Optical and microwave communications system conceptual design for a realistic interstellar explorer

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ABSTRACT

The concept of a realistic interstellar explorer has been addressed by the Johns Hopkins University Applied Physics Laboratory (JHU/APL) with support from the NASA Institute for Advanced Concepts (NIAC). This paper discusses the requirements, conceptual design and technology issues associated with the optical and RF communications systems envisioned for this mission, in which the spacecraft has a projected range of 1000 AU. Well before a range of 100 AU interactive control of the spacecraft becomes nearly impossible, necessitating a highly autonomous craft and one-way communications to Earth. An approach is taken in which the role of the optical downlink is emphasized for data transfer and that of the microwave uplink emphasized for commands. The communication system is strongly influenced by the large distances involved, the high velocities (20 AU/year or ~ 95 km/s) as well as the requirements for low-mass (~ 10 kg), low prime power (~ 15 W), reliability, and spacecraft autonomy. An optical terminal concept is described that has low mass and prime power in a highly integrated and novel architecture, but new technologies are needed to meet the range, mass, and power requirements. These include high-power, "wall-plug" efficient diode-pumped fiber lasers; compact, lightweight, and low-power micro-electromechanical (MEM) beam steering elements; and lightweight diffractive quasi-membrane optics. In addition, a very accurate star tracking mechanism must be fully integrated with the laser downlink to achieve unprecedented pointing accuracy (~ 400 nrad RMS). The essential optical, structural, mechanical, and electronic subsystems are described that meet the mission requirements, and the key features of advanced technologies that need to be developed are discussed. The conclusion from this preliminary effort is that an optical communications downlink out to 1000 astronomical units (AU) is within the realm of technical feasibility in the next 5-10 years if the identified technical risks for the new technologies can be retired.
Keywords: interstellar explorer, optical communications, link analysis, diffractive optics, RF tone-tracking

1. OVERVIEW

This paper describes the concept of a hybrid optical/microwave communications system for the Realistic InterStellar Explorer (RISE) and addresses implementation and technology issues necessary to meet its projected mission requirements. This effort was supported by the NASA Institute for Advanced Concepts (NIAC)[1]. The conclusion from this preliminary effort is that an optical communications downlink out to 1000 astronomical units (A.U.) is within the realm of technical feasibility in the next 5-10 years despite constraints on spacecraft mass and power established in previous studies[2]. It is also possible to uplink a minimum bandwidth RF signal for command and data handling using a tone-tracking receiver with a very long integration time.

The spacecraft's communication system is strongly influenced by the large distances (100-1000 AU) and velocities (20 AU/year or ~95 km/s) involved in the mission. As a consequence, low-mass, low prime power, reliability, and spacecraft autonomy are extremely important. Well before a range of 100 AU interactive control of the spacecraft becomes nearly impossible, necessitating a highly autonomous craft

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and one-way communications to Earth. Although microwave communication techniques have a long and successful history of use in space missions, optical terminals tend to be much smaller in size, and have much higher gain and data rates, provided that they can be very accurately pointed. Using new technologies, optical links can be designed and built in a timely fashion for the realistic interstellar probe (RISE). These technologies include high-power, "wall-plug" efficient laser diode-pumped fiber lasers; compact, lightweight, and low-power micro-electromechanical (MEM) beam steering elements; and lightweight diffractive quasi-membrane optics. In addition, novel and very accurate star tracking systems must be fully integrated with the laser downlink. Proposed mass and prime power constraints can be met <u>if</u> these advanced technologies can be developed that are focused on such a mission.

2. MISSION CONCEPT AND REQUIREMENTS

The primary goal of the RISE mission is to send a probe through the boundary of the heliosphere to obtain scientific data. Several purposes given for this mission include: exploring the interstellar medium, the structure of the heliosphere and its interaction with the interstellar medium, and several astrophysical processes and phenomena as described in the references[3-5]. Other studies have considered interstellar missions that use optical communications as far back as the invention of the laser[6,7-9]. A secondary goal is to put the RISE spacecraft on a course with an ultimate destination of a nearby solar system. The boundary of the heliosphere is ~ 300 AU. To reach the 1000 AU mission range within the anticipated mission time of 50 years requires that the RISE spacecraft achieve a high escape velocity. To achieve this it is necessary to use a solar gravity assist based on a launch to Jupiter with a retrograde slingshot trajectory to eliminate heliocentric angular momentum. In its trajectory it is necessary for the RISE spacecraft to fall within four solar radii of the sun's center at perihelion. To also reach another nearby solar system of interest, the RISE spacecraft will be pointed towards Epsilon (ε) Eridani. The planned trajectory for the RISE mission is shown in Fig. 1 and is described in greater detail in reference 10.
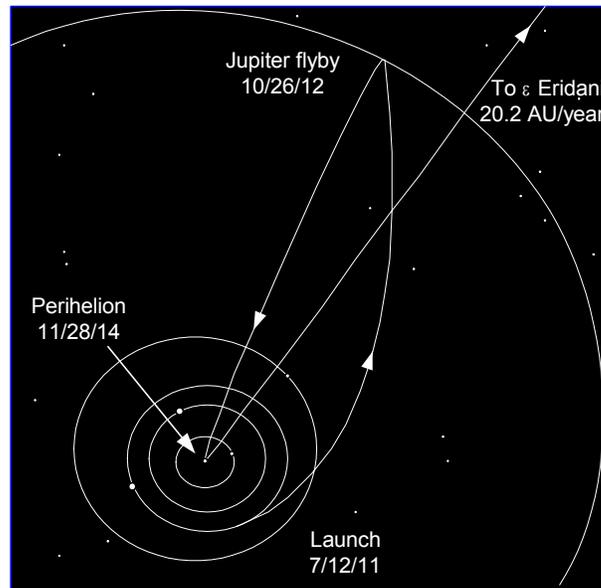

Figure 1: Plan view of the RISE trajectory within the solar system.

