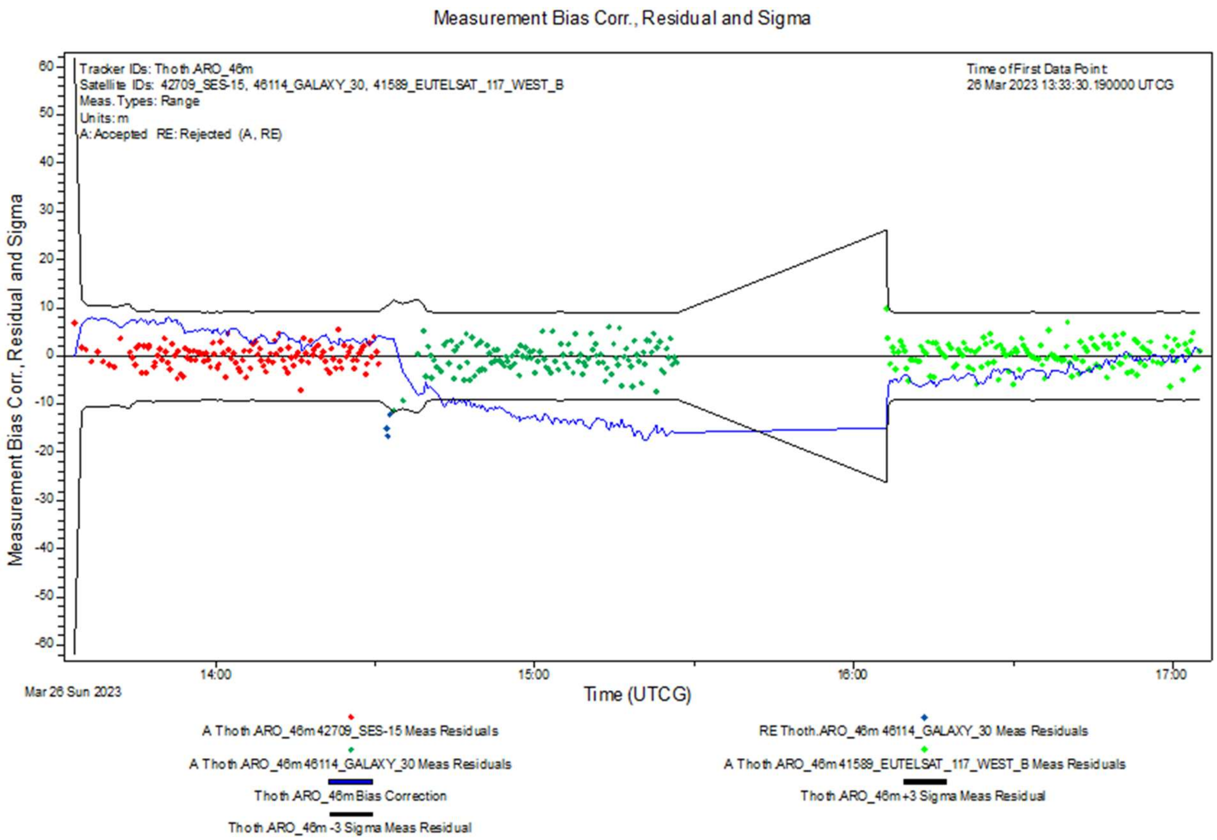


Fig. 1 Earthfence DSR Range Residual Validation (courtesy: Exa Research)

The results from the metric testing show that the performance capability of the Earthfence Deep Space Radar is well within specifications and achieving meter scale precision and 25-meter accuracy at a station range of more than 30 million meters on three spacecraft in differing sky locations and observed in succession. Azimuth residuals are shown in the figure below. There is a small bias that does not significantly impact accuracy, and results are well within the 0.1-degree accuracy specification.

