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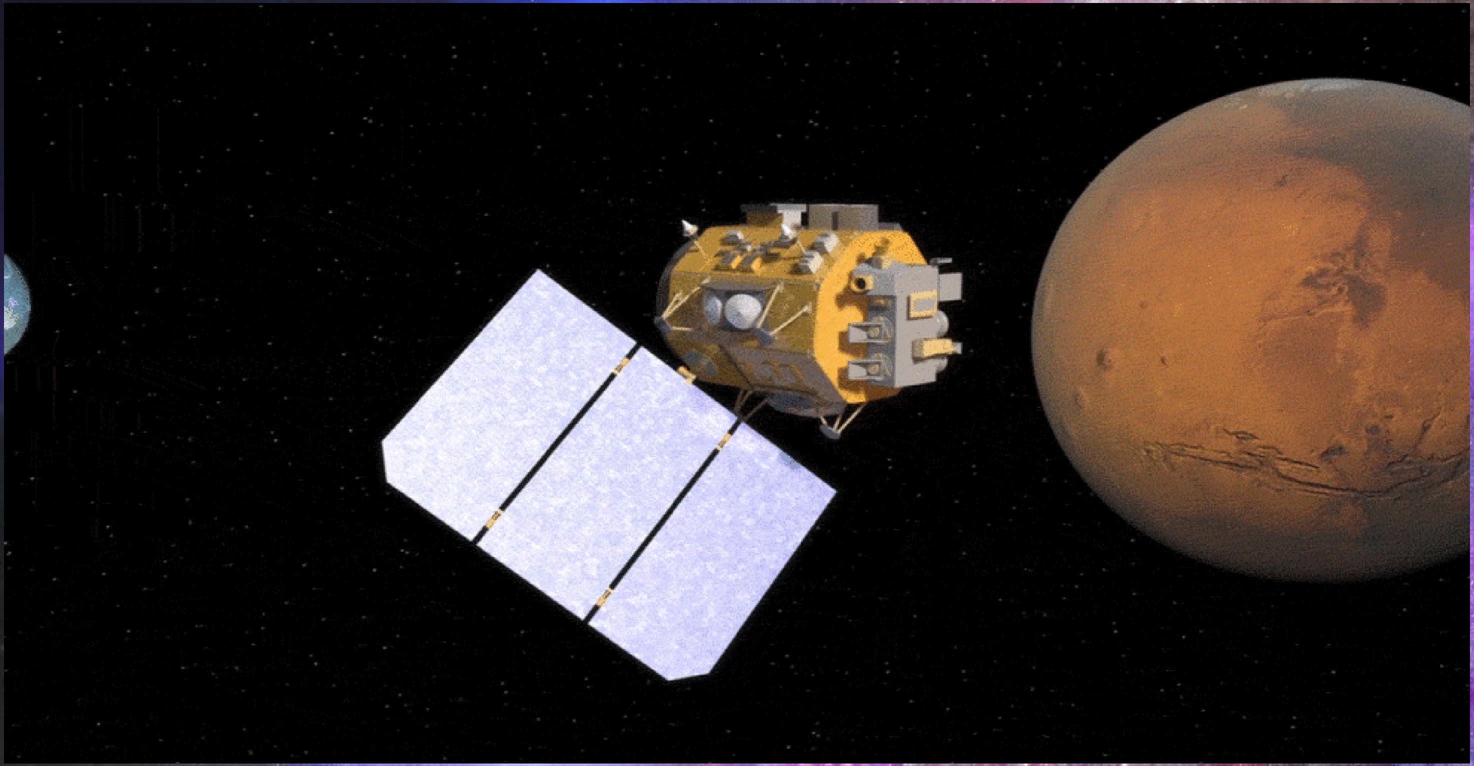
Space Qualification of Photonic Integrated Circuits (PICs) for Next Generation Optical Communications



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2019 NEPP Electronics Technology Workshop (ETW)

JPL Radiation Effects Engineering

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June 18, 2019

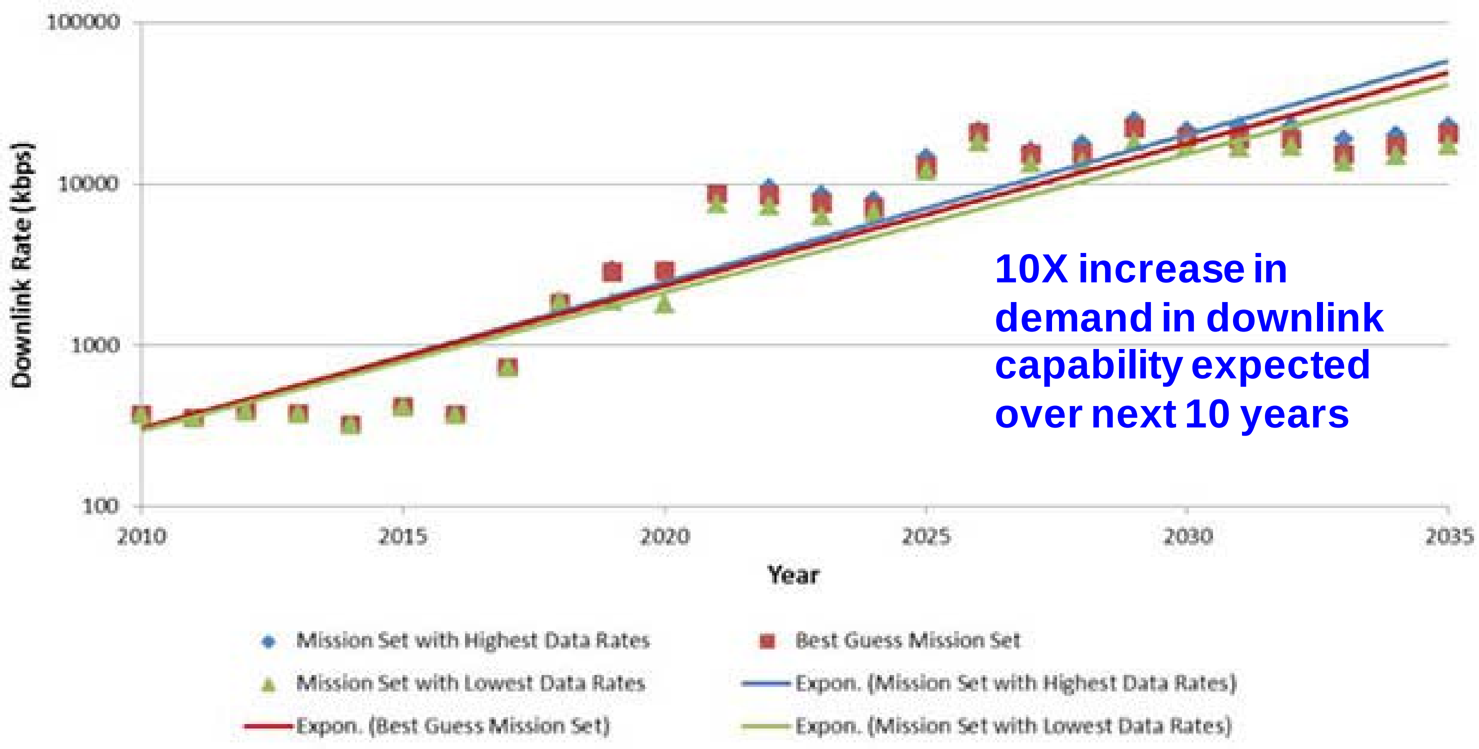
Conceptual animation depicting a satellite using lasers to relay data from Mars to Earth. ***Credits: NASA's Goddard Space Flight Center***

Agenda

- **Space-based optical (laser) communications**
  - Current state, challenges, advantages, potential
  - Emphasis on size, weight and power (or SWaP) benefit
- **NASA Technology Roadmap – Optical Communications and Integrated Photonics**
- **Future outlook of commercial integrated photonics in space**
- **NEPP FY19: space qualification of next generation photonic integrated circuits (PICs)**

http://www.hexjam.com/uk/living/23-jokes-only-very-smart-people-will-understand

NASA Space Communications: Increasing Data Rate Demands and Extreme Challenges



- Primary challenge for deep space communications systems is establishing high data rate capability over long link distances, while maintaining *high reliability and signal fidelity* to accommodate long system lifetimes.
- This challenge must be met within the constraints of demanding performance requirements and a continual need for reduction in *size, weight, power and cost (SWaP-C)*.

https://scienceandtechnology.jpl.nasa.gov/research/research-topics-list/communications-computing-software/deep-space-communications

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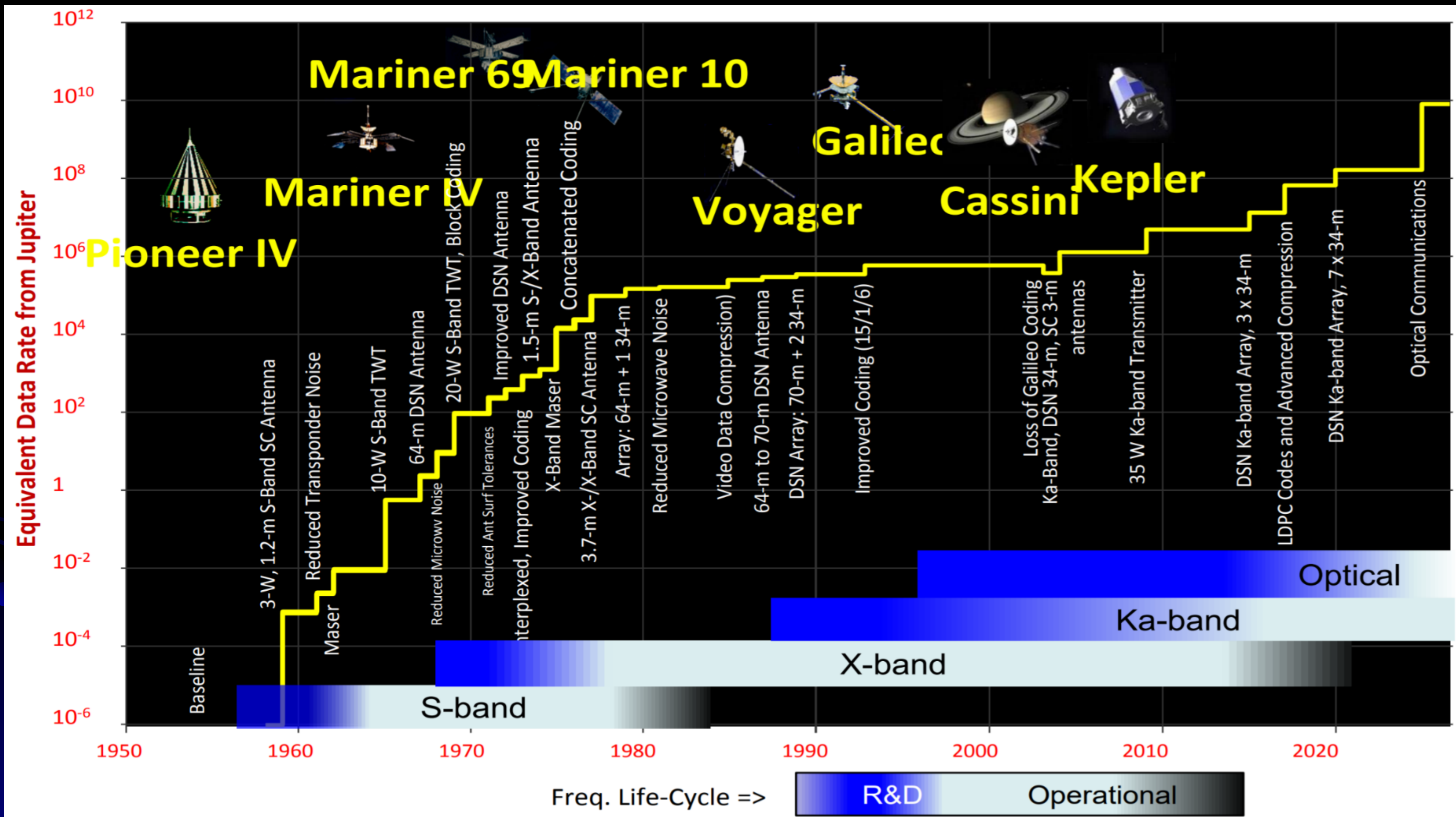
Evolution of Deep Space Communications Data Rates



NASA has moved space communications systems from S-band to X-band and Ka-band (100X faster) to meet growing demand for high volume data returns from science missions.