The Delta III launch vehicle planned for this mission will deploy the RISE spacecraft in a "cocoon" structure to protect the spacecraft until it passes Jupiter and completes it solar perihelion maneuver, after which it is jettisoned. During this phase of the mission the optical communications system must be protected from the extreme thermal, radiation and particulate contamination environment of the inner solar system close to the ecliptic. The RISE spacecraft must also withstand high launch loads, high perihelion

thrust and temperatures, and low asymptotic temperatures over its lifetime. In later phases of the mission the optical communications and star tracker system must also operate in relative close proximity to the radioisotope thermoelectric generators (RTGs).

The design requirements for the optical communications system as originally conceived were derived from the overall realistic interstellar explorer mission and spacecraft concept as described in reference 2. These are: a range up to 1000 AU, downlink optical antenna of 1 meter diameter, receive telescope aperture of 4 meters, bit rate of 500 bps in a burst mode, pointing accuracy of 400 nrad (1-σ), bit error rate of 10^{-6}, mass of 10 kg, and effective prime power of 15 W (intermittently available). For the purposes of this study the power required for burst transmissions is assumed to be the maximum available from the spacecraft power bus, however, the mass is that apportioned only to the optical communications system. In actuality, the laser burst transmission power requirements will have to be met by using a charge storage device that stores energy at a lower rate prior to each burst.

The proposed realistic interstellar explorer is required to point the optical "antenna" boresight at a receiver on Earth once a day to well within the beamwidth of the laser transmitter, which is approximately 2.4 µrad for a 1 micron wavelength transmitter. This corresponds to an absolute pointing and control requirement of ± 400 nrad (1-σ). In order to achieve such a tight pointing requirement, a number of errors must be characterized and controlled. These include trajectory knowledge derived from an onboard clock and ephemerides to track the receiving station and downlink platform so that the spacecraft-to-earth line-of-sight orientation is known sufficiently accurately within the total spacecraft pointing error budget. In order to maintain the transmitter boresight accurately a high-precision star tracker is also needed, which must be aligned very accurately with respect to the laser antenna. Alignment errors between the transmitter and star tracker can be minimized by using the same optical system for the star tracker and laser transmitter and compensating any residual dynamic errors in real-time. This must be accomplished subject to various spacecraft perturbations, such as propellant bursts, or solar radiation induced moments. To also avoid significant beam loss when coupling into the receiver near Earth, the beam shape should be controlled, i.e., be a diffraction-limited single mode beam as well.

Boresight error control is the most technically challenging part of the whole optical communications system because of the above-mentioned perturbations, as well as others such as control quantization and fuel requirements. Slow spacecraft rotation about the nominal transmitter boresight (for spin stabilization) tends to cancel disturbance torques, such as solar pressure acting through a center-of-pressure to center-of-mass offset. This dominates early in the mission but should diminish with distance from the sun, although there is a tradeoff between higher rotation rate for disturbance cancellation and fuel use to move more angular momentum while tracking. By thrusting only in symmetric couples this disturbance can be minimized. Any precession or nutation about the spin axis must be compensated by the pointing and tracking control system to maintain the laser boresight.

Two-axis pointing (tip/tilt) mirrors that are accurate to 1 µrad (3-σ) are readily available[11], but they are relatively large for this particular spacecraft mass and power budget. Wide field-of-view trackers with 200 nrad accuracy are in development, which are sufficient for the realistic interstellar explorer, although they do not at present meet the mass and power constraints either.

3. OPTICAL DOWNLINK COMMUNICATIONS SYSTEM

3.1   General discussion

Although an RF communications system can be used effectively in the inner solar system, after attaining a distance of several AU, it becomes increasingly difficult to use it as a downlink on a very low power, low-mass spacecraft like the RISE. The RF system can continue to be used as the uplink for limited mode commands and wellness tests. This system will be described in section 4.

Once the spacecraft has left the inner solar system, however, communications must occur predominately via the optical down-link. Although for the mission's initial phases in the inner solar system the Earth optical terminal can be located on the ground (as other studies[8] have considered), as the probe's distance increases, the uncertainty and attenuation of the Earth's atmosphere will significantly limit performance of the optical link. Thus, an orbiting Hubble-class relay station would be preferred. Because of the mission's long range, the communications system must function with high peak power, thus requiring development of high-power high-efficiency laser transmitter technology with excellent beam quality.

