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Preliminary Downlink Design and Performance Assessment for Advanced Radio Interferometry Between Space and Earth (ARISE)

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Advanced Radio Interferometry Between Space and Earth (ARISE) is a space very long baseline interferometry (VLBI) mission with a nominal launch date of 2008. It consists of an inflatable 25-m radio telescope circulating in a highly elliptical Earth orbit with a perigee of 5,000 km and an apogee of 40,000 km. The objective is to observe in conjunction with Earth-based telescopes to obtain high-resolution maps of quasars and active galactic nuclei for science investigations.

ARISE requires an 8-Gb/s downlink of science data, which is a challenge using today's technology. In this article, 8-Gb/s systems using both traditional radio frequency (RF) and laser communication are proposed with the goal of minimizing both the cost and the risk of the design. Either option requires appropriate technology investments. The RF system requires the use of dual polarization, high-order modulations such as 32-quadrature amplitude modulation (QAM), and spectrally efficient square-root raised-cosine (SRRC) filters to meet the Federal Communications Commission (FCC) spectral allocation. If additional bandwidth is allocated by the FCC, constant-envelope modulations such as cross-correlated trellis-coded quadrature modulation (XTCQM) can be used in place of SRRC filters and QAM to reduce the power required on the spacecraft. The proposed laser communication system uses on–off keying (OOK) and wavelength division multiplexing (WDM). The wavelength of 1550 nm has the advantage of lower background light subtended at the ground receiver for downlink communications. The critical components of the system are based on mature fiber-optic technologies. The downlink transceiver terminal will be a modified Optical Communications Demonstrator (OCD) that has been in development at JPL over the past 3 years.

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This article includes a road map on how the 8-Gb/s RF and laser communication systems can be developed with a series of demonstrations between now and the launch date. The demonstrations are needed to verify technologies and to raise the confidence level of the designs. With the completion of the demonstrations, both the RF system and the laser communication systems can be deployed with relatively low risk.

I. Introduction and Background

The Jet Propulsion Laboratory (JPL) has completed a feasibility study for an aggressive space very long baseline Interferometry (VLBI) mission—Advanced Radio Interferometry Between Space and Earth (ARISE)—with a nominal launch date of 2008. It consists of an inflatable 25-m radio telescope circulating in a highly elliptical Earth orbit with a perigee of 5,000 km and an apogee of 40,000 km. The objective is to observe in conjunction with Earth-based telescopes to obtain high-resolution maps of quasars and active galactic nuclei for science investigations. The resulting observations potentially could produce images up to 5,000 times better than images provided by the Hubble Space Telescope. The proposed mission is part of a series of space VLBI missions, following the VLBI Space Observatory Program (VSOP), RadioAstron, and VSOP 2, with VSOP 2 scheduled for 2006.

One of the specific requirements for space VLBI missions is to correlate the data gathered by the space telescope with the corresponding data produced at the ground stations. The wideband high-data-rate downlink from the spacecraft to a ground station has been identified as one of the critical technologies that warrant special attention. JPL's Space and Earth Science Program Directorate (SESPD) and Telecommunications and Mission Operations Directorate (TMOD), in preparation of the *Astronomy Decade Report* to the Astronomy Survey Committee, have agreed to submit the ARISE mission for consideration. The submittal will include the spacecraft and supporting ground resources, including tracking stations worldwide, that can support up to 8-Gb/s data rates from a maximum distance of 40,000 km.

This article, based on an in-depth study prepared for SESPD and TMOD,[4] concentrates on the telecommunication design options for delivery of 8-Gb/s science data from the spacecraft to a ground station. Section II describes the telecommunication design options. Both traditional radio frequency (RF) systems and laser communication systems are discussed. Either option requires appropriate technology investments. However, they can be relatively low risk with the completion of a series of demonstrations. Section III describes the road map of how the two options can provide the 8-Gb/s downlink for ARISE, with intermediate demonstrations presented. Section IV provides the summary.

II. Telecommunication System Design

The scientific requirement of delivering 8 Gb/s of data from the spacecraft to a ground station presents technical challenges for telecommunications design. Section 2.A briefly summarizes the mission requirements imposed on the telecommunication system; Section 2.B describes the downlink options using RF at a 37- to 38-GHz band; and Section 2.C describes the downlink options using laser communications. Sections 2.B.3 and 2.C.3 describe the technology readiness for each option.

A. Requirements

Besides the 8-Gb/s downlink requirements for science data, the ARISE mission must include two-way Doppler measurements and accurate time stamping of data. Sending and receiving 2-kb/s command and

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[4] T.-Y. Yan, C. C. Wang, A. Gray, H. Hemmati, A. Mittskus, N. Golshan, and M. Noca, *ARISE Telecommunication Design Study Report* (internal document), Jet Propulsion Laboratory, Pasadena, California, December 1998.

telemetry data between the spacecraft and a ground station can be accomplished using a transponder at 8 GHz (X-band) in addition to the 8-Gb/s downlink transmitter. Both the Small Deep Space Transponder (SDST) designed and developed by Motorola for the Deep Space One (DS1) mission and the currently in-design Spacecraft Transponding Modem (STM) could perform the desired command and telemetry functions. This article will focus on the delivery options of 8 Gb/s.

1. Data Delivery Requirements. Space VLBI missions typically generate monumental amounts of science data that must be delivered to a ground station for processing and distribution. The required data throughput for ARISE is specified at 8 Gb/s. Data volume generated at the spacecraft prohibits the use of recording devices onboard the spacecraft and, therefore, must be downlinked to data recorders on the ground. Due to white-noise-like characteristics of the data and the 10^{-3} error rate of the high-speed data recorder, the bit-error-rate requirement for the 8-Gb/s downlink is set at 10^{-4} so that errors caused by the communication system do not significantly degrade the science data.

2. Spacecraft Requirements. This article assumes that there will be sufficient isolation between the observing radio telescope and the downlink transmitter for both RF and optical options. One unique problem of the RF option is the cross-coupling of the 1.2-m high-rate downlink antenna and the 25-m inflatable antenna. The downlink frequency of 37 to 38 GHz is very close to two of the ARISE observation bands at 43 GHz and 22 GHz. The transmitted signal of the telecommunications system is many orders of magnitude larger than the observed signal at 43 and 22 GHz, and the transmit power spectrum of the telecommunications system may not undergo sufficient attenuation at these frequencies. Cross-coupling of the transmitted signal to the 25-m antenna can contaminate the signal in the observed bands. Judicious placement of the antennas and the use of absorbing material and other techniques need to be examined in detail. Interference between the optical downlink wavelength of 1550 nm and the 25-m telescope is assumed to be negligible. The pointing control of the spacecraft at 50 arcsec and the stability of 0.03 arcsec/s for science requirements are assumed to be sufficiently stable for both RF and optical communications.

3. Ground Requirements. Currently, JPL operates a ground network of 11-m stations for VLBI missions. This article assumes the existing ground network for RF downlink. A separate study currently is being conducted by the Space VLBI Program Office for the upgrade of 11-m stations from 13 GHz (Ku-band) to 37–38 GHz (Ka-band). The station front end is assumed to have adequate bandwidth for down-converting the wideband signals for subsequent demodulation to baseband.

At present, NASA does not have an infrastructure for receiving Earth-orbiting or deep-space optical signals. JPL will begin construction of a 1-m telescope at the Table Mountain Facility near Wrightwood, California, that is scheduled for completion in 2000. For optical communications, a total of three 1-m ground stations separated by at least 500 km would provide both coverage of the spacecraft for downlink reception as well as spatial diversity for weather conditions. A preliminary site selection has included receivers in Hawaii, Southern California, and Mount Lemmon, Arizona. Based on the current spacecraft inclination of 32 deg and ground-receiver stations in Hawaii, Southern California, and Arizona, the estimated observation times for the ARISE spacecraft from these stations over a period of 3 days are 17, 18 and 22 hours, respectively.

B. RF Communications

This section first describes the conceptual design that could satisfy the data delivery requirement within the 37- to 38-GHz allocation. RF communications between Earth-orbiting satellites and ground stations represents a mature combination for transmitting science data. Section 2.B.1 describes the design constraints and the technical approach. Section 2.B.2 compares the two classes of modulation schemes that could be used as interim demonstrations. The first class includes constant-envelope or quasi-constant-envelope modulations that allow the use of fully saturated amplifiers with good power efficiency. The second class of modulation uses less spectrum but requires the use of linear amplifiers that are less power efficient. The system design is compatible with the current 11-m ground station. Section 2.B.3 discusses the technology readiness level of the design.

