

Deep-Space Navigation Using Optical Communications Systems

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Optical communication links using lasers can potentially deliver data rates much higher than those possible using radio frequencies. If optical communications equipment is going to be carried by future deep-space missions, this equipment, with some adaptations, could also be used to perform tracking for trajectory determination. A number of experiments have been performed in Earth orbit and in lunar orbit using optical data links, while other missions have demonstrated optical links over interplanetary distances. Laser ranging using corner cube retroreflectors is a well-established technique that has been used for orbit determination of Earth orbiting spacecraft, for geodesy, and for lunar research, achieving centimeter-level precisions, but it is not a practical method for deep-space distances. There are two main optical tracking types that are being considered for deep-space navigation. The first is optical astrometry of spacecraft: a telescope on the ground images the laser beam coming from a spacecraft against the star background, determining its plane-of-sky position as seen from the observatory. This type will greatly benefit from the release of the high-accuracy star catalog produced by ESA's Gaia mission, allowing for the generation of plane-of-sky measurements with an accuracy similar to that obtained today using VLBI tracking techniques. The second is optical ranging using active optical systems at both ends of the link, requiring a more careful design of the spacecraft optical communications system. One of the advantages of using optical frequencies is that they are not affected by charged particles in the signal path the way that radio frequencies are, eliminating solar plasma and ionospheric effects from the light-time calculation and the corresponding noise. On the other hand, clouds would preclude any type of optical communication, and daytime light scattering precludes astrometric measurements. This paper presents our analysis so far of the performance that could be achieved using optical data types in a number of deep-space scenarios. One of the questions that we are trying to answer is whether spacecraft equipped with optical communications terminals would also need to carry radio-frequency equipment for navigational purposes. We also want to understand how accurately we will be able to navigate spacecraft in different mission types and phases, and what would be the constraints, advantages, and disadvantages of using optical communications systems for deep-space navigation.

Key Words: Navigation, Orbit Determination, Optical Communications, Deep Space

1. Introduction

Since the first interplanetary spacecraft, radio-frequency communications systems have been the main means to obtain the tracking data necessary to navigate in deep space. Optical navigation, i.e. the use of images to track solar system bodies against the star background, has also been used, especially when the position of the target object has not been determined well enough to navigate just using radio-frequency data. Using optical navigation requires carrying a suitable camera, either one that can also be used for other purposes, e.g. science imaging, or a dedicated one. Up to now, active deep-space spacecraft have always been equipped with a radio system in order to transmit data to the ground and to receive commands from the ground, and this communications link has also been used to perform navigational tracking.

Communications in the optical frequencies can substantially increase the data rates possible for command and telemetry when compared with radio-frequency links. NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) mission carried out a Lunar Laser Communication Demonstration that achieved uplink data rates up to 20 Mbps and downlink data rates up to 622 Mbps, both at lunar distances. This mission also performed round-trip Time of Flight (TOF) measurements that showcased the ranging capabilities of the

optical system, down to errors of a few cms when compared with high-precision ephemeris.¹⁾

There are a number of deep-space mission types that could greatly benefit from increased data rates: planetary relay spacecraft could dedicate less time to transfer the data to the Earth when using optical links, and missions surveying other bodies could send more data or spend less time communicating with the Earth with higher data rates.

Since it is very probable that future deep-space missions will carry optical communications systems, we were interested in investigating the potential and constraints of using those same systems for navigation.

2. Optical Tracking

Radio-frequency tracking can produce measurements of the Doppler shift of the signal's frequency, perform ranging to measure the round-trip light-time of the signal and, when the signal is received at two distant ground sites, calculate the difference in arrival time between the two to determine the plane-of-sky position of the spacecraft. At optical frequencies, coherently measuring the Doppler shift could be very challenging, but precisely measuring the round-trip light-time has been already demonstrated in a number of missions. While at Earth's orbit it is possible to use retroreflectors to bounce

laser signals, at deep-space distances that approach is not sufficient, and an active system is needed on the spacecraft to track the uplink signal and transmit the necessary ranging data on an on-board generated downlink signal. In addition, it should be possible to perform astrometric measurements by imaging the return signal against the background of stars, to determine the plane-of-sky position of the spacecraft as seen by an observatory on the ground.