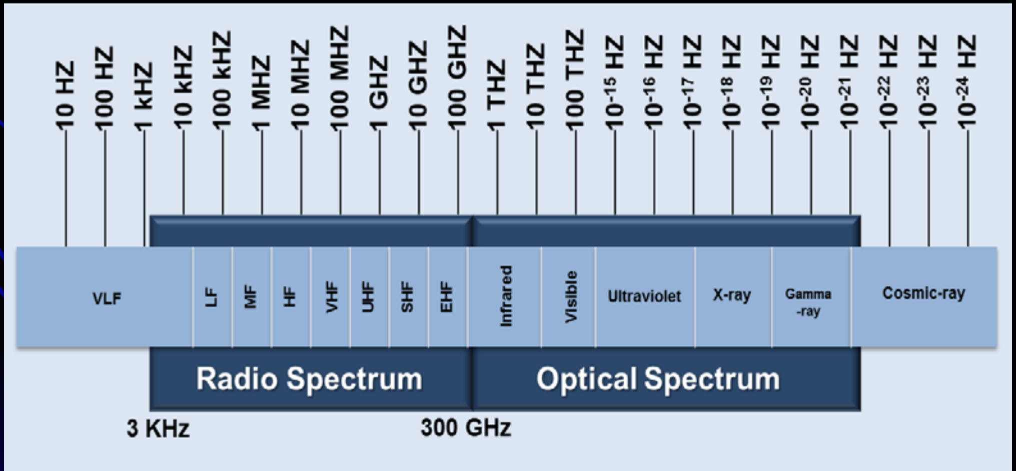
John Rush, "NASA Advisory Council ITIC Committee Space Communications and Navigation Optical Communications Update"

Optical Communications is the Future of Space Communications

- Future demand for near-Earth and deep space missions will exceed capacity available in RF Ka-band (GHz) driving move to higher BW, unregulated / unconstrained optical communications spectrum (THz).

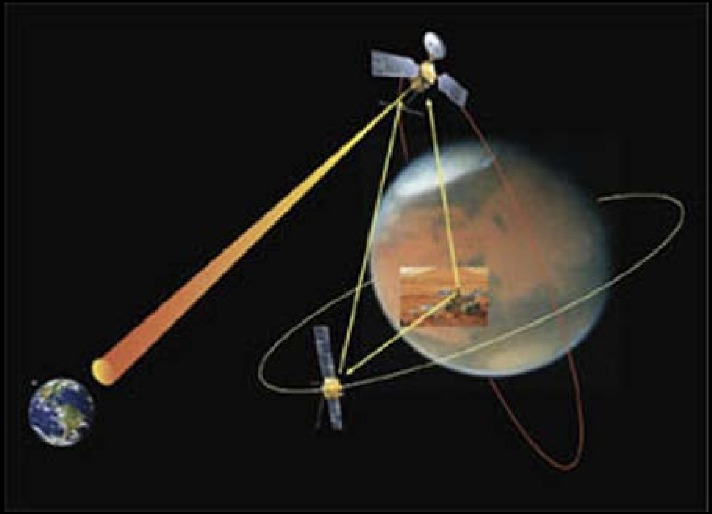
- **With optical (laser) communications NASA can realize data rates 10-100X better than RF (for same SWaP allocation) over both interplanetary and shorter near-Earth distances.**

- Optical communications requires less SWaP including significantly less aperture size than RF antennas to achieve same data rate.



Key Challenges for Space Optical Communications

- Maturity/flight heritage of efficient, robust and reliable space laser transmitters (R&TD, demo).
  - Lack of on-orbit reliability and radiation data on operating lifetime of lasers and optical components.
- Data transmission rates decline as density of received photons is reduced.
  - Efficient lasercom links from deep space require detection of extremely faint signals.
  - Additive optical background noise from sunlight also poses a challenge to performance.
  - Requires atmospheric correction techniques. Successful with meter-class ground-receiving apertures but not yet cost effective on 8-12 meter-diameter aperture ground receivers required for deep space comm.
- Requires operation of lasercom links with sufficient availability in presence of atmospheric variability (weather, clouds, moisture, turbulence).
  - Need cost-effective networks with site diversity.



Interplanetary laser communications concept demonstrating links from a Mars orbiter to Earth, and proximity links from Mars surface assets to orbiters

Primary challenge of laser communications: operating at full performance potential over long distances and operational lifetimes despite atmospheric / environmental disturbances (i.e. cloud cover, wind, radiation, etc.) that can disrupt data transmission and system reliability.

Space Optical Communications Potential

- Depending on mission application, an optical communications solution can achieve:
  - **50% savings in mass**
    - Reduced mass enables decreased spacecraft cost and/or increased science through more mass for the instruments
  - **65% savings in power**
    - Reduced power enables increased mission life and/or increased science measurements
  - **Up to 100X increase in data rate**
    - Increased data rates enable increased data collection and reduced mission operations complexity

- Eliminates issues such as microwave spectral congestion, spectrum allocation, and constrained BW common with RF communications
- Enables new science for missions requiring substantial BW (i.e. hyperspectral imagers and instruments with high definition in spectral, spatial, temporal modes)
- Establishes "virtual presence" at remote planet or other solar system body, enabling high data rate communications with future space explorers

Space Optical Communications Outlook

- Early tech demos with 10 cm optical module design support near-Earth (including lunar) optical communications.
- Progress from near-Earth capabilities to development of larger terminals to support deep space optical communications (DSOC) and enable Earth-based satellites to use as relays for DSOC.
- Increasing laser lifetime will be critical for long duration missions. Narrow beam widths also will require more precise acquisition and tracking, as well as vibration mitigation.
- Increasing laser power efficiency from current 10-15% to 30% while decreasing SWaP-C will be important factors in moving optical communications capability forward, especially for deep space applications.
- Further development in beaconless tracking to enable optical communications to outer planets.

NASA Technology Roadmap

- NASA roadmaps are a set of documents that consider a wide range of needed technologies and development pathways for the next 20 years (2015-2035). The roadmaps focus on research and development (R&TD).
- **Technology Area (TA) 5: Communications, Navigation, and Orbital Debris Tracking and Characterization Systems**
  - **5.1 Optical Communications and Navigation:**
    - Deals with various technologies required to make communications and navigation with light practical and seeks to take advantage of the virtually unconstrained bandwidth available in optical spectrum.
    - Increase performance and efficiency in systems that provide communications, navigation, and orbital debris tracking and characterization capabilities for all mission classes.
    - Provide higher data rate links for near-Earth and enable more efficient photon-starved links for deep-space.

Increased reliability is an underlying goal for both performance and efficiency which must ultimately translate into an overall mission lifecycle cost reduction.

https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_5_communication_and_navigation_final.pdf

Overarching Goals for NASA Space Communications Capability

- Develop optical communications to a level of availability that matches RF and utilizes unrestricted optical bandwidth for orders of magnitude advances.
- Transform present NASA space communications from being a connection provider to being a flexible service provider (with the goal of networks that are tolerant to disruptions and delays).
- Increased data rates (e.g., 10 - 100X) without increasing mass, volume, power, and/or spectrum.
- Increased security without increased complexity.
- Assured data delivery via robust, low latency, automated or autonomous, and networked connectivity throughout the solar system.

Near-term: *address deficiencies identified by established missions*

Long term: *provide NASA with advanced space communications capabilities that missions can then infuse to provide new mission capabilities, including enhanced public engagement and, potentially, spinoffs to commercial endeavors*

Integrated Photonics Roadmap

- **5 .1 .1 Detector Development:** Development of high detection efficiency, low-dark-count, low-jitter photon counting detectors for both ground and flight applications.
- 5 .1 .2 Large Apertures: Multi-meter diameter optical apertures for both ground (> 10 m diameter) and flight (> 5 m diameter) applications.
- **5 .1 .3 Lasers:** High direct current (DC)-to-optical power efficiency, high peak-to-average power, reliable, flight-qualified lasers.
- 5 .1 .4 Acquisition and Tracking: Techniques and technologies for efficient, accurate pointing of the optical terminal—primarily in flight—but may include interaction with the ground terminals or be “beaconless.”
- 5 .1 .5 Atmospheric Mitigation: Measurement and modeling of the atmospheric channel and its effects on optical propagation, and techniques and technologies for mitigating atmospheric effects.
- 5 .1 .6 Optical Tracking: Optical techniques for ranging and Doppler measurement derived from the optical communications signal.
- **5 .1 .7 Integrated Photonics:** Next generation of highly integrated systems including lasers, optics, modulators, demodulators, encoding, and decoding.

5.1.7 Integrated Photonics Roadmap: Goals, Challenges, and Benefits

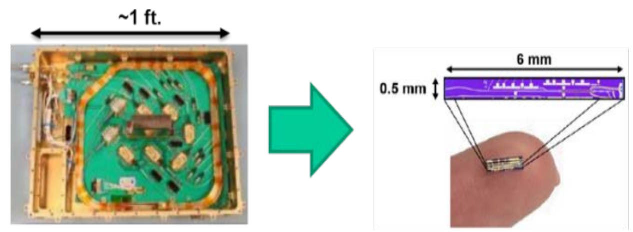
- **Future cost and SWaP efficiency** of optical communications systems will depend upon more highly integrated photonic systems replacing multiple bulky and power hungry systems all requiring individual testing and integration.
  - Ideally, these will be derivatives of similar technology being developed in commercial fiber optic systems of 40 to 100 Gb/s data rates.
- ***Goal:*** provide highly integrated systems combining lasers, modulators and demodulators, encoders and decoders, detectors, and associated electronics in one combined unit.
- ***Challenges:***
  - Use technology being developed for commercial fiber optic world — space qualify it with potential modifications — and integrate it with spacecraft data systems.
  - Attenuation, blockage by clouds, background noise from radiation, scintillation from Earth's atmosphere.
- ***Benefits:*** meeting these challenges will ensure extremely high data rates for Inter-Satellite Links (ISLs).