1. Conceptual Design. This section describes issues related to frequency management, the effect of propagation on the telecommunications design, and the overall system block diagram for the spacecraft terminal.

The Federal Communications Commission (FCC) has allocated the spectrum of 1 GHz between 37 GHz and 38 GHz for space VLBI missions. Of the 1-GHz allocation, 500 MHz is designated as primary use, and the rest of the 500 MHz is for shared use. ARISE possibly could petition to the FCC for an exemption to use the spectrum between 38 GHz and 39.5 GHz. This article describes technologies to downlink 8 Gb/s of data with and without this extra 1.5-GHz spectrum. However, in the event that this spectrum becomes available, requirements on the spacecraft power as well as technical or programmatic risks would be reduced substantially.

Figure 1 shows the spectral mask currently considered by the Space Frequency Coordination Group (SFCG) for missions after 2002. (In the figure, PCM denotes pulse-code modulation and PM phase modulation.) Given this spectral constraint and the requirement of downlink at 8 Gb/s, it is evident that transmitting using dual polarization and a spectrally efficient modulation are required. In the ARISE RF telecommunication system design, both left-handed circular polarization (LHCP) and right-handed circular polarization (RHCP) will be used within the allocated spectrum. There are no regulation or bandwidth restrictions for optical frequencies.

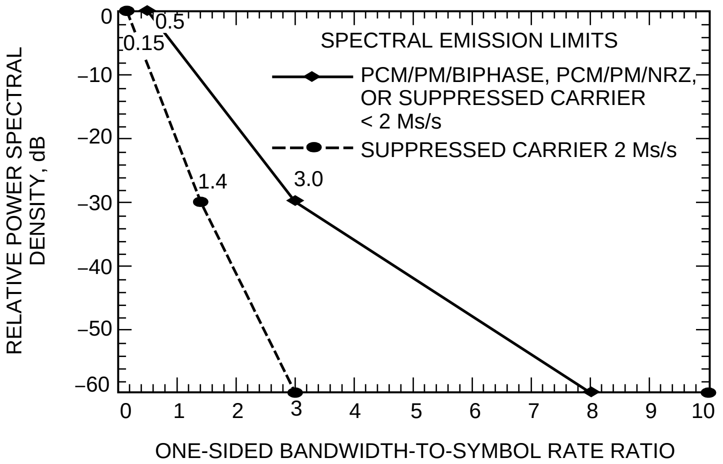

Fig. 1. The spectral mask currently considered by SFCG.

Propagation of RF signals through the atmosphere suffers from space loss. In addition, an effect called depolarization, which is caused by nonspherical water droplets in the atmosphere distorting the orthogonal polarization of electromagnetic fields by different amounts, could cause cross-coupling of one channel onto the other and produce interference and cross-talk. NASA has collected a significant amount of propagation data at Ka-band. Using the empirical formulae derived from the data collected at 27 GHz and scaling the attenuation values by the square of the operating frequency, the atmospheric attenuation is predicted to be less than 5 dB for 95 percent weather availability. Furthermore, the depolarization cross-coupling is no more than −33 dB at Goldstone, California, for an average year at an elevation angle of 30 deg.

As mentioned earlier, this article assumes the availability of 11-m ground stations for RF downlink. A separate study is being conducted to assess the complete ground operating and front-end cost. The telecommunication design follows the convention that science data are provided to the modulator (MOD) in the non-return-to-zero (NRZ) format. The 8-Gb/s data are transmitted using dual polarization—each polarization carries up to 4 Gb/s of data, as shown in Fig. 2. The 4-Gb/s data are divided into four 1.024-Gb/s streams that are compatible with the VLBI recorder data rate. The data then are modulated on four carriers spaced so that the resulting spectrum does not overlap. The signals then are summed, amplified, and fed to the spacecraft antenna, which also accepts the signal of the other polarization. At the receiving ground station, the orthogonal polarizations are separated, passed through a low-noise amplifier (LNA), and then downconverted (D/C) from RF signals to an intermediate frequency (IF) signal. The IF signal then is filtered by a bank of bandpass filters (BPFs), each tuned to the appropriate frequency. The demodulators (DEMODs) will process the IF signal to baseband to recover the digital data. Frequency-domain multiplexing (FDM) allows the modulator and the demodulator to run at 1.024 Gb/s instead of 8 Gb/s, reducing the development risk of the system. The combination of the modulator and the demodulator determines the end-to-end performance and the spectral occupancy of the telecommunication system. This article addresses the modulator, power amplifier, and demodulator for ARISE. Modifications required to bring the front end of the 11-m ground station will be addressed separately.

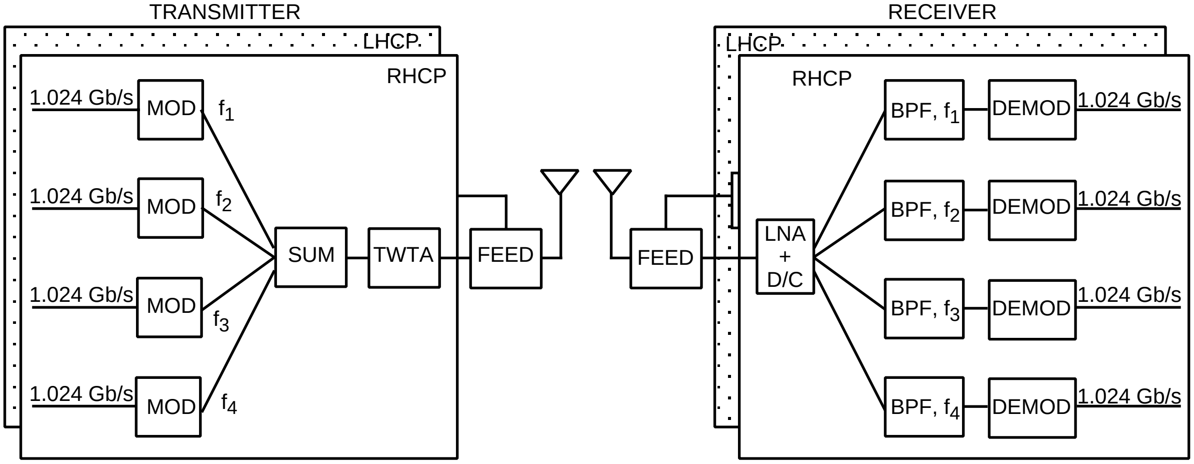

Fig. 2. The functional block diagram of a spacecraft transmitting terminal.

2. Modulation Schemes. This section compares the relative merit of two classes of modulation schemes. The choice of either modulation depends on the outcome of the petition to the FCC for additional downlink spectrum. Theoretically, the minimum required RF bandwidth for transmitting a signal with rate-W symbols per second (s/s) through a linear channel is W Hz. However, this requires an infinitely sharp bandpass filter, which does not exist in practice. Raised-cosine filters with excess bandwidth ranging from 0.25 to 0.5 often have been used to produce intersymbol interference (ISI)-free sampling points under linear assumptions [1]. Square-root raised-cosine (SRRC) filters have been widely implemented in transmitters and receivers for their spectral efficiency. Unfortunately, this performance cannot be extended to nonlinear channels. The two classes of modulation techniques discussed in this section present trade-off alternatives in terms of direct current (DC) power efficiency and spectral efficiency. First, we discuss the constant-envelope or quasi-constant-envelope modulations that use fully saturated amplifiers for power efficiency; then we describe modulations that use much less spectrum, but require the use of less power-efficient linear amplifiers; and then we summarize the trade-off in a power-versus-bandwidth comparison chart.

The recently released Consultative Committee for Space Data System (CCSDS) Phase 3 *Efficient Modulation Methods Study* [2] discussed a number of suppressed-carrier modulation schemes that can meet SFCG spectral emission limits [2]. The study has focused on constant-envelope or quasi-constant-envelope modulations with fully saturated amplifiers. The objective was to retain power efficiency for space applications to minimize spectral regrowth after nonlinear amplifications. Representative modulation schemes discussed in the report include binary-phase-shift keying, non-return-to-zero data format (BPSK/NRZ); binary-phase-shift keying, Manchester-coded data format (BPSK/Bi-ϕ); quadrature-phase-shift keying (QPSK); offset QPSK (OQPSK); minimum-shift keying (MSK); Gaussian MSK (GMSK); 8-phase-shift keying (8-PSK); and Feher-patented QPSK (FQPSK).

