Chapter 7
Future Prospects and Applications

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7.1 Current and Upcoming Projects in the United States, Europe, and Japan

The concept of free-space optical communications was conceived shortly after the invention of lasers. Strides have been made in developing and demonstrating the technology ever since. Early experiments that targeted terrestrial point-to-point, air-to-ground, and space-to-ground links were not fully successful because the technology was immature. Most of these demonstrations were government-funded, both for civilian and military applications.

The promise of laser communication, high data-rate delivery with significantly reduced aperture size for the flight terminal, led to the continued funding for the successful experiments and provided the incentive for further demonstrations. Table 7-1 presents a chronological summary of major successful laser-communication technology demonstrations [1–5] to or from air or space. Plans for additional major experiments are discussed below.

7.1.1 LUCE (Laser Utilizing Communications Experiment)

The Optical Inter-orbit Communications Engineering Test Satellite (OICETS) carrying the LUCE payload is planned for launch into low Earth orbit (LEO) in 2005 (Fig. 7-1). LUCE has an aperture diameter of 26 cm and is equipped with 200-mW 847-nm diode lasers for 50 megabits per second (Mbps) transmission to the European Space Agency's (ESA's) Advanced Relay

Table 7-1. Summary of major accomplishments in laser-communications technology.

Year	Experiment	Performing Organizations*
1980	AFTS (Airborne Flight Test System) 1 gigabit per second (Gbps) link from aircraft [1]	McDonnell Douglas (U.S. DoD)
1990	RME (Relay Mirror Experiment) Precision laser beam pointing [2]	Ball Aerospace (U.S. DoD)
1992	GOPEX (Galileo Optical Experiment) Uplink from Earth to deep-space [3]	JPL (NASA)
1995	LCE (Laser Communication Experiment) Bi-directional link from terminal at geosynchronous Earth orbit (GEO) [4]	CRL (Japan) and JPL (NASA)
1998	GEOLite (Geosynchronous Lightweight Technology Experiment) Multi-Gbps link from GEO orbit [5]	Lincoln Laboratory (U.S. DoD)
1998	SILEX (Semiconductor Intersatellite Link Experiment) Low Earth orbit (LEO) to GEO and LEO- and GEO-to-ground [6]	ESA

* Organizations Listed: Communication Research Laboratory (CRL), U.S. Department of Defense (DoD), European Space Agency (ESA), Jet Propulsion Laboratory (JPL), National Aeronautics and Space Administration (NASA)

and Technology Mission Satellite (ARTEMIS). It is capable of receiving 2.048-Mbps links from ARTEMIS at 819 nanometers (nm) [7–8].

7.1.2 Mars Laser-Communication Demonstrator (MLCD)

NASA is planning for the first deep-space laser-communication downlink in the 2009–2011 time frame from Mars distances utilizing the Mars Laser Terminal (MLT) being built by the Massachusetts Institute of Technology (MIT) Lincoln Laboratory flying aboard the Mars Telecom Orbiter spacecraft [9]. MLCD will demonstrate data rates on the order of 1 to 80 Mbps from the longest distance (about 2.4 astronomical units [AU]) to the shortest distance (about 0.67 AU), assuming a 5-equivalent-diameter aperture. This data rate is at least an order of magnitude higher than state-of-the-art RF Mars communication systems.

