



# EU-ESA WORKSHOP

Astrometric and Radar Observations of NEOs

October, 2025

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# EU-ESA Workshop

## Astrometric and Radar Observations of NEOs

October 2025  
ESRIN, Frascati, Italy

The EU-ESA Workshop on Astrometric and Radar Observations of NEOs was organised as part of a task entrusted by the EU to ESA under the Space Programme (2021), aiming to promote networking of Member State facilities and research centres involved in NEO-related activities.

*Within this task a mechanism will be developed for promoting networking activities among MS facilities and research centres in the field of NEO-related activities. This task can be realised at varying budget levels. The main mechanism is the organisation of a yearly conference on NEOs. One conference per year will be organised until Q4/2027.*

This specific workshop brought together experts in astrometry, radar observations, and orbit determination to assess current techniques for astrometric and timing uncertainty estimation, identify key uncertainties, and establish pathways to improve the astrometric and dynamical characterization of potentially hazardous NEOs.

All information about the workshop, including the list of participants, the presentations provided, and the recordings, is available on the official website: <https://indico.esa.int/event/590/>

**This report is solely endorsed by its authors. While its content draws on presentations and conversations held during the EU-ESA Workshop, the analyses and recommendations offered here reflect the authors' own interpretation of those exchanges. They should not be understood as expressing the official views or consensus of all workshop participants.**

The workshop was co-organised by the European Space Agency (ESA) and the European Commission, with participation from academic institutions, observatories, and planetary defence stakeholders.

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# 1 Executive summary

Planetary defence is a critical component of the efforts to safeguard Earth from the potential hazards posed by near-Earth objects (NEOs). It is an inherently interdisciplinary field that extends far beyond astronomical discovery and analysis, encompassing international coordination, decision-making structures, mitigation planning, and disaster-management policies (Rathnasree & Barucci, 2020, National Science & Technology Council, 2018). At its scientific foundation lie four essential tasks: the discovery of NEOs (Gregori et al., 2023, Tonry et al., 2018), systematic follow-up observations to refine their trajectories (Vaduvescu et al., 2017), rigorous and transparent orbit determination (Fenucci et al., 2024), and, when an object presents a non-zero impact probability, the accurate determination of its physical properties, impact modelling, and the development of appropriate response strategies.

The first pillars of planetary defence are therefore the precise measurement of an asteroid's position and the reliable determination of its orbit. The 2025 EU-ESA Workshop, held at ESA ESRIIN (Frascati, Italy) from 6-8 October, focused on improving this foundational capability. Participants examined how NEO positions can be most effectively measured using complementary techniques, classical astrometry, radar delay-Doppler observations, and stellar occultations, each offering distinct strengths and challenges. The workshop also reviewed the current methods, algorithms, and software for orbit determination, highlighting both their performance and their limitations when incorporating diverse observational data sources. In addition, emerging technologies were discussed, including artificial intelligence, advances in CMOS detector architectures, synthetic-tracking methodologies, and new opportunities provided by spacecraft-based observations.

This document presents a synthesis of the main results, technical discussions, and perspectives shared during the EU-ESA Workshop on Astrometric and Radar Observations of NEOs. Its objective is to consolidate the insights from the astrometry, radar, and orbit-determination communities and to outline pathways for improving the accuracy, robustness, and interoperability of NEO measurements within the broader context of planetary defence.

**The views and recommendations presented in this report are solely those of the authors. While they draw upon presentations and discussions held during the EU-ESA Workshop, they reflect the authors' interpretation of those exchanges and should not be taken as representing the official views or consensus of all workshop participants.**

# Program of the EU-ESA Workshop on Astrometric and Radar Observations of NEOs

## Orbit Determination and Impact Monitoring Session

### Asteroid orbit determination and impact monitoring at ESA: the Aegis software

**Speaker:** Francesco Gianotto (ESA NEOCC)

**Co-Authors:** L. Faggioli, M. Fenucci

This talk presents the risk assessment pillar of the NEOCC activities, covering asteroid orbit determination, impact probabilities computation over the next 100 years, and the detection and analysis of imminent impactors (see the [NEOCC risk list](#)). Orbit determination and long-term impact monitoring are performed with Aegis (Fenucci et al., 2024), while Meerkat supports imminent-impactor screening by searching for potential impacts on short timescales and issuing alerts to the community (Frühauf et al., 2021, Gianotto et al., 2023).

The presentation highlights developments of the NEOCC toolchain, including the transition to a PostgreSQL replica of the MPC database reducing reliance on MPEC-based ingestion. It also introduces key capabilities such as transparent orbit-fit outputs (RWO files), MOCA (Monte Carlo method for Asteroid impact Monitoring) as complement to the LoV approach, impact corridor products, and a set of NEO analysis and visualisation tools available through the [NEOCC portal](#).

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### Advancing orbit determination and impact monitoring with ADES and high-precision astrometry: an example on 2024 YR4

**Speaker:** Marco Fenucci (ESA NEOCC)

**Co-Authors:** F. Gianotto, L. Faggioli

This talk discusses the Astronomy Data Exchange Standard (ADES) for impact monitoring and its implications for orbit determination. ADES, was introduced to replace the legacy 80-columns format, enables reporting of per-observation uncertainties, including astrometry and timing, and can also support the exchange of orbit-fit diagnostics (residuals, weights, and rejection flags). The case of 2024 YR4 is used to compare impact-monitoring results obtained with traditional residual-based statistic weighting versus approaches that incorporate ADES-reported uncertainties. While blindly trusting ADES can lead to unstable solutions when uncertainties are overly optimistic or inconsistently interpreted, the talk shows that applying minimum uncertainty “floors” (and avoiding overly aggressive rejection) yield behaviour closer to the carefully curated operational solution. The presentation also illustrates the strong value of early radar and high-precision astrometry for rapidly shrinking uncertainties, and notes that improved communication and reaction time for radar observations remain important gaps to address.