The basic characteristics of the RISE optical communications system concept that we initially assumed[2] have been revised to simplify the operation of overall spacecraft data handling operations. Initially a bi-directional optical link was envisioned in which the downlink and uplink were at two different wavelengths isolated by a polarizing beam-splitter in which the downlink receiver at the earth would be operated in a coherent homodyne detection mode. Such systems, however, are difficult to align accurately, are heavier, more complex and add (theoretically) only 6 dB of performance margin over an ideal quantum-limited direct detection approach. In practice, the margin may actually be less than 6 dB. Thus, for the optical downlink receiver, a direct detection system was assumed. It works almost as well, especially if operated in the quantum-limited mode of photon counting.[12]

The overall opto-mechanical telescope structure is shown embedded within the basic spacecraft truss in Figure 2.
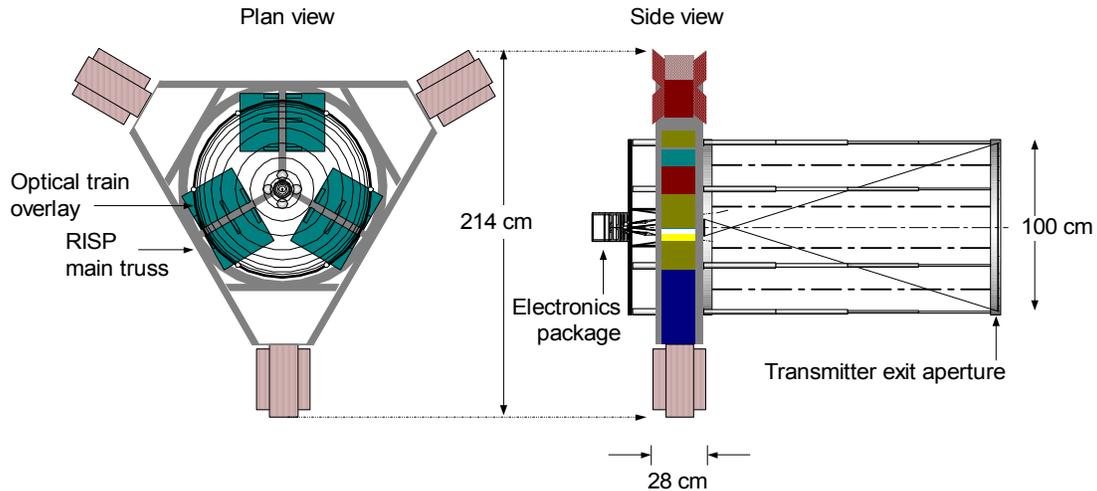

Figure 2: Overall RISE telescope structure and its placement in the spacecraft truss.

3.2 Optical link analysis

For our original link analysis the basic assumptions about the system were that implementation losses are small enough compared to other factors that they could be neglected to first order in determining initial requirements, that the downlink receiver (on Earth) is signal shot noise limited, that the bit rate is only 500 bps (in a burst mode), and that the required bit error rate (BER) is 10^{-6}. From the analysis outlined in Figure 3 for an on-off-keying (OOK) modulation technique used with a direct-detection receiver, the required average transmitter power is 360 mW at 100 AU and 36 W at 1000 AU.

However, other factors, such as link implementation losses and the gain afforded by the use of an optical amplifier at the receiver have not been taken into account. The expected types of link loss we consider are those due to transmitter and receiver optical components and pointing errors. By operating the receiver in Earth orbit and the link out of the plane of the ecliptic, Earth's atmosphere and interplanetary dust should not be significant factors, in which case link losses as low as 3 dB could be achieved with proper optical design.

Using coherent detection at the Earth terminal in conjunction with a laser diode on the spacecraft requires extremely stable narrow linewidth emission on board the RISE. Since this is very difficult to do, especially with laser diodes, a case can be made to use an incoherent direct detection system. There are several practical reasons to do this: (1) it simplifies the transmitter optics on the spacecraft; (2) it does not pay to use coherent detection at low data rates because of a criterion emerging from consideration of coherent (BPSK) modulation.[12] (This criterion requires that the link bandwidth be on the order of 10^5 greater than the laser linewidth, a condition that cannot be met with the specified communication rate of only 500 bps), (3) it is very difficult to achieve sufficient beam quality in laser diode or fiber laser arrays to support effective coherent mixing at the receiver, and (4) as already mentioned, the Earth receiver is not seeing significant background light that would otherwise drive the design to coherent detection (all other objections being negligible).

Optical amplifiers used in conjunction with the earth terminal receiver should also improve the overall link loss by as much 30 dB, however their contribution to the overall receiver noise is not negligible. They typically add 5-7 dB to the system noise figure.
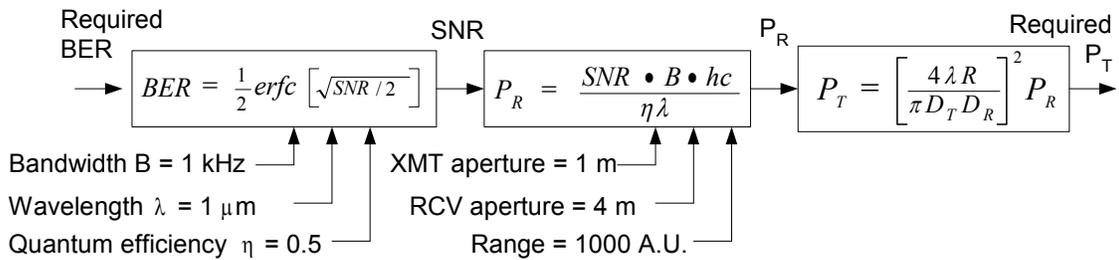
Required BER → $BER = \frac{1}{2} erfc\left[\sqrt{SNR/2}\right]$ → SNR → $P_R = \frac{SNR \bullet B \bullet hc}{\eta\lambda}$ → P_R → $P_T = \left[\frac{4\lambda R}{\pi D_T D_R}\right]^2 P_R$ → Required P_T

Bandwidth B = 1 kHz
Wavelength λ = 1 μm
Quantum efficiency η = 0.5
XMT aperture = 1 m
RCV aperture = 4 m
Range = 1000 A.U.