It has been shown that the frequency spectrum of unfiltered traditional BPSK, QPSK, OQPSK, and 8-PSK rolls off very slowly, particularly with nonideal data [2]. Such systems produce a transmitted RF spectrum with significant energy at frequencies many multiples of the data rate from the carrier frequency. Filtering with Butterworth filters provides the most cost-effective approach for nonlinear channels. Usage of SRRC filters was not considered due to envelope fluctuation after filtering. The more spectrally efficient modulations, such as GMSK and FQPSK [3,4], also were included in the study. GMSK is a continuous phase modulation (CPM) that is widely used in the digital wireless global system for mobile (GSM) cellular systems with noncoherent receivers. It has not received similar attention in space-based communication links because the spacecraft typically are power constrained, and coherent demodulation requires sophisticated receivers that are more complex than traditional receivers.

Feher-patented QPSK (FQPSK) [3], a proprietary waveform-coded OQPSK scheme, has been selected by the Department of Defense (DoD) joint services Advanced Range Telemetry for future device procurements. JPL has been evaluating this modulation scheme and has developed an optimal receiver structure. The modulation has demonstrated well-behaved spectral efficiency for both linear and saturated amplifiers [4]. Recently JPL has developed a class of quadrature modulation schemes called cross-correlated trellis-coded quadrature modulation (XTCQM) [4]. It encompasses FQPSK as a specific embodiment and provides the ability to demodulate FQPSK signals with minor modifications to traditional QPSK receivers. These pulse-shaped modulations, while not constant envelope, generate modulated waveforms that are close to constant envelope and have the property of having very limited spectral regrowth even when passed through nonlinear amplifiers. Figure 3 illustrates the power spectral density of an implementation of XTCQM that meets the SFCG spectral emission mask. Since FQPSK is a specific realization under XTCQM, the rest of the article will not distinguish FQPSK from XTCQM.

To accommodate the 8-Gb/s downlink using XTCQM, a total of 4 GHz of spectrum is required using dual polarization. The 99.9 percent power containment of XTCQM occurs at approximately W Hz, where W is the NRZ data rate, resulting in a spectral efficiency of 1 b/s/Hz for each polarization. Unless the FCC is willing to allocate the necessary bandwidth, constant-envelope modulations with fully saturated amplifiers do not appear to be valid options for ARISE. However, XTCQM is a viable alternate for

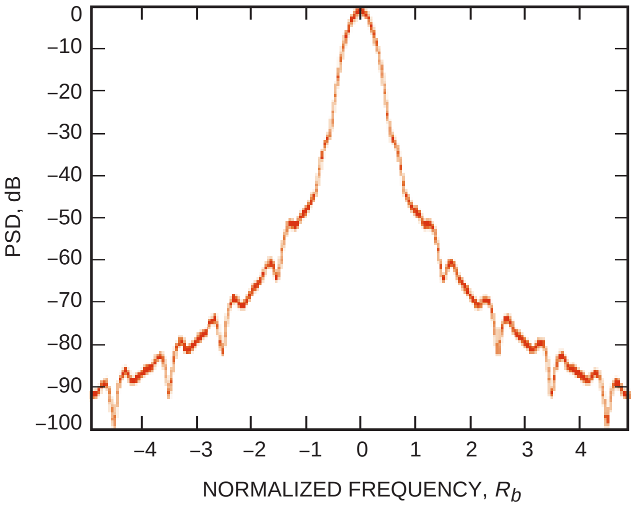

Fig. 3. The power spectral density of XTCQM.

VSOP 2 due to its low power consumption and technological risk. In the event that ARISE could settle for a lower data-delivery requirement, XTCQM represents an excellent choice for the downlink delivery mechanism.

Higher-order modulation schemes, such as M-ary quadrature amplitude modulations (M-ary QAM) and M-ary phase-shift keying (M-ary PSK), traditionally are considered to be power inefficient for satellite communications when M exceeds four [5]. These modulations often use SRRC filters to counteract the adverse affects of ISI as well as to provide improved bandwidth efficiency [1]. QAM is not a constant-envelope modulation, but standard M-ary PSK is. However, when PSK signals are generated by quadrature modulations followed by SRRC filters, the filtered signal can no longer be constant envelope.

In general, QAM-type modulations require higher average power than that required for constant-envelope modulations [6,7]. This is due to the requirement that the amplifier in the transmitter operate in the linear region and not the more power-efficient saturation region. Furthermore, when SRRC filtering is used, the peak-power requirement of the amplifier at the transmitter must be increased to maintain linearity. It has been shown that M-ary QAM has better spectral efficiency than M-ary PSK when M is greater than or equal to eight. Therefore, only QAM will be addressed in this article [1,5,8,9].

QAM has found widespread use in terrestrial communications both in wireline modems and wireless microwave links [6,7]. Various techniques have been developed to improve the performance of QAM. Trellis-coded modulation (TCM) as well as predistortion and distortion compensation that allow the transmitter amplifier to operate partially in the saturation region have shown promising results [5,8,10–14]. Such improvements could provide gains of between 1 and 6 dB in power efficiency. Many such improvements have not been validated in hardware, and, in most cases, all such improvements increase processing complexity and are often system dependent. This article assumes that these technologies are in the development stage and will be considered when the technologies become more mature. Therefore, we include no such performance gains in the link budget or bandwidth-versus-power comparisons.

In order to obtain the 8-Gb/s rate, using SRRC filters with excess bandwidth of 0.25 and dual polarization, a spectral efficiency of 3.2 b/s/Hz can be achieved for QPSK (or 4-QAM) using a 10-W power amplifier per polarization.[5] A spectral efficiency of 6.4 b/s/Hz can be achieved for SRRC-filtered 16-QAM using a 25-W amplifier per polarization and 8 b/s/Hz for 32-QAM using a 49-W amplifier per polarization. Figure 4 shows a sample constellation at a bit-error rate (BER) of 10^{-4} of 16-QAM and the corresponding spectral occupancy.

Figure 5 summarizes the bandwidth-versus-power performance for the candidate modulation schemes discussed previously in this section for the 8-Gb/s downlink. In contrast to the commonly used null-to-null main lobe of the power spectral density (PSD) as the spectral efficiency measurement, a more stringent 99.9 percent power containment as the efficiency measure. The vertical axis of power amplifier DC power makes use of the assumption that fully saturated amplifiers are 60 percent efficient, as opposed to the 30 percent efficient linear amplifiers. As shown in Fig. 5, XTCQM requires 4-GHz of bandwidth and is the most power-efficient scheme. The SRRC-filtered QPSK (or 4-QAM) requires 2.5 GHz of bandwidth. However, this scheme depends on the assumption that the FCC potentially could allocate an additional 1.5 GHz between 38 GHz and 39.5 GHz. The SRRC-filtered 16-QAM requires 1.25 GHz of bandwidth, and the SRRC-filtered 32-QAM requires 1 GHz of bandwidth. The SRRC-filtered M-PSK schemes are not considered due to their higher power requirements and less than impressive bandwidth efficiency.

Currently, all four modulation schemes are being used in one form or another for terrestrial communications systems at far lower data rates than 8 Gb/s. However, the use of them for satellite communications is limited. Therefore, each modulation poses specific risks that must be assessed based on current developments in telecommunication hardware. The following section discusses the technology readiness level of three major components—the modulator, demodulator, and power amplifier.

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[5] Ibid.

