Performance of Northrop Grumman's Mission Extension Vehicle (MEV) RPO Imagers at GEO

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ABSTRACT

This paper will describe and illustrate the real-life performance of the Rendezvous and Proximity Operations (RPO) sensors used by Space Logistics LLC's Mission Extension Vehicles (MEV) built by Northrop Grumman. MEV-1 launched in 2019 and performed rendezvous, proximity operations, and docking (RPOD) with the Intelsat 901 satellite in the GEO graveyard orbit approximately 300km above GEO in February of 2020. MEV-2 launched in 2020 and performed a similar RPOD sequence with the Intelsat 10-02 satellite directly in geostationary orbit in February and March of 2021. These vehicles use three dissimilar sensing phenomenologies to provide all required relative navigational data to enable the above RPOD capabilities. These include visible spectrum imagers (narrow and wide field of view), long wave infrared (LWIR) imagers (narrow and wide field of view), and active scanning LIDAR. This paper will explore the performance of each of these sensors during these real-life missions at GEO and potential implications for future Space Situational Awareness capabilities.

1. INTRODUCTION

The Space Logistics LLC Mission Extension Vehicle (MEV) is the culmination of over a decade of development work by its prime contractor, Northrop Grumman Space Systems (NG), and several of NG's heritage companies. Conceived as the first generation capability in the new satellite servicing marketplace, MEV offers valuable life extension services for spacecraft that were not designed to be serviced.

The MEV is built on Northrop Grumman's heritage GEOStar spacecraft bus with two key technological developments. The first is a quasi-universal docking system that is compatible with a majority of GEO spacecraft currently on orbit that were not originally designed to be docked with. The second, is the incorporation of a powerful and flexible RPO sensor suite consisting of cutting-edge hardware and software that builds upon Northrop Grumman's heritage RPO systems including the Cygnus space station resupply vehicle.

MEV performs life extension of satellites that were not built prepared for in-orbit refueling. To perform its mission, the MEV performs a semi-autonomous rendezvous with the client vehicle, and docks to it using two features present on approximately 80% of all GEO satellites, those being a zenith-facing liquid apogee engine (LAE) nozzle, and a surrounding launch adaptor ring. After docking, the client vehicle's propulsion system and attitude control is completely disabled, allowing MEV to assume full responsibility for client vehicle pointing and orbit management.

While the MEV docking system is certainly a work of artistic ingenuity, this paper will only be exploring the performance of the MEV RPO sensor suite, a set of rad-hard cutting-edge sensors which provide raw data feeding the MEV relative navigation algorithms. These include a visible spectrum camera set, a long wave infrared (LWIR) camera set, and a scanning LIDAR. The RPO sensor suite allows MEV to track client vehicles from 50+km, as well as hold centimeter-level relative position during the precision docking event.

At customer request, MEV and next generation vehicles can use their sensing capability to provide multispectral inspection of a client vehicle from close range, as well as collect high density 3D inspection scans via LIDAR. But the most visceral demonstration of this capability came from the post MEV-1 docking release of the first commercially captured images of spacecraft in active operation in the GEO belt, taken from above GEO.

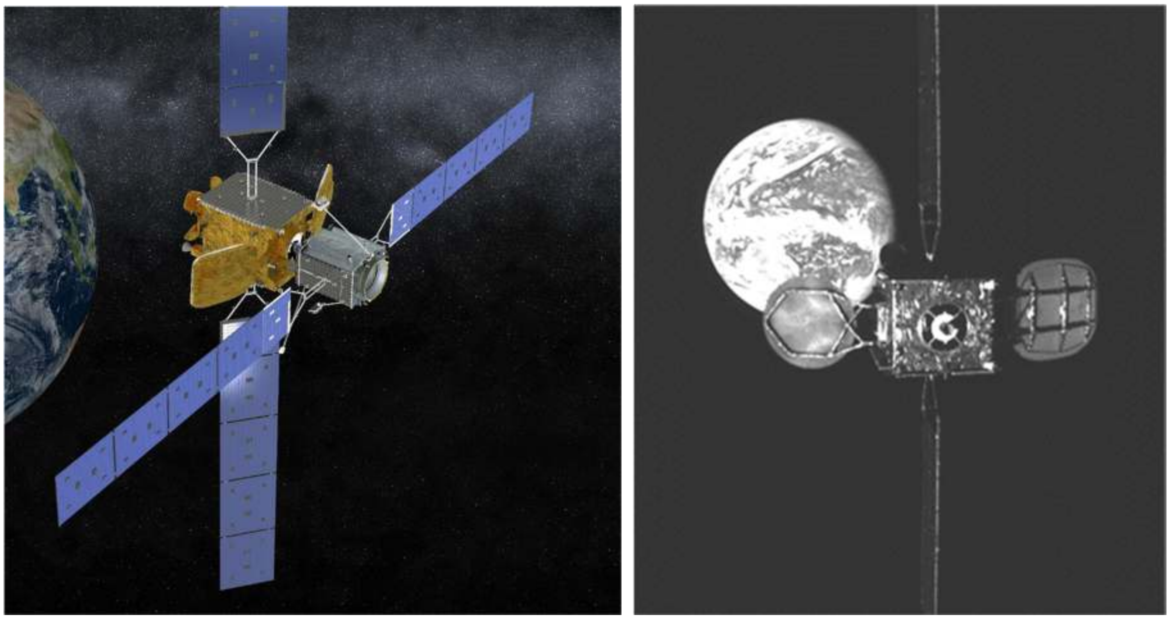

Fig. 1. Left: Artist rendition of MEV-1 providing life extension services, Right: Image of IS-901 taken from MEV-1 during approach for docking

2. MEV RPO Sensor Suite Philosophy

From the outset, the MEV was tasked with a unique and challenging mission: to rendezvous with other spacecraft that had been designed with neither precision localization capabilities, nor with provisions to enhance detection, tracking, or relative navigation. The international CONsortium For Execution of Rendezvous and Servicing (CONFERS) refers to this as a satellite that is “unprepared” for servicing.

Northrop Grumman (NG) has long heritage with ‘prepared’ RPO through automated Cygnus cargo resupply runs to the International Space Station (ISS), but the availability of relative GPS navigation in LEO as well as a full suite of navigation fiducials on the ISS place that mission firmly in the realm of ‘prepared’ RPO.

Therefore, MEV would be breaking new ground with a sensor suite chosen to be as flexible and diverse, because the mission engineers knew one thing for certain—that conditions on-orbit would be unpredictable on the ground. MEV client vehicles will generally have been in active service for at least 15 years, in the harsh GEO environment, subjected to season after season of solar wind, micro abrasion, thermal cycling, and even micrometeorite impacts.

While every effort would be made on the ground to quantify and qualify sensor performance against ‘representative’ materials, it was an accepted truth at the outset that characterization could not be rigorous without the (unrealizable) retrieval of an actual decommissioned bus from the GEO graveyard, setting it up in the lab, and running full optical properties tests on its blanketing, array cover glass, OSR panels, etc.

Therefore, to ensure mission success in the face of extensive uncertainty about the properties of the RPO target, the sensor suite incorporated three dissimilar phenomenologies to provide the most robust performance across the operational regime: visible spectrum imagery, LWIR imagery, and scanning LIDAR in the near infra-red band.

3. MEV Visible Sensor System

The MEV Visible Sensor System (VSS) consists of six individual cameras and associated control and interface units provided by Jena-Optronik GmbH (JOP). MEV-1 was the first flight and operational use of the JOP ASTRO Head, a fully rad-hard camera system designed for a 15+ year GEO lifetime. This system leverages the vendor’s extensive heritage in space grade precision optical instruments such as star trackers.

The VSS cameras each use identical focal planes and control electronics, paired with one of two optical trains: a 'Narrow Field of View' (NFOV) variant optimized for long range client vehicle detection and tracking, or a 'Wide Field of View' variant optimized for close range inspection and relative navigation. All of the cameras sport a spectral range of 400-900 nm, with the majority of the sensitivity lying in the visible band.

MEV hosts an extensive suite of machine vision processing algorithms for use at various operational ranges and mission phases. Each of the camera variants in the VSS is paired with a duplicate, precision aligned and configured for synchronous capture. This provides fault tolerance for monocular algorithms, and the option for stereovision processing.

The full VSS camera complement consists of 2x NFOV for long range tracking and navigation use, 2x WFOV for close range navigation and inspection use, and a second 2x WFOV 'Docking Camera' pair positioned specifically for monitoring client capture with the docking mechanism.

As shown in Fig. 2, below, the VSS NFOV cameras are able to easily detect and allow classification and tracking of a Resident Space Object (RSO) from a relative range in excess of 30 km. The VSS is especially effective at long range detection and tracking because is using the high intensity solar output as an illuminator, providing good performance even when the RSO is only resolvable at the sub-pixel level.

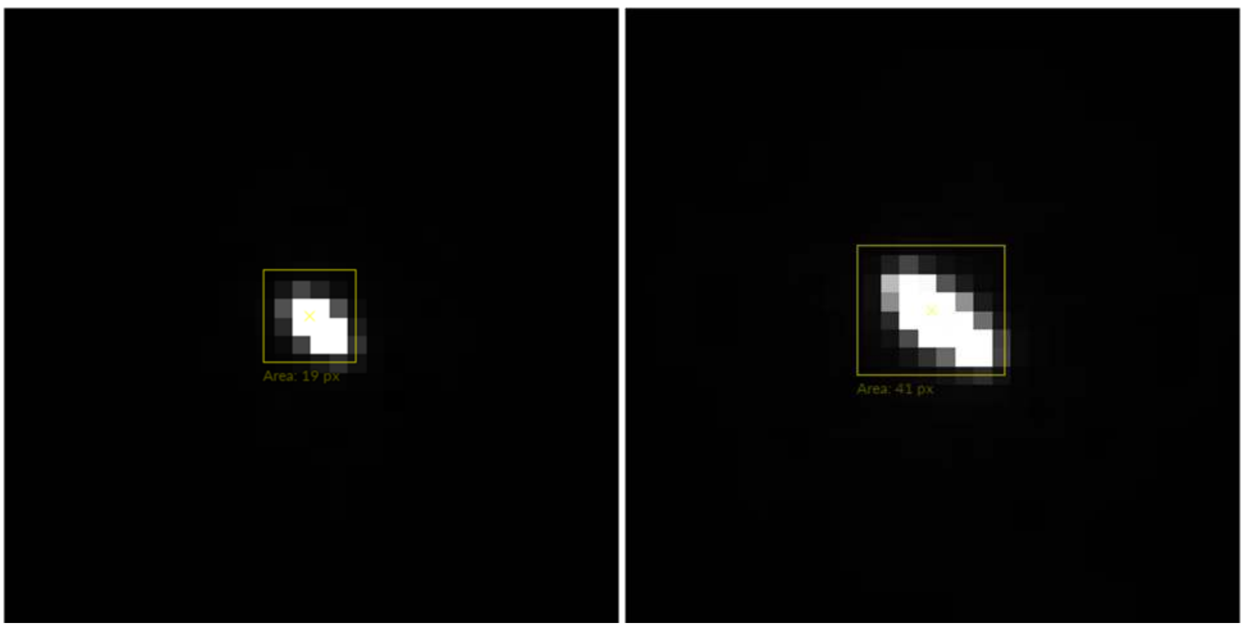

Fig. 2. VSS images of IS-10-02 at 33 km and 22 km. Overlay shows resolved client vehicle size in pixels on the VSS NFOV camera.

