EVN Target of Opportunity Proposal

rcvd:

(1) Date Prepared: August 19, 2025

(2) Title of Proposal: 2005 FA22: First VLBI Radar Observation of a Near-Earth Object for Physical Characterization

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(4) Related previous or current VLBI proposal(s): ○ Resubmission

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(7) Scientific Category: ○ astrometry & geodesy ○ galactic ○ extragalactic ⊗ other: Solar System

(8) Wavelength(s) requested (small circles denote bands less widely available across EVN stations):
∘ 90cm ○ 21cm ○ 18cm ○ 6cm ○ 5cm ○ 3.6cm ○ 3.6/13cm ○ 1.3cm ∘ 7mm
○ Global Network standard bands ⊗ Special frequencies: 7167 MHz

(9) Recording format:
Bandwidth per BaseBand channel: 16 MHz
Aggregate bit rate:________ (4 BB channels at 32 MSamples/sec of ○ 1 bit, ⊗ 2 bit)

(10) ○ Multi-epoch observation: ______ epochs of ______ hours each, separated by ______

(11) Network	Requested antennas	Total time requested
EVN	Ef/Eb, Mc, Ir, Ys, Jb-1, Jb-2	3.5 h*
e-MERLIN	Cm, Da, De, Kn, Pi	3.5 h*
VLBA		
other NRAO		
Non-VLBI Intruments		

(*) The requested time does not include potential receiver switching times for antennas without frequency or receiver agility.

(12) ABSTRACT (Do not write outside this space. Please type)

Near-Earth Objects (NEOs) are small Solar System bodies that pose impact risks and offer scientific insights into planetary formation. Radar observations are essential for determining their orbits, shapes, and spin states. We propose VLBI radar observations of the asteroid 2025 FA22 during its close approach on 18 September 2025. Using continuous wave (CW) transmission from DSS-63 and reception by a VLBI array combining long (EVN) and short (e-MERLIN) baselines, we aim to achieve precise sky-plane localization, Doppler spectroscopy, and sub-beam astrometry. This approach allows both resolved imaging of surface features and accurate tracking of unresolved echoes, including spin characterization via speckle analysis. The campaign will refine 2025 FA22's trajectory and spin state and support shape modeling. This unique opportunity will demonstrate the value of VLBI radar for NEO studies and help define future European strategies for planetary defense and high-resolution asteroid characterization.

Scheduler use only

(11/19)

(13) Observation type: ◯ Spectroscopy ◯ Pulsar ⊗ Phase referencing

(14) Polarization: ◯ Single Polarization ⊗ Dual Circular Polarization

(15) Assistance required:
Observation Setup: ◯ Consultation ⊗ Extensive help ◯ Observe file preparation
Postprocessing: ◯ Consultation ⊗ Extensive help ◯ Calibration service

(16) Correlator: ⊗ JIVE, ◯ Socorro, ◯ Bonn, ◯ Other ______________
Special processing: ◯ XPol ◯ Pulsar gate ◯ Multiple Fields: _______
Averaging time: _________ Spectral channels per baseband channel: _________
⊗ Other special processing: Near field VLBI using PRIDE software

(17) Postprocessing Location: JIVE + INAF-IRA (Bologna/Medicina)

(18) Source list: ⊗ J2000 ◯ B1950
If more than 4 sources, please attach list. If more than 30, give only selection criteria and GMST range(s)

	Source 1	Source 2	Source 3
Name(s)	2025 FA22 (@06:40UT)	2025 FA22 (@07:55 UT)	2025 FA22 (@09:10 UT)
RA [h : m : s]	06 : 25 : 30.414983	06 : 13 : 23.906525	06 : 01 : 21.611282*
Dec [d : ′ : ″]	+00 : 18 : 55.10328	+01 : 50 : 52.84580	+03 : 22 : 14.33154*
GMST range (Europe)	see (19)	see (19)	see (19)
GMST range (US)			
Band(s)	5 cm: 6.0/6.7 GHz	5 cm: 6.0/6.7 GHz	5 cm: 6.0/6.7 GHz
Total flux density [Jy]	125 (*)	126 (*)	124 (*)
Expected correlated FD [mJy]			
RMS needed [mJy/beam]			
Field of view [″]			
Velocity resolution [km/s]			

(*) Flux density (Jy) has computed over the narrow frequency interval (few Hz) containing the radar echo, not over the full 16-MHz recorded bandwidth.