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Orbit Determination and Impact Monitoring Session

**Identifying and Understanding Bad Tracklets: Inaccurate and Mis-Attributed Astrometry**

**Speaker:** Peter Veres (CfA/MPC)

**Co-Authors:** F. Spoto, J. A. Perez-Hernandez, M. Payne

This talk describes how the Minor Planet Center (MPC) ingests observations, identifies, and handles “bad tracklets”. Incoming data may be attributed or non-attributed. The MPC performs attribution and orbit fitting, leading to correct attribution, misattribution, or ambiguous cases. The presentation explains why the fixed 2” residual threshold is inadequate across diverse instruments characteristics, given differences in pixel scales, seeing, trailing, stacking, and source confusion. Using numerous real examples, it shows how problematic tracklets can arise from both astrometric and photometric issues (e.g., anomalous magnitudes can reveal misidentifications or measurement artifacts). A key focus is the impact of bad tracklets on short NEOCP arcs, where a single early error can strongly bias predictions and waste follow-up effort. The talk concludes with statistics on deleted NEOCP tracklets and with steps toward improved automation, submission practices, and quality control (including timing and archival data).

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Astrometric Observation Uncertainties Session

**Computing Astrometric Uncertainties**

**Speaker:** Dave J. Tholen (University of Hawaii)

This talk discusses how to represent astrometric uncertainties in a practical and consistent way. The presentation separates three main uncertainty contributors: the astrometric solution, centroiding on the target, and timing. It notes that short exposures can be affected by anomalous refraction, where atmospheric turbulences makes reference stars “wobble” and prevents uncertainties from decreasing as expected by averaging many stars. A pragmatic approach is to add an extra term in quadrature so the reduced chi-square of the astrometric fit is brought to unity. For target centroiding the talk highlights additional effects that are hard to capture in simple formulas, including offsets between spatial and temporal centroids (e.g., transparency/seeing/tracking changes during an exposure) and chromatic differential refraction that grows at large zenith distance. Finally, it emphasises that timing errors can dominate for fast-moving objects and encourages observers to calibrate their timing (e.g., using GPS-satellite observations), clarifying the distinction between per-observation timing scatter (rmsTime) and a systematic timing calibration uncertainty that can apply to a tracklet or night (uncTime), with the bias itself expected to be corrected by the observer.

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## Astrometric Observation Uncertainties Session

### On the uncertainties of astrometric observations

**Speaker:** Federica Spoto (CfA/MPC)

**Co-Authors:** J. A. Perez-Hernandez, M. Payne, P. Veres

This talk is starting with a short overview of the MPC's role as the central hub that receives and publishes astrometry for small bodies, performs identification/designation, and maintains the observation and orbit catalogues. It emphasised the scale of current operations and notes that upcoming next-generation surveys are expected to significantly increase the volume of data.

It then focusses on ADES replacing the legacy 80-columns format, showing how adoption has grown over the last decade and explaining ongoing MPC/JPL efforts to make ADES easier to use. ADES is presented as flexible enough to carry richer metadata, including per-observation uncertainty information, while still offering both machine-readable (XML) and human readable (PSV) options.

Finally, the talk describes how the MPC evaluates the consistency of submitted uncertainties through post-fit residual analyses, using these diagnostics to detect systematic issues and to guide feedback to data providers. The presentation closes by noting that the MPC is proposing a similar community standard for orbit exchange, aiming for discussion and refinement ahead of a planned submission for approval at the 2027 IAU General Assembly in Rome.

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### Predicted astrometric uncertainty for NEO Surveyor tracklets

**Speaker:** Joseph Masiero (Caltech/IPAC), Federico Marocco (IPAC), Garrett Levine (Yale)

**Co-Authors:** A. Mainzer, F. Masci, S. Carey, S. Diniega, T. Linder

NEO Surveyor will be a 50 cm space telescope observing in two mid-IR bands. It is expected to launch in 2027 with a 5-year nominal survey and covering the  $\sim 45^\circ$  to  $120^\circ$  solar elongation regions. It is optimised for discovering and measuring NEOs through their thermal emission, and includes a targeted follow-up mode that can interrupt the survey to observe objects of planetary defence interest.

For astrometry, a dual-band calibration strategy tied to Gaia using a pre-determined distortion model will be used. Simulations suggest a per visit astrometric capabilities consistent with NEOWISE. End-to-end tests with the MPC on simulated data show high reliability, but also highlight that linkability can be limited by crowding/confusion in the ecliptic or near the galactic bulge.

Orbit simulations indicate that the biggest improvement in follow-up predictability comes from obtaining a third tracklet, which sharply reduces on-sky uncertainty and should make many discoveries recoverable from the ground near their best observability window (weeks to a few months after discovery).

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## Astrometric Observation Uncertainties Session

### NEOCC side-activities enabling precision astrometry

**Speaker:** Francisco Ocaña (ESA NEOCC)

During this talk Francisco covered the basic principles of how to perform high quality astrometric measurements. The most important part is to know your telescope and system. Its timing accuracy, the instrument technology, the read-out mode, the shutter system, etc. It is also highly important to train in many different observing conditions.

The most important factor is to know as well as we can the uncertainties and biases of your clock. For this, there exist tools developed by Bill Gray ([satellites ephemerides](#), [astrometry check](#)). However, determining the clock biases and uncertainties is not enough, it is important to properly report the correct values in the ADES fields `uncTime` and `rmsTime`. `uncTime` being the uncertainty on the determined bias from which all observations should be corrected before sending them to the MPC. `rmsTime` on the other hand corresponds to any random error that could affect individual observations.

The talk finished by presenting how astrometric observation can be obtained at very low elevation and low solar elongation.

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### High-precision astrometry at ESA NEOCC

**Speaker:** Marco Micheli (ESA NEOCC)

During this talk Marco Micheli briefly introduced the motivation for the NEOCC telescope network and then used the rest of the presentation to seed discussion topics for the workshop rather than give a standard status report. The main questions raised were: how to secure access to telescopes worldwide, how to obtain reliable astrometry from very wide-field systems, what pixel sampling is “good enough” relative to seeing, and what observing strategy works best for fast movers.

He also highlighted challenges and potential approaches for crowded-field astrometry (Milky Way/galactic centre), cometary astrometry (need for robust, possibly standardised techniques), and low-elongation observations, especially the impact of differential chromatic refraction and the need to at least include it in the error budget.