Integrated Photonics Overview

- Integrated photonics is the next generation disruptive technology critical to meeting size, weight, power and cost (SWaP-C) and performance goals for deep space optical communications (DSOC).
- Photonic integrated circuits (PICs) have chip scale integration of multiple optical elements or components which enable complex functions analogous to electronic ICs.
- PIC optical component include: optical amplifiers, MUX/DEMUX, lasers, modulators, LEDs, detectors, optical fiber, lenses, attenuators, switches (optocouplers).
- PIC materials include: Si, SOI, $LiNbO_2$, GaAs, InGaAs, InGaAsP, InP, SiO_2.
- ***Key benefits of PICs: over 50% less mass and power, 100X size reduction, higher BW and data rate, no-cost redundancy, aperture-independent (fiber-coupled), transparent to modulation format, versatile and scalable.***

Comparison Between Photonic ICs and Electronic ICs

Parameters	Photonic Integrated Circuits	Electronic Integrated Circuits
Mode of Function	Analog	Digital
Raw materials Used	InP, GaAs, $LiNbO_3$, Si, SOI	Majorly Silicon
Fabrication Technique	Photolithography	Photolithography
Primary Device (component)	No Particular Device is Dominant	Transistor
Data Transfer Rate	Data is Transmitted at the Speed of Light	Data is Transmitted at the Speed of Electron Flow



Optical communications transmitter made with discrete photonic components

Photonic Integrated Circuit (PIC) Transmitter

http://www.credenceresearch.com/report/photonic-integrated-circuits-market

Space Applications for Emerging Integrated Photonics

- Next generation optical communications systems (inter-satellite or satellite-to-ground, modulators) enabling…
  - Broadband internet satellite connectivity, high bit-rate/spectrally efficient satellite links, high speed comm between deep space probes
- Scientific instruments on satellites or rovers (cameras, LIDAR, spectrometers)
- Signal distributions (MOEM-based switches, mixers, analog or digital optocouplers, intra-satellite communications)
- Sensing (i.e. star-trackers, gyroscopes, temperature, strain, metrology)

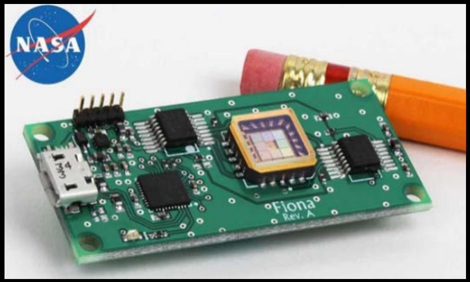
Spectrometer Optical Data Comm LIDAR

Overview of Planned NEPP Work FY19

- **Problem Statement:** DSOC requirements are demanding in terms of high peak-to-average power, high extinction ratio, radiation, lifetime reliability (including temperature) and stability. Current state-of-the-art integrated photonic chips are only designed and qualified for terrestrial communication systems in commercial applications as well as academia. As a result, risks associated with reliability of PICs in the space environment are not well understood.

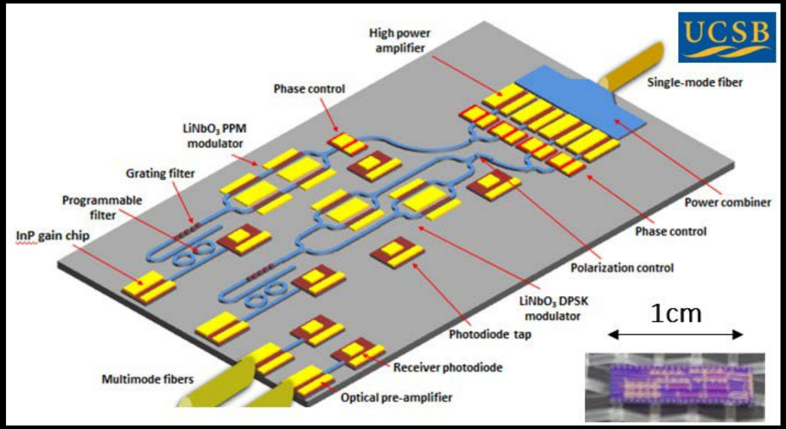
- **Solution:** Develop, test and validate novel mission assurance methodologies for screening and qualifying a commercial photonic-integrated laser transmitter (PILT) for reliable operation in deep-space applications.

- **Importance to NEPP:**
  - Position NEPP as leader in development and qualification of advanced integrated photonics for space.
  - Fill knowledge gap on methods for reliability screening and qualification of integrated photonics for space not addressed by Telcordia standards.
  - Reduce risk of flight insertion of integrated photonics into NASA space applications, enabling order of magnitude improvements in SWaP-C and performance.



Technical Approach

1) UCSB will fabricate and design custom PILT pathfinder and testbed. Professor Klamkin recently received 3-year NASA research award from the Advanced Component Technology Center to produce low-SWaP integrated micro-photonic circuits for space-based applications.
2) We will develop analytical tools and test protocols to explore failure mechanisms and assess design margins of various commercial photonic components and materials on the PILT. This will include performance characterization and quantification of key life and reliability parameters.
3) Based on findings, define risk mitigation strategies for use of advanced PICs in space.
4) Use results of simulations, testing, and analysis to establish guidelines. We will leverage existing Telcordia standards for discrete photonic components and the body of knowledge on individual chip materials.
5) Second year (if funded): perform design iterations based on findings in year 1; provide feedback to UCSB for creation of a new design iteration of the ILT to be put through our newly-developed qualification method.



Innovation of NEPP Integrated Photonics Task

We propose to develop screening and qualification guidelines for PICs using a custom photonic-integrated laser transmitter (PILT) built by UCSB as a technology pathfinder/baseline.

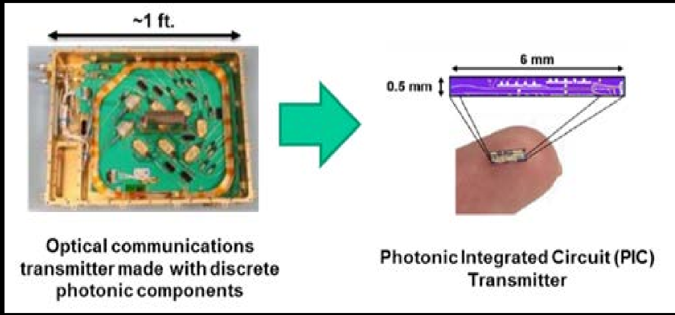
- Using versatile, reconfigurable PIC technology, we seek to demonstrate the feasibility, radiation hardness and reliability of an optical subsystem miniaturized onto single, scalable chip with a “USB drive” form factor and designed to meet end-of-life requirements for space-based missions.
- Development of these space qualification methodologies will leverage established industry standards for commercial photonic components (Telcordia) as well as military standards for semiconductor devices to address current unknown reliability weaknesses of PICs for use in space.

How does it compare to state-of-the-art (SoA)?

- Presently, industry standards do not exist for component selection, design, and fabrication of highly reliable commercial PIC for space.
- From a performance perspective:
  - Discrete designs using SoA space lasercom transmitters have high average power (>1W) and peak power (~kW) to support deep-space links but require fiber-based lasers and amplifier with external modulation. Issues: Large SWaP footprint due to fiber packaging constraints.
  - Terrestrial datacom transceivers: 10/40/100 Gpbs PIC transceivers exist in Datacom (Cisco). Issues: Incompatible with space applications; low output power (<10mW) and coherent modulation formats suitable only for short-reach, low-noise fiber networks.

Overall Objective:

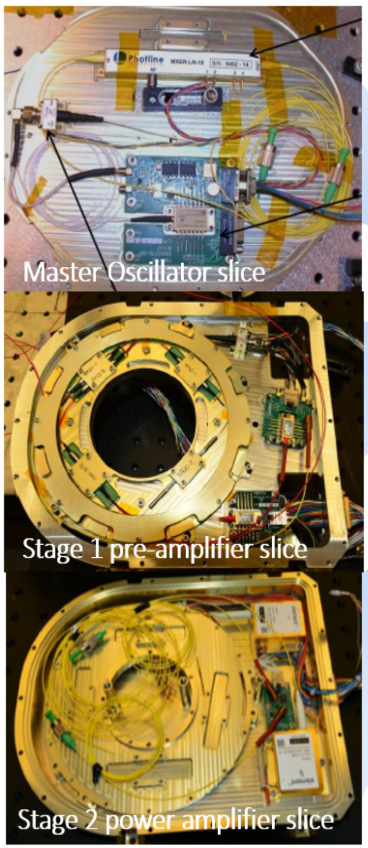
Bridge technology gap between academic research and flight prototype development of integrated photonics. This work seeks to combine radiation and reliability screening of PILT research pathfinders with performance characterization in deep-space optical links to distill a novel, final prototype solution with path to flight.

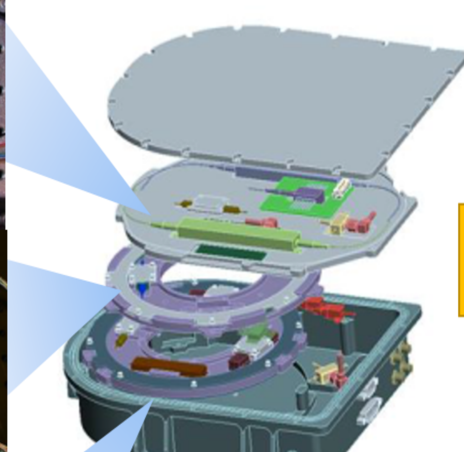


Integrated Photonics Advantages

Fiber-based Transmitter

DSOC Laser Transmitter assembly



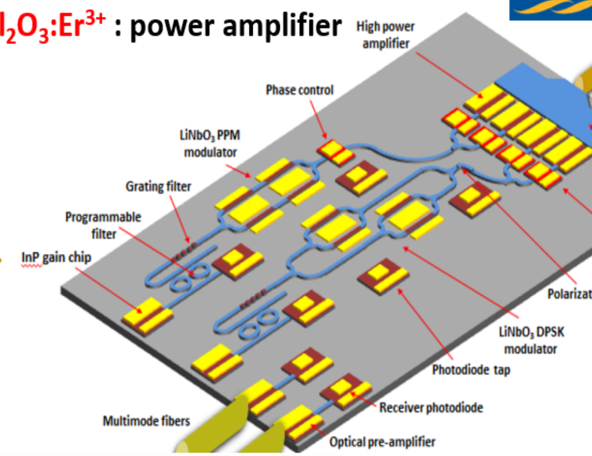


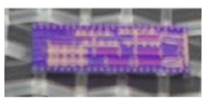
Future

Photonic Integrated Transmitter

Integration platforms chosen for best device performances

- InP : laser & pre-amplifiers
- $LiNbO_3$: modulator
- $Al_2O_3:Er^{3+}$: power amplifier





	Discrete	Integrated
Size and Weight	8” x 10” x 2.12”, 3.4kg	2” x 0.5” x 0.25”, 0.2kg
Robustness/Stability	Large footprint, fibers	Small footprint
Redundancy	Possible (SWaP limited)	“Unlimited” (at no cost)
Functionality (Modulation)	Single (PPM)	Multi (PPM, DPSK)
Output Average Power	6W	1W (in progress)
Performance	Mature	Under development
Environmental Testing	Mature	Unknown yet

Miniaturization, integration and scalability designed to optimize performance and emphasize SWaP savings.