Figure 3: Functional flow of the link analysis for the RISE mission.

3.3   Mass and prime power budget

Given the overall spacecraft mass and power constraints allocated to the optical communication system, i.e., 10 kg and 15 W (assuming that the entire spacecraft power budget is available for burst communications), we projected subsystem mass and prime power fractions. All components except for the laser total 6 W, which is generous to allow for deployment and periodic adjustment of the optics via electro- and/or thermo-mechanical means. The 9 W for the laser can be supplied by using energy storage accumulated at a lower rate over a longer period of time prior to each laser burst. Previous studies have indicated that the amount that can be devoted to each subsystem depends on the telescope aperture and transmitter power as suggested by a recent JPL study[13]. Our percentages for the RISE are given in Table 3 and differ by devoting most of the mass and power to the laser subsystem. We also compared our total system mass and power numbers to actual deployed laser communications systems, which require at least three times the power and twice the mass, but although some systems were an order of magnitude greater in each attribute.

Table 3: Mass and Power Budget versus Optical Communications Subsystem

Subsystem	Mass (kg)	Power (W)
Laser	6	9
Optics	2	0.1
Pointing and tracking	0.5	1.1
Thermal and mechanical	1	4.5
Processor	0.5	0.3
Total	10	15

3.4 Conceptual design

3.4.1 Opto-mechanical

The optical train of the RISE optical communications system must be very low-mass with a very large aperture. The overall concept is illustrated in Fig. 4. This translates into a design that incorporates some very thin diffractive elements in a shared aperture configuration with smaller refractive elements. Although a fully baffled telescope would minimize stray light entering the star tracker field-of-view, for a downlink-only system, this would be unnecessary as long as the star trackers are baffled and pointed away from the sun and carefully stopped. A small refractive beam collimator is used to couple the laser transmitter beam cross-section to a two-stage beam expander, whose exit pupil would be 1 meter in diameter to achieve the desired beamwidth. Separate lenses form the images on each focal plane array (FPA) used for tracking purposes, but share a portion of the same aperture as the laser beam expanders.

The laser downlink is co-boresighted with the spacecraft spin axis, and the laser transmitter consists of a quad redundant fiber laser, with ~ 20 W per channel, each with a diffraction-limited single-mode Gaussian beam. They are bundled in the transmitter box as part of a rigid mechanical structure in which the exit pupil of each laser is coupled to a collimating lens with a pupil of 10 mm. The optical train consists of this collimator and a two-stage beam expander with an overall beam expansion ratio of 100:1. Beginning with a collimated beam diameter of 10 mm, the first stage beam expander has a 10:1 magnification using rigid diffractive elements, yielding a 10 cm exit pupil. The second stage beam expander also has a 10:1 magnification but uses a thin membrane diffractive output lens with a 1meter exit pupil.

In between the first and second beam expanders are two closely-spaced pupil planes devoted to a detector and lenslet array. The first surface of a relatively thick element would contain a sparse lenslet array, and the second surface would contain a co-registered sparse detector array. This Shack-Hartmann array of lenslet/photodetectors is thus used to measure the laser beam profile for beam wavefront control, whose samples are processed to support the beam steering actuators as well as the fiber lasers. By using the photodiodes in the near field some degree of beam steering feedback and even transmitter health monitoring can be accomplished by measuring the focal deviation from the corresponding set of registered lenslets. The error signal driving the beam steering mirror is also controlled by an embedded inertial measurement unit (IMU) to compensate for any spacecraft ambient vibration up to 100-1000 Hz.

3.4.2 Electronics architecture

As a strawman design concept we assumed that the electronics architecture is constructed from standard 4 x 4 in circuits boards would be used in an APL developed "integrated electronics module[16]". Fig. 5 shows the transmitter, star tracker, and inertial measurement unit (IMU) package as an integral unit. From left to right it contains power conditioner, fiber lasers, laser drivers, FPA and track processor power conditioner, tracking and data processor, laser downlink modulators, beam steerer drivers, and a monolithic block containing the IMU, beam steerer actuators, fiber-to-free space coupler, focal plane arrays, and input optics. Although this particular embodiment shows a processor board for the star tracker, this function could also be located in the central spacecraft processing unit.

