Tracking Objects in Cislunar Space: The Chang'e 5 Case

Roberto Furfaro  
*University of Arizona*  
Vishnu Reddy  
*University of Arizona*  
Tanner Campbell  
*University of Arizona*  
Bill Gray  
*University of Arizona*

1. Abstract

We present the results of the University of Arizona-led campaign in observing and tracking of the Chang'e 5 spacecraft and the booster en-route to the Moon and back. Part of the Chinese lunar exploration program, Chang'e 5 is the 5th lunar exploration mission and China's first lunar sample return mission. The spacecraft was launched at 20:30 UTC on November 23, 2020 from the Wenchang Spacecraft Launch Site and landed on the lunar surface on December 1, 2020. The overall theoretical and practical goal of our observational campaign was to answer the following question: “How long can one keep optical custody of the spacecraft and its booster on its way to the Moon and back”. The campaign employed a combination of publicly available passive radio frequency (RF) data and dedicated optical observations collected with a 0.5-meter, F/2.8 Raven-class telescope located in Tucson, Arizona. Data were processed using orbit determination methods and tools typically employed in tracking Near Earth Objects (e.g. iterative batch least square, simplex methods) to iteratively reconstruct trajectories for both spacecraft and boosters. As a result, we successfully demonstrated optical recovery and custody of the spacecraft all the way to the Moon. Additionally, optical astrometry was used to successfully predict the impact location and time of the booster. More importantly, we demonstrated the feasibility of collecting optical measurements for spacecraft located well within the cone of shame (down to ~2 degrees from the Moon) using Raven-class telescopes.

2. Introduction

As humans plan to return to the Moon’s surface as early as 2024, many nations are already deploying an increasing number of space objects in the cislunar space. Defined as the volume comprised within the Moon’s orbit, general awareness of cislunar space is critical to support unconstrained access and operations including both surface and orbital domains. However, legacy Space Domain Awareness (SDA) systems were not designed to detect, track and catalog space objects transiting in such environments. This has given rise to a new discipline named Cislunar Space Domain Awareness (XDA [1]). XDA’s fundamental goal is to build and maintain a catalog of space objects transiting and residing in the cislunar space using a combination of ground-based and dedicated space-based platforms. XDA is extremely important for many reasons. Currently, most activities in cislunar space are going unmonitored and only self-reported. Continuous detection, tracking, and identifying of such space objects is highly desired to 1) avoid strategic surprises; 2) maintain strategic and tactical high ground; 3) support US allies and partners; and 4) protect humans in space by ensuring safe access to the lunar surface. Effective XDA is nevertheless challenging. Indeed, comprehensive coverage from ground-based optical telescopes is limited by the Moon’s brightness and Rayleigh scattering. This difficulty of imaging space objects within ~15 deg from the Moon’s center defines the so-called “Cone of Shame”. Conversely, active radar systems may require a prohibitive amount of power to illuminate space objects at lunar distances due to inverse square law.

In this paper, we summarize the results of the University of Arizona-led campaign in observing and tracking of the Chang’e 5 spacecraft and the booster en-route to the Moon. The overall theoretical and practical goal of the observational campaign was to answer the following question: “How long can one keep optical custody of the spacecraft and its booster on its way to the Moon and back”. The campaign employed a combination of publicly available passive RF data and dedicated optical observations collected with the a 0.5-meter, F/2.8 Raven-class telescope located in Tucson, Arizona. Data were processed using orbit determination methods and tools typically employed in tracking Near Earth Objects (e.g. iterative batch least square, simplex methods) to iteratively reconstruct trajectories for both spacecraft and boosters.
3. Chang’e5 Mission Overview

Chang’e 5 is the 5\textsuperscript{th} lunar exploration mission of the Chinese space agency. It also represents China’s first sample return mission \cite{2} and it is part of an ambitious Chinese Lunar Exploration Program \cite{3}. The spacecraft was launched at 20:30 UTC on November 23, 2020 from the Wenchang Spacecraft Launch Site and landed on the lunar surface on December 1, 2020. The overall mission architecture and concept of operations are illustrated in Figure 1. The spacecraft system comprises an orbiter, a lander, a descender, and a re-entry capsule. More details can be found in \cite{4}. As far as our observational campaign, we are interested in tracking both integrated spacecraft and booster on its way to the Moon and the booster on its way to the Earth surface.

![Figure 1. Chang’E5 overall mission architecture and concept of operations.](image)

4. Methods

We have developed a customized process that combines passive RF and optical observations to show the feasibility of tracking the Chang’e 5 spacecraft and booster on its way to the Moon. The overall workflow is illustrated in Figure 2. The process started with a pre-launch trajectory estimation based on the latest available information regarding launch date and time. An orbit optimization process is implemented to estimate the initial orbit. Amateur passive RF data, including RA, DEC and doppler data are employed to refine the initial orbit estimation as part of the optimization process. Optical tracking is subsequently executed to derive Chang’e 5 astrometric data and perform orbit improvement via a best fit approach. The latter is shown to yield an uncertainty estimation less than 1 arcsec. As orbit prediction via high-fidelity dynamic propagation deteriorates, follow-up observations are further required anytime than the predicted uncertainty is more than 1 arcsec. The follow-up optical observations are employed to recompute the spacecraft orbit if case of maneuvering. Additionally, long-arc observations are collected to support quantifying the effects of Solar Radiation Pressure (SRP). Spacecraft lunar arrival is determined by orbit integration via a high-fidelity model to find the time of perilune. The lunar return trajectory for the rocket body is also computed fitting optical observation. The predicted impact is computed by propagating forward the computed orbit until it intersected the Earth’s atmosphere.

