Exo-Atmospheric Telescopes for Deep Space Optical Communications

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Abstract— For deep space optical communications, optical telescopes located above the Earth's atmosphere would have significant performance advantages over telescopes mounted on the Earth's surface. Link outages due to cloud cover would be eliminated, atmospheric attenuation would be eliminated, and signal degradation due to stray light would be reduced. A study has been conducted to compare various exo-atmospheric platforms for the Earth end of the optical link. The three most promising platforms among many initially considered were selected for detailed study: satellites, free-flying airships and tethered airships. System configurations were compared that would have data rate capability comparable to a 6-m to 10-m diameter ground-mounted telescope, 100 percent line-of-sight coverage to a deep space spacecraft in the ecliptic, and at least 80 percent coverage in the event of failure of one Earth terminal. Based upon technical feasibility and readiness, life-cycle cost, performance and risk, a satellite platform is recommended. However, it is noted that airship technology may be advanced in the next decade or so to a level where airships should be reconsidered. Finally, this study provides a basis for a future study to compare systems using Earth-mounted and exo-atmospheric telescopes.

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1. INTRODUCTION

Optical communications systems have great potential for use in deep space communications. Optical systems can have wider bandwidths than radio frequency systems, and very high effective isotropic radiated power (EIRP) can be achieved because of the narrow beamwidths of optical telescopes. Optical systems also have significant disadvantages, many of which arise because of the Earth's atmosphere. This paper is based on a recent study of various approaches to using exo-atmospheric Earth terminals to eliminate the effects of the atmosphere. Such a system could

- Minimize sky irradiance (background) and thus achieve higher signal-to-noise reception for equivalent apertures,
- Minimize atmospheric attenuation of the communication signal,
- Avoid weather-related outages, yielding improved availability,
- Improve uplink capability,
- Reduce (eye) safety concerns from the laser, and
- Eliminate aircraft avoidance concerns.

The study focused on determining what an operational above-the-atmosphere laser communication Earth terminal would look like, and how much it would cost. Specific goals were:

- To define candidate designs of above-the-atmosphere Earth terminals for implementing a deep-space laser communication capability.
- To evaluate the platform options for a deep-space laser communication capability, including airships, independent satellites, or hosting by other NASA assets (e.g., TDRSS). This evaluation includes rough cost estimates.
- To identify the principal risks that must be retired prior to implementing an operational deep-space laser communication capability, and to determine whether a demonstration mission would be necessary or worthwhile in retiring those risks.

Figure 1 is a concept for an orbital system showing a Laser Orbiting Earth Terminal with links to a deep space Remote Terminal and to the Earth via the Tracking Data Relay Satellites (TDRS).

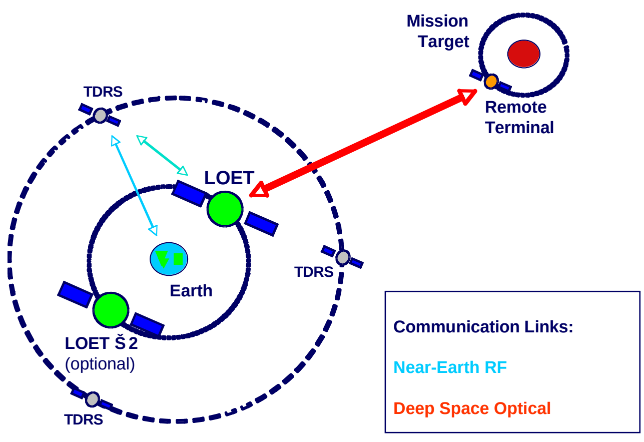

Figure 1 - Laser Orbiting Earth Terminal

The study was conducted by a team of NASA and industry personnel, as indicated by the list of authors and their affiliations. A Final Report [1] was prepared for the NASA Space communications Architecture Working Group (SCAWG).

2. Requirements and Design Parameters

A set of requirements was established to facilitate a fair comparison of candidate systems. A basic premise was to be compatible with the Mars Laser Communications Demonstration (MLCD), which was a planned experiment on the Mars Telecommunications Orbiter (MTO) spacecraft. Although the MTO mission has been cancelled, the parameters were retained for this study.

Functional Requirements

The functional requirements are:

1. The system shall be the Earth-side terminal for a non-terrestrial (above the Earth's surface) Deep-Space Optical Communication System.
2. There shall be one or more Earth terminals located above most of the atmosphere in order to eliminate most atmospheric effects on the optical signal path.
3. The system shall transmit uplink beacon signals to deep-space spacecraft.
4. The system shall transmit uplink data signals (primarily commands) to deep-space spacecraft.
5. The system shall receive downlink data signals (primarily telemetry) from deep-space spacecraft.
6. The system shall be capable of providing operational support to one or more deep-space missions (the Terminal can be sequentially slewed to cover multiple targets, but is not expected to operate with multiple targets simultaneously).
7. A system configuration shall be identified which provides continuous coverage to one remote terminal located near the ecliptic plane (except when the remote terminal is within 3 degrees of the Sun).
8. The system shall have reliability comparable to that of the TDRSS network terminals (design for 7 year lifetime with a 10 year goal).
9. The system shall assume that TDRSS communication is available for the link between the Terminal and the ground.
10. The system need not assume that RF communication is unavailable. In cases where it is more cost-effective to use RF (e.g., low bandwidth communication, ranging) because of technological maturity, there is no requirement to duplicate the function using the optical link.