3.4.3 Beam steerer

To minimize weight a meso-scale or micro-scale beam steering mechanism is envisioned, as shown in Fig. 6(a). A meso-scale or micro-electromechanical system (MEMS) implementation is preferred from the standpoint of mass, power, and resistance to cryogenic temperatures and radiation flux. It would be a much lower power system than present state-of-the-art piezo-driven tip/tilt mirrors. The position dynamic range of the micro-positioner actuators must be calibrated with respect to the star tracker FPA angle measurements through a different optical system (the diffractive beam expander) even though they share the same overall composite aperture.
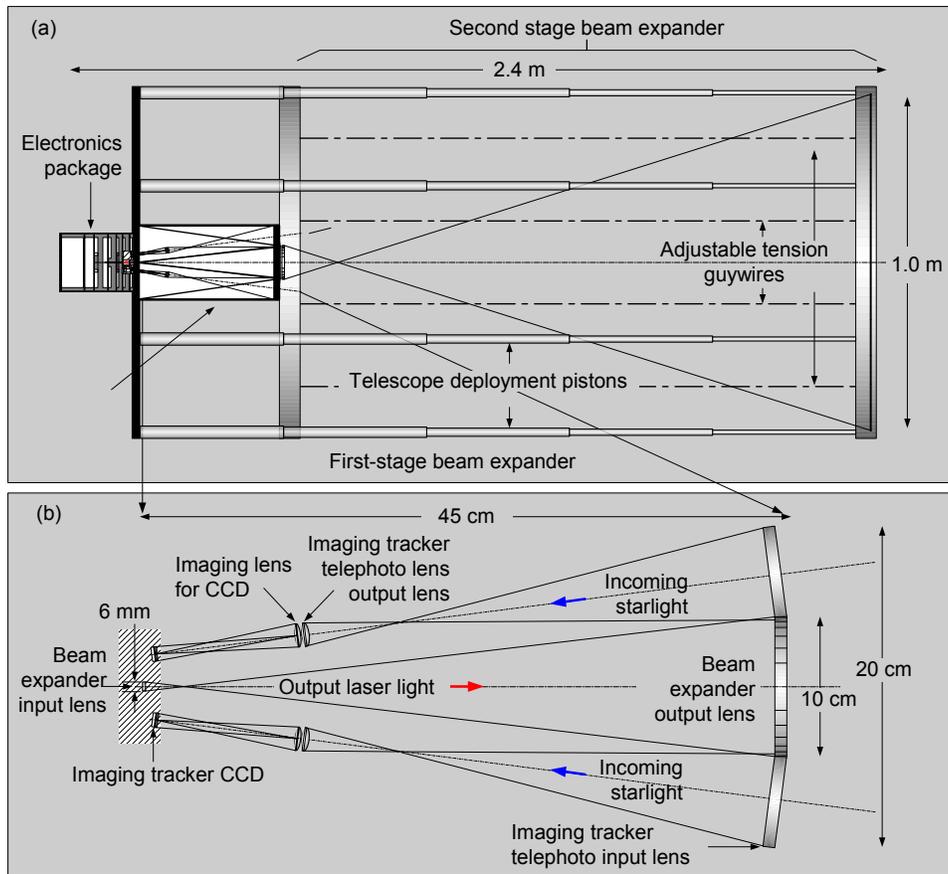
Fig. 4: (a) Basic opto-mechanical layout of the optical communications and star tracking systems, including (b) a detailed optical layout of the first stage beam expander and star tracker optics in one plane (pitch or yaw).
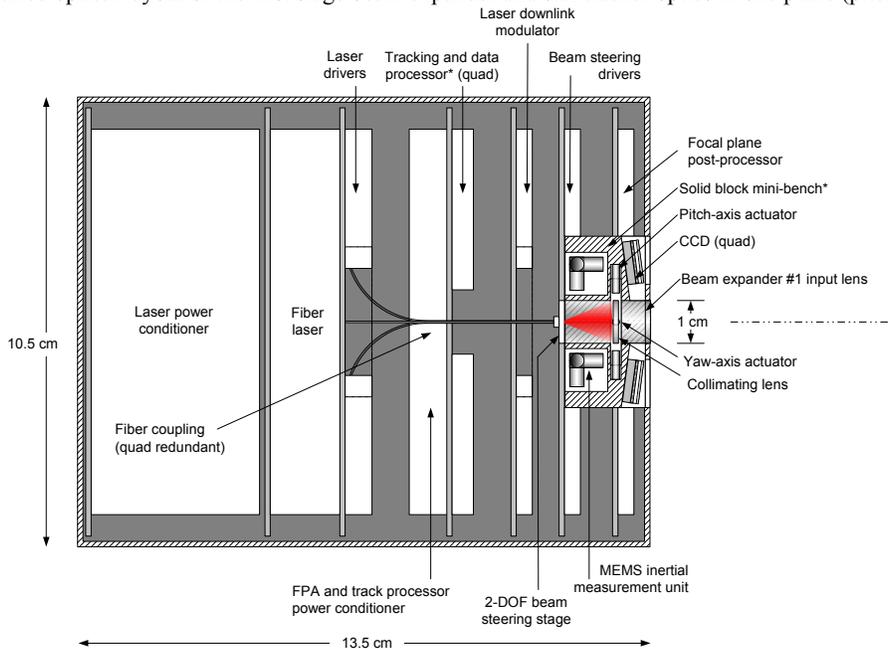

Fig. 5: Cross section of the electronics and mechanical packaging for the laser downlink and star tracking subsystems.

