Photonics on the Mission to Mars

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ABSTRACT

Human missions to Mars present some unique challenges for photonics devices. These devices will have exposure to many different space environments. During assembly they will be exposed to the earth orbiting environment. Upon departure they will need to function through the Earth's Van Allen Radiation Belt. While the general interplanetary environment is less challenging than the radiation belt, they will operate in this environment for 18 months, subject to sudden saturation from solar flares. These components must continue to function properly through these saturation events presenting quite a challenge to photonic components, both optical and electronic. At Mars, the orbital environment is more benign than the Earth's. Components used as part of the landing vehicles must also deal with the pervasive dust environment for 3 – 6 months. These assembly and mission execution environments provide every form of space environmental challenges to photonic components. This paper will briefly discuss each environment and the expectations on the components for successful operation over the life of the mission.

Keywords: Photonics, Space Radiation, Space Environment, Interplanetary Space

INTRODUCTION

An interplanetary transportation vehicle (ITV) supporting human exploration of interplanetary space, such as missions to Mars, will have a significantly longer life in space than previous human exploration missions. Interplanetary space missions will be on the order of 4 years including transportation vehicle assembly time in low earth orbit (LEO). Figure 1 shows a possible trajectory for an interplanetary mission to Mars[1]. For the Apollo lunar missions, the Apollo spacecraft was launched already assembled, spent 4 hours in LEO, 3 days in route to the moon, a week on the lunar surface (using the Lunar Excursion Module (LEM)), and then 3 days back from the moon with a direct earth atmosphere re-entry[2]. The Shuttle Orbiter, using the Extended Duration Orbiter (EDO) kit, could stay up to 16 days in low earth orbit[3]. Comparing these 3 human rated space transportation systems, an ITV will spend 18 months in LEO, significantly longer than Shuttle, and 34 months in interplanetary and Martian space, significantly longer than Apollo for moon exploration. Assembly time in LEO does have some corollary (mainly to the ITV habitation systems) to the International Space Station (ISS), which took 60 months to assemble and has been occupied in space for 12.5 years[4]. These legacy systems provide some experience in operation in LEO and the earth moon system, and can be extrapolated to missions in interplanetary and Martian space. Table 1 summarizes the differences in the various space environment mission durations.

Environment	ITV	Apollo	Shuttle Orbiter	ISS
Launch Site	6 months	6 months	30 years	6 months[5]
LEO	18 months	2.5 hours	16 Days (EDO)	12.5 years
MEO	2 hours/2 hours	2 hours/2 hours	None	None
Interplanetary/Lunar	18 months	12.5 days	None	None
Martian Orbit	12 months	None	None	None

Table 1: Comparison of Human Rated Vehicles in various Interplanetary Mission Space Environments

As can be seen in Table 1, the ITV will spend considerably longer time in the various environments than previous human rated transportation systems. The ITV elements, shown in Figure 2, must be assembled and operated successfully and reliably over these durations in each of these environments. In addition, each of the ITV elements will be launched from a tropical environment at the launch site which adds another dimension to the environmental picture.

