Space-based Sub-THz Inverse Synthetic Aperture Radar (ISAR) Image Formation and Orbital Optimisation for Monitoring of Geostationary Assets

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1. Introduction

➢ The Pervasive Sensing group at the University of Birmingham is exploring in-orbit conditional monitoring of satellites using **inverse synthetic aperture radar (ISAR)** as a technique for dedicated observation of high-value space-based assets.

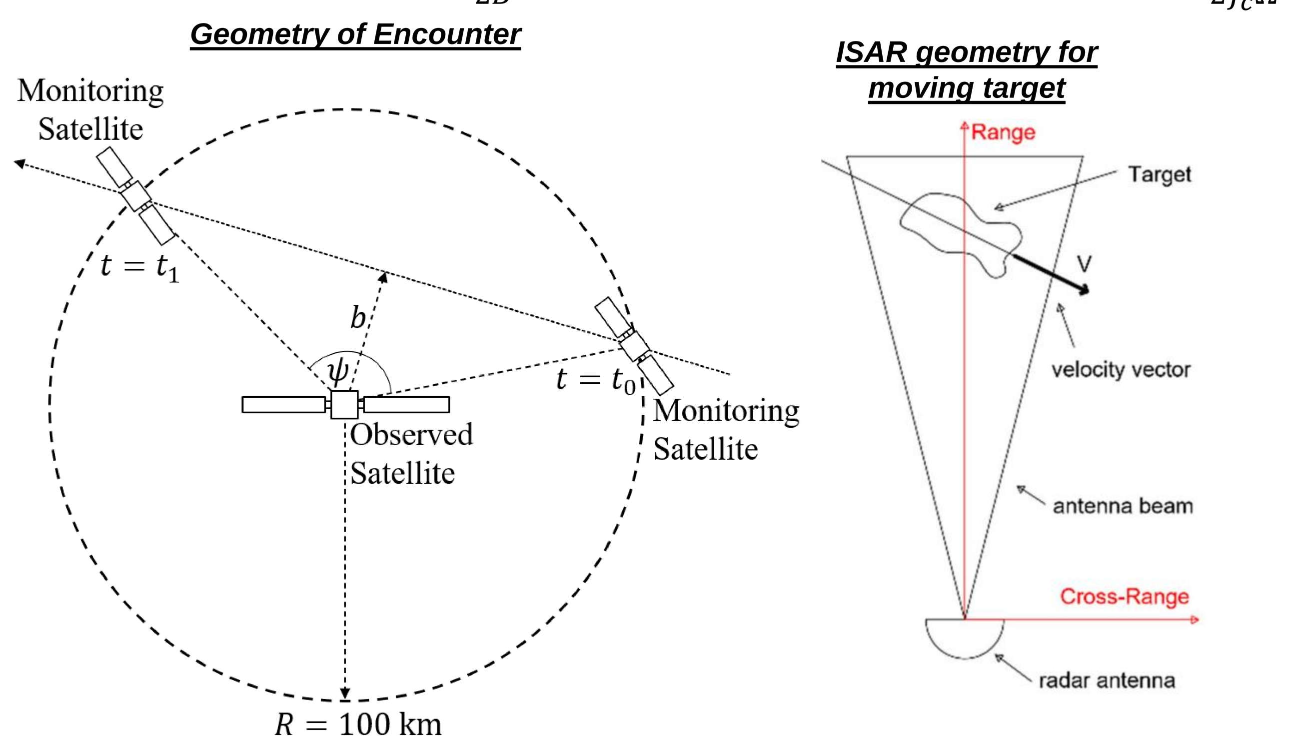
➢ The feasibility of **geostationary orbit (GEO) observation** by optimising monitoring satellite orbital parameters for multi-frequency sub-THz ISAR data acquisition has been assessed. A proprietary propagation simulator, **GOFOD**, has been used to devise scenarios for which launch conditions, stability, periodicity and time of dwell on the target will deliver the best **observation of key features**.

➢ A metaheuristic radar simulation software **GEIST** has been developed to synthesise **high-resolution ISAR images**. Sub-THz wavebands in the region $70-300\,\mathrm{GHz}$ enable wide signal bandwidths, giving **fine range resolution**. They also give greater sensitivity to surface texture, allowing us to **resolve features of centimetre scale** at ranges up to $100\,\mathrm{km}$.

2. Encounter Geometry and ISAR Synthesis

ISAR is an imaging method that uses transmitted **radio frequency** signals and the **relative velocity** of the antenna and target object to produce a 2-D image.