A two-degree-of-freedom (2-DOF) meso-scale or micro-scale (MEMS) stage would be used for positioning the collimating lens to steer the beam. It is based on a recently developed NIST designed macro-scale monolithic planar system,[14] shown in Fig. 6(b) below. It uses mechanical amplification, filtering, and common mode rejection of two orthogonal piezo-actuated positioners with angular deviation errors less than 480 to 720 nanoradians. With the current design the positioner peak-to-peak deflection would be 100 microns, but it would have to be extended to 1000 microns in our system. By proper design the corresponding angular resolution would be 100 nrad, and the maximum range would be 1000 μrad, yielding a dynamic range of 40 dB. The required bandwidth needed to handle expected spacecraft disturbances would have to better than 100 Hz but probably less than 1 kHz.
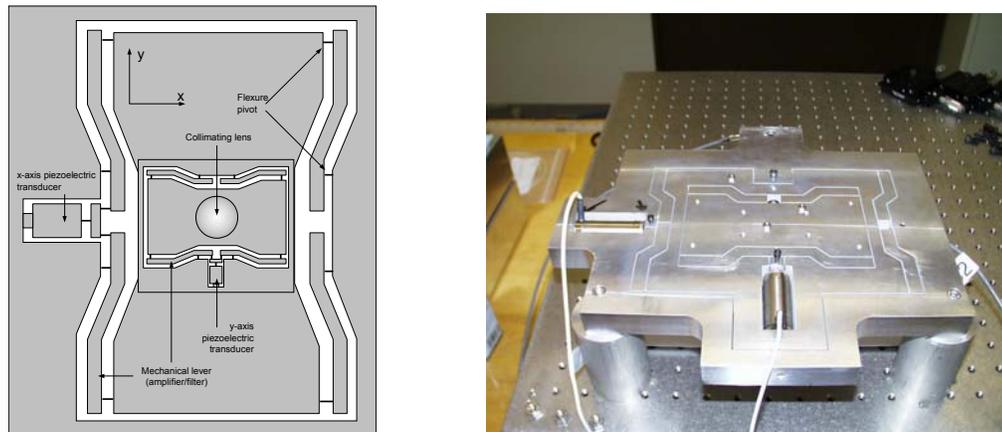

Fig. 6:   (a) Design concept for a basic beam steering element that would use a stationary fiber laser or laser diode array, and a collimating lens positioned by the 2-D meso or micro-scale translation stage shown in plan-view, and (b) photograph of the current NIST monolithic macro-scale technology[14].

3.4.4   Star tracker design

The star tracker FPA's could take the form of either charge-coupled devices (CCD's) or Complementary Metal Oxide Semiconductor (CMOS) adaptive pixel sensors (APS), with approximately 1000 x 1000 detectors. One of the star trackers could also serve as a solar tracker, as well as locating the earth to initially point the telescope for acquisition and subsequent tracking prior to a downlink burst transmission[2]. To increase system redundancy for such a long mission and to provide a design which includes the best features of previous designs in a single aligned optical system, a quad redundant set of focal plane arrays was placed on a rigid platen (a precision low coefficient of thermal expansion mini-bench) circumscribing the beam steering position transducer. This insures minimal misalignment between the two optical systems. Coupled with an adjacent inertial measurement unit (IMU) in the same mechanical block, contributions to the system pointing error budget from these different sensors should be minimized. Details of this design concept are given in Reference 15.

4. RF COMMUNICATION SYSTEM CONCEPT

4.1   System Design

The RF communication system provides uplink commanding throughout the mission and downlink telemetry during the early portions of the mission. These functions must be accomplished with minimal mass and power consumption (goals of 1 kg and 1 W, respectively). Once the spacecraft has been launched and checked out, the optical communication system will be used thereafter for returning downlink telemetry.

The RF communication system shown in Figure 7 consists of redundant X-band transceivers connected to two medium gain antennas (on transmit, one receive). Each transceiver includes a transmitter, receiver, and ultra-stable oscillator (USO). The relatively low RF output power (0.5 W) enables the transmitter portion of the system to include an internal solid-state power amplifier. Redundant low noise amplifiers are connected in close proximity to the receive antenna for minimum noise figure. The medium gain antennas, with a 3 dB beamwidth on the order of 30°, are used to provide relatively broad beamwidth coverage for the early portion of the mission.
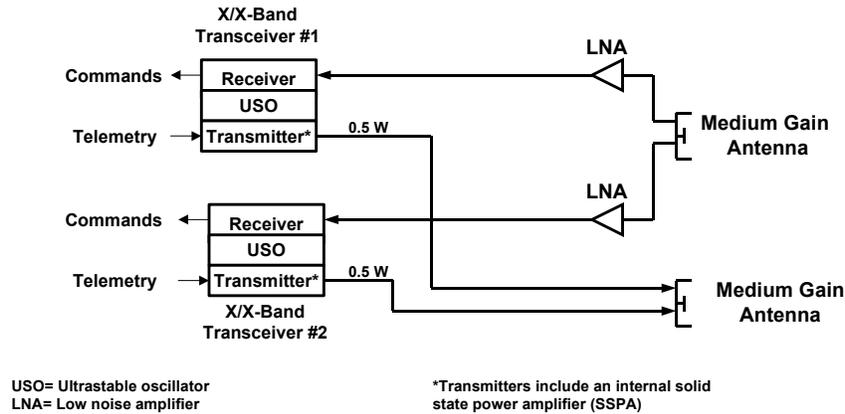

Figure 7. RF communication system block diagram

Unlike many current deep space systems, the spacecraft transceiver is assumed to be noncoherent (downlink frequency not related in phase to the uplink frequency). Coherency is typically required to enable accurate Doppler navigation; however, in this case the complexity is of limited value because the downlink portion of the system is used only for the early portion of the mission. Radio navigation could be provided using a two-way noncoherent technique developed by APL[16] during the early part of the mission and by using one-way uplink Doppler tracking during the rest of the mission. The USO is a very important part of the spacecraft because it enables one-way Doppler tracking (uplink or downlink), low-bit-rate operation, and precision on-board timekeeping. Its stability is assumed to be on the order of 10^{-13} over 10 to 100 seconds with a drift rate on the order of 10^{-12} per day.