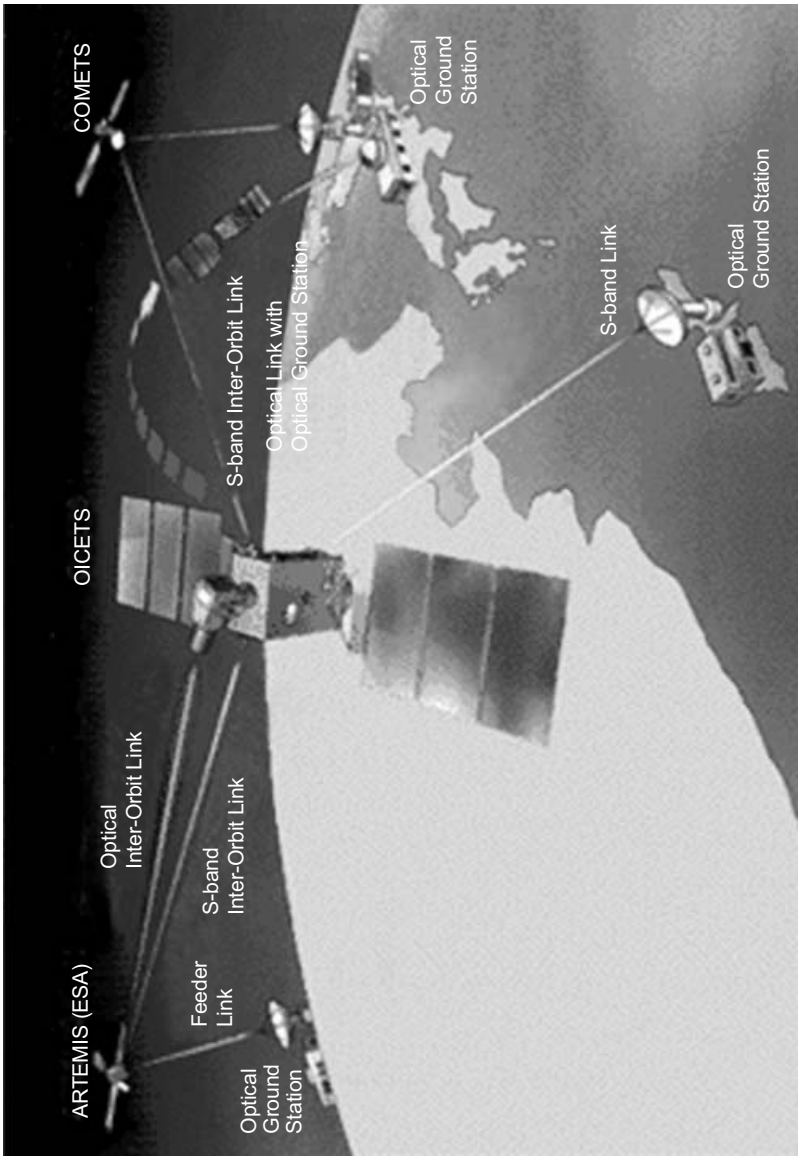

Fig. 7-1. Artist concept of the laser communications terminal on Japan's OICETs spacecraft communicating with the European Space Agency ARTEMIS and COMETS spacecraft (COMETS = Communications and Broadcast Engineering and Test Satellite).

7.2 Airborne and Spaceborne Receivers

Use of ground-based receivers was discussed extensively in Section 5.2. Here, we briefly discuss the merits of airborne and spaceborne receivers. These alternative options will offer significant advantages over ground-based systems when made practical through technology development and validation to the extent where cost, reliability, and redundancy against single point failure (for spaceborne receivers) become attractive. A more quantitative description of the advantages is provided below.

7.2.1 Advantages of Airborne and Spaceborne Receivers

The main advantage of airborne and spaceborne receivers is that they are above the clouds and most if not all of the atmosphere. This increases link availability and removes the atmospheric-turbulence-imposed limitation of operating many times diffraction limited for both transmission and reception. Dramatically reduced sky background contributed by scattering of sunlight from atmospheric constituents also benefits the data-receiving function. As a result, with such a platform, the required equivalent aperture size is considerably less than that required for ground-based terminals. The collection area is a function of the platform altitude. For example, relative to a ground-based terminal, a nearly 35 percent reduction in the required aperture diameter is expected with an airborne terminal located at a 20-km altitude. Similarly, a reduction of nearly 50 percent in aperture diameter can be expected when utilizing a spaceborne platform for the receiver.

