# Utilising Australian National Infrastructure to support Cislunar Space Domain Awareness

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## ABSTRACT

There is a renewed focus on Space Missions to the Moon. The late 1950s and 1960s was the Golden Era of off planet space exploration, starting with artificial satellites and then increasingly focussed on the Moon, with the USA and the Soviet Union launching numerous missions. The triumph of the Space Race was the crewed Moon Landing by Apollo 11 in 1969. This was the 72nd mission to the Moon, and the last decade (2014-2024) has witnessed approximately 30 further Lunar missions. Now 10 countries of the Earth have reached the Lunar Surface, and the IM-1 mission in February 2024 has become the first private spacecraft to soft land on the Moon. The United States has announced the Artemis program will return humans to the Moon this decade. A Lunar Gateway will be established in Lunar orbit adding to the 6 active lunar orbiters of July 2023. Enhanced capability in cislunar SDA (XDA) will be required as the Moon presents a challenging orbital environment with only a handful of stable orbits. Observations of cislunar space present significant challenges due to the large distances involved and rapidly changing geometry. Trajectories in cislunar space are highly chaotic and maintaining custody can be very difficult. Sensor technologies can be broken into both active and passive methods in electro-optical and radio frequency systems. Active methods in electro-optical (laser ranging) and RF (radar) present a particular challenge due to the prohibitive power levels required. Passive electro-optical observations suffer from the issue that even though the object to be tracked is geometrically accessible, there may be poor illumination by the Sun. Additionally, the high albedo of the Moon presents dynamic range challenges for passive optical observations. Hence, passive RF methods can have significant benefit as the object itself is illuminating the sensor by transmitting RF signals, and only a receiver is required. Given the distance from a cislunar object, a radio telescope of substantial size is required. The era of the large-N radio telescope array has begun, illustrated by the development of the Square Kilometre Array (SKA) and the new generation Very Large Array (ngVLA). Consequently, existing single dish radio astronomy infrastructure of medium size is increasingly available for new and alternate uses, such as SDA. The NASA Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission serves as a pathfinder to study the orbit stability of the future Lunar Gateway space station. We evaluate the feasibility of using the CSIRO Mopra 22m Radio Telescope to derive orbital parameters for CAPSTONE based on the spacecraft's own RF transmissions at X band. The Mopra dish is located approx 450km from the only southern hemisphere NASA Deep Space Network (DSN) station at Tidbinbilla (Canberra, Australia), meaning that downlink transmissions to the DSN should illuminate an RF footprint over both sites. Following object detection, Doppler range rate processing is performed and compared to simulated GMAT results from the spacecraft truth data, which is available from the JPL Horizons system. Additional RF analysis can include pattern of life study and polarisation characteristics. Possible extension of the signal capture and processing to interferometry and Very Long Baseline Interferometry (VLBI) observation is also considered.

## 1. INTRODUCTION

With the increased access to space and an ever increasing number of satellites in LEO, the Space Domain Awareness (SDA) field has received increasing attention within the past decade [5, 14, 15]. The number of spacecraft is predicted to increase significantly over the next decade. Keeping pace with the rapidly growing population of active, maneuvering, civilian satellites, requires the development of new capabilities, including a civilian SDA sensor network, to support the next generation of Space Traffic Management (STM) systems. One way to determine the orbit of satellites is using radio frequency (RF) measurements. Typically, ranging measurements are used by satellite operators, since these provide both frequency offset measurements due to the Doppler effect and round-trip time [6]. However, ranging measurements typically can only be used by the operator of the satellite. An alternative to ranging is mono- or bi- or multi-static radar. These however, require a high power transmitter to illuminate the targets and are costly to build. The barrier to entry for all of the above described systems is even greater in the cislunar regime. As the path length is greater, even more power is necessary for radar systems. Additionally, while LEO SDA is well catered for by both civilian, military and commercial entities, cislunar SDA has been the pure domain of NASA's DSN or the largest space radars in the world, such as the Goldstone Space Radar.