Finally, he stressed two practical community issues: dealing with velocity-space uncertainty when searching/stacking (including for “negative observations”), and incentivizing follow-up of very faint LSST-era targets (deep stacking on a single object) while encouraging non-astrometric observers (e.g., acquisition images for spectroscopy/polarimetry) to share data that can still yield valuable astrometry.

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## Astrometric Observation Uncertainties Session

### Influence of the dynamic classification of asteroids on observation astrometric errors

**Speakers:** Nicolò Stronati (Cranfield University), Marta Ceccaroni (Cranfield University)

**Co-Authors:** L. Faggioli, M. Micheli

This work was motivated by the study of so-called “broken orbits”, where large residuals disappear when the observational arc is split in two, due to dynamical events such as close encounters. To distinguish real dynamical effects from observational artefacts, the study examined how astrometric residuals depend on observation quality and weighting, at a time when individual uncertainties were not yet available and residual statistics had to be used instead.

By separating observations into near-Earth objects and main-belt asteroids, it was found that most observatories show similar performances for both classes, but a small number exhibit systematic differences. These differences are linked to observing strategies, reduction pipelines, manual re-measurement practices, and their evolution over time. The main conclusion is that including the dynamical class of an asteroid in the weighting scheme could improve orbit determination by capturing station-dependent behaviours that are not fully described by magnitude, rate of motion, or epoch alone

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### Impact of Observation Time Uncertainty on Orbit Determination: An experiment with real data

**Speaker:** Davide Bracali Cioci (SpaceDyS)

The talk explored how timing uncertainties should be handled in orbit determination as tools transition to using full ADES information via an MPC database replica. In the standard weighting approach, uncertainties in RA and Dec are treated symmetrically, producing a circular confidence region on the sky. Introducing timing uncertainty breaks this symmetry: it propagates mainly along-track, stretching (and effectively rotating) the confidence region, while the cross-track direction is largely unaffected.

Two strategies were outlined: (1) fitting the observation times as additional parameters, or (2) mapping time uncertainty into an on-sky positional uncertainty via the object’s apparent angular rate (the approach used here). Test comparisons of orbit solutions with and without timing uncertainty showed that most objects change little, but fast-moving objects with large timing uncertainties can exhibit significant orbit shifts and altered residual acceptance.

The conclusion emphasized an open operational question: does accounting for timing uncertainty increase or decrease the number of virtual impactors and the overall assessed impact risk?

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Software and New Technologies Session

**NEODetect: An AI-based real-time system for faint NEO trail detection — latest enhancements**

**Speaker:** Szabolcs István Velkei (Machine Intelligence Zrt)

**Co-Authors:** K. Vass

This talk presented NEODetect, a deep-learning-based system for the real-time detection of faint, fast-moving near-Earth objects and space debris. Its main objective is to identify high apparent-speed objects that are difficult to detect with traditional stacking or software-tracking methods, enabling earlier alerts for planetary defence. The system is designed to operate both on premises near telescopes and in the cloud, delivering detections within a few seconds of image acquisition.

NEODetect relies heavily on synthetically generated training data to compensate for the scarcity of real high-speed NEO observations and is optimized to detect long, faint streaks. It is currently deployed at the K88 observatory, where it complements classical tracking: deep learning is most effective for very fast and faint objects, while traditional methods remain better suited for slower detections. The main limitations are coarse astrometry and the lack of photometry in the initial detection stage, which are being addressed through a second neural network aimed at refining positions, motion, and brightness estimates.

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**Astrometrica: Basic functions and practical application**

**Speaker:** Herbert Raab, Peter Birtwhistle

This talk reviewed the long-term development of Astrometrica, from its origins in the late 1980s for photographic plates to its current role as a widely used tool for CCD astrometry. The core functionalities were outlined, including image calibration, reference star matching, moving-object detection, track-and-stack, and ADES-compliant reporting. The developer invited feedback from the community and discussed possible future developments, including collaborative or more open development models.

The second part focused on practical usage, highlighting common pitfalls in astrometric measurements and how to address them. Through concrete examples, the talk showed how issues such as poor centering, problematic frames, reference star mismatches, or overly strict settings can affect astrometric quality, and how careful inspection of fits and residuals can lead to more reliable results, particularly for time-critical NEO follow-up.

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Software and New Technologies Session

**Exploring the Impact of Camera Timing on NEO Astrometry**

**Speaker:** Daniel Parrott

During this talk, Daniel Parrott highlighted the importance of accurate camera timing from astrometric measurements. While timing errors of several seconds are generally negligible for slow-moving main-belt objects, fast-moving NEOs quickly become sensitive to timing errors, requiring sub-second accuracy and, for the fastest objects, fractional-second precision.

Two main approaches to improving timing accuracy were discussed. The first relies on imaging GNSS/GPS satellites, whose well-known ephemerides and rapid apparent motion allow observers to measure systematic and random timing offsets between the FITS header timestamp and the true exposure start time. This analysis showed that timing delays depend on camera settings such as binning and include an irreducible random component at the level of a few hundredths of a second. The second approach timestamps exposures directly at the camera using GPS-synchronized hardware, such as LED pulse systems, providing millisecond or better accuracy and eliminating software-induced delays.

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**sCMOS Detectors for NEO Observations: Opportunities and Challenges**

**Speaker:** Miguel R. Alarcón (IAC)

**Co-Authors:** J. Licandro, M. Serra-Ricart

This talk gave an overview of CMOS sensors and the main features that matter for astronomy. Unlike CCDs, CMOS devices perform readout at the pixel level, so the detector behaves as an array of many slightly different sensors. This enables very fast readout with low noise and reduced cooling requirements, but it also introduces pixel-to-pixel response variations (bias, gain, linearity, dark current) that must be characterised and calibrated.

The talk highlighted several CMOS-specific effects relevant for astrometry and photometry, including random telegraph noise (“salt-and-pepper” pixels with intermittent jumps) and, for some sensor families, charge persistence after near-saturation exposures. Another key point is the rolling-shutter behaviour, where different rows are not exposed at exactly the same time, which can matter for short exposures and fast-moving targets unless corrected.