The drawback of this type of sensing is its sensitivity to eclipses, which will happen with varying degrees of frequency depending on the orbit and season. Unlike the other phenomenologies in the MEV RPO sensor suite, passing into temporary eclipse will result in a loss of all tracking from these visual sensors for the duration, and MEV must either rely on propagated relative state, or one of the other active sensor types.

Fig. 3, shows increasing target profile fidelity as range decreases, and as the number of pixels on target climbs, MEV imagery is able to support basic stadiametric operations in addition to angles-only spot tracking.

Fig. 4, begins to show the high dynamic range of the IS-10-02 spacecraft materials in this imaging band that is evident as range closes. At this distance, exposure time is adjusted to resolve additional structural and brightness detail, and as demonstrated in Fig. 5, and Fig. 6, the client vehicle is viewed from multiple angles as MEV maneuvers in preparation for final docking approach.

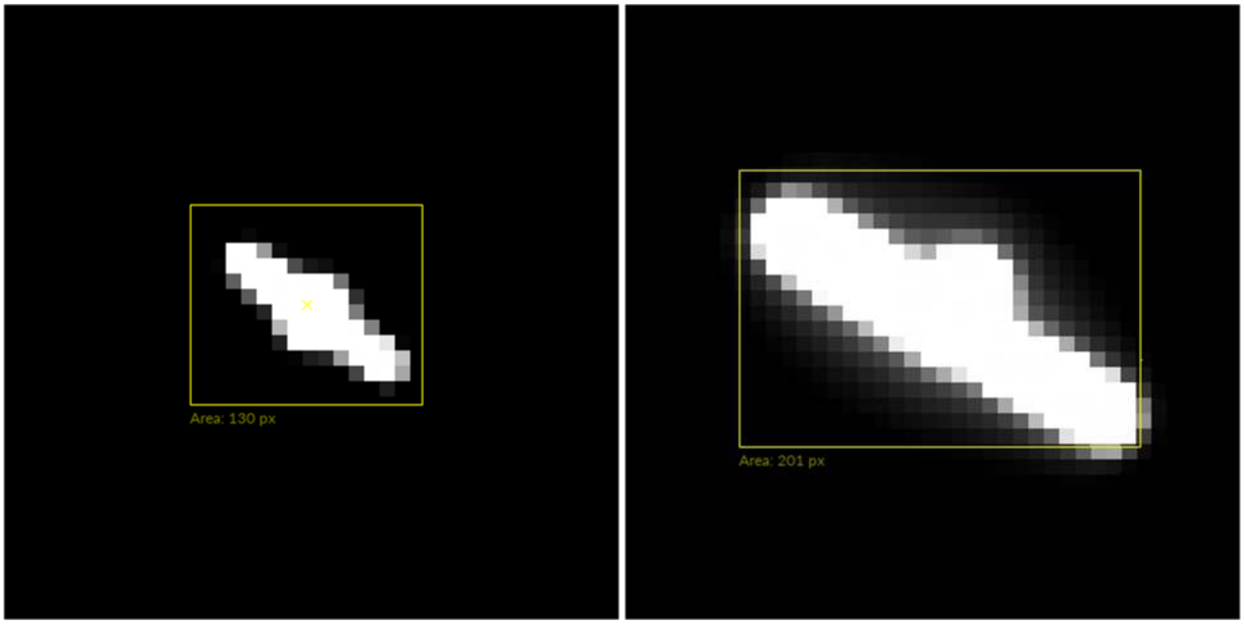

Fig. 3. VSS images of IS 10-02 at 10 km and 5 km. Overlay shows resolved client vehicle size in pixels on the VSS NFOV camera.

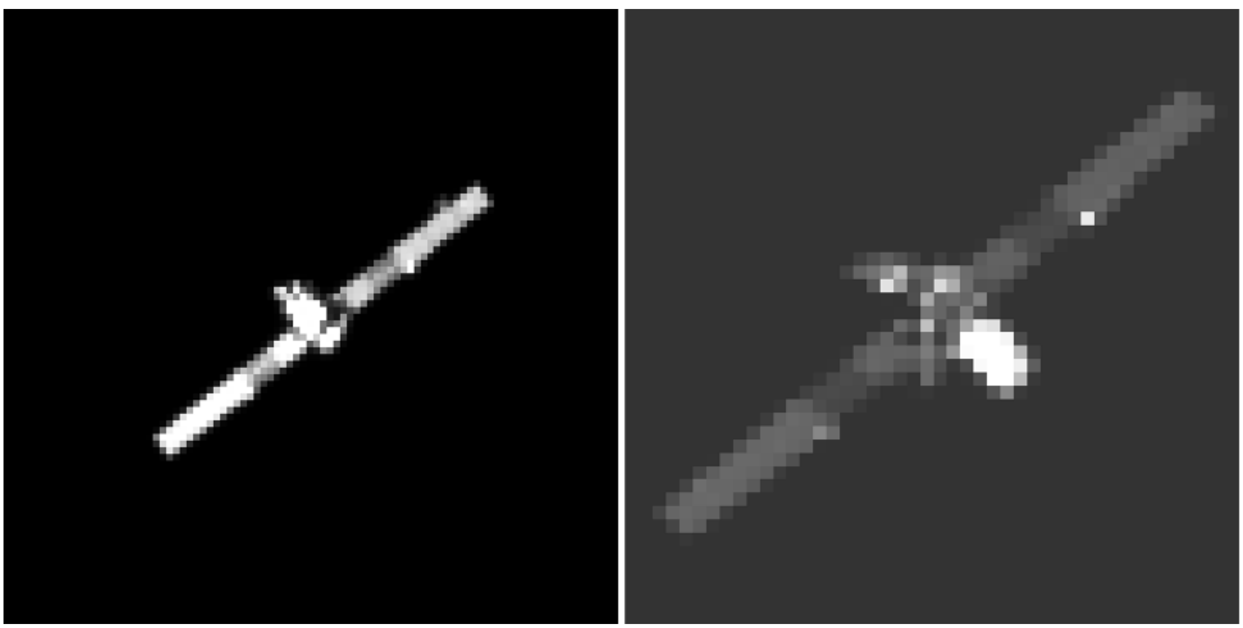

Fig. 4. VSS images of IS 10-02 at 2 km and 1 km.

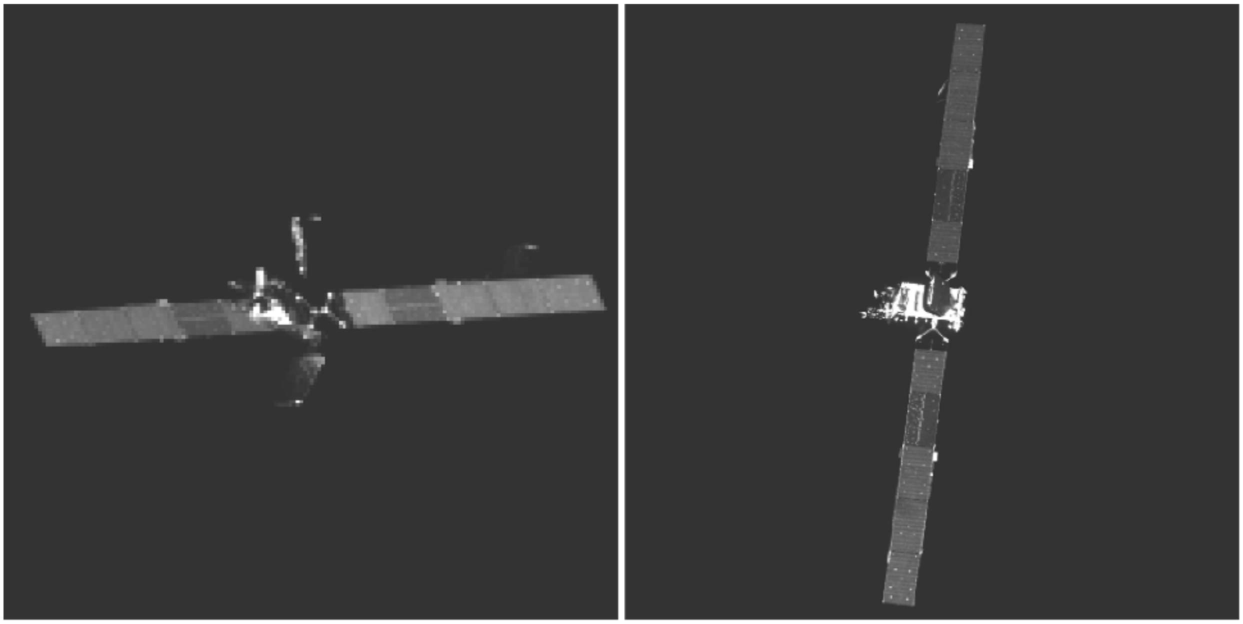

Fig. 5. VSS images of IS 10-02 at 300 m and 150 m.