Optical receivers also need the capability to transmit laser signals to the deep-space assets. The laser transmissions are needed to provide beacon-pointing reference sources and/or provide uplink commands. Intuitively it appears that airborne and spaceborne assets utilizing a single platform for both receiving and transmitting would be cost effective; however, issues relative to transmit–receive isolation and the point-ahead required will need to be carefully considered. One of the overriding advantages of placing the transmitting lasers above the clouds and the majority of the atmosphere will be removal of the severe limitations induced by turbulence on transmitting lasers from the ground. The benefits could be of the order of 30 dB.

In general, taking most if not all the atmosphere out of the optical channel involved in a deep-space communication link opens the possibility of near-diffraction-limited performance. The important ramifications of this are the possibility of overcoming performance penalties associated with atmosphere-induced limitations on how small the communications detector field of view can be. This of course has a two-fold effect of increasing background and limiting detector bandwidth.

Allowing near-diffraction-limited operations also opens up the possibility of implementing coherent communications. Coherent communications are immune to background contamination, and even though sky radiance backgrounds are not of concern in this case, the possibility of communicating at very small SEP/SPE (Sun–Earth–probe/Sun–probe–Earth) angles becomes possible. This is significant for a variety of deep-space configurations, reducing outages near solar conjunctions as well as allowing greater tolerance to having stars or planets in the detector field of view. Stabilized lasers used for coherent techniques also open up new possibilities for utilizing the laser communications sources for novel light science investigations since detection becomes sensitive to the optical phase.

The extent to which near-diffraction-limited performance can be embraced will be tempered by the associated stringent pointing control requirement. This, in turn, will be influenced by the stability and quiescence of the airborne/spaceborne platform, as well as the cost of flight-qualified large optics. One can speculate that a work-around may be to limit aperture size but to have many apertures. Use of multiple apertures will likely result in performance inferior to a single aperture; however, the cost versus performance of adopting an array architecture in space needs to be evaluated. The added advantage of deploying arrays in space is the redundancy they provide, eliminating a single point of failure

7.2.2 Disadvantages of Airborne and Spaceborne Receivers

The disadvantages for airborne and spaceborne receivers need to be distinguished from each other. Airborne systems can be re-deployed multiple times and are therefore readily accessible for hardware reconfiguration; however, there are concerns about platform attitude control and stability and their influence on pointing stability, as well as field-of-view blockage. To first order, the pointing stability can be considered as comprised of coarse and fine components. The coarse pointing will need to be a fraction of the attitude uncertainties thought to be of the milliradian (mrad) class, whereas the fine pointing will need to be a fraction of the diffraction-limited spot size, which can be anywhere from tens to thousands of nanoradians (nrad) depending on how many times diffraction limited the terminal design is. In fact, for airborne systems, residual turbulence may still require a 5- to 10-μrad class of communications fields of view requiring approximately 0.1- to 1-μrad-class pointing accuracy.

Conversely, spaceborne platforms require redundancy built in to prevent potential single-point failures. Moreover, there is the question as to where spaceborne receivers need to be deployed in order to provide maximum coverage of deep-space assets. For an operational receiver system, a constellation of orbiting receivers may be required. In addition, it will be

necessary to get the data from these assets back to Earth and/or to provide adequate buffering at the receiver. Placing optical receivers at Lagrange points or the Moon is also viable. Again the design chosen to provide very high performance will dictate the amount of pointing and platform stability control required. Here cost performance trade-offs are needed.

Another cost trade-off that should be carefully evaluated is the comparison of implementing adaptive optics systems on the ground to compensate for atmospheric turbulence versus deploying systems in space. In other words, if adaptive optics that largely compensated for atmosphere-imposed limitations could be implemented, then the only advantage of going airborne or spaceborne would be getting above the clouds. Once again the question needs to be answered as to the cost of implementing a ground network with adaptive optics versus an airborne or spaceborne system. The answer will require further study and evaluation of ongoing and emerging technologies in diverse areas and the costs associated with them. Many of the limitations discussed here are engineering problems and are certain to be alleviated with time, making them viable platforms to host the receive terminal.