Satellite ephemeris estimation from RF signals has been done using a variety of methods. These methods can mainly be separated into active methods, passive single station methods and passive multi-station methods. The active methods use a controlled illuminator, and consists typically of radar systems. The passive single station methods use merely a single antenna to receive the RF signals. When only a single aperture is used for receiving, the only direct information that can be extracted from the received RF signal is the frequency offset caused by the Doppler effect due to the relative velocity between the transmitter (satellite) and receiver (ground station) [2]. The Doppler frequency can be estimated and can be used for orbit determination. Multiple co-located receivers at one receiver site can be used to determine the angle of arrival of an emitted signal. Passive multi-station methods utilize geographically dispersed receivers. With the appropriate synchronisation, the time and frequency of observations between stations will differ. The emitter's location can then be determined through the difference of the arrival frequencies and times as well as the geometry of the receivers. Typical methods within this category are time difference of arrival (TDOA) and frequency difference of arrival (FDOA) [4, 16]. The measurements obtained through the above methods can be used for orbit determination and refinement. This can be done through measurement models in orbit determination tools such as GMAT [10], Orekit [12] or STRF [3].

Cislunar space is not merely an extension of GEO. The Lagrange points and regions near the Moon are far more chaotic than the GEO belt and below. Object custody is an important consideration in the cislunar regime. If an object is lost, the search space to find it again can expand very rapidly, making cislunar SDA an important area of research [9]. Examples of optical and RF based SDA in the cislunar regime can be found [7].

In the initial stages of this work, we have focussed on object detection and pattern of life characterisation of certain spacecraft at cislunar distance. In further steps of this work, we propose to utilise spectral Doppler estimation techniques. One spectral method is the coarse Doppler estimation through a grid search [19, 18]. While most of these coarse Doppler estimation methods estimate the Doppler frequency sufficiently for successful demodulation of the signals, the fit of spectral Doppler estimation methods is normally limited by the fast fourier transform (FFT) bin resolution. However, interpolation techniques can be used for more accurate spectral estimations [1]. Further methods involving matched filters are detailed in [17].

This paper is organised as follows: In Section 2 we present background on the Doppler effect. Next, a system description of the CSIRO Mopra telescope is presented in Section 3. The target spacecraft for a campaign of observations at S and X-band are next introduced in Section 4. The methodology employed in determining telescope scheduling and pointing and data capture is presented in Section 4.3 and Section 4.4. This is followed by the results of an observational campaign aimed at the detection of Cislunar targets with the Mopra telescope in Section 5. Cislunar object pattern-of-life is considered in Section 6.

## 2. BACKGROUND

Orbiting spacecraft exhibit an observed relative velocity from ground stations. This velocity is called the *range rate* and indicates the rate at which the spacecraft is approaching the ground station (negative) or departing the ground station (positive). The range rate is zero when the spacecraft is at its closest approach to the ground station. That is, the orbital velocity of the spacecraft and Earth's procession is orthogonal to the ground station range vector. Radio waves, like any other form of acoustic or electromagentic (EM) wave exhibit Doppler effects when two objects are moving relative to each other. The Doppler frequency is given by

$$f_d = -\frac{v_r}{\lambda} \tag{1}$$

and depends on the range rate $v_r$, measured in m/s, and the wavelength, which is given by

$$\lambda = \frac{c}{f_c}, \quad (2)$$

where $f_c$, measured in Hz, is the carrier frequency and $c = 299\,792\,458\,\mathrm{m/s}$ is the speed of light.

By measuring the Doppler frequency with respect to the carrier frequency $f_c$, the range rate can be estimated. The range rate is a many-to-one map, mapping the spacecraft's orbital motion into a single parameter. Thus, no unique spacecraft state exists for a single Doppler measurement. However, by observing the Doppler frequency over time, such as an entire pass or multiple passes, a spacecraft's orbit can be determined using batched least squares methods or Kalman filter [11] methods through OREKIT [13], GMAT [10], STRF [3] or other orbit determination tools.

## 3. MOPRA SYSTEM DESCRIPTION

The CSIRO Mopra 22m antenna was historically part of the Australia Telescope National Facility. It shares many common design elements with the 22m antennas of the nearby Australia Telescope Compact Array (ATCA) and at times is included in the Australian Long Baseline Array (LBA).

