System Requirements for a Deep Space Optical Transceiver

C. Chen, J. W. Alexander, H. Hemmati, S. Monacos, T.Yan, S. Lee, J. R. Lesh and S. Zingales
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

The functional requirements and design drivers for an Optical Communications subsystem are assessed based on the system requirements imposed by a proposed Europa Orbiter mission. Unlike near-Earth optical communications systems, deep space missions impose a unique set of requirements that drives the subsystem design. Significant challenges on laser efficiency, thermal control, pointing and tracking, stray/scatter light control, and subsystem mass/power need to be addressed for a successful subsystem implementation. The baseline design concept for a lasercom subsystem for the Europa orbiter mission employs a 30-cm diameter, diffraction-limited telescope, and a diode pumped solid state laser operating at 1.06 ?m to support downlink communications. The baseline pointing and tracking approach is to perform Earth Image tracking with occasional calibration using the Earth-moon or Earth-star images. At high phase angles when the Earth image does not provide sufficient brightness for high rate tracking, inertial sensors (accelerometers) measurements are used to propagate the knowledge of the optical boresight at a higher rate in between celestial reference updates. Additionally, uplink beacon tracking will be used to support pointing at short range and near solar opposition when Earth image along does not provide sufficient signal power for tracking.

1. INTRODUCTION

Laser communication (lasercom) technology has been under development for both intersatellite cross-link and deep space return link applications for more than two decades. For crosslink terminals, lasercom technology can potentially offer significant performance improvements using lower transmit power and smaller aperture diameters. Unlike RF crosslink systems where the spectrum usage is tightly regulated, optical crosslinks are not subject to frequency regulation, and hence are very attractive for high bandwidth applications such as LEO constellations. By virtual of its narrow transmit beamwidth, lasercom technology can also offer significant potential of frequency reuse and improved channel security. The technologies needed to implement LEO or GEO optical crosslinks have been under development over the last two decades. These investments are expected to lead to full-up system implementation within the next decade.

For deep space return links applications, the advantages of lasercom technology lies primarily on the promise of improved data return with lower mass and power of the subsystem. Deep space optical return link must overcome significant existing asset investment of the RF network. Nevertheless, the smaller beam divergence resulting from the short operating wavelength can permit communication systems to use a smaller aperture antenna while providing comparable or increased channel throughput when compared to a RF system. For planetary missions, the reduction in communications system size can also lead to a simplified spacecraft design and, in some cases, the reduction in size can also permit a wider diversity of launch vehicle options. This latter fact is particularly important given the fiscal projection for NASA's planetary program. Smaller spacecrafts currently being proposed for the planetary and space physics missions will impose stringent demands on the communication system. For these missions, laser communication technology offers an attractive method of providing increased data throughput while at the same time decreasing the mass and size of the communications subsystem.

The system requirements and design for a deep space optical link are very different from that of a near Earth optical crosslink terminal. This is because of deep space mission tends to have a much wider range of mission parameters, including data rates, distance, thermal environment, and orbital geometry. A deep space link, for example, needs to function from launch (a few thousand km) to the end of mission (10's of AU). Successful subsystem design must take into account the mission coverage, dynamic range, and operational requirements for communications and beam pointing. Lack of a well-defined set of customer mission requirements can lead to over-simplification of design and a system concept that appears adequate but, on closer examination, cannot achieve the coverage requirement of any particular mission.

During FY1998, a development effort was initiated under JPL's Advanced Deep Space System Development (ADSSD) Program. The goal of the effort was to develop an implement-able conceptual design that can be validated in both laboratory environment and on short-term flight demos. The subsystem is intended to provide link augmentation to future deep space missions that require high rate downlinks. Such a system is envisioned to support future deep space missions by providing a significant enhancement of data return capability in addition to planned RF telecommunications subsystem.

Using the Europa Orbiter mission as a reference, a baseline subsystem design concept was developed. Because of cost limitation, it is assumed throughout the study that only minimal technology development effort will be included. Furthermore, it is assumed that a 10-m class ground station will be available as a companion terminal to receive the optical downlink, and that a kW-class uplink laser is available as either an uplink source or a pointing reference. The cost of the ground station and regulatory issues of operating a kW-class laser are not addressed during the study. During the study, a number of design decisions were made based on consideration of the mission, spacecraft design, and pointing acquisition and tracking. This report is a summary of the high-level design decisions that lead to the conceptual design of the lasercom terminal.