7.2.3 Airborne Terminals

The airborne platforms include balloons, airships, and airplanes. The best reception availability is obtained when the airborne terminals are located in the most southerly or most northerly latitudes because line-of-sight blockage by the Earth is minimized.

7.2.3.1 Balloons. The balloon platform instabilities may be overcome with a gimbal-mounted receiver telescope. However, the location of the balloon itself has to be limited for the purpose of data relay with the ground. For example, scientific, free-flyer balloons that are wind driven are not useful to this application. The required number of balloons is largely dependent on the field-of-view restrictions for the optics. Since current balloons accommodate the payload on tethers below the balloon, field of view is often severely restricted. Balloons made of materials that are transparent at the signal wavelength may allow a see-through capability to the payload, albeit with some signal attenuation. Currently available tethered balloons have a very small payload weight capacity and require technology development in order to serve as good candidates for optical communication receiver host platforms.

A 20-km-altitude tethered balloon-based laser communications receiver called Space Relay Communication Link (SPARCL) has been conceptually analyzed [10]. An altitude of 20 km will be sufficient to circumvent much of the atmospheric effects. This concept assumes that the laser-communication payload is mounted on top of the balloon. One of the main challenges identified at the operational altitude is when the balloon encounters high wind regions. In

that case, active control of the balloon was deemed necessary. This study suggests that use of a high-altitude balloon-based receiver concept is technically feasible; however, significant technology development is necessary before the receiver can be used operationally.

7.2.3.2 Airships. Station keeping is a major requirement for an airship serving as the platform for a receiving terminal. For that task, the aerodynamic drag on the airship has to be kept to a minimum. Typically, the airships are designed for minimum drag. Therefore, the terminal has to be located within the airship. Airships could have a lifetime of many years and are capable of landing for recovery. Limited radio-frequency (RF) communication with the airship is provided. Instrument-available electrical DC powers exceeding 1 kW are planned for the airships that are under development [11]. Tethered aerostats can carry heavy payloads. The maximum altitude for current tethered airships is about 6 km [11]. This altitude is too low to fully mitigate the atmospheric effects (e.g., clouds).

For any of the airborne dirigibles that are engine driven, air turbulence effects generated by the engine fans must be taken into account.

7.2.3.3 Airplanes. The altitude of 12.5 to 13.7 km still has 20 percent of the air molecules of sea level so airplanes can still fly, but it is above most water vapor so infrared observations can be made that are impossible for ground-based stations. Consequently, there has been a string of aircraft-borne infrared observatories since the mid 1960s [28]. First, a NASA Convair CV 990 had telescopes pointed out a window. Then, a NASA Lear jet was fitted with a 30-cm telescope in place of an emergency exit window. In 1974, a United States Air Force C-141 Stratolifter had a 91.5-cm telescope mounted in front of the left wing to become the Kuiper Airborne Observatory (KAO). In 2005, operations are set to begin with the joint NASA space agency Stratospheric Observatory for Infrared Observation (SOFIA), a 2.5-m telescope mounted on a Boeing 747SP [29].

None of these airborne facilities were developed with optical deep-space communication in mind. Nevertheless, their stratospheric location mitigates most atmospheric effects, particularly clouds. Moreover, their evolution has proceeded along a learning curve in dealing with the major problems of maintaining pointing accuracy and instrument function despite vibration, wind gusting, and temperatures in the range of –40 deg Celsius.

The limitation for airplane-borne facilities is cost for fueling and maintaining the facility. This is especially so considering that even SOFIA's 2.5-m telescope is at the low end of the size range needed for deep space communication.

7.2.4 Spaceborne Receiver Terminals

Unaffected by atmospheric effects, spaceborne terminals can theoretically provide availability exceeding 98 percent. Spacecraft located at the most favorable GEO and medium Earth orbit (MEO) provide higher availability relative to those in favorable LEO orbits. The required spacecraft-pointing capability, on the order of half of the field of view (approximately ±1 mrad), is well within the capability of current spacecraft platforms.