Fig. 1: Panoramic view of the CSIRO Mopra 22m Radio Telescope

Mopra has frequency coverage, with selected gaps, from 1 GHz up to 116 GHz. The specific bands of interest for this project are the 3cm and 13cm systems, which allow detection of spacecraft emissions in the S-band and X-band RF regions.

| BAND | 20cm | 13cm | 6cm | 3cm | 12mm | 3.5mm | 2.6mm |
|---|---|---|---|---|---|---|---|
| Frequency Range GHz | 1.3-1.8 | 1.8-3.0 | 4.5-6.7 | 8.0-9.2 | 16.0-25.0 | 78-116 | |
| FWHM | $33'$ | $22'$ | $10'$ | $5'$ | $2'$ | $36 \pm 3''$ | $33 \pm 2''$ |
| System Temperature[a] | 35 K | 36 K | 38 K | 38 K | 45 K | 170 K | 450 K |
| Sensitivity (Jy/K) | 11 | 14 | 11 | 11 | 15 | 22 | ∼30 |
| Zenith opacity[b] $\tau$ | 0 | 0 | 0 | 0 | 0.05 | 0.1 | 0.18 |
| Line flux sensitivity[c] (10 mins, 10 km/s, 2 IFs) | 51 mJy | 51 mJy | 30 mJy | 22 mJy | 24 mJy | 70 mJy | 238 mJy |
| Main Beam Efficiency | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.49 | 0.42 |
| Line brightness sensitivity[c,d] (10 mins, 10 km/s, 2IFs) | 6.6 mK | 5.3 mK | 3.9 mK | 2.9 mK | 2.3 mK | 6.5 mK | 18.9 mK |

Table 1: Mopra system parameters

Fig. 2: Specification of the Mopra telescope RF bands

## 4. SPACECRAFT OF INTEREST

### 4.1 Korean Pathfinder Lunar Orbiter

The Korean Pathfinder Lunar Orbiter, also known as Danuri, is Korea's first lunar mission. It was was placed into an elliptical lunar orbit, then circularised into a 100 km nominal polar orbit. Korean Pathfinder Lunar Orbiter (KPLO)

Fig. 3: Closeup view of the CSIRO Mopra 22m Radio Telescope

has an approximate orbit period of 2hrs. Extended operations will continue in a 70km orbit. The total mass is 550kg, and communications is via S-band (TT and C) and X-band (payload data).

An image of KPLO is shown at 4. We will be mainly concentrating on reception of the S-band signals.

### 4.2 Capstone

Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) is a 12U Cubesat spacecraft. It was launched on 28th June 2022 by a 3 stage Rocket Labs Electron Rocket. CAPSTONE features both S and X band radios.

CAPSTONE uses the X-band link for downlink to the Deep Space Network (DSN), and the S-band link for radio ranging to NASA's Lunar Reconaissance Orbiter (LRO). The spacecraft is seen in 5.

CAPSTONE is in a highly elliptical orbit termed a Near Rectilinear Halo Orbit (NRHO), which is shown in 6. The apolune of the orbit is 70,000km, and the perilune 3000km. The orbit is the same as the Lunar Gateway: a 9:2 resonant southern L2. The orbit has a period of approximately 6.5 days. CAPSTONE has a mass of approximately 25 kg and it does have propulsion for orbit control [8].

### 4.3 Observing Methodology

NASA's DSN is the primary Earth based communications system in contact with both CAPSTONE and KPLO. The DSN consists of 3 stations around the globe, in Madrid (Spain), Tidbinbilla (Australia) and Goldstone (California). The DSN operates in a "follow-the-sun" model, where the staff at a particular DSN station conduct operations across the whole network based on the daytime at that location. The spacecraft mode of operation is to initiate contact with the ground at a programmed time, which is reflected in the schedule of the DSN.

In order to point the Mopra telescope, NASA's JPL Horizons server system is used to produce an observer table for the spacecraft containing the azimuth and elevation based from the Mopra location and altitude. This is further processed into a form compatible with the Mopra antenna control system.