The conclusion was that modern scientific CMOS (sCMOS) sensors are now fully capable of high-quality scientific work, often comparable to CCDs, provided observers understand their systematics and account for them in calibration and timing.

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Software and New Technologies Session

**Commissioning and First-Light Results of ESA's Flyeye-1 Telescope**

**Speaker:** Dora Föhring (ESA NEOCC)

**Co-Authors:** E. Cordelli, E. Doeling, F. Ocaña, J. Klug, L. Conversi, M. Micheli, M. Devogele, P. Ramirez Moreta, R. Kresken, R. Messing

The Flyeye is the first ESA Planetary Defence telescope dedicated to the discovery survey of near-Earth objects. The ESA planetary defence programme aims at comprehensive detection and early warning of NEOs larger than 40 m and to provide at least three weeks notice for potential mitigation actions and the development of an international planetary defence network.

The Flyeye has a unique optical design with a wide field of view of about  $45^{\circ 2}$  and a limiting magnitude of  $\sim 21$ . It is a one-metre-class telescope using a beam splitter and 16 folding mirrors to feed 16 identical CCD cameras, forming a "compound eye" configuration. The system delivers a pixel scale of about  $1.5''/\text{pixel}$  and is optimized for rapid sky coverage and discovery of fast-moving objects.

At the time of the workshop, Flyeye-1 was in the integration and testing phase, while the dedicated observatory on Monte Mufara was under construction. The telescope is expected to be shipped and begin operations around 2026, to be followed by additional Flyeye units to extend coverage to the southern hemisphere.

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**Synthetic Tracking on Umbrella (STU): Real-Time NEO Detection Using GPU-Accelerated Processing**

**Speaker:** Mălin Stănescu (Astroclubul București)

This talk presents the Umbrella software suite developed within the Parasol project, focused on real-time NEO detection using synthetic tracking. Synthetic tracking improves the signal-to-noise ratio of fast-moving objects by coherently stacking short exposures along many possible motion vectors, trading increased computational cost for improved sensitivity with smaller telescope.

The implementation is highly optimized using GPU acceleration and a staged filtering approach, allowing synthetic tracking to run near real time even on large multi-CCD cameras and relatively modest hardware. The pipeline integrates images preprocessing, detection, and web-based validation, and has been demonstrated successfully in survey-like conditions on several telescopes.

Limitations include sensitivity to detector artifacts (bad pixels, crosstalk, bleeding) that generate false positives, and the possibility for very low-SNR objects to be missed due to noise dominating pixel-level clustering. Ongoing developments aim to improve robustness, reduce latency, enhance reporting standards compliance, and make the software more broadly available to the community.

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## Astrometry from Space Session

### The James Webb Space Telescope as a Planetary Defense Asset

**Speaker:** Bryan Holler (STScI)

**Co-Authors:** A. Rivkin, M. Micheli, M. Devogele

The James Webb Space Telescope (JWST) is a powerful but non-trivial asset for planetary defence, imaging and astrometry of moving targets. JWST is a 6.5 m infrared telescope operating at the Earth-Sun L2 point. The NIRCAM instrument (0.6-5  $\mu\text{m}$ ) is passively cooled while MIRI (5-28  $\mu\text{m}$ ) is actively cooled.

Both use up-the-ramp non-destructive readout, producing 4D data cubes. This readout scheme offers major advantages, larger dynamic range, cosmic-ray rejection, and flexible post-processing, but also introduces significant complexity, large data volumes, pixel-dependent timing, and detector-specific artifacts.

For high-precision astrometry, standard pipeline processing is not sufficient. The cosmic-ray rejection (“jump”) step can remove stellar PSF cores, degrading plate solutions, and must be disabled. Accurate astrometry further requires careful handling of pixel-level timing and sufficiently wide fields to include enough Gaia reference stars. These challenges were illustrated using JWST observations of 2024 YR4, demonstrating that precise astrometry is achievable, but only with tailored processing strategies.

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### High-precision astrometry of moving targets with HST

**Speaker:** Marc Buie (SwRI)

This talk gives a high-precision astrometry start-to-finish workflow for moving target with HST, focusing on the algorithmic steps needed to reach reliable results.

A key requirement is an accurate spatially varying PSF across the detector and high-quality ephemerides. In particular the HST-centric distance, plus the post-observation reconstruction of HST’s orbit since its motion around Earth produces rapidly changing parallax during an exposure, making stellar trails non-linear (curved). This curvature must be modelled in the trailed-PSF fitting to avoid biased positions. An onboard parallax correction mitigates this at the telescope level, but precise reduction still requires correct spacecraft position information.

The practical reduction sequence is: choose an appropriate fitting region, identify one reference star, derive a first WCS offset, update the WCS zero-point, then measure additional stars (minimum of three) for the full plate solution. Uncertainties are propagated using MCMC-derived PDFs: one PDF for the WCS solution and one for the target measurement, which are then combined to obtain the final RA/Dec probability distribution rather than relying only on Gaussian error ellipses. The tools implementing this approach are provided publicly (IDL-based).

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## Astrometry from Space Session

### Including Gaia FPR astrometry in the estimation of Main Belt Asteroid Masses

**Speaker:** Oscar Fuentes-Muñoz (JPL/Caltech)

**Co-Authors:** D. Farnocchia, J. Giorgini, R. S. Park, S. Naidu

Gaia FPR astrometry provides sub-milliarcsecond precision for  $\sim 157000$  asteroids (2014-2020), including  $\sim 500$  NEOs, enabling very high-precision orbit determination within JPL's pipeline. At this accuracy level, effects usually neglected become significant, most notably the offset between an asteroid's photo-centre and its centre of mass at non-zero phase angles. A size-dependent correction and an additional uncertainty term were introduced to account for shape and photometric effects not explicitly modelled.

The approach was validated through prediction tests and applied to several cases. For the kilometre-scale NEO 1950 DA, Gaia data significantly reduced the orbital uncertainty and slightly increased the estimated impact probability in 2880. The same framework allowed a rough size constraint for (16) Psyche by minimizing orbit-fit residuals. Finally Gaia's precision enables mass estimation of main-belt perturbors from close encounters, with results consistent with spacecraft and binary-asteroid measurements, improving dynamical modelling for both main-belt objects and NEOs.