Performance Requirements

The performance requirements are:

1. The system shall operate at Sun-Earth-Probe (SEP) angles down to 3 degrees.

2. The beacon signal shall be capable of providing an optical power flux density of at least 2 pW/m^2 at a range of 2.66 AU whenever the SEP angle is at least 3 degrees, and a flux density of 20 pW/m^2 at a range of 0.66.
3. The system shall have a probability of at least 95 percent of illuminating the spacecraft target with the required beacon signal strength, without using a downlink signal from the spacecraft as a reference.
4. The uplink shall have at least the following data rate capabilities:
    a. 100 bps to the Mars Lasercom Terminal, per the MLCD uplink specifications, for a demonstration-class mission;
    b. 10 kbps to Mars at a range of 2.66 AU with a SEP angle of 3 degrees;
    c. 100 kbps to Mars at a range of 0.6 AU at night;
    d. 10 Mbps to compatible spacecraft systems under conditions such that the link budget can support this data rate.
5. The downlink shall have at least the following design data rate capabilities:
    a. 1 Mbps from the MLCD system at a range of 2.66 AU with a SEP angle of 3 degrees (with a goal of 4 Mbps);
    b. 10 Mbps from the MLCD system at a range of 0.6 AU at night (with a goal of 60 Mbps or the maximum data rate capability of the MLCD, whichever is less);
    c. 150 Mbps from compatible spacecraft systems under conditions such that the link budget can support this data rate.
6. The system shall be capable of providing the required link performance to any supported spacecraft with probability at least 95 percent, provided that the spacecraft is in the plane of the ecliptic, is not within 3 degrees of the sun, and is not occulted by another object.

Design Parameters

Design parameters for key elements of the system are stated here. These are targeted specifically at the 2020 time frame operational system point design. These are stated as parameters rather than requirements because they are not absolute, and future design efforts may lead to improved trades.

Table 1 shows the uplink parameters.

The uplink aperture of 50 cm was selected as a reasonable value for the 2020 time frame, and is equal to the remote terminal aperture for that time frame.

Table 1. Uplink Parameters

Uplink Parameter	**Value**
Transmit Effective Aperture	50 cm
Operating wavelength	1076 nm
Transmitter Average Power, Beacon	100 W
Transmitter Average Power, Data	20 W
Transmit Beamwidth, Beacon (FWHM, defocused)	7.5 μrad
Transmit Beamwidth, Data (FWHM, Airy disk)	2.5 μrad
Effective Isotropic Radiated Power, Beacon	159.5 dBm
Effective Isotropic Radiated Power, Data	163.6 dBm
Transmit Pointing Accuracy, Beacon with Mars tracking	4.5μrad (3σ)
Transmit Pointing Accuracy, Beacon with Downlink tracking	< 1.2 μrad (3σ)

Beacon and data powers and beacon and data beamwidths were determined from pointing, acquisition and tracking (PA&T) analysis detailed in the appendices to the Final Report [1]. They are selected to meet the worst-case criterion of 20 pW/m^2 at the remote terminal. This is the value being specified for the MLCD mission, from which our EIRP values are calculated.

Transmit pointing and tracking accuracies are likewise determined from PA&T analysis.

Table 2 shows the downlink parameters.

Table 2. Downlink Parameters

Downlink Parameter	**Value**
Receive Effective Aperture (Area Equivalent)	2.6 m (5.0 m^2)
Corrected Focal Plane Field of View	600 μrad
Minimum Diffraction Limited Performance (Equivalent Aperture)	50 cm
Communications Detector Instantaneous Field-of-View	17 μrad
Pointing Accuracy	<120 μrad (1σ, open loop)
Tracking Accuracy	10 μrad
Operating wavelength	1064 nm
Detector Quantum Efficiency	50%
Sun Shielding, Maximum Stray Light (SEP>=3 deg)	0.01 W/(cm^2 sr μm) (TBR)

The receive effective aperture is the nominal equivalent aperture for a monolithic circular primary telescope of equivalent clear collection area.

The communications detector field of view is selected as 17 µrad (3.4") to readily accommodate available detector apertures and to minimize stray light.

Pointing accuracy must accommodate the corrected focal plane field of view and the field of regard of the tracking system sensor. The tracking accuracy is dictated by the communications detector instantaneous field of view.

Detector quantum efficiency is a critical design driver. Current state of the art for the selected operating wavelength of 1064 nm is ~30%. The selected value of 50% is considered attainable for an operational mission in the 2020 time frame.