2. OBJECTIVES AND HIGH LEVEL REQUIREMENTS

Traditionally, the communications system requirements are flown down from the science objectives which define the data volume/data rate requirements, and from the higher level requirements that identify mission operability and coverage requirements. Furthermore, for deep space missions the spacecraft and the communications system designs tend to be closely coupled with mission and trajectory planning. For the lasercom terminal development effort, such a flow down process cannot be directly applied because of the lack of a committed mission with well-stated mission plan and coverage requirements. Lack of a customer mission also implies that the system requirements are at best "objectives". It is recognized that the development of objectives is a highly subjective process. For the conceptual effort, these development objectives were guided by the following rationales:

1. Need to achieve performance advantage over comparable RF system implementation
2. Need to have minimum impact on the spacecraft design
3. Need to provide adequate pointing acquisition and tracking capability
4. Need to provide operability and mission coverage similar to past RF missions. This includes coverage over most mission phases, including near-Earth cruise phase and during solar conjunctions, and including the capability to support spacecraft navigation and time correlation services

Each of these high level objectives are further expanded as follows:

Performance Advantages over RF
One of the desired characteristics of the lasercom terminal is to demonstrate link advantage relative to RF. By operating at a wavelength of 1 um instead of 1 cm (Ka-band), optical link has a theoretical 78.9 dB advantage when aperture sizes and other losses are equal. Realistic comparison of a deep space return link, however, shows that the optical link has only minimum performance advantage over the RF technology. This is because

1. Cost consideration limits the aperture diameters to be much smaller than that of the RF system (0.3 m vs. 1.5 m for spacecraft antenna, and 10m vs. 70m for ground station).
2. Diode-pumped solid state laser has much lower power efficiency compared to RF amplifiers (10% vs 40%). EDFA technology can potentially achieve a better efficiency (~20%). However, reduction in antenna gain and receiver sensitivity more than compensate for the increased efficiency.
3. Optical system is much more sensitive to pointing loss and atmospheric attenuation.
4. The detection sensitivity is significantly worse at optical frequency, even with the use of high order PPM modulation (1 bit/60K vs. 1 bit/10 photons). The optical receiver sensitivity can further degrade to 20-30 photons/bit under daytime conditions with current receiver technology.

Shown in Table 1 is the performance comparison between the proposed optical link and a near-term achievable RF link performance using Ka-band. Assuming equal power for the receiver and for monitor and control functions, the comparison is based on a constant DC power consumption by the transmit power amplifier. The optical link estimate is based on a 30 cm-aperture diameter transmitter and a 10m-diameter receiver using 256-ary PPM and a 1.06 um diode-pumped solid state laser. The Ka-band performance projection is based on the assumption that continuing improvements in Ka-band will lead to (a) implementation of Ka-band reception capability on the 70 m stations, (b) improved receiver aperture efficiency with either the array feed or adjustable mirror technology, (c) improved spacecraft Ka-band transmitter power efficiency with high efficiency TWTAs, and (d) Improved transmit aperture efficiency using off axis or displaced-axis antenna.

Table 1. Comparison of optical and near term Ka-band system performance

		Ka-Band		Optical		Advantages
1	Transmit EIRP		dB		dB	dB
	Antenna diameter, ideal gain	1.5m	54.03	0.3m	118.95	62.42
	Antenna Efficiency (including beam shaping, etc.)	80%	-0.97	51%	-2.92	-1.96
	Waveguide/path loss		-2.00	70%	-1.55	0.45
	Transmit Power Efficiency	40%	-3.98	10%	-10.00	-6.02
2	Pointing Loss		-0.50		-2.00	-1.50
3	Space Loss, 1 AU		-226.07		-304.97	-78.90
4	Atmospheric Attenuation at 30 degrees, 90% weather		-0.40		-1.40	-1.00
5	Receiver Gain					
	Receiver Antenna Gain	70m	87.41	10m	149.40	62.00
	Receiver Aperture Efficiency including path loss	43%	-3.67	45%	-3.47	0.20
6	Detection Efficiency (bits/Joule)	1 bit/60K	210.82	1 bit/10 hv	177.29	-33.53
	NET OPTICAL GAIN					4.67