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### Space-based NEO targets: opportunities and challenges

**Speaker:** Tobias Hoffmann (ESA ESOC)

This talk reviewed how space-based assets complement ground-based NEO observing, especially when geometry or solar elongation makes Earth-based data sparse or impossible. It illustrated current and near-term capabilities through recent case studies, including NEO follow-up with L2-class observatories, instrument-validation observations by deep-space missions, and rapid-response imaging of the interstellar object 3I/ATLAS from Mars-orbiting spacecraft when the target was effectively inaccessible from Earth.

A central message was that using spacecraft as "opportunistic observatories" requires operational readiness: accurate ephemerides and careful pointing strategies under constraints such as thermal limits, attitude stability, power, and downlink bandwidth. The talk also emphasized the need for common data standards and reference-frame discipline (e.g., consistent ephemeris formats and clearly specified frame/IAU model choices), since small angular differences can translate into kilometre-scale errors in deep space. Finally, it highlighted coordination and planning pathways to make time-critical, cross-agency spacecraft observations more efficient for planetary defence needs.

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## Astrometry from Space Session

### Analysis of NEOMIR's detection capabilities given an astrometric precision of 0.2"

**Speaker:** Margherita Maria Revellino (ESA NEOCC)

**Co-Authors:** K. Muinonen, M. Popescu, M. Micheli, P. Tanga, T. Müller

NEOMIR is a proposed mid-IR space survey designed to detect small NEO arriving from solar elongations 30-70°. The talk assessed how orbit uncertainty shrinks over time as a function of NEOMIR arc length and astrometric precision, and whether ground follow-up is feasible. The workflow simulates observations of synthetic impactors, applies detectability constraints, then performs orbit determination and impact assessment and a Monte-Carlo sampling approach to generate geocentric ephemerides, impact probabilities, and impact corridors.

NEOMIR would detect the large majority of "mission-relevant" synthetic impactors and recognized imminent impactors, but mostly do not localize the impact corridor without additional geometry. However, even a small number of ground-based measurements can dramatically improve predictions, enabling precise impact time/location refinement and straightforward recovery. Digest2 behaviour on short arcs was also tested and most objects would still be flagged as NEO-like with limited NEOMIR data, allowing downstream triage and follow-up planning.

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## Stellar Occultation Session

### Occultation-based astrometry

**Speaker:** Marc Buie (SwRI)

Stellar occultations are traditionally used to measure asteroid size and shape, but they also provide extremely precise relative astrometry between the occulting body and the star. In the Gaia era, star positions (and proper-motion/parallax propagation) are accurate enough that occultations can yield high absolute astrometry, in some cases competitive with radar and applicable to distant objects.

The limiting factor is often predictability. If orbit uncertainties are too large, or if uncertainties are reported conservatively, shadow-path prediction become so broad that deterministic deployments require unrealistically large station counts, making many events effectively serendipitous. There is thus a need for accurate positions and realistic uncertainty modelling/weighting when preparing predictions.

Single positive chord provides an astrometric constraint at the scale of the object's angular size. Series of campaigns can be performed. An initial event to improve the orbit (astrometry-first), followed soon by denser multi-chord campaigns for shape/size once predictions tighten, while remaining cautious about non-Gaussian uncertainties driven by unknown topography or complex shape.

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Stellar Occultation Session

The role of stellar occultations in NEO astrometry

**Speaker:** Paolo Tanga (OCA/Lagrange)

**Co-Authors:** A. Siakas, D. Souami, F. Spoto, K. Tsiganis

Stellar occultations provide mas level astrometry limited by Gaia star positions which has made occultations of NEOs possible. They strongly improve the orbit and the positional uncertainty to  $\sim$ the size of the object.

However, a precision in semi-major axis of  $\sim 10^{-9}$ - $10^{-10}$  is needed. Without that, the predicted shadow path is too uncertain for practical campaigns. Dynamical, star properties, and Earth topography effects, can shift the path by hundreds of metres. Observations are demanding, events last only 0.01-0.1s, tracks are narrow, and fast photometry, precise timing, and coordinated mobile campaigns are required. For very small NEOs, diffraction effects can be observed.

NEO occultations need professional-amateur collaboration. The ACROSS network was created to coordinate such efforts. By the end of 2025,  $\sim$ 80 occultations of 17 NEOs had been recorded. Repeated campaigns on targets such as Didymos allowed detection of the post-DART orbital change of  $\sim$ hundreds metres in semi-major axis and  $\sim 0.1$ s in orbital period.

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Radar Observations Session

Physical characterisation of near-Earth objects using planetary radar observations

**Speaker:** Anne Virkki (Univ. Helsinki / FGI)

Radar (Radio Detecting and Ranging) is a powerful technique for NEO studies as it provides both physical characterization and extremely precise astrometry. Unlike optical observations, radar uses its own illumination: a transmitter sends a radio signal toward the target and the received echo depends on the target properties, position and velocity, the receiving system, and the transmitted power.

For orbit determination, radar is uniquely valuable as it directly measures the range and radial velocity, information that optical astrometry alone cannot provide. Combined with plane-of-sky astrometry, radar yields a true 3D constraint on the object's position and motion, dramatically tightening orbital solutions.

Two main observing mode are used. Continuous-wave (CW) radar transmits an unmodulated sinusoid and measures the Doppler shift, constraining the line-of-sight velocity and providing clues about rotation and size through echo bandwidth. Delay-Doppler radar modulates the transmitted signal to measure the signal delay (hence range). Combining delay and Doppler produces 2D delay-Doppler images that can resolve shape and surface features and enable detailed physical modelling.

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Radar Observations Session

**The Effelsberg 100 m telescope and its potential for NEO observations**

**Speaker:** Alexander Kraus (Max-Planck-Institut für Radioastronomie)

**Co-Author:** U. Bach

This talk presented the 100 m Effelsberg radio telescope, outlining how its high sensitivity, broad receiver coverage, and flexible back-ends make it a strong European asset not only for radio astronomy but also as a potential receiver in planetary-radar experiments. Although the facility is optimized for a wide range of astronomical programs, its frequency agility and ability to track non-sidereal targets allows it to participate in bistatic campaigns when paired with an external transmitter.