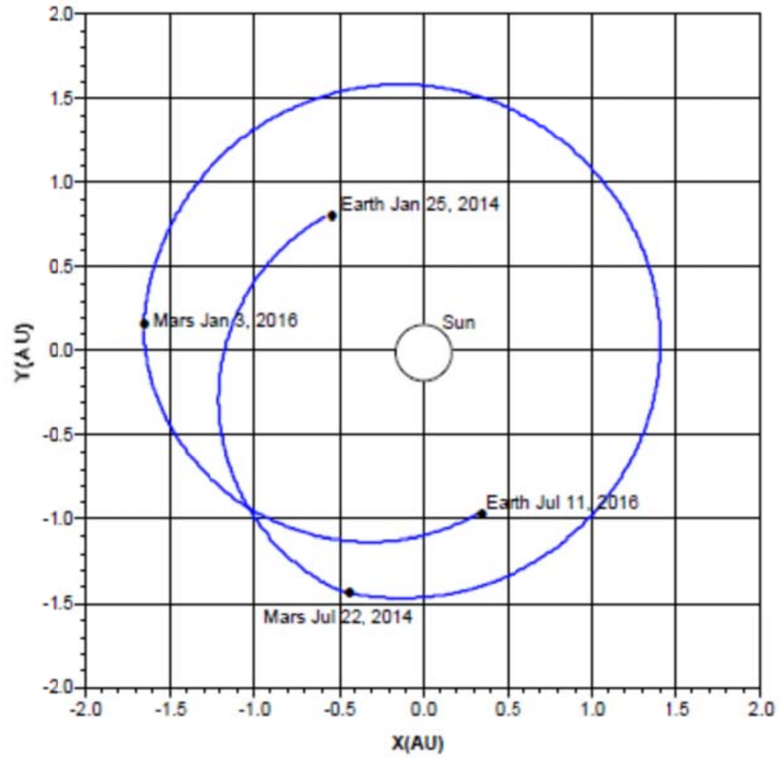

Figure 1: ITV Mars Trajectory

There are various types of potential photonic devices for use on an ITV. These include guidance systems, communication systems, and sensor applications. Fiber optic gyroscopes (FOG) provide a highly accurate, compact, low heat dissipation approach to guidance. LIDAR applications can be used to detect space debris in transit and in orbit to avoid potential damage to the spacecraft. LIDAR may also be used to monitor the atmosphere at Mars for landing and rendezvous operations. Photonic imagery systems may be used to monitor the ITV external systems and hull integrity, and investigate potential damage. Imagery may also include monitoring of surface landing sites. Communication systems have a variety of photonic components. Optical networks and components are likely to comprise the on-board data networks. Free space optical communications with Earth will include many photonic components and can provide a large bandwidth flow of data and imagery in support of crew and vehicle health, scientific data, and mission progress. 3 dimensional imagery or holography would also greatly enhance communication between the Earth, ITV, and Mars landing sites. This would particularly be helpful in visualizing topography or repair operations. Photonic sensors such as fiber bragg gratings to monitor temperature, pressure, and stress/strain, infrared temperature sensors, crew environment, and liquid levels can also be used to monitor and maintain the ITV systems.

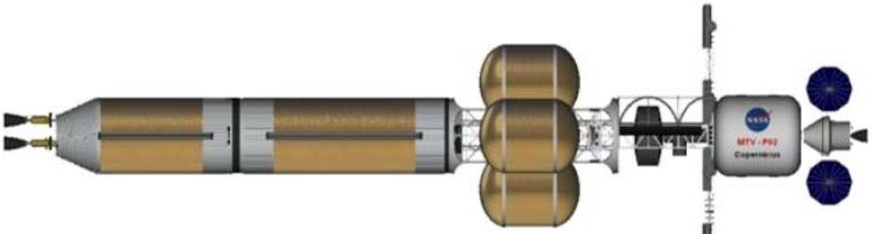

Figure 2: Interplanetary Transfer Vehicle

For photonic systems, operation in each of the environments presents some unique challenges. These environments include tropical conditions at the launch site: micro gravity, vacuum pressures, atomic oxygen, ionizing radiation (solar flares, cosmic rays), meteorites (particles and streams), and solar radiant energy (thermal and UV exposure) in LEO; high radiation fluences in MEO; ionizing radiation (solar flares, cosmic rays), meteorites (particles and streams), and solar radiant energy (thermal and UV exposure) in interplanetary space[6] and in Martian space[1]. The optical systems must be able to survive these environments either through protection in stowage or actual continued operation. Since the welfare of the crew is at stake, flight critical photonic systems must be operable through all possible environmental encounters. This paper considers each of the candidate environments and the implications to the potential photonic systems for use on interplanetary human exploration missions.

LAUNCH SITE

At the launch site, each stage of the ITV will be launched the Space Launch System (SLS) as illustrated in Figure 3. The ITV stages will be processed in controlled environments and contained inside the fairing while at the launch pad. The photonic components will need to retain functionality and reliability in the temperature range (0 C – 50 C) and potential high humidity at the launch site[6]. Photonics adversely affected by moisture will need to be sealed to prevent entrance of moisture on sensitive surfaces. Exposure to UV solar light will not be an issue since the stage is contained within the fairing. During launch and ascent flight, the photonics will experience high vibration and must operate after exposure to these environments. While the photonics devices will have to survive these environments, these are not seen as challenging. The launch site environments are well within military standards for military and aviation systems. Terrestrial optical communications operate in these environments for years and are well understood.

Figure 3: Space Launch System (SLS)

EARTH ORBIT

Once on orbit, the stage will be assembled with the ITV. The ITV will remain parked in low earth orbit (LEO) until the final stores and crew are on-board. Assuming a vehicle of 4 stages as illustrated in Figure 2, assembly, test, and checkout could take up to 15 months. Another 3 months should be expected for arrival of the crew and final stores before mission departure. Thus, the photonics should expect to be stored and/or operate in the LEO environment for 18 months.

Atomic oxygen (AO) is unique to the low earth orbit environment. Photonic materials which are reactive with oxygen will need to be protected while the IVT is parked in LEO. System which are exposed (i.e., outer hull) and need to operate in LEO during assembly or earth departure will need to be resistant to AO. The Space Shuttle Evaluation of Oxygen Interaction with Materials-third phase (EOIM-III) and Long Duration Exposure Facility (LDEF) experiments provide some information on organic material exposure in the AO environment.[7]

While Earth's atmosphere is the source of AO, it also provides protection from solar ionizing radiation. Assuming 0.76 mm Al shielding, the annual total dose is estimated at 1 krad (Si)[6] . A conservative estimate then for the total duration during IVT assembly is chosen as 2 krad (Si).

While parked in LEO during assembly, exposure to the solar radiance will be cyclical based on the orbital period. The solar radiance is 1367 W/m^2 .**Error! Bookmark not defined.** This is much higher than on the surface of the Earth where the atmosphere absorbs and scatters the solar energy. This radiance can produce temperatures of 150 C on externally mounted components. In addition the Ultra Violet (UV) portion is still high at 0.5 W/m^2 in LEO[6].