Range resolution: $\Delta R = \frac{c}{2B}$ Cross-range resolution: $\Delta CR = \frac{c}{2f_c\Omega}$



b: Closest approach distance ψ: Observed angular span B: Signal bandwidth f_c: Signal centre frequency
t_0: Start of encounter t_1: End of encounter R: Radar range Ω: Coherent integration angle

3. Monitoring Satellite Orbital Assessment

GOFOD: Geocentric **O**ptimiser **F**or **O**rbit **D**etermination

➢ GOFOD has been used to model the orbits of monitoring and observed satellites, and optimise the encounter, prioritising long-term stability and diversity of observation perspectives.

➢ Minimised revisit time is crucial, and here is achieved using a highly-inclined co-orbiting monitoring satellite, allowing **high relative velocity** (1-3 km/s) for a large synthetic aperture.

➢ Fig. 1 shows the results of orbital fine-tuning, giving the most favourable initial trajectory for long-term (100 day) stability.

➢ With this orbital configuration, the monitoring spacecraft observes the GEO asset twice per day. Achieve **coverage of near and far-side** of the satellite within 24 hours, to monitor changes to the satellite configuration over time.

➢ Station-keeping manoeuvres will be required maintain adequate separation for time spans longer than 100 days, as **orbital perturbations** from Earth's oblateness (J2), lunar and solar gravity, and solar radiation pressure cause drift over longer timeframes

