Earthfence: a GEO capable deep space radar

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Unclassified Abstract

Earthfence is a software defined digital radar system specifically designed to surveil GEO Resident Space Objects (RSOs). The system comprises a large aperture fully-steerable antenna equipped with a digital radar and supercomputer cluster for data analysis. A Data Acquisition System comprises FPGAs that generate customisable pulses that are amplified and transmitted. Radar return signals are digitised in complex quadrature at the feed on reception and transmitted over secure fiber networks to a Xeon processor cluster that performs pulse decompression and object identification. The radar operates in all illumination and weather conditions reporting targets typically within 30 seconds of observation. The system operates seven modes that may be tasked autonomously and streamed live using interfaces including the Air Force's Unified Data Library developed by Bluestaq LLC.

The first Earthfence system is in operation at the Algonquin Radio Observatory where it is deployed on the facility's 46 m (150 foot) antenna. Operating in C-band, the radar detects RSOs with RCS greater than three square meters (32 square feet) and exceeds 25 m (80 foot) range accuracy at ranges up to 42,000 km (26,000 miles) using an approach that is virtually undetectable.

The system was developed to TRL-9 by Thoth Technology Inc. in collaboration with Analytical Graphics Inc., the Canadian Space Operations Centre (CANSpOC), the Build in Canada Innovation Program, and Defence Research and Development Canada.

In this talk, we introduce Earthfence and describe development and deployment timelines towards our technical goals to advance our sensitivity to sub-square meter RCS and to extend Earthfence coverage to Low Earth Orbit (LEO). We describe the results of joint operations with other ground and space based sensors including the Near Earth Object Surveillance Satellite (NEOSSat). We present accuracy comparisons with space-track.org and discuss our recent experiences participating in the Civil-Commercial Operations Cells in Sprint Advanced Concept Training (SACT). Our recent development work on Space Object Identification (SOI), where we utilise additional parameters such as RCS and RF emission in a Bayesian inference model to reduce miss-tagging, is discussed. Our work on Non-resolved Object Characterisation using Doppler and Inverse Synthetic Aperture Radar (ISAR) is described.

1. Introduction

Earthfence is a unique Deep Space Radar (DSR) solution designed specifically to surveil Resident Space Objects (RSOs) and debris in geostationary (GEO) orbits. The Earthfence DSR is a digital C-band pulse compression radar system operating at 5.7 GHz. Earthfence consists of a software defined acquisition, data management and analysis system engineered for Space Domain Awareness (SDA) and Space Traffic Management (STM). Thoth currently operates an Earthfence DSR from the 46 m parabolic antenna located at the Algonquin Radio Observatory (ARO).

The Earthfence DSR system comprises a large aperture fully-steerable antenna equipped with a digital radar and supercomputer cluster for data analysis. A data acquisition system comprises FPGAs that generate customisable pulses that are amplified and transmitted. Radar return signals are digitised in complex quadrature at the feed on reception and transmitted over secure fiber networks to a Xeon processor cluster that performs pulse decompression and object identification. The radar operates in all illumination and weather conditions, reporting targets typically within 30 seconds of observation. The system operates in seven modes that may be tasked autonomously and streamed live using interfaces including the Air Force's Unified Data Library (UDL) developed by Bluestaq LLC.

The Earthfence DSR detects RSOs with Radar Cross Section (RCS) greater than 3 m^2 (32 square feet) and exceeds 25 m (80 foot) range accuracy at ranges up to 42,000 km (26,000 miles) using an approach that is virtually undetectable. GEO targets are illuminated by a pencil-like radar beam with a width ~35 km in diameter. Typical measurement time is 2 seconds; analysis time is typically 20 seconds. Clients receive meta data by bulk transfer or by live stream transfer to the Unified Data Library (UDL) with latency less than one minute. Earthfence is available as an occasional or regular monitoring service and as a backend installation that can be integrated with an existing +25 m diameter ground station antenna.

The Earthfence DSR system was developed to TRL-9 by Thoth Technology Inc. in collaboration with Analytical Graphics Inc. (AGI), the Canadian Space Operations Centre (CANSpOC), the Build in Canada Innovation Program (BCIP), and Defence Research and Development Canada (DRDC). Thoth has contributed over 12,000 DRS observations to Sprint Advanced Concept Training (SACT) events.

