Deep-Space Optical Communications

Visions, Trends, and Prospects

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Abstract—**Current key initiatives in deep-space optical communications are treated in terms of historical context, contemporary trends, and prospects for the future. An architectural perspective focusing on high-level drivers, systems, and related operations concepts is provided. Detailed subsystem and component topics are not addressed. A brief overview of past ideas and architectural concepts sets the stage for current developments. Current requirements that might drive a transition from radio frequencies to optical communications are examined. These drivers include mission demand for data rates and/or data volumes; spectrum to accommodate such data rates; and desired power, mass, and cost benefits. As is typical, benefits come with associated challenges. For optical communications, these include atmospheric effects, link availability, pointing, and background light. The paper describes how NASA's Space Communication and Navigation Office will respond to the drivers, achieve the benefits, and mitigate the challenges, as documented in its *Optical Communications Roadmap*. Some nontraditional architectures and operations concepts are advanced in an effort to realize benefits and mitigate challenges as quickly as possible. Radio frequency communications is considered as both a competitor to and a partner with optical communications. The paper concludes with some suggestions for two affordable first steps that can yet evolve into capable architectures that will fulfill the vision inherent in optical communications.**

Keywords—data rate, deep-space optical terminal, DOT, Flight Laser Transceiver, FLT, GLR, GLT, Ground Laser Receiver, Ground Laser Transmitter, hybrid ground terminal, LADEE, LLCD, Lunar Atmosphere and Dust Environment Explorer, Lunar Laser Communication Demonstration, Mars Laser Communications Demonstration, Mars Telecommunications Orbiter, MLCD, MTO, optical communications, optical cross-link, optical link, PPM, pulse-position modulation, radio-frequency communications, RF communications, roadmap, SCaN, Single Optical Site, Space Communication and Navigation, spectrum

I. INTRODUCTION

Deep-space communications is either at, or at least approaching, a watershed in its ongoing developmental history. For over 60 years, development and implementation of radio-frequency (RF) and microwave communications techniques have paced the development of modern rocketry and space flight. Looking back to the mid-20th century, we can recall the huge promise of the rapidly expanding communications industry. Much of what had been developed by icons such as Bell Laboratories was infused into space exploration missions by communications engineers. These same engineers, not content with performance adequate for terrestrial links, pushed these techniques to their limit, and developed many new ones, so as to enable communications across and even beyond the solar system. This leaves communications engineers of the early 21st century with a wonderful legacy and a difficult problem. The problem is, of course, where do we go from here? Although there are still useful improvements to be made in RF and microwave communications, much of the potential that was envisioned 60 years ago has already been realized. Most will agree that the next great leap forward will be made by moving up in frequency from RF to the optical portion of the electromagnetic spectrum. The performance benefits, as well as the technical challenges, of such a move are quite evident, well understood, and traceable to fairly basic communications theory. Yet this leap is proving to be quite elusive. The paper will examine some of the past and present factors that have set the stage for this next great advance. A projection of future requirements will be estimated. NASA's plan for meeting these requirements, realizing performance benefits, and overcoming challenges will be discussed. Some novel concepts will also be considered.

II. "A BRIEF HISTORY OF OPTICAL COMMUNICATIONS"

Although there can be some debate about the earliest beginnings of optical communications, we will take for our first significant event a patent application in 1880 submitted by none other than the archetypical communications engineer, Alexander Graham Bell. Bell focused sunlight into a narrow beam that struck a reflective diaphragm, which vibrated in response to sound inputs. The vibrations caused a variation in light reflected through a lens that aimed the beam at an early photodetector. The varying light intensity caused a variation in resistance of the detector, which in turn varied the current through a telephone connected to the detector. Although sound was reproduced at the telephone diaphragm, the apparatus lacked the fidelity and volume to be practical [1].

Fast-forwarding from there, we have the foundations of fiber-optics technology established by N. S. Kapany at the University of London in 1955. Invention of the (ruby crystal) laser, by T. H. Maiman of Hughes Research Laboratories, occurred in 1960, followed shortly thereafter (in 1962) by the gallium arsenide solid-state laser, courtesy of R. N. Hall of General Electric and M. I. Nathan of IBM. Succeeding years, through the late-1970s, witnessed many developments in optical fibers leading to the vast deployment by telephone companies of fiber-based networks around the world [1].

As these advances were occurring in Earth-based laboratories, space exploration missions were exploiting the limits of RF-based communications technology and pressing ever farther out into the solar system. At the same time, instrument designers were creating new detectors for upcoming missions that had orders of magnitude more ability to generate digital data. Something had to be done! NASA and JPL recognized the performance potential of deep-space communications via free-space lasers during the late 1970s and early 1980s. As we begin to discuss events pertinent to deep-space optical communications, it should be noted that a very extensive history (81 pages in length) has previously been documented by Lesh and Hemmati [2]. Readers seeking additional details are referred to that work. Here we must be content with a few highlights. A seminal concept, from 1978 and still applicable today, is the work of J. Pierce on the attainability of multiple information bits (2.5) per photon [3]. To achieve this channel capacity, Pierce suggested the use of direct photon detection (photon counting) by means of pulse-position modulation (PPM) and codes with reasonable length and elaborateness.

By the early 1990s, JPL, in partnership with TRW and Stanford Telecommunications, had completed a four-year study of a Deep Space Relay Satellite System (DSRSS). Study objectives were to determine technical and cost feasibility of such a system for evolution of the Deep Space Network (DSN) beyond the year 2000 and develop satellite designs that would provide 10-dB telemetry improvement over projected 70-m Ka-band performance [4, 5]. At the same time, JPL conducted a largely in-house analysis of an alternative to the DSRSS concept, called the Ground Based Advanced Technology Study (GBATS) [6]. The ultimate goal of these two studies was to enable a decision in 1996 of how and when optical communications would be implemented in the DSN.

It is worth noting that the DSRSS study did consider usage of either RF or optical frequencies. Further, the study tacitly assumed that a site above the Earth's atmosphere, i.e., space basing, was the logical choice for either frequency region. A major conclusion was that an optical-based system is the only reasonable approach to obtaining significant telemetry growth for an in-orbit facility. It was clear that an optical system could meet the 10-dB performance goal. In fact, the study derived an 11.3-dB advantage over a 70-m antenna at 32 GHz. However, the space-based microwave option had to be eliminated due to excessive launch costs. Another conclusion was that a direct detection system appeared to be the most promising approach. This consisted of a 10-m non-diffraction-limited (photon-bucket) aperture, hinged for deployment in low Earth orbit (LEO) with a subsequent boost to geosynchronous Earth orbit (GEO). A significant plus was that this system required only extrapolation of demonstrated technologies—as opposed to development of new ones. However, two issues were noted. First, the entire system architecture, which included one satellite, one launch vehicle, and five user terminals, had a very high cost. Second, a backup system (not costed in the study) would be needed to overcome an in-orbit failure of the primary system.

The GBATS study derived two ground-based architecture options, both utilizing optical frequencies. Some items were specified to be common to both options. Commonality for the ground-based optical terminal led to preselection of a 10-m-diameter, segmented, photon-bucket aperture, utilizing a Cassegrain configuration with a 1-m secondary, and supported by an azimuth-elevation mount. Commonality at the system level required the following: only downlink telemetry reception, but for both day and night; reception to within 10 degrees of the Sun; signal acquisition down to 15 deg elevation; wavelengths between 500 and 2000 nm; and a concept of operations (ConOps) closely resembling that of the current DSN. Commonality at the subnet level required the following: 100% line of sight to the ecliptic for continuous coverage; 90% weather availability; stations situated at high altitudes (>1 km), i.e., mountain tops; site locations with a minimum of 66% cloud-free days; and one terminal per geographic site. Link geometry and weather were found to drive the subnet topologies for the two architecture options, specifically the need to have multiple sites for continuous line-of-sight coverage and spatial diversity to counter the effects of weather.

GBATS Option 1 was called the Linearly Dispersed Optical Subnet (LDOS). It was characterized by six stations located approximately 60 deg apart in longitude about the Earth's equatorial region. As a result, each site would be located in a different climatic region. Weather diversity would be ensured by the fact that 2–3 stations would always be in view of any user. The LDOS ConOps provides 90% weather availability by virtue of the fact that multiple stations in different climate regions have mutual line of sight. These stations use ephemeris predictions to coarse-point simultaneously to the user spacecraft. For LDOS, multiple stations with line of sight simultaneously support a single user. Of these, the station with the worst elevation angle determines the telemetry rate. Once coarse pointing has been achieved, a fine-steering mirror centers the optical signal on the detector, after which telemetry reception begins. At the other end of the link, the user spacecraft coarse-points to Earth utilizing onboard star-tracker data, after which it fixes on the Sun or illuminated Earth and offset points using a fine-steering mirror. Following this setup, telemetry transmission begins.