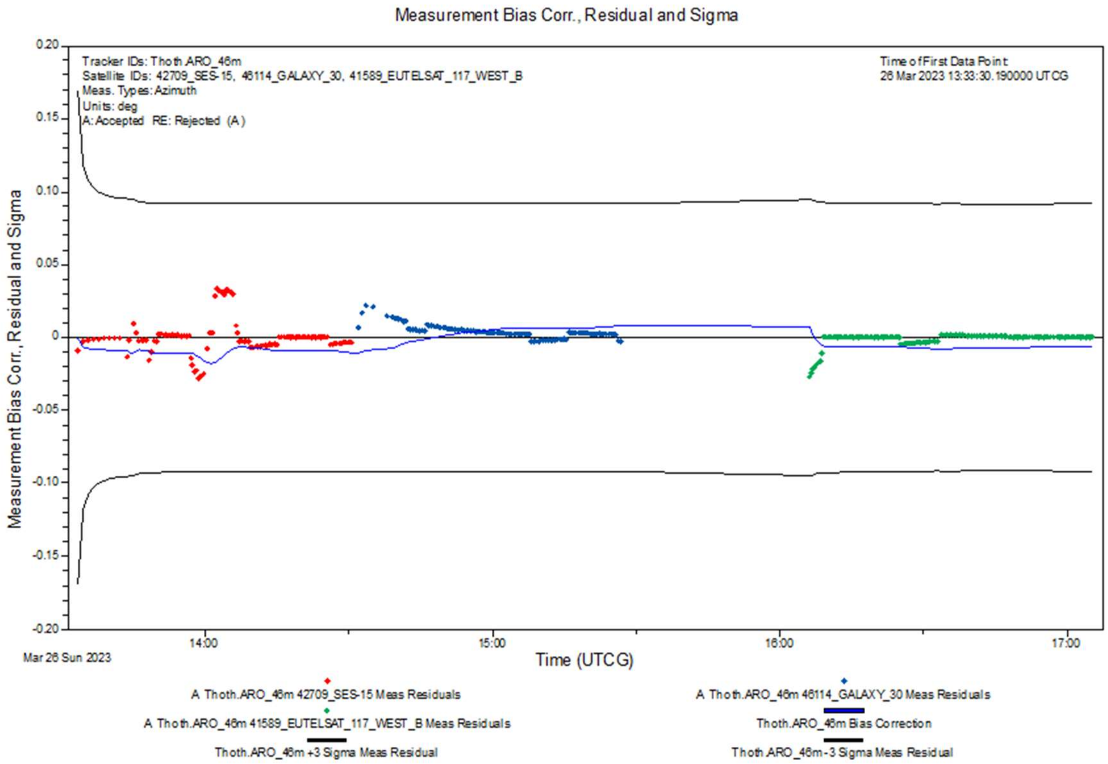


Fig. 2 Earthfence Azimuth Residual Validation (courtesy: Exa Research)

The figure below shows the elevation residuals. There's a small elevation bias of about -0.04 degrees likely because of structural droop induced by thermal effects; however, this is well within the 0.1-degree accuracy metric.

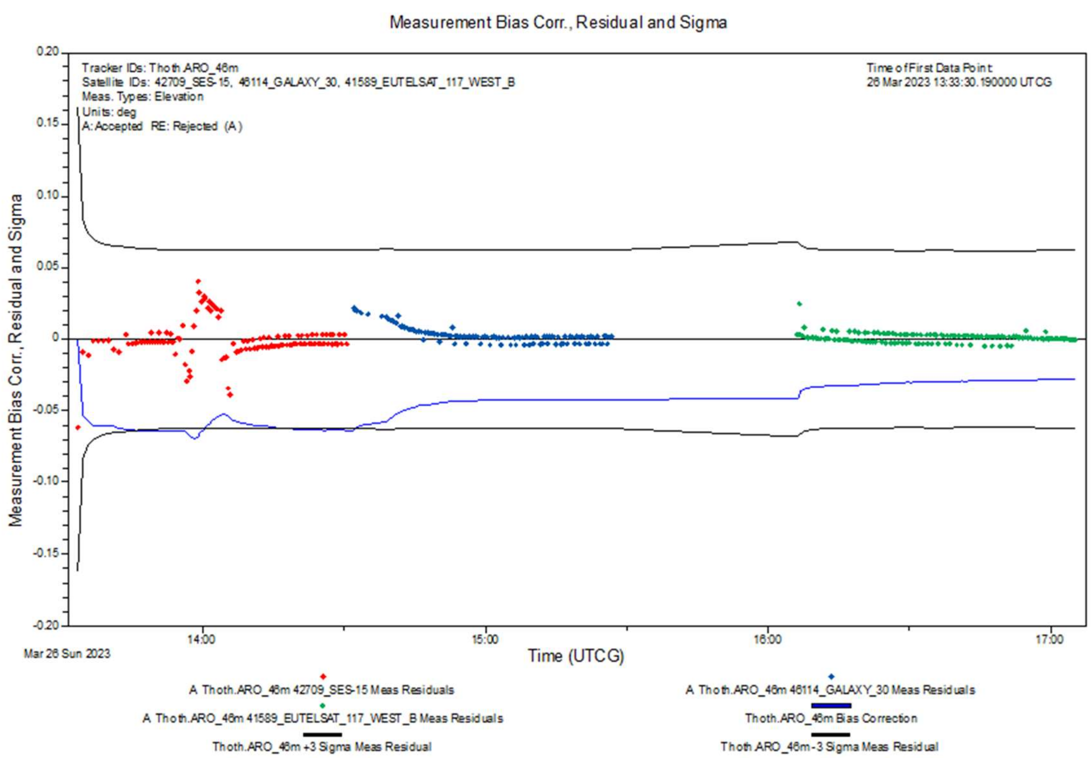


Fig. 3 Earthfence Elevation Residual Validation (courtesy: Exa Research).

4. Quantile-Quantile Range Assessment

A Range Quantile-quantile plot is shown below. The residuals are all well within the error bounds with slope near one. This indicates they are nicely matched to a normal distribution.