PIC Qualification Challenges

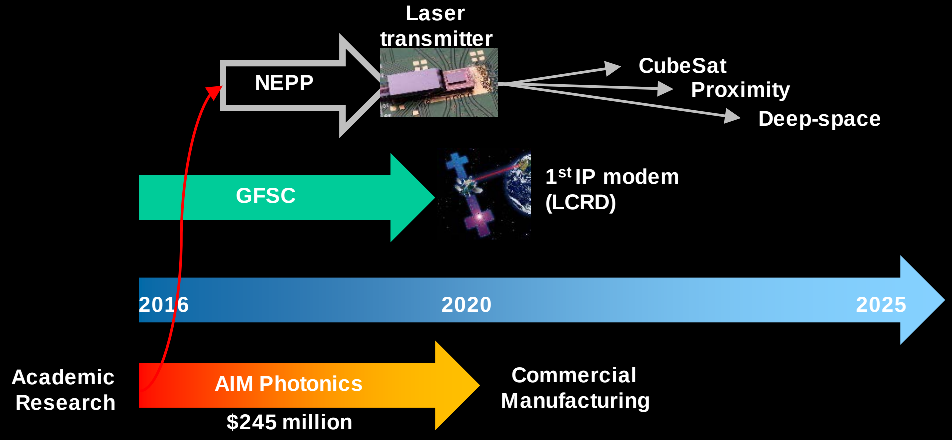
- Materials, Process, Performance Unknowns:
  - Unlike bulk CMOS, used for silicon electronics, there is no single material suitable for all integrated photonics applications (Si, SOI, silicon nitride, lithium niobate are all popular substrates)
  - Lack of statistically significant radiation, reliability and lifetime data for COTS-based photonics
  - Radiation tolerance
  - Failure modes and mechanisms
  - Environmental temperature limits for operation and storage
  - Lack of physics models on which to base design of reliability tests/accelerated life tests
  - Lack of standards in component selection, design, fabrication of highly reliable integrated photonics for space
  - PIC design challenges in generating Watt-level outputs needed for deep-space optical communications
- Packaging unknowns:
  - Effect of packaging design on functional performance
  - Sensitivity to launch environments (e.g. shock, vibration, thermal cycling)
  - Sensitivity to outgassed materials
- Other issues:
  - Difficulty diagnosing optical train problems in PICs due to small physical size
  - Potential CTE mismatch problems with higher levels of integration
  - Integrated platform must be designed to operate at high optical power levels while maintaining performance uncooled over a wide temp range (<-40°C to +100°C) for DSOC

Future Impact and Summary

NEPP work is intended to…

- Demonstrate feasibility of commercial PIC technology with path to flight from tech demo to high reliability mission (i.e. Mars2028 will require high optical power output and long lifetime).
- Address NASA Technology Roadmap (TA5) Optical Comm & Integrated Photonics (5.1.7).
- Define challenges impacting development and integration of PICs for space applications – understand risks associated with mission specific environments (radiation, reliability).
- Demonstrate scalability of photonic building blocks for PILT to enable complex on-chip optical signal processing for various purposes (e.g. laser altimeters, interferometers, LIDAR). Spin-offs will directly benefit other optical instruments and NASA mission science applications.
- Address deep-space optical comm needs. Potential to augment other optical science capabilities.

Trends in optical communications



PIC is brand new technology with imminent commercialization

Critical Milestones
Yr 1: Establish library of figures of merit for evaluating PICs for space. • Identify potential reliability risks based on industry survey. • Develop simulation models to explore potential radiation degradation and study impact on link performance. • UCSB to develop pathfinder PILT based on initial feedback. • Identify diagnostic reliability and radiation tests for PICs. • Document screening and space qual methods in guidelines.
Yr 2: Refine guidelines based on PILT performance and reliability testing. • Use guidelines to perform radiation and environmental tests on PILTs provided by UCSB (at no charge). • Characterize performance under radiation and reliability stresses. Benchmark against SoA space and terrestrial transmitters. • Feedback results from testing to UCSB to aid PILT design improvements and converge on flight transmitter prototype.

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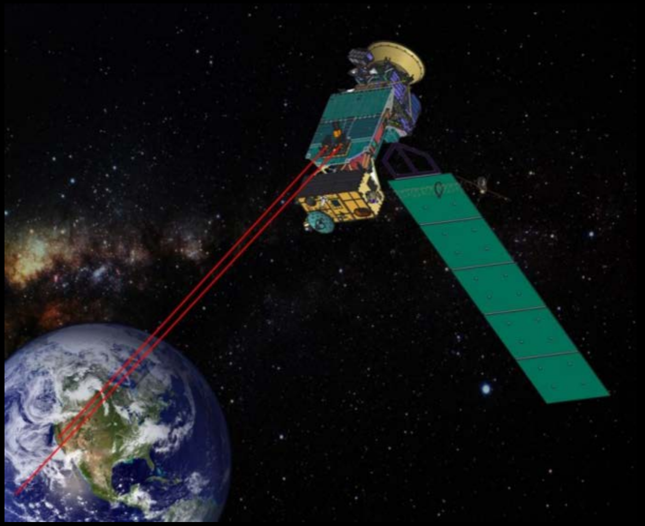
jpl.nasa.gov

BACKUP

Past Space Optical Comm Demonstrations

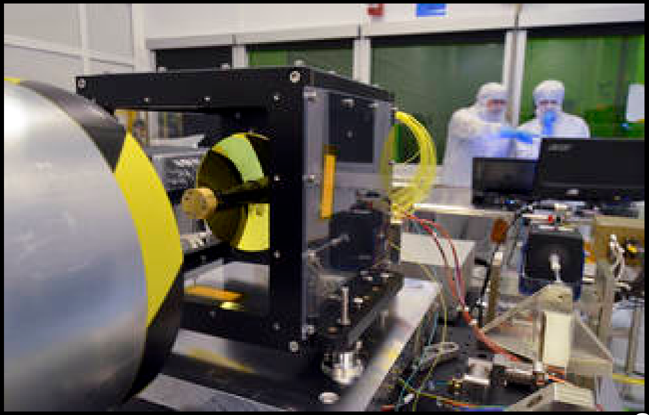
- 2013-14: Pathfinder Lunar Laser Communications Demonstration (LLCD) optical terminal flight on Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft first to demonstrate high data rate laser optical communications capability *to LEO and beyond*.
  - Data transfer at 622 Mbps (downlink) from Moon to Earth. Space terminal smaller, lighter and used less power than RF (~3-6X Ka-band system on LRO).
  - 10 cm optical module technology for LEO / GEO.
  - Predicted optical communications for in-situ relays improves link performance by orders of magnitude.
  - Primarily coherent modulation augmented with Serially Concatenated Pulse-Position Modulation (SCPPM) and superconducting nanowire photon counting detectors, which will be key factors in future deep-space optical communications.
  - Demonstration of coherent modulation enables multi-Gbps operation at LEO and GEO.
  - Challenges: flight implementation of signal processing and storage (electrical or photonic) for modulation, demodulation, encoding, decoding, and routing functions as bit rates approach 100 Gb/s.



Future Space Optical Comm Demonstrations

- LCRD will launch in 2019 and fly for 2-5 years.
- Flight and ground segment to demo 2 simultaneous bidirectional optical links (DPSK downlink: 1.2 Gbps; uplink: 1.25 Gbps).
- Two ground terminal laser modems in CA and HI; LCRD payload in GEO. Payload has two identical optical terminals connected by space switching unit (data router), also connected to RF downlink.
- Modems translate digital data into laser or RF and back again. Once data is converted to laser light, optical module beams data to Earth. Controller electronics module commands actuators to point and steady telescope from vibration on spacecraft.
- LCRD mission objectives:
  - demo bidirectional optical comm between GEO and Earth,
  - measure and characterize optical comm system performance over various atmospheric conditions and validate models,
  - develop operational procedures and assess applicability for future missions,
  - transfer laser communications technology to industry for future missions,
  - provide on-orbit capability for test and demo of standards for optical relay communications.
- Laser terminal for LEO ISS to LCRD being designed to relay data to ground at Gbps rates (flight 2021). Future Earth-orbiting NASA missions to fly copies of it to relay data through LCRD to ground.
- Optical terminals, developed by foreign space agencies, are progressing toward operational capability in the next year – high data rates up to 6 Gb/s for LEO and GEO crosslinks.

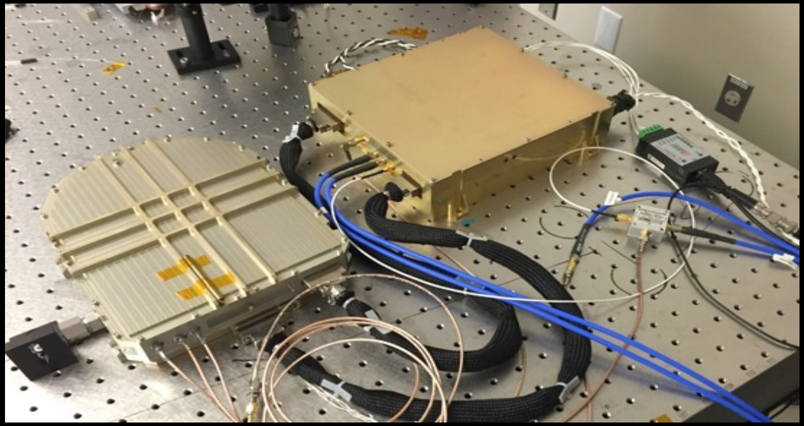
NASA is developing a trailblazing, long-term tech demo of what could become the high-speed internet of the sky. Laser Communications Relay Demonstration (LCRD) will help demonstrate that optical communications can meet growing need for higher data rates for scientific downlink and astronaut communications as well as enable lower SWaP. LCRD will advance optical communications technology toward infusion into deep space and near-Earth operational systems, while growing capabilities of industry sources to produce affordable optical communications systems and components for use on ground and space.



Source: https://www.nasa.gov/feature/goddard/2017/nasa-taking-first-steps-toward-high-speed-space-internet

Areas of Emphasis at JPL

- Key areas of emphasis in **optical** communications research and development at JPL include:
  - long-haul optical communications (DSOC)
  - optical proximity link system development
  - in-situ optical transceivers
- DSOC is developing technologies to enable streaming high definition imagery and data communications over interplanetary distances.
- Also advances in JPL's optical proximity link systems with low complexity and burden can boost surface asset-to-orbiter performance by a factor of 100 (20 dB) over current state-of-the-art. This improvement would benefit planetary and lunar orbiters to communicate with landers or rovers.



Laser transmitter assembly with module on the left in the laser optical module; the laser electronics module is shown on the right. Peak power 1 kW. (Credit: NASA)

Mars Reconnaissance Orbiter (MRO) Example

- **Bandwidth:**
  - At MRO's max data rate of 6 Mbps (the highest of any Mars mission), it takes 7.5 hrs to empty its on-board recorder and 1.5 hrs to transfer a single image back to Earth from the onboard High Resolution Imaging Science Experiment (HiRISE) camera. New high-resolution hyperspectral imagers put further demands on their communications system, requiring even higher data rates.
  - With an optical communications solution at 100 Mbps, the recorder could be emptied in 26 minutes, and an image could be transferred to Earth in less than 5 minutes.

- **Antenna Size:**
  - MRO uses a 3 meter antenna to communicate with Earth.
  - If MRO was using optical communications, it could use 20 cm aperture telescope instead.

https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_opticalcomm_benefits.html

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Deep Space Optical Communications Feasibility Study for NASA Missions

Program	Mission	Rough Data Rate*	Suitability for Optical Comm
Discovery	TIME	~0.44 kbps from surface of cloud-enshrouded Titan	No; environment not conducive
Discovery	Comet Hopper	~18 kbps while touch-and-go with potentially ice- and dust-enshrouded comet up to 4 times in 2 years	No; environment not conducive
Discovery	PriME	~50 kbps while rendezvousing with a potentially ice- and dust-enshrouded comet	No; environment not conducive
Discovery	Whipple	~2.5 Mbps from an ETO at about 0.4 AU from Earth	Yes; possible data-rate-driven optical comm candidate. Ka-band is a viable alternative, but optical may provide mass/volume/cost benefits.
Discovery	NEOCam	~30 Mbps (possibly up to 260 Mbps) from a SEL1	Yes; possible data-rate-driven optical comm candidate. Ka-band is a viable alternative, but optical may provide mass/volume/cost benefits.
New Frontiers	SAGE	~250 kbps for 21 days post-flyby; carrier acts as relay while flying by Venus	Possible; however, comm is not a strong driver
New Frontiers	MoonRise	See Lunar South Pole–Aitken Basin Sample Return	—
New Frontiers	Comet Surface Sample Return	~18 kbps while sampling a potentially ice- and dust-enshrouded comet	No; environment not conducive
New Frontiers	Lunar South Pole–Aitken Basin Sample Return	~198 kbps from a lunar relay orbiter	Possible; however, comm is not a strong driver
New Frontiers	Saturn Probe	~1.6 kbps from Saturn; carrier acts as relay	Possible; however, comm is not a strong driver for the probe, but extended mission for the carrier could be a driver
New Frontiers	Trojan Tour and Rendezvous	~30 kbps from Jupiter vicinity (possible mass, power, volume–driven candidate)	Yes; possible data-rate-driven optical comm candidate. Ka-band is a viable alternative, but optical may provide mass/volume/cost benefits.