GBATS Option 2 was called the Clustered Optical Subnet (COS). It was characterized by nine stations located in groups of three approximately 120 deg apart in longitude about the Earth's equatorial region. This option fell just shy of the requirement to provide 100% line of sight to the ecliptic but was deemed "good enough". Weather diversity would be ensured by the fact that stations within a cluster are on the order of 200 km apart. The COS ConOps provides 96% weather availability by virtue of the fact that stations in different weather cells within a cluster have mutual line of sight. These stations within a cluster use ephemeris predictions to coarse-point simultaneously to the user spacecraft. For COS, each cluster is dedicated to a single user. The telemetry rate is determined by the elevation of the user spacecraft at hand-over from one cluster to another. Once coarse pointing has been achieved, a fine-steering mirror centers the optical signal on the detector, after which telemetry reception begins. At the other end of the link, the procedure is exactly the same as it is for LDOS.

Both the LDOS and COS subnets showed a gain of 8.5 dB (at night) and 6.4 dB (daytime) with respect to the 70-m antenna at 32 GHz. The ground-based approach was noted to have the following deficiencies. Relative to RF, ground-based optical is more susceptible to weather—requiring additional sites to provide the same availability as that of the current DSN. It is more sensitive to altitude—because of its susceptibility to atmospheric loss. It also has some tracking exclusion limitations—because no links are allowed within 10 deg of the Sun. Finally, ground-based optical is affected by daytime sky background. This is important because inner planets are always within 90 deg of the Sun, and outer planets are within 90 deg of the Sun at least 50% of the time.

A few issues were noted for either of the ground-based architectures. First is the obvious need for multiple (6–9) stations. Closely related to this is the fact that some of the sites must be outside the continental US. Because signals must traverse the Earth's atmosphere, daytime performance does suffer some loss. And finally, especially for LDOS, pointing of user spacecraft may need to adapt to weather outages at any one site. Many of these concerns still remain today [7].

Throughout the 1990s, developments were also occurring on the flight side of the deep-space optical link. Besides the obvious need for a flight-qualified laser, the system intended for a spacecraft would also have to perform the necessary functions of acquisition and tracking as well as beam-point ahead. To avoid the complexity, mass, and cost of a system that would perform these functions via independent subsystems, a very significant amount of systems integration was sought—and achieved [8]. The goal of an integrated deep-space optical terminal came to fruition in the mid-1990s at JPL in what was known as the Optical Communications Demonstrator (OCD). This flight terminal had a 10-cm aperture. It could be either body-mounted to a deep-space vehicle or, if necessary, gimbal-mounted so as to enable pointing independent of the main spacecraft bus. The OCD was considered as the basic optical flight terminal on many mission studies conducted over the ensuing years and was instrumental in making comparisons between mission architectures with either RF or optical links. The OCD also came to fruition in the form of laboratory-qualified hardware and was instrumental in influencing the design of later optical flight terminals [2].

Much more than studies were occurring as the 1990s progressed and the new millennium began. This was the era when system-level demonstrations of optical communications with actual spacecraft began. The earliest of these was the Galileo Optical Experiment (GOPEX) in 1992 [9]. For this demonstration, the spacecraft's high-resolution imaging camera looked back at Earth and successfully received laser pulses from both the 60-cm telescope at JPL's Table Mountain Facility (Wrightwood, California) and the 1.5-m telescope at the United States Air Force (USAF) Starfire Optical Range (Albuquerque, New Mexico). Between November 1995 and May 1996, NASA-JPL and the Japanese Space Agency (NASDA) conducted the Ground/Orbiter Lasercomm Demonstration (GOLD) [10]. This experiment demonstrated bidirectional laser links between a Japanese Engineering Test Satellite (ETS-VI), in a geosynchronous transfer orbit, and two telescopes at the Table Mountain Facility. Data rates of 1 megabit per second (Mbps) were achieved. Another key development of the mid-1990s was the Compensated Earth-Moon-Earth Retro-Reflector Laser Link (CEMERLL) [11]. This demonstration utilized the USAF 1.5-m Starfire telescope for uplink, Apollo corner-cube arrays on the lunar surface for turnaround, and a 3.5-m Starfire telescope for downlink. The experiment proved the value of adaptive optics on the uplink laser. In 1998, the European Space Agency (ESA) launched the SPOT-4 satellite, which carried an experimental optical communications terminal into LEO. A companion terminal was carried on the Artemis satellite, launched into GEO in 2001. Subsequently, a 50-Mbps optical cross-link was achieved between the two satellites [12]. Also during the 1998–2000 time period, JPL characterized atmospheric turbulence effects on optical communications by conducting tests on a link between its Table Mountain Facility and Strawberry Peak, a mountain 46 km away [13]. In 2001, the National Reconnaissance Office (NRO) had a successful flight demonstration using the Geosynchronous Lightweight Technology Experiment (GEOLite) [14]. During 2005, the Japanese Space Agency (JAXA) launched the Optical Inter-Orbit Communications Engineering Test Satellite (OICETS) into LEO to demonstrate optical cross-links in space. Later that year, optical links were successfully established with ESA's Artemis satellite. The following year saw establishment of successful links between OICETS and both Japanese and German ground stations. During 2009, 50-Mbps downlink and 2-Mbps uplink bidirectional links were established between OICETS and the NASA-JPL Optical Communications Telescope Laboratory (OCTL) at Table Mountain [15]. Most recently, researchers in Germany have demonstrated a coherent bidirectional space-to-ground optical link at 5.6 gigabits per second (Gbps) between the Near Field Infrared Experiment (NFIRE) satellite in LEO and a ground station hosted at the ESA site in Tenerife, Spain. They have also conducted intersatellite links between NFIRE and the German TerraSAR-X satellite [16].

III. Drivers for Optical Communications

While interest in optical communications systems has been growing since the 1980s, moving forward with their implementation and demonstration has historically proven to be a "hard sell". Much of this reticence had to do with the amount of available "head room" associated with existing RF communications technology. In the 1980s through the early 1990s, the most demanding deep-space missions typically had downlink data rates in the tens of kilobits per second. NASA was still completing the initial reconnaissance of the solar system; and, as Fig. 1 shows, tens of kilobits per second was about what was needed to return the first images of other planets. Such rates presented little threat of consuming the allocated spectrum bandwidth; and, while closing the deep-space communications links at these rates was a challenge for its time, it was apparent that moving toward higher RF bands, applying better forward-error-correction coding techniques, improving the noise temperature of the receivers, increasing the available receiving area, and improving the spacecraft-side