Upon departure from LEO, the ITV must travel through the Van Allen Radiation belt in Medium Earth Orbit (MEO). The space radiation levels are high in this region. Photonic components must operate through this region without performance degradation. The time through this region is short (~ 2hours), though the radiation exposure levels are high.

INTERPLANETARY

Interplanetary space is a more benign background radiation environment than MEO once through the radiation belt. Solar Flares in any space environment (Earth Orbit, Interplanetary Space, or Mars Orbit) represent the highest space radiation levels and mission critical photonics will need to operate through these events without failure. Since these events travel at the speed of light, warning time is very short. A few minutes of lower radiation levels are possible as the outer boundary of an event encounters the ITV should a system need to be safed prior to the full intensity of the flare engulfing the vehicle. Figure 4 illustrates the total dose levels encountered on a single leg in interplanetary space for different levels of aluminum shielding[1].

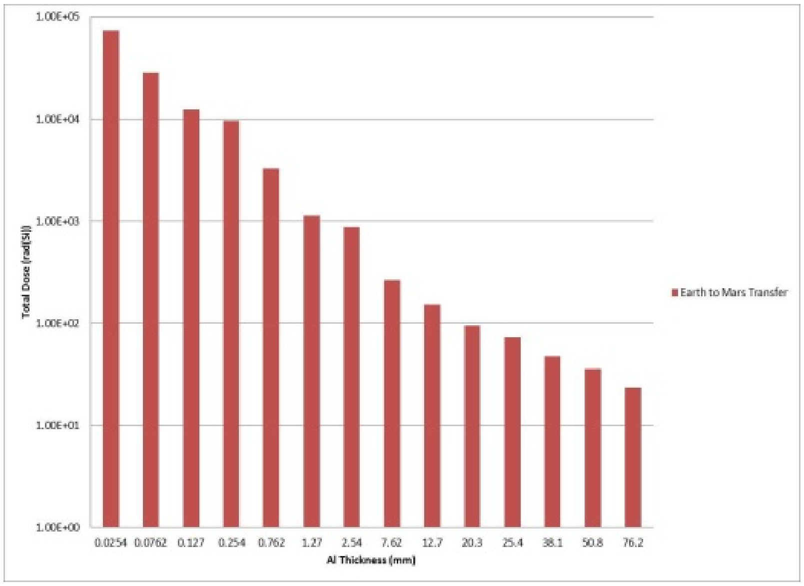

Figure 4: One Way Interplanetary Total Dose vs. Al Shielding

Solar exposure is constant and will be the most challenging in this region. Solar intensity is a direct relationship to the distance from the Sun. The ITV trajectory varies from 0.98 AU to 1.7 AU (at Mars)**Error! Bookmark not defined.**. The ITV will likely rotate on its axis to provide cycles in the shade and in direct sun light. While internal vehicle temperature will be kept comfortable for the crew (25 C), external temperatures will again be in the 150 C level while still 1 AU from the sun.

Meteorite impacts are possible in interplanetary space. Figure 4 shows the fluence distribution of by mass and velocity of the meteorite particles. This shows that the highest fluence is for small particles (10^{-12} to 10^{-10} g) with velocities less than 30 km/s. Note that the peak is for 10^{-11} g at 10-15 km/s. In addition to this general fluence, there are meteor streams have much higher fluence that will be encountered during the flight to Mars. These streams will produce a much higher probability of impact when they are encountered.[1]