* All rates are rough estimates for prime science. In some cases, exact rates are proposal proprietary.

Table 1 continues on next page

Reference: Design Reference Missions for Deep-Space Optical Communication IPN Progress Report 42-205 May 15, 2016 https://ipnpr.jpl.nasa.gov/progress_report/42-205/205B.pdf

Deep Space Optical Communications Feasibility Study for NASA Missions

Program	Mission	Rough Data Rate*	Suitability for Optical Comm
New Frontiers	Venus In Situ Explorer	Concepts with relay data rates that range from ~25 kbs to ~14.5 Mbps	Yes; possible data-rate-driven optical comm candidate
New Frontiers	Io Observer	~50 kbps from intense Jupiter radiation environment (mass, power, volume [MPV] constrained)	Mixed; MPV constraint makes optical attractive, but high radiation environment may be impractical for optical comm terminal
New Frontiers	Lunar Geophysical Network	~125 kbps from each of four landers	Possible; however, comm is not a strong driver
HEOMD	Asteroid Redirect Robotic Mission (2013–2021)	~100 kbps baseline; but, stereo HDTV from CubeSats desired	Yes; possible data-rate-driven optical comm candidate
HEOMD	Asteroid Redirect Crewed Mission (2021–2027)	~24.2 Mbps from lunar DRO; HDTV coverage desired; ~5.8 Mbps uplink	Yes; possible data-rate-driven optical comm candidate
HEOMD	Crewed Mission to NEA (2027–2033)	~25 Mbps from ~0.6 AU; HDTV coverage desired; ~6 Mbps uplink	Yes; possible data-rate-driven optical comm candidate
HEOMD	Crewed Mission to Lunar Surface (2027–2033)	~25 Mbps from lunar surface; early desire for ~150 Mbps; ~6 Mbps uplink	Yes; possible data-rate-driven optical comm candidate
HEOMD	Crewed Mission to Mars' Moons (2027–2033)	~25 Mbps from Mars orbit; ~6 Mbps uplink	Yes; possible data-rate-driven optical comm candidate
HEOMD	Crewed Mars Orbital Mission (2033+)	~25 Mbps from Mars orbit; ~6 Mbps uplink	Yes; possible data-rate-driven optical comm candidate
HEOMD	Crewed Mars Surface Mission (2033+)	~150 Mbps from Mars surface habitat at 2.5 AU; ~25 Mbps uplink	Yes; possible data-rate-driven optical comm candidate
HEOMD	Crewed Mars Surface Mission — Minimal (2033+)	~150 Mbps from Mars surface habitat at 2.5 AU; ~25 Mbps uplink	Yes; possible data-rate-driven optical comm candidate
SMD	Wide-Field Infrared Survey Telescope (WFIRST) (2025)	~150 Mbps from SEL2	Yes; possible data-rate-driven optical comm candidate

* All rates are rough estimates for prime science. In some cases, exact rates are proposal proprietary.

Table 1 continues on next page

Reference: Design Reference Missions for Deep-Space Optical Communication IPN Progress Report 42-205 May 15, 2016 https://ipnpr.jpl.nasa.gov/progress_report/42-205/205B.pdf

Deep Space Optical Communications Feasibility Study for NASA Missions

Program	Mission	Rough Data Rate*	Suitability for Optical Comm
SMD	Gravitational-Wave Surveyor Mission (2045)	~90 kbps from each of 3 S/C in ETO; laser-links to maintain formation	Possible; however, comm is not a strong driver
SMD	CMB Polarization Surveyor Mission (2040)	~100 Mbps from SEL2	Yes; possible data-rate-driven optical comm candidate
SMD	Far-Infrared Surveyor Mission (2040)	~100 Mbps from SEL2	Yes; possible data-rate-driven optical comm candidate
SMD	Large UV/Visible/IR Surveyor Mission (2035)	~24.5 Mbps from SEL2	Yes; possible data-rate-driven optical comm candidate
SMD	X-ray Surveyor Mission (2035)	~8 Mbps from SEL2	Yes; possible data-rate-driven optical comm candidate
SMD	Exo-Planet Direct Imaging Mission (2030)	~>24.5 Mbps from SEL2	Yes; possible data-rate-driven optical comm candidate
SMD	Interstellar Mapping and Acceleration Probe (IMAP) (NET~2022)	~76.4 kbps from SEL1	Possible; however, comm is not a strong driver
SMD	Dynamical Neutral Atmosphere–Ionosphere Coupling (DYNAMIC) (NET~2026)	~1.4 Mbps from each of two S/C in Molniya orbits	Possible; however, comm is not a strong driver
SMD	Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI) (NET~2030)	~1.4 Mbps from each of two S/C in 8 Earth-radii circular orbit	Possible; however, comm is not a strong driver
SMD	Explorer Missions (2018, 2024, 2030)	Significant concept variability from kbps to Mbps	Possible
SMD	Mars 2020 (2020)	~10 kbps direct-to-Earth at 2.6 AU; ~128 kbps to 2 Mbps to relay orbiter	Optical has not been selected
SMD	Europa (2022–2024)	~134 kbps at 6.4 AU within Jupiter's intense radiation belts	Mixed; data rate makes optical attractive, but high radiation environment may be impractical for optical comm terminal
SMD-	Mars Sample Return (>2026)	~10 kbps direct-to-Earth at 2.6 AU for ERV and rover; relay is ~>5.2 Mbps	Yes; possible data-rate-driven optical comm candidate

* All rates are rough estimates for prime science. In some cases, exact rates are proposal proprietary.

Reference: Design Reference Missions for Deep-Space Optical Communication IPN Progress Report 42-205
May 15, 2016 https://ipnpr.jpl.nasa.gov/progress_report/42-205/205B.pdf

NASA Design Reference Missions for Deep Space Optical Communications

Article Page No./ DRM	Location	Orbit Type	Example Mission Type	Example Mission Name	Start, CY	Finish, CY	Wave-length, nm	Min Range, AU	Max Range, AU	Max SEP, deg	Min SEP, deg	Terminal Class	Transmit Power, W	Aperture Diameter, m	Downlink Data Rate Requirement	Uplink Data Rate Requirement
11. Small Optical Terminal at Mars	Mars	Heliocen-tric/Mars	Lander Demo Optical Terminal or CubeSat at Mars	Mars 2020	2022	2023	1550	0.42	2.6	180	3	Small	1	0.05	~10 kbps DTE at 2.7 AU; ~128 kbps to 2 Mbps to relay orbiter	[1 kbps*]
11. Medium Opti-cal Terminal at Mars	Mars	Heliocen-tric/Mars	Mars Orbiter	NeMO	2022	2023	1550	0.42	2.6	180	3	Medium	4	0.22	~>5 Mbps	[100 kbps*]
12. Large Optical Terminal at Mars	Mars	Heliocen-tric/Mars	Crewed Mars Surface	Crewed Mars Surface	2036	2038	1550	0.42	2.5	180	3	Large	20	0.5	~150 Mbps to 600 Mbps	~25 Mbps
12. Deep Space Observatory–Nighttime	SEL2	Sun–Earth Lagrange Point 2	Observatory	WFIRST at L2	2024	2025	1550	0.009	0.011	175	~160	Medium	4	0.22	~150 Mbps to 262.5 Mbps	[100 Mbps*]
13. Deep Space Observatory–Dawn or Dusk	ETO	Solar Earth Trailing Orbit	Observatory	Whipple	2020	2022	1550	0.4	0.4	80	75	Small	1	0.05	~2.5 Mbps	[1 Mbps*]
13. Deep Space Observatory–Daytime	SEL1	Sun–Earth Lagrange Point 1	Observatory	NEOCam	2020	2020	1550	0.009	0.011	~20	3	Small	1	0.05	~30 Mbps (possibly up to 260 Mbps)	[100 Mbps*]
14. Medium Opti-cal Terminal at Jupiter Distance	JSL3	Heliocen-tric/Jupiter Trojan	Outer Planets	Trojan Tour and Rendezvous	2030	2031	1550	4.2	6.2	180	3	Medium	4	0.22	~12.5 to 30 kbps	[1 kbps*]
14. Large Optical Terminal at Saturn	Saturn	Heliocen-tric/Saturn	Outer Planets	Saturn Atmospheric Entry Probe or Enceladus Life Finder	2039	2040	1550	8.5	10.5	180	3	Large	20	0.5	~1.6 kbps relay [1 Mbps*]	[10 kbps*]
15. Large Optical Terminal at Jupiter	Jupiter	Heliocen-tric/Jupiter	Outer Planets	Europa Clipper	2024	2025	1550	4.2	6.4	180	3	Large	20	0.5	~134 kbps	[10 kbps*]
15. Inner Planets	Venus	Heliocen-tric/Venus	Inner Planets	Venus In Situ Explorer	2024	2026	1550	0.28	1.72	50	3	Medium	4	0.22	~25 kbps to ~14.5 Mbps relay	[100 kbps*]
16. Very Small Terminal at Lunar Distance	Moon	Geocen-tric/Moon	Crewed Lunar (Surface)	Crewed Lunar (Surface)	2027	2029	1550	0.003	0.003	180	3	Very Small	0.002	0.02	~25 Mbps; early desire for ~150 Mbps	~6 Mbps
16. Mars Trunk Line	Mars	Heliocen-tric/Mars	Mars Relay Crewed Mars Orbital	Aerostationary Orbiter Crewed Mars Orbital	2030	2031	1550	0.42	2.6	180	3	Large	10	0.3	~250 Mbps	[100 kbps*]

*Provisional value in absence of customer statement.

Reference: Design Reference Missions for Deep-Space Optical Communication IPN Progress Report 42-205 May 15, 2016 https://ipnpr.jpl.nasa.gov/progress_report/42-205/205B.pdf

Integrated Photonics Technology Candidates

5.1 Optical Communications and Navigation
5.1.7 Integrated Photonics

5.1.7.1 Multi-Mode Coherent Transceivers

TECHNOLOGY

Technology Description: Integrated photonics providing lasers, modulators, detectors, encoding, decoding, and electronics for coherent inter-satellite links (ISL).

Technology Challenge: Frequency/spatial mode multiplexing; flight-qualified multiple-input multiple-output (MIMO) receiver with less than a few hundred W power dissipation. Efficient operation at 1,550 nm; long-term stability (> 50,000 hours); develop receiver topology; signaling/ coding/bandwidth filtering mass, pointing, and launch accomodations.

Technology State of the Art: Single-mode coherent transceivers. Narrow linewidth lasers "brick-wall" coherent receiver. Diffraction limited large aperture.

Parameter, Value:	TRL
5.6 Gb/s milliHertz linewidth, not flight, 1.44 bits/photon limit (heterodyne); 2.89 bits/photon limit (homodyne), 2.4 meter (Hubble)	2

Technology Performance Goal: Multi-mode flight coherent transceiver 100 Hz linewidth flight laser photon counting coherent receiver 10 meter diffraction limited flight optical transceiver aperture.