Stray light suppression at 3 degrees SEP angle is a challenge, as discussed in the telescope section.

3. PLATFORM SELECTION

Of the large number of possible platforms to host the optical Earth terminal, five were initially selected for consideration. Two orbital options were considered: dedicated satellites, and non-dedicated satellites wherein the optical terminal would be mounted on satellites that have other principal applications. Three sub-orbital platforms were considered: high-altitude tethered balloons, high-altitude powered airships, and high-altitude aircraft. After considerable study, a down-selection was made to one orbital and one sub-orbital platform. Selected for detailed study were dedicated satellites and powered airships.

Non-dedicated satellites were eliminated from detailed study for both technical and practical reasons. Technically, there would be a major conflict between orienting the satellite to point the telescope, and orienting it for its primary functions. If the satellite were oriented for its primary functions, a steerable platform would be needed for the telescope, which would be costly in terms of mass, and would not result in near-spherical coverage. A practical reason to eliminate this option from the study was that a realistic result would require detailed knowledge of the host satellite and its functions, which was not available because there was no specific candidate host spacecraft.

High-altitude aircraft were eliminated because of high operational costs, a probable high-vibration environment, and turbulence effects on the uplink. The aircraft would probably operate a low enough altitude that atmospheric effects would cause broadening of the uplink laser beam, causing loss of uplink performance.

Tethered balloons were eliminated for several reasons. Operational costs would be high, because maintenance facilities and teams would be needed at each location. There are safety concerns because of the very long and heavy tethers. There would need to be a safe zone about the ground terminal with diameter of 10 to 20 km or even more. Finally, the technology is so immature that risks are hard to assess.

4. SYSTEM CONCEPTS

Telescopes

Two types of downlink (or receive) telescopes were studied: 1) A large aperture, segmented primary mirror telescope with a spherical primary mirror; the Spherical Primary Optical Telescope (SPOT), which generally has a relatively high technology readiness level and high cost-effectiveness [2]. 2) A multiple telescope configuration, also known as a telescope array or multi-aperture telescope, was studied because of high modularity, low cost, and compact envelope. For the considered telescope size class, cost and technology readiness level reasons, deployable solutions were not considered.

The considered segmented telescope has a primary mirror of six segments and is assumed to be equipped with a simple wave front sensing and control system. The telescope array has six individual apertures, each of which is based on fixed, monolithic primaries. Where the segmented primary telescope needs one set of corrector optics, the telescope array needs 6 sets of corrector optics.

Stray light control is challenging because of the shallow SEP angle of 3 degrees. The goal has been to avoid a traditional baffle, which would be very impractical for 3 degrees SEP angle. Instead, the focus has been on obtaining adequate stray light control by applying field stops, using tight spectral filtering, and partial baffling around the corrector optics. Furthermore, an optional, short partial baffle around the segmented primary mirror is considered. For the telescope array, placing of a solar filter in front of each primary mirror is an additional option.

The single aperture configuration is conceptually simpler, but for the collecting area of 5 square meters considered in this study, the multiple apertures may be easier to package and more scaleable.

For the 5 square meter collecting area, both a single-aperture and multiple-aperture approach are considered viable solutions both technically and economically, for the case of an orbital configuration. In the case of a sub-orbital configuration, using a multi-aperture may make contamination issues easier to deal with because the telescope apertures are sealed, but the outermost surface still needs careful consideration.

Mounting and Pointing the Optical Payload

Two major factors in the system design are that the telescopes must be pointable to almost any direction, and that the mounting and pointing must reduce the impacts of host vehicle motion and vibration on pointing accuracy.

Dedicated Satellites— For the dedicated satellite platform, the entire platform is oriented to point the telescopes, with fine steering used to achieve the final required accuracy. Figure 2 shows the dedicated satellite concept that uses six individual receiving telescopes in an array configuration, with a smaller uplink telescope in the center. Figure 3 shows the configuration with one large receiving telescope, consisting of six segments but with only one detection system. In this case, the uplink telescope is mounted on one side of the receiving telescope.

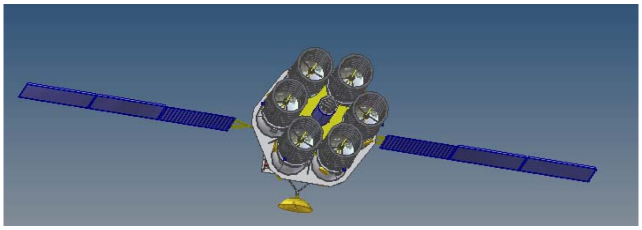

Figure 2 – Dedicated satellite with array of six receiving telescopes

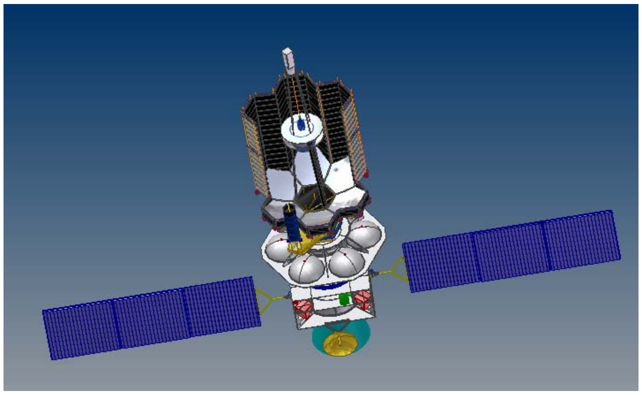

Figure 3 – Dedicated satellite with single receiving telescope having six segments