Several studies have been conducted in the past on the feasibility and costs of spaceborne, Earth-orbiting communication relay satellites. In a 1993 NASA-funded study, TRW and Stanford Telecom conceptually designed and costed a space-based transceiver for optical communications [12,13]. JPL's Advanced Project Design Team studied both direct-detection and coherent-detection configurations for an optical relay satellite. A comparison of the results of these past studies is given in [14]. JPL based its cost estimation on a combination of grass roots estimates and quotes for mission operations, the launch vehicle, and the various spacecraft subsystems. Cost models were used for other mission components, including payload, systems engineering, integration and test, management, and reserves. To reduce the cost, the Next Generation Space Telescope technology development heritage was assumed for the front-end optical signal collection aperture. JPL's Advanced Project Design Team study showed that the most probable cost of a single 7-m direct-detection telescope on the relay satellite was a factor of two less than the previous estimates [14].

This cost now exceeds that of an eight-station ground-based facility [6]. Moreover, a single spaceborne station is limited in coverage, whereas an eight-receiver ground-based station provides full coverage of the spacecraft. The majority of the cost is for the host spacecraft and the launch vehicle. To make the spaceborne receiver attractive relative to the ground-based receivers, innovations in the technology of lightweight, low-cost telescopes (photon collectors) are required to minimize the overall cost per spacecraft.

7.2.5 Alternative Receiver Sites

A third category of receiver/transmitter station sites is the Moon. As with space-based receivers, such sites will avoid the atmospheric effects. However, maintenance and upgrades are cost prohibitive at this time. Moon-based radio telescopes have been studied in some detail [15].

7.3 Light Science

In a manner analogous to traditional radio-science measurements, "light-science" measurements are possible through use of the laser beam transmitted from a spaceborne laser-communication terminal for positional reference and light propagation experiments. Several preliminary studies have been made into

viable scientific applications of laser communications [16,17]. Some of these are (1) light-propagation experiments that include occultation investigations of probe planetary limbs and scattering from the medium throughout interplanetary space; (2) enhanced knowledge of Solar-System body (e.g., planet, moon asteroid, or comet) properties; (3) tests of fundamental theories of physics; and (4) improved knowledge of Solar-System ephemerides. Some of these measurements are unique to optical communication technologies and the application of today's state-of-the-art tracking capability. Many science measurements can be made with incoherent systems (which may include pulsed laser sources), while others require (or are more precise with) coherent systems.

Some of the possible light-science measurements are discussed in further detail below.

7.3.1 Light-Propagation Experiments

Light-propagation experiments include occultation and interplanetary light-scattering. In general these experiments can be designed to detect intensity or phase. Each type of sensing imposes requirements on the laser source used by the laser communications system. For example, frequency-stabilized lasers used for phase-sensitive detection may not be easily useable if the receiver is ground-based and limited by atmosphere-induced turbulence and background. Furthermore, light-propagation experiments from ground-based measurements will need to have reliable independent means of calibrating the atmospheric attenuation. Use of suitable celestial sources in the vicinity of the laser communication terminal is a possibility. However, being able to perform light-science measurements where received signal can be easily correlated to phenomena in the intervening medium, in the absence of atmospheric perturbations, offers clear advantages.

7.3.2 Occultation Experiments to Probe Planetary Atmospheres, Rings, Ionospheres, Magnetic Fields, and the Interplanetary Medium

In occultation experiments, laser light from the flight terminal on one spacecraft is received by a second spacecraft or by an Earth-based terminal as the transmitting spacecraft passes behind the limb, atmosphere, or rings of a planet. As the transmitting spacecraft is occulted, its laser is observed (i.e., received) by the receiving terminal. The laser output from the flight terminal can be either continuous or pulsed at high repetition rates. Detecting intensity alone would involve looking for deterministic changes in received average power that offer a clearly discernible signature representative of attenuation or refractive bending.