Unfortunately, optical tracking is going to be affected by local weather much more than radio tracking. While cloud cover and storms can increase the noise of radio data – especially at higher frequencies – could cover, fog or dust can completely preclude the transmission of optical signals. In addition, while it should be possible to perform optical communications and ranging down to a few degrees away from the Sun direction, high-precision astrometry will require local darkness, as atmospheric sunlight – or even moonlight – scattering can easily overcome the light received from stars. These constraints can be alleviated by deploying multiple ground terminals, close enough to be within the beam width of the returned signal, but far enough to ensure that the weather is uncorrelated and that at least one of them will be able to track under adequate conditions most of the time.

The most important contributor to high-precision astrometry is going to be the release of the star catalog created by ESA's Gaia mission.²⁾ This catalog, together with advances in observing techniques and instrumentation, could allow for nanoradian-level ground astrometry.³⁾

JPL is in the process of calibrating a new camera mounted on Pomona College's 1-m telescope that will be used to demonstrate the techniques and performance achievable with narrow-field ground astrometry, in that process validating the assumptions for our analysis.³⁾ Work is also underway to set up a high-power laser at the Optical Communication Testbed Laboratory at Table Mountain Observatory to perform ranging experiments,¹³⁾ as well as to add ranging capabilities to a prototype deep-space spacecraft optical terminal.¹⁴⁾

2.1. Ground-based Optical Ranging

The use of optical links to perform deep-space ranging was discussed in Ref. 4) as part of an integrated optical communications system, and it was also discussed in Ref. 5) in a monograph dedicated to optical communications. By now, it has also been tested by a few missions. Deep-space optical ranging experiments have been carried out with the Mercury Laser Altimeter on MESSENGER,^{6,7)} with the LOLA on Lunar Reconnaissance Orbiter,⁸⁾ and, as mentioned earlier, within the Lunar Laser Communications Demonstration on the Lunar Atmosphere Dust Environment Explorer,¹⁾ but those systems were not designed to provide operational optical tracking capabilities that could replace radio-frequency tracking systems. The development of new deep-space optical terminals may allow for the design of systems for which optical ranging is not an afterthought, but a required capability.

Error budgets for deep-space optical ranging show that accuracies from a few millimeters to a few centimeters should be possible with integration times similar to those used for radiofrequency ranging.⁹⁾ Optical ranging has the advantage that is

not affected by charged particles in the light path – solar plasma and ionosphere – which are one of the most important error sources for radiometric tracking. For optical ranging, and with an appropriate design of the ground and flight terminals, the dominant error source should be the uncertainty and fluctuation of the tropospheric delay through the neutral atmosphere.

The measurement model for optical ranging is the same as for radio ranging, but with no ionospheric group delay and, possibly, with a different modeling of the tropospheric delay. Optical ranging should be possible with a two-way measurement, but also as a one-way measurement if high-precision atomic clocks are available at both sides of the link.

2.2. Ground-based Optical Astrometry

The Gaia catalog, once it is published and it is properly tied to the International Celestial Reference Frame¹⁰⁾ will improve ground-based astrometry in a number of ways. It will provide positions and proper motions for stars up to the 20th magnitude, greatly densifying the set of sources that can be used to reference spacecraft measurements. The density would also facilitate the calibration of telescope distortion, or even the real-time calibration of differential tropospheric refraction. Because so many sources will be available, the field of view of the telescope can be reduced, increasing resolution and allowing for the sampling of a smaller area of the troposphere, and thus reducing the effect of atmospheric turbulence.³⁾ It is expected that the absolute accuracy of the catalog will be about 7 μ s for star magnitudes between 3 and 12, up to a few nanoradians for a star magnitude of 20.²⁾

When compared with the most accurate method for radiofrequency plane-of-sky tracking – delta-Differenced One-way Ranging (delta-DOR) – astrometry has the advantage of requiring only one ground station to generate measurements, allowing for more tracking opportunities. It also has the significant disadvantage of being precluded by both cloud cover and sunlight scattering; missions near Mercury or Venus are not going to be good candidates for astrometric tracking.

One of the challenges of spacecraft astrometry is that spacecraft exhibit a large proper motion against the star background. In that, they are similar to planets and other solar system bodies. Post-processing of multiple short-exposure images can be used to fit the motion of the spacecraft and obtain a more accurate position.¹¹⁾

It is expected that, when using the appropriate techniques to perform ground-based astrometry, and under favorable conditions, it should be possible to perform 5-nrad spacecraft astrometry on a 1-m telescope, and 1-nrad astrometry on a 5-m telescope.³⁾

The measurement model that we are using in our analysis is simply the right ascension and declination of the spacecraft, as seen from the ground observatory, in the EME2000 frame. We are assuming that observers will process their images to calibrate them and provide that data to the spacecraft navigation team.