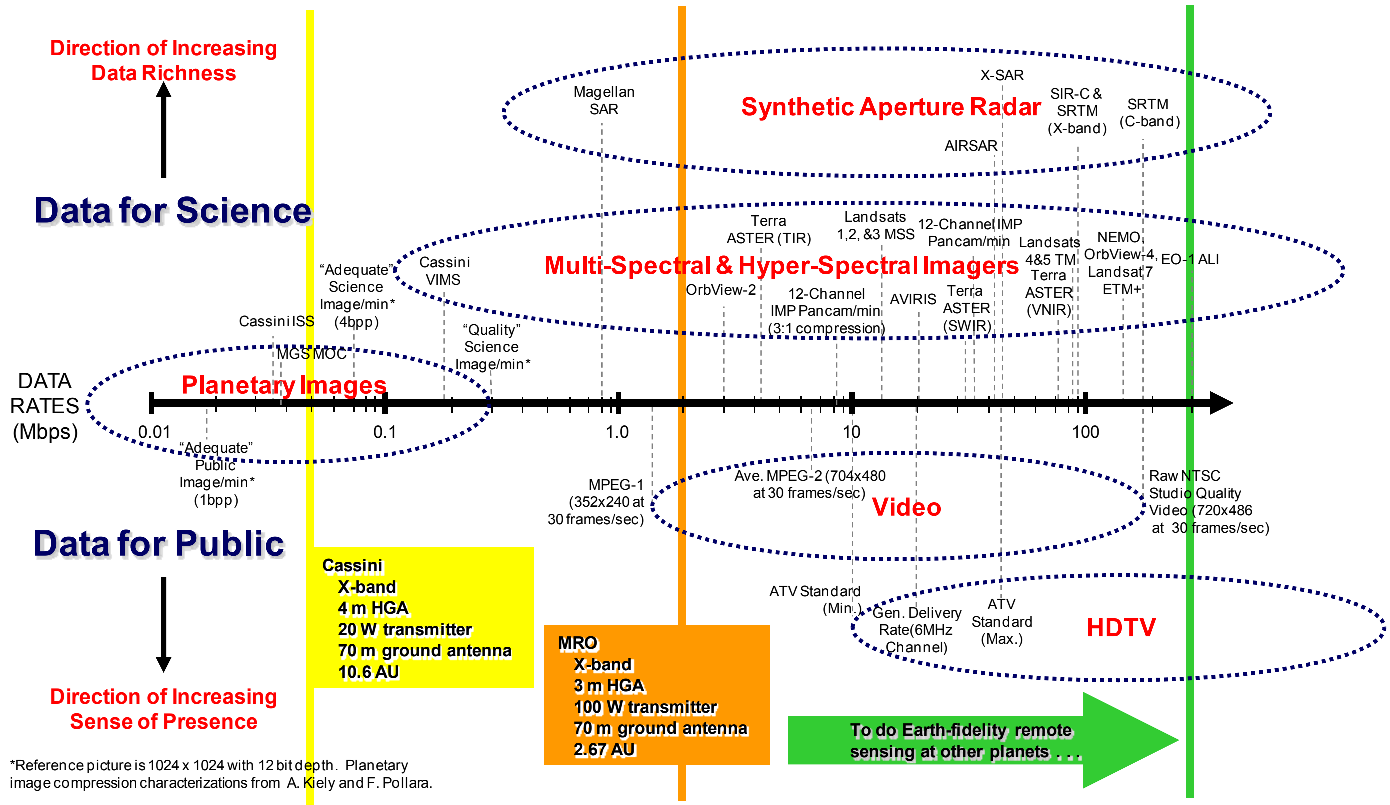

Figure 1. Required data rates as a function of data type.

equivalent isotropically radiated power (EIRP) would allow even higher data rates. Hence, pursuit of optical communications systems without first making these improvements to existing RF systems proved to be tough to "sell".

However, by the mid-1990s, the preliminary reconnaissance of the solar system was essentially complete. NASA had been to just about all of the solar system's planets at least once, and what remained was to go back to these destinations and examine them in more detail. As Fig. 1 shows, the return of higher-fidelity multispectral images, synthetic aperture radar observations, and near-real-time video requires more than an order-of-magnitude increase in data rates relative to what was needed for the initial reconnaissance of the solar system. And, to be able to conduct remote sensing of other planets at the same fidelity that we conduct remote sensing at the Earth today, we need to enable data rates more than three orders of magnitude higher than those being relied upon in the early 1990s.

Astrophysical missions manifest a similar pattern of escalating data rates. NASA's "Great Observatories" program in the 1990s and early 2000s conceived of and launched the Hubble Space Telescope, Compton Gamma Ray Observatory, Chandra X-ray Observatory, and Spitzer Space Telescope. Data rates for these observatories ranged from 0.5 Mbps to 2 Mbps. Today, NASA is constructing the James Webb Space Telescope with an information bit rate of roughly 25 Mbps—more than an order of magnitude higher than the last of the "Great Observatories". Observatory concepts for investigating dark energy a decade from now postulate data rates of around 150 Mbps—some two orders of magnitude higher than the "Great Observatories".

Human exploration data rates have similarly followed suit. In the late 1960s and early 1970s, the Apollo spacecraft's S-band downlink ran at about 50 kilobits per second (kbps). Today, the Space Shuttle and International Space Station Ku-band downlinks run at about 50 Mbps. Concepts for human exploration missions to the Moon, near-Earth objects, and Mars in the next 15 to 25 years involve Ka band downlink rates as high as 150 Mbps.

Fig. 2 summarizes most of these historical and projected data-rate driver trends. On average, deep-space mission data rates increase one to two orders of magnitude per decade, driven by the need to return the larger data volumes associated with observing at higher spatial, spectral, and temporal resolutions.

The rates we see today are the result of a steady progression along the RF improvement path outlined earlier: use of increasingly higher-frequency bands (e.g., S to X to Ka), more efficient error-correction coding schemes, cryogenic low-noise amplifiers on the ground receivers, larger ground receiving area, better spacecraft antenna gain, and higher-power amplifiers for the spacecraft transmitters. However, we are rapidly approaching the point where we have almost "picked all of the low-hanging fruit". Note that, beginning in 2020, the projected rates for deep-space mission drivers appear to flatten out at around 150 Mbps. There are at least two reasons for this:

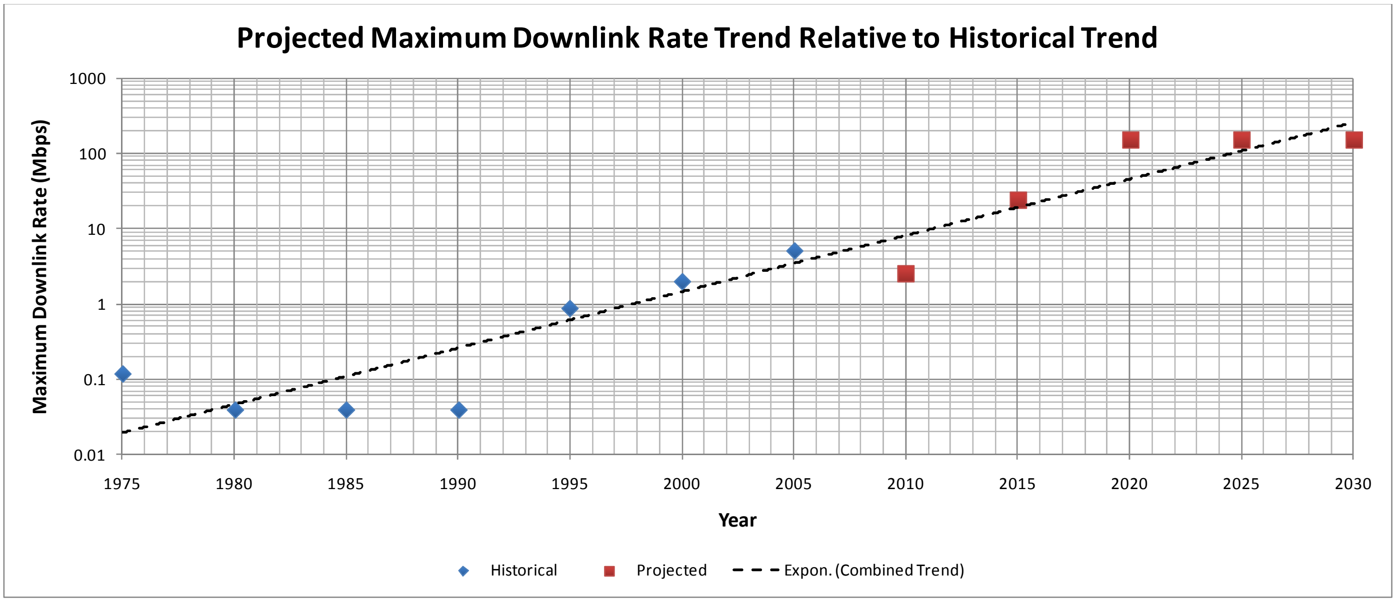

Figure 2. The historical and projected downlink rate trend.

(1) the sheer difficulty of closing 150-Mbps links at planetary distances, and (2) available allocated spectrum.

The end-to-end difficulty of closing a 150-Mbps link at Mars maximum distance is immense. A Mars Reconnaissance Orbiter (MRO)–class spacecraft at Mars maximum distance can send ~1 Mbps at X-band to a 70-m ground station, implying that it would take an array of roughly 150 70-m antennas to close the same link at 150 Mbps. If we could magically convert the 70-m antennas to operate at Ka-band with the same efficiency as at X, and we postulated a 100-W Ka-band transmitter onboard the spacecraft instead of an X-band transmitter, we could reduce the required number of ground antennas by roughly a factor of four. If we doubled the size of the spacecraft high-gain antenna to 6 m, we could reduce the required number of ground antennas by another factor of four. And if we tripled the spacecraft transmit power to 300 W rather than 100, we could further reduce the required number of ground antennas by a factor of three. This still leaves us requiring more than three 70-m-equivalent Ka-band antennas, or an array of roughly twelve 34-m antennas. This number far outstrips the number currently available at any of the complexes. Even if we were to build to this number at one or more complexes, this single 150-Mbps link would use up all the available capacity, leaving the other missions simultaneously dependent upon this complex without coverage. Additional gains from more efficient coding, coupled with improved data compression and, perhaps, some onboard data processing, might help to ameliorate this situation. But clearly, in the link difficulty realm, there is no longer the vast amount of RF improvement "head room" that there was when deep-space optical communications first made its debut in the 1980s.