2. Earthfence DSR Accuracy

Earthfence DSR calibration was achieved in collaboration with AGI. Fig. 1, below, shows Earthfence DSR range residuals for tracks on Intelsat-907 in meters.

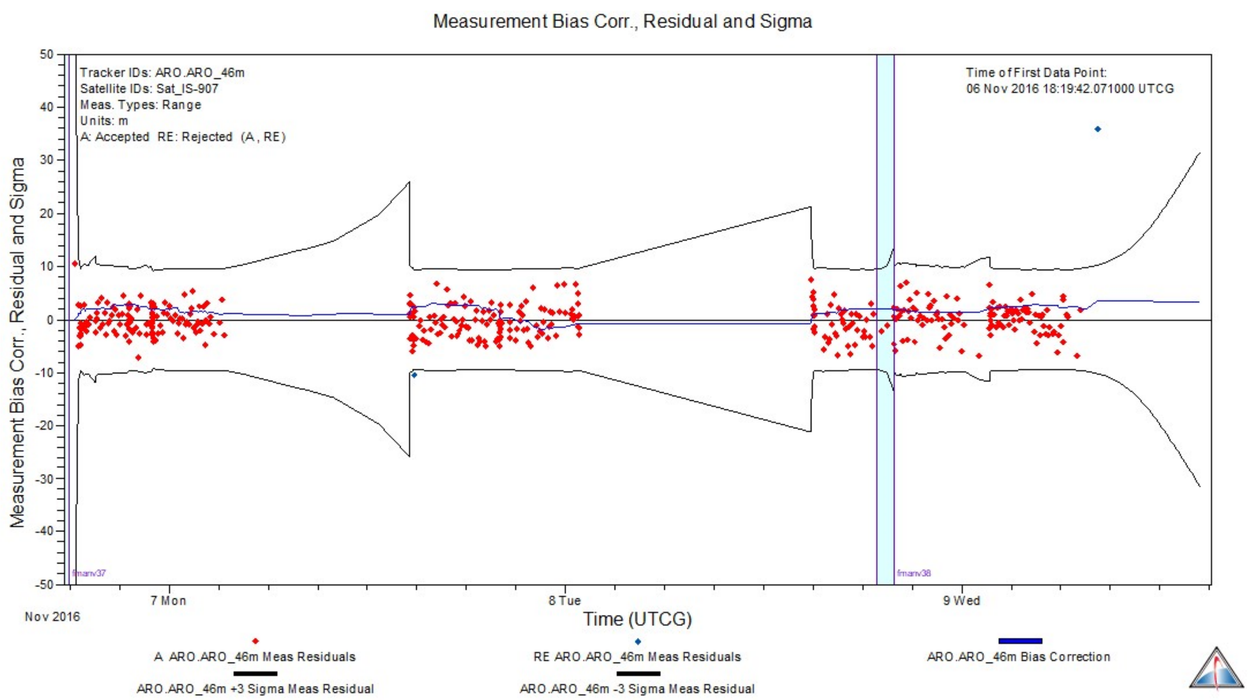

Fig. 1 Earthfence DSR range residuals (courtesy: AGI)

Earthfence DSR testing also included tasking on Space Surveillance Network (SSN) calibration satellites to set baseline values for accuracy needed for US SSN utilization. Regularly scheduled metric accuracy tasking included SSN calibration targets TDRS 12 and TDRS 6. The following figure illustrates the feedback received from the US SSN test results for the calibration targets. The results from the metric testing show that the performance capability of the Earthfence DSR is well within specifications.