3. Analysis Approach

The purpose of this research to assess how well missions could be navigated with optical systems. We are not proposing or advocating to remove the radio systems and, in any case, carrying them may still be advisable to ensure that we can establish communications under non-nominal conditions, since

deep-space optical communications require a stable platform and precise pointing. We want to understand under which circumstances missions already using optical communications can also rely on those same links for navigational tracking. Radios may still be needed, but they could be cheaper and lighter if they are needed only for off-nominal situations that do not require high data rates or precise tracking functions.

The navigation performance required by missions depends on the accuracy with which the mission trajectory needs to be reconstructed and predicted. Missions with more demanding delivery requirements, such as a Mars landing mission, require a higher level of cruise navigation performance than, for example, a Mars orbiter mission. While optical navigation may not always perform better than radio frequency navigation, it may be more than adequate for many types of missions.

We are looking at a number of deep-space mission scenarios to compare the performance of radio and optical navigation, using realistic assumptions and constraints. For each scenario, we simulate the relevant trajectories and sets of tracking data for different measurement types. We then assess navigation performance metrics for different combinations of data types and assumptions. One of the objectives of our research is to determine how sensitive the navigation performance is to the assumptions, in order to focus efforts and development in those areas that can produce a greater payoff, and to relax the performance requirements for those elements to which we are not sensitive.

The simulations and analyses were performed using the Mission Analysis, Operations, and Navigation Toolkit Environment (MONTE), a JPL multi-purpose software supporting the design, analysis and navigation of deep space missions.¹²⁾ We added the capability to simulate optical-communications tracking using appropriate measurement models and scheduling constraints.

The processing setup included the consideration of frame tie errors, in order to model possible discrepancies between the Gaia frame and the ICRF, both at a global and a local scale. It also included other errors typically considered in this kind of analysis, such as media, earth orientation, station locations, star or quasar catalogue errors, planetary ephemeris, and spacecraft dynamical uncertainties.

One finding that was evident early on was that the degradation of astrometric performance due to scattered sunlight would make some phases of interplanetary missions more difficult to support if precise astrometry is required to achieve the necessary navigation performance. This could be the case for final approaches for non-Type I Earth-Mars missions, or for Venus or Mercury missions, and could also affect missions to other solar system destinations if the final approach takes place close to solar conjunction.

The analysis performed in this study did not take into account the effect of weather on the availability of optical data. It was assumed that at all times a ground station with clear sky was available to perform the measurements. This could be accomplished by having multiple telescopes within the footprint of the returned laser signal, by performing redundant or dynamic scheduling of the tracking passes that takes into account local weather, and also by optimally siting the optical

terminals.

4. Analysis of a Mars Lander Delivery

One of the most navigationally demanding scenarios is the delivery of a Mars lander to the atmospheric entry point, so it can safely land on the surface of the planet. Two metrics are important in this case: how precisely we deliver the spacecraft to the nominal target, and how well the spacecraft knows its state - position and velocity - relative to a Mars-fixed frame. Delivery errors reduce the Entry, Descent and Landing safety margins by requiring the spacecraft to accommodate a wider range of entry conditions. Knowledge errors map into landed position errors, as there is no GPS on Mars and the spacecraft needs to propagate its entry state using gyroscopes and accelerometers to actuate controls and land in the right place.

For our analysis, we simulated one of the possible interplanetary trajectories of NASA's next Mars rover mission, Mars 2020. This spacecraft is scheduled to launch in late summer 2020 and land in early spring 2021. The spacecraft is very similar to the Mars Science Laboratory, launched in 2011, for which we were able to perform very precise navigation, since it was a fairly dynamically quiet spacecraft, a spinner that only needed to perform routine thruster firings not more often than once a week.¹⁵⁾

The analysis compared the performance achievable with the X-band data planned for Mars 2020 with that possible with different scenarios including optical data; see Ref. 16) for details. Continuous coverage was simulated immediately following launch, around Trajectory Correction Maneuvers (TCMs), and for the final 45 days. The majority of cruise was covered with almost-daily coverage.