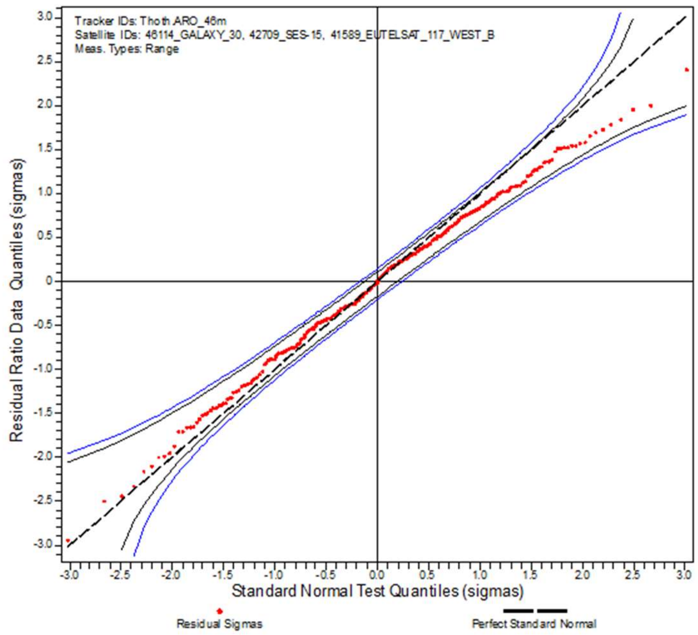


Fig. 4 Earthfence DSR Quantile-Quantile Plot (courtesy: Exa Research).

During the current year ThothX was able to substantially upgrade the existing amplification stages. The commercial of-the-shelf units are modified for radar application by ThothX. The recent upgrade significantly increased the transmit performance of the deep space radar. The radar now calibrates at an output power of +5dB whereas previously the result was -7dB a difference of 12dB (a geometric power advantage factor of 20).

5. Detection Performance Enhancement

ThothX is embarked on a roadmap to increase GEO detectivity to a capability that can detect objects the size of a football in GEO (Radar Cross Section of 0.16 meters squared) to meet at a fraction of the cost, a performance level similar to the United States Space Force's proposed Deep Space Advanced Radar Capability (DARC) program.

Thoth was able to commission the new amplification stage and overcome the technical problems associated with a significantly higher noise environment. Thoth successfully modified its proprietary noise suppression hardware to perform at higher equivalent isotropic radiated power levels and provide enhanced isolation. A quantitative assessment of the performance enhancements based on live radar data was conducted to validate improvements in detection power and radar sensitivity. Additionally, Thoth has discovered other methods to enhance the radars VSWR (Voltage Standing Wave Ratio) which enhanced performance by several Decibels.

Transmission power levels were also compared using Thoth's radar diagnostic characterization system that monitors actual outgoing power performance. Overall, the radar performance on previously observed targets was increased by approximately 10dB (a factor of ten). Thoth conducted a full sky survey to quantitatively assess the actual performance enhancement against real resident space objects.

6. Survey Results

ThothX conducted a recent sky survey of RSOs over a three-day period. Of note, seventy-eight previously undetected RSOs were detected by the upgraded radar, thirty-one of which were observed to be tumbling in their graveyard orbits.

Canadian spacecraft observed include 33453/CIEL-2, 26624/Anik F1, 21726/Anik E1 (launched 1991), 28868/Anik F1R, 28378/Anik F2, 31102/Anik F3, 39127/Anik G1.

United Kingdom spacecraft observed include 26695/Skynet 4F, 33055/SKYNET 5C, 20918/INMARSAT 2-F1, 21940/INMARSAT 2-F4, 24307/INMARSAT 3-F2, 25153/INMARSAT 3-F5, 33278/INMARSAT 4-F3, and 40384/INMARSAT 5-F2

Particularly of note was the observation of 28393/AMAZONAS where the Space Force TLE was 7.3 days old. This illustrates the radar's ability to support catalogue maintenance activities by locating spacecraft where previously there was no observation data available to recompute a TLE. The new results also included the DirectTV cluster.

Other notable observations included radar tracks on Brazilsat B1 (a spin stabilized spacecraft), 20391/COSMOS 2054, 26599/CHINASAT 32 (BEIDOU 1), as well as the recently deployed Galaxy 31, 32, 33, 34, 36 spacecraft. The DSR also detected rocket bodies recording radar observations on 22044/SL-12 RB(2) IUS RB(2), 53962/ATLAS 5 CENTAUR RB, and a DELTA 4 RB.

7. Continuous Custody Observations

As a demonstration of operations capability, ThothX acquired sequences of more than 125 independent radar observations. A recent server upgrade has enabled a significant advance in observation cadence and Thoth is now able to observe continuously at a cadence of 30 seconds or less with results available on the UDL with a latency of less than two minutes. The Figures below show the difference in range between the propagator model and the observed range for the three WAAS calibration RSOs visible to ARO (41589, 46114, 42709/SES-15). The tracks show smooth variation against delta range. The observations are continuous with an interval of less than 30 seconds. The Signal to Noise is estimated at 5 meters or less. These observations were further utilized to provide an independent assessment of metric accuracy described earlier. A continuous custody demonstration over more than twelve hours was also performed and live streams to the UDL during the End-to-End Space Surveillance Exercise.