A similar situation now exists in relation to available spectrum [17]. Fig. 3 shows available spectrum relative to two hypothetical missions—one operating at 25 Mbps and one operating at 150 Mbps, consistent with the rate trend in Fig. 2. The first of Fig. 3's two plots focuses on Category A spectrum, assigned to missions within 2 million km of the Earth (i.e., out to just beyond Sun-Earth Lagrange points L1 and L2). The second of the plots focuses on Category B spectrum, assigned to missions beyond 2 million km (i.e., generally planetary missions). The hypothetical missions in both plots assume quadrature phase-shift keying (QPSK) modulation and a rate ½ error-correction code. In either plot, a single 25-Mbps mission uses up just about the entire spectrum allocation at either S-band or X-band. Only at Ka-band does any real "head room" for high-rate deep-space missions remain. Given that most deep-space missions occur in very different parts of the sky, judicious frequency reuse can further contribute to this "head room". However, in the case of two Mars orbiters, they would be in the same part of the sky. And, as can be seen from Fig. 3, just two such spacecraft attempting to simultaneously downlink to the Earth at 150 Mbps would exceed the Ka-band spectrum allocation. Of course, there are at least a couple of potential methods for mitigating this situation. For instance, such spacecraft could apply more bandwidth-efficient modulation schemes and/or make use of dual polarizations to bring down double the data at the same frequency. However, pursuing either of these approaches generally necessitates applying more power to the signal transmission. To the extent that planetary missions are extremely power-constrained, these mitigation measures start to lose their attractiveness. So, at least for the high-rate Mars case, optical communications begins to look like a competitive solution.

With the available "head room" for improvement in RF communications diminishing, the prospects for optical communications now look brighter. Exactly when optical communications may be employed to surmount the RF link difficulty and spectrum challenges facing deep-space missions will depend on how the mass, power, volume, operational-environment performance, and life-cycle-cost characteristics of optical communications systems evolve relative to those of potential RF solutions. The following sections describe the technology development and demonstration strategy that

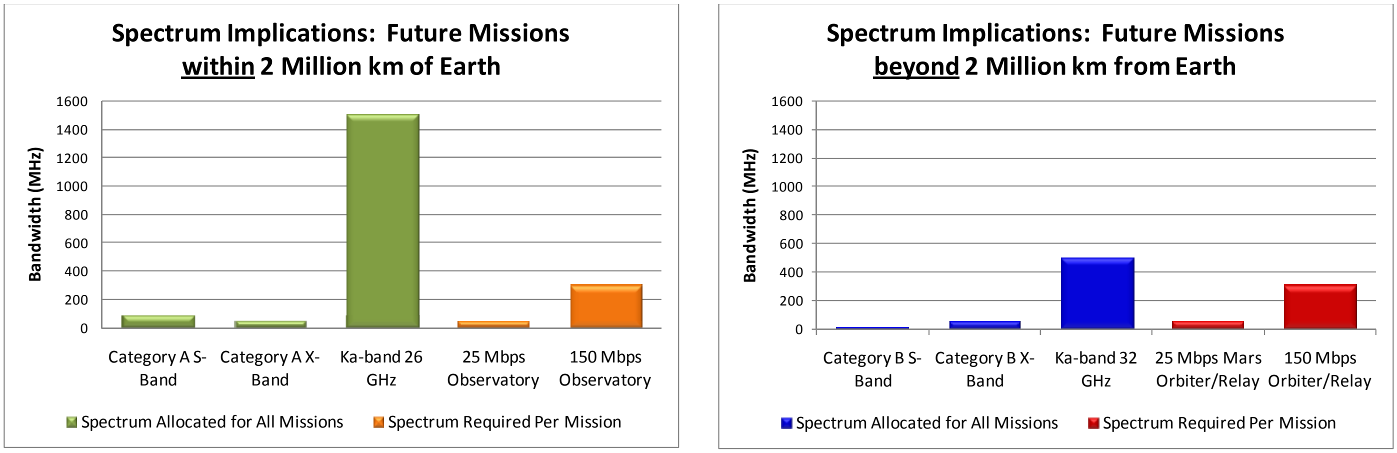

Figure 3. Category A and B spectrum allocations relative to high-rate mission bandwidth requirements.

NASA's Space Communication and Navigation (SCaN) Office is pursuing to spur this evolution.

IV. SCaN Optical Communications Roadmap

The SCaN Office at NASA headquarters has the management responsibility to provide tracking, telemetry, and command services to NASA's fleet of spacecraft. The NASA field centers have the execution responsibility of actually delivering these services. For spacecraft near Earth, these services are provided by the Space Network (SN) of Tracking and Data Relay Satellites (TDRS) and the Near-Earth Network (NEN) of small ground stations, both of which are operated by the Goddard Space Flight Center (GSFC); for more distant spacecraft, these services are provided by the DSN, operated by the Jet Propulsion Laboratory (JPL). In either case, networks whose performance and reliability are sufficient to meet the needs of user spacecraft are required. Currently SCaN and the field centers are meeting the needs of the existing and near-term users by means of RF communications links. At this time the networks are beginning a migration to Ka-band for high-rate data transfer. However, as discussed above, eventually even Ka-band capacity will be outstripped by growing spacecraft needs for more data transfer.

As we have seen, data rate trends point, not surprisingly, inexorably upward. So eventually, to obtain the orders-of-magnitude improvements that will be needed, optical systems will be required. Remote-sensing instruments onboard spacecraft in Earth orbit have immense capability to generate data. And this capability is matched by the ability to send such data volumes down to investigators on Earth. The short link distance makes this quite practicable. It is only natural for investigators to want these same instruments to generate these data volumes at the Moon, Mars, or even further out in the solar system. To do otherwise would be tantamount to repeating the achievements of previous missions. That would make neither scientific nor economic sense. In the long run, NASA needs more productivity from its exploration fleet of science spacecraft. Theoretically, the achievement of much higher data rates could be accomplished at RF. Practically, this would necessitate much higher power transmitters and much larger antennas on user spacecraft. Accommodating these systems into the design of future spacecraft would have significant impacts on volume, mass, and power requirements for these missions. These impacts would, in turn, most likely translate into higher costs. Equally important, they would consume resources that could otherwise be allocated to the science instrument payload, which, after all, is the reason for doing the mission in the first place. Finally accommodating these systems would reduce propellant reserves, which would then translate into shortened mission life.

Because SCaN and the field centers bear a responsibility to meet the needs of future users, they are developing and implementing a roadmap that will bring optical communications to fruition. Fundamentally, there are two main reasons to utilize optical links: higher data rates, and lower burden on the user spacecraft. Table I provides a comparative view of downlink data rates attainable with today's DSN as well as with an upgraded RF capability and an optical network. The table assumes an MRO-class reference spacecraft, with rate 1/6 turbo-coding, 3-dB link margin, 90% weather, and 20-degree DSN antenna elevation. Variable spacecraft parameters are shown in the second row of the table. The table does show that although there is room for growth at RF, achieving it will place increasing demands upon spacecraft and ground systems. Finally spectrum constraints will impose an unavoidable, if arbitrary, cap on such growth at RF.

Therefore, SCaN has developed an *Optical Communications Roadmap*, which seeks to achieve the future required data rates without placing undue burden on user spacecraft. Although the SCaN Office was formed in 2007, it in fact inherited a substantial legacy of past and ongoing work in the field of optical communications. Fig. 4 depicts some broad developmental activities between 2004 and 2008, for the most part directed toward near-Earth applications but developing strategic technology such as PPM that would be useful in deep-space applications.

In the early 2000s, NASA's Science Directorate had plans to deploy a dedicated relay asset at Mars called the Mars Telecommunications Orbiter (MTO). One key element of the MTO payload was an optical communications package called the Mars Laser Communications Demonstration (MLCD).