7.3.2.1 Atmospheric Occultations. Characteristics of the atmosphere around a planet or other bodies in space can be determined through measurements of a flight-terminal laser's attenuation or complete occultation due to the atmosphere [18,19]. In addition to direct intensity detection, wavelength perturbations due to Doppler could in principle be sensed, allowing for simultaneous tracking of the spacecraft velocity component along the line of sight and of the average laser signal. For example, for a high polar orbit around Mars, a 1000-nm laser would undergo a ±2.5-GHz change due to Doppler variations. While it is non-trivial to sense 1/1000th of a nanometer and smaller changes in wavelength, and would require a laser line width that is much narrower, the interesting possibility of extracting signatures of average laser power fluctuation as a function of position in orbit presents itself. Refractive bending could thereby be extracted.

When two flight optical-communication terminals are used, it becomes possible for one terminal to acquire occultation data through reception of laser light from the second flight terminal. If a flight terminal transmits two or more different coherent wavelengths, in conjunction with a suitable space (or ground) receiver, relatively precise atmospheric data can be extracted from the relative phase delay of each received frequency. The precision of this method can be further enhanced if a second but un-occulted flight terminal in the same vicinity is used as a reference.

In atmospheric-occultation experiments, typical goals are to determine temperature and pressure as functions of altitude in the stratosphere and troposphere, determine composition (e.g., methane and helium abundances), characterize the vertical structure of the ionosphere, and investigate turbulence and other irregularities.

7.3.2.2 Ring-Investigation Experiments. In ring-occultation experiments, typical goals are to determine the size and size distribution of ring particles, radial structure of the ring system, and vertical structure of the rings (e.g., whether ring structures are widely distributed or confined to a plane). As in atmospheric-occultation experiments, this is traditionally done in radio frequencies by transmitting two wavelengths coherently from the spacecraft to the ground. Depending upon the proximity of a laser-communications-bearing spacecraft to such rings, backscattered light intensity patterns and the intensity and angular characteristics could be utilized to investigate the density, size, and shape of particles in the Mie-scattering-sized regime.

7.3.3 Enhanced Knowledge of Solar-System-Object Masses and Gravitational Fields, Sizes, Shapes, and Surface Features

An optical terminal provides means to gather information about gravitational fields and the sizes, shapes, and surface features of intercepted

planets, moons, and other interplanetary objects. Gravitational fields are measured through observing changes in the spacecraft trajectory and velocity. These changes are measured by astrometry techniques, by observing Doppler effects on the received wavelength, and (in the case of a pulsed optical transmitter) by observing the timing of the received laser pulses. The sizes and shapes of moons and other objects, as well as some surface features, can be determined through multiple occultations. Surface features can also be measured through sounding the surface of an object with the flight terminal laser, and then receiving the reflected light with either the same or a different flight terminal receiver. However, practicality of the sounding technique is dependent on surface and atmospheric characteristics of the object observed.

7.3.3.1 Improved Knowledge of Solar-System Body Properties. Precise optical tracking of a spacecraft trajectory during target approach can provide information about the mass and gravity field of the target. Similarly, precise tracking of a spacecraft as it passes through a system of satellites can aid in the calculation of relative center-of-mass locations and velocities. In a hybrid system with both RF and optical capabilities, remote optical tracking data would be a valuable supplement to conventional RF Doppler and very long baseline interferometry (VLBI) data used to determine target masses, positions, and motions. Such optical observations may rival or surpass conventional RF data in their accuracy and usefulness for some measurements.

The capability of precise spatial tracking of a spacecraft, together with improved ephemerides for planets and satellites, would put navigational abilities on a whole new level. Collision avoidance, now a primary concern, would give way to a mode that facilitates closer approaches to planets and other Solar-System objects. This capability would also refine trajectory and encounter sequences to conserve propulsion fuel.