Parameter, Value:	TRL
100 Gb/s geosynchronous Earth orbit (GEO)-GEO < 100 Hz linewidth; > 40 W average power; > 20% direct current-optical efficiency; 5 bits/incident photon coherent receiver; 10 meter or > diameter; < 0.1 wave total optical wavefront error at 1 μm	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Coherent modulation/demodulation systems for ISL and ultimately for direct-to-Earth communications with adaptive optics receivers.

Capability Description: 10 to 100 Gb/s ISL in Earth orbit 0.1 to 1 Mb/s links to planetary orbiters.

Capability State of the Art: Earth orbiting ISL.

Parameter, Value:

1.2 Gb/s GEO (2017 NASA Laser Communications Relay Demonstration).

Capability Performance Goal: Multi-mode coherent transceivers. Deep-space coherent orbital transmitter. Deep-space coherent orbital receiver.

Parameter, Value:

40 to 1,000 Gb/s point-to-point links < 100 Hz linewidth flight lasers;

Photon counting coherent receiver > 10 meter diffraction limited apertures

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Hyperspectral Infrared Imager (HyspIRI)	Enhancing	--	2023*	2020	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_5_communication_and_navigation_final.pdf

Integrated Photonics Technology Candidates

5.1 Optical Communications and Navigation 5.1.1 Detector Development	**5.1.1.1 Tungsten Silicide (WSi) Photon Counting Detector Array**

TECHNOLOGY

Technology Description: Tungsten Silicide (WSi) large-area superconducting nanowire single photon counting detector array.

Technology Challenge: Fabrication yield and material physics are challenges.

Technology State of the Art	TRL	Technology Performance Goal	TRL
Medium format free-space-coupled array.		Free-space-coupled photon counting detector for PPM 16-128 for 12 meter telescope.	
Parameter, Value: 160 x 160 micron 64 pixel array; 40% detector efficiency (DE); 100 ps jitter; < 3 dB saturation loss at 0.4 Gigaphotons/sec	3	**Parameter, Value:** 640 x 640 micron 256 pixel array; 70% DE; 50 ps jitter; < 3 dB saturation loss at 2.0 Gigaphotons/sec	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Photon counting arrays for ground receivers.

Capability Description: Provide large active area, low jitter, high detection efficiency, low dark-count, high saturation rate detector array operating in the 1.0-1.5 micron band for multi-meter telescopes for Gb/s data rates.

Capability State of the Art	Capability Performance Goal
Multi-mode fiber coupled photon counting detector for PPM 16 (Lunar Laser Communications Demonstration) 62 micron diameter.	Match atmospheric blurred spot of > 10 meter optical ground receivers. Support multi-GHz modulation formats. Reduce spacecraft transmitter power and mass requirements. Support daytime operations and multi-GHz modulation formats.
Parameter, Value: 62 x 62 μm, 16 pixel array at 155 Mb/s; 100 ps jitter, 60% DE; < 10 kHz dark count rate; < 3 dB saturation loss at 0.1 Gigaphotons/sec	**Parameter, Value:** 1 mm area; < 50 ps jitter; > 80 DE; < 1 MHz dark count; < 3 dB saturation loss at 5 Gigaphotons/sec

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_5_communication_and_navigation_final.pdf

Integrated Photonics Technology Candidates

5.1 Optical Communications and Navigation
5.1.1 Detector Development

5.1.1.2 Indium Gallium Arsenide (InGaAs) Flight Photon Counting Detector Array

TECHNOLOGY

Technology Description: Indium Gallium Arsenide (InGaAs) kilopixel radiation-tolerant photon counting detector array.

Technology Challenge: Reducing avalanche volume and stray capacitance is a challenge.

Technology State of the Art: 32 x 32 radiation-tolerant flight photon counting array.

Parameter, Value:
~1 Megaphoton/pixel with < 1 dB saturation ~300 ps jitter 32 x 32 array size;
~40% detection efficiency;
~5 krad tolerant

TRL 4

Technology Performance Goal: High-flux, 128 x128 radiation-tolerant flight photon counting array.

Parameter, Value:
> 10 Megaphoton/pixel with < 1 dB saturation;
< 150 ps jitter;
> 128 x 128 array size;
> 40% detection efficiency;
> 10 krad tolerant

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Photon counting detector arrays for flight receivers.

Capability Description: Provide high flux capable radiation-tolerant flight photon counting array for uplink beacon tracking and communications.

Capability State of the Art: None

Parameter, Value:
Not applicable

Capability Performance Goal: High-rate uplink communications rates. Precision pointing of the terminal. Precision ranging.

Parameter, Value:
100 Mb/s uplink data rates;
Sub-microradian pointing < 1 centimeter precision ranging at interplanetary ranges.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	2 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_5_communication_and_navigation_final.pdf

Integrated Photonics Technology Candidates

5.1 Optical Communications and Navigation 5.1.3 Lasers	**5.1.3.1 High Direct Current (DC)-Optical Efficiency, Space-Qualified Pulse-Position Modulation (PPM) Laser Transmitter**

TECHNOLOGY

Technology Description: Laser transmitter for photon efficiency communications at deep-space ranges.

Technology Challenge: In-band pumping; efficient pump laser diode development; fiber damage mitigation; and parts selection, radiation, and packaging (including thermal design) are all challenges.

Technology State of the Art	TRL	Technology Performance Goal	TRL
Technology State of the Art: Thermal-Vac tested PPM laser amplifier. **Parameter, Value:** 4 W average power, 640 W peak power; 2 GHz modulation bandwidth; ~10% efficient	5	**Technology Performance Goal:** PPM laser transmitter suitable for 0.3 Gb/s at 0.4 A.U. throught 22 centimeter transmit aperture. **Parameter, Value:** 4 W average power, 640 W peak power; > 20% DC-optical efficiency; > 20,000 hours mean time to failure (MTTF)	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Efficient 1.5 μm space qualified pulse-position modulation (PPM) laser transmitter.

Capability Description: 1.5 μm space qualified PPM laser transmitter with equivalent or higher (> 20% direct current-optical) efficiency than present 1.06 μm lasers; need > 2 GHz modulation bandwidth, 5 to 20 W average power, > 1 kW peak power.

Capability State of the Art	Capability Performance Goal
Capability State of the Art: PPM laser transmitter suitable for 622 Mb/s at 0.003 A.U. through 10.8 centimeter transmit aperture. **Parameter, Value:** 0.5 W average power, 8 W peak power; 5 GHz modulation bandwidth; ~10% efficient	**Capability Performance Goal:** PPM laser transmitter suitable for 1 Gb/s at 1 A.U. through 40 centimeter transmit aperture. **Parameter, Value:** 20 W average power, 3,200 W peak power; > 20% DC-optical efficiency; > 50,000 hours MTTF

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	2 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_5_communication_and_navigation_final.pdf

Jet Propulsion Laboratory
California Institute of Technology

Integrated Photonics Technology Candidates

5.1 Optical Communications and Navigation 5.1.3 Lasers	**5.1.3.1 High Direct Current (DC)-Optical Efficiency, Space-Qualified Pulse-Position Modulation (PPM) Laser Transmitter**

TECHNOLOGY

Technology Description: Laser transmitter for photon efficiency communications at deep-space ranges.

Technology Challenge: In-band pumping; efficient pump laser diode development; fiber damage mitigation; and parts selection, radiation, and packaging (including thermal design) are all challenges.

Technology State of the Art: Thermal-Vac tested PPM laser amplifier.		**Technology Performance Goal:** PPM laser transmitter suitable for 0.3 Gb/s at 0.4 A.U. throught 22 centimeter transmit aperture.	
Parameter, Value:	**TRL**	**Parameter, Value:**	**TRL**
4 W average power, 640 W peak power; 2 GHz modulation bandwidth; ~10% efficient	5	4 W average power, 640 W peak power; > 20% DC-optical efficiency; > 20,000 hours mean time to failure (MTTF)	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Efficient 1.5 μm space qualified pulse-position modulation (PPM) laser transmitter.

Capability Description: 1.5 μm space qualified PPM laser transmitter with equivalent or higher (> 20% direct current-optical) efficiency than present 1.06 μm lasers; need > 2 GHz modulation bandwidth, 5 to 20 W average power, > 1 kW peak power.

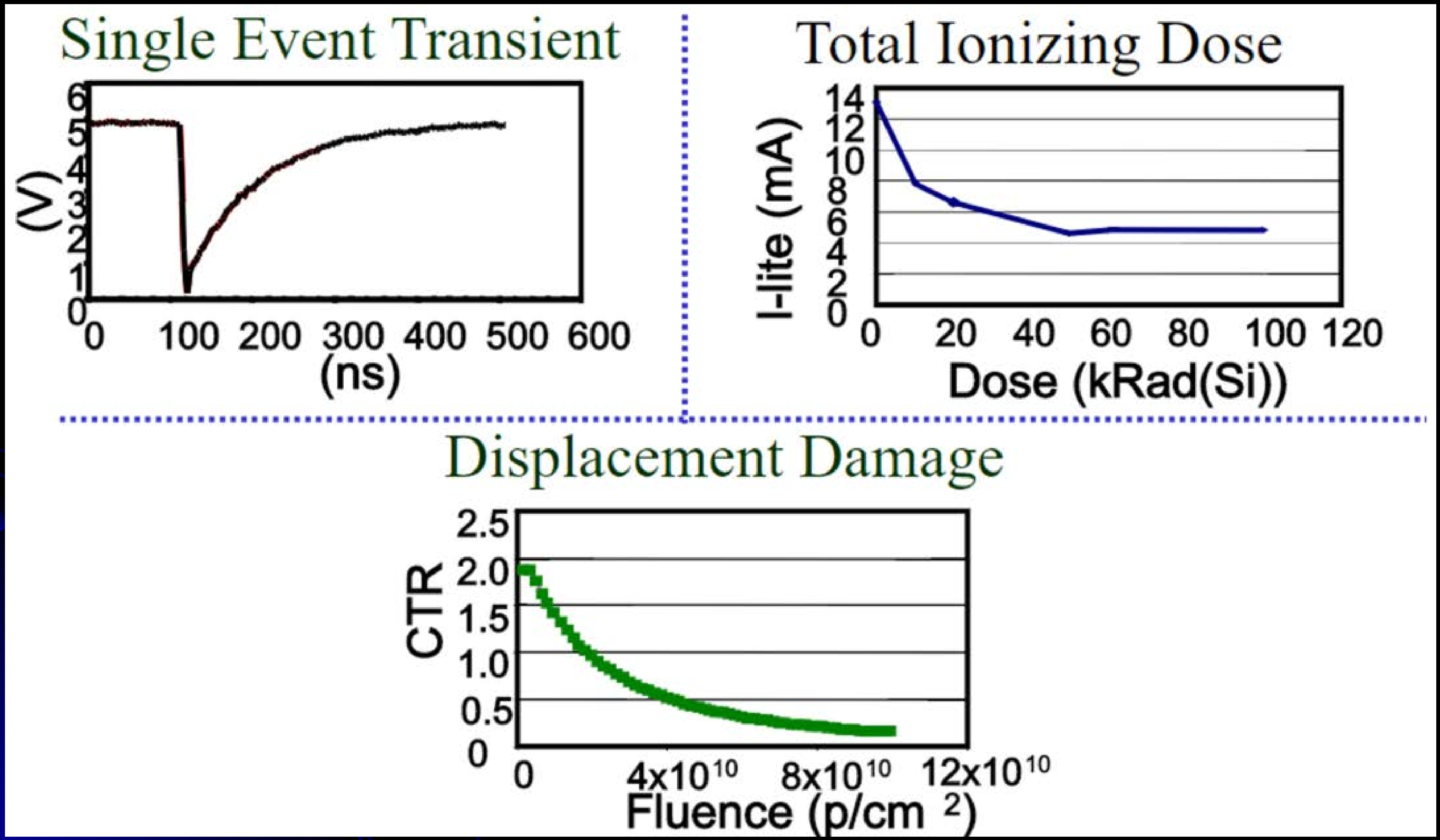
Capability State of the Art: PPM laser transmitter suitable for 622 Mb/s at 0.003 A.U. through 10.8 centimeter transmit aperture.	**Capability Performance Goal:** PPM laser transmitter suitable for 1 Gb/s at 1 A.U. through 40 centimeter transmit aperture.
Parameter, Value: 0.5 W average power, 8 W peak power; 5 GHz modulation bandwidth; ~10% efficient	**Parameter, Value:** 20 W average power, 3,200 W peak power; > 20% DC-optical efficiency; > 50,000 hours MTTF

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	2 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_5_communication_and_navigation_final.pdf

Primary Radiation Effects in Optoelectronics



Optoelectronics Radiation Risk Level

Device	Displacement Damage	Total Dose	SEE
Transmitters LED Lasers	Danger!!	Probably OK!	Probably OK!
Receivers PD APD CCD	Danger!!	Probably OK!	Beware
Switches Optocouplers	Danger!!	Probably OK!	Beware
Optics Optical Fibers Connectors Lens	Probably OK!	Danger!!	Probably OK!