In order to achieve comparable or better performance compared to an RF system, the lasercom terminal design needs to:

1. employ high order PPM instead of OOK modulation. A baseline of 256-PPM is selected. Either diode-pumped solid state laser or EDFA can be used, depending on the peak-power/average power trade,
2. employ optical aperture diameter of at least 1/5 to 1/10 of the Ka-band antenna. Assuming a Ka-band antenna diameter of 1.5 m, the optical aperture should be at least 15-30 cm. We shall assume a 30-cm aperture.
3. employ diffraction-limited transmit optics, needed to achieve maximum antenna gain advantage.
4. provide a tight transmit pointing budget and pointing loss (2 dB)

Mission and Coverage Consideration

Even though optical communications technology can offer comparable data rate as a RF system, optical link exhibits a number of short-comings for mission coverage. The are:

1. Difficulty in handling attitude constrained mission phase: For almost all deep space missions, the mission profile will impose limits on spacecraft attitude and pointing of spacecraft during certain mission phases. Examples of such mission phases are the launch phase or inner cruise phase where spacecraft attitude is constrained by the trajectory or thermal consideration. Even with a gimbaled antenna, there will be coverage holes that can potentially limit the mission planning.
2. Difficulty in providing high link availability on demand: Certain mission phase will require high visibility in the spacecraft state, such as during orbit injection or maneuver burns. Timely return of spacecraft data will allow adequate planning and execution of the mission. The optical downlink is much more sensitive to the weather outage and hence will require either multiple ground stations or a mission design that is less sensitive to coverage gaps.
3. Difficulty in maintaining link with degraded spacecraft performance: This can include degraded station-keeping capability, degraded star tracker performance, or loss of time reference. Traditional sun-pointing safe mode is not available because of the narrow optical downlink will lead to unmanageable acquisition time.
4. Limited Solar Conjunction/opposition availability: This limit is imposed by the sun-spacecraft-Earth geometry. In addition to the effect of increase background noise at Earth receiver, the small Sun-Probe-Earth (SPE) angle also implies that the spacecraft's pointing and tracking detector will experience increased background noise level which can lead to pointing outage. Shown in Figure 1 is a plot of the SPE angle versus the phase angle, and shown in Table 2 is the outage period due to the sun exclusion angle for a spacecraft at Jupiter. If a lasercom terminal is designed to operate at a limiting SPE angle of 2 degrees, there will be 48 days of pointing outage per revolution of the Earth-Jupiter geometry (13 months). In contrast, RF system outage occurs only during superior conjunction when the SPE angle is within 1

degree (SEP angle of 5 degrees), which lasts approximately 14 days. In order to provide good mission coverage and reduce time loss during conjunction, therefore, the system should be designed to operate at a reasonable SPE angle

Because of the overage consideration, for near-term mission the prudent design choice is to employ a RF link to close the coverage gap identified above. Such a link can also be used to provide command and tracking information, thus eliminating the need to provide uplink receiver and tracking capability at the optical payload.

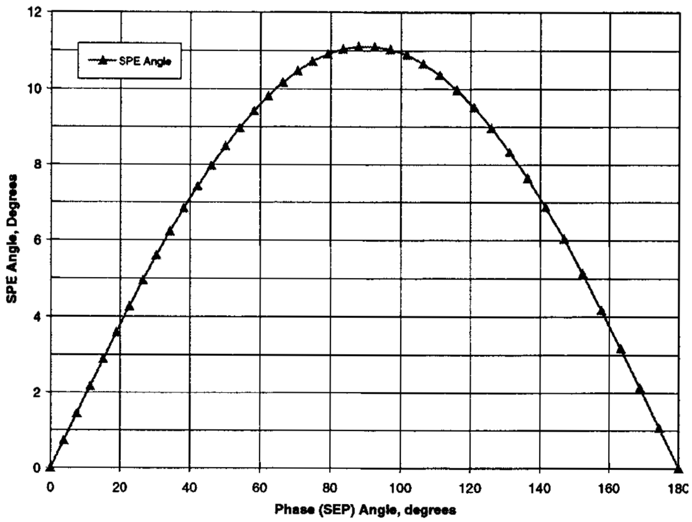

Figure 1. SPE and SEP angle for the Earth-Europa geometry

Table 2. Outage period due to SPE for a Jupiter mission

Criteria	Jupiter Opposition Outage	Jupiter Conjunction Outage
SPE angle > 1 degrees	10 days	14 days
SPE angle > 2 degrees	20 days	28 days
SPE angle > 3 degrees	30 days	42 days