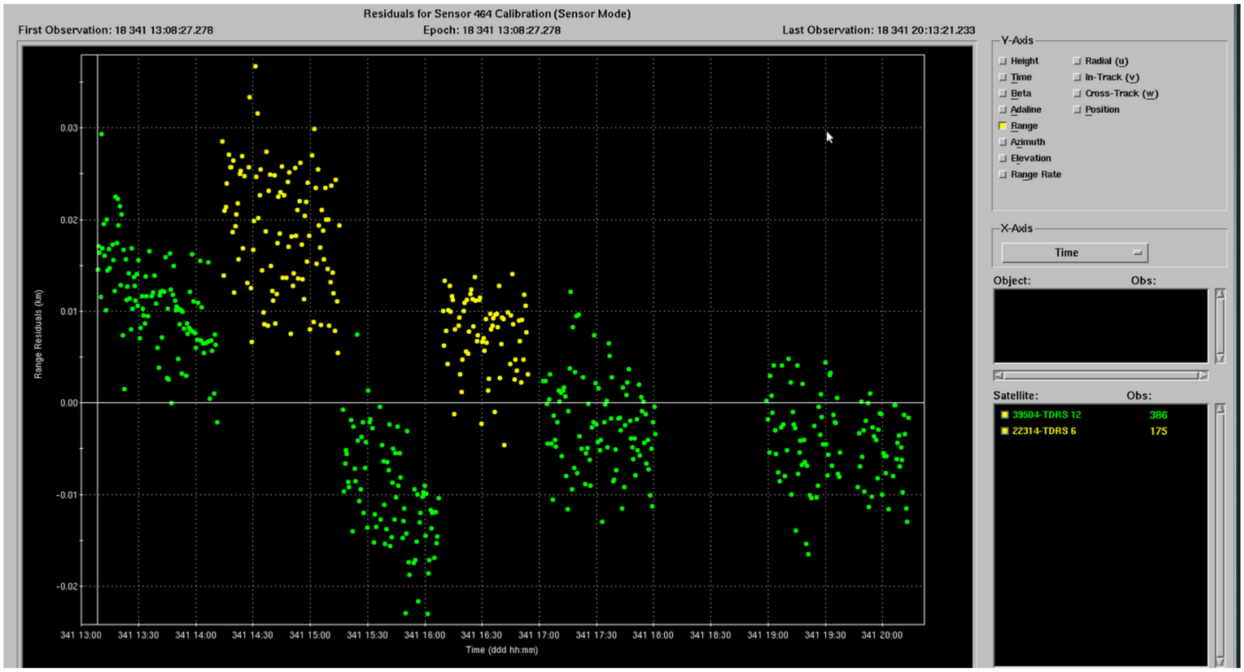

Fig. 2 Earthfence DSR calibration results for TDRS 6, 2 (Courtesy: CANSpOC)

3. Earthfence DSR Proximity Observations

Earthfence DSR is able to resolve objects closer than 25 m and can record station transits. The radar can be tasked to observe a specified list of objects, verifying that no other spacecraft are in close vicinity. The scan strategy consists of two parts: an initial spiral scan is initiated with the intention of locating the primary spacecraft. A proximity spiral scan begins about the spacecraft once found. The following figure shows proximity operations of three Anik spacecraft in a cluster.