The orbit determination process relies on Orbit Determination (OD) tools and methods derived from our experience with current planetary defense efforts. The overall OD process rely on the ability to integrate the dynamical model of the forces acting on the spacecraft \cite{5}. The model includes 1) Newtonian forces from perturbers (i.e. planets, moons, large asteroids) which are automatically or manually selected based on their close proximity with the artificial satellite, 2) Non-spherical planet effects, where equatorial bulge J2 together with zonal terms J3 and J4 for Earth, Mars and all...
four gas giants are automatically included as soon as the artificial object is within 0.015 AU distance. Lunar J2, J3 and J4 are also handled and can be customized as needed; 3) Atmospheric drag which is modeled for Earth re-entry and impact prediction; 4) Non-gravitational effect, such SRP, which is generally modeled as a radial force proportional to the Sun’s. The system ingests astrometric and/or passive RF data and perform Initial Orbit Determination (IOD). Methods for IOD in the pipeline include Gauss, Herget and Vaisaala methods which are employed in a semi-automatic fashion (user-select). The initial orbit estimate is set a starting point for a more accurate OD process that accounts for multiple observations. Indeed, for a set of given observations, the batch least-square method coupled with the selected physical model is employed to find accurate and robust predictions. Residuals are reported in a file for subsequent analysis. Additional capabilities include: 1) Determining uncertainties with Monte Carlo and statistical ranging (employed for short-arc observations) methods, 2) Predicting impact location for Earth re-entry or Lunar impact.

Figure 2. Workflow for Chang’e 5 (spacecraft and booster) tracking via passive RF and optical observations

5. Results

Figure 3 shows an overview of the optical observations for Chang’e 5 collected with the 0.5-meter, F/2.8 Raven-class telescope located in Tucson, Arizona. It is demonstrated that using passive RF data as initial input for SO location, both spacecraft and rocket body were successfully tracked optically. More than 1,200 astrometric observations were collected and employed to provide robust orbit determination. Importantly, the rocket body was tracked until 3.5 hrs before impact from Tucson, Arizona. Its derived astrometry was used to successfully pinpoint the impact location in the Pacific Ocean.
Figure 3. Chang'e 5 optical observations overview

Figure 4. shows the predicted trajectory for Lunar Insertion Orbit (LOI). We have computed the trajectory assuming that the LOI burn occurs at the periapsis (∼200 km) while targeting a lunar circular orbit with assumed date for LOI to be Nov 28th 12:58 UTC. We projected two scenarios where 1) a Thrust Correction Maneuver (TCM) occurs and 2) TCM does not occur. For case 1) we use the OD jump in residual to predict a TCM \( \Delta v = 16.5 - 12.9 \text{ m/sec} \) with LOI of \( \Delta v = 788.8 - 792.4 \text{ m/sec} \). The predicted date for TCM was between Nov 27th 9:30 UTC and Nov 28th 1:40 UTC. For case 2), LOI is estimated to be \( \Delta v = 779.6 \text{ m/sec} \) with a lunar orbit of about 250 km and date of LOI 28th 13:07 UTC.

Figure 4. Propagated trajectory to LOI via high-fidelity dynamical models
Figure 5 shows the evolution of the predicted rocket body impact as function of the available optical observations over four (4) days (Nov 26-30, 2021). For prediction date of Nov. 26, 2020 (Figure 5A): First prediction show left is based our first eight hours of data. We found the R/B on Nov. 25th evening and returned Nov. 26th morning. The impact times are spread out over ~3.5 hours. If the R/B returned early, it would have landed south of Hawaii; if it came back late, the Earth would have rotated underneath it by 3.5 hours and it would come in above New Guinea. For prediction date of Nov. 29, 2020 (Figure 5B): This prediction based on data till Nov. 29.08 UTC, a bit over a day before re-entry, with the object having just tipped past apogee a few hours earlier and starting back toward re-entry. The chart is about ten kilometers on a side, and the expected impact area is about five kilometers long, mostly in the east/west direction still, and the uncertainty in position is still mostly just due to not knowing when it would re-enter. We lost the object against the Moon, and then it was in eclipse and/or it was daylight or below the horizon. For prediction date of Nov. 29, 2020 (Figure 5C): It shows the prediction with our final observations, just 3.5 hours before re-entry. The chart is about 2 km on a side, with the expected impact area a few hundred meters long. Importantly, Chang'e 5 rocket body impact was observed by Geostationary Lightning Mapper (GLM) on GOES 17 (Figure 6). Astrometric measurements predicted an impact on 2020 11 30 at 15:41:41.7, at +4.488, W136.386 at 50 km altitude. GOES 17 GLM observed the impact on 2020 11 30 at 15:41:41, at +4.545, W136.51. As a note, we had a very well-defined trajectory, but no clear idea where along that track it would become visible. Which is why the GOES 17 GLM lat/lon does not match our prediction more precisely.
Figure 6: Impact location in the South Pacific off the coast of Hawai‘i

6. Summary and Conclusions

We have successfully demonstrated optical recovery and custody of the Chang’e5 cislunar spacecraft and R/B to the Moon and back using publicly available passive RF data. Optical astrometry has been used to successfully predict impact location of cislunar return vehicles. Additionally, we have demonstrated the feasibility of optical measurements well within the cone of shame (2.3°) using Raven-class telescopes.

7. ACKNOWLEDGMENTS

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8. REFERENCES

[1] https://spaceforcejournal.org/posturing-space-forces-for-operations-beyond-geo/googl