TABLE I. FUTURE DOWNLINK POSSIBILITIES AT RF AND OPTICAL

Spacecraft Capabilities	**Data Rate Today**		**Data Rate ~2020**		**Data Rate ~2030**		
	3-m Antenna X-Band 100-W Transmitter		***3-m Antenna Ka-Band 180-W Transmitter***		***5-m Antenna Ka-Band 200-W Transmitter***		***1-m Optical 1550-nm 50-W Transmitter***
DSN Antennas	1 × 34m	3 × 34m	1 × 34m	Equiv to 3 × 34 m	1 × 34 m	Equiv to 7 × 34 m	10-m Optical
Mars (0.6 AU)	20 Mbps	60 Mbps	400 Mbps	*1.2 Gbps	*1.3 Gbps	*9.3 Gbps	5.5 Gbps
Mars (2.6 AU)	1 Mbps	3 Mbps	21 Mbps	64 Mbps	71 Mbps	*500 Mbps	300 Mbps
Jupiter	250 kbps	750 kbps	5 Mbps	15 Mbps	16 Mbps	115 Mbps	70 Mbps
Saturn	71 kbps	213 kbps	1.4 Mbps	4 Mbps	4.7 Mbps	33 Mbps	19 Mbps
Neptune	8 kbps	24 kbps	160 kbps	470 kbps	520 kbps	3.7 Mbps	2.2 Mbps

*Performance will likely be 2–3 times lower due to need for bandwidth modulation

Unfortunately MTO fell victim to other priorities, and with it went MLCD—but not before some very productive technology efforts had been conducted and a Preliminary Design Review (PDR) had been completed. The MLCD flight terminal was to have a 30-cm aperture, with 5 W of laser power and operation at 1064 nm. Pointing was to be accomplished with a magneto hydrodynamic (MHD) inertial reference unit (MIRU) and a fast-steering mirror used to track an uplink beacon from Earth. Design of the flight terminal was provided by MIT's Lincoln Laboratories (MIT-LL), which also contributed a concept for a test ground terminal. JPL provided a second ground terminal option, which was to rent time on the 5-m Hale telescope at the Palomar Observatory. This option would have enabled 30-Mbps downlink from the flight terminal on MTO.

Following the MTO/MLCD cancellation, funding from NASA's Space Operations Mission Directorate and other sources was obtained to at least keep the technology advancing. As the chart shows, these efforts led to a 70-mm gimbal-supported and MIRU-pointed prototype terminal, and designs for a 10-cm terminal.

Fig. 5 depicts developmental activities, targeted specifically at deep-space optical communications, conducted in the wake of the MLCD cancellation and leading up to the current time. As shown on the figure, between 2007 and 2011, JPL has made significant progress in photon-counting detectors, higher-power lasers, low-power–high-speed electronics, vibration-isolation platforms, and larger prototype and flight terminals. These efforts have been targeted towards a hoped-for flight opportunity on the European Mars 2016 Trace Gas Orbiter. Unfortunately, this opportunity has also evaporated. Despite

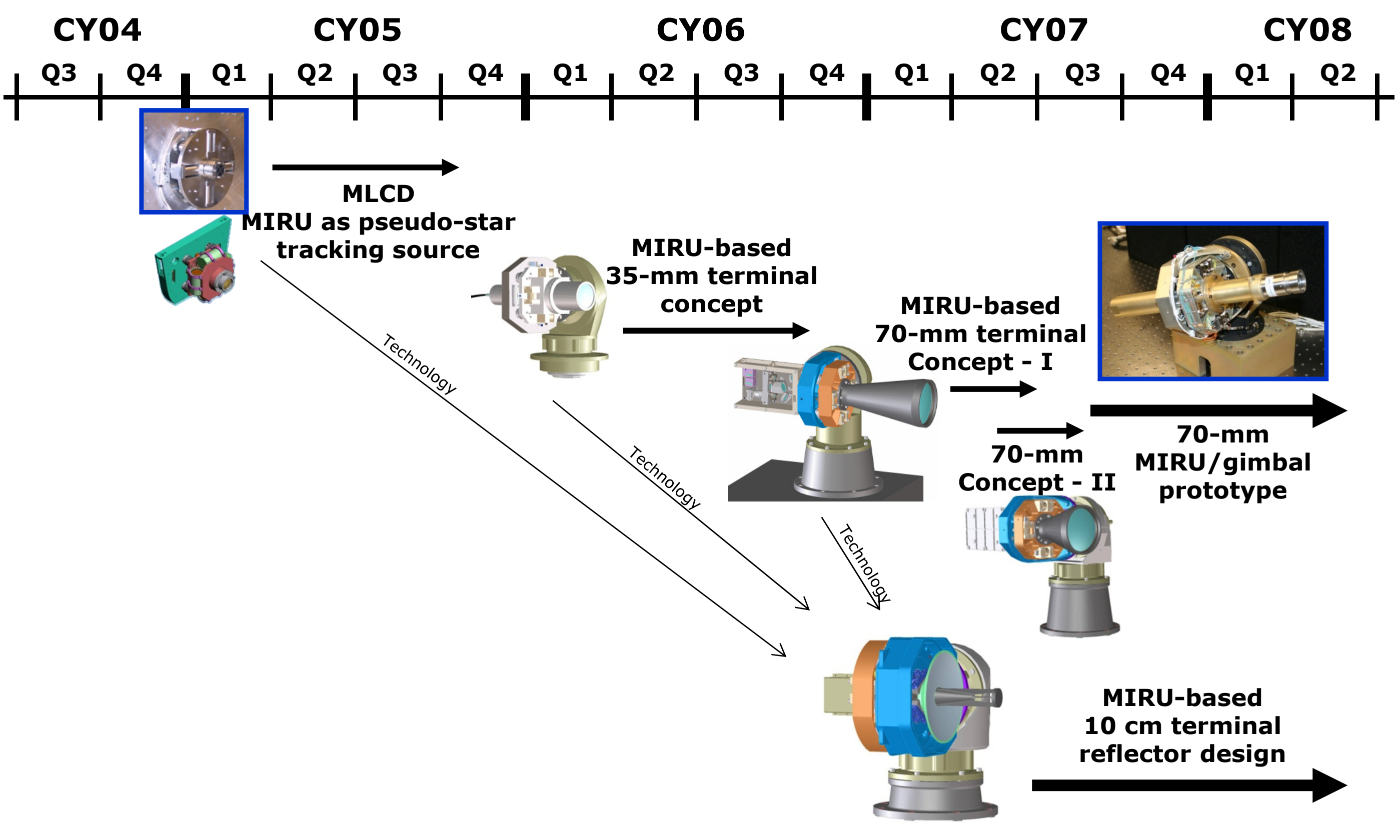

Figure 4. SCaN optical program background.