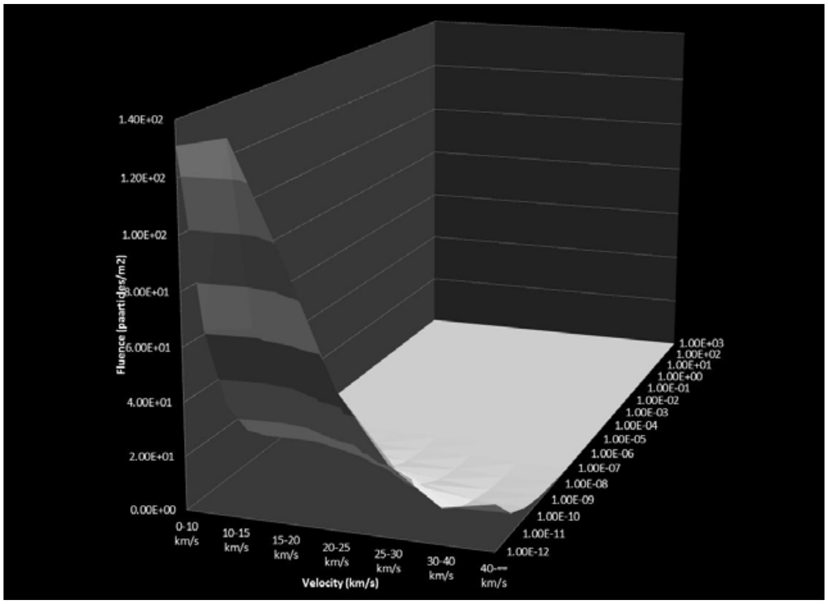

Figure 5: Interplanetary Meteorite Fluence Distribution

MARS

The Martian orbital environment is different than the Earth orbital environment due to the further distance from the Sun (1.6 AU) and the chemical content of the atmosphere. Due to free oxygen being present only in trace amounts in the Martian atmosphere, atomic oxygen is not an issue in the Martian orbit. The radiation environment is similar to the environment in interplanetary space. Solar flare radiation should be lower as the radiation cloud expands with the distance from the sun. The solar irradiance is also lower with distance from the Sun at 589 W/m^2.[1] UV exposure will be lower and external heating will also be much lower.

TOTAL MISSION

For photonic application on the ITV, total mission effects are perhaps the most interesting. Total mission is defined as Earth Departure to Earth Return. Figure 6 shows the total radiation dose from Earth departure to Earth return. Assuming a 0.762 mm thick aluminum case, the total dose experienced by an instrument is 11.2 krad (Si). An exposed instrument, with no shielding would essentially receive 253 krad (Si).[1] Assuming 2 krad(Si)/yr in LEO, an exposed system would be expected to receive 256 krad(Si) for the Mars mission.

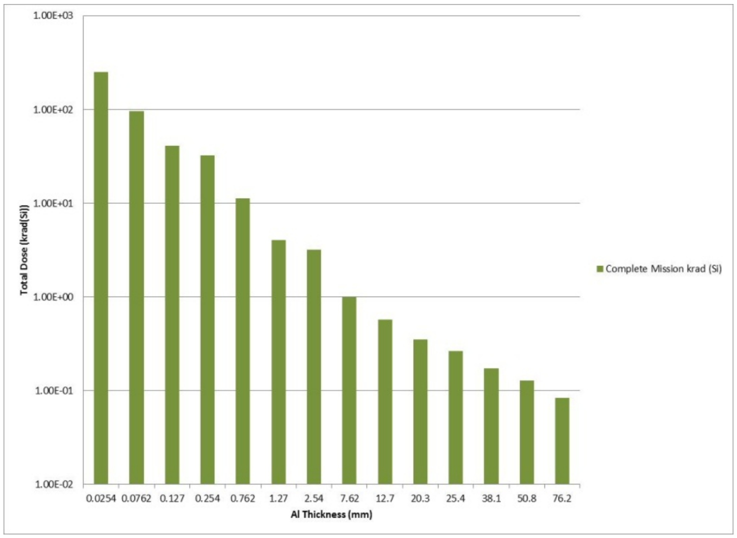

Figure 6: Total Radiation Dose from Earth Departure to Earth Return

Thermally, the maximum external temperature is 150 C. The highest solar irradiance is 1367 W/m^2 with 0.5 W/m^2 UV intensity[1]. These provide the bounds for externally mounted photonic devices.

Meteorite Fluence is shown in Figure 8[1]. The fluence is very similar to the interplanetary meteorite fluence. Since fluence is based on area, this is expected as a result of the long path length in interplanetary space. However, impact flux is expected to be higher near planetary bodies and during intersections with meteorite streams. The fluence is still predominantly for tiny mass particles with velocities below 30 km/s. Meteorite Flux is shown in Figure 7[8]. This figure shows that the most probable impacts are for the low mass particles. The main concern for these impacts is in abrasion to optical surfaces. The red region in the chart shows particles with enough mass to penetrate external surfaces. These particles will need to potentially be detected and avoided or broken up prior to impact.