Spacecraft Design Consideration

Lightweight and low power design is essential for the mission. The most significant impact of the mass and power consideration is the elimination of a coarse pointing gimbal and rely on the spacecraft to provide coarse pointing of the downlink. Without a coarse pointing gimbal, the optical subsystem should provide an acquisition and tracking field of view (field of regard) comparable or larger than the achievable spacecraft dead band cycle. This will generally depend on the type of thruster used, fuel consumption, and spacecraft moment of inertia. We shall assume a spacecraft deadband cycle of 2-3 mrad and a maximum point ahead of +/-500 urad, leading to a field of view requirement of greater than 5-7 mrad.

Platform vibration is another consideration. Optical link is very sensitive to the vibration environment because of its narrow transmit beamwidth, and active vibration compensation is needed to maintain pointing. It is desirable that the optical communications subsystem be designed to operate over a wide range of spacecraft platform without imposing special mechanical interface requirements on the host spacecraft. Furthermore, because of mass consideration, it is more desirable to provide a high tracking update rate and directly compensate for line-of-sight jitter using a steering mirror within the subsystem instead of actively isolate the entire optical terminal from spacecraft. Since little in-situ measurements of the spacecraft jitter spectrum is available, an equivalent update rate requirement of 2 kHz is assumed. This update rate will allow a reasonably designed system to provide adequate tracking performance. Passive mechanical isolation may be used to lower the tracking update rate requirement, although they tend to be massive.

Thermal management under varying solar illumination condition is also an important issue. Unlike near-Earth system where the distance to Sun is near constant, deep space system can expect solar thermal loading variation from nearly 2000 W/m2 to 25-40W/m2. The problem is compounded by the fact that the Sun can be illuminating the subsystem from many different directions, even at very close to the optical boresight where it will be absorbed by the internal baffle. Finally, depending on the laser selected, the subsystem needs to maintain temperature control to within approximately 1 degrees of the set point (around room temperature) to control the emission of pump diode. Active thermal control using thermoelectric cooler is not a option because of the power efficiency consideration. As a result, a heat pipe is baselined to provide subsystem thermal management.

Pointing and Tracking Consideration

Pointing acquisition and tracking (PAT) is the major design driver for the proposed deep space optical communications. Inaccurate beam pointing can result in large signal fades at the receiving site and a severely degraded system performance. This problem is compounded by the fact that the amplitude of platform jitters due to spacecraft deadband cycle and random vibration are much larger than the transmit beamwidth. As a result, a dedicated pointing control function needs to be an integral part of the lasercom subsystem design. The required pointing accuracy of the transmit signal is typically on the order of a few microradians for a diffraction-limited system. In contrast, the beam pointing requirement for a RF communication system is on the order of 0.1-0.5 degrees, which can be several orders of magnitude less stringent

Because of the application of forward error correction code on the downlink, the performance of the overall link exhibits a sharp drop off with only a small change in the downlink signal power. Shown in Figure 2 is a plot of the downlink frame rejection rate calculated with a 256-ary PPM link using APD detector. The downlink is assumed to be coded with NASA standard (255, 223) Reed Solomon code. It is seen that with only a 15% change in signal power the decoded frame error rate can vary by 2 orders of magnitude. Therefore, the link performance is dominated by the probability that a pointing-induced fade will result in a signal dropoff below threshold. At a "designed" frame drop out rate of 0.01 (1%), the pointing loss can exceed 2 dB when the 3 sigma pointing accuracy is approximately 1.9 urad from a 30cm-diameter, diffraction-limited transmit aperture. Even at a distance of 6 AU, the pointing requirement of 2 urad presents a very small fraction of Earth diameter for pointing the downlink.