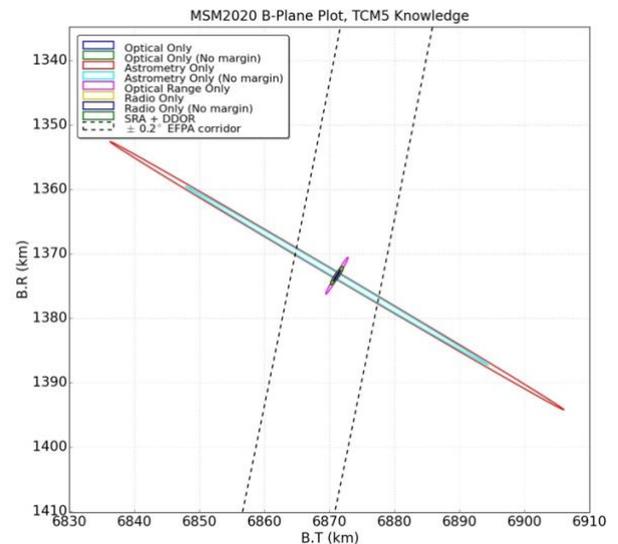


Fig. 1. Simulated Mars 2020 entry knowledge performance with different data-type combinations (3- σ).

The variational and sensitivity analysis showed that the astrometry-only case was very poor – as expected – in the line-of-sight direction, similarly to what could be expected from a radiometric delta-DOR-only case. Adding ranging made the

optical-only case perform as well as, or even better than, the radio-only case, because of the better line-of-sight accuracy and the more frequent plane-of-sky measurements (Fig. 1 and 2.) Varying the telescope size had a noticeable effect on the navigation performance, while the frame effects – at the level that they were being varied – had negligible impact, as did the level of optical range accuracy for this particular application (Fig. 3.)

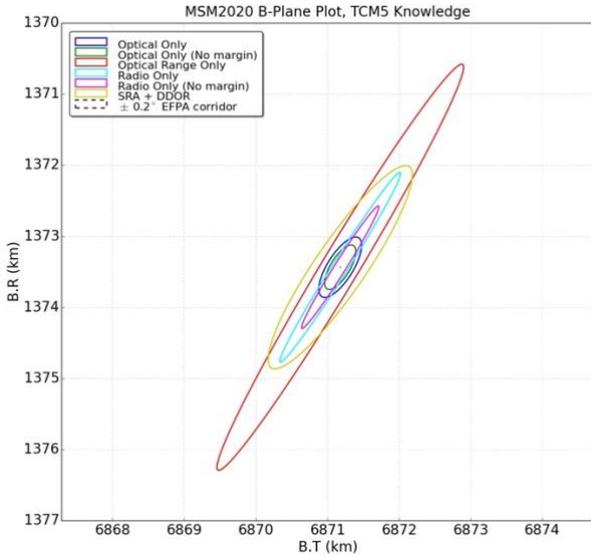


Fig. 2. Simulated Mars 2020 entry knowledge performance with a smaller selection of data-type combinations (3- σ).

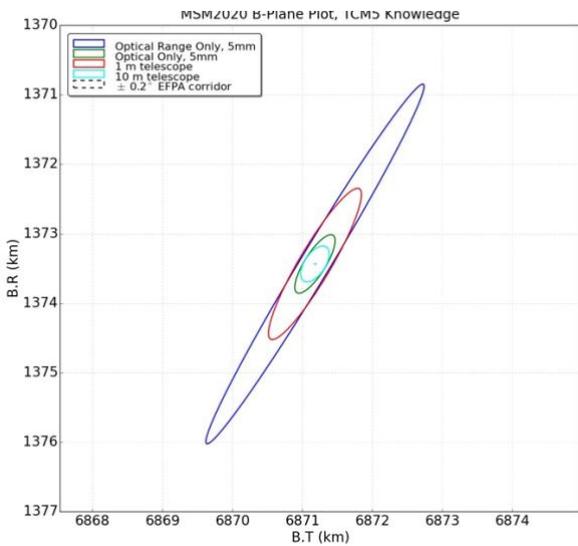


Fig. 3. Simulated Mars 2020 sensitivity to optical data combinations and assumptions (3- σ).