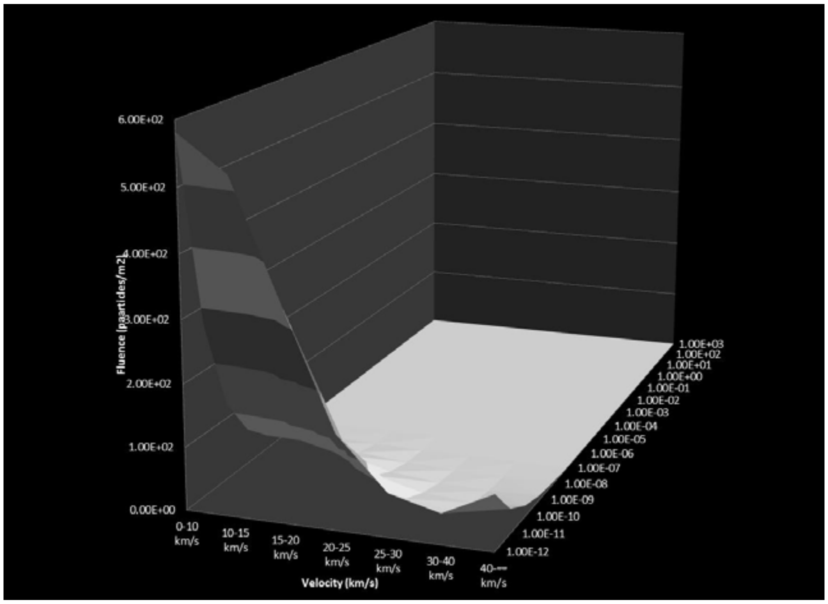

Figure 7: Meteorite Flux in Mars Orbit

PHOTONIC EFFECTS

There are many applications for photonics on an ITV. Various papers have discussed a variety of photonic components for space application.[6,9,10,11] Optical communication networks onboard the vehicle will be essential. These networks pro vide for very high (> 1 Gpbs) bandwidth necessary to support a highly automated vehicle. These networks include laser diodes, amplifiers, optical modulators, fiber optics, and optical receivers. Fiber optic data busses have a good history in spaceflight and have demonstrated good performance in the LEO environment[12,13,14,15,16]. The ISS has been operating with a Fiber Distributed Data Intreface (FDDI) optical bus[17] for 12.5 years in LEO. Various other missions have demonstrated good operation in LEO or MEO including the Long Duration Exposure Facility (LDEF)[18,19], Microelectronics and Photonics Test Bed (MPTB), Solar Anomalous Magnetospheric Panicle Explorer (SAMPEX)[20], Wilkinson Microwave Anisotropy Probe (MAP), X-Ray Timing Explorer (XTE), Hubble Space Telescope (HST) Solid State Recorder (SSR), and Photonics Space Experiment (PSE) (all, except LDEF, using MIL-STD-1773 Fiber Optic Multiplexed Data Bus) [21,22]. The Air Force Research Laboratory (AFRL) is currently planning a MEO test satellite for various photonic devices.[23,24, 25] Some recent work is showing improvement in the radiation hardness of Er-doped fibers.[26,27] Er-Doped Fiber Amplifiers gain loss has been improved on 40 krad(Si) irradiation by controlling atomic element content with in the fiber. Operation for the duration of the mission in interplanetary space and Mars orbit is well supported by the level of exposure these devices have experienced. An excellent database of fiber optic radiation test data for commercially available fibers in 2002 shows there are many options for fiber selection.[28] One are that does need to addressed for fiber optic applications are the cable lengths. An ITV will require lengths of several hundred meters to transport data from fore to aft. Satellite applications have fairly short distances compared with this. While repeaters can be utilized, these present failure and maintenance problems as well as adding to thermal dissipation along the vehicle. Minimizing or eliminating the need for signal repeaters is important for application on long vehicles such as an ITV.

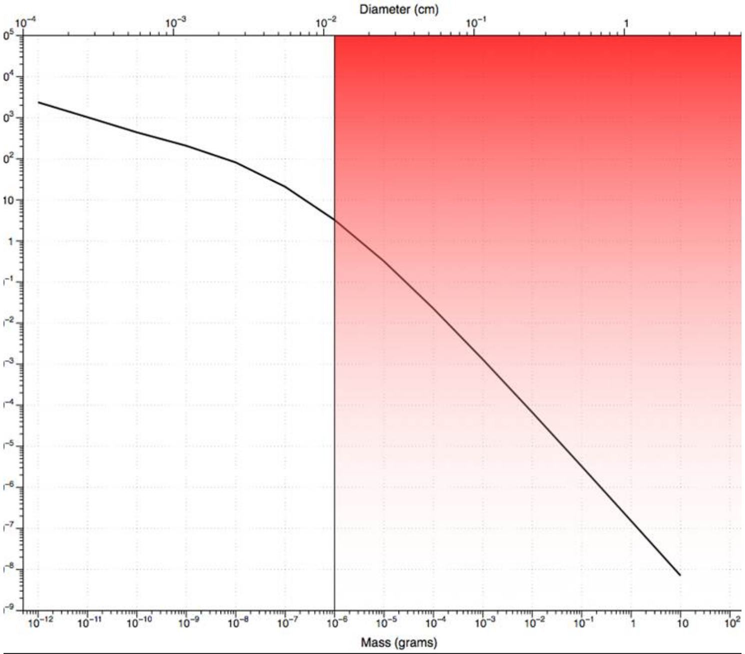

Figure 8: Meteorite Flux from Earth Departure to Earth Return

Free space optical communications with Earth is also a potential application[29]. This enables the high bandwidth to return mission video, scientific data, and vehicle and crew status for strategic mission following on Earth based control centers. Several demonstrations of optical communication have been successfully accomplished. The European Space Agency (ESA) demonstrated optical communications between satellites (ARTEMIS and SPOT4), from satellite to ground, and from satellite to an aircraft. This also included optical communication with the Japanese OICET satellite. Laser communication has also been demonstrated between the Near Field Infrared Experiment (NFIRE) and the TerrSAR-X satellites.[30] NASA is currently preparing to launch the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission with the Lunar Laser Communication Demonstration (LLCD)[31] shown in Figure 9. Recent work has focused on locating and tracking the Earth from planetary distances within the solar system. [32,33] Free space optical communications scales up significantly from the