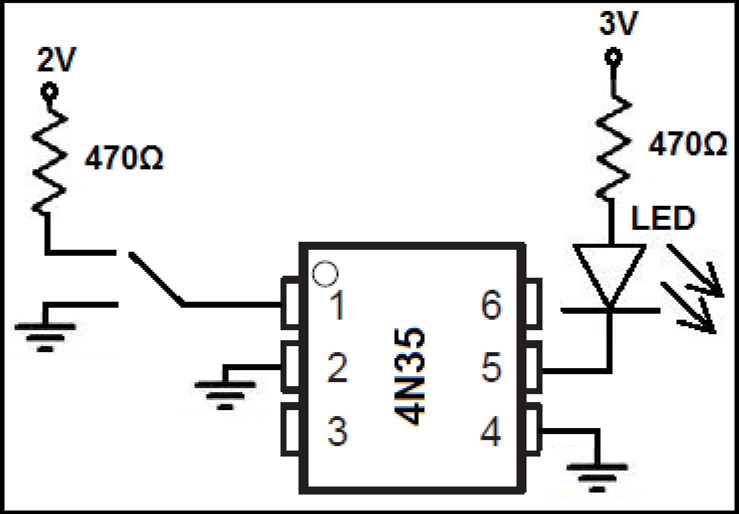
Danger!! Beware Probably OK!

Summary of Radiation Effects in Optoelectronics

Device	Displacement Damage	Total Dose	SEE
Transmitters LED Lasers	**Non-radiative recombination** **Decrease in minority carrier lifetime**	**Darkening of integrated components**	**Transients**
Receivers PD APD CCD	**Generation of electon-hole pairs** **Charge trapping**	**Surface recombination** **Darkening of integrated components** **Flatband voltage shift**	**Transients**
Switches Optocouplers	**Non-radiative recombination** **Decrease in minority carrier lifetime in transmitter** **Loss of response in receiver**	**Surface recombination** **Darkening of integrated components**	**Transients**
Optics Optical Fibers Connectors Lens	**-**	**Radiation induced colour centres** **Increased absorption**	**-**

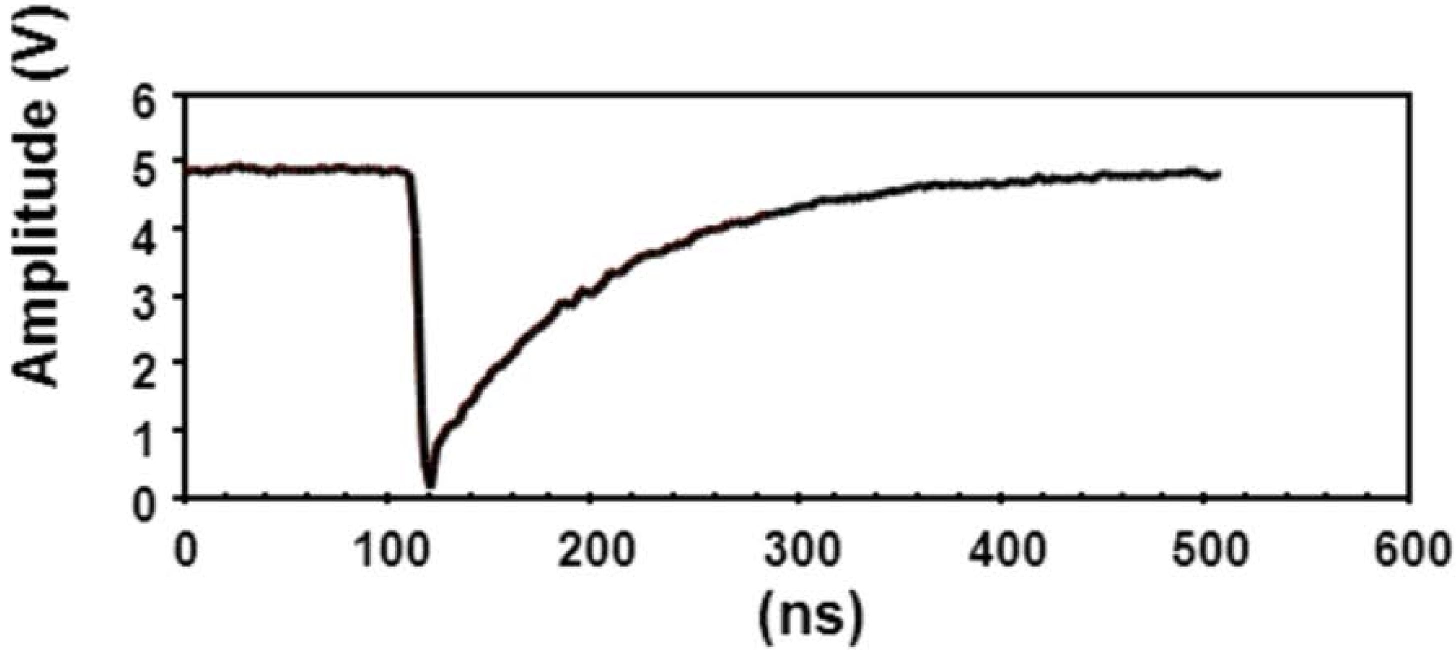
Optocoupler Radiation Design Guidelines

- When radiation response is KNOWN design mitigations can be used
- **Single Event Transient**
  - Observed in devices that operate at >5 MHz
  - Circuit filtering is possible
- **Total Ionizing Dose (TID)**
  - Shielding can help reduce dose
- **Displacement Damage (DD)**
  - Not Amphoterically doped
  - LED wavelength < 800 nm
  - Maximize LED drive
  - Operation of phototransistor in saturation