Within the ESA-led effort to explore European radar concepts for NEO studies, Effelsberg was tested in coordinated experiments using a DSN antenna as the transmitter. A key result was successful radar detection of an NEO in late 2023, demonstrating that the bistatic configuration can deliver measurable constraints on target properties and even reveal companion signatures consistent with a satellite. The talk also highlighted practical limitations that will shape future operations, particularly radio-frequency interference (including satellite emissions) and the need to select usable bands and observing geometries carefully.

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**The ESA “NEO Observation Concepts for Radar Systems” Project and Beyond**

**Speaker:** Giuseppe Pupillo (INAF-IRA)

**Co-Authors:** A. Margheri, R. Orosei, S. Righini

This talk presented results from ESA’s NEO Observation Concepts for Radar Systems project, highlighting the key role of radar in planetary defence. Radar adds range and range-rate measurements to optical astrometry, which can significantly reduce the orbital uncertainties and improve impact predictions.

European radar assets were assessed in performance and feasibility. Europe has several receiving antennas but is strongly limited by the lack of a dedicated high-power transmitter. Bistatic experiments using NASA DSN transmitters and European receivers demonstrated successful detections and valuable measurements.

Recent observations delivered Doppler astrometry, constraints on rotation and size, surface roughness, and shape information, including binaries and contact-binary candidates. A first radar + VLBI experiment of an NEO confirmed feasibility but revealed technical challenges, especially tracking and near-field correlation. Overall, the results support the case of a coordinated European radar capability, with a transmitter remaining the critical missing element.

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## Radar Observations Session

### Towards a European Planetary Radar: Concepts, Architectures, and Trade-offs

**Speaker:** Marco Alessandrini (ESA/ESAC)

This talk presented the ESA perspective on the need to develop a European planetary radar capability following the loss of Arecibo. It highlighted that Europe currently lacks dedicated planetary radar infrastructure, despite having relevant expertise in space antennas, space surveillance, and NEO observations.

Two main architectural options were discussed: a traditional single large dish with a very high-power transmitter, and a phased-array system composed of many smaller antennas transmitting coherently. While the first approach is technically mature, it suffers from a single point of failure. The phase-array concept is more scalable and resilient, but requires precise phase control and atmospheric compensation, and has only been demonstrated so far at small scale.

A stage roadmap was outlined toward a European planetary radar system, starting with studies and technology development and potentially growing to an array of order of 100 antennas over roughly a decade, enabling applications in planetary defence, space situational awareness, and planetary science.

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## 2 Discussions

This section synthesises the main discussion outcomes of the workshop, with an emphasis on methodological best practices, limitations in current workflows, and recommendations for improving astrometric quality, orbit determination reliability, and data handling within the small-body community. The points below reflect collective experience and consensus rather than individual contributions.

### 2.1 Recommended Practices for Reliable Astrometry

The discussions highlighted several recurring sources of degraded astrometric quality and corresponding mitigation strategies:

- **Avoid reporting astrometry derived directly from synthetic tracking detections.** A significant fraction of problematic astrometry arises when measurements are extracted directly from synthetic-tracking detections. Synthetic tracking should be used exclusively as a detection tool. Once an object is identified, observers should compute a preliminary orbit, derive an improved motion model, re-stack the data using the updated motion, and perform astrometric measurements on the refined stack. Reporting detections measured solely from synthetic tracking is strongly discouraged and should be prevented at the software level where possible.
- **Iterative re-stacking for poorly constrained objects.** For objects with short observational arcs and large orbital uncertainties (e.g., newly discovered NEOCP objects), stacking using nominal predicted rates can lead to biased or degraded astrometry. Observers should iteratively recompute the orbit after adding new measurements, update the motion model, and re-stack the images accordingly. This approach significantly improves source morphology, signal-to-noise ratio, and astrometric precision.
- **Exposure-time limitations.** Very short exposures are subject to atmospheric and optical effects that do not average out, potentially leading to underestimated uncertainties. For high-precision astrometry, exposure times should be chosen such that seeing and refraction effects are adequately averaged, within the constraints imposed by target brightness and trailing.

### 2.2 Stacking Strategies and Non-Linear Motion

Participants discussed limitations of simple stacking assumptions and emphasized the need to account for non-linear apparent motion in astrometric measurements.

- **Constant-rate stacking is insufficient for objects with rapidly varying motion.** For fast-moving or nearby objects, motion curvature across the field of view or during the observing sequence can introduce systematic errors if not explicitly accounted for.
- **Non-linear motion should be captured through multiple reported positions.** Since instantaneous motion parameters cannot currently be reported directly, observers should submit multiple astrometric measurements spanning the observing arc to encode non-linear motion effects.

## 2.3 Preservation of Reduction Metadata and Limitations of ADES

The discussion emphasized that long-term astrometric reliability and interpretability depend critically on preserving information about how observations are reduced, and that current ADES mechanisms do not yet capture this context adequately.

- **Loss of reduction context limits long-term scientific value.** Participants emphasized that astrometric quality cannot be fully assessed without knowing how observations were reduced. Corrections such as differential chromatic refraction, colour assumptions, calibration choices, and processing workflows are often lost once data are submitted, making it difficult to explain why some observations perform well in orbit determination while others do not.
- **Current ADES mechanisms are insufficient for metadata capture.** Although ADES represents a significant improvement over legacy formats, its existing comment fields and publishable notes were widely viewed as too limited in length and structure. Critical reduction metadata is forced into free-text comments, which are neither standardized nor machine-readable, and in practice capture only a small fraction of the relevant information.
- **Reduction metadata should be treated as first-class information.** The discussion stressed that metadata describing how astrometry is produced is as important as the measurements themselves. Suggestions included extending ADES with additional structured fields, introducing standardized flags or tags for common corrections and assumptions, or maintaining linked records of observatory-specific reduction procedures that evolve over time.
- **Need for a clearer, community-driven ADES evolution process.** It was noted that the pathway for proposing changes to ADES is not well defined and is difficult to navigate for individual contributors. Participants suggested a coordinated community review, such as a formal questionnaire to observers, to identify missing metadata elements and inform a future revision of the format.