Airships— Figure 4 shows a high-altitude powered airship configuration. The optical subsystem is mounted on a gimbaled platform, which is in turn mounted onto the top of the airship. The gimbaled platform has approximately hemispherical coverage. Some approximate parameters of the airship system are given in Table 3.

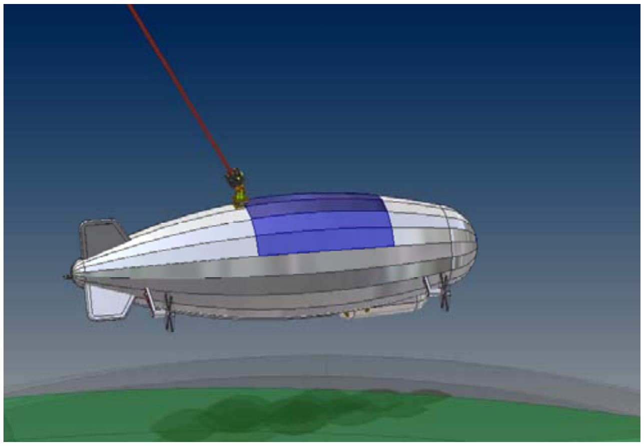

Figure 4 – Airship configuration

Table 3. Airship Parameters

Disturbance Free Payloads— For both the satellite and the airship systems, a Disturbance Free Payload (DFP) approach is used to isolate the telescopes from the vibration of the host vehicle, and for fine pointing. This approach was developed by the Lockheed Martin Advanced technology Center. The payload is magnetically mounted to the host vehicle using “voice” coils. There is no physical connection, except for needed wiring. Pointing error signals from the optical payload are used by the control system as feedback signals. Host vehicle vibration is attenuated on the order of 40 dB to 60 dB, depending on the vibration spectrum and on the update rate and signal-to-noise ratio of the pointing error signals. The DFP is also used for fine pointing of the telescope, over a pointing range on the order of 1 degree.

Satellite Platform System and Operations Concepts

Figure 5 is a sketch of the satellite platform system that helps to illustrate the operations concept. As shown in Figure 1, two orbiting Earth terminals are needed to achieve 100 percent coverage of remote terminals located anywhere in the ecliptic. If one Earth terminal fails, there is still at least 85 percent coverage.

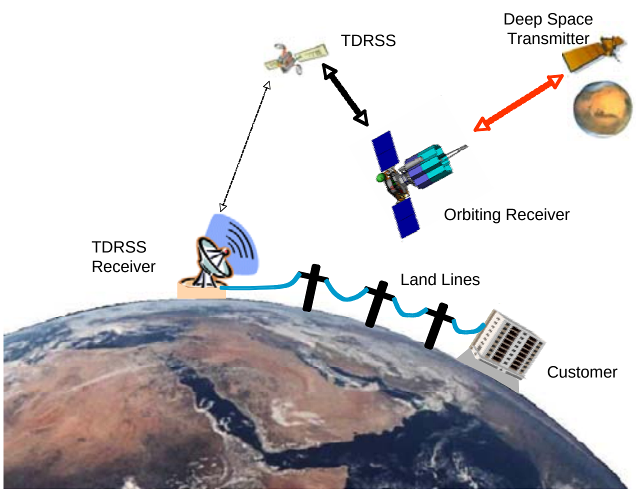

Figure 5 – Satellite Platform System

The downlink optical signal path is from the remote terminal to the orbiting receiver. The orbiting terminal transmits the received signal over a radio frequency link to a TDRSS satellite, which relays the signal to a standard TDRSS Earth terminal, which in turn relays the signal to the customer over existing networks. The uplink path is just the opposite.

Operations are rather simple. Normal TDRSS operations are used for the Earth end of the links. The orbiting Earth terminal is operated by a typical Mission Operations System (MOS) for satellite missions, perhaps sharing a facility with another mission. There is no routine maintenance, except for the MOS. It is estimated that the orbiting Earth terminals will have a lifetime of approximately seven years. System upgrades will be made when satellite replacements are necessary.