5. Analysis of a Mars Orbiter

For this analysis, we used the orbit determination setup of NASA’s Mars Atmosphere and Volatile Evolution (MAVEN) mission.¹⁷⁾ MAVEN is a Mars orbiter with a 4.6-hour period, an inclination of 75° and an eccentricity of about 0.47. It has a

low periapsis in order to sample the upper levels of Mars’ atmosphere.

The measurement simulation follows the tracking schedule used in operations, with daily passes that are eight hours long. Some of these passes are performed using a low-gain antenna, however, since the high-gain antenna is body-fixed and cannot be pointed to the Earth when the spacecraft is collecting science data. This could be solved by using a gimbaled optical terminal, but it highlights the issue that optical links could impose greater pointing constraints than radio links.

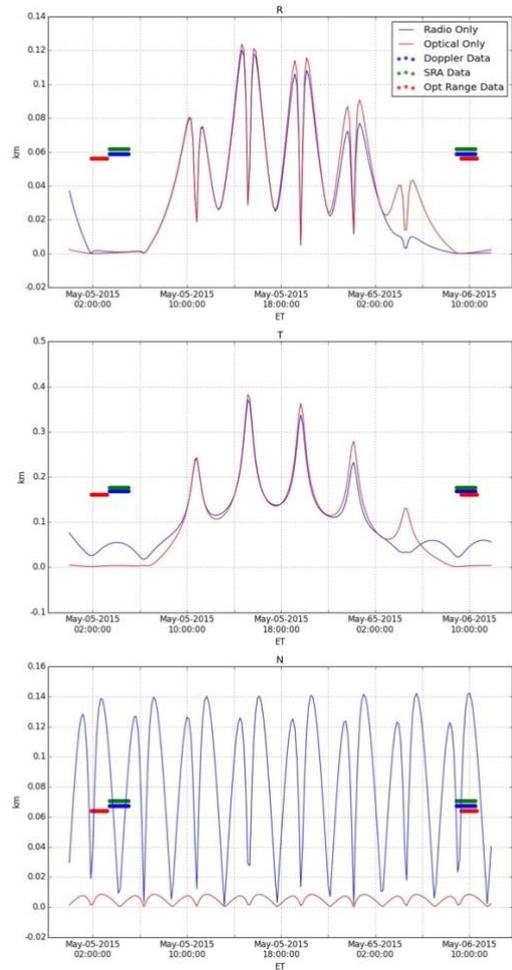


Fig. 4. Simulated MAVEN trajectory reconstruction performance in an RTN orbital frame with a Sun-Earth-Mars angle of 15° (1- σ).

For this scenario, we only simulated line-of-sight data, range and Doppler in the radio-frequency case, and range in the optical case. The orbit determination setup is otherwise the same in both cases.¹⁶⁾

The performance metric that is compared in this scenario is the trajectory position error for reconstructed orbits. MAVEN requires trajectory reconstructions with better than 3-km accuracy. Orbit prediction errors are of course a function of the reconstructed orbit accuracy, but are dominated by errors in the prediction of the atmospheric density, that would affect both cases in the same way.

Figures 4 and 5 show that when similar tracking data

schedules are used, optical outperforms radio during tracking passes, but during data gaps which data type is better seems to depend on the observing geometry. In any case, both cases are able to comply with the orbit reconstruction requirements. Modifying the optical range accuracy from 5 mm to 5 cm made little difference in the accuracy of the solution.