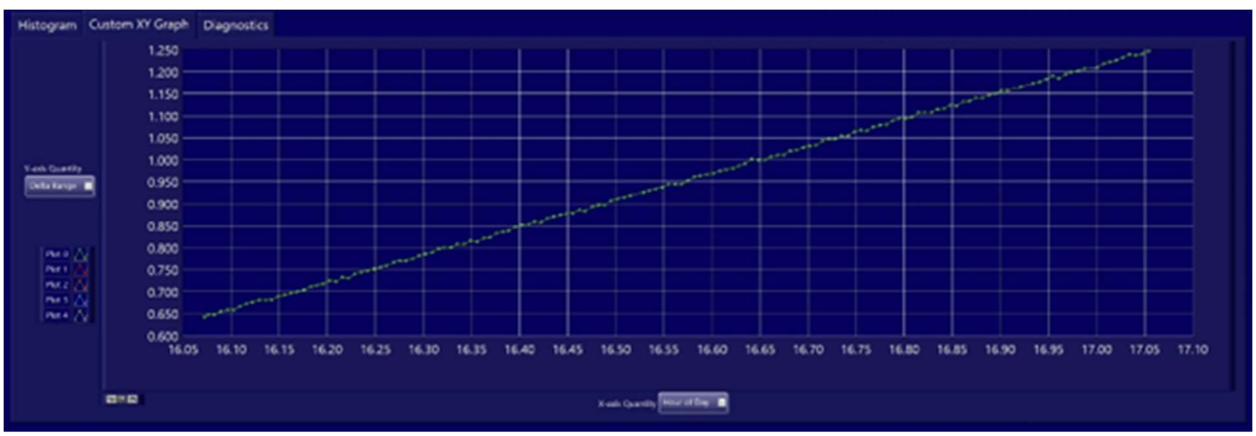


Fig. 5 Continuous Custody Observations (one hour of delta range data in Kilometers shown).

8. Radar Characterization of Resident Space Objects

This section describes an investigation into how Inverse Synthetic Aperture Radar (ISAR) imaging of a satellite in geosynchronous orbit (GEO) may help characterized the object. The work was performed to understand imaging results derived from real Earthfence data with an ISAR algorithm applied. An ISAR image has dimensions of range and cross-range. The transmitted pulse bandwidth determines the resolution in the range direction. The ability to resolve points in the cross-range direction depends on a rotation of the object relative to the radar. The cross-range resolution depends on the Doppler history differences between points separated in cross-range, which in turn depends on the rate of rotation and the observation time. The data for an ISAR image consists of a succession of radar returns that are stacked to form a 2-D array. A Fast Fourier Transform (FFT) in the pulse transmission time direction then separates the Doppler frequencies from different points, to give an image in the dimensions of range and cross-range.

A satellite in GEO is nominally stationary with respect to the radar, except for the solar panels, which rotate to face the sun. In this situation, an ISAR image would only be able to resolve the solar panels in the cross-range (Doppler) direction, whereas the image of the satellite body antenna would collapse to a single line at zero-Doppler. However, real radar observations have shown some cross-range resolution of the satellite antenna, possibly from small oscillations in the attitude of the satellite over time. This effect was investigated by simulation.

9. Combined Ground based Radar and Space based Optical Sensors

The team was recently able to collect simultaneous observations of the same RSA using both ground-based radar and space based optical sensor morphologies, considered one of the most robust sensor network architectures for continuous monitoring of space objects. The residual ratios for TELSTAR 14R are shown in the Figure below that includes SDA data collected by NEOSSat microsatellite and by Earthfence deep space radar. The Figure shows the residual ratios (normalized measurement residuals), that have been divided by the measurement root variance deriving from the orbit covariance and measurement white noise from the OD solution for TELSTAR_14R using data from March 2023. The elements are Earthfence AZ, EL, RANGE and NEOSSAT RA/DEC measurements. The validation goal is to have the points inside the +/-3 sigma bounds. As can be seen from the figure, both sensors are achieving this measurement performance goal.