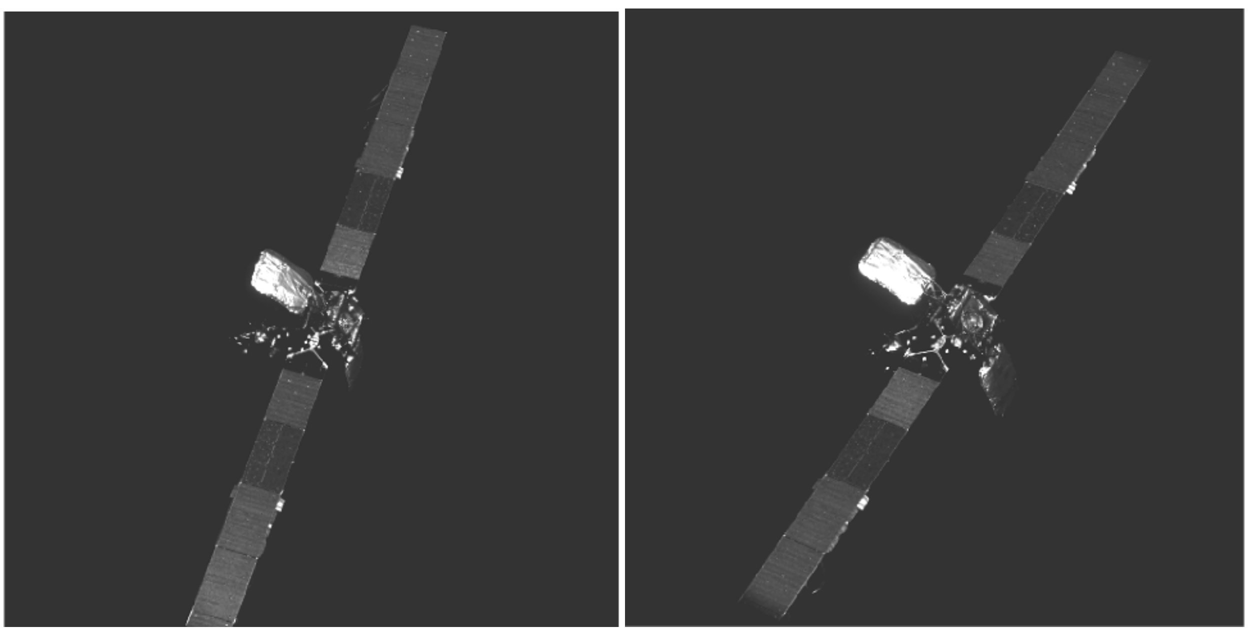

Fig. 6. VSS images of IS 10-02 at 100 m and 90 m.

Fig. 7, shows the transition point from the VSS NFOV to the WFOV camera set during the terminal phases of the approach. The VSS NFOV cameras are fixed-focus, fixed-aperture, and are optimized for best resolving performance outside of 15m. The images shown have been captured concurrently with the two camera sets, highlighting the different focal lengths and capturing a beautiful pair of views of the Earth hanging in the background.

Fig. 8, shows the final approach to capture range as MEV holds position relative to IS-10-02 and awaits final 'GO' call from the ground to grapple the client vehicle. Fig. 9, shows the view from the WFOV Docking Camera pair at this critical range, with the MEV docking mechanism visible in left frame, as it is primed to extend into the client vehicle LAE, and cinch the two spacecraft together.

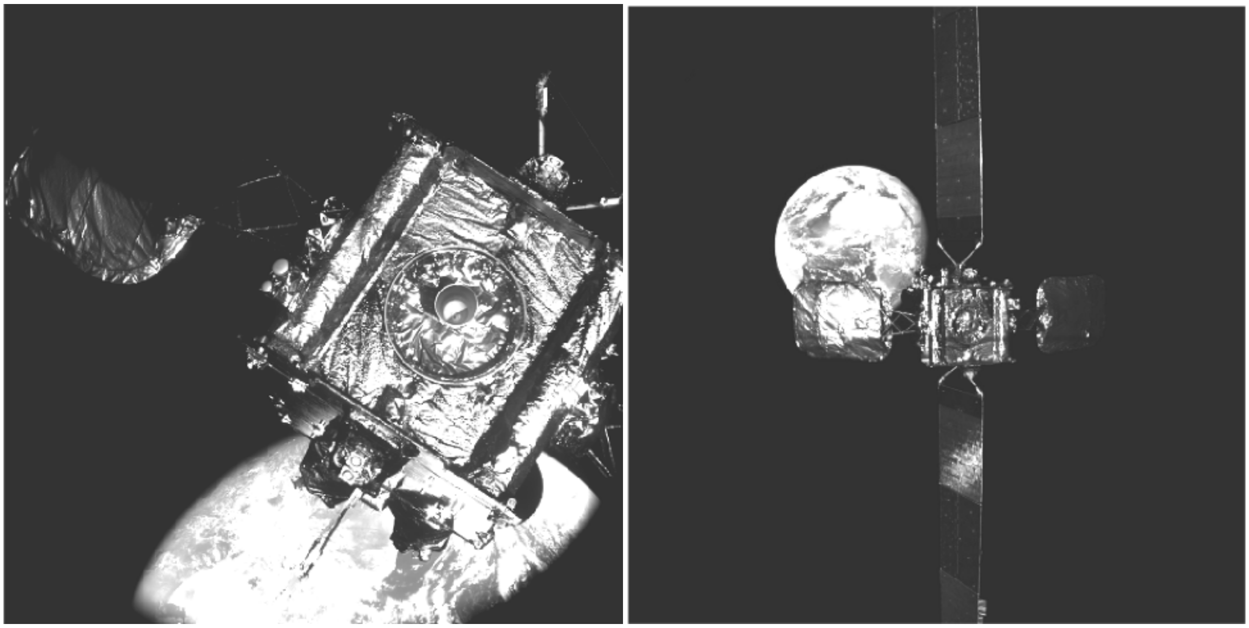

Fig. 7. VSS images of IS 10-02 at 15 m. Left, NFOV. Right, WFOV. Earth is a prominent backdrop in GEO.

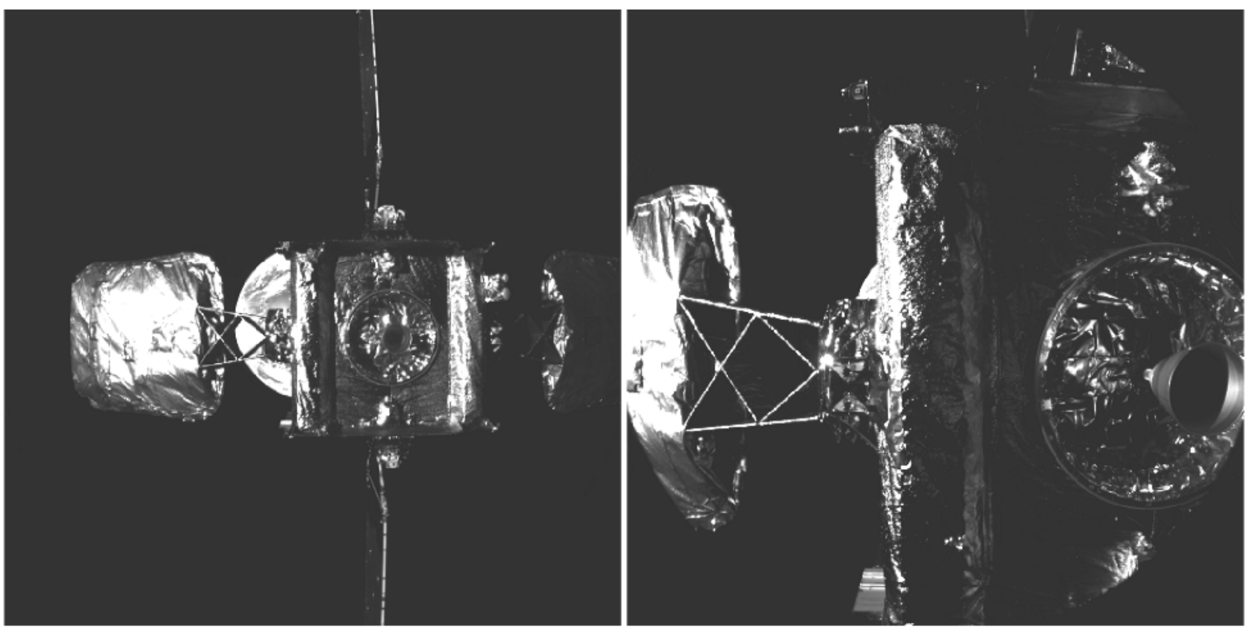

Fig. 8. VSS images of final 10-02 approach, 6 m and 2 m.

Overall, the VSS is shown to provide a robust detection, tracking, and relative navigation capability that works well across multiple mission phases.

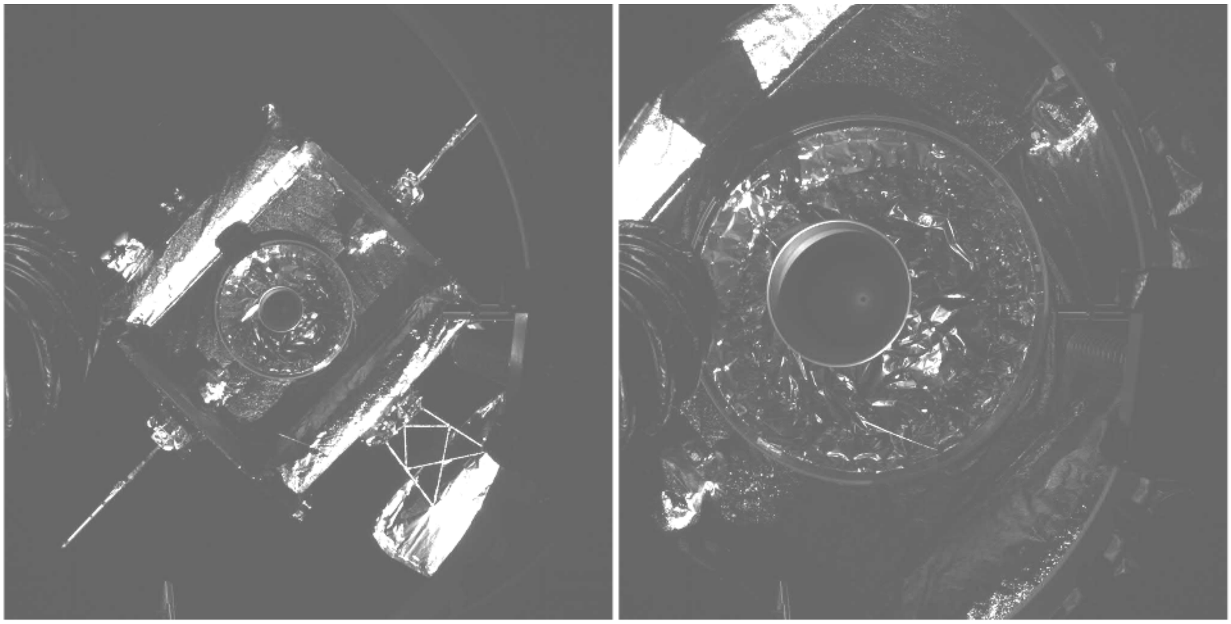

Fig. 9. VSS Docking Camera images of IS-10-02, final approach and ready position. Stowed MDS visible in left of both frames.