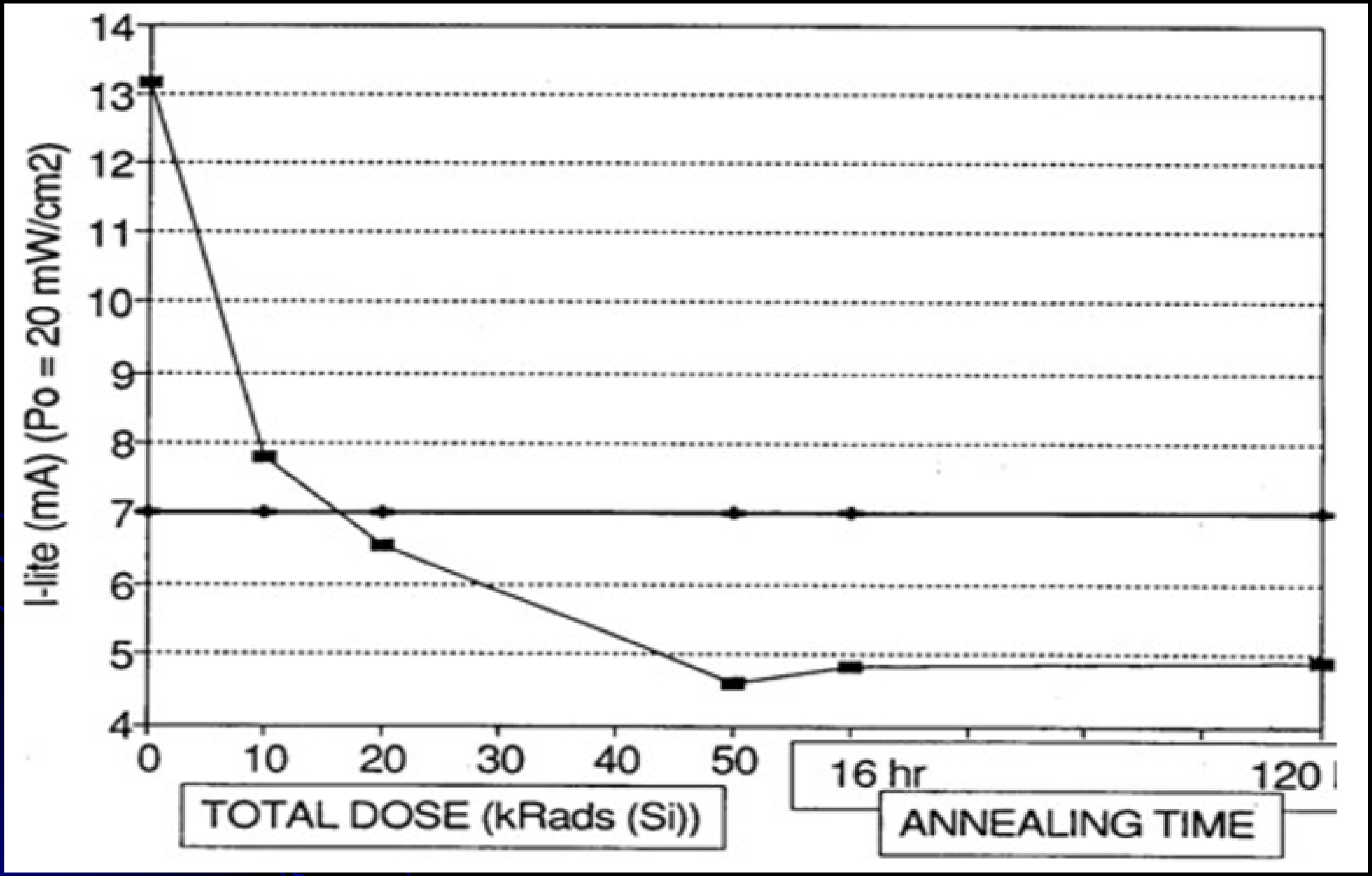


Example SET in Optoelectronics

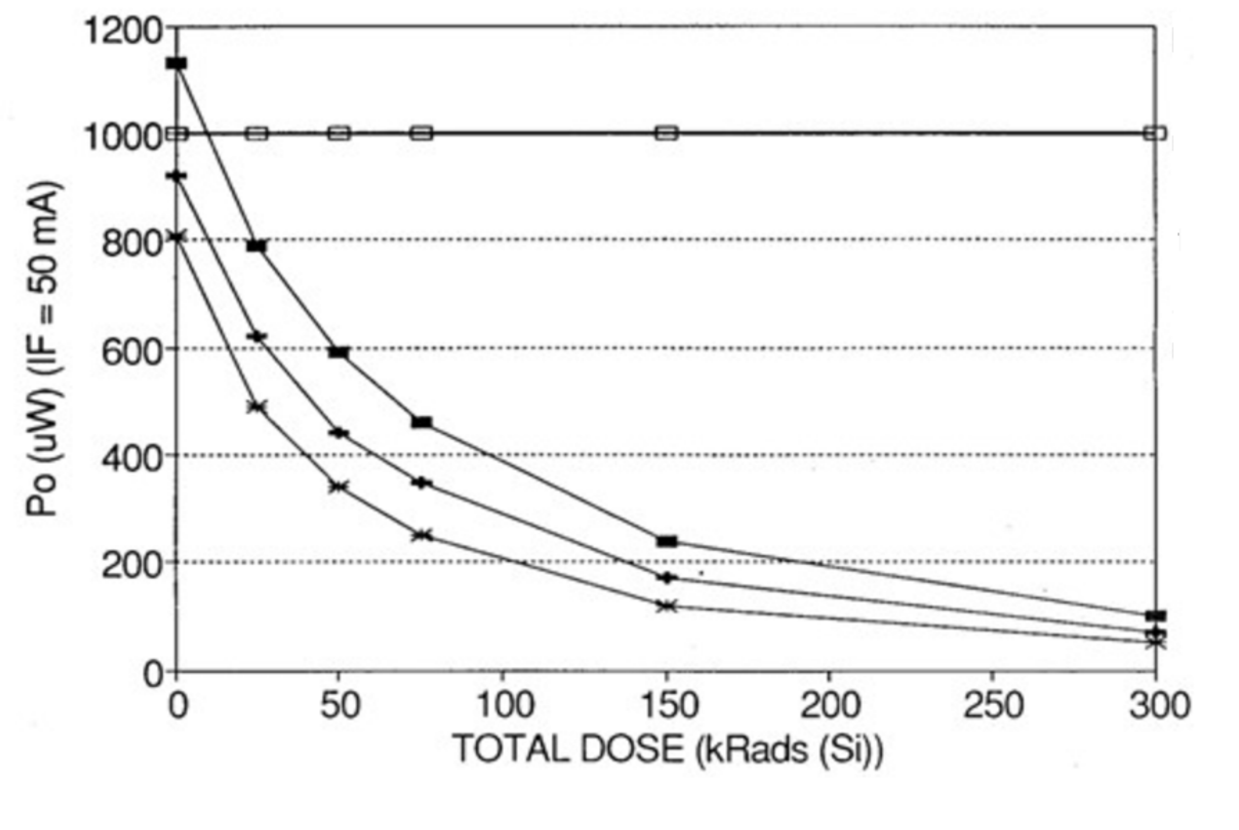
Single event transients induced in photodetector can be passed to circuitry that follows the optocoupler if the amplification stage recognizes the SET as a valid signal



TID Degradation in Phototransistor



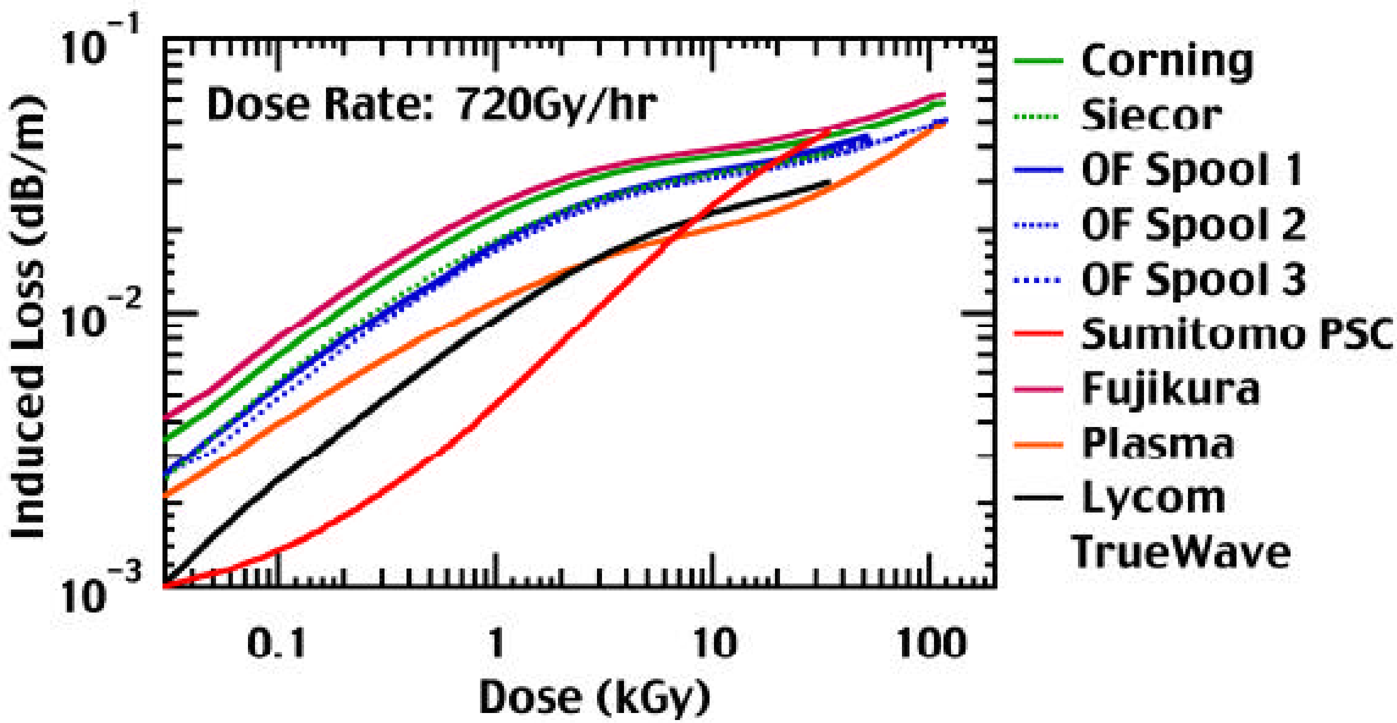
TID Degradation of LED



R. Reed, “Radiation effects in Active Optical Components”

Fiber Attenuation vs Dose

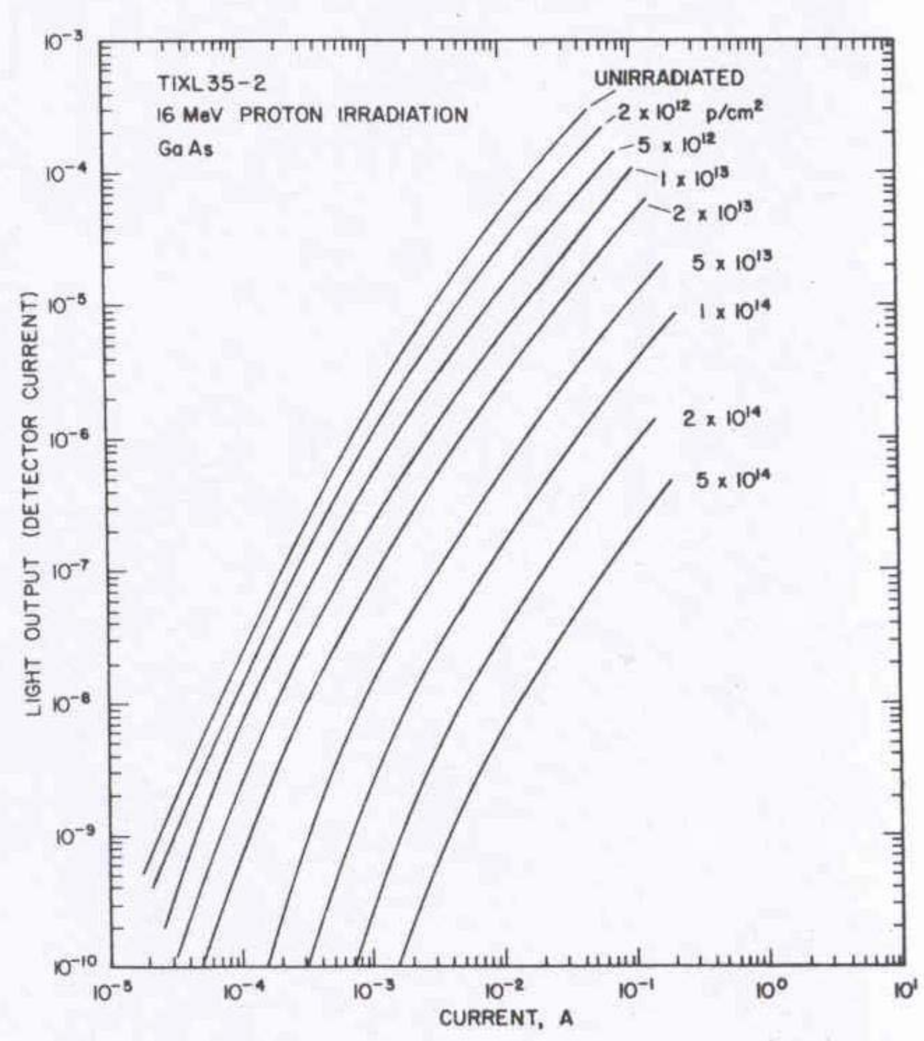
- Gamma damage (COTS single mode fibers)

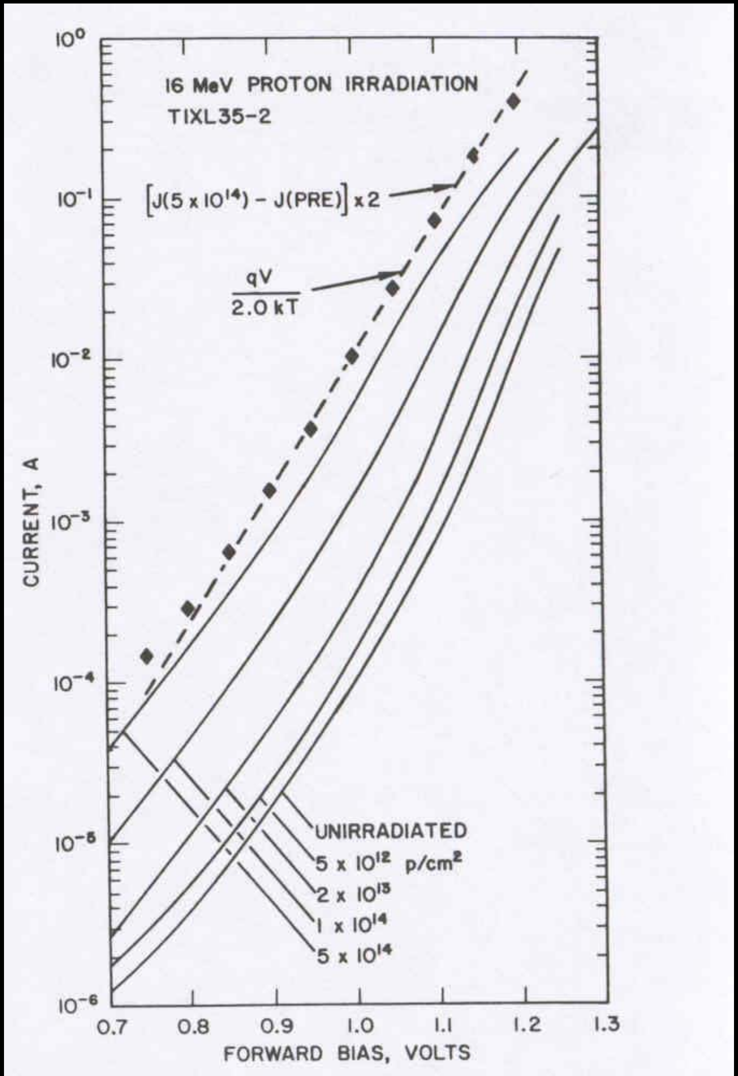


- Loss below 0.1dB/m
- PSC fibre advantageous only below ~ 10-20kGy