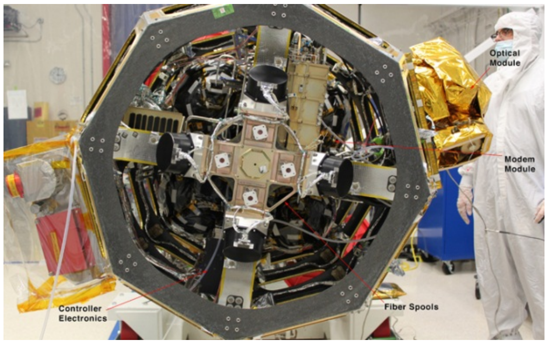

Figure 9: Lunar Laser Communication Demonstration

photonic scale and will still make use of photonic components to beam steer, transport data to the laser transmitters, and transport data from the optical receivers. Testing of liquid crystal beam steering devices has shown no degradation after 2.2 Mrad (Si) exposures. Some degradation from < 2 krad (Si) neutron exposure (applicable to nuclear reactor cores) was seen. [34,35] Promise was also shown with acousto-optic tunable filters (AOTF) where only small changes in optical characteristics where measured after 788.6 krad(Si) proton and 1 Mrad(Si) gamma ray exposures. An AOTF has flown on the ESA Mars Express mission. [36] Much still needs to be demonstrated for planetary communications in this area and much progress has been made internationally in this area over the past decade.

Optical gyroscopes will provide for ITV guidance. These systems could be either Ring Laser Gyroscopes (RLG) or Fiber Optic Gyroscopes (FOG)[37,38]. These gyroscopes use many photonic components such as laser sources, modulators, receivers, and for the FOG, fiber optics. FOG's are currently operating on Mars in the Spirit and Opportunity rovers. Recent testing at 100 krad(Si) shows FOG components (super luminescent diodes (SLD), $LiNbO_3$ modulators, couplers, detectors) are relatively radiation hardened with selection of geometrical polarization maintaining fiber being a key consideration.[39] FOGs are used on Soyuz TM spacecraft in support of the ISS[40]. RLGs are currently available for space application in LEO, MEO, and interplanetary space[41,42].

Light Detection and Ranging (LiDAR) may be used for meteorite detection (for collision avoidance) and Mars atmospheric scanning. NASA has been working on the characterization and improvement of space based laser for LiDAR applications.[43] The LiDAR In-space Technology Experiment (LITE) flew on board the Space Shuttle in September 1994, as shown in Figure 10, providing some early demonstration of LiDAR capabilities.[44] LiDAR instruments have since been flying in LEO and planetary missions including Mars Orbiter Laser altimeter (MOL), the Ice, Cloud, and land Elevation Satellite (ICESAT), and the Mercury surface, space environment, geochemistry and ranging (MESSENGER) probe.[45]

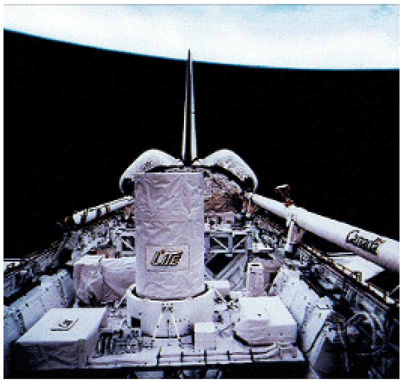

Figure 10: LiDAR In-space Technology Experiment (LITE) on-orbit in 1994

Sensing of systems will be essential to enable a highly automated vehicle. There are numerous applications of optical sensing that can be applied to the ITV. These include fiber brag gratings (FBG) for monitoring stress/strain, temperature[46] , pressure, infrared sensing for thermal monitoring[47], chemical sensing for crew cabin environmental monitoring and nuclear reactor monitoring, remote sensing[48], and radiation sensors[49]. An excellent survey of fiber optic sensing systems was reported, indicating optical fiber systems could operate with inorganic fibers and coatings to 1000 C or higher. Fiber optic sensors with organic coatings were reported up to 385 C. This included attachment mechanisms and tubing. [50] Fiber optic sensors are also reported to have excellent life in nuclear reactor environments (high gamma and neutron radiation). FBG's tested well under low reactor exposure levels > 4Mrad(Si) and reactor temperatures of 70 C.[51] Fiber extensometers showed outstanding response at 1.6 Trad(Si) with reactor temperatures up to 150 C. [52] Fibers along with Vertical Cavity Surface Emitting Lasers (VCSEL), and detectors performed well at 1.35 Grad(Si) or greater at reactor temperatures up to 200 C. [53] Fiber photometers have also been tested to 18 Mrad(Si) at 22 C. [54] Assuming a dose rate of 18 Mrad(Si)/hr in a nuclear core yields 35 Grad(Si) total dose over a 4 year mission. This estimate shows fiber optics are candidates for operating in and around nuclear thermal engines.

Optical coatings are also used for a variety of applications to protect surfaces (i.e., solar cells, lenses, mirrors) against abrasion or contamination (e.g., low adhesion of drops or particles)[55,56,57,58,59]. These surfaces all show low adhesion for various contaminants. Data is not available however for the durability under the impact energies for the fluence and flux levels estimated for an interplanetary mission.