7.3.3.2 Optical Reference-Frame Ties. Precise spatial tracking of a laser-carrying spacecraft might also be used to help tie together optical star reference frames, which typically are more accurate in right ascension than in declination. By tracking the spacecraft as it moves through several values of declination, and assuming a continuous Kepler trajectory, one could calculate the angular distance between separated reference stars.

7.3.4 Tests of the Fundamental Theories: General Relativity, Gravitational Waves, Unified Field Theories, Astrophysics, and Cosmology

A suitably configured optical flight terminal provides tools of unprecedented accuracy for testing the fundamental theories of general

relativity, gravitational waves, unified field theories, astrophysics, and cosmology.

7.3.4.1 Tests of General Relativity and Unified Field Theories, Astrophysics, and Cosmology. Several experiments that would require or benefit from a laser communications capability on spacecraft are possible. These include light-deflection tests of general relativity, gravitational-wave detection, tests of the change with time of the gravitational constant G, and observation of a gravito-magnetic interaction. Some of these tests will be accomplished by precise astrometric measurements [20], while others require precise laser Doppler and/or ranging data.

In the areas of astronomy, astrophysics, and cosmology, there are numerous scientific goals that would benefit from coherent laser communications technologies in space. Several goals currently being pursued with astrometric interferometers [20,21] include refinement of the cosmic distance scale and of the mass estimate for our galaxy, and a search for other planetary systems. These interferometric instruments use laser metrology systems to control systematic errors. Another scientific goal is improved understanding of the composition, concentration, and velocity of interplanetary and cosmic dust. For this, coherent optical Doppler techniques will be useful.

7.3.4.2 Effects of Charged Particles on Electromagnetic Wave Propagation, Including Test of l/f Hypothesis. An important existing problem in spacecraft navigation and orbit determination is inconsistencies between Doppler and range data. The inconsistency between Doppler and range data is attributed to incomplete modeling of non-gravitational accelerations on spacecraft, e.g., solar pressure and non-ideal thruster behavior such as leaks or exhaust-plume impingement on parts of the spacecraft.

While it is probable that the nongravitational accelerations are the cause for most, if not all, of the range–Doppler inconsistencies, by deweighting range, one masks any other effects that might exist and that would also lead to inconsistencies. Such effects could be of considerable scientific interest. One such effect is that the calibration of the effects of free electrons along the transmission path on electromagnetic signals is incorrect. Such free-electron-induced perturbations have a 1/frequency (1/f) dependence. Therefore, testing with higher frequency optical signals will reduce this uncertainty.

7.3.5 Enhanced Solar-System Ephemerides

By comparing actual optical range data with predictions based on current ephemerides, the accuracy of Solar-System ephemerides can be greatly enhanced. One benefit of light science is the potential for making real-time

angular measurements from a single station, in contrast to the long passes and multiple stations required by radio-frequency VLBI. Another benefit is the possibility of direct spacecraft–target tracking with Solar-System bodies.

Candidate optical angle-tracking techniques used in astrometry show promise of nanoradian (about 1/5,000 arcsec) angular accuracy from the ground and picoradian (prad) (1/5,000,000 arcsec) accuracy from space for measurements of relative angular position between a flight-terminal laser and sufficiently bright, point-like targets [18,22,23,27]. For target-relative measurements, the extended discs and non-uniform brightness of planetary bodies may limit achievable tracking accuracies to a few tens of nanoradians—a few tens of kilometers at Saturn, for example. However, the better tracking accuracies possible for measurements between point sources can potentially be exploited for other important mission enhancements, such as remote optical tracking of landers, rovers, and orbiters.

Astrometric telescopes currently in use on the ground have demonstrated night-to-night reproducibility for differential angular measurements that are 20 nrad or better for point-like stars of apparent visual magnitude 11 and brighter [18,24]. For reference, a 5-W visible-wavelength (532-nm) laser at Saturn firing through a 30-cm telescope would have an apparent visual magnitude of about 11.