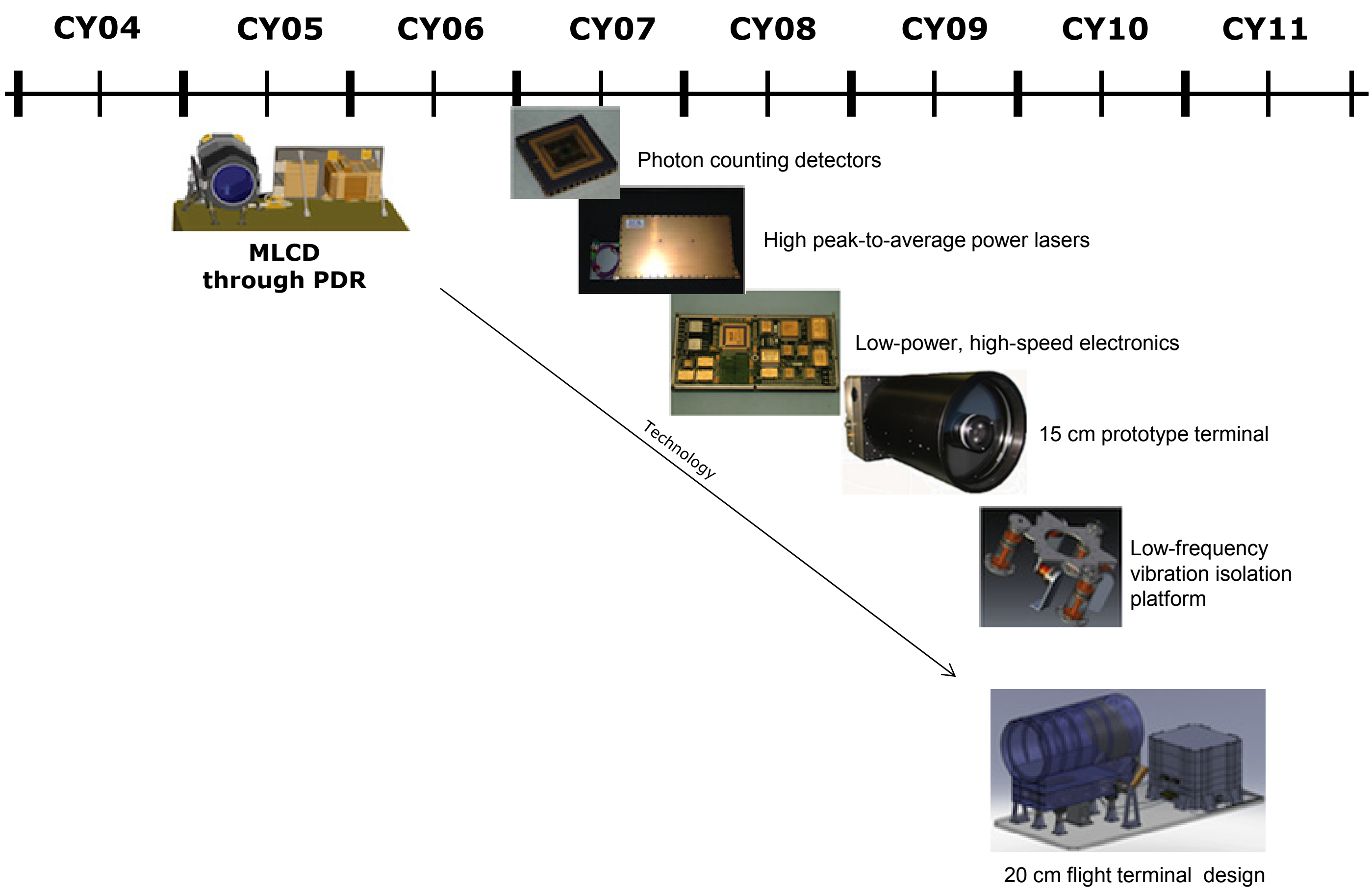

Figure 5. SCaN deep-space optical program background.

the obvious disappointment of two Mars flight opportunities that did not materialize, SCaN has no intention of giving up. For the foreseeable future SCaN will continue to apply its two-pronged strategy for optical communications capability: support the needed development activities, and conduct the requisite flight demonstrations.

The general development strategy is the same as has traditionally been employed for development of advanced RF capabilities. For the spacecraft end of the link, SCaN will sponsor the initial development activities for the relevant subsystems. These include detectors, lasers, electronics packages, prototype terminals (i.e., telescopes), vibration-isolation platforms, and integrated terminal design. Once these prototype activities are deemed successful, the idea is that production of systems and subsystems will migrate to private industry. User missions will eventually be expected to obtain their optical communications flight equipment from commercial providers.

For the Earth end of the link, SCaN will provide shared infrastructure, i.e., systems that can be utilized by any number of missions, just as the current RF networks are shared among a host of users. At the moment, the optical infrastructure is expected to comprise first experimental, then operational ground stations. Although the most obvious manifestation of these stations will be their large-aperture telescope facilities, bearing some likeness to astronomical observatories, they will also contain uplink lasers as well as a host of needed back-end and facility support systems. Current thinking assumes ground-basing for the Earth end of the link; however, space-basing has been, and may continue to be, considered.

Fig. 6 shows SCaN's strategic roadmap for development of optical communications. It starts with the Lunar Laser Communication Demonstration (LLCD), which will fly on the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft planned for launch in 2013. The LLCD flight terminal has heritage from MLCD, albeit with some differences. The system will be developed by MIT-LL, and will have a 10-cm aperture, with 0.5 W of laser power and operation at a wavelength of 1550 nm. It will implement beacon-aided acquisition and tracking using an Earth-based beacon collocated at the ground station. The baseline ground station is to be a portable terminal, also provided by MIT-LL, with arrayed aperture equivalent to that of an 80-cm monolithic telescope. JPL's 1-m-aperture OCTL is also being considered as a backup ground station, although with lower data-rate capability. Modulation and coding approaches are identical to those of MLCD. This system should support downlink rates of 622 Mbps from the Moon. Although the end-to-end system is quite a bit smaller than that postulated for MLCD, the data rates are much higher simply because of the difference in lunar and Mars link distances.

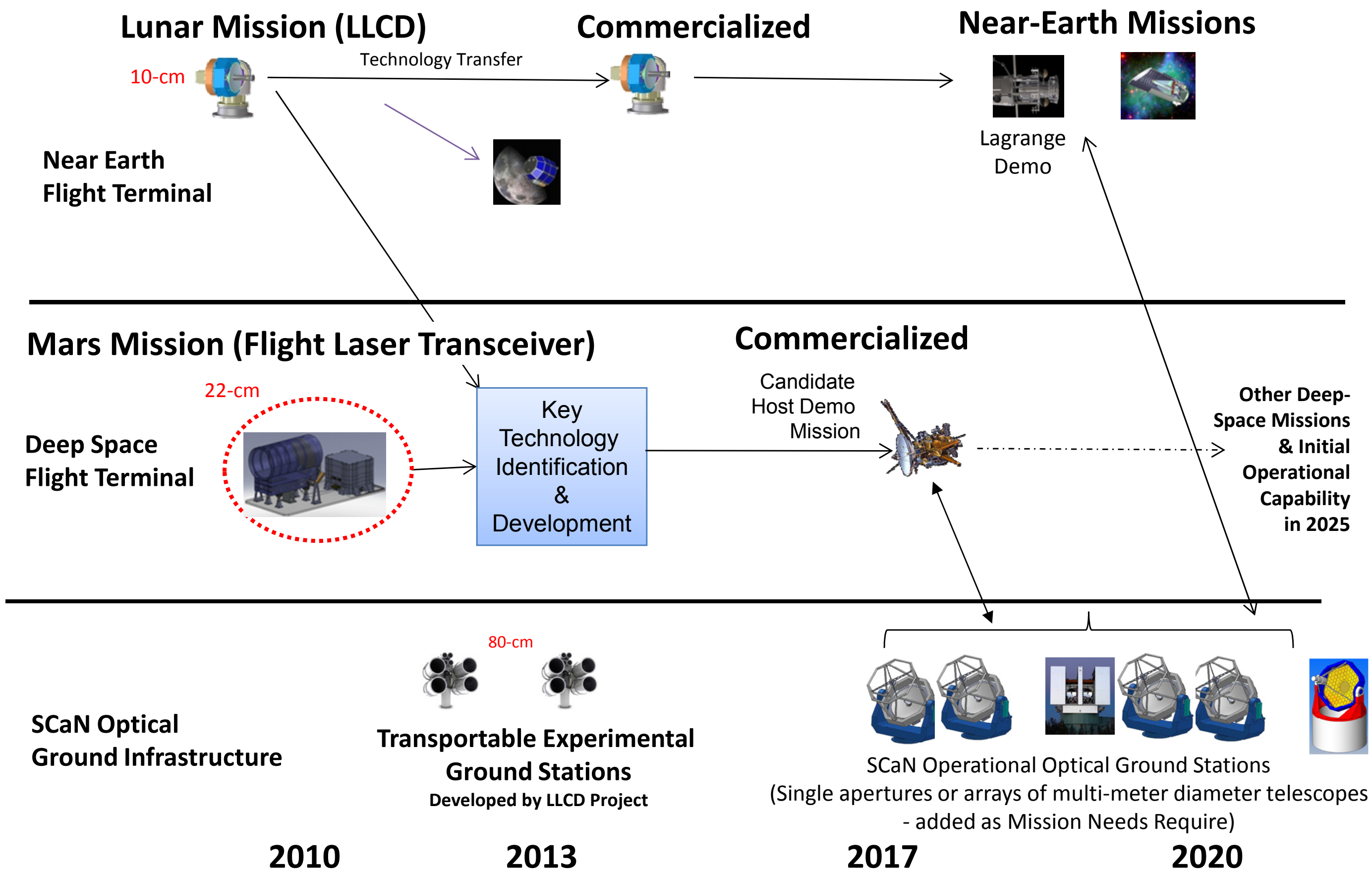

Figure 6. NASA strategy for optical communications development.

Following LADEE/LLCD, SCaN envisions notional demonstrations on missions to the Sun-Earth Lagrange points or otherwise deployed in near-Earth space. There are no current mission commitments for a deep-space demonstration, although SCaN will continue to pursue all potential opportunities as they arise. In the meantime, JPL has supported SCaN's roadmapping activity by conducting a pre-Phase-A study of an end-to-end system called Deep-Space Optical Terminals (DOT), comprising a Ground Laser Transmitter (GLT), Flight Laser Transceiver (FLT), and Ground Laser Receiver (GLR), plus additional elements. The study was characterized by formal traceability to SCaN requirements, the prime one being achievement of 10 times the MRO Ka-band downlink capability (267 Mbps) at equal or lesser user burden (38 kg, 110 W, 3-mrad pointing). Given the absence of an identifiable host platform, the study was directed to be non-mission-specific—albeit applicable to missions (most likely at Mars) that might fly circa 2018. The study generated a plan to retire risks so as to convince project managers of the readiness of the technology for future Mars missions.