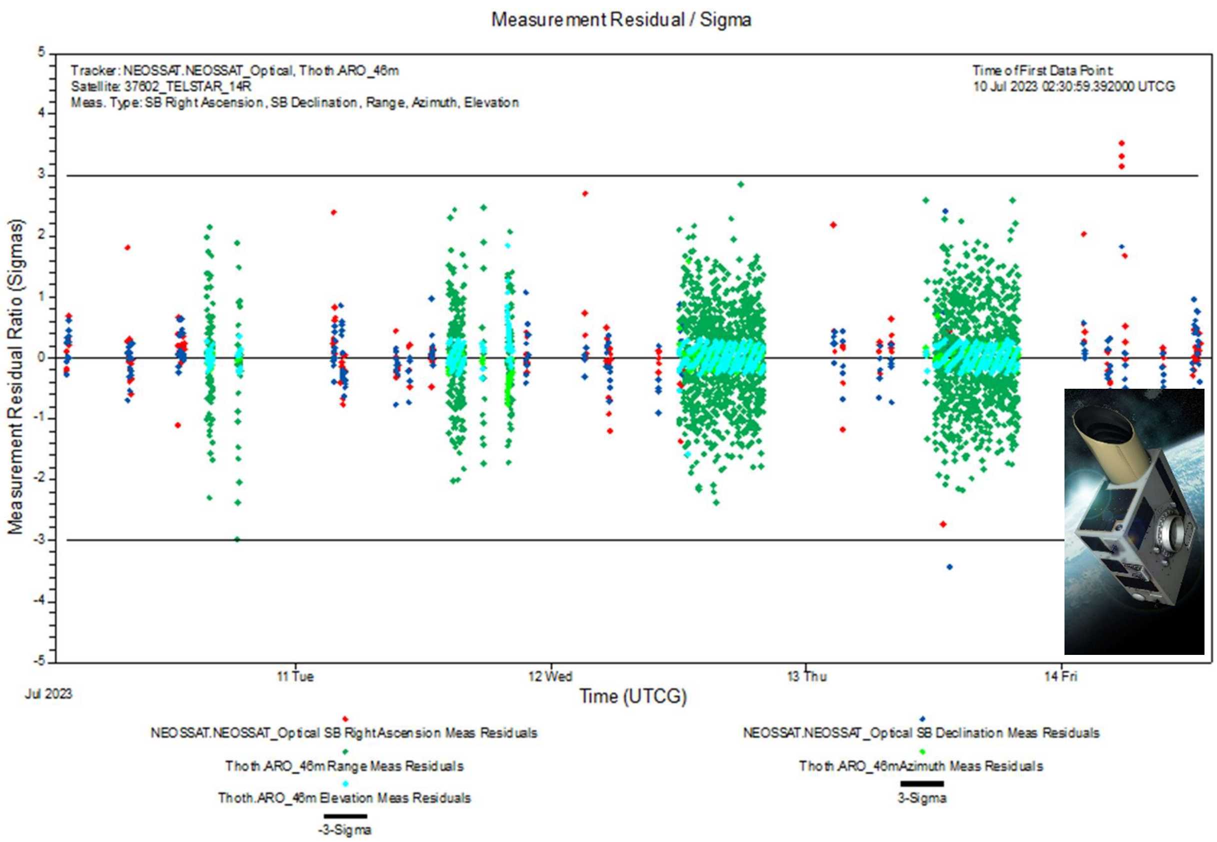


Fig. 6 Measurement Residual Ratios, Earthfence Americas and NEOSSat Comparison.

10. Inverse Synthetic Aperture Radar Simulation

The geometry of the simulation is shown below. This indicates the location of the radar on the earth, and a model of rotating satellite. The points are placed in an ECEF (Earth Centered Earth Fixed) coordinate system which has its origin at the center of the earth, x-axis in the equatorial plane toward the GEO location of the satellite, and z-axis is north. During the simulation, points that represent the solar panels and satellite are first rotated in a local coordinate system with its origin at the center of the satellite. In the figure, arrows indicating the rotation of the solar panels, and the oscillation of the satellite, are shown separately. The solar panels are first rotated in yaw to face the sun, and then the satellite is rotated according to the specified oscillation.

After rotation, the points are translated to the ECEF coordinate system, and the range to each point from the radar is calculated and used to simulate the complex compressed radar pulse returns at each pulse transmission time.

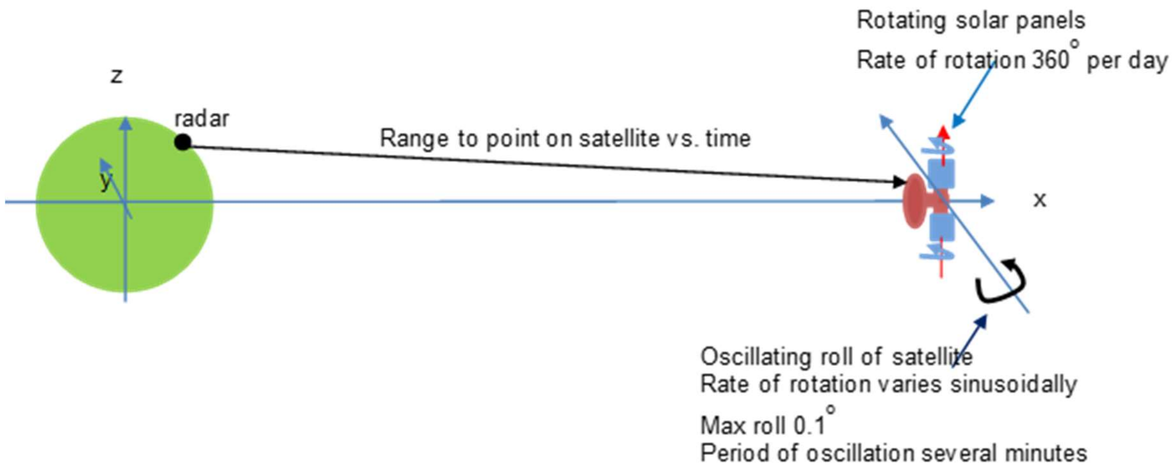


Fig. 7 RSO Simulation Geometry (courtesy: MDA Systems Ltd.)

The Figure below shows the point model, which is meant to represent approximately the shape of the Terrestar-1 antenna with the large reflector antenna on one side. The points representing the solar panels are green, and the satellite body and antenna are red.

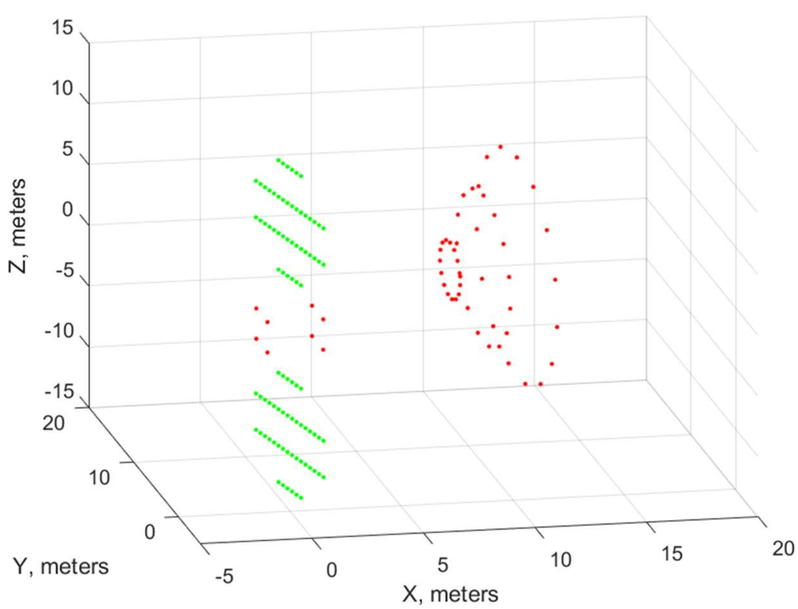


Fig. 8 RSO Simulation Point Model, Terrastar-1 Shown (courtesy: MDA Systems Ltd.)