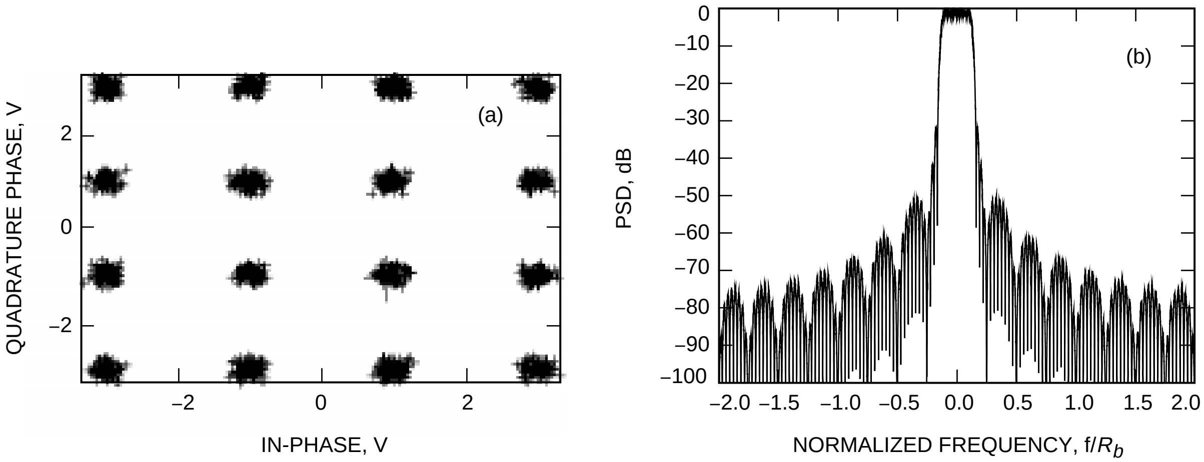

Fig. 4. A constellation of (a) 16-QAM and (b) the corresponding spectral occupancy at a bit-error rate of 10^{-4}.

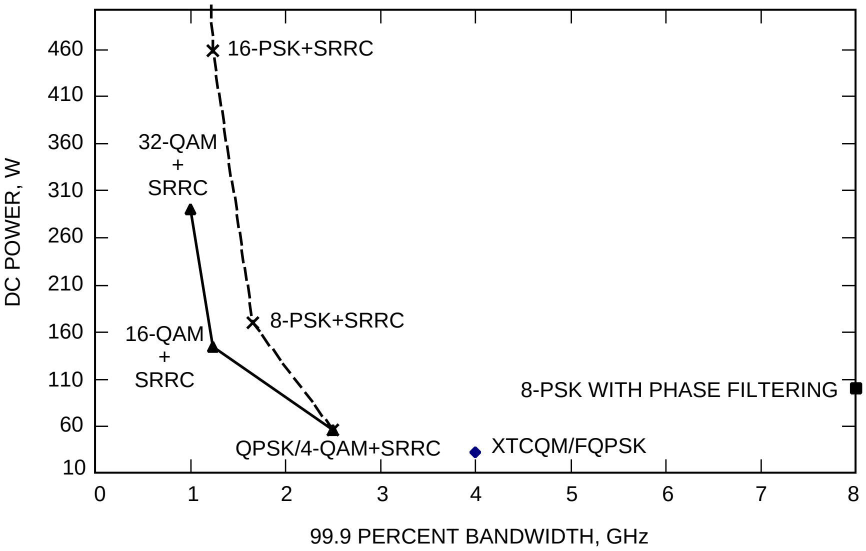

Fig. 5. A comparison of DC power and bandwidth at 8 Gb/s with dual polarization for various modulation schemes.

In general, risk increases as the allocated bandwidth decreases. Therefore, the most prudent approach is XTCQM followed closely by QPSK (or 4-QAM). Both modulations are based on tried-and-true QPSK systems. XTCQM can be operated with power amplifiers at saturation mode while SRRC-filtered QPSK requires linear amplifiers. In contrast, both 16-QAM and 32-QAM modulations with SRRC filters represent higher risk because of the requirements of high power linear amplifiers at 25 W and 49 W, respectively.

3. Technology Readiness. The ARISE mission requirement of 8-Gb/s downlink within a 1-GHz bandwidth at Ka-band presents technical challenges for both transmitters and receivers. From previous discussions in Section II, it is evident that SRRC-filtered 32-QAM modulations with linear amplifiers could meet the spectral containment while other techniques such as SRRC-filtered 16-/4-QAM and XTCQM are valuable interim alternatives if there is additional bandwidth or if the downlink data rate is lower. This section discusses technology readiness in general and in detail for the modulator, demodulator, and power amplifier.

In 1996, JPL conducted a 6-month study to identify cost-effective approaches to upgrade Deep Space Network (DSN) stations for future higher-rate telemetry.[6] Two industrial contracts were awarded—to TRW Inc.[7] and Lockheed Martin Western Development Laboratory[8]—for a comprehensive investigation. Both results indicated that, for data rates in excess of 100 Mb/s to the low Gb/s, OQPSK, 8-PSK, and QAM at Ka-band represent the most reasonable modulation choices. However, little attention was paid to spectral containment in these studies. It also is evident from these reports that reproduction costs for individual receiver units are prohibitively high.

Since then, for the past 2 years, JPL has been collaborating with NASA's Goddard Space Flight Center (GSFC) to develop a flexible high-data-rate all-digital demodulator for the upcoming Earth Observation Satellite (EOS) missions. The purpose is to replace conventional analog and hybrid high-rate receivers operating in the 10- to 600-Mb/s range [15,16] by digital signal processing to significantly reduce the recurring engineering cost through very large scale integration (VLSI) and subsequent application-specific integrated circuit (ASIC) development. Although this does increase the initial nonrecurring cost, the resulting ASIC makes desktop high-rate receivers commercially available in the coming years.

For high-rate communications on the order of hundreds of Mb/s, conventional serial digital processing requires gallium arcsenide (GaAs) technology to achieve the necessary processing rates. Unfortunately, GaAs has the disadvantages of high power consumption, heavy cooling requirements, and relatively low density of transistor capacity per unit area. Parallel architectures enable the use of slower electronics in complementary metallic oxide semiconductor (CMOS) to process high-rate applications [17]. They also take advantage of frequency-domain processing rather than the conventional time-domain approach. NASA currently has a patent pending [18] for the parallel algorithms jointly developed by JPL and GSFC. The algorithms allow the demodulator to be operated in 75-MHz CMOS technology and can demodulate data rates ranging from 600 Mb/s down to a few hundred Kb/s using BPSK, QPSK, OQPSK, and other variations of the pulse-shaped QPSK modulation scheme for spectral efficiency. Figure 6 shows the prototype demodulator tested in the laboratory. GSFC is on contract with Atmel Inc. to produce the final ASIC operating up to 600 Mb/s. The ASIC is scheduled for delivery by the second quarter of 1999. A description of the ASIC can be found in [15,16].

The production demodulator ASIC will perform all the functions of a traditional BPSK/QPSK demodulator, including carrier and symbol-timing recovery, using a single CMOS ASIC. It offers

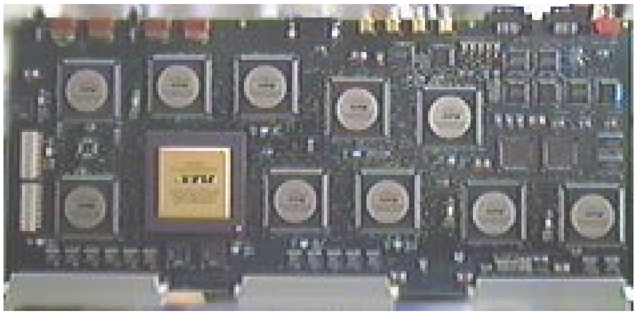

Fig. 6. The prototype quadrature digital demodulator.

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[6] Current DSN Block V receivers are limited to a 2-Mb/s uncoded-telemetry downlink.

[7] TRW, *Final Report on High Speed Data Transmission Technologies Study*, JPL Contract 960667, Redondo Beach, California, February 11, 1997. The report is TRW proprietary, and information from it may not be divulged to the public without prior permission.

[8] Lockheed Martin Western Development Laboratories, *Final Report on High Speed Data Transmission Study*, JPL Contract 960637, San Jose, California, February 1997. The report is Lockheed Martin proprietary, and information from it may not be divulged to the public without prior permission.

flexibility in selection of modulation schemes, reliability due to size and power reductions, and significantly reduced reproduction costs. It is estimated that the current design has utilized the maximum necessary parallelization of processing given current technology growth rates of GaAs, analog-to-digital converters (ADCs), and CMOS hardware. In addition, if speed growth rates of GaAs, ADCs, and CMOS continue as they have been for the past decade, the current modulator and demodulator algorithms could be reimplemented in the future using state-of-the art digital hardware to achieve higher data rates. The 1-Gb/s data rate for XTCQM or SRRC-filtered QPSK could be achievable by 2002 even if GaAs and CMOS growth rates per year for the next 3 years are half of what they have been for the past several years.