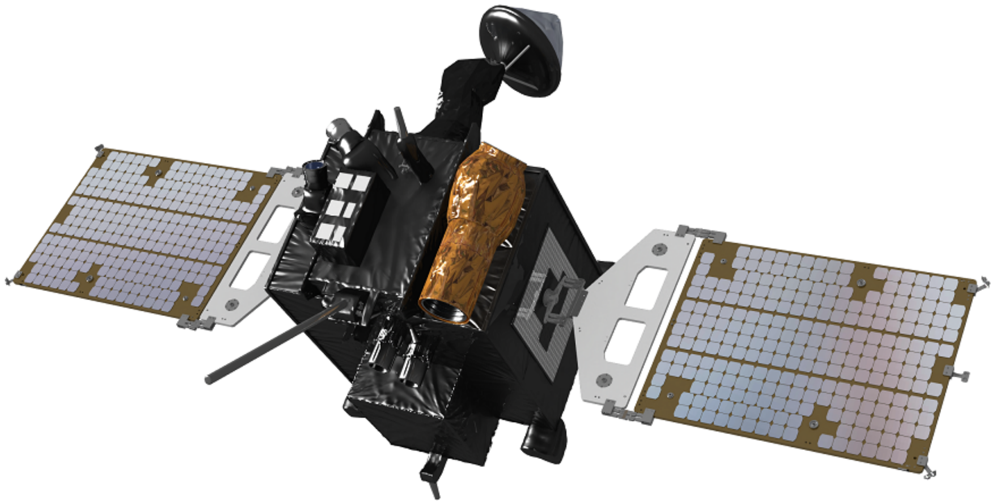

Fig. 4: Rendered image of KPLO

Fig. 5: Rendering of CAPSTONE


Fig. 6: NRHO orbit of CAPSTONE

### 4.4 Data acquisition and processing

The Mopra telescope has a data acquisition system capable of digitising voltages with bandwidths ranging from 4-64 MHz. In the case of the results presented, the sampled bandwidth was universally 16 MHz. Some waterfall plots show zoomed spectra as the Doppler shift is very small compared to the sampled bandwidth.

4 bit IQ sampling - complex

FFT - 160,000 point complex Fast Fourier Transform

Integration - 20 seconds

This represents a data decimation factor of 200. We retain fine frequency information at the expense of less time resolution.

## 5. RESULTS

### 5.1 Spacecraft Detection Bandpasses

7 shows the detection bandpasses for KPLO at S-band and CAPSTONE at X-band. For KPLO, SNR of main peak is approx 35 dB above the noise bandpass. Similarly, for CAPSTONE, there is approx 17 dB carrier above the noise bandpass.

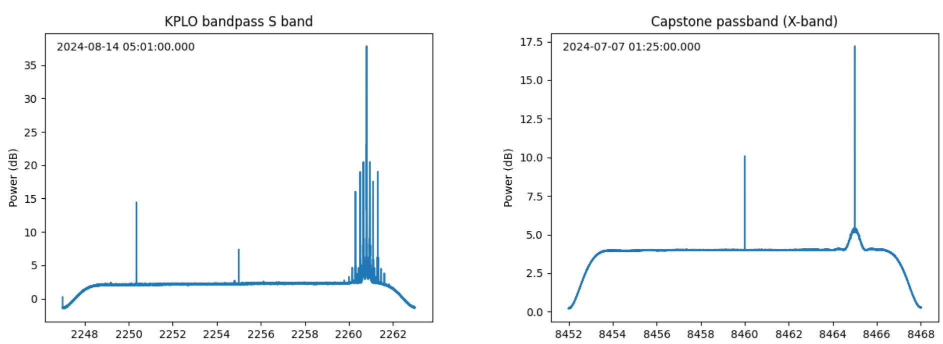


Fig. 7: Bandpasses for KPLO at S-band and CAPSTONE at X-band

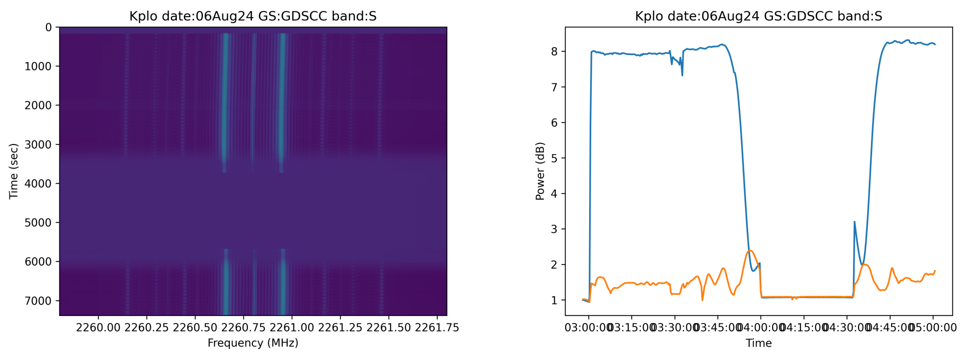


Fig. 8: RF waterfall and RF power vs time for KPLO with Goldstone GS 14th Aug 2024