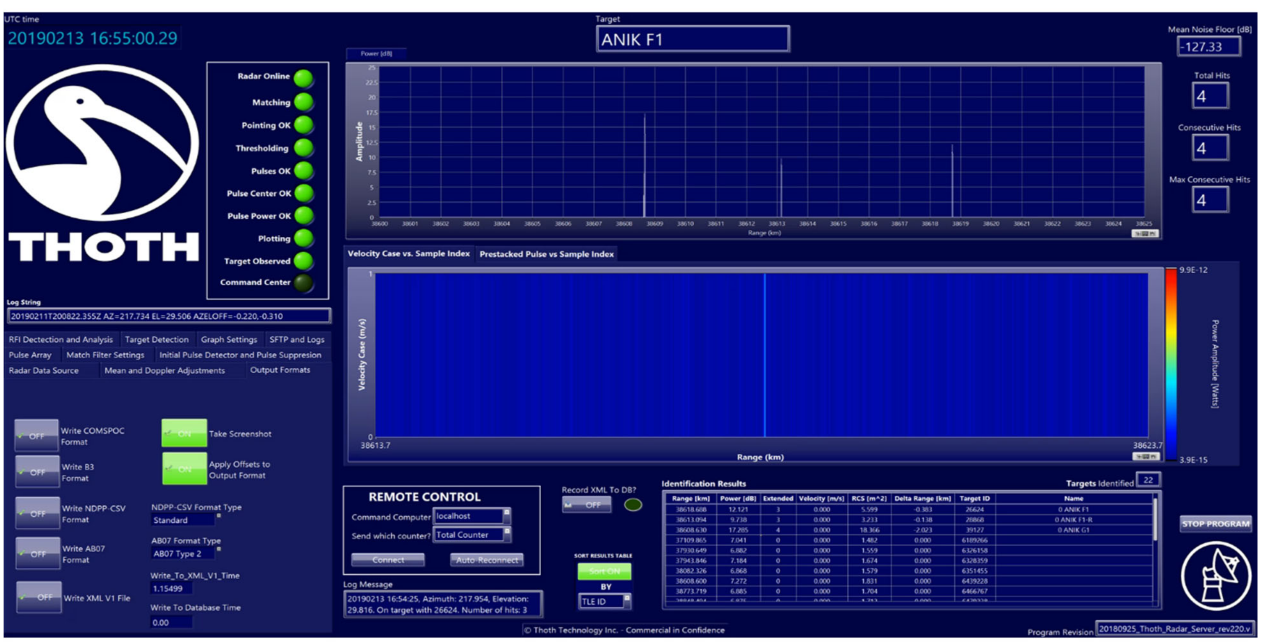

Fig. 3 Three Anik spacecraft in a cluster

Thoth has contributed over 12,000 DSR observations to SACT exercises and responds to high-priority requests for pattern of life information, determining status from delta range and RCS data.

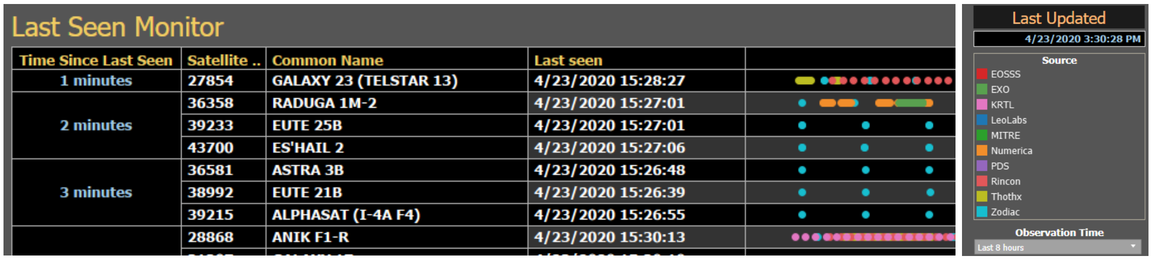

Fig. 4 ThothX Earthfence DSR low latency contributions, SACT

4. Earthfence DSR Operational Modes

ThothX Earthfence DSR has seven operational modes to meet different mission objectives.

Table 1 Summary of different modes of radar operation.

Mode	**Description**
Sky-survey	Raster scan sky sector to identify or locate previously unknown GEO targets.
Lost-in-space mode	Find targets with stale TLEs.
Tracking mode	Tracking of spacecraft to verify orbital performance.
Monitoring mode	Ongoing monitoring capability to revisit assets.
Characterization mode	Extraction of target radar cross section; size, spacecraft attitude; spin state; deployment of arrays.
Proximity operations mode	Proximity of other spacecraft; search for neighbouring craft.
Full Catalog Search	Perform a search of all GEO public catalogue targets in view.

5. Earthfence DSR and ISAR

Thoth is developing and applying Inverse Synthetic Aperture Radar (ISAR) to Earthfence DSR data imaging. Classically, radars make one-dimensional measurements of returned power along the range axis defined by line of sight between radar and target. For a target significantly larger than the range sample of the radar, a complex radar return is collected comprising intensity measurements relating to the power returned along the range axis. ISAR is a method of obtaining additional information about an axis perpendicular to the range axis normally referred to as the cross-range axis. The method exploits rotational motions of the target during image sequence acquisition to form a Fourier spectrum of structural variations in the cross axis. The most common example where ISAR has been deployed previously is in the imaging of large vessels rolling at Sea in order to yield rigging and other structural features. The technique does not produce a “real” image; rather is yields information about the cross-axis motion of reflected phase centers emitted by a complex 3D structure. The relative motion of the target must be removed before the ISAR method is applied or it will distort range-axis structure.