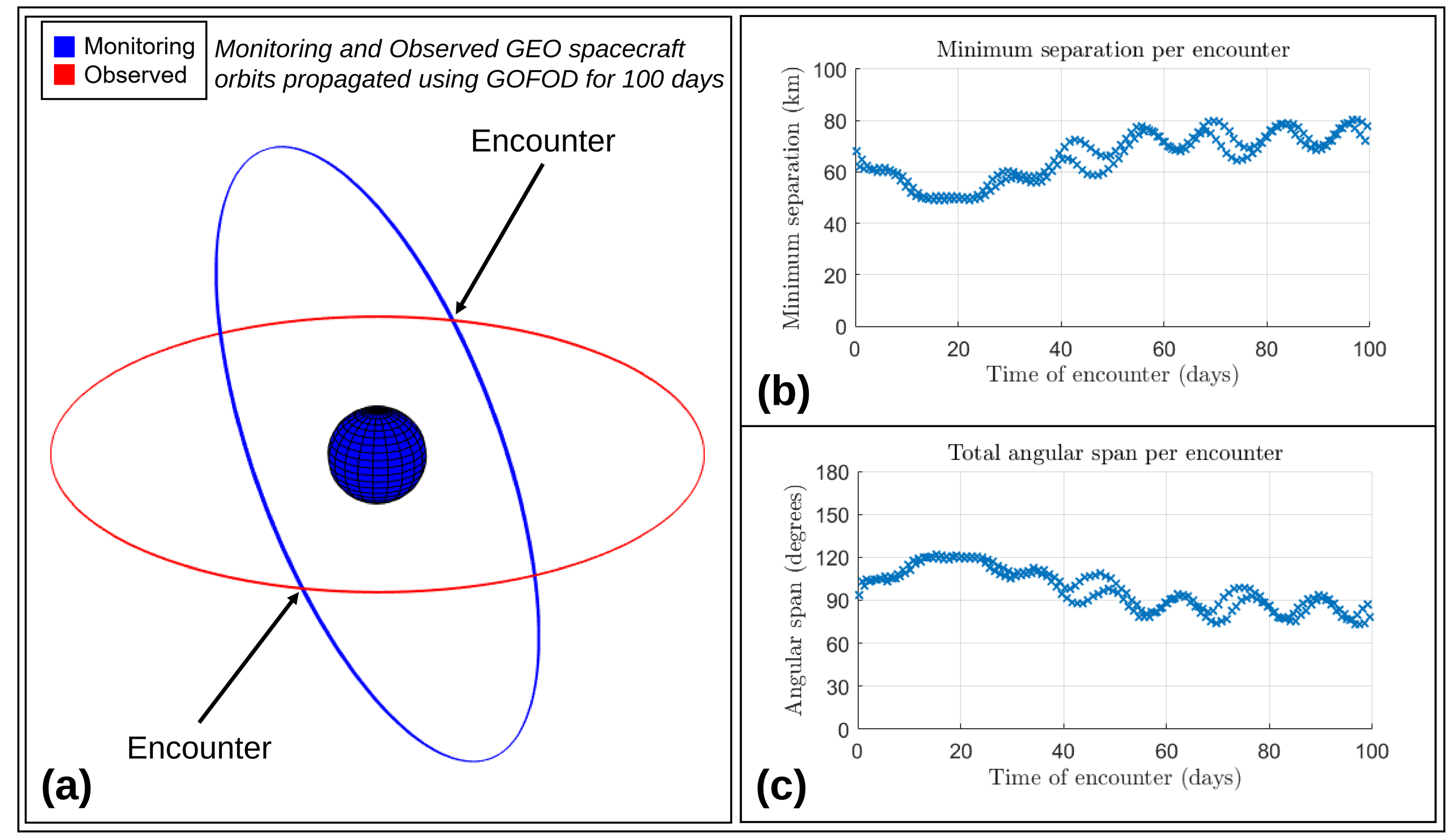


Fig. 1: Orbit diagram showing positions of encounters between the two spacecraft (a), and encounter parameters over 100-day propagation showing closest approach distances b and total angular span ψ, (b), (c).

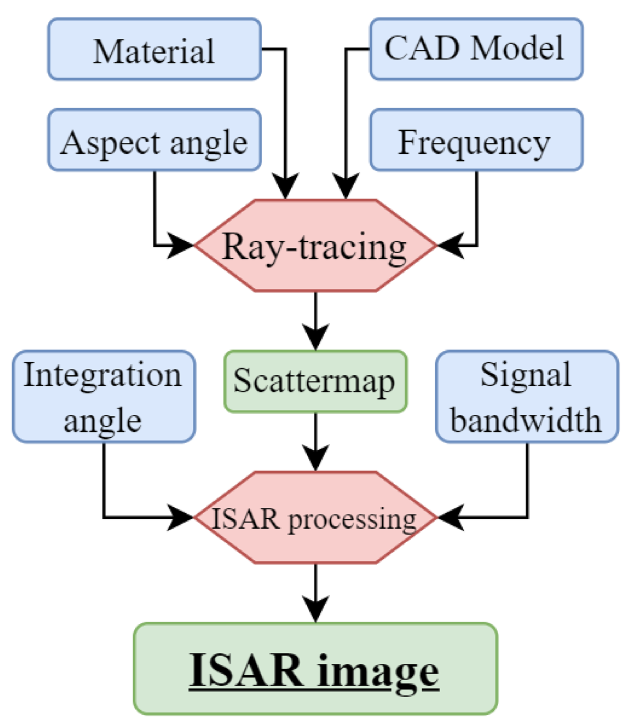
4. ISAR Simulation Method

GEIST: Graphical **E**lectromagnetic **I**SAR **S**imulator for **T**Hz waves

➢ Uses **ray-tracing** in open-source software **Blender** to create point-cloud map of target.

➢ Metaheuristic – Reproduces the **important features** of ISAR imagery.

➢ Built to generate large datasets: huge **computation time improvement**.



5. ISAR Simulation Results

➢ ISAR simulations of static and realistic flyby parameters have been conducted using GEIST.

➢ High resolution ISAR images of a GEO asset are seen in Fig. 2. A bandwidth of $6\,\mathrm{GHz}$ was used for both $75\,\mathrm{GHz}$ and $300\,\mathrm{GHz}$ images, giving a range resolution of *2.5* cm. To achieve $5.7\,\mathrm{cm}$ cross-range resolution at both frequencies, $0.5°$ integration was used for $300\,\mathrm{GHz}$, while $75\,\mathrm{GHz}$ required $2°$.

➢ By **splitting the total angular span** ψ into smaller sub-integrations of angular width Ω (given by the desired cross-range resolution), we can **synthesise many ISAR images** that view the spacecraft from different perspectives. A selection of these ISAR frames can be seen in Fig. 4. The solar panels of the model of the satellite have been shortened to accelerate computation time.