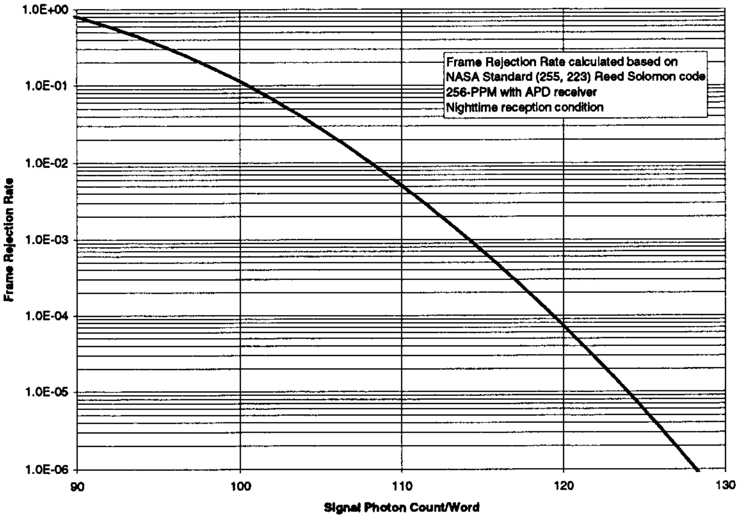

Figure 2. Probability of frame error versus signal power for a reference 256-ary PPM link using APD detector.

The tight pointing accuracy is achieved with a combination of accurate celestial reference (tracking reference) and with tight pointing control using a high update-rate feed back control loop. The required tracking update rate is estimated to be 2 kHz for the study. The celestial target, to which the receiver location is referenced, can be an uplink beacon from Earth, the sun illuminated Earth, or other celestial sources such as the moon or bright stars, etc. Shown in Table 3 is a summary comparison of various available pointing references. Note that none of the reference sources can provide the desired 2 kHz tracking update rate over the full range of Earth-Europa geometry. As a result, inertia sensor assisted tracking is necessary to close the pointing control loop at the desired 2 kHz update rate.

Even with inertia-sensor assisted pointing, none of the celestial source by itself can provide adequate pointing reference for all mission phases. This will include the cruise phase of the mission with range over 0.5 to 6 AU, and the solar conjunction/opposition mission phase when the sun-spacecraft-Earth angle is small. Both Earth and Moon image by itself has the problem of highly variable signal intensity due to phase (Earth-Sun-Spacecraft) angle. Stray light control for a broadband tracking source is also a challenge. Additionally, Earth albedo can lead to large shift in perceived brightness center. Tracking the Earth-moon system is a viable option when the phase angle is less than 120 degrees and when the distance is sufficiently large that the Earth-moon system falls within the acquisition detector field-of-view. This method uses the well known Moon albedo model as a calibration of the unknown Earth albedo. At high phase angle, and when the Earth-moon system is close to the Sun, Earth-moon system tracking can not be used because of the sharp drop in signal intensity and the increased solar background.