Airship Platform System and Operations Concepts

The proposed global configuration of the airship system is shown in Figure 6. Just as the Deep Space Network requires three locations in order to achieve 100 percent coverage of distant spacecraft, there must be three airships located at three approximately equally-spaced longitudes. The airships are flown above the jet stream and above most of the atmosphere, at an altitude of approximately 18 km. Station is maintained by the airship propulsion system, which can maintain air speeds up to 35 kts. The southern hemisphere was chosen so that the airships could be located over oceans for safety reasons, and because over-flights of land areas would be minimized to enhance political acceptability.

Figure 6 – Airship System Global Configuration

The airships require maintenance approximately annually. This is necessary to repair the fabric and to service the power and propulsion systems, the gimbaled platform and the optical payload, and other elements. Thus there are four airships, with three on station, and one being serviced or in-route between its station and the home facility. A home facility would be located in the United States, with an emergency facility in Australia. It is estimated that the airships would need to be replaced every five years.

Figure 7 illustrates the communications links for the airship system, and the maintenance facility. The communications links are basically the same as for the satellite system. The maintenance facility is quite complex and expensive. A large hanger is required to house the airships as they are serviced. Staffing, parts, supplies security, are safety systems are required. The MOS is not shown. This would be more complicated than for a satellite system because of the need to fly the airships, schedule maintenance, and handle emergencies.

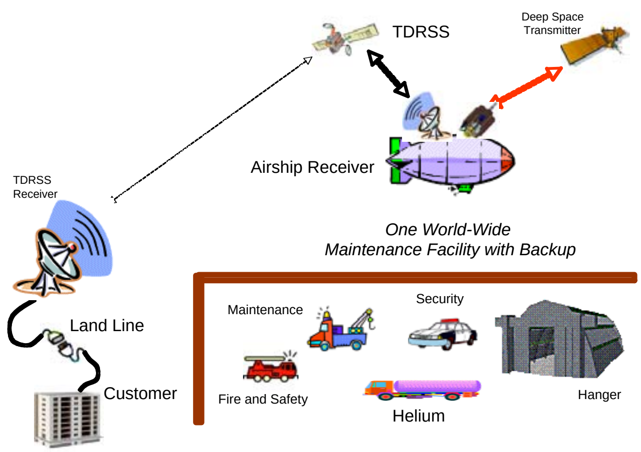

Figure 7 – Airship System Communications Links and Maintenance Facility

5. POINTING, ACQUISITION AND TRACKING

Pointing, Acquisition and Tracking of the optical payload are three distinct steps. First, in order to send a beacon signal to the remote terminal, the uplink telescope must be accurately pointed to the remote terminal without benefit of having received a downlink signal from the target. This is called blind pointing. Acquisition is the step of receiving the downlink signal from the remote terminal, after the remote terminal receives the beacon signal. When the downlink signal is received, it is tracked to maintain pointing of the receive telescope, and for accurate pointing of the uplink telescope in transmitting uplink data. This tracking needs to be more accurate than the blind pointing, so as to enable use of a narrower uplink beamwidth for data transmission than for the beacon signal, thereby making better use of laser power.

Pointing

Blind pointing requires use of a reference signal. Either the uplink telescope or separate star tracker telescopes can be used to track the reference signal(s). Using the uplink telescope minimizes mass and simplifies alignment of the receive and transmit optics. This works well when the remote terminal is orbiting a planet, as the planet makes a good reference. When not orbiting a planet, the uplink telescope can be used as a star tracker, provided that there are a sufficient number of sufficiently strong stars within the field of view with the telescope pointed close to the target spacecraft using a priori information. However, this approach does not work when there is stray light from the Sun. Analysis shows that the approach does not work well when the SEP angle is less than approximately 40 degrees, which is an unacceptable situation. Therefore, separate star trackers are needed. The recommended configuration is two star trackers, mounted approximately orthogonally to each other and to the uplink telescope.

Table 4 shows an error budget for blind pointing using Mars as the reference signal during orbit mode blind pointing. Mars tracking is used as the reference thru the 50 cm uplink telescope aperture. The total mispoint angle estimate is 1.254 µrad (3- sigma). There is a 71.8 % margin in the pointing accuracy relative to the total allocation of 4.44 µrad.

Table 5 shows an error budget for blind pointing using star trackers. A case is deliberately shown wherein the mispoint allocation is not met. The total mispoint angle estimate is 6.936 µrad (3 sigma). This situation occurs because the host spacecraft in this case is assumed to have a very high vibration environment, typical of an Iridium satellite. The largest contribution to the error is the residual tracking error, that is, the error in attenuating the spacecraft motion. Better tracking of the vibration would require a higher update than the 0.5 Hz that is used. But a higher update rate would mean higher pointing knowledge jitter, because of shorter star-tracker detection intervals.