(19) Preferred VLBI session or range of dates for scheduling, and why:
The requested observing window is strictly fixed by the timing of a dedicated JPL/NASA radar transmission from the DSS-63 antenna in Madrid, scheduled from 06:40 to 09:10 UT on 18 September 2025. This transmission window has been set to ensure both a useful signal-to-noise ratio (achievable only near the close approach) and the common visibility of the target from the Tx and all selected EVN and e-MERLIN antennas (see Fig.1). Due to the high proper motion of the target (see Fig. 2), it will be necessary to perform a differential tracking for each individual antenna and change phase-reference calibrators during the observation. We are working with individual stations to support local implementations of the non standard tracking where required. Considering also the observation of other calibrators (e.g., fringe-finder calibrators, flux calibrators, etc.), **the required observing window extends from 06:10 to 09:40 UT on 18 September 2025**.

(20) Dates which are NOT acceptable, and why:
The asteroid will only be observable within the date and time window specified in the previous section.

(21)justification, not in excess of 1000 words
(*i.e.*, 4p using 11-point or larger font, including figures).
Preprints or reprints will not be forwarded to the referees.

1 Background

Near-Earth Objects (NEOs) are asteroids or comets with orbits approaching Earth's, posing a potential impact hazard that motivates global monitoring for planetary defense. With sizes from meters to kilometers, NEOs are also of great scientific interest, as they are relatively unaltered remnants that provide unique insights into the Solar System's formation and evolution.

Ground-based observations rely on both optical and radar techniques. Radar systems employ different waveforms depending on the experiment, configuration (e.g., monostatic or bistatic), and scientific objectives [1]. Unlike passive optical techniques, radar is active: it transmits signals to the target and analyzes the reflected echoes, providing precise information about the NEO's orbit, shape, rotation, and surface. This enables imaging with meter-scale resolution. However, radar is limited by range (signal strength drops with the fourth power of distance) and a narrow field of view, making it better suited for follow-up characterization than for discovery. In this context, we recently concluded an ESA-commissioned study [2] regarding an evaluation of existing or potentially upgradable European assets, along with the tools and expertise needed for post-observation analysis. In this framework, we have also successfully carried out several radar observations of NEOs in single dish mode, which have enabled us to measure key physical parameters such as their rotation periods. The most recent, conducted in late November 2024 on asteroid 2006 WB, was performed using the Sardinia and the Lovell radio telescopes as receivers, detecting the echo with a similar configuration we will use in this experiment. All current observational activities are designed to support the development of a future European radar network for NEO monitoring, potentially coordinated by ESA and developed in synergy with NASA's planetary radar facilities and programs.

2025 FA22 was discovered on March 29, 2025 by Pan-STARRS 2. It has an absolute magnitude of 21.5, implying a diameter near 160 meters (± factor of two). The object will approach Earth at 0.0056 au (2.2 lunar distances) on September 18, 2025, which is the closest approach by a >100 m NEA since 2022. Radar observations will be possible from both hemispheres, starting around September 17–18. However, no physical characterization will be available until radar data are collected, due to low optical observability before the encounter. The Minor Planet Center has classified 2025 FA22 as a Potentially Hazardous Asteroid.

2 Goals of the proposed VLBI observation

We propose VLBI radar observations of 2025 FA22 using continuous wave (CW) transmission, diverging from the traditional monostatic or bistatic CW radar approach. Standard CW radar provides a Doppler spectrum encoding the line-of-sight velocity distribution of surface scatterers, but lacks range resolution and sky-plane localization. This results in ambiguities in spin state, shape interpretation, and most critically, the 180° pole ambiguity. Instead, VLBI radar in CW mode directly addresses these limitations. By introducing interferometric delay measurements between spatially separated antennas, it enables 2D localization of the radar echo centroid in the plane-of-sky. We expect to achieve an angular resolution on plane-of-sky of the order of a hundredth of an arcsecond, i.e. one order of magnitude better than the best high-precision ground-based optical asteroid astrometric measurements, which generally do not go below 0.1 arcseconds. This angular resolution also breaks the north-south ambiguity, allowing a proper target shape reconstruction from delay-Doppler imaging, and constrains the true spin vector.
The "space-object VLBI radar" method, developed by the Radiophysical Research Institute of Nizhny Novgorod, has shown excellent performance in tracking space debris and asteroids [3]. During the 2013 flyby of 2012 DA14, radar echoes from Evpatoria, received at Medicina and Irbene, enabled extraction of Doppler shifts and interferometric delays [4], yielding radial and angular velocities with far higher accuracy than standard bistatic radar.