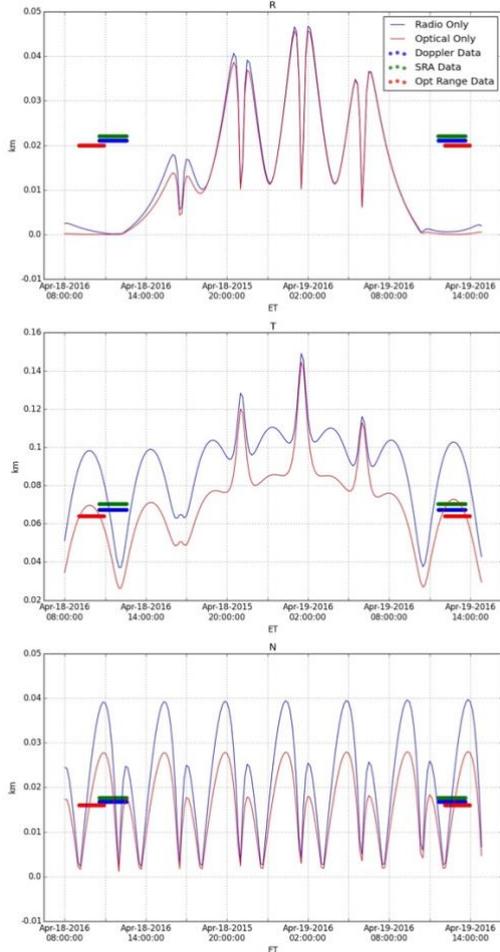


Fig. 5. Simulated MAVEN trajectory reconstruction performance in an RTN orbital frame with a Sun-Earth-Mars angle of 6° ($1-\sigma$).

6. Analysis of Asteroid Rendezvous

We analyzed another promising scenario for optical tracking: that of asteroid rendezvous missions. While high-accuracy astrometry is not possible for comets, it should be possible for asteroids using similar methods as those used for spacecraft – once the Gaia catalog is available – enabling a precise measurement of the position of the spacecraft with respect to the asteroid. The analysis setup used for this scenario mimics that used to analyze possible future missions to visit asteroids, and compares the results obtained using different combinations of ground-based radiometric data, ground-based optical data and on-board optical imaging. The performance metrics that are used are the delivery errors after the last maneuver before the flyby, expressed in B-plane coordinates.

We have looked so far at two possible missions, one to Odysseus, a Trojan asteroid, and one to Psyche, a metallic main-belt asteroid.

6.1. Odysseus Rendezvous

Odysseus is a Trojan asteroid with a mean diameter of 63 km. In this scenario we simulated a slow flyby at a nominal altitude of 50 km and a velocity of 0.05 km/sec on Aug 6, 2037. While the simulated mission used solar-electric propulsion, we assumed that there was a forced coast for 28 days before the flyby, and used a three-moth arc of data, with the last maneuver five days before the flyby. One thing that we found out early in this analysis is that the encounter was taking place at a small probe-Earth-Sun angle that precluded the collection of astrometric data for the last few weeks before the encounter.

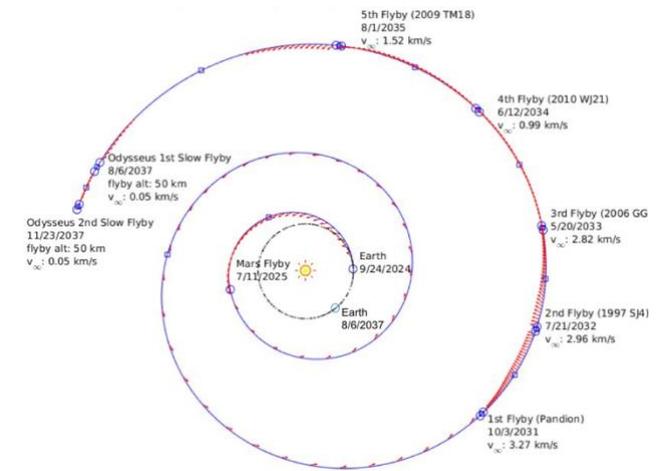


Fig. 6. Trajectory for the Odysseus scenario.

Table 1 shows the performance metrics for the different cases that were analyzed. We used a measurement weight for astrometric observations of 1 milliarcsecond and an optical range weight of 5 cm. In addition to the spacecraft state, we estimated once-per-day attitude desaturations, and impulse burns leading up to the flyby, as well as the asteroid ephemeris and mass. The case with the early Data Cut-Off (DCO) used realistic constrains for astrometry, while the late DCO cases unrealistically assumed that we could perform astrometric measurements even in daylight. These cases were analyzed to assess the performance with a more favorable geometry.

Table 1. Odysseus scenario flyby delivery results

Case	B-plane	LTOF
	ellipse (km, $1-\sigma$)	(sec, $1-\sigma$)
Radio + on-board optical	1.7×1.7	468
Optical with early DCO	1.9×1.7	2175
Optical with late DCO	1.7×1.7	120
Optical with asteroid astrometry, late DCO	1.7×1.7	54
Ground optical only, late DCO	4.6×2.7	109

For the first four cases, we added on-board imaging of the

asteroid, and in the last two cases we added precise ground astrometry of the asteroid. The results show that, if it is possible to perform astrometric measurements up to the maneuver DCO, optical tracking can perform as well as radio tracking and outperform it in the prediction of the Linearized Time of Flight (LTOF), potentially simplifying operations. The case without on-board optical showed very good performance in LTOF, but worse performance in terms of the B-plane targeting.