Three solutions were identified to overcome this deficit. First, the uplink beacon laser power could be increased thereby allowing use of a wider uplink beamwidth, thus loosening the required blind pointing. Second, the system could be mounted on a quieter spacecraft. The residual tracking error without changing the update rate would be approximately 10 times lower for an Olympus or Landsat vibration environment, and more than 100 times lower for a highly stable satellite such as the Relay Mirror Experiment (RME). Third, gyro sensors could be used to increase the update rate to the DFP up to about 10 Hz. With this change the residual jitter due to the satellite vibrations can be significantly reduced, but the necessary analysis has not been done. Although cost and performance trades are needed to determine the best approach, there appears to be a viable solution.

Acquisition

Acquisition is the step of receiving the downlink signal from the remote terminal. After blind pointing is accomplished, the beacon signal is radiated towards the remote terminal. The field of view of the remote terminal and the a priori pointing of the remote terminal must be such that the Earth terminal is within the FOV. The remote terminal receives the beacon signal, measures the direction to the Earth terminal, calculates the required pointing for its downlink beam, and radiates the downlink beam to the Earth terminal. The Earth terminal then tracks the location of the remote terminal, as described below, and radiates the uplink data signal to the remote terminal. Telemetry reception can begin approximately one round-trip-light-time (RTLT) after beacon radiation begins. Uplink data can be received 1.5 RTLT after start of beacon radiation. In an planetary orbit situation, the remote terminal may go into an come out of occultation, and it is important to complete acquisition as soon as possible after occultation. In this case, uplink radiation can begin before occultation ends, so that the beacon signal is received as soon as occultation ends. Acquisition of downlink occurs one-half RTLT after end of occultation, and uplink data is received one RTLT after end of occultation.

Table 4. Error budget for blind pointing using Mars as the reference signal

Error Sources	Estimate	justification	assumptions
	urad		Use 10 Hz update rate throughout
total mispoint allocation, radial	4.440	required to deliver 2 pW/m2 at 2.6 AU with 7.49 urad FWHM beamwidth	use high power for initial uplink step; 50.7 W out of telescope (100 W laser)
JITTER ESTIMATE (1 sigma)	0.160	RSS of jitter components	
pointing knowledge jitter	0.070	50 cm aperture; 10 nm filter (1062-1072 nm); 30ke/pixel noise level; 10 Hz; 2 urad/pixel; InGaAs sensor	
residual tracking error	0.130	DFP isolates telescope from s/c vibration; assume Iridium type vibration as worst case;	DFP platform like response -60 dB transmissibility for DFB for all frequency bands; 10 Hz update rate
sensor non-uniformity error	0.060	InGaAs FPA, assume sky radiance flux levels (will be lower)	
fine pointing mechanism	0.020	400 nrad FPM with 20x optical mag	
BIAS ERROR ESTIMATE	0.405	RSS of bias components	
pointing knowledge bias	0.370	bias due to Mars phase: no seeing effects; using edge detection	
s/c ephemeris	0.070	varies with range; worst at close ranges	worst case @ 0.5 AU with 5 km s/c position knowledge
point ahead	0.002	max point ahead angle = 200 urad; max DFP attitude control error = 10 urad	=200uradX10urad=2nrad
misalignment (thermal, mechanical)	0.150	using optical metering	use pick-off part of uplink with a retro on same FPA
TOTAL MISPOINT ERROR ESTIMATE	1.254	=srt(2)*(bias + 3*jitter); radial	
MARGIN, urad	3.186		
MARGIN, %	71.759	need 30 % margin as reserve: standard engineering practice	30 % at early phases of project (study phase) and due to maturity of technology

Table 5. Error budget for blind pointing using star trackers with noisy spacecraft

Error Sources	Allocation	Estimate	justification	assumptions
	urad	urad		Use 0.5 Hz update rate throughtout
total mispoint allocation, radial	4.440	4.440	required to deliver 2 pW/m2 at 2.6 AU with 7.49 urad FWHM beamwidth	use high power for initial uplink step; 50.7 W out of telescope (100 W laser) specified by Michael Dennis
JITTER ESTIMATE (1 sigma)	1.110	1.484	RSS of jitter components	
pointing knowledge jitter		0.750	separate aperture; 50 cm aperture; 18 stars of mag 9 or greater; 3deg FOV; 1E6e/pixel noise level (SEP= 88); 0.5 Hz; 51 urad/pixel	star tracker has separate aperture than uplink telescope;
residual tracking error		1.280	DFP isolates telescope from s/c vibration; assume Iridium type vibration as worst case;	DFP platform like response -40 dB transmissibility for DFB for all frequency bands; 0.5 Hz update rate
fine pointing mechanism		0.020	400 nrad FPM with 20x optical mag	
BIAS ERROR ESTIMATE	1.110	0.453	RSS of bias components	
pointing knowledge bias		0.000	assume stars are symmetric point source; & optics do not distort PSF	
s/c ephemeris		0.340	varies with range; worst at close ranges	worst case @ 0.1 AU with 5 km s/c position knowledge
point ahead		0.002	max point ahead angle = 200 urad; max DFP attitude control error = 10 urad	=200uradX10urad=2nrad
misalignment (thermal, mechanical)		0.300	using optical metering	have a metering laser diode that goes to star tracker
transformation error in roll-axis of star tracker		0.000	using two orthogonally mounted star trackers	
TOTAL MISPOINT ERROR ESTIMATE		6.936	=srt(2)*(bias + 3*jitter); radial	
MARGIN, urad		-2.496		
MARGIN, %		-56.215	need 30 % margin as reserve: standard engineering practice	30 % at early phases of project (study phase) and due to maturity of technology