4. MEV Infrared Sensor System

The MEV Infrared Sensor System (IRSS) consists of four individual cameras and associated control and interface units. Provided by Malin Space Science Systems (MSSS), the MEV product line incorporates the Malin ECAM-IR3a, a member of the successful ECAM product line that has flown multiple deep space missions for NASA. The IR3a is an LWIR imager, using an uncooled microbolometer to provide sensitivity in the 8-14 µm band.

Like the VSS, the IRSS cameras each use identical focal planes and control electronics, paired with one of two optical trains: a 'Narrow Field of View' (NFOV) variant optimized for long range client vehicle detection and tracking, or a 'Wide Field of View' variant optimized for close range inspection and relative navigation.

Also like the VSS, to allow use of stereo image processing algorithms, each IRSS camera is implemented in a precision aligned duo with an identical duplicate, separated by a baseline appropriate to the operational range, and configured for synchronous capture. The full IRSS camera complement consists of 2x NFOV for long range tracking and navigation use, and 2x WFOV for close range navigation and inspection use.

The IRSS NFOV cameras are able to detect and allow tracking of a Resident Space Object (RSO) from a relative range in excess of 10km. While detection and tracking has a lower effective maximum range than the VSS, the IRSS is much more lighting-agnostic within its effective range, as will be shown in the images below. Additionally, imaging in the same band as a significant portion of the client vehicle's thermal signature provides the ability to retain tracking for a short duration during periodic eclipses.

We start the sequence of typical MEV LWIR imaging capabilities with Fig. 10, showing a fully resolved client vehicle at just over 3 km.

Fig. 11, shows increasing target fidelity as range decreases, and as the number of pixels on target climbs, MEV imagery is able to support basic stadiametric operations in addition to angles-only spot tracking.

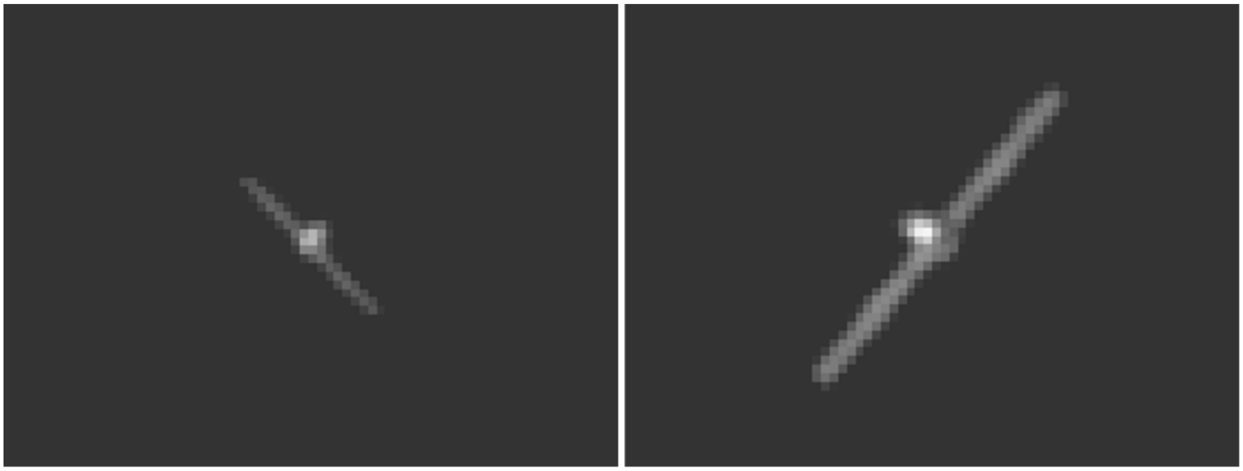

Fig. 10. IRSS images of IS-10-02 at 3.2 km and 2.1 km.

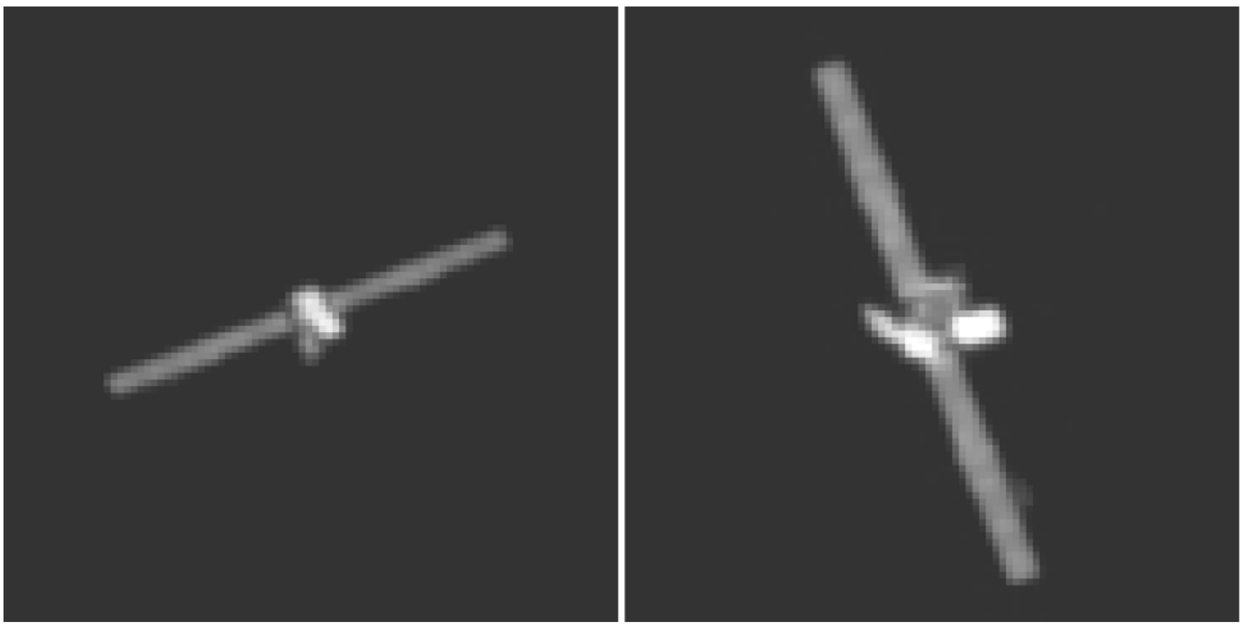

Fig. 11. IRSS images of IS-10-02 at 1.5 km and 1 km.

Fig. 12, shows a much more uniform image of the IS-10-02 spacecraft than the comparable Fig. 5, capture from the VSS. Likewise, as MEV-2 orbits to face the aft end of the client vehicle in Fig. 13, the more uniform brightness across the entire vehicle structure is evident when compared to the VSS at similar stages in Fig. 6.

The highly dissimilar nature of the visible vs. LWIR imaging provides robust competing nav solutions, even when fed into the same algorithmic pipelines. This provides confidence that there are no common mode errors in the relative navigation data being fed to vehicle GNC.

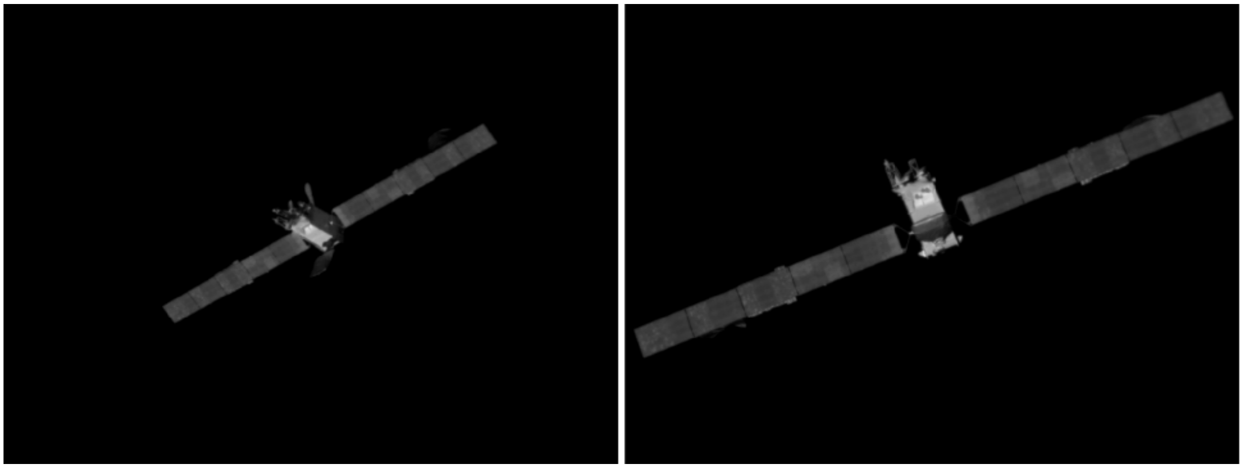

Fig. 12. IRSS images of IS-10-02 at 220 m and 160 m.