Consider a DSR observing an object whose structure is largely planar with respect to the radar (theta =0), where theta is the angle of rotation. Consider two parts of the structure a distance D apart in the perpendicular. One part of the structure will occur D*sin(theta) in front of the other part. Phasing occurs when D*sin(theta) = 0.5 * lambda, where lambda is the radar wavelength. For small angles and lambda ~ 0.05m then the phasing will occur at difference length scales according to the Table below:

Table 2 Characteristic relationship between cross-axis structural size and rotation angle

D (Distance between elements)	Theta (rotation angle, Rad)	Theta (Degrees)
0.1 m	0.25	14.3
1 m	0.025	1.43
10 m	0.0025	0.143

The table illustrates that small structure is enforced at large angles and that large structure is enforced at small angles giving rise to harmonic information content that may be revealed by inverse Fourier Transform.

Applying the technique to DSR observations, the typical rotation rate of a GEO RSO is theta_dot = 360/(24*2600) = 0.0041 degrees/sec. For a typical Earthfence standard DSR observation of 30 seconds, theta_min = 0.12 degrees and, consequently D_max = 0.5* lambda/theta_min = 14.3 m indicating that the technique should yield information about large scale structure of the order of 30 m (or characteristic of the typical size of a GEO DSR). For an observation sequence over T seconds the smallest observable structure D_min = 0.5* lambda/(T*theta)dot). The figures below show early imaging results from the application of ISAR to Earthfence DSR data.

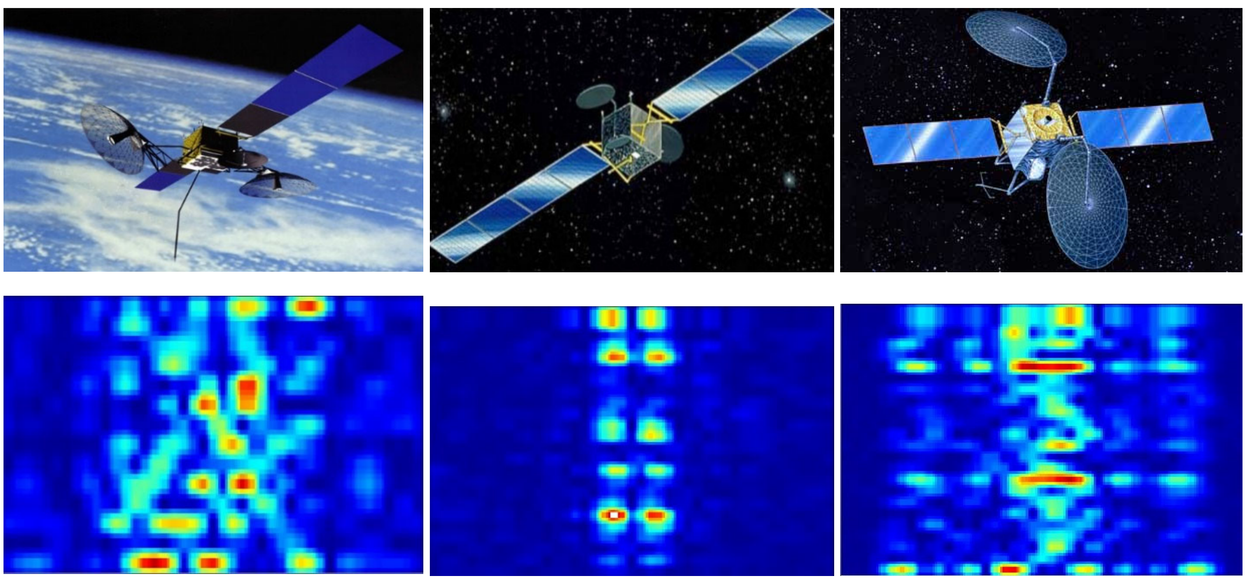

Fig. 5 Artist Impression of RSO (top), ThothX Earthfence DSR ISAR beta image obtained (bottom), Realtime Tracking Experiment sponsored by DRDC.