Each of these applications will need operational reliability in the space environments for the full duration of the 4 year mission. Within this context there are 3 main characteristics that drive photonic component selection and certification: Thermal, UV exposure, abrasion resistance (for exposed components), and radiation effects. Thermal characteristics of most photonic components are well known as optical performance is affected by component thermal conditions. The microgravity conditions of space (only solar gravity in interplanetary space) means convective cooling is not a thermal control option. Thus, radiative and conductive thermal controls are the only options. Most instruments are controlled conductively on spacecraft and the heat dumped overboard through large radiators. For the ITV, heat conduction will be a major limitation on the vehicle design and device selection. Devices will need to have extremely low heat dissipation, not requiring active thermal control. This will be a large challenge to laser devices. At the component level, waste heat should be < 5W, < 20 W for an integrated system. Thus, high efficiency and low dissipative power needs to be a major focus for devices inside the ITV compartments. External devices can dissipate more heat radiatively. Device selection, then, will be based on the intended thermal environment. Thermal relaxation of optical polymers will need to be well understood in order to operate in external thermal environments where temperatures of 150 C may be seen for 4 years. Fiber optic devices (communication systems, FOG, sensors) have been shown to work well in space and can handle the thermal environments imposed by an interplanetary mission. Similary, free space optical communications and Lidar applications have a good history in space operation and appear viable for ITV applications. The next step in all of these photonic devices is to examine packaged devices and ways to minimize the thermal dissipation during operation. This type of work is usually done in produce design but much benefit can be gained from research into materials and techniques that optimize performance and minimize thermal dissipation.

UV performance is also well understood for optical components. Inorganic photonic devices are much less sensitive to UV exposure than organic photonic devices. The organic devices have cross linking which affect both optical and structural properties of the material. These devices will have to be protected from UV exposure throughout the mission.

Meteorite impacts are primarily a concern for photonic devices directly exposed to impact. The small size of the particles most likely to impact will create an abrasive effect on the optical surfaces. The high impact velocity of even the smallest particles can be abrasive. Thus exposed surfaces will need to be insensitive to this effect or some sort of impact shielding will need to be considered for the photonic instrument. Thus abrasion resistance is important for coatings and testing should be formulated to examine their durability at the fluence and flux levels anticipated for an interplanetary mission.

Radiation testing of various devices again show good performance. Fiber optic communications have a good history with long durations in LEO. The key to fiber optic applications (communications, FOG, sensors) is to use high purity silica fibers to avoid darkening centers. Free space optical communications also has been demonstrated in space and more long distance demonstrations are planned. Lidar, likewise, has a good history in space enduring the space radiation environment in LEO. Optical coatings do not show sensitivity to radiation levels tested. Many of the tests, however, are at levels of 200 krad(Si) or lower. For a 4 year interplanetary mission, total dose rates of 260 krad(Si) will be seen and testing should be done to levels which exceed this. 300 krad(Si) is a good target for testing of unshielded photonic devices and components for an interplanetary mission. 15 krad(Si) is sufficient for photonic devices and components with at least 0.762 mm Al shielding (typically provided by the device package or case).

As mentioned above, organic devices offer much promise for high optical performance with low thermal dissipation. Radiation effects need to be understood for these components and have been the focus of much research of the past few years for organic photonic components[55,60,61,62,63,64 ,65,66.] Table 2 shows a summary of the total dose proton and electron radiation testing for various organic photonic devices reported in the literature. This is not an exhaustive summary and provides a survey of many recent results. As can be seen from this table, there is testing on several materials that meet the dosage received with some level of Al shielding. There is little data for these materials at the higher direct exposure levels. Table 3 shows the testing results for total dose gamma ray for photonic devices as reported in the literature.

Material	Energy MeV	Total Dose krad(Si)	Result	Source
dimethylsilicone (DMS) w 30% SMO	63.8	198.2	No statistical change in response	protons
Ge doped SI FBG	63	10000	Shift in optical power wavelength center and reflection	protons
Mach Zehnder LD-3 polymer	64	600	EO Polylmer Degradation	protons
DR-1/MA film	64	500	EO Polylmer Degradation	protons
polyimide waveguide	64	600	EO Polylmer Degradation	protons
polydimethylsiloxane (PDMS) polymers	63.8	148.6		protons
Silicone	64	148.6	no degradation in outgassing	protons
Silicone	64	148.6	No degradation over 8 years	protons
CLD1/APC optical modulator	0.1	1000	12% increase in Vpi over 2 weeks after exposure	electrons
TP7 optical modulator	0.1	1000	20% increase in Vpi over 2 weeks after exposure	electrons
EO CPW1/APC modulator	25.6	100	Significantly improved Vpi	proton