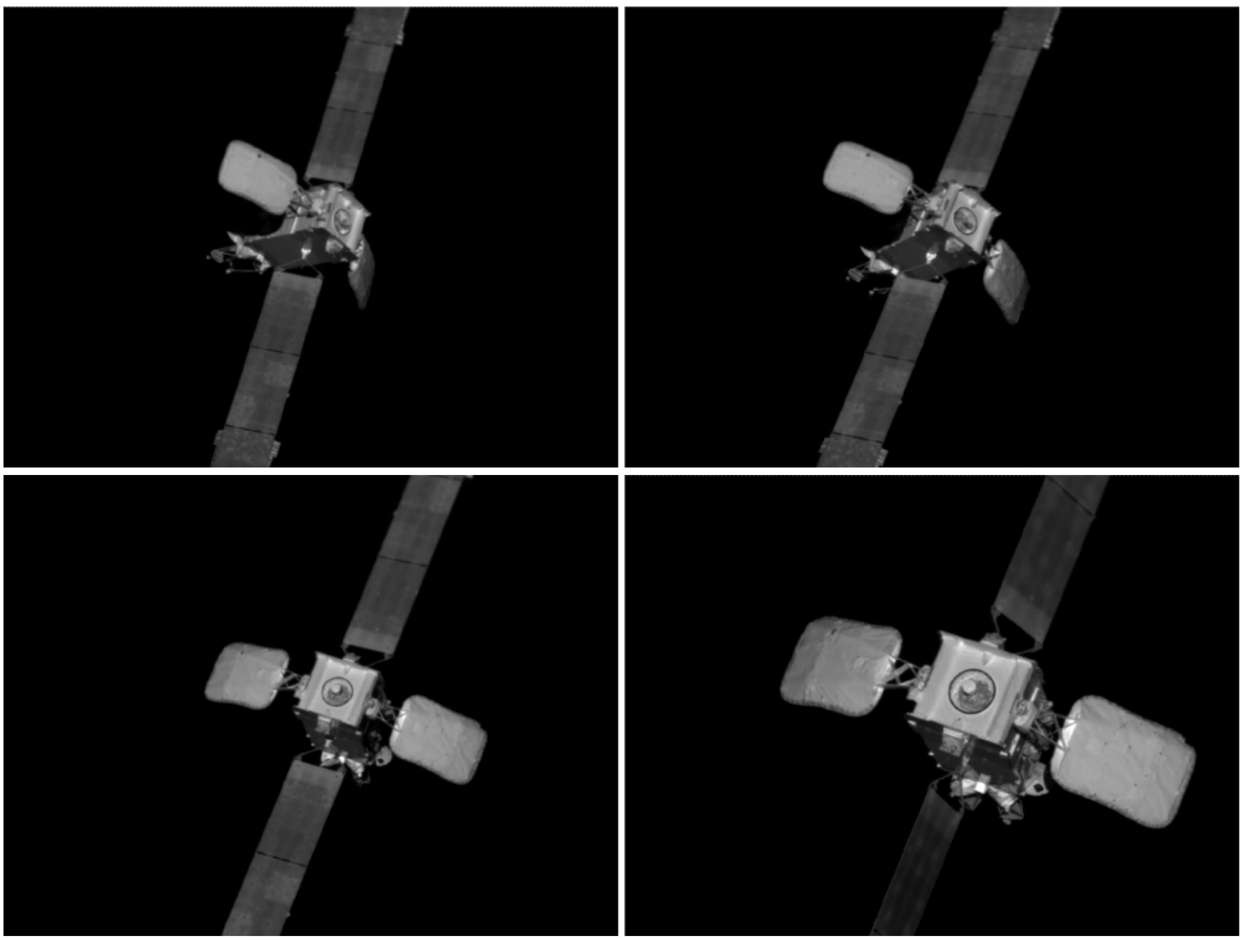

Fig. 13. IRSS images of IS-10-02 at 100 m, 90 m, 80m, 60 m, MEV2 circling aft to begin final approach.

Fig. 14, shows the transition point from the IRSS NFOV to the WFOV camera set during the terminal phases of the approach. Like the VSS, the IRSS NFOV cameras are fixed-focus, fixed-aperture, and are optimized for best resolving performance outside of 15m. The images shown have been captured concurrently with the two camera sets, highlighting the different focal lengths and capturing a beautiful pair of views of the Earth hanging in the background. Once again, note the significant differences in the dynamic range and resolvable detail vs. VSS Fig. 7, highlighting the importance of dissimilar sensing methods in the face of uncertain material properties and client vehicle structure.

Fig. 15, shows the final approach to capture range as MEV holds position relative to IS-10-02 and awaits final ‘GO’ call from the ground to grapple the client vehicle.

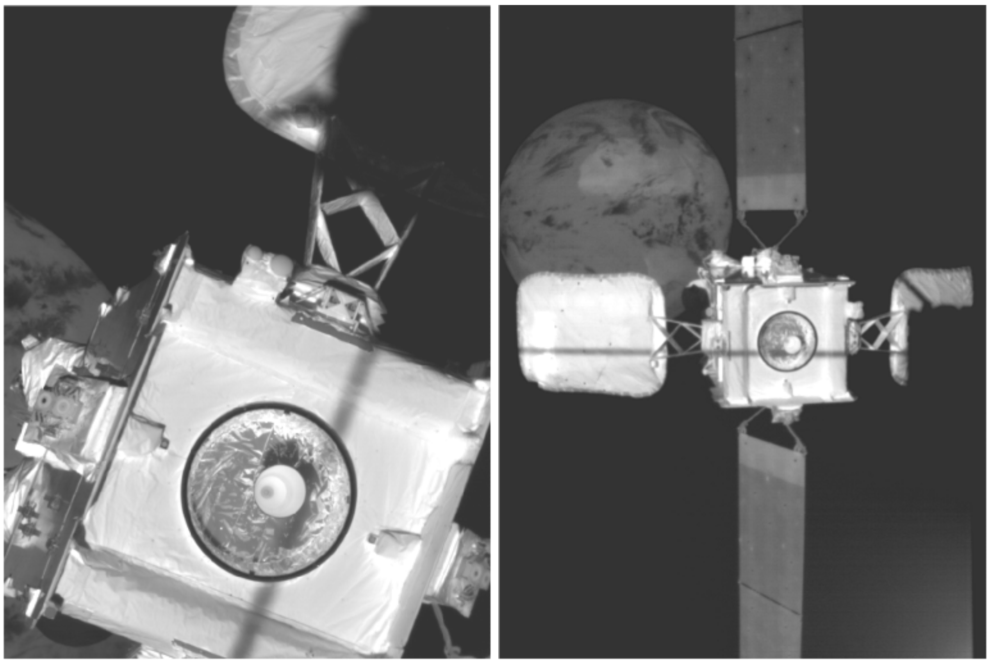

Fig. 14. IRSS images of IS-10-02 at 15 m. Left, NFOV. Right, WFOV. Earth is a prominent backdrop in GEO.

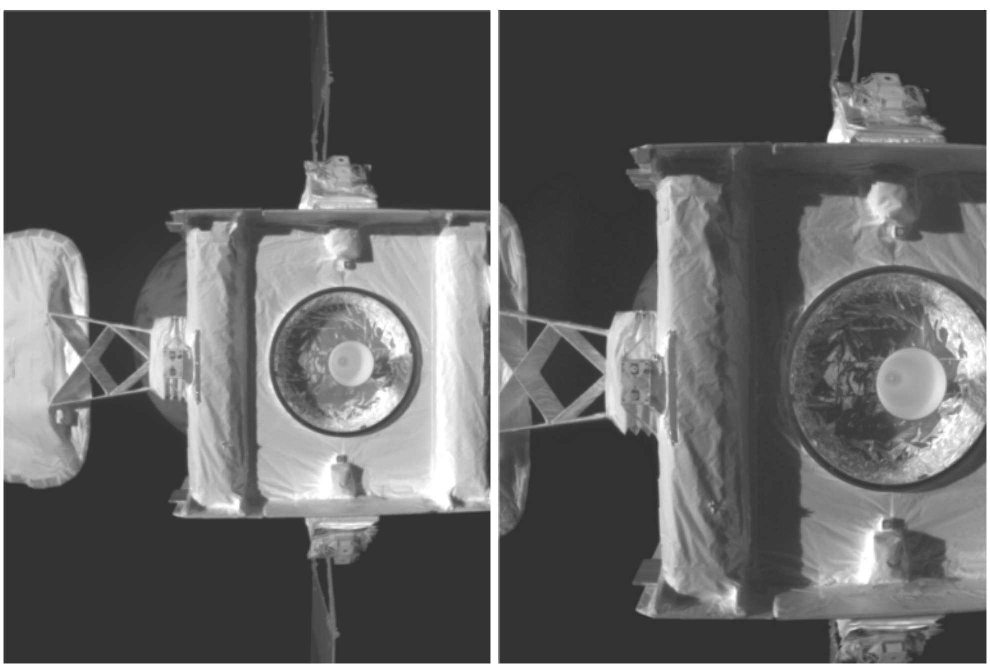

Fig. 15. IRSS images of final IS-10-02 approach, 9 m and 4 m.

Overall, the IRSS is shown to provide a robust detection, tracking, and relative navigation capability that works well across multiple mission phases.

5. MEV LIDAR System

The MEV LIDAR system consists of a single, self-contained unit. Provided by Jena-Optronik GmbH. MEV-1 was the first flight and operational use of the JOP RVS3000-3D, a fully rad-hard, high-output scanning LIDAR system designed for a 15+ year GEO lifetime and built upon the vendor's extensive heritage in space grade LIDAR systems that have flown on the STS, Cygnus, ATV, and other vehicles.

While heritage LIDAR systems flown by NG on the Cygnus vehicle were designed to take advantage of the 'prepared target' nature of the ISS, which has an extremely well-known geometry and sports numerous features such as retroreflector clusters to aid rendezvous ops, the RVS3000-3D was specifically designed to track and enable rendezvous with vehicles that had not been designed to facilitate servicing operations. Compared to configurations intended for approach to the ISS, an additional laser amplification stage was added to the LIDAR emitter and the beam divergence was significantly reduced, all in the name of maximizing return energy from distant RSOs without corner-mirror retroreflectors or similar LIDAR fiducials.

With these hardware modifications and software upgrades over heritage systems, MEV-2 was able to consistently detect and track the IS-10-02 client vehicle at a range in excess of 2 km, providing a full 3DOF relative position to guide the approach.

Fig. 16, shows the raw point cloud from a single LIDAR scan at long range. When range to the client vehicle is still in excess of 2km, its structure can clearly be recognized, and the centroid of the returns provides an extremely consistent and robust 3DOF position solution. The 3D data has been projected in 'facing' and 'top' views, and a capture from the IRSS at the same timestamp has been provided for reference.

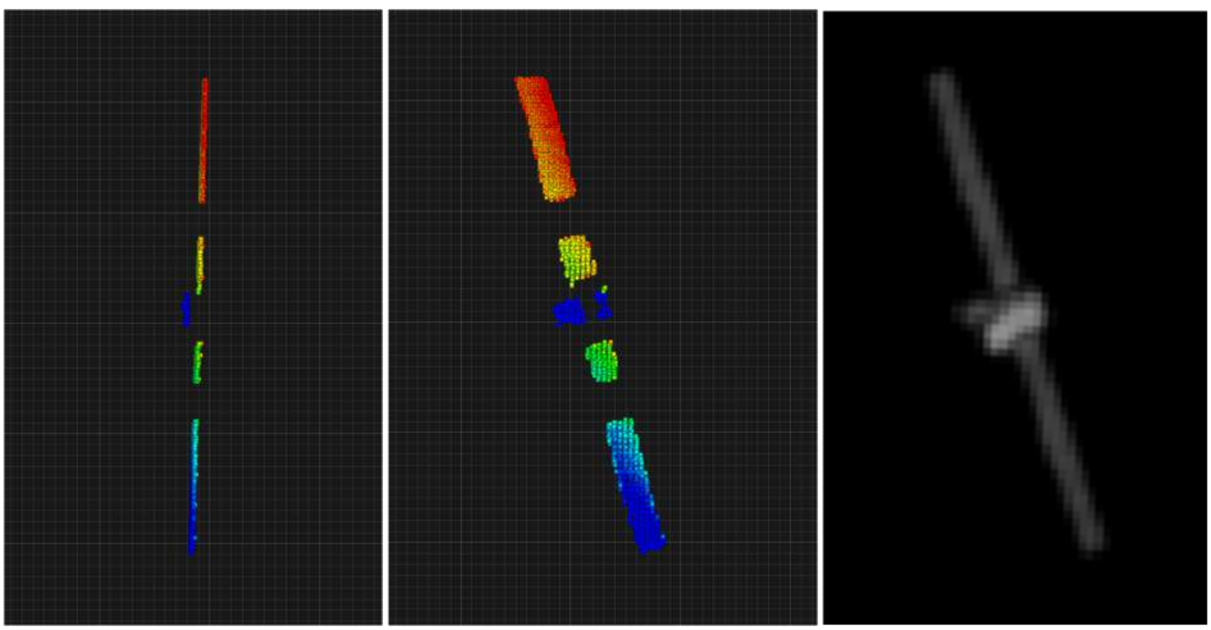

Fig. 16. LIDAR point clouds, IS-10-02, at 2000 m. 'Top' and 'Facing' projections of the 3D data. IRSS output from same time provided for reference.