For the GLT, the requirement is for a 200-kbps uplink at Mars minimum range (0.42 AU), along with a ranging signal. The best current point design favors an uplink wavelength of 1030 nm, along with a 1-m aperture using 5 kW average laser power and 20 "beams" on the aperture [18]. For the FLT, a major challenge is tracking a dim uplink beacon so as to adequately determine direction for the large-angle point-ahead downlink—due to extreme range, operational limitations on available uplink, and the Sun in the FLT's field of view (FOV) at low Sun-probe-Earth (SPE) angles. The terminal must operate with SPEs down to 3 deg and survive looking into the Sun. Efficient flight-qualified photon-counting detectors are needed to track the dim uplink beacon as well as a vibration-isolation system. High-peak-power flight-qualified laser systems are needed to maximize downlink rate. The best current point-design terminal is body-mounted with a 22 cm-aperture, 4-W-average and 640-W-peak laser power. The downlink signal is based on a 16–128 serially concatenated PPM with a maximum data rate of 267 Mbps. The FLT also supports 30-cm precision ranging. Finally, it should be compatible with numerous launch vehicles [19]. For the GLR, the driving requirement is for 267 Mbps downlink at Mars minimum range (0.42 AU). Link closure will require gain of 142 dB. The best current point-design terminal is one of approximately 12-m aperture, most likely with a segmented primary; however, an array of 2.2-m telescopes is considered a viable alternative. It has previously been shown that ground-based optical direct-detection arrays, where the array telescope diameters exceed the coherence length of the atmosphere, will have performance equivalent to that of a single-aperture receiver with the same total collecting area [20]. For early demonstrations, rented use of existing astronomical facilities,

TABLE II. SCaN's Top-Level Demonstration Objectives

Objective	LLCD	Lunar Lander	Sun-Earth L1	Sun-Earth L2	Mars
High Data Rate (10× RF)					
Pointing, Acquisition, & Tracking for Lunar/L1/L2					N/A
Pointing, Acquisition, & Tracking for Deep Space					
Daytime Reception at Ground Terminals					
Low-SEP Downlink Acquisition					
Low-SPE Uplink Beacon Acquisition					
Lifetime in Space					
Weather & Ground Station Handover					

most likely the Large Binocular Telescope (LBT) on Mt. Graham in Arizona, is suggested. Efficient photon-counting detectors will also be needed on the ground to maximize downlink rate. The downlink wavelength, planned to be 1550 nm, is considered "eye-safe" as well as being compatible with Department of Defense (DoD)– and industry-compatible developments. There also exists a low-rate requirement of 4 Mbps downlink at 5-deg and 3-deg Sun-Earth-probe (SEP) angles. Thus the GLR must be capable of looking angularly close to the Sun, notably when Mars is at its maximum range of 2.6 AU. The low-rate condition translates to a required gain of 124 dB. The low-rate link favors a dedicated 2.2-m aperture that will eliminate any need to point the LBT close to the Sun. In addition, this aperture could be an excellent element choice for an arrayed architecture [21].

With the DOT study as a guide, SCaN will work with industry towards its goal of flight system commercialization. SCaN will also continue to work with the NASA Field Centers on development of optical ground infrastructure. Fig. 6 shows the LLCD portable experimental stations evolving into an array of 2.2-m operational telescopes. Another option, not depicted, is a monolithic (or segmented) telescope of 10–12-m aperture. If the arrayed option is selected, it should have the potential to grow to the equivalent of the monolithic telescope.

The major immediate hurdle is that of flight demonstrations. These are needed in order to prove out the performance of the developed capabilities and to test their reliability in a real-world environment. Without the relevant flight demonstrations, mission managers will not choose optical communications as their baseline option. Their confidence must be gained by successful demonstrations.

Table II summarizes SCaN's optical communications risk-reduction objectives that will be the focus of a program of robust flight demonstration and validation. The rows list the critical capabilities that need to be validated. The columns show potential demonstration opportunities. The color-coding in the table addresses the degree of capability validation that can occur on the potential demonstration opportunities. Green indicates that a given opportunity will be able to validate a listed capability; red that the opportunity will be unable to validate the capability; yellow that the opportunity is currently thought to yield an ambiguous assessment.

The roadmap in Fig. 6 culminates with operational optical communications capability for NASA that provides reliable, high-rate optical communications services to our spacecraft. In order to accomplish this, SCaN will first focus on building a ground infrastructure that will provide a global capability with ground stations sited such that clouds and other atmospheric effects are dealt with through diverse station location. Realizing that other international space agencies are also interested in optical communications, and face the same issues relative to dealing with weather to provide reliable service, NASA is working with other interested space agencies to explore the potential of international cross-support. The Optical Link Study Group (OLSG) has been formed under the Interagency Operations Advisory Group (IOAG) to determine if interoperability of optical communications would be mutually beneficial to member agencies. The OLSG is cochaired by NASA and ESA. If it is determined that there is a case for interoperable cross support, the next task will be to determine the parameters that all spacecraft and ground stations should adhere to in order to implement this cross support potential.

V. Affordable Early Step 1: Single Optical Site Subnet Concept

As mentioned before, LDOS and COS architectures required multiple ground stations in order to ensure high availability (>95%) for the optical link. There are a number of concepts that are being investigated for the initial ground stations and their evolution into the reliable infrastructure mentioned above.

Past operational experience with spacecraft RF links has shown that the bandwidth provided by the optical link is most likely to be used for bulk science data that can typically tolerate long latencies. If latency is not an issue, a single optical site (SOS), along with adequate storage onboard the spacecraft and adequate link capacity, could be used to provide the main benefit of the optical link—namely its greater capacity—without the need for massive expenditures on infrastructure.

If maximizing data return is the primary objective, aggregating the photon-collecting capability at a single site is far more efficient than dispersing it in order to increase availability. The argument for this is as follows. Suppose we have five optical ground stations that could either be collocated or be dispersed among five locations with independent and identically distributed weather patterns. At each site a single ground station would have an availability of p and a capacity of C when the link is available. Under the COS or LDOS architectures, the spacecraft data rate does not exceed the capacity C; therefore the expected capacity of the link is

$(1-(1-p)^5)$ C. On the other hand, if all five stations are collocated, the spacecraft data rate could be increased to 5C (assuming that, for the optical array, the capacity would increase linearly with number of its elements); therefore the expected capacity of the link is 5pC. This is greater than the capacity of the dispersed architecture. For example, with $p = 0.6$, the expected capacity of the dispersed architecture is 0.99C whereas the expected capacity of the collocated stations is 3C.

It should be noted that even though the expected capacity of the SOS is greater than that of the dispersed architectures for the same collecting area, SOS has a much higher probability of unsuccessful transmissions than do the dispersed architectures. In order to alleviate this problem, a proper ConOps for SOS using retransmissions and addition of a medium- to high-rate X-band system to the spacecraft is needed. This ConOps was developed and its results were presented in [22]. Under the SOS ConOps, the spacecraft must carry an X-band system for reliable communication of spacecraft engineering data and time-sensitive science data needed for spacecraft science planning and operations. To this is added, of course, the optical telecommunications terminal plus adequate storage to accommodate successful transmission of bulk science. The spacecraft will transmit its bulk science data during its view period of the station over the optical link. The spacecraft will then be informed of what data packets were received correctly through the X-band uplink telecommand. Upon receipt of this acknowledgement, the successfully received data will be purged from the spacecraft's storage. The data that were not received successfully will be kept on board the spacecraft to be retransmitted over subsequent passes. Under this ConOps, data are lost only if the spacecraft storage is full as it collects new data. In such cases, either the spacecraft erases old (but not successfully received) data to make room for the new data, or the spacecraft discards the newly collected data depending on the priorities that the mission assigns to each.

Note that the requirement for the spacecraft to carry an X-band system is not much of a burden since an X-band link would be needed in any case for uplink telecommand and emergency-mode communications. The only additional expense for the RF system may be the need for adding a high-gain antenna to the spacecraft for enabling moderate- to high-rate communications on the RF system. If latency is not an issue, from the results of queuing theory it is obvious that in order to achieve negligible loss rates while achieving the maximum possible data return, the spacecraft needs to have large amounts of storage. If the required storage is prohibitively large or expensive, then the SOS architecture is not useful. This question was also answered in [22]. Based on this analysis, for optical data rates anticipated for missions over the next two decades, onboard storage required for SOS operations could typically be met with existing solid-state flash memory technology for 99% completeness. There is one exception, and that is at Jupiter, where the radiation environment makes radiation-hardened memory essential; for this case the cost and weight of the required storage is expected to be prohibitive.