4.2   RF Link Analysis

Figure 8 shows the results of an RF link analysis for the mission. It assumes the use of the 70-m diameter Deep Space Network antennas on the ground. As can be seen, the capability to command the spacecraft at 7.8 bps exists out to an Earth range of 30 AU using existing DSN methods and capabilities. This can be extended much further by using "open-loop" commanding, where an unmodulated carrier is transmitted and its frequency is precisely controlled to transfer low-bit-rate command information.

The downlink capability is very limited, with 10 bps operation possible out to an Earth range of only 2 AU. The spacecraft is within this range for only the first five months of the mission. After that period, the optical communication system must be used for downlink telemetry.

4.3   Open Loop Commanding

Deep space command receivers operate by phase-locking to the uplink carrier signal, then generating a coherent reference for use in demodulating the phase-modulated uplink signal. Modern receivers use a threshold carrier tracking loop bandwidth of $2B_{LO} = 18$ Hz to achieve lock to signals as low as −158 dBm. However, when the carrier power is below −158 dBm, the loop bandwidth of the receiver must be reduced below the 18 Hz value typically used today. This is not practical at very low signal levels because of the requirements that the low loop bandwidth places on the uplink signal stability.

-100.0

-125.0

-150.0

-175.0

-200.0

-225.0

Total Received Power (dBm)

UPLINK

DOWNLINK

Major Assumptions:
Medium gain antenna on spacecraft (G= 15 dBic)
70m dish on ground, transmit power= 18.4 kW
S/C transmit power= 0.5 W
S/C receiver noise figure= 1.0 dB
S/C passive loss= 1.0 dB
Uncoded uplink, Rate 1/6 Turbo-coded downlink

Uplink 7.8 bps, 3 dB margin

Uplink receiver lock threshold

Downlink 10 bps, 3 dB margin

Downlink receiver lock threshold

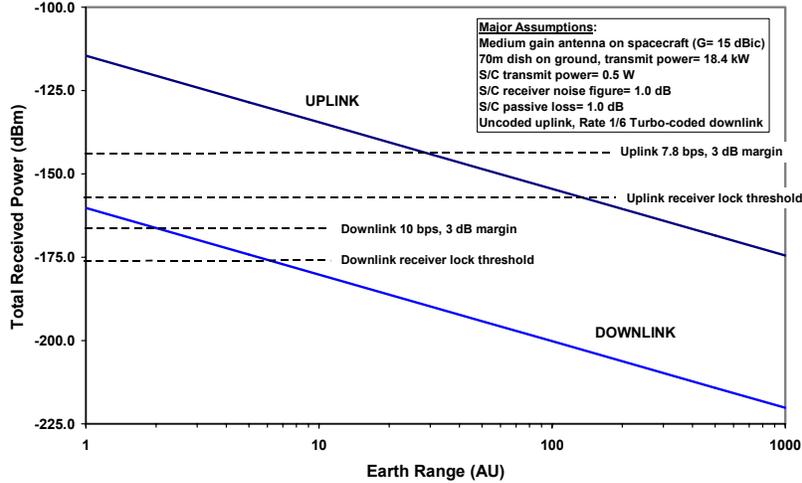1   10   100   1000

Earth Range (AU)

Figure 8. RF link analysis results

An alternative is to operate the command receiver in an open-loop configuration and use a signal processor to estimate the received uplink frequency. The precise value of the uplink frequency (controlled by the ground station) can be used to convey low-bit-rate command information to the spacecraft. This technique requires a combination of long integration time and excellent on-board frequency stability.

A well-know fundamental limit in communication theory is expressed by the Shannon-Hartley theorem:

$$C = B \log_2 \{1 + S/N\}$$

where C is the channel capacity in (bps), B is the channel bandwidth (Hz), S is the signal power (W), $N=N_o B$ is the noise power (W), and N_o is the noise power spectral density (W/Hz). When the channel bandwidth is very wide, then $C \approx 1.44 (S/N_o)$.

The spacecraft receiver noise power spectral density is about $N_o = -175$ dBm/Hz. At 1000 AU, Figure 8 indicates that the uplink total received power using a 70-m ground antenna is S = -175 dBm, so the theoretical channel capacity is $C \approx 1.44$ bps. This could in theory be approached by using an error correction coding scheme. In practice, coding schemes developed by the DSN have performed to within 2 dB of the Shannon-Hartley limit at high bit rates with phase-locked receivers. If we assume that a sub-optimal open-loop system can be designed that is, conservatively, a factor of 10 dB worse than the Shannon-Hartley limit, then we should be able to command at a rate of up to 0.14 bps into the spacecraft at 1000 AU. In practice, for the RISE mission we need to command only at very low bit rates (say one 16-bit command every hour). This implies that, with appropriate processing, we should be able to command the spacecraft out to 1000 AU using an RF uplink, thereby eliminating the need for an optical command uplink. Synchronization can be achieved by sending each command at a previously agreed upon time, say at the top of each hour. This, of course, requires accurate timekeeping on the spacecraft that is provided by the USO.