As range decreases, the LIDAR is able to paint the target with a much denser scan pattern, and detailed 3D information about the client vehicle structure can be gathered. Fig. 17, shows projections of the IS-10-02 point cloud from a range of 220 m.

During the final stages of the approach, the LIDAR focuses on a subset of the full vehicle structure to optimize performance of the internal 6DOF relative position estimation algorithm. In addition to providing an even more robust navigation solution, it allows a direct overlay of the client model onto the point cloud based solely on the data output by the LIDAR. This is demonstrated first in the set of visualizations of LIDAR data captured at a range of 60 meters in Fig. 18, as well as with increasing fidelity at 15 meters in Fig. 19.

Fig. 20, shows an additional MEV capability for client vehicle inspection. While holding a tight relative position, the LIDAR is used to perform an ultra-high density structural scan, proving three-dimensional surface profile data with millimeter precision. Closely knit scan lines generate hundreds of thousands of returns, and the dense point cloud is downlinked to the ground for analysis.

Fig. 21, shows the final approach to capture range as MEV holds position relative to IS-10-02 and awaits final 'GO' call from the ground to grapple the client vehicle.

Overall, the LIDAR is shown to provide a robust detection, tracking, and relative navigation capability that works well across multiple mission phases. Importantly, the LIDAR is fully immune to any effects of lighting or time of day, including dropouts during eclipses. This makes the LIDAR a valuable addition to the MEV RPO suite.

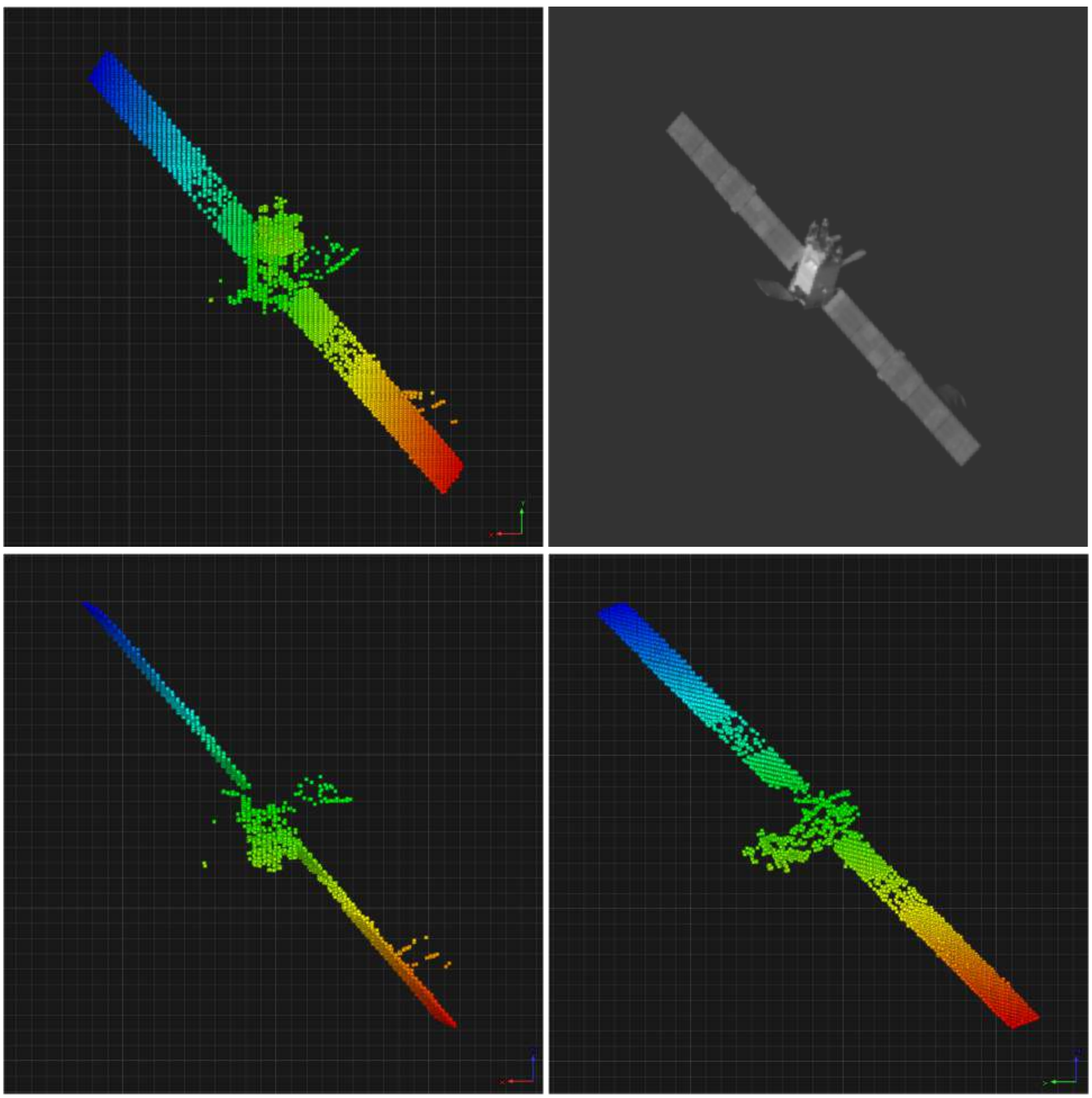

Fig. 17. LIDAR point clouds, IS 10-02, at 220 m. ‘Top’, ‘Side’, ‘Facing’ projections of the 3D data. IRSS output from same time provided for reference.

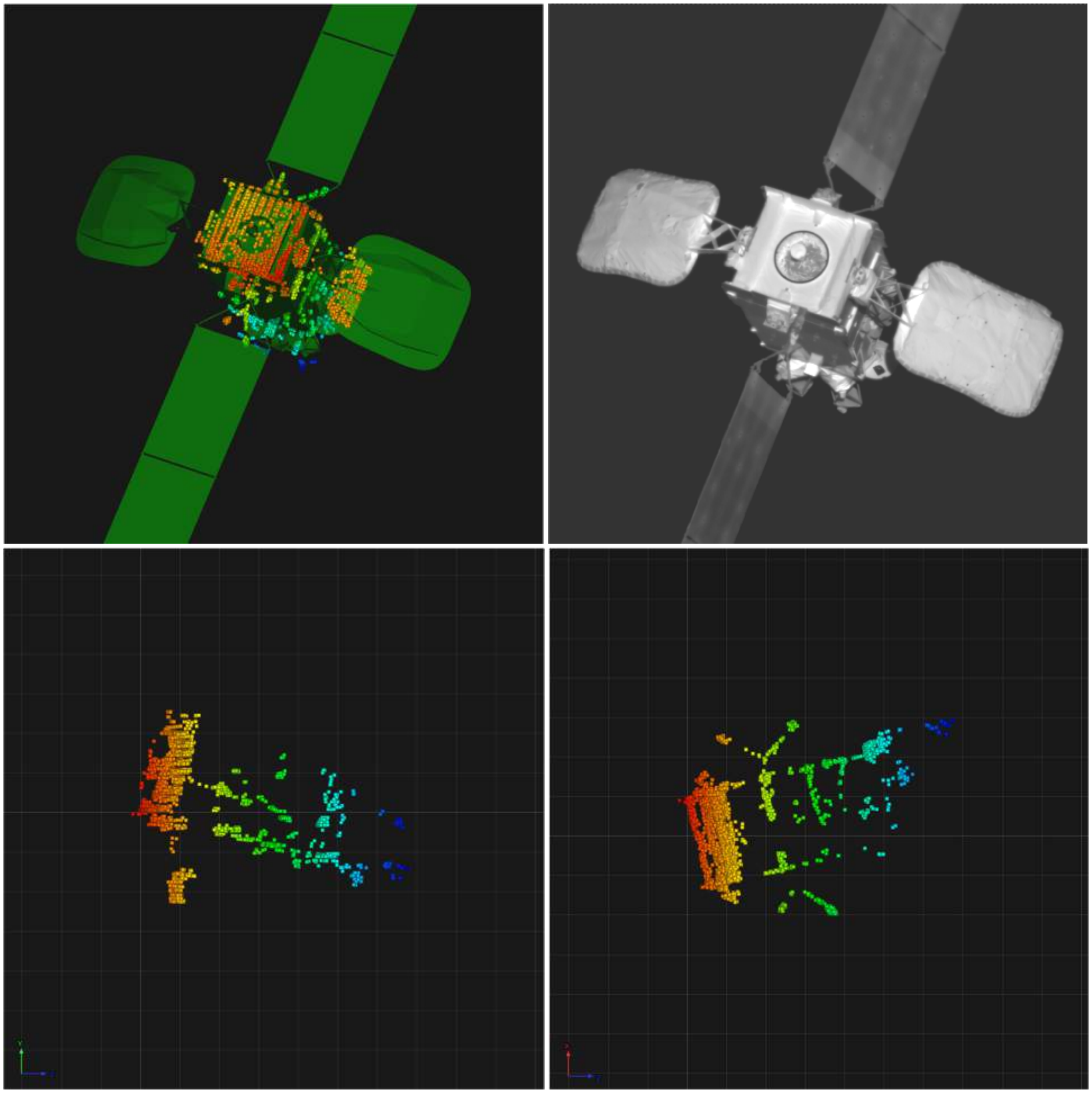

Fig. 18. LIDAR point clouds, IS-10-02, at 60 m. 6DOF solution with model overlay, IRSS image from same time reference. Top and side views of 3D data, showing aft deck, array roots, and bus structure.