Table 6. Error budget for tracking of the MLCD signal

Error Sources	Estimate	justification	assumptions
	urad		Use 10 Hz update rate throughout
total mispoint allocation	4.440	required to deliver 2 pW/m2 at 2.6 AU with 7.49 urad FWHM beamwidth	use lower power during tracking step; 50.7 W out of telescope (100 W laser) specified by Michael Dennis
JITTER (1 sigma, one-axis)	0.425	RSS of jitter components	
pointing knowledge jitter	0.400	5 W downlink; 50 cm aperture; 3E4 e/px noise level (SEP=3deg); 10 Hz; 10 nm filter; InGaAs;	1064 nm
sensor non-uniformity error	0.060	InGaAs FPA, assume sky radiance flux levels (will be lower)	
residual tracking error	0.130	DFP isolates telescope from s/c vibration; assume Iridium type vibration as worst case;	DFP platform like response -60 dB transmissibility for DFB for all frequency bands; 10 Hz update rate
fine pointing mechanism	0.020	400 nrad FPM with 20x optical mag	
BIAS, one-axis	0.250		
pointing knowledge bias	0.200	presence of Mars signal introduces bias shift on centroiding: assume no seeing effects	assume downlink is symmetric point source; & our optics donot distort PSF
point ahead	0.002	max point ahead angle = 200 urad; max DFP attitude control error = 10 urad	=200uradX10urad
misalignment (thermal, mechanical)	0.150	using optical metering	use pick-off part of uplink with a retro on same FPA
TOTAL MISPOINT ERROR ESTIMATE	2.158	=srt(2)*(bias + 3*jitter); radial	
MARGIN, urad	2.282		
MARGIN, %	51.395	need 30 % margin as reserve: standard engineering practice	30 % at early phases of project (study phase) and due to maturity of technology

Tracking

Tracking is the process of using the signal received from the remote spacecraft for uplink telescope pointing. The uplink telescope is used for this tracking, because the receive telescope is designed for detection of the telemetry data, and uses detectors which are not suitable for tracking. Table 6 shows an error budget for tracking the signal that was planned for the MLCD. The pointing allocation of 4.44 μrad necessary for the beacon uplink is met with more than 50 percent margin. This pointing is also adequate for a low data rate uplink, with the same uplink beamwidth used for the data as for the beacon.

The tracking performance using the MLCD signal is not sufficient to meet the 1.2-μrad uplink pointing accuracy for high rate uplink data circa 2020. But the tracking performance will be significantly better then, because the remote terminal will have more than ten times higher EIRP. This will reduce the major error source, pointing knowledge jitter, by more than a factor of three. The residual tracking error can also be reduced as discussed for blind pointing. This will enable further reduction in pointing knowledge jitter by use of a lower update rate. Optimization has not been done, but there is confidence that the required performance can be met.

6. COST ESTIMATES

Cost estimates were made for the satellite and airship systems, in FY05 dollars, with no adjustment for inflation. Details are given in the Final Report [1].

The cost estimates include all significant and identified costs. These include the host platform (satellite bus or airship), the launch vehicle, the payload (telescope, support structure, DFP system, communications package, PA&T system), mission operations, management, system engineering, replacement every 7 years for the satellite system and every 5 years for the airship system, new technology infusion, and maintenance.

For the satellite system, cost estimates for the satellite bus and launch systems were made by the GSFC Integrated Mission Design Center (IMDC). Payload and mission operations costs were made by the study team. The implementation cost was estimated at $972M, and the annual recurring cost was estimated at $114M, with an estimated uncertainty of 20 percent.

For the airship system, the overall cost estimate was made by JPL, with inputs from the rest of the team. Due to the low technology readiness level, the airship costs are estimated to have an uncertainty of 50 percent. Overall, the implementation cost was estimated at $1,137M, and the annual recurring cost at $197M, with uncertainties of 30 percent.

The airship system is estimated to cost more than the satellite system, mainly because twice as many units are required. The implementation cost is estimated to be approximately 17 percent higher for the airship system. However, the uncertainty in the costs is greater than the difference in the estimates. It is possible that further development of airship technology could lead to lower implementation costs.

The difference in annual recurring costs is more significant, with the airship system costing an estimated 73 percent more per year than the satellite system. This is mainly due to the shorter replacement cycle (5 yr vs. 7 yr) and the higher operations and maintenance costs.