6. Earthfence and NEOSSat

ThothX is also engaged in radar and optical data-fusion exercises using the Earthfence DSR and the Near Earth Object Surveillance Satellite (NEOSSat). NEOSSat is a dual mission microsatellite for asteroid astronomy and Space Situational Awareness (SSA) research. Initial tests to conduct quasi simultaneous observations of the Anik cluster at 111^{o}W show that the Earthfence DSR at ARO is well positioned for GEO cluster custody over North America. In recent quasi simultaneous operations, the ARO Earthfence DSR provided 5135 observations of the Anik cluster objects to 2 m^2 RCS and maintained custody of the cluster during dayside passes; NEOSSat provided 245 detections on Anik cluster objects and maintained custody during nightside passes. Earthfence DSR and optical data are also complementary, as optical provides plane-of-sky information, while radar provides range. Additionally, radar has high accuracy capability that is not dependant on weather conditions and that can operate day and night, while optical has wide survey, high throughput capability. The figure below shows quasi-simultaneous operations of the Earthfence DSR at ARO and NEOSSat observing the Anik Cluster.

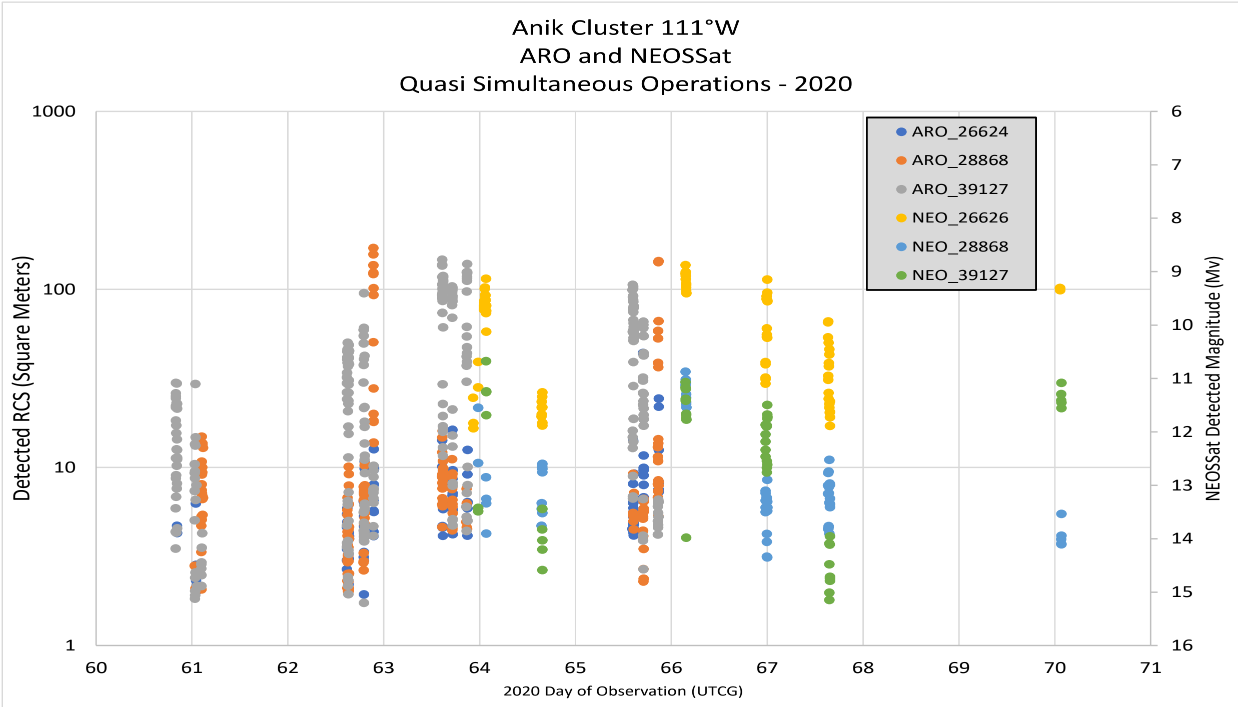

Fig. 6 Quasi Simultaneous ARO and NEOSSat Operations

7. Conclusion

Earthfence DSR operated by ThothX provides high-frequency ranging, RCS data on known GEO RSOs in the public catalogue with meter scale precision. In operation since 2018, the capability has reached TRL-9 through BCIP and can be used for SDA and STM. Earthfence DSR provides an independent and nearly undetectable means to determine whether RSOs are operating according to flight plan and can be operated in survey mode to validate catalogues or to observe in real-time proximity operations around a particular spacecraft. Earthfence DSR is available as a commercial service to select, qualified Five Eye clients, and as a backend system that can be integrated with existing antenna assets with +25 m diameter.