Table 2: Summary of Proton and Electron Total Dose Testing

Material	Energy MeV	Total Dose krad(Si)	Result	Source
dimethylsilicone (DMS) w 30% SMO	1.17&1.33	184.956	No statistical change in response	gamma rays
Mach Zehnder LD-3 polymer		4000	EO Polylmer Degradation	gamma rays
polyimide waveguide		580	EO Polylmer Degradation	gamma rays
		5800	EO Polylmer Degradation	gamma rays
polydimethylsiloxane (PDMS) polymers		152		gamma rays
Silicone		182.8	no degradation in outgassing	gamma rays
Polymer w/ Fullerene on Siloxane	1.17&1.33	204.7	Improved Optical Transmission	gamma rays
	1.17&1.33		Improved Optical Transmission	gamma rays
Polymer w/ DR1 on Siloxane	1.17&1.33	204.7	Improved Optical Transmission	gamma rays
	1.17&1.33		Improved Optical Transmission	gamma rays
Polymer w/ NLS-1 on Siloxane	1.17&1.33	204.7	Improved Optical Transmission	gamma rays
	1.17&1.33		Improved Optical Transmission	gamma rays
Polymer w/ SWCNT	1.17&1.33	175.4	No change (several day delay in post irradiation measurement)	gamma rays
Polymer w/MWCNT	1.17&1.33	175.4	No change (several day delay in post irradiation measurement)	gamma rays
CLD1/APC	1.17&1.33	208	No change in EO performance Thermal relaxation biggest effect	gamma rays
CLD1/APC	1.17&1.33	428	No change in EO performance Thermal relaxation biggest effect	gamma rays
CLD1/APC	1.17&1.33	850	No change in EO performance Thermal relaxation biggest effect	gamma rays
EO CPW1/APC modulator		100	no change to improvement in Vpi	gamma rays
EO CPW1/APC modulator (Dupont)		162	No change in 2, one degraded Vpi	gamma rays
EO CPLD75/APC modulator		55	some degradation in Vpi	gamma rays

Table 3: Summary of Gamma Ray Total Dose Testing

Most of the organic materials shown in Tables 2 and 3 where tested at much lower levels < 1 Mrad. Comparing these levels to Figure 6, the lowest test levels are still above the 0.0762 mm Al shielding. Several of the organic materials where tested above the 255 krad unshielded level. And two were tested at or above 4 Mrad. The silicone testing showed that silicone, DMS, and PDMS did not show any changes from their mechanical properties after radiation exposure. These materials look promising for interplanetary space application. It is curious that the polymer with fullerenes, polymer with DR1, and polymer with NLS-1 all showed improved optical transmission after exposure to gamma rays. This is a good result and may indicate a small radiation dose as part of the production process could improve performance for terrestrial and space applications. However, improved performance levels and trends must be well understood and accommodated in photonic system design so that the system is not saturated or driven into a lower performance range (i.e., near saturation). Stable optical performance is the ideal situation. Improving performance with exposure, even degrading performance with exposure, is still useful if the performance changes are well understood and accommodated in the design. The carbon nanotube doped polymers look promising. However, the question of relaxation or healing after exposure needs to be confirmed with further testing. Similarly, CLD1/APC looks promising from a radiation exposure stand point. However, thermal relaxation is a concern and long term thermal relaxation mechanisms and performance impacts need to characterized and understood.

CONCLUSION

There are many applications for photonic devices on an Interplanetary Transfer Vehicle (ITV). Optical communications, optical gyroscopes, optical sensing, and optical coatings are all applications that will contribute to a successful human mission into interplanetary space. Many of these devices have a good history in LEO or interplanetary spaceflight and will perform well in ITV applications. Long distance cable runs need to be investigated to minimize or eliminate the need for signal repeaters in space rated fiber optic networks. There are 4 primary space environmental effects that drive photonic application: Thermal, UV exposure, Radiation total dose, and exposed surface abrasion. Thermal properties and UV exposure limits are well understood for photonic materials and devices. Thermal dissipation of packaged devices needs to be investigated to minimize thermal dissipation. Organic components show promise and thermal relaxation of organic electro-optic polymers needs to be characterized and understood to ensure optical performance will not degrade unacceptably during the mission duration. Inorganic devices show good radiation performance. Fiber optic purity is important in selection of fiber. VCSELs show excellent radiation hardness. Material selection is also important for detector and other optical components. Testing for space environment exposure should be done to 300 krad (Si) total dose for external devices and 15 krad(Si) total dose for devices with at least 0.762 mm Al shielding. There has been much testing on organic photonic materials and devices recently. These testing results show mixed results. Some applications show no affect or improvement in mechanical or optical performance. Other testing shows degrading optical performance. Where optical performance is not stable with radiation exposure or thermal environments, further testing and understanding of physical and chemical responses is needed. Optical coatings show low adhesion and excellent space radiation hardness. Their durability to meteorite impact energies at the fluence and flux levels expected needs to be investigated. Fiber optic sensors and communications showed excellent hardness in thermal nuclear rocket engine applications. Overall, Photonic applications are essential for communications bandwidth, accurate guidance, accurate sensing, and protective coatings. These photonic applications offer great benefits to the execution of human exploration of Mars. .

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