There are still some open issues with regard to SOS operations. First is the issue of site selection. The SOS should be located in a place that has existing infrastructure and good weather in addition to proper coverage of the ecliptic. For proper site selection, atmospheric data from the candidate sites need to be collected, and link performance statistics from them need to be derived. In addition, the preliminary analysis performed in [22] was based on the independence of weather conditions from pass to pass. In reality, a single geographical location could have persistent bad weather over several days, which in turn could mean that the storage requirements for the spacecraft could be higher than those calculated in [22]. However, lacking adequate atmospheric data, this analysis cannot be performed adequately at this time. In all likelihood, the result of such analysis would indicate that the size of the storage on the spacecraft could be kept small by using two optical sites that are geographically separated such that the weather at each site is either uncorrelated or, better yet, anticorrelated with the weather at the other site.

Finally, it should be noted that a single optical site does not preclude eventual transition to a dispersed architecture. As additional stations are put in place, the ground optical network could transition from an operations concept tailored for an SOS to one applicable to a dispersed network. The result is that missions could reap the benefits of optical communications much sooner than they otherwise would if only a dispersed-network ConOps were allowed.

VI. Affordable Early Step 2: Combined RF-Optical Hybrid Ground Terminal

A second approach to early and affordable implementation of optical communications is also under investigation at JPL. This approach involves modification of existing 34-m DSN antennas, designed for X-band (8 GHz) and Ka-band (32 GHz), for reception of optical signals. Preliminary results [23] have shown promise that dual RF-optical communications may indeed be possible on the same ground terminal. Besides the operational and cost benefits that can result from dual use of the same aperture, such an approach may offer the utmost in network integration, also a current priority for the SCaN Office. DSN antennas being considered are characterized by robust backup structures, large collecting areas, and millidegree pointing capabilities, all of which support optical communications. Two candidate design concepts are under consideration.

The first concept involves modification of the inner 26-m-diameter portion of a 34-m antenna's main reflector, by polishing and coating the existing aluminum panels to a high degree of reflectivity. Although these RF panels are polished to optical smoothness, they must still operate with large FOVs due to underlying surface imperfections. The panels will generate large (several-cm-diameter) spots at the Cassegrain focus corresponding to a FOV of hundreds of microradians. Large-area photon-counting-detector arrays then convert the optical fields to photon counts for downstream digital processing. A solar energy filter over the main reflector protects the antenna from sunlight and the panels from dust.

The second concept, a more extensive redesign, replaces some panels with optical reflectors. In this concept the optical surfaces, which could be either monolithic or arrayed, would be equivalent in aperture to a traditional 10-m-aperture terminal.

This approach relies on high-quality glass mirrors that replace a fraction of the aluminum panels of the antenna. The intent is to achieve a much smaller optical FOV while still maintaining adequate RF performance. These mirrors will generate much smaller spots, typically limited by turbulence to approximately 50 microradians FOV. To reduce implementation cost, spherical mirrors could be used, given that the overall antenna focal length is large. As in the other concept, a solar energy rejection filter provides protection from heat and dust.

Factors most identified with optical receiver performance are collecting area, FOV, and the ability to point close to the Sun, i.e., immunity to reflected sunlight under realistic daytime conditions. A minimum SEP angle of 10 deg is specified, which corresponds to outages of approximately 30 days per year. A 3-degr SEP-angle limit reduces outage time to 10 days per year. To this list can be added the spatial and temporal acquisition algorithms for acquisition and tracking of the downlink laser. Naturally, the most appropriate metric to evaluate performance is data throughput at a given bit error rate (BER). Preliminary analyses indicate that optical data rates of hundreds of Mbps, perhaps approaching 1 Gbps from typical Mars distances (0.87–2.5 AU), may indeed be achievable. Link design assumes a wavelength of 1550 nm, a nominal spacecraft telescope diameter of 0.5 m, and average power of 20 W. The laser link employs PPM with four slots.

For either option, the ground receiver first undertakes spatial acquisition, in which its optical axis is coarse-pointed to the spacecraft and then fine pointed to center the laser signal over the detector array. Next, the receiver performs spatial tracking, wherein the position of the focused spot is monitored, with needed corrections applied for any noted drift. The receiver then proceeds to establish temporal acquisition, which synchronizes its clock with PPM slot boundaries. As above, tracking then corrects for any noted temporal drifts. Successful pointing and tracking operations then enable symbol-detection, which is, after all, the reason for the activity. All of these operations are dependent upon the quantity of photons collected (both signal and background), as well as their spatial and temporal distribution. The general idea is to collect signal photons and reject background photons by concentrating the signal energy into a small area in the detector-plane.

For the 26-m polished panel concept, analysis shows that at all but the closest distance considered, some form of error-correction coding will be necessary to achieve the required BER. Two codes are considered: a rate ½ (15120, 7558) serially concatenated convolutional PPM code, and a rate 7/8 (8176, 7154) low-density parity-check (LDPC) code currently proposed as a Consultative Committee for Space Data Systems (CCSDS) high-rate standard. The more powerful rate ½ code attains 7 dB coding gain over uncoded BER at error probabilities of interest to missions (BER = 10–6), whereas the rate 7/8 code provides 4 dB of coding gain. The rate 7/8 code requires an average of more than 16 photons to reach BER = 10–6. With only about 15 signal photons received at the greatest distance of 2.5 AU, this high-rate code does not support the required link BER of approximately 10–6. In this case, a lower code rate is used, at the cost of additional overhead. The threshold of the rate ½ code is less than 14 signal photons per pulse on the average in the high-background environment. Therefore this lower-rate code does achieve the required BER with a 26-m polished panel receiver even at the greatest distances considered.

Uncoded BERs for the 10-m glass mirror receiver are not as good as those of the 26-m polished panel receiver at any distance, despite much better optical surface quality. This is due to an 8.3-dB reduction in signal energy for the smaller aperture. However, since the background energy is also much less, given the better optics, coded performance remains acceptable at moderate distances. The threshold is approximately 5 signal photons on average for the rate ½ code and a little more than 8 photons for the rate 7/8 code, which means that acceptable performance can be achieved at intermediate distances of 1.25 AU or less with either code. However, if the less powerful rate 7/8 code was employed, then the required performance could not be achieved at distances much greater than 1.25 AU, since more than 8 photons would be required to reach the coding threshold, which is not feasible with the 10 m receiver.

Data rates in the range of hundreds of Mbps to 1 Gbps do appear feasible. The 26-m polished panel concept outperforms the 10-m glass mirror concept despite the latter's narrower FOV, since the larger aperture collects many more signal photons. Acceptable performance, with appropriately selected codes, can be achieved with either design.

VII. Summary

The justification for evolution towards a deep-space optical communications capability is abundantly clear. This is traceable primarily to ever-growing mission requirements for data rates as well as the spectrum needed to accommodate such rates. To this may be added a potential reduction in user-burden. RF communications still has some potential for growth. Although this potential is much more limited than it was a few decades ago, missions will nevertheless likely prefer to exploit it rather than make the riskier leap to optical communications. Ultimately, however, there will be no alternative to optical communications. In such an environment, communications engineers can pursue two strategies. First, they can continue to invest in technologies that will improve the performance, operability, risk, and cost of optical systems. Second, they can validate these technologies by conducting demonstrations in the relevant environments. This is the essence of the SCaN *Optical Communications Roadmap*. Part of this roadmap strategy is to explore novel operational concepts that have the possibility of lowering the cost of optical systems, in essence reducing the barrier to entry. This paper has described deep-space optical communications in its historical context as well as to offer some hopefully cogent thoughts about its future. If we, as communications engineers, are diligent and persistent, we should be able to launch this 21st-century communications capability on a developmental trajectory that is every bit as exciting and rewarding as the 20th-century RF developments that preceded it.

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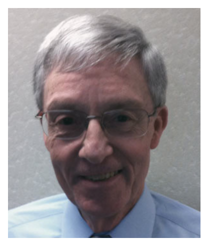

John Rush joined NASA at GSFC in 1986 and has worked on a number of NASA programs in the areas of communications and navigation. He began working on the second TDRS ground terminal while at GSFC and later became the Level II Avionics Manager for the Space Station Program where he managed the early prototyping of the avionics system currently flying on the International Space Station. In 1995 Mr. Rush joined the NASA Headquarters Office of Space Communication where he has focused on space communication system architecture and technology development. He has recently managed the Space Communication Architecture Working Group in the establishment of NASA's future space communication and navigation architecture. Mr. Rush received a B.S. in Physics from the Worcester Polytechnic Institute in 1969, and an M.S. in Computer Science from George Mason University in 1994. He is currently the manager of System Planning for the Space Communication and Navigation Office at NASA Headquarters.