The joint JPL–GSFC-developed all-digital high-rate receiver is capable of demodulating data rates in excess of 600 Mb/s for near-Earth satellite communications. The core component of the receiver is a demodulator ASIC that will be available by the second quarter of 1999. Figure 7 shows the preliminary fixed-point software simulations based on hardware design language (HDL) for ASIC code at JPL. It demonstrates that this ASIC could demodulate XTCQM with performance equal to or better than that of current commercial-off-the-shelf (COTS) receivers. The ASIC has the flexibility of accepting an external processor to perform the custom processing necessary for M-ary QAM and M-ary PSK. The VSOP or VSOP 2 demonstration will be developed based on this ASIC.

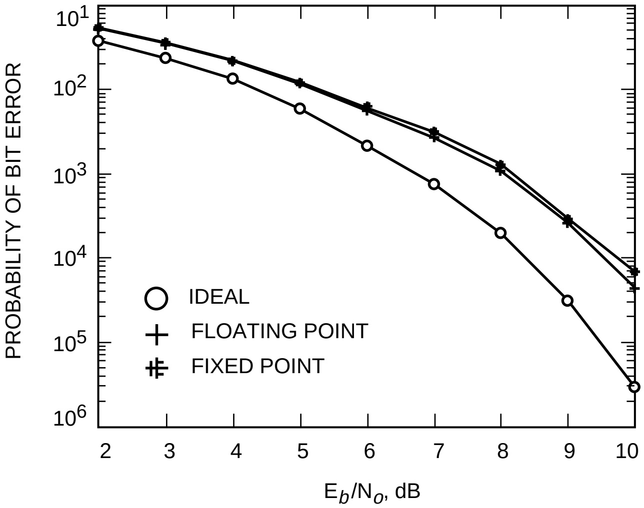

Fig. 7. Performance simulation of XTCQM using the JPL/GSFC ASIC.

Traditionally, the demodulator is more complex to develop and implement than the modulator. To implement a demodulator in GaAs with all of its complex functionality likely would require multiple ASICs, which translates to multiple one-time development costs for each ASIC. Since the construction of a digital SRRC filter at 500 Ms/s (or 1 Gb/s) is virtually identical for both the modulator and demodulator, they suffer from the same development risk. This being the case, the extensive work that has been accomplished in high-rate signal processing for QPSK and XTCQM by JPL–GSFC appears to be the foundation on which to build the higher-rate communications systems needed for ARISE [1,19–24].

SRRC-filtered QPSK (4-QAM), 16-QAM, or 32-QAM modulations require power amplifiers with peak linearity characteristics. Both solid-state power amplifiers (SSPAs) and traveling-wave tube amplifiers (TWTAs) are available options to deliver the final transmitter amplification. Due to the downlink power requirement, at present, SSPA is not a reasonable option. Low-power SSPA transmitters (~1 W) at high Ka-band are in development to support the terrestrial point-to-point spectrum allocation at 38 GHz. Final products will be several years away and will not fill the need for the link as budgeted. A TWTA would be a more viable baseline.

Currently, NASA Lewis research Center (LeRC) is developing a 20- to 30-W TWTA at 32 GHz for deep-space Ka-band downlink applications. Extending the same technology to the higher frequency band between 37 to 38 GHz appears to be reasonable and requires some engineering effort. Preliminary study at JPL indicated that, by allowing the amplifier to operate partially in the saturated region, the peak linearity requirement on the TWTA could be relaxed. At present, a 25-W average with 30 percent efficiency amplifier operating at a 3- to 4-dB back off is feasible within the 37- to 38-GHz band. The amplifier would require approximately 83 W of DC power from the spacecraft bus and represents minimal development risk.

As mentioned earlier, there are many ways to further enhance the performance of the QAM-type modulation scheme for space communications by slightly alternating the constellation or by choosing different degrees of back off. The main objective is to reduce the peak-power linearity requirement on the power amplifiers. Figure 8 shows the effect of backing off the peak power on BER performance. It shows that if the maximum power is limited to 71 percent of the peak, there is little degradation at a BER of 10^{-4}. Other possibilities include frequency multiplexing a number of QAM channels with lower powers. Currently, LeRC believes that the single-tube solution appears more promising than multiplexing several lower power channels.

To support an 8-Gb/s downlink for ARISE within a 1-GHz bandwidth, SRRC-filtered 32-QAM requires an average of 49 W of transmitting power per polarization. Given current state-of-the-art technology for RF amplifiers at Ka-band, supporting 32-QAM would require technology investment. LeRC has the necessary foundation for needed development.

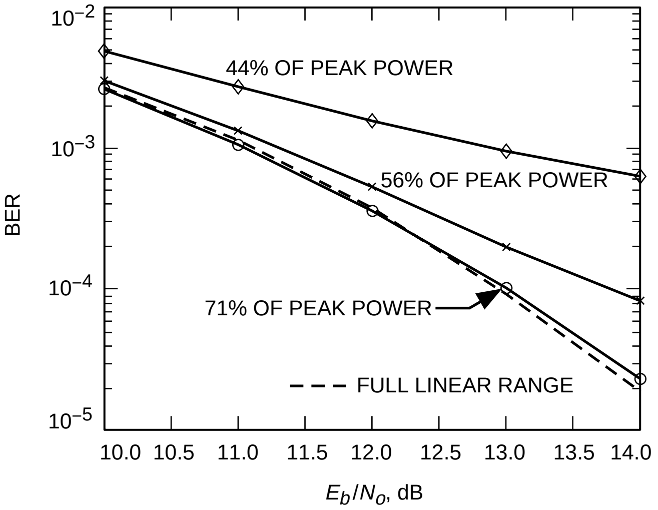

Fig. 8. BER performance for various amplifier saturations.

C. Optical Communications

This section begins the discussion of using lasers as transmitting devices for downlink data delivery at 8 Gb/s. Over the past 6 years, JPL has conducted two highly successful and publicized system-level demonstrations for optical communications, albeit at much lower data rates. The first of these, the Galileo Optical Experiment (GOPEX), demonstrated the ability to transmit modulated laser beams from the ground to the Galileo spacecraft (using the imaging camera as a detector) at link ranges up to 6 million km in December 1992. The second demonstration, the Ground Optical Link Demonstration (GOLD), performed a series of two-way optical communications demonstrations between JPL's Table Mountain Facility and the Japanese Engineering Test Satellite VI (ETS-VI) in Earth orbit at a range of 40,000 km during the summer of 1996.

Unlike for RF communications, there presently are no FCC regulations that govern the spectral containment for optical frequencies. This article assumes the availability of several ground stations with 1-m-class telescopes to receive downlink science data and proceeds to describe the optical terminal for interim or ARISE applications. The X-band transponder described in Section II.A, such as the SDST or STM, remains onboard for command and telemetry functions. Section II.C.1 describes the conceptual design of the optical downlink terminal; Section II.C.2 discusses the transceiver configuration; and Section II.C.3 describes the technology-readiness level of some critical components and system-level demonstration at 8 Gb/s.

1. Conceptual Design. Over the past 3 years, JPL has been heavily engaged in designing and developing a reduced-complexity optical communication terminal for high-data-volume applications. This terminal is called the Optical Communications Demonstrator (OCD) and has the ability to point microradian-level beams with a very small number of detectors or steering elements. Using only a single steering mirror and a single detector array, the OCD can accomplish the functions of beacon signal acquisition, beacon tracking, transmit/receive beam coalignment, and transmit-beam point-ahead offset. The architecture of the OCD is scalable in the sense that the front housing of the terminal design can be scaled to meet link-margin requirements without modifying the after housing of the terminal.

Figure 9 shows the current OCD with a 10-cm aperture and weight of less than 6 kg. The transmitting laser source, which is not shown in the picture, is connected to the rear of the OCD via a single-mode fiber for thermal isolation. Although the original OCD was designed to be a laboratory demonstration model, its design goal of minimum complexity and size makes it well suited for high-altitude aircraft or space-flight applications. The front housing of the OCD shares a similar design with the successful Wide Field Planetary Camera (WF/PC) II used for the Hubble Space Telescope.