Practical implementations of the above system remain to be defined. One similar system, implemented on the Deep Space 1 spacecraft, provided tone-based telemetry capability on the downlink[17].

4.4   Mass and Power

Figure 9 shows the mass trend of recent deep space transponder and transceiver systems. The transponder systems to-date have been of the "box and harness" architecture, while the transceiver systems to-date have

been plug-in cards within an "integrated electronics module[18]." While the two system types are not directly comparable, a general trend can be observed by plotting their masses. Note that the curve has fallen sharply since the 1996 timeframe. A 400 g transceiver system using highly integrated RF parts and low-power digital circuitry is currently being developed at APL[19]. Therefore, it is within reason to expect that further integration of the RF and digital functions into one or more chip sets will bring the mass down to 200 g by the year 2015.
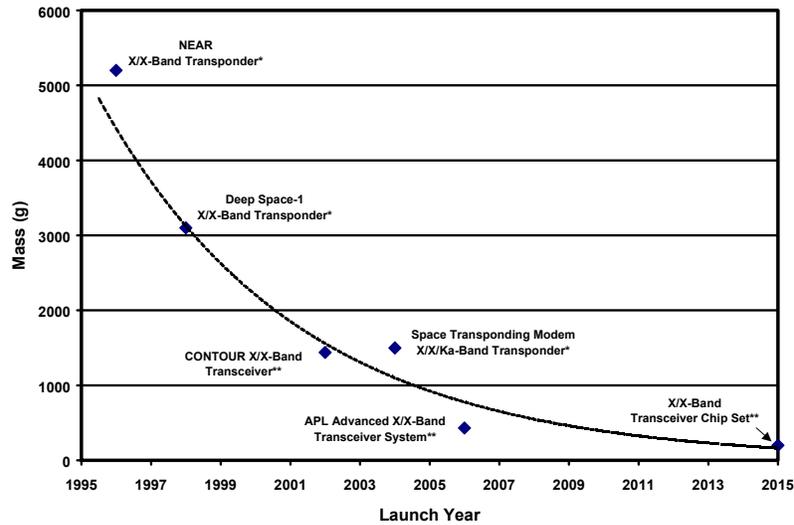

Figure 9. Deep space transponder/transceiver system mass trend. In all cases, the telemetry conditioning and command detection functions are included in the mass. *Includes the power converter and internal crystal oscillator(s); **Excludes power converter and external crystal oscillator.

5. CONCLUSIONS

The realistic interstellar explorer optical system requirements are approximately an order of magnitude below existing or conceptual system designs, which are also less capable in terms of transmitter power. This drives consideration of several enabling technologies already mentioned, which are: high-powered wall-plug efficient, compact, light-weight laser diode or fiber laser arrays, light-weight compact low-power meso-scale or micro-scale (MEMS) beam steering elements, light-weight low-mass large-area optical components, e.g., diffractive optics, such as binary Fresnel lenses, high dynamic range CCD or CMOS star tracking cameras with sophisticated post-detection processing and tone-based commanding to enable RF uplink communications to 1000 AU.

The most important outcome of our study is the need for high-power laser diodes or laser diode pumped fiber lasers. Because they are so wall-plug efficient (~60%), they are very attractive as laser sources but will likely have to be arranged in arrays to achieve the high average power needed at such enormous link distances and to have sufficient redundancy and reliability for the corresponding long mission durations. Although laser diode arrays are presently available with the necessary output power, they are not configured to achieve a coherent, well-formed beam pattern. Some experimental or lower power laser diodes have been fabricated into well-behaved arrays, e.g., vertical cavity self-emitting laser (VCSEL) arrays, which can be spatially coherently coupled to get a relatively clean diffraction-limited single mode beam. A spatially-tight, temporally-stable light output for large powers and low-duty cycles is difficult to achieve because each laser (Fabry-Perot) cavity is disturbed significantly by pulsed modulation, causing frequency changes primarily from thermal disturbances of the cavity size. This drives consideration of external cavity laser diode technology, e.g., distributed feedback (DFB) lasers or distributed Bragg reflector (DBR) lasers. Extrapolations of laser diode output powers[13] indicate that within the time frame of 5-10 years, laser diode arrays should reach the powers needed. Reference 13 also indicates a projection for

MOPA (master oscillator power amplifier) technology, which is a technology that involves the separation of the gain medium and the modulator section of a laser diode, whereas newer technology employs erbium doped fiber amplifiers (EDFA's) with gains on the order of 30 dB. Laser diode arrays are available now, however, in excess of the required output power (40 W). Fiber lasers are now routinely available with CW powers of 200 W.

ACKNOWLEDGEMENTS

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4. NIAC Annual Meeting Presentation, Goddard Spaceflight Center, 6-7 June 2000
    Solicited presentation on Interstellar Probe concepts presented (R. L. McNutt, Jr.) at meeting of the Sun-Earth Connections Advisory Subcommittee (SECAS), NASA HQ, June 13-15, 2000
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