The Figure below illustrates the yaw of the satellite, which is a rotation about the z-axis. This includes both the yaw of the solar panels, y_{panel}, and the yaw oscillation of the satellite as a whole, y.

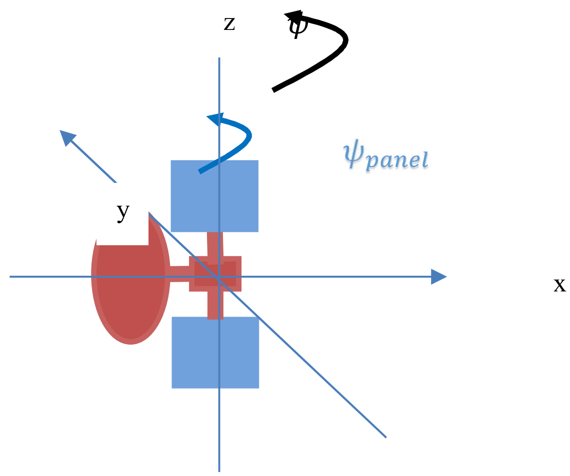


Fig. 9 Illustration of Simulated Satellite Yaw (courtesy: MDA Systems Ltd)

The Table below lists the simulation parameters, which are based on the current configuration of the actual radar in terms of the wavelength, range bandwidth, range sampling rate, and pulse repetition interval (PRI). The oscillation satellite was modelled by a roll, or rotation about the y-axis, that varies sinusoidally in time. Based on input from Thoth, the expected maximum roll angle is 0.1 degrees, with a period of several minutes. A period of 8 minutes, or 480 seconds was chosen, to avoid aliasing for the given PRI, and to have enough lines within a fraction of the cycle to produce an ISAR image.

Table 1 Simulation Parameters

Simulation Parameter	**Value**
Wavelength	0.057 m (C-band)
Range bandwidth	3 m range resolution
Range sampling rate	1 m range sampling
Pulse Repetition Interval (PRI)	30 sec
Oscillation	Roll (about y axis), Maximum roll angle $\rho_{max} = 0.1^{o}$, Period of oscillation $T\rho$ = 8 minutes = 480 seconds
Number of lines	Attitude oscillation: 8 lines (240 sec, 1/2 period of oscillation)

11. Simulated Imaging Results

Then, a sequence of such ISAR images was produced, each from a 240 second observation interval, but starting at different times so that the intervals overlapped by 120 seconds, or one quarter of the period of oscillation. A sequence of images is shown below. Images are formed from the part of the roll cycle around a peak of the sinusoid, where there is no linear component of the phase variation. In these images the energy from the antenna is at the zero-Doppler position, although it is sometimes blurred. The Figure below shows a sequence of ISAR images where a yaw oscillation was simulated. The maximum yaw angle was 0.1 degrees, and the period of oscillation was 480 seconds, as was used in roll simulations.