The next few paragraphs describe the conceptual design of the spacecraft terminal using four-wavelength division-multiplexed (WDM) technology for downlink at 8 Gb/s. Each of the four lasers operates at 2 Gb/s and at slightly different colors relative to each other (2- to 10-nm wavelength separation). It offers the advantage that, with very minimal modifications, the same system can be used for the precursor missions, such as VSOP 2, requiring a data rate of 1 Gb/s. Also, multiple laser transmitters will provide for some level of redundancy, enhancing the reliability of the systems. Another advantage of implementing the WDM scheme is relaxation of the requirements for the ground-receiver detector bandwidth, since the communication link for each channel is at 2 Gb/s.

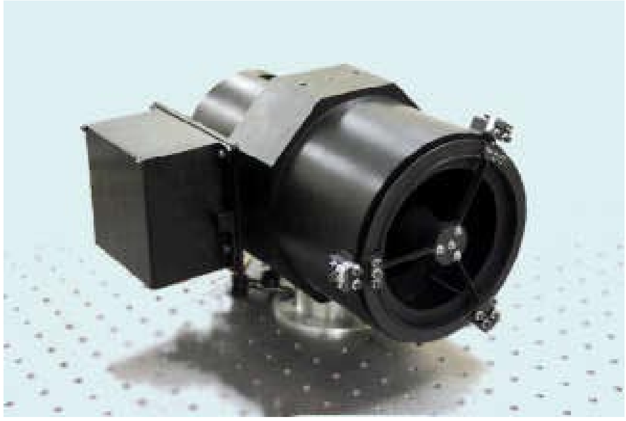

Fig. 9. The optical communication demonstrator.

To provide sufficient link margin for each laser transmitter, the OCD will be scaled to a 15-cm aperture with ground receiving stations having an aperture diameter of 1 m. Appendix B of the report cited in Footnote 4 shows a link margin of 6 dB for such a design. The wavelength of 1550 nm has the advantage of lower background light subtended at the ground receiver for downlink communications. The WDM technology is very well developed for fiber-optic components at 1550 nm. The technology of high-power, high-data-rate lasers at 1550 nm is maturing for fiber land-line applications. Preliminary estimates indicate the requirement of three stations in the southwestern United States (including Hawaii) located at least 500 km apart from each other could ensure over 90 percent availability. A laser beacon from each ground receiver site guides the pointing.

Optical downlink begins with the ephemeris available to both the spacecraft and the ground station. Once the coarse-pointing mirror brings the ground receiver within the field of view of the spacecraft transceiver, a beacon emanated from the vicinity of the ground receiver station will aid the acquisition and tracking. For the communication range of 40,000 km, a moderate-level laser power will be adequate as the laser beacon. The focal-plane array [charge-coupled device (CCD) or active pixel sensor (APS) array detector] utilizes the beacon signal to infer point-ahead information as well as the magnitude of jitter of the host spacecraft's platform. That information is fed to the fine-pointing mirror, which then precisely points the laser transmitter beam back at the direction of the beacon signal with submicroradian accuracy. Figure 10 shows a possible construction of the spacecraft terminal based on OCD.

Propagation of optical signals through the atmosphere suffers from similar space loss as RF signals. Since 1994, JPL has engaged in the development of an atmospheric visibility monitoring (AVM) station to obtain atmospheric transmission statistics to support optical communications experiments and missions. Data are collected via a set of three autonomous systems, all located in the southwestern United States, to observe stellar objects around the clock. Data from the three sites are processed on a regular basis to obtain cumulative distribution functions of atmospheric attenuation at different spectral regions. These data also will be used to determine spatial diversity information. The current wavelength range is from 500 to 900 nm. Work is under way to upgrade the AVM system to obtain improved data at the important 1064-nm wavelength. Modifying the observation filter and the array detector potentially could extend the wavelength to 1550 nm for ARISE.

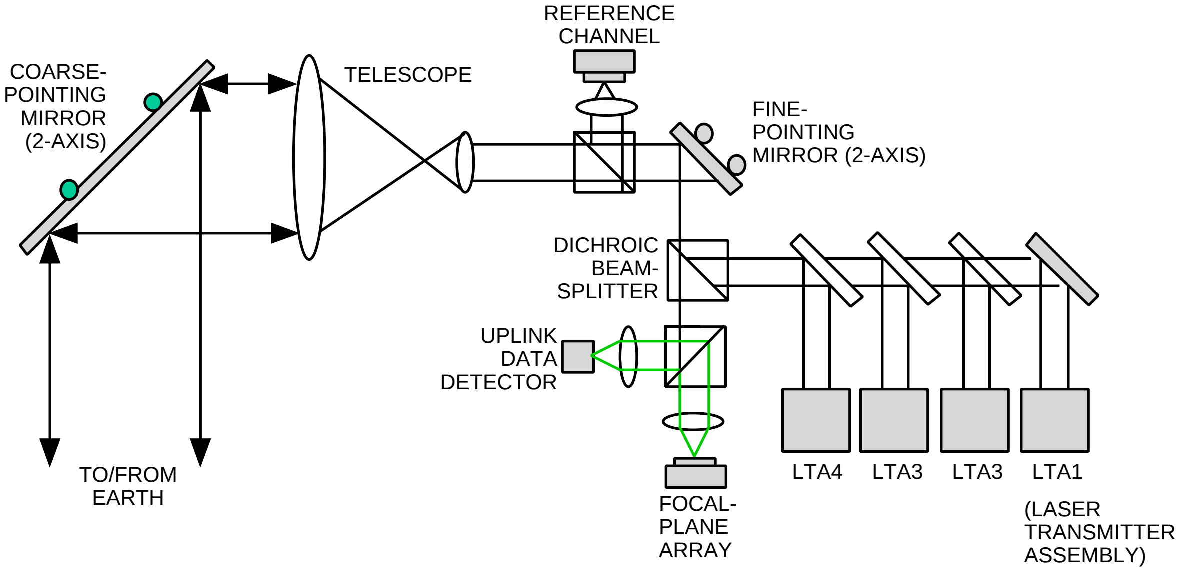

Fig. 10. The functional schematic of the spacecraft transceiver.

2. Transceiver Components. This section describes major components for the transceiver. Prior optical communication studies and the most recent X2000 study indicated that optical wavefronts will be mostly noncoherent arriving at the ground telescope. Direct detection coupled with on–off keying (OOK) provides the most effective approach as a modulation scheme for near-Earth optical downlink. The spacecraft transceiver can be divided into three major functional areas: the laser transmitter assembly (LTA); the opto-mechanical assembly (OMA), which includes the coarse- and fine-pointing mirror; and the electronics processing assembly (EPA). This section describes the laser transmitter, together with the necessary components for WDM; various components of OMA; and the EPA.

The laser transmitter consists of a low-power oscillator directly or externally amplitude modulated, followed by a semiconductor or fiber power amplifier. Lasers with adequate levels of power and reliability for 2 Gb/s are now commercially available with sufficient technology maturity. The 1550-nm fiber amplifiers also are now commercially available. A 1550-nm transmitter with 10 W of power and greater than a 2.5-Gb/s data rate is being space qualified by IRE-Polous Corporation. Fueled by the requirements for fiber-optic communication, the technology of these sources is advancing very rapidly. The 1550-nm fiber master oscillator power amplifiers (MOPAs) can be tuned over 40 nm, which enables the WDM technology to accommodate a total of four lasers separated by 10 nm. Another option for a multichannel system is a two-color transmitter wherein each is polarization coupled.

The opto-mechanical assembly, which includes the coarse- and fine-pointing mechanisms and the telescope itself, is described in the following. (The EPA, described in later paragraphs, controls operations of both the coarse- and the fine-pointing mirrors.)

(1) Coarse-Pointing Mirror: The function of the coarse-pointing mirror is to bring a portion of the Earth, where the ground receiver is located, within the field of view of the telescope and to hold that position to within a few milliradians. Since the ARISE orbit causes the viewing angles to vary fairly rapidly, a coarse-pointing mirror is provided in front of the telescope aperture to ease the spacecraft design burden.