7.3.5.1 Science Benefits of Remote Optical Tracking: Ephemeris Improvement. Optical measurements of the angular separation between a laser-carrying spacecraft and a Solar-System body (e.g., planet, satellite, or asteroid) made remotely from Earth or Earth orbit would complement traditional RF data types based on range, Doppler, and quasar-relative VLBI measurements [25,26].

An important implication of a remote optical tracking capability is that the target position could be estimated accurately prior to encounter in all three dimensions, two by onboard optical measurements and the third (along the spacecraft trajectory) by a remote measurement.

With a laser on the spacecraft, the angular separation between target and spacecraft might be observed optically from the vicinity of Earth (this assumes an Earth–asteroid separation of about 3 AU, a spacecraft–target relative velocity of about 7 km/s, and a 45-degree angle between the trajectory and the Earth–asteroid line of sight). The remote data and the onboard data are complementary because of the different viewing angles, and they would be of comparable accuracy if ground-based astrometric techniques could achieve accuracies of 25–50 nrad for angle measurements between an asteroid and a laser-carrying spacecraft.

A smaller ephemeris improvement should be expected for a target such as Saturn, because of its extended disk (~100-μrad angular diameter) and

increased distance. To rival the 10-km metric accuracy of onboard optical data, ground-based data must be capable of 10-nrad accuracy for measurements of the angular separation between the spacecraft and Saturn. The primary obstacle to a precise measurement of relative position is calibration of the offset between Saturn's center of mass and its geometric center of brightness.

For large (~0.5-arcsec) and nearly circular targets such as Titan or Saturn, limb-fitting techniques can be used to deduce the geometric center and approximate center of mass. Such techniques have the advantage of being relatively insensitive to albedo variations. Center-of-mass information can then be refined through use of the tracking data obtained prior to and during the encounter(s).

Judged from their performances to date and predicted capabilities, astrometric telescopes that use Ronchi rulings and have fields of view of at least a few milliradians appear to be suitable instruments both for aiding in calibration of offsets between center of brightness and center of mass for extended bodies and for use with target-relative navigation and tracking. Interferometers, on the other hand, are not well suited to measurements on extended sources because the fringe overlap degrades fringe contrast, making a bright, extended body appear quite dim.

An onboard optical communication system, if appropriately configured with imaging capability, can also provide means for optical navigation. More study is needed to determine how accurately remote optical navigation and tracking techniques can be made to work with Solar-System bodies and to determine the optimum techniques and navigation strategies.

7.3.6 Applications of Coherent Laser Communications Technology

Traditional occultation experiments on Solar-System bodies, rings, or atmospheres have used coherent radio-frequency communications systems at two or more wavelengths. For example, the Voyager spacecraft transmitted X- and S-bands to Earth through the atmosphere and rings of other planets. Some of the potential science benefits offered by optical analogs of these coherent radio measurements are briefly covered below.

Coherent laser communication technology is applicable to the development and deployment of optical flight terminals. Development of a flight terminal also presents the opportunity for advances in coherent laser communication technology and its application to light science. The optical flight terminal provides a useful test bed for optical communication and other extremely long-range applications of laser technology.

To perform light science with coherent laser communications payloads will require frequency-stabilized lasers with sub-kilohertz line widths, 1–10 W average power, and phase-matching (or at least frequency-matching)

transponders. The narrowband filtering intrinsic to coherent detection permits communications and tracking under conditions of much higher background light (noise) than what is possible with incoherent detection.

Sensitive range and Doppler data capable of detecting small perturbations to the relative separations of two co-orbiting satellites above Earth (or any Solar-System object) would permit inference of the gravitational field with excellent spatial resolution. For Earth, such measurements would contribute to a better understanding of plate tectonics and continental drift.

7.4 Conclusions

In conclusion, it would be fair to say that optical communication, as an operational capability, holds much promise. Technology demonstrations in the near future will retire the risks of implementing a future communications capability. At that time, exploiting the potential benefits of performing light science will inevitably be explored.

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