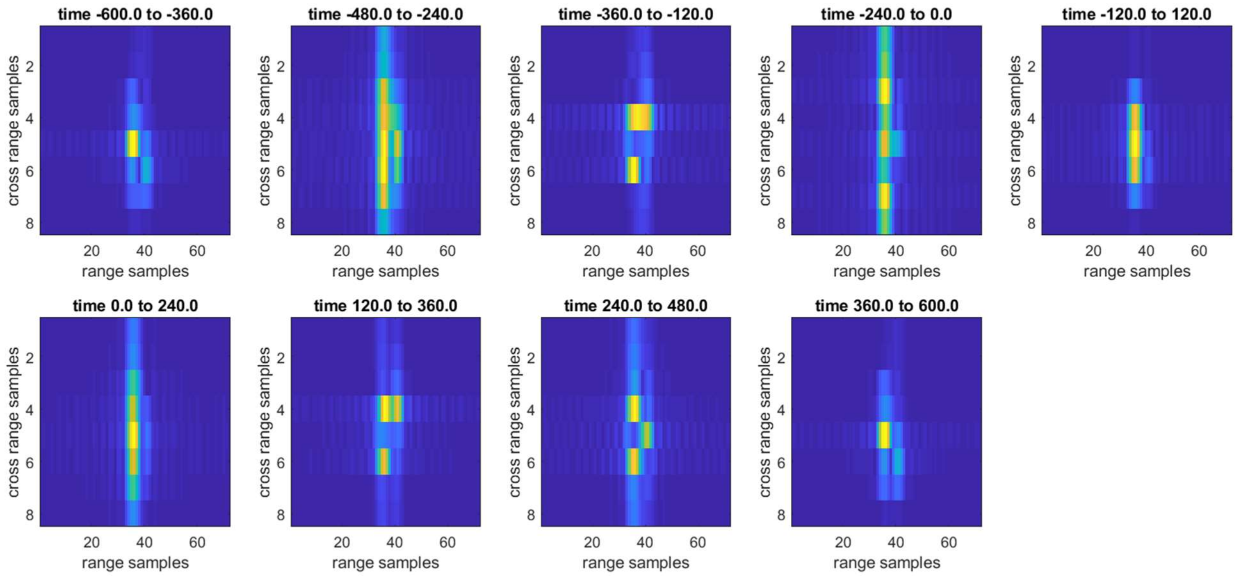


Fig. 10 Sequence of Simulated ISAR images at different overlapping short observation intervals – yaw oscillation (courtesy: MDA Systems Ltd)

12. Actual Radar Images

ThothX acquired real ISAR radar images of GEO targets using Earthfence Americas. An example ISAR image of VIASAT-1 acquired in March 2023 is shown in the Figure below along with an antenna deployment test picture and an artist's impression of the on-orbit configuration.

Fig. 11 Real ISAR images of VIASAT-1, March 2023 (ISAR image, left, antenna deployment testing, center, Artists impression of On-orbit Configuration, right).

13. Canadian Direct Learning Objective (DLO) Exercise

In this DLO, Canadian satellite operator Telesat initiated the exercise by reporting an anomaly in the inclination of the ANIK F2 spacecraft consistent with propulsion loss, triggering dynamic tasking of the GEO radar by the CANSpOC ops team through Defence Commercial Operations Cell (JCO) by a dynamic tasking order to the ThothX radar through the Unified Data Library (UDL) chat, dropping an injection, "Ex Ex Ex – ID ce05 / State of Health for ANIK F2 (23878) / Nov 16 1545 UTC / DS." This statement translates as "Exercise, Exercise, Exercise. New Task ID ce05. All providers requested to provide data on a State of Health Update for Anik F2. Request dated Nov 116, 1545 Universal Time. For Deep Space Providers Only"

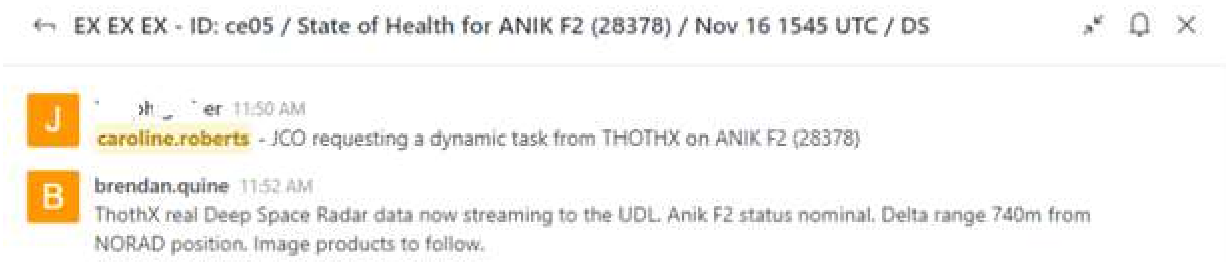


Fig. 12 Earthfence DSR range residuals (courtesy: Exa Research)

An end-to-end surveillance exercise was conducted. Using the Deep Space Radar the team responded to a State-of-Health request live streaming radar data within seven minutes of injection.

14. Global Expansion

The ThothX team is pursuing a rapid global expansion plan in order to offer complete coverage of the GEO belt. The figure below shows our existing very large aperture Americas radar and its radar control center. ThothX recently acquired an exclusive lease on an antenna in Carnarvon, Western Australia to provide coverage of the Pacific theatre including the GEO belt over Asia, New Zealand and Australia. A press release from the Government of Western Australia announcing the new initiative is shown in the figure. Most recently, ThothX has recently entered a partnership to develop another radar station in Europe, the three stations providing complete global coverage.