(2) Fine-Pointing Mirror: The two-axis fine-pointing mirror with a diameter of approximately 2.5 cm typically is driven by voice-coil actuators. The function of this mirror is to compensate for the host spacecraft platform jitter and to implement the required point ahead. Different versions of fine-pointing mirrors have flown on a number of different spacecraft. A number of fine-pointing mirrors manufactured by Left Hand Design (LHD) Corporation are in the process of space qualification for different JPL programs.

(3) Telescope: Design of the 15-cm-aperture telescope is similar to the design of the original OCD 10-cm telescope. Some weight reduction of the primary mirror might be required to maintain the balance of the mounting scheme. OCA Applied Optics, Garden Grove, California, under contract to JPL in 1996, has completed a scalable design of the OCD up to 20 cm.

The central processing unit within the EPA, described below, provides necessary drivers and interface and control functions for various sensors and opto-mechanical mirrors. The main objective is to accomplish acquisition, tracking, and pointing (ACQ/TRK/PTG) for the terminal. The majority of the control functions are embedded in the software development.

(1) Acquisition and Tracking Detector: The focal-plane array (FPA) in conjunction with a laser beacon and a reference from the laser transmitter comprises the acquisition and tracking mechanism. The FPA could be either a CCD or an APS with, for example, 512×512 pixels. This area detector infers the pointing information and provides that to the fine-pointing mirror. The CCD technology is well developed and has flown onboard

a number of deep-space probes. The APS technology is advancing rapidly, and a version of this detector is now flying onboard the DS1 spacecraft. The APS detectors have a smaller size than CCDs and consume lower DC power.

(2) Processing Hardware and Software: The central processing unit makes use of the current high-speed, versatile, digital signal processing (DSP) chips, such as TMS32C40, as a dedicated processor. Hardware construction will be functionally similar to the OCD architecture. Development of ACQ/TRK/PTG software requires special attention, although the core engine will be based on the laboratory development for OCD or the upcoming prototype terminal for Space Station demonstration. The laboratory prototype must be space qualified and go through a rigorous development process.

3. Technology Readiness. Over the past few years, NASA has funded a number of development efforts to demonstrate the potential benefits of laser-based communications. The OCD described in Section II.C.1 is a laboratory engineering optical terminal capable of transmitting at least 500 Mb/s for near-Earth applications. Technology development such as acquisition and tracking was demonstrated in the laboratory in 1997, and the terminal will become available as a prototype for system-level demonstrations. A space-borne experiment sponsored by the International Space Station Engineering Research and Technology (ISSERT) Office at Johnson Space Center currently is being studied and planned for 2003, with over a 1-Gb/s data rate. An earlier 2001 flight is proposed for the Space Transportation System (STS) with the same platform as a precursor test.

During the months of August and September 1994, a study was performed to assess the technical challenges and expected cost of an air-to-ground demonstration using the OCD and NASA's ER-2 aircraft. It was concluded during the study that OCD easily could be adapted for flight with minimum repackaging. The benefits of a high-rate optical communication capability also were validated by the Laser Communication Demonstration System (LCDS) study. The LCDS program is an industry-based study to perform the Phase A/B planning of a flight demonstration of optical technology in Earth orbit. Two study contracts were awarded in 1995, one to a team led by Ball Aerospace and the other to a team led by Motorola. The study identified a number of potential applications for high-rate (>750-Mb/s) optical communication systems and also provided a baseline design of the system that will provide on-orbit demonstration of the technology. Although the LCDS program was not funded for subsequent development, the study provided both a thorough evaluation of its potential applications and an excellent system engineering and cost study of a spaceborne demonstration program.

Table 1 shows an estimate of the technology readiness level (TRL) of each critical component. In general, most component technologies for optical communications are readily available for near-Earth high-volume downlink applications. The missing components are the system-level integration and the confidence of accepting such an approach. Furthermore, the ground network for supporting optical communication as an operational system has not reached the level of maturity similar to that of RF communications. Since the required pointing accuracy is orders of magnitude tighter than that of the Ka-band downlink, a low-gain system at low data volume, such as an X-band transponder, should be onboard to provide backup or emergency functions.

The following paragraphs discuss individual components for the optical communication system that have not reached level 7. They include descriptions of the laser technology and the WDM technology, and are followed by estimates of mass, power, and physical dimensions.

The 1550-nm fiber amplifiers are now commercially available. A 1550-nm transmitter with 10 W of power and greater than a 2.5-Gb/s data rate is being space qualified by IRE-Polous Corp. for Lincoln Laboratories. Some of the activities on high-power, high-data-rate transmitters are given in Table 2. Recently, high power (>1 W) and high data rates (>2.5 Gb/s) have also been achieved with the 980-nm semiconductor MOPAs.

Table 1. Technology-readiness level of major components.

Component	TRL level	Notes/flight heritage
Laser transmitter	5	High-power, high-data-rate version being qualified for Lincoln Laboratories by IRE-Polous.
WDM	5	Heavily used in fiber-optic communications with >10-year lifetime. Made mainly of silicon glass or quartz. Do not expect qualification issues.
Focal-plane array	8	CCDs have flown on many JPL space missions. APS flying on DS1.
Fine-pointing mirror	8	Ball Aerospace, TRW have flown them in space. LHD working on space qualification.
Transmit/receive aperture	8	Even though the exact copy of the telescope baselined here has not flown in space, many of the same kind have flown in space before.
Coarse-pointing two-axis mirror or gimbal	7	Versions have flown in space. Latest version to be launched on the STRVII spacecraft in a few months.

Table 2. Activities on high-power, high-data-rate transmitters.

Power, W	Data Rate, Gb/s	Wavelength, nm	TRL	Manufacturer
>5	10	1550	≥5	IRE-Polous for Lincoln Laboratory
>5	2.5	1067	4	SDL delivered to JPL under Small Business Innovative Research (SBIR)
1	2.5	980	3–4	SDL will deliver in January 99 under SBIR

Fiber-optic communication systems now operate in the field at 1- to 10-Gb/s data rates, with much of their technology directly benefiting the free-space laser communication systems. A WDM could efficiently combine transmitter sources with wavelength separation as little as 1 nm. For ARISE, a separation of 10 nm is sufficient. The WDM technology at 1550 nm has been well developed for the fiber-optic communication industry. However, its virtual nonexistence for space communications poses some technical and programmatic risks.

For a transceiver capable of delivering 8 Gb/s from the 40,000-km range, weight and power consumption are estimated at 22 kg and 135 W given today's technology. The dimensions of the transceiver are roughly 20 cm by 25 cm by 40 cm. Estimated cost of the flight-qualified terminal is approximately 15 million in 1998 dollars with a 20 percent confidence margin. With improvements in the technology of semiconductor and fiber MOPAs, a reduction of 30 to 50 percent in the laser power consumption is expected. The mass and power consumption of electronics that interface the transceiver with the spacecraft are not included in the above estimates.

III. Road Map

This section describes the road map for telecommunication technology development from the current 128 Mb/s of VSOP to 8 Gb/s for ARISE. A series of demonstrations is anticipated between the years 1999 and 2006 for the planned nominal launch date of 2008 for ARISE. The technology is leveraged on current developments at JPL, other NASA centers, and industry. RF demonstrations will be based on the current 11-m stations, while optical demonstrations will be based on the 1-m-telescope Optical Telecommunication Laboratory (OCTL) currently planned by JPL.

A. Interim Technology Demonstrations—RF

The RF development and demonstration road map is shown in Fig. 11. Station validation and VSOP compatibility testing can start in the second quarter of 1999 using the demodulator developed by JPL–GSFC at 128 Mb/s using QPSK. This test can validate the compatibility of the VLBI ground-station receiver front end and the JPL–GSFC demodulator functionally and operationally. With the JPL–GSFC jointly developed XTCQM modulator, which will be ready shortly afterwards, demonstrations using spectrally efficient XTCQM could begin in 2000 at 500 Mb/s at 250 Ms/s using 500 MHz of spectrum. The same setup can provide the 1-Gb/s data rate needed for VSOP 2 by using either two 500-MHz bands or dual polarization in a subsequent demonstration. In order to support the 8-Gb/s downlink for ARISE, an SRRC-filtered QAM modulator, a receiver, polarizers, and a linear amplifier at 37 to 38 GHz need to be developed. These technologies can be demonstrated in a series of laboratory and field experiments first using SRRC-filtered QPSK at 1 Gb/s, followed by SRRC-filtered 16-QAM and 32-QAM at an increasing data rate. As shown in the block diagram in Fig. 2, the downlink data are divided into eight 1-Gb/s streams. Each demodulator needs to process 1 Gb/s of data, which corresponds to 200 Ms/s for the SRRC-filtered 32-QAM.