We ask for a VLBI array that includes both long (EVN) and short (e-MERLIN) baselines. This is a novel approach for this kind of studies and it enables to investigate two complementary regimes:

- Resolved regime (e.g., EVN): When the apparent angular size of the asteroid exceeds the interferometric resolution, the echo can be spatially resolved across the surface. This allows imaging of individual scattering regions, mapping of shape asymmetries, and localization of rotation poles—key to breaking degeneracies and informing 3D shape models.
- Unresolved regime (e.g., e-MERLIN): If the asteroid appears point-like, it is still possible to determine its absolute position on the plane of the sky with high precision using interferometric techniques. Additionally, the unresolved regime allows for speckle tracking [5], a distinct technique that exploits fluctuations in the radar echo to determine the spin state of the target — including its rotation period, spin axis orientation, and sense of rotation. Given that the estimated speckle pattern scale is about 220 km, this measurement is accessible to this configuration.

The unique combination of the EVN and e-MERLIN is the only way to access both regimes in a single campaign, which significantly enhances science return, providing both geometric detail and astrometric robustness. Network flexibility ensures coverage across a range of target sizes and geometries, making this an optimal opportunity.

Observing 2025 FA22 with VLBI radar in CW mode is a unique and high-value opportunity. The encounter geometry, target size, and SNR conditions are ideal for a rare application of this technique. **This campaign would not only yield a rich dataset for this specific object, but it can also set the stage and the technical strategies for future NEA characterization using VLBI radar.**

3 Technical specifications

Due to the close proximity of the target, even slight differences in the locations of the antennas on Earth lead to noticeable variations in the apparent sky position of the object. Each station will therefore observe the target from a slightly different perspective, resulting in unique coordinates for tracking and pointing. For this reason, a single set of sky coordinates cannot be provided in advance. Moreover, the target orbit is subject to refinements in the days leading up to the observation. Accurate astrometric coordinates will therefore only be available shortly before the observation and will be distributed with the final schedule. The expected motion on the sky (see Fig. 1) may also require the use of multiple phase calibrators along the track to ensure adequate phase referencing.

The expected flux density is approximately 125 Jy, estimated using a conservative assumption on the NEO's physical size — specifically, adopting the lower bound on its diameter. Even under this assumption, we expect a robust detection on the shorter baselines, with a signal-to-noise ratio of at least 15 per baseline.

The DSS-63 (70m, Madrid) will transmit on 18 Sept 2025 from 06:40 UT to 09:10 UT a continuous wave (CW) signal at 7167MHz with 20kW of power. As part of the preparatory work, we have verified that the available VLBI receivers are compatible with the transmission parameters. The signals reflected from the target will be received by the VLBI network and processed accordingly.

The data processing scheme we intend to use involves two main steps:

- Analysis of the visibilities corrected for near-field effects, which enables high-resolution astrometric localization of the echo centroid on the plane-of-sky, angular tracking and interferometric imaging.
- Spectral analysis of the received signals, from which we extract accurate Doppler shifts per antenna.

This is why **we request to store the raw data streams from individual antennas**, in addition to the interferometric measurements. These are essential for performing the above steps and ensuring a full scientific return from the observations.

References

[1] Shantanu P. Naidu et al. "Radar imaging and physical characterization of near-Earth Asteroid (162421) 2000 ET70". In: *Icarus* 226.1 (2013), pp. 323–335. ISSN: 0019-1035. DOI: https://doi.org/10.1016/j.icarus.2013.05.025. URL: https://www.sciencedirect.com/science/article/pii/S001910351300225X.

[2] Giuseppe Pupillo et al. "Toward a European Facility for Ground-Based Radar Observations of Near-Earth Objects". In: *Remote Sensing* 16.1 (2024). ISSN: 2072-4292. DOI: 10.3390/rs16010038. URL: https://www.mdpi.com/2072-4292/16/1/38.

[3] Maria B. Nechaeva et al. "VLBI studies at the Radiophysical Research Institute". In: *Radiophysics and Quantum Electronics* 50.7 (2007), pp. 527–541. DOI: 10.1007/s11141-007-0047-3. URL: https://doi.org/10.1007/s11141-007-0047-3.

[4] Maria B. Nechaeva et al. "VLBI Radar of the 2012 DA14 Asteroid". In: *Radiophysics and Quantum Electronics* 57.10 (Mar. 2015), pp. 691–699. DOI: 10.1007/s11141-015-9555-8.

[5] Michael W. Busch et al. "Determining asteroid spin states using radar speckles". In: *Icarus* 209.2 (2010), pp. 535–541. ISSN: 0019-1035. DOI: https://doi.org/10.1016/j.icarus.2010.05.002. URL: https://www.sciencedirect.com/science/article/pii/S0019103510001831.