Table 3. Comparison of various celestial reference sources for optical pointing

	Earth Image Tracking	Moon Image	Earth-Moon System	Stars	Beacon
Expected signal wave-band and stray light consideration	400-900 nm due to focal plane technology Need to control solar stray light with stops	Same as Earth Tracking	Same as Earth Tracking	Same as Earth Tracking	Can use narrowband filter. Filter bandwidth limited by Doppler to approx. 0.1-0.2 nm unless uplink is tunable. Note: Earth at low phase angle is still much brighter.. Earth at 5AU provides approximately 6E6 photons/nm/s
Expected Signal Level	See Table 3-a	40X weaker than Earth image, and is generally separated from earth image when viewed from Jupiter	Same as Earth and Moon cases	7.5 mag star is ~as bright as the Earth at 160 deg. phase angle. 11.5 mag. star is as bright as the Moon at the same phase angle.	Depends on range. At 6AU it is <5E5 photons/s with 500W, 1.06 um uplink
Achievable Tracking Update Rate	Depend on phase angle, with difficulty in achieving 2 kHz at > 150 degrees	40X slower than Earth tracking. Cannot achieve 2 kHz rate at all phase angles	Same as Earth Tracking. Moon update can be 40X slower	See Table 3-b Cannot achieve 2 kHz rate at all phase angles	Insufficient for 2kHz tracking update rate
Background Noise Control	Field and Lyot stops	Field and Lyot stops	Field and Lyot stops	Field and Lyot stops	Field and Lyot stops + Narrowband filter.
Quality of measurement (Knowledge of the receiver location based on measured value)	Albedo variation can cause large shift of center of brightness	Good with sufficient integration time. (Moon has a well characterized albedo)	Good	Good (0.12 urad with Tycho catalog, and 0.005 urad with Hipparcos catelog)	Varies (significant error at low phase angle due to Earth background. Less or no problem when phase angle > 90 degrees)
Attitude control and knowledge requirements on the S/C:	Twist knowledge better than 0.16 mrad for point ahead	Same as Earth Tracking	Same as Earth Tracking	Depends on Earth-star offset. Generally not expected to be a problem.	Same as Earth tracking
Coverage (Range of Applicability)	1. Limited by stray light to at least 2 degrees SPE angle 2. Cannot achieve desired accuracy due to unknown Earth albedo. 3. At close range limited by field of view of optics	1. More sensitive to stray light than Earth tracking. 2. At close range it is also limited by the optical system field of view	1. Limited by solar stray light. 2. At close range it is limited by the optical FOV	Depend on field of view and cut off magnitude. 5 Stars at 11th mag of greater when FOV>0.8 degrees	Limited to when ground station can be seen from spacecraft. Susceptible to weather outage

Table 3-a. Estimated Earth signal, assume 100% optical efficiency and current detector quantum efficiency

			Detected Photons		
Phase Angle	Distance	Total Photons 400-900 nm	No phase law, no optics loss, PGT device	Lambertian Model, PGT device	Moon Model, PGT device
90	5.2 AU	5.7E9	7.0E8	1.7E8	6.2E7
160	4.3 AU	3.9E9	1.0E9	2.8E7	1.0E6
170	4.3 AU	3.9E9	1.0E9	7.0E6	2.0E5

*assume low QE (12.5%) of Photogate APS

Table 3-b. Signal strength from stars of different magnitudes

Star Magnitude	Flux with no optical loss	Flux with 25% system efficiency	Number of frames/sec. For accurate centroiding
7.5	1.0E6	250,000	25 to 50
10.0	1.0E5	25,000	5 to 10
11.0	4.0E4	10,000	1 or 2

Star tracking is an alternative to Earth/moon tracking, Stars have well known position and intensity distribution. However, a large detector field of view is necessary go ensure sufficient stars for attitude determination. Furthermore, stars generally does not provide sufficient signal flux for high bandwidth tracking (see. Table 3-b). Therefore, inertia sensor updates are needed to augment star tracking to provide the desired 2 kHz tracking update rate. Finally, stray light can limit the applicability of star tracking when the field of view is close to the Sun.

Beacon tracking is attractive since it allow the use of narrowband filter to reduce the scattered sun light. The bandwidth of the filter is limited only by the expected Doppler shift of the uplink. For a planetary mission, the Doppler can be as large as +/-100 ppm. The filter bandwidth, therefore, must be greater than 0.1-0.2 nm. At high phase angle, beacon and narrow band filter can provide a much higher tracking SNR than Earth/moon image tracking. Beacon tracking is also needed at close range when the Earth/moon tracking is limited by the detector field of view. However, even with a very narrow-band filter, Earth image at low phase angle (small SEP angle) can be much brigher than the uplink beacon. The large background level, coupled with unknown Earth albedo, can lead to an unknown tracking offset much greater than the pointing error budget. Therefore, beacon tracking cannot be used for low phase angle tracking.

3. DESIGN DRIVERS AND REQUIREMENTS

Shown in Table 4 below is a summary of the design drivers and the resulting design choices that led to the baseline design. The baseline design has a body-mounted, diffraction-limited 30 cm-diameter aperture, and supports both uplink and downlink communications using 256-ary optical pulse-position modulation. Diode-pumped Nd:YAG or Nd:YVO4 solid-state laser provide the necessary peak power operation for the high order PPM. The subsystem shall be designed to operate with its field-of-view within 2 degrees of the Sun. Therefore, lyot and field stops shall be incorporated into the optical design. Precision thermal control of the pump laser diodes, which is required to maintain the power efficiency, is accomplished using a loop heat pipe, which can provide high heat dissipation capacity while maintaining control of the temperature set point accurately at relatively low power consumption.