B. Interim Technology Demonstrations—Optical

The interim demonstrations for optical communications follow a different development cycle due to the availability of ground stations and the receivers. The high-data-rate experiments currently are planned using the International Space Station and the Space Transportation System. Both demonstrations will accommodate at least a 1-Gb/s downlink. System-level demonstrations at 2 Gb/s will provide sufficient technology readiness for the 8-Gb/s downlink for ARISE using WDM. Figure 12 shows the road map for optical demonstrations.

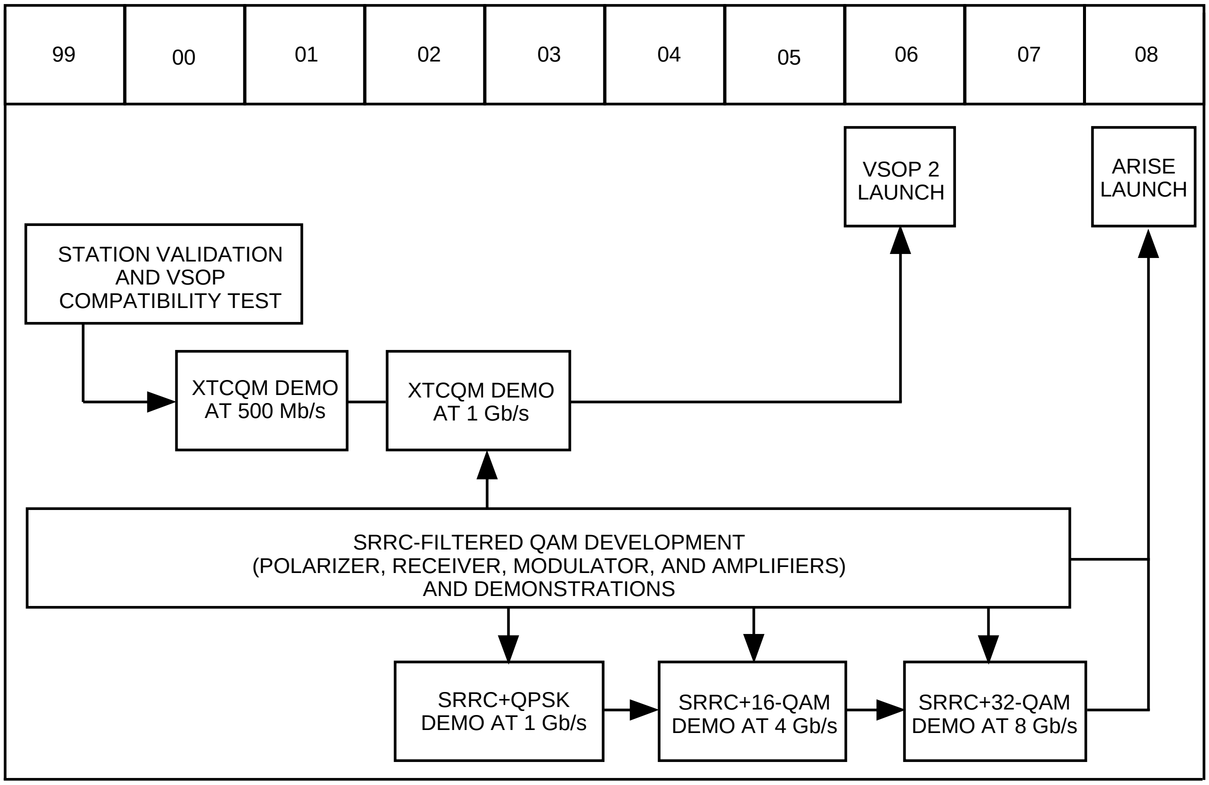

Fig. 11. The RF technology development and demonstration road map.

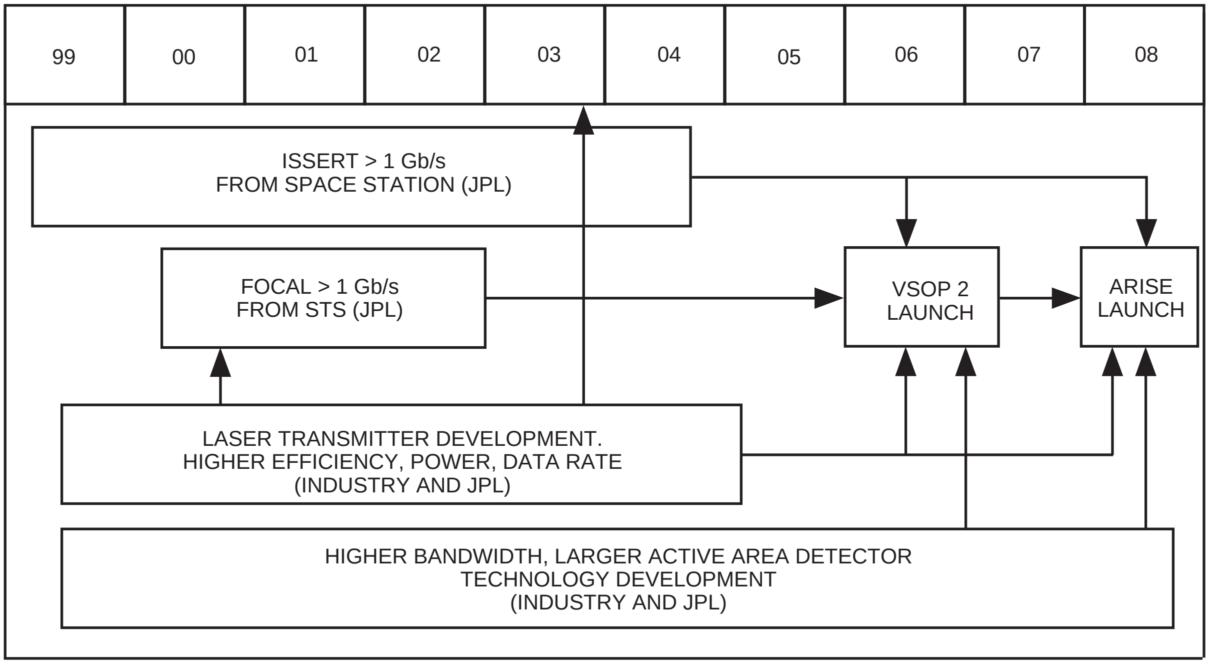

Fig. 12. The road map for optical communication technology development between 1998 and 2008.

IV. Summary

This article was prepared based on an in-depth study prepared for SESPD and the TMOD Program Office and on the latest research effort and current information available to the authors. It is reasonable to assume that military agencies have similar classified programs of developing high-rate modulators and demodulators on the order of a few Gb/s for space applications. It generally is agreed upon that military products customarily tend to be designed for very specific applications and often are expensive to adapt to commercial uses.

VSOP 2 represents an interim opportunity for NASA to demonstrate a 1-Gb/s downlink to an 11-m ground station for RF and to the JPL OCTL station for optical communications. Telecommunications design and technology for RF and optical communications from Earth-orbiting satellites at 1 Gb/s are readily available today. To provide an 8-Gb/s downlink for the RF designs, high-order modulation is needed unless the FCC allocates additional spectrum for space VLBI. TWTA at 37 GHz needs be developed, and isolation between the inflatable science antenna and the 8-Gb/s downlink antenna should be examined. Although no demodulators exist today for the proposed data rate, the high rate JPL–GSFC ASIC can be modified to receive spectrally efficient modulations such as XTCQM and SRRC-filtered QAM. For the laser communication option, the component technologies are mature, but system-level demonstrations are needed to raise the confidence level of the design in order to support the mission. In addition, upgrading current ground stations for both RF and optical communications to support the 8-Gb/s downlink and for ground data distribution is essential.

The 2-year span between launch dates of VSOP 2 and ARISE as scheduled might be too tight to validate the entire spectrum of interim demonstrations, such as 2 Gb/s and 4 Gb/s. To fully validate the technologies, other opportunities are recommended as precursor demonstrations for ARISE before 2008.

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