## 2.4 Incentives, Coordination, and Persistence in Follow-up Tools (NEOFixer)

The discussion focused on how current follow-up coordination tools and success metrics shape observer behaviour, and how improved incentive structures and persistence mechanisms could better align effort with scientific and planetary defence priorities.

- **Current success metrics incentivize the wrong behaviour.** The discussion noted that amateur follow-up effort is often judged by “how many circulars” are obtained, which unintentionally rewards high-volume observations of easy/bright objects and discourages time-consuming recoveries of faint or difficult targets that the community actually needs.
- **Need for reward mechanisms aligned with planetary defence objectives.** Participants asked how to recognize observers who spend full nights on challenging targets but risk being “scooped” by larger facilities. A proposed solution was to gamify recovery work with a leader-board:

- assign targets a *value score* (e.g., based on recovery importance/uncertainty reduction),
  - award observers points for completing high-value recoveries,
  - optionally include a mechanism to reduce duplication by allowing observers to declare intent/attempts.
- **Persistence and logging are required to avoid duplicated effort.** It was emphasized that current NEOFixer lack durable memory: “observed/found” status may disappear within  $\sim 12\text{--}24$  h, creating repeated work when reductions/submissions cannot be turned around immediately. A more persistent public log (who attempted/found/observed, and when) was identified as a key improvement.
  - **Prioritization schemes should reflect global goals (NASA vs ESA emphasis).** It was noted that NEOFixer priorities reflect NASA-funded objectives (e.g., emphasis on larger NEOs), which can differ from ESA framing (greater emphasis on actual impact probability). If rankings/leader-boards are adopted broadly, the scoring parameters should be agreed at an international level to avoid systematically over-observing the same top-ranked targets while other objects remain under-observed or lost.

## 2.5 Orbit Determination Transparency and Diagnostics

The need for greater transparency and diagnostic capability in orbit determination software was repeatedly emphasized:

- **Access to orbit-fit metadata.** Orbit determination systems should provide users with clear access to all assumptions and inputs used in the fit, including weighting schemes, uncertainty models, rejected observations, and predicted observables. This information is essential for diagnosing discrepancies between predicted and observed quantities.
- **Residual statistics by observatory and epoch.** Community access to residual distributions as a function of observatory, instrument, and time was identified as a priority. Such statistics would support improved weighting schemes, quality control, and feedback to observers.
- **Quantifying the impact of uncertainty modelling.** It was suggested that orbit determination tools should provide metrics or diagnostics quantifying how different uncertainty treatments influence the resulting orbital solution. This would allow users to assess whether reported uncertainties are realistic and appropriately balanced.

## 2.6 PSF Sampling and Detector Considerations

The discussion highlighted practical limits on PSF sampling and detector behaviour that directly affect achievable astrometric precision, particularly for faint and fast-moving objects.

- **Oversampling does not improve astrometric precision beyond adequate PSF sampling.** Once the PSF is sufficiently sampled, additional pixels do not add centroiding information but instead reduce per-pixel signal-to-noise, degrading performance for faint targets.
- **There is a practical lower limit on PSF sampling for reliable centroiding.** Empirical experience indicates that astrometric reconstruction becomes unreliable when the PSF FWHM falls below  $\sim 1.6$  pixels, with optimal performance typically achieved near two pixels FWHM.

## 2.7 Observatory Coordinates and Timing Accuracy

The discussion identified observatory location and timing metadata as underappreciated but critical contributors to systematic astrometric errors.

- **Inconsistent observatory reference frames introduce systematic position errors.** A significant fraction of observatory coordinates are likely referenced to the geoid or mean sea level rather than the WGS84 ellipsoid, leading to tens of metres systematic offsets.
- **GPS satellite observations provide a robust validation method.** Observing GPS satellites enables direct validation of observatory longitude, latitude, elevation, and timing, revealing both systematic offsets and long-term trends.
- **The effective observatory position corresponds to the telescope's mechanical reference point.** For large-aperture systems, the relevant position is the intersection of the telescope's mechanical axes rather than the location of ancillary infrastructure.
- **Local multipath effects can bias traditional GPS measurements.** Reflections and local obstructions can affect GPS antenna solutions, whereas astrometric observations of GPS satellites offer a complementary and often more reliable alternative.
- **GPS-based validation should be integrated into observatory code assignment.** It was suggested that GPS satellite observations be required when assigning new observatory codes, both to improve data quality and to encourage best practices in timing calibration.

## 2.8 Remeasurement and Replacement of Astrometry

The discussion emphasized that early astrometric measurements often warrant revision and that current mechanisms for updating published data are inadequate.

- **Early astrometry should be revisited once orbital solutions improve.** Measurements obtained during discovery or early follow-up, particularly those based on synthetic tracking, can bias orbit determination and should be remeasured when better motion models become available.
- **Current replacement procedures are manual and risk information loss.** The existing process for replacing published astrometry is labour-intensive and can compromise historical records, including discovery attribution.

- **A future system should support automated replacement with full provenance.** Participants identified the need for infrastructure that allows astrometry to be updated while preserving complete submission history, timestamps, and references as a high priority.

## 2.9 CMOS vs. CCD: Sampling, Noise Behaviour, and Timing/Systematics

The discussion compared practical astrometric and photometric performance of CMOS and CCD detectors, highlighting areas where CMOS systems offer strong capabilities but introduce additional operational sensitivities.