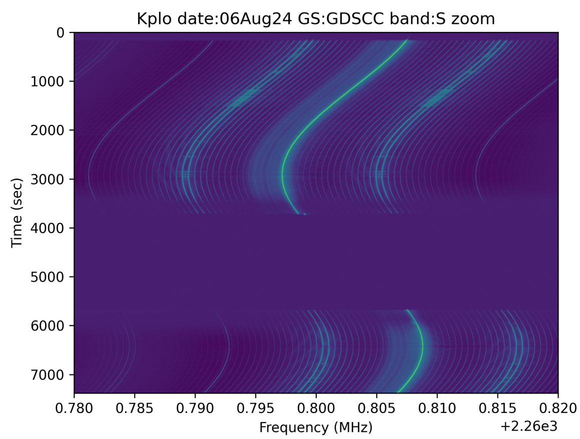


Fig. 9: Zoomed RF waterfall for KPLO with Goldstone GS 14th Aug 2024

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## 6. CISLUNAR PATTERN OF LIFE FOR SELECTED SPACECRAFT

The waterfall plot for KPLO in 9 very clearly shows the expected orbital period. It is yet to be confirmed, but we suspect the large fade out is when KPLO passed behind the back of the moon.

For CAPSTONE, the analysis of the waterfall plots shows that the spacecraft has 2 distinct modes of operation. A 50% duty cycle mode shown in 10 and only seen when NASA's Tidbinbilla node of the DSN is the ground station. This mode exhibits a coherent clock clocking operation each time the "on" duty cycle occurs. Refer 12.

The other mode of operation is seen at both DSN sites, and is more continous. There may be only one clock lock operation at the start of a 4 hr pass. This type of contact with the DSN is shown in 13 for a contact with Goldstone and 11.

## 7. CONCLUSION

We present clear results demonstrating RF detection success for both KPLO at S-band and CAPSTONE at X-band. There is very clear demonstration of the excellent low system temperature of the Mopra 22m telescope. Pattern of life behaviour can be inferred with the well disciplined signal capture equipment.

Future work will investigate extracting Doppler shifts from the received data, performing Orbit Determination. We

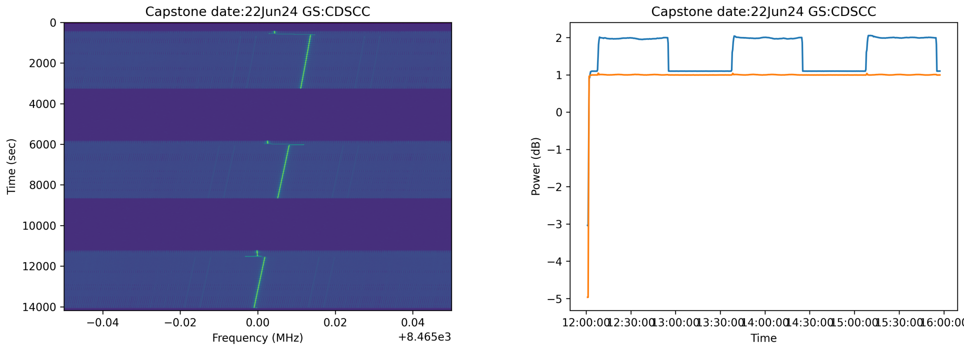


Fig. 10: RF waterfall and RF power vs time for Capstone with Tidbinbilla GS 22nd June 2024