We point out that the cost comparisons are valid only for the chosen system configurations, with a two-satellite system compared to a four-airship system. These systems would provide highly reliable real time communications to one remote deep space terminal, and would probably provide adequate coverage for a small number of contemporaneous missions, depending on the needs of these missions.

Further studies are needed to perform cost and system configuration trades for realistic overall deep space communications needs. The trades should include both exo-atmospheric and terrestrial optical systems, as well as microwave systems. The trades should also be for system configurations to support the feasible range of future mission sets. Identifying realistic future mission sets may be the hardest and least accurate part of the needed work. The study reported on here provides useful data on the potential exo-atmospheric system elements.

7. Technology Challenges and Risk

Most of the technologies used for the recommended satellite configuration are either established or are reasonable extrapolations of current capabilities, having Technology Readiness Levels (TRLs) of 6 or above. However, the desire is to be able to incorporate systems capable of greatly improved performance into a high-availability architecture for operational deployment. In this sense, there is system risk that could potentially be mitigated by a technology development and demonstration.

Pointing

Accurate pointing of the uplink is required in order to achieve adequate flux density at the remote terminal using a realistic laser power level. This is already a concern in the case of the Mars link, and will be even more significant as the range increases to more distant links. Some relevant risk areas are platform stability, star tracker performance under realistic conditions, alignment between the star tracker and the uplink path, and optical isolation between the uplink and the tracking detector.

For example, the DFP approach is recommended for platform stability. This needs to be more completely assessed, and, as a backup, a fast steering mirror approach coupled with a passive isolation system should be considered.

Optical isolation between the uplink transmit optical channel and the tracking detector is a significant risk when tracking the signal from the remote terminal, and if using the transmit telescope as a star tracker. Significant back-scatter from the high power uplink into the tracking detector will reduce the SNR and thereby reduce the accuracy of the knowledge.

Near-Sun Telescope Performance

The Earth terminal transmit and receive telescopes need to be operated angularly close to the Sun for significant amounts of time. Not only does this exacerbate the stray light issues, but the coatings and mirror materials that are used need to be compatible with the solar exposure. In-depth analysis is needed of materials for aperture coatings and solar filters.

Detectors

There is ongoing development of improved photo-counting detectors appropriate for ground terminals. Improvements in speed, detection efficiency, dark current noise, and/or detector dead time, depending on the specific detector technology, are essential to enable future capacity requirements. Space qualification is needed.

Laser Power Amplifiers

High power optical fiber amplifier technology is progressing at a fast pace for terrestrial applications. NASA has the opportunity to leverage this work for deep-space laser communications. Higher power may be needed for beacon signals to distances beyond Mars, and is needed to achieve the high telemetry rates proposed for 2020 and beyond. Improved efficiency is key to achieving higher power in the input-power-limited spacecraft environment.

Thermal Management

The concentrated power dissipation of high-power laser components is of concern for space-borne missions, especially from the perspective of reliability. There are also impacts on pointing biases. Appropriate thermal management strategies and reliability assessments are needed.

Airships

The technology readiness level for high altitude airships is fairly low. High lift capability (~1000 kg) is needed for a top-mounted payload on an airship that operates at an altitude of 18 km. Fabrics, power systems, propulsion, navigation and control all present technology challenges. Technology development and demonstration are necessary before airships can become a viable operational approach.

Risk Mitigation Approach

In many areas, the first and perhaps most important step to mitigate the identified risks should be more detailed analyses. These analyses will identify the needed testing, and will provide a basis for judging the test results – which should validate the analyses.

Some of the risks can be mitigated by ground testing. These include lasers, detectors and coatings. Space qualification for such components is well understood. Radiation susceptibility can be characterized at appropriate facilities.

Airborne testing may be suitable for some technologies. The cost and benefits of such testing need to be assessed in each instance. For example, a pointing experiment on an aircraft might be very expensive and might lead to erroneous conclusions for a satellite application.

Space-based testing of a fully functional configuration is essential before implementing a fully operational satellite system. This would provide assurance that the necessary technologies are in place, but that the necessary system engineering has been done to ensure that the terminal performs as expected. The ISS might be a suitable platform for such a demonstration. To reduce costs, the receive aperture and thus the downlink data rate could be reduced. A suitable remote terminal would be needed, similar in characteristics to the MLCD terminal.

8. SUMMARY AND CONCLUSIONS

The following conclusions are made:

1. Exo-atmospheric optical Earth terminals are feasible.
2. Dedicated satellites have both the lowest cost and the lowest risk.
3. The biggest technical challenge is pointing the uplink beacon sufficiently accurately.
4. High-altitude powered airships may become cost-competitive, but a major development would be required, and telescope pointing would be difficult.
5. Technology developments by NASA are recommended in the areas of telescope pointing, near-sun telescope performance, photon-counting detectors, high-efficiency laser amplifiers, and thermal management.
6. It is recommended that NASA leave airship development up to other agencies.
7. System studies are needed to compare the costs of ground-based to exo-atmospheric systems, for comparable and justifiable overall operational capabilities.

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