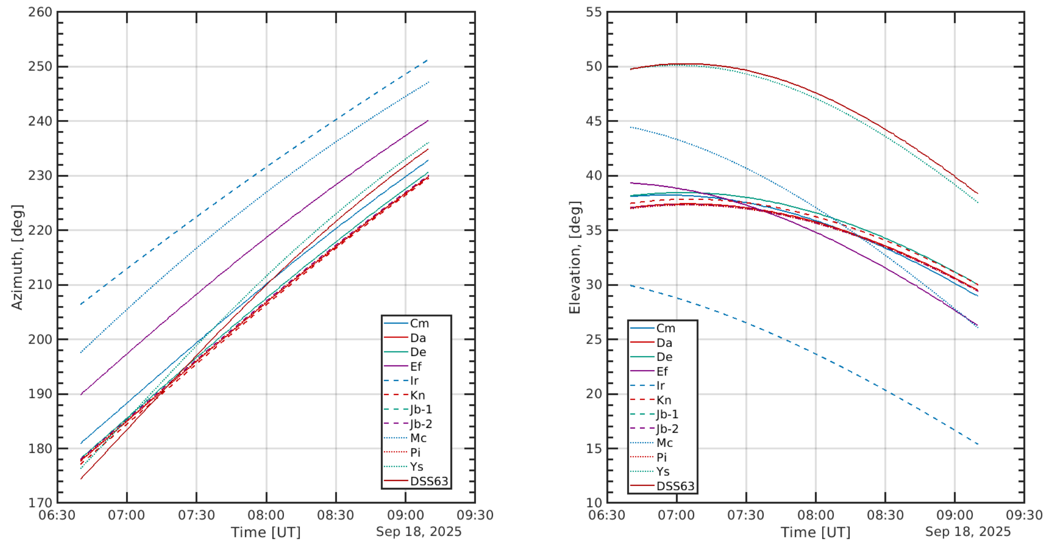

Figure 1: Pointing coordinates (azimuth and elevation) of asteroid 2025 FA22 for selected receiving antennas during the radar transmission from the DSS63 antenna on 18 September 2025 (06:40–09:10 UT).

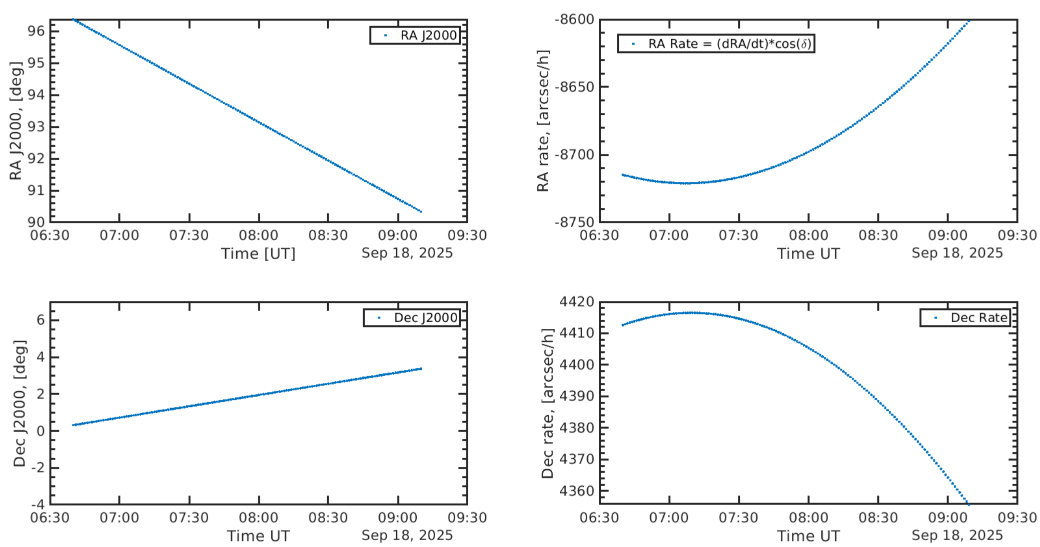

Figure 2: The J2000 Right Ascension (RA) and Declination (Dec), and their respective rates of change for asteroid 2025 FA22. The panels show RA **(top left)** and its rate corrected for declination, (dRA/dt)*cos(Dec) **(top right)**, Declination **(bottom left)** and its rate, dDec/dt **(bottom right)**. All values are for the Effelsberg observatory during the DSS63 transmission window (06:40–09:10 UT, 18 September 2025)”