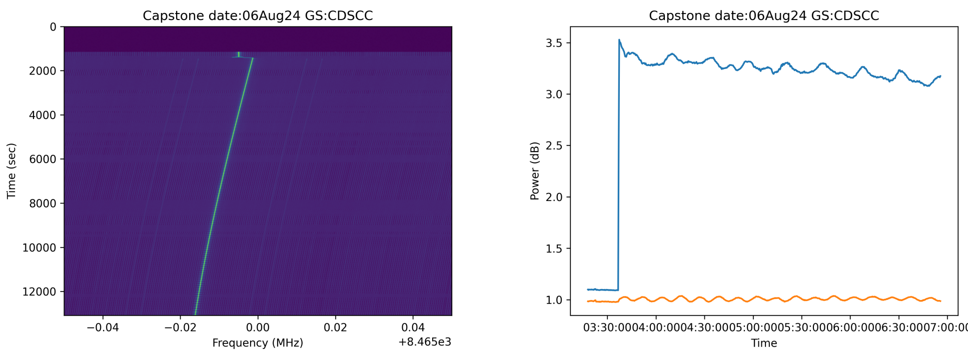


Fig. 11: RF waterfall and RF power vs time for Capstone with Tidbinbilla GS 6th Aug 2024

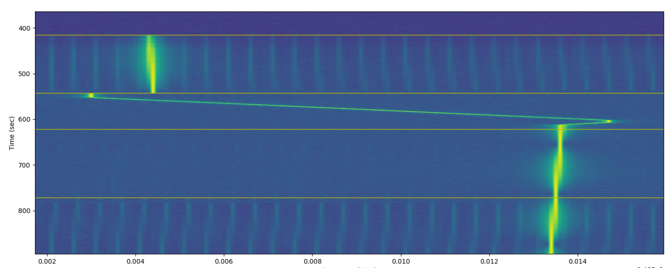

Fig. 12: Suspected coherent clock lock process with DSN uplink for CAPSTONE

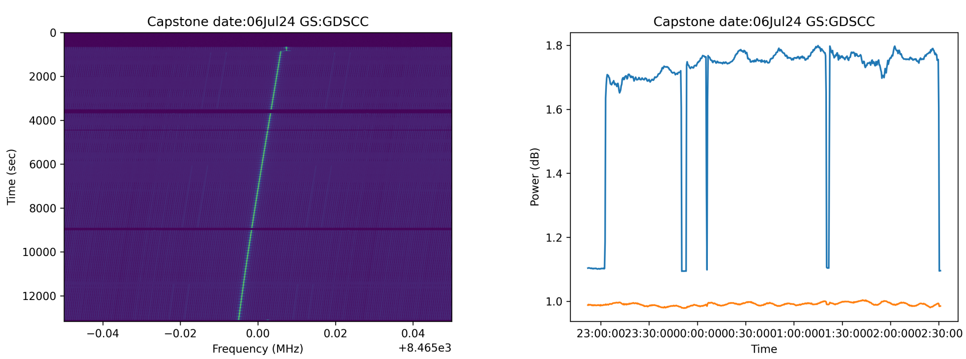


Fig. 13: RF waterfall and RF power vs time for Capstone with Goldstone GS 06th July 2024

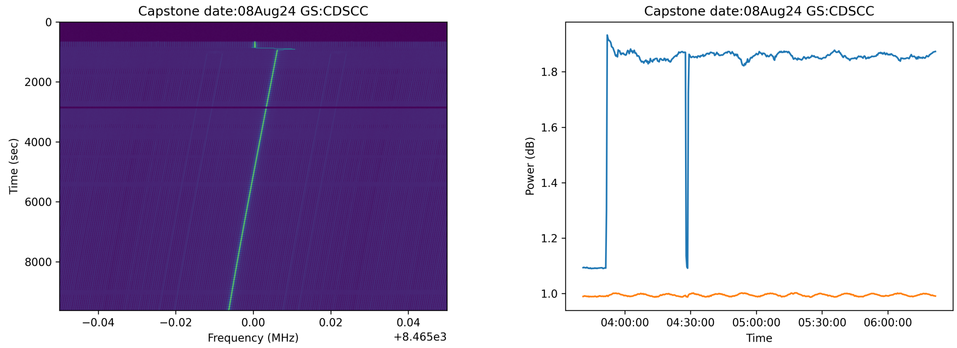


Fig. 14: RF waterfall and RF power vs time for Capstone with Tidbinbilla GS 8th Aug 2024

will determine the uncertainty and bias in the measurements, before attempting Initial Orbit Determination. Finally, significant work must take place in defining appropriate observational strategies for cislunar IOD and custody maintenance. Possible application of optical angle measurements and other radio technqiues such as bistatic radar and Very Long Baseline Interferometry (VLBI) are also to be considered.

## 8. ACKNOWLEDGEMENTS

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