Table 4. Design Drivers and Choices

Drivers	**Design Choices**
Data rate consideration. The desire to be competitive with near term Ka-band technology	Use high order PPM modulation Aperture diameter of 30 cm diffraction-limited optical system Transmit pointing budget of less than 2 dB
Difficulty in covering all mission phases and providing coverage on demand	Provide RF backup link
Limit Solar Conjunction and Opposite Outage	Require minimum SPE angle of 2 degrees
Spacecraft Mass	Body mounted antenna No Active Platform Jitter Isolation
Handle a wide range of potential spacecraft vibration spectrum	Design for high tracking update rate of approx. 2 kHz
Thermal Control Power and tight requirement on controlling laser junction temperature	Heat Pipe for thermal management
Acquire and track with body mounted antenna	7 mrad field of view for acquisition/tracking detector
Tracking at low SPE angle	Stringent stray light and surface polish requirement Lyot and field stops in optical path Use Uplink Beacon tracking at high phase angle Use Earth-moon image tracking at low phase angle Incorporate inertia sensor to increase tracking update rate
Track at short range (0.5 AU)	Use Uplink beacon tracking
Provide capability of Earth/moon system tracking	Provide focal plane array tracking capability
Provide capability for uplink beacon tracking	Provide switch-able narrow band filter
Sun protection - Boresight close to the Sun	Shutter in optical path

The subsystem is designed to achieve a pointing loss budget of 2 dB (1.9 urad, 3σ overall pointing). This pointing accuracy is accomplished using a 2 kHz pointing control loop. At low Earth phase angles (<120 degrees), Earth Image tracking with occasion calibration using the Earth-moon or Earth-star images provide the necessary tracking update rates. Tracking the Earth-moon/Earth-stars system allows the optical communications subsystem to point the downlink signal without the need of an uplink signal, thus improving the link availability. Earth image tracking is also desirable because of its high brightness (over most of the orbit period) and angular proximity of Earth intensity centroid to the receiver location. At high phase angles when the Earth image does not provide sufficient brightness for high rate tracking, inertial sensors (accelerometers) measurements are used to propagate the knowledge of the optical boresight at a higher rate in between celestial reference updates. The inertial sensors measurements are integrated and combined with the celestial reference target measurements to provide knowledge of the telescope pointing at a higher rate needed for closed-loop control of the downlink. Additionally, uplink beacon tracking is required to support pointing at short range and during opposition when Earth image along does not provide sufficient signal power for tracking. A switch-able narrowband filter shall be included to allow efficient beacon tracking.

Finally, to avoid direct sun-light from damaging the optics with inadvertent exposure, an optical shutter shall be incorporated into the optical design.

3. SIMPLIFICATION OPTIONS

The design drivers and the resulting design choice shown in Table 4 were identified in order to support the mission as either prime or augmentation telecom subsystem. These design choices, however, greatly increase the system complexity. Eliminating the drivers (e.g. increasing the SPE exclusion angle) can significantly reduce the complexity. Shown in Table 5 is a subjective list of priorities, taking into accounts the various mission needs. From the list of priorities, a number of de-scope options are available. These include: (a) eliminate uplink and ranging requirements, (b) eliminate design redundancy, (c) relax SPE angle of 2 degrees for stray light rejection, (d) ignore Earth-Image tracking and rely instead solely on beacon tracking, (e) eliminate inertia sensor-assisted tracking loops. Shown in the following table is a summary of design simplification options and their effect on link outages. Due to the limited amount of time spent on analyzing individual design options, the outage presented in the table should only be regarded as an order of magnitude reference.