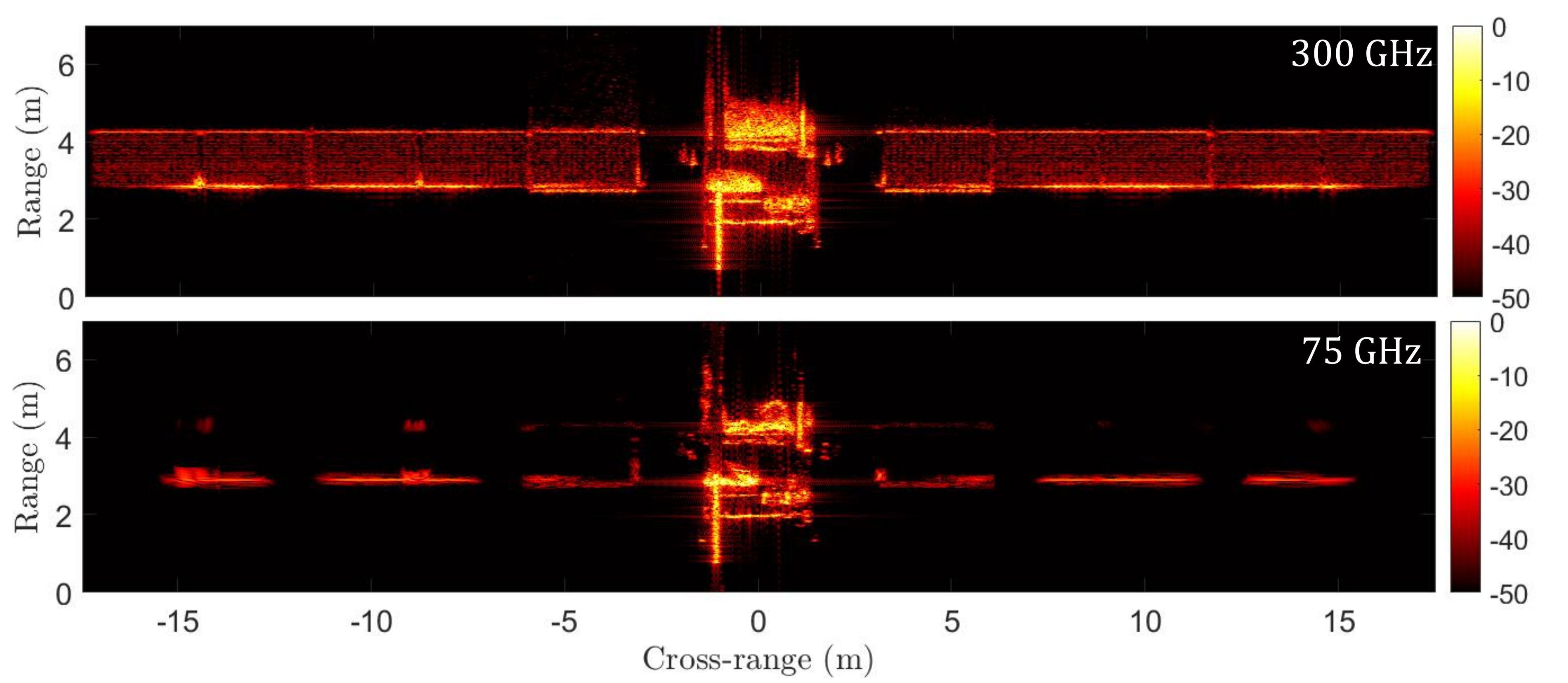


Fig. 2: Multi-frequency GEIST simulations. Resolutions – Range: 2.5 cm. Cross-range: 5.7 cm

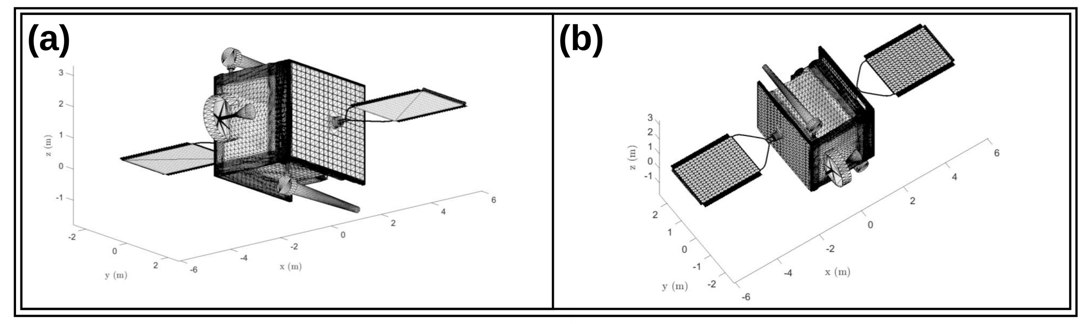


Fig. 3: Boresight perspective of GEO asset used for Fig. 4 ISAR simulations at (a) t_0 and (b) t_1