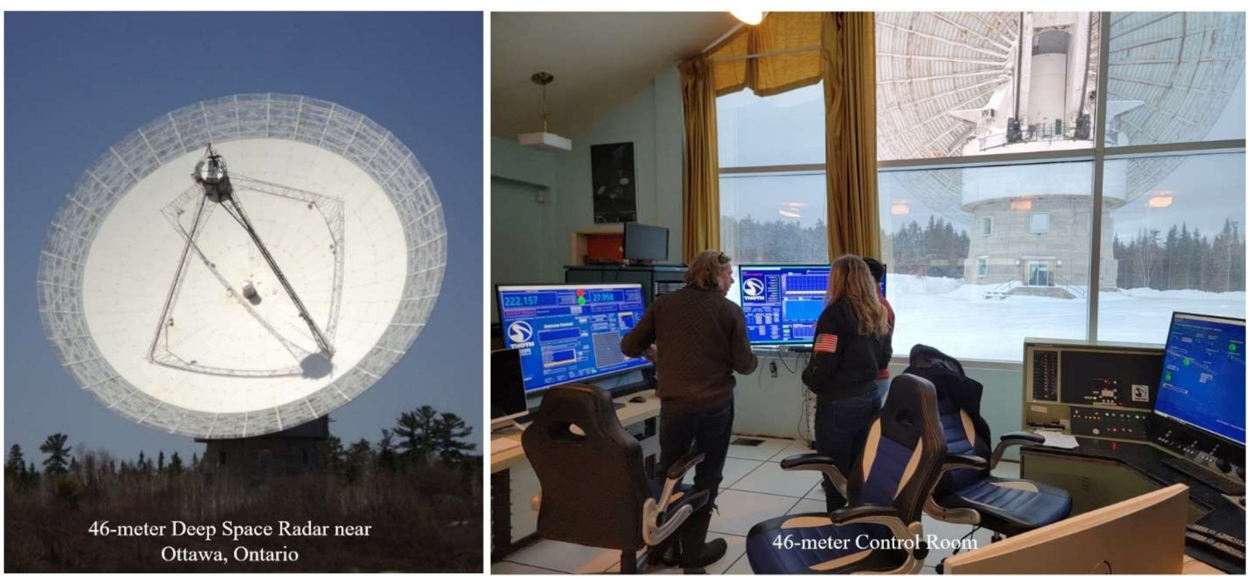
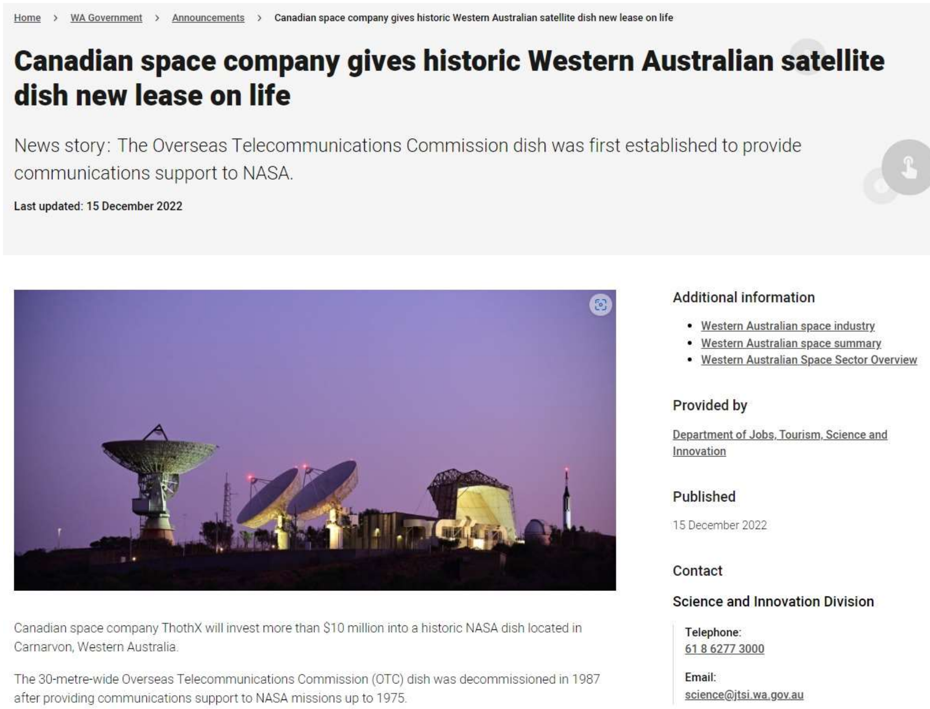


Fig. 13 Earthfence DSR Americas (Image Credit: Thoth Technology Inc.)



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Canadian space company gives historic Western Australian satellite dish new lease on life

News story: The Overseas Telecommunications Commission dish was first established to provide communications support to NASA.

Last updated: 15 December 2022

Canadian space company ThothX will invest more than $10 million into a historic NASA dish located in Carnarvon, Western Australia.

The 30-metre-wide Overseas Telecommunications Commission (OTC) dish was decommissioned in 1987 after providing communications support to NASA missions up to 1975.

Additional information

- Western Australian space industry
- Western Australian space summary
- Western Australian Space Sector Overview

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Fig. 14 Earthfence Pacific (antenna, image left): Press Release by Government of Western Australia, (courtesy: WA Government).

Fig. 15 Earthfence Meridian (Image Credit: Reddit/dirksn).

15. Conclusion

In this paper, we describe Earthfence, a new and capable deep space radar sensor that can provide independent measurement of spacecraft range for objects in Geostationary orbit.

Results from an independent assessment of metric accuracy are described for the deep space radar through the comparison of range and angle results with those computed for sensor data recorded by GNNS sensors on three spacecraft over North America. The radar significantly exceeded its specified performance criteria achieving meter scale range results on these calibration targets and providing measurements with a noise sigma of 2.5m well within the 25-meter accuracy specification.

We describe a recent demonstration of custody operations including the enhanced detection of GEO RSOs in a deep survey of the GEO belt assessable to Thoth's Americas radar station and the continuous custody of RSOs over periods of hours or days. We reported on the development of RSO characterisation modes including a methodology for the acquisition of spacecraft ISAR imagery. We describe a dynamic tasking exercise initiated by spacecraft operator Telesat during a Space Force Vulnerability Period and in fulfillment of a CanSpoC Direct Learning Objective as well as the combination of space based optical and deep space radar data in demonstration of a high-reliability and robust sensor architecture.

Lastly, we present our global domination plan to deploy our novel deep-space-radar and other RF sensing technologies in support of a global unclassified space domain awareness solution for planet Earth.