Table 5. Subsystem Design Simplification Options

Design	Implications	Superior Conjunction Outage	Opposition Outage
Current Baseline	• Complex	28 days	20 days
Drop Uplink and Ranging Requirements	• Very little in terms of functions	Same	Same
Eliminate redundancy on receiving path, but maintain downlink transmitter redundancy	• Reduced complexity in optical design, • Potential increase in optics transmittance • Mass savings, but with insignificant power savings	Same	Same
Relax requirements on SPE angle to 5 degrees instead of 2 degrees	• Simplifies stray light rejection problem -- but not likely to eliminate the need for Lyot and field stops	70 days	49 days
Limit SEP angle to 30 degrees (1-m OCTL station specification)	• Large outages twice a year • SPE angle allow Earth image only tracking (no inertia sensor)	80 days	90 days
Eliminate option to track Earth/moon system. Perform on beacon tracking only.	• Lose one-way link capability and requires uplink signal be available for downlink • Simplifies focal plane design and signal processing. • Requires high power beacon • Require very low frame rate at tracking (< 1Hz) at superior conjunction. Not easy to achieve even with inertia sensors • Earth background is brigher than uplink beacon and can affect tracking accuracy at SEP less than 30 degrees. • Requires calibration of Earth image-induced centroid shift	>130 days	20 days

Design	Implications	Superior Conjunction Outage	Opposition Outage
Eliminate option to track beacon (track Earth moon system only)	• Simplify focal plane design • Earth tracking available only to phase angle of approx. 155 degrees. Higher phase angle tracking maybe difficult • At shorter range when the angular extent of Earth image is large, excessive signal processing on the focal plane may not be feasible.	28 days	50 days
Eliminate need for inertial sensor	• Eliminate option to track uplink beacon since it is too weak. • Earth bright enough only at phase angle < 130 degrees	28 days	90 days

4. CONCLUSION

The design of an Europa-Orbiter mission provided a realistic assessment of the complexity for an operational optical communication system. The study concluded that the operational requirements and design of a deep space optical communications subsystem are very different from that of a near-Earth optical communications subsystem. Significant challenges on laser efficiency, thermal control, pointing and tracking, stray/scatter light control, and subsystem mass/power need to be addressed for a successful subsystem implementation. Despite the challenges, the study has shown that, with the exception of radiation hardness issues, an operational optical communications system can be implemented; albeit with brute force.

Although the design effort attempts to provide a conscious effort in addressed most of the known problem. Time and resource constraints have limited the scope of the study. As a result, a number of open issues still remain. These are

1. Trade off of mission coverage requirements versus complexity. The desire to reduce conjunction/opposition outage drives the current baseline design in several ways: (1) it imposes stringent demand on stray light rejection and the need for Lyot and field stops, (2) it imposes requirements to track both Earth/moon system and uplink beacon. Relaxing the coverage requirement may lead to a simplification of design, at the expense of increased conjunction/opposition outages.

2. Stray light control requirements and resulting surface quality/cleanliness requirements are not addressed. The achievable stray light performance has been estimated using a typical BRDF scaling curve. However, the validity of such a curve for the lightweight material remains to be verified.

3. Platform jitter consideration: Platform jitter drives the required tracking bandwidth and hence the design of the acquisition and tracking concept. If the platform jitter is significantly lower than modeled, then a less complex pointing concept may be employed. If the contrary is true, then passive isolation may have to be employed to reduce the amount of vibration coupled into the subsystem.

4. Potential improvements in tracking detector sensitivity needs to be addressed. This include detectors with internal gain to reduce effect of read noise. Having such a detector can potentially reduce the required photons/frame and improve the tracking update rate for low intensity sources (such as Moon/stars)

5. Radiation issues: The component /design identified have not address the radiation sensitivity issue. Aside from the electronic parts issue (including the detector array), the optical design may be affected by the radiation issue as a mostly reflective design is needed to reduce the scintillation noise from radiation.

6. The design of the laser to meeting the efficiency goal (10%) over the full range of PRF has not yet been address. The laser efficiency is a strong function of the PRF. At low PRF the reduced efficiency can lead to additional system loss not currently modeled in the link design.

7. Mass and power estimates are crude at present as it has not yet been fully addressed by the subassembly designer.

8. Ground system implementation issues: The system requirements and link design are based on a set of assumed ground system performance parameters. The validity of these assumption, as well as the assumed atmospheric propagation effects, need to be valiated.

5. ACKNOWLEDGMENTS

The research described in this report was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors would like to acknowledge the work of S. Monacos, T-Y. Yan, S. Lee, H. Hemmati, J. Sandusky, G. Ortiz of JPL for their contributions in the development of the conceptual design concept.