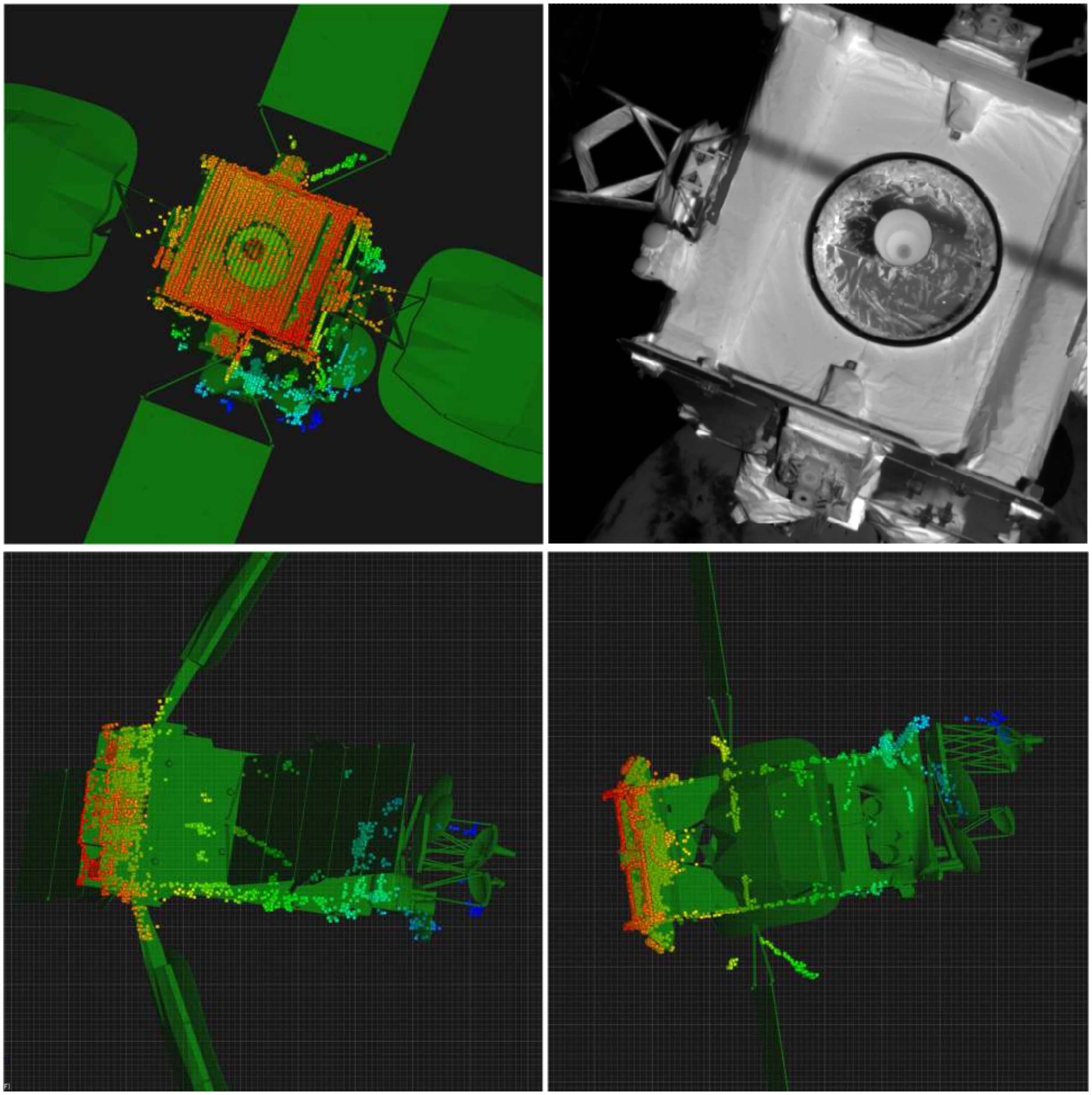

Fig. 19. LIDAR point clouds, IS-10-02, at 60 m. 6DOF solution with model overlay, IRSS image from same time reference. Top and side views of 3D data, showing aft deck, array roots, bus structure, and visible forward RF equipment.

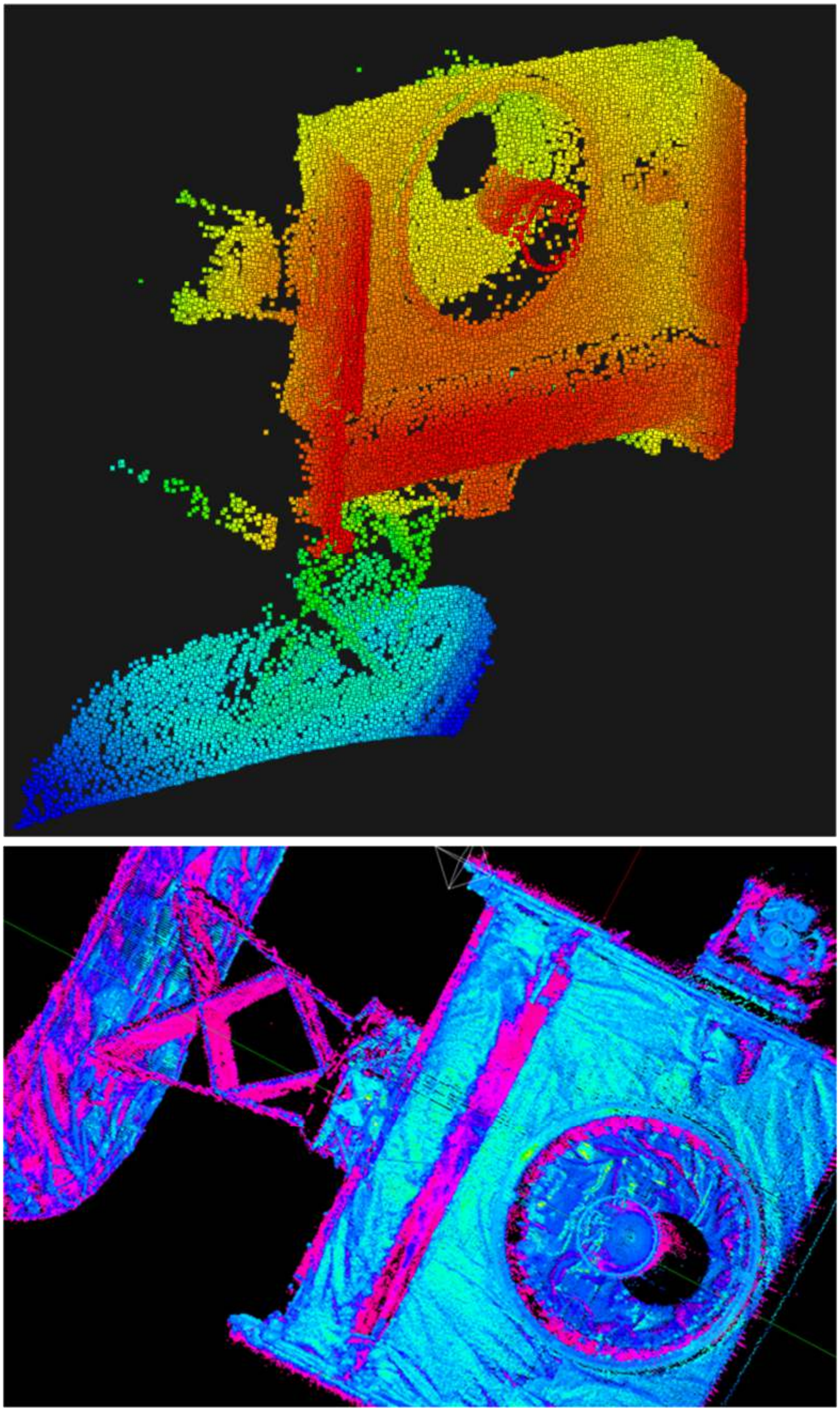

Fig. 20. LIDAR high density inspection scan of IS 10-02 at 7 m. Depth colorized, then return amplitude colorized.

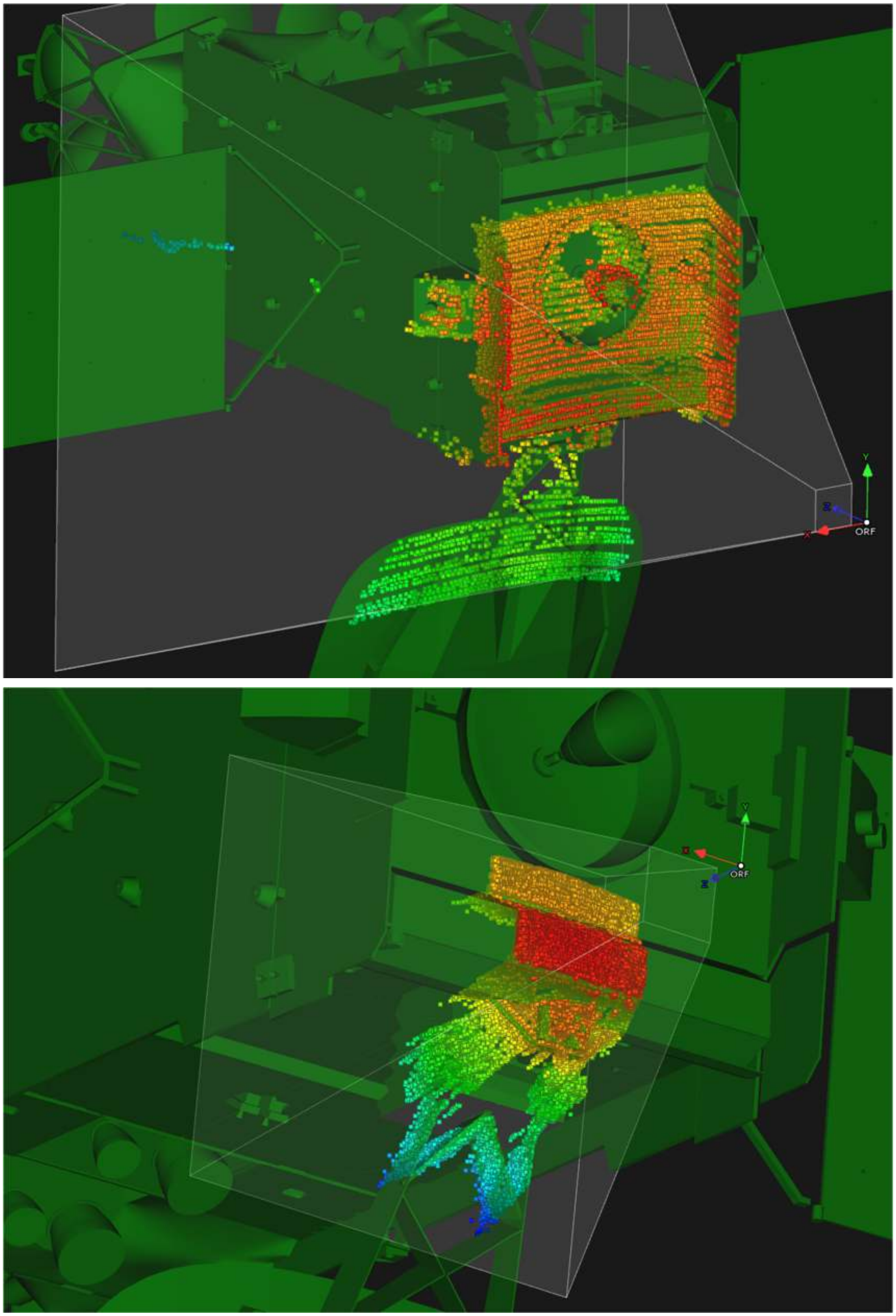

Fig. 21. LIDAR point clouds, IS 10-02, at 7 m and 2 m. 6DOF solution with model overlay.

6. ADDITIONAL ON ORBIT OBSERVATIONS

While MEV mission operations have been primarily focused on RPOD operations with the IS-901 and IS-10-02 client vehicles, the vehicle sensor suite produced other interesting data outside of the core capability requirements.

For instance, while the optical sensors were designed and configured for client vehicle tracking inside 50km or so, they were quite performant when used to collect wide angle views of the Earth and the Moon to aid in early calibration operations. In Fig. 22, below, we can see a lucky conjunction where MEV2 happened to image both the Earth and the Moon concurrently with the VSS and IRSS.

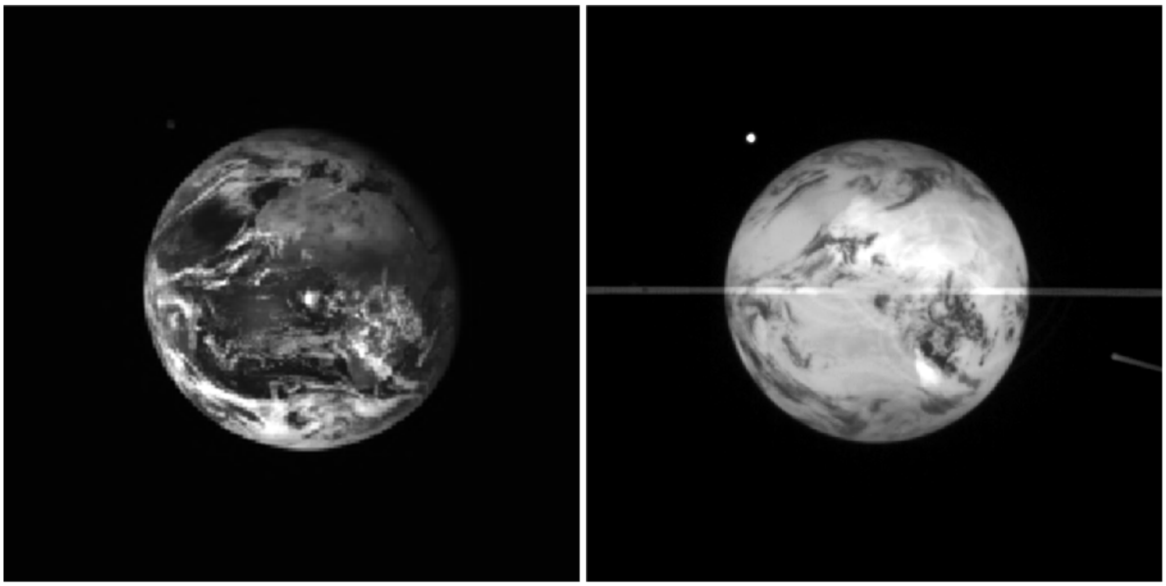

Fig. 22. Concurrent VSS and IRSS captures of the Earth and Moon. Streaking on the LWIR image is a result of prior sun-crossings, and calibration was still in process.

Additionally, while the driving requirements of the sensor suite were focused on RPOD performance, the various imaging systems (and the VSS especially) were observed to capture what appear to be non-sidereal objects (potentially other RSOs) within the vicinity of RPOD or sensor calibration operations.

For example, in Fig. 23, below, when MEV2 is within 2km of IS10-02, and happens to be looking down the GEO belt at this point in the approach, three non-star objects are clearly visible in the background when the image is adjusted to over-expose the client vehicle.

The VSS was operating in a mode at less than its full imaging resolution at the time, and using a short exposure time due to the brightness of IS10-02, which is not ideal for long range sensitivity. Even with these collection parameters, these other objects stand out starkly.

Fig. 23. VSS images during approach to 10-02, looking down the GEO belt. Three non-star objects are clearly visible in the background.

In another case, the VSS was being calibrated using the starfield. Therefore, the system was operating with a long integration time capture as many dim stars as possible.

When the resulting calibration images were correlated with the star catalogue, there were many transient signatures seen crossing the field of view over successive captures that are clearly non-sidereal. Fig. 24, shows a sequence of such captures, separated by 1 min each. The star catalogue is overlaid onto the field (all of the ‘black star’ outlines), and transient non-stars highlighted over the 4 minute span.

Even though the MEV sensor suite was never intended to provide general space situational awareness (SSA) capability, it is clear that the core system is able to outperform its primary mission of imaging individual known client vehicles with well-known TLEs to support an RPOD mission.

The upcoming NG Mission Robotic Vehicle (MRV), which builds on the successful MEV design with the addition of an advanced robotic capability, is also being equipped with an even more sensitive VSS. Current performance modeling, validated by the MEV-1 and MEV-2 on-orbit data, shows that MRV will be able to detect and track GEO-comm sized RSOs at a minimum range of 100km, and much farther out in optimal lighting conditions.

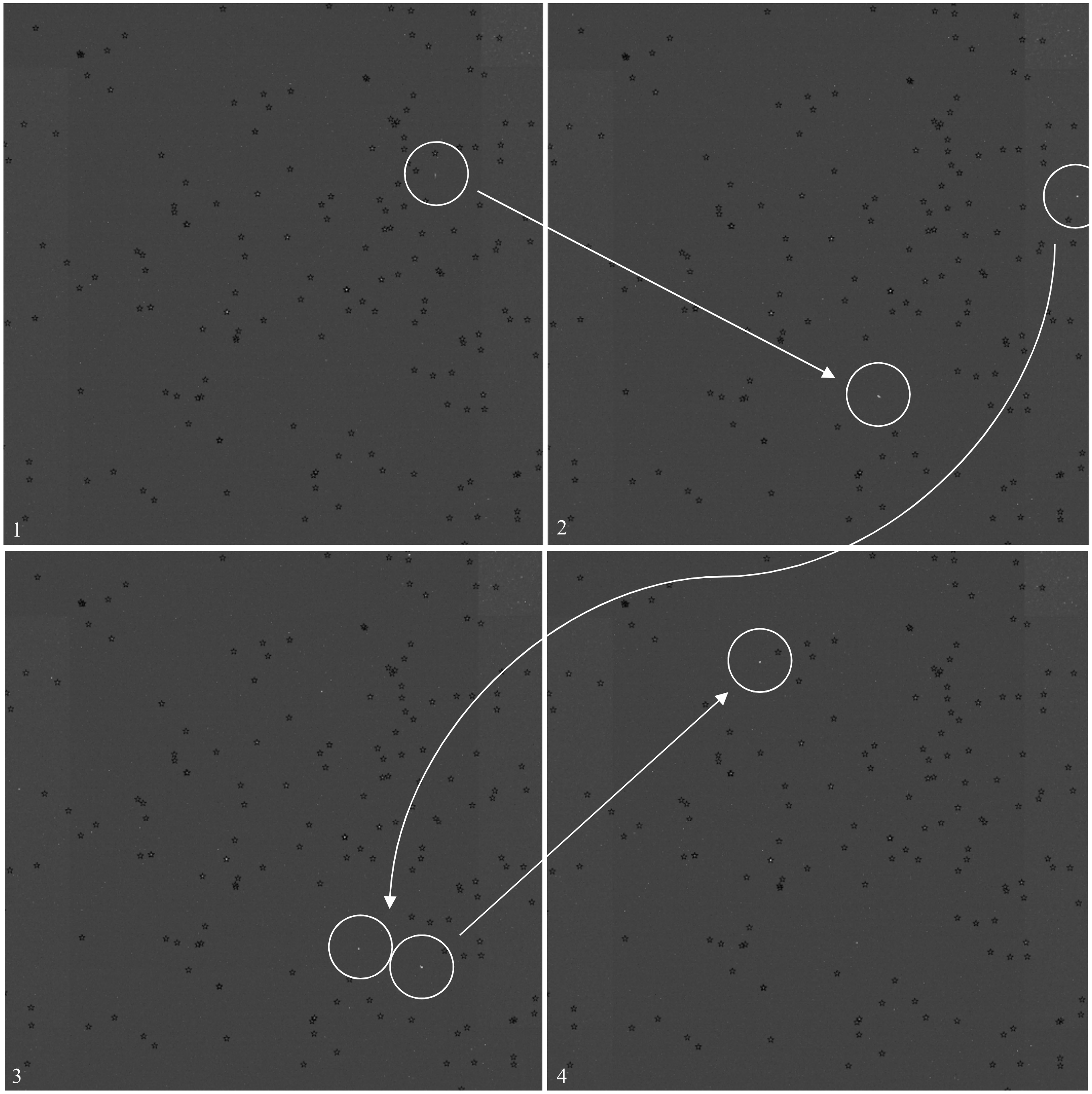

Fig. 24. VSS images during long exposure starfield calibration. Star catalogue is overlaid in black, non-star bright objects observed moving through the field of view have been circled and correlated between successive frames.

7. CONCLUSIONS

The MEV RPO sensor suite has been demonstrated to be a robust and flexible hardware array that enables the core mission of RPOD with commercial GEO-comm clients, a truly groundbreaking capability that at this time is still unique in the marketplace.

Furthermore, the combination of multiple sensor phenomenologies, wide range of adjustable sensitivities, and the precise pointing and RSO tracking capabilities of the core vehicle has been proven to be a valuable starting point for new mission capabilities for MRV and beyond.