6.2. Psyche Rendezvous

Psyche is a main-belt metallic asteroid with a 250-km mean diameter. The flyby for this case is assumed to happen at an altitude of 50 km at 0.25 km/s on December 15, 2030. The trajectory was designed to allow for a flyby with near-optimal ground observing conditions. As for the previous case, this is an electric propulsion mission concept, but with a 28-day forced coast before the flyby. We used a 10-week data arc up to a last maneuver five days before the flyby for our analysis, with the same set of parameters being estimated as in the Odysseus scenario. Figure 7 shows that in this scenario, Psyche and the Earth are in the same side of the Sun on the period leading to the flyby, optimizing astrometric observability.

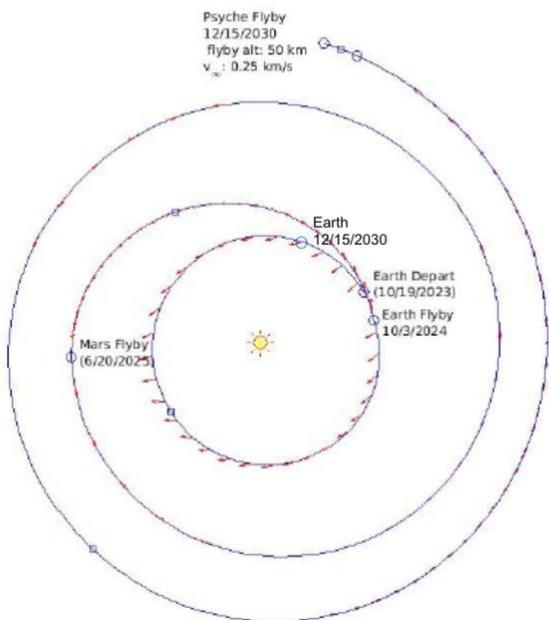


Fig. 7. Trajectory for the Psyche scenario.

Table 2 shows the cases that we analyzed in this scenario, and the resulting performance metrics. Performing Gaia-enabled high-precision ground astrometry of the asteroid improves the LTOF performance of the radio case. The last three cases, with different combinations of optical tracking, produce similar results. In a scenario like this, we could use an on-board optical system optimized for terminal navigation and we could perform distant navigation using only ground-based optical tracking.

We also run variations on the range weight and astrometry accuracy, and observed that the LTOF results were very

sensitive to the astrometry quality – i.e. telescope size – but not sensitive to the range weight for the 5 mm and 5 cm values that were analyzed.

Table 2. Psyche scenario flyby delivery results

Case	B-plane ellipse (km, 1- σ)	LTOF (sec, 1- σ)
Radio + on-board optical	2.0×1.9	112
Radio + on-board optical + asteroid obs.	2.0×1.9	18
Optical, ground + on-board	2.0×1.9	25
Optical + asteroid observations	2.0×1.9	17
Ground optical only, inc. asteroid obs.	2.4×2.0	19

7. Conclusion

Ground-based optical taking can be competitive with radio-frequency tracking under the appropriate conditions. If a geographically diversified network of telescopes is available to ensure availability even when some of them are not able to observe, optical tracking could replace radio tracking for a number of deep-space mission scenarios.

Ground astrometry will greatly benefit from the release of the dense and highly accurate Gaia star catalog, and deep-space optical ranging is free from charged particle effects that dominate S and X-band radiofrequency error budgets.

Optical tracking could impose additional constraints on the spacecraft attitude if the on-board terminal is not gimballed, and may not work at all when the spacecraft cannot control its attitude or point precisely.

A telescope diameter of around 5 m may provide plane-of-sky accuracies competitive with delta-DOR, and range accuracies of about 5 cm seem to be sufficient for navigation applications, while higher accuracies could enable new scientific investigations.

Performing ground-based astrometry of a spacecraft and its asteroid target may produce a very precise measurement that complements on-board imaging of the asteroid by the spacecraft.

Acknowledgments

We would like to thank Chengxing Zhai, Michael Shao, Todd Ely, Christopher Jacobs, Joseph Lazio, and Slava Turyshev for their help with our research.

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology. © 2017 California Institute of Technology. Government sponsorship acknowledged

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