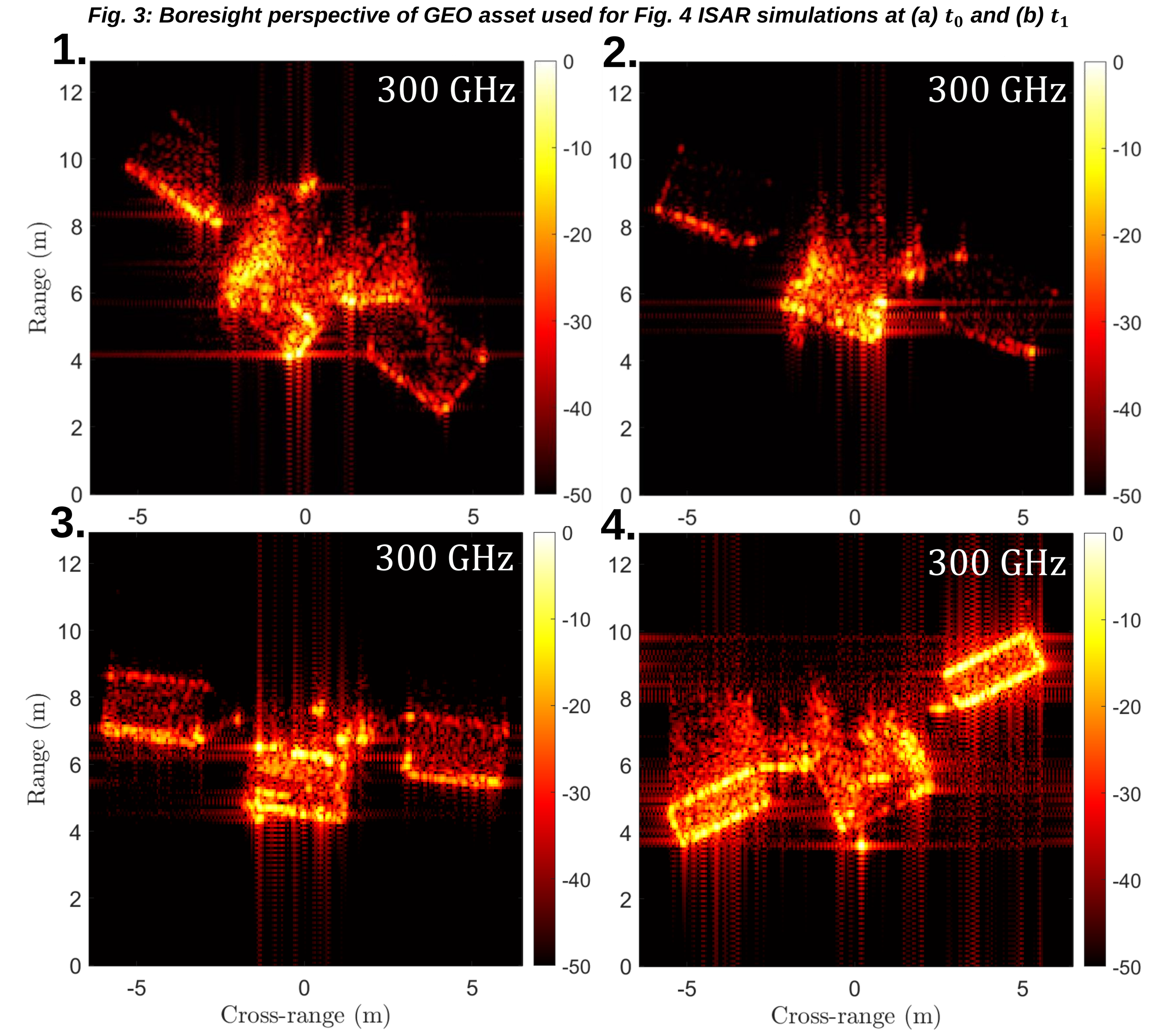


Fig. 4: Single-frequency GEIST simulations at 300 GHz, showing the change in perspective during an encounter (1-4). Resolutions – Range: 2.5 cm. Cross-range: 5.7 cm

6. Conclusions and Future Work

We have conducted a study to demonstrate the viability of dedicated space-based inverse synthetic aperture radar (ISAR) monitoring platforms for observation of high-value GEO assets. This required the development of novel radar simulator GEIST.

We have used the proprietary orbit propagator GOFOD to model the orbits of GEO assets, and optimised monitoring platform orbital parameters to ensure greatest long-term stability and dwell on the target without the use of station-keeping manoeuvres, enabling us to deliver the best observation of key satellite features with the shortest possible revisit time.

Following this, we have used the encounter data to generate ISAR images using GEIST, demonstrating its ability to rapidly produce images with different perspectives. This work represents a significant step toward autonomous decision-making on-orbit.

Future directions for the work include:

➢ Experimentation using GOFOD of longer observation epochs incorporating station-keeping manoeuvres and exploring different orbital scenarios.

➢ Performing detailed verification of GEIST using full electromagnetic simulation software and by comparing to experimentally acquired measurements.

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