- **CMOS can perform extremely well, but is less forgiving operationally.** Participants emphasized that CMOS-based systems can deliver excellent astrometry and photometry, but require tighter control of sampling, calibration, and timing-related systematics than “traditional” CCD workflows.
- **PSF sampling requirements appear more stringent for CMOS.** Multiple comments highlighted that performance is highly sensitive to proper PSF sampling, with  $\sim 2$ -pixel FWHM repeatedly cited as a practical sweet spot; when sampling is poor, CMOS advantages in throughput can be negated.
- **Over-sampling can be harmful for faint-object work.** Over-sampling spreads flux over too many pixels, reducing per-pixel signal-to-noise and target detectability; binning strategies or optical choices that place typical seeing near the two-pixel regime were discussed as pragmatic mitigations.
- **Sampling-related effects are more critical for CMOS detectors than for CCDs.** Participants noted that CMOS sensors appear less forgiving of suboptimal sampling, and that poor sampling can negate the signal-to-noise advantage of larger apertures in some regimes.
- **Noise behaviour can deviate from idealized  $\sqrt{N}$  expectations.** Practical cases were reported where CMOS noise appears non-linear (e.g., in gain-transfer-style diagnostics), motivating an empirical approach: identify problematic behaviours or pixels, apply robust corrections or masking, and avoid over-reliance on simplistic analytic noise models.
- **Timing systematics are a CMOS-specific risk area.** Rolling-shutter and readout-timing effects, as well as camera-control (SDK/software) dependencies, were discussed as potential sources of time biases that can change after hardware, firmware, or software updates, reinforcing the need for periodic timing validation.

## 2.10 Stellar Occultations: High-Reward Constraints, Scalability, and Planetary Defence Use Cases

Stellar occultations were repeatedly highlighted as a high-impact technique for both *orbit improvement* (astrometric leverage) and *physical constraints* (size/shape/binarity). However, the discussion emphasized that scalability is limited less by instrumentation than by logistics, coordination, and the ability to act on short notice.

- **Equipment cost is not the main barrier, operations/support dominate.** Participants noted that a functional mobile occultation setup can be assembled for *a few thousand euros* (basic standardised systems) and that a capable portable system (including cases/shipping solutions) can be on the order of *a few to several k-euros per unit*. The dominant costs are *hidden* and recurring: equipment curation and repair, documentation, training, transport logistics, storage/warehouse space, and campaign coordination. The workshop sentiment was that these support layers are rarely budgeted adequately by funding agencies.
- **Reliable results require teams and coordination, not just volunteers.** The discussion stressed that individuals acting opportunistically will not deliver the event rate or data quality needed for planetary-defence-relevant outcomes. As soon as the concept scales to coordinated deployments (deciding where to go, ensuring coverage, and maintaining readiness), it becomes an organizational project with significant staffing needs.
- **Feasibility is set by ephemeris uncertainty relative to object size.** A recurring rule-of-thumb was that successful occultation strategies depend on the ratio of positional uncertainty to target diameter:

  - If uncertainty is only a few object diameters, a targeted mobile campaign can be effective.
  - If uncertainty is large, the success probability becomes a “lottery”, making systematic targeting inefficient without a large network.
- **Mobile campaigns are powerful but scale poorly with uncertainty.** Even in favourable cases, covering the predicted path at the  $\sim 2\sigma$  level was described as requiring on the order of *tens of telescopes and dozens of observers* for a single attempt, with the possibility of multiple attempts needed. This was viewed as feasible occasionally, but not at a sustained cadence (monthly/weekly) without dedicated funding and management.
- **Robotic networks and mobile deployments are complementary (not either/or).** A key conclusion was that fixed/robotic assets are well suited to obtaining a *first detection/refinement* (and to operating more often), after which mobile resources become more efficient once predictions tighten. Conversely, achieving meaningful probability via a dense robotic mesh for small NEOs was recognised as an extremely large infrastructure effort.
- **Planetary-defence-only optimization changes priorities, but does not remove quality requirements.** The discussion explored a strict planetary defence framing. Participants noted that if the only goal is *astrometry*, fewer chords/stations may suffice than for physical characterization. However, the consensus was that relaxed requirements (e.g., “yes/no” detections without timing precision) do not automatically yield *believable* data: validation against false positives and adequate S/N remain necessary.
- **A rapid-response concept: paired-station, high-cadence “serendipitous” scanning at close approach.** An alternative approach was proposed for close fly-by opportunities: operate *pairs* of stations separated by metres to hundreds of

metres to enable coincidence checks and reduce correlated false signals, then record high-cadence data (e.g., 10–20 Hz) while tracking the object across the sky, effectively scanning many stars and hoping to observe an occultation. Key practical constraints discussed were data volume, real-time (or near-real-time) event detection, and the need for automation.

- **Trade-off at close approach: more star encounters vs. harder event detection.** Participants noted an inherent trade-off: close approaches increase the number of potential star encounters (larger swept sky area), but higher angular rates and short event durations can make detection and confirmation more challenging, implying that an optimal regime likely exists and should be explored quantitatively.

## 2.11 Planetary Radar in Europe: Capability Gaps and Near-Term Options

The radar discussion focused on structural limitations in European planetary radar capability and on identifying realistic, staged pathways to gain operational relevance.

- **The core European limitation is transmission capability.** The discussion converged on the fact that Europe already possesses strong receiving assets, but lacks accessible high-power transmitters suitable for planetary radar. Safety regulations, airspace and satellite constraints, infrastructure requirements, and incompatibility with cryogenic radio-astronomy receivers make the addition of new transmitters to existing facilities structurally difficult.
- **Phased-array transmission is strategically attractive but not near-term ready.** Distributed uplink arrays offer scalability and long-term flexibility, but coherent transmission over large baselines remains technically challenging due to synchronization and atmospheric phase stability. The consensus was that this approach should be pursued as a research and development activity rather than an immediate operational solution.
- **Madrid DSN provides the most realistic near-term path to European radar capability.** The discussion identified existing DSN infrastructure near Madrid as a pragmatic opportunity to enable planetary radar without waiting for a new European facility. Planned transmitter upgrades (from  $\sim 20$  kW to  $\sim 80$  kW) already improve capability, and further increases (order  $\sim 250$  kW) were discussed as technically feasible. A scheduled maintenance break around  $\sim 2029$  was highlighted as a natural insertion point for additional hardware, potentially allowing a limited but operational planetary defence radar capability at modest incremental cost, contingent on institutional alignment and funding.
- **Consensus: pursue incremental demonstrations while keeping long-term options open.** Rather than a single large-scale investment, the workshop favoured upgrade-and-demonstration pathways to build operational experience, relieve pressure on existing facilities (e.g., Goldstone), and maintain momentum while longer-term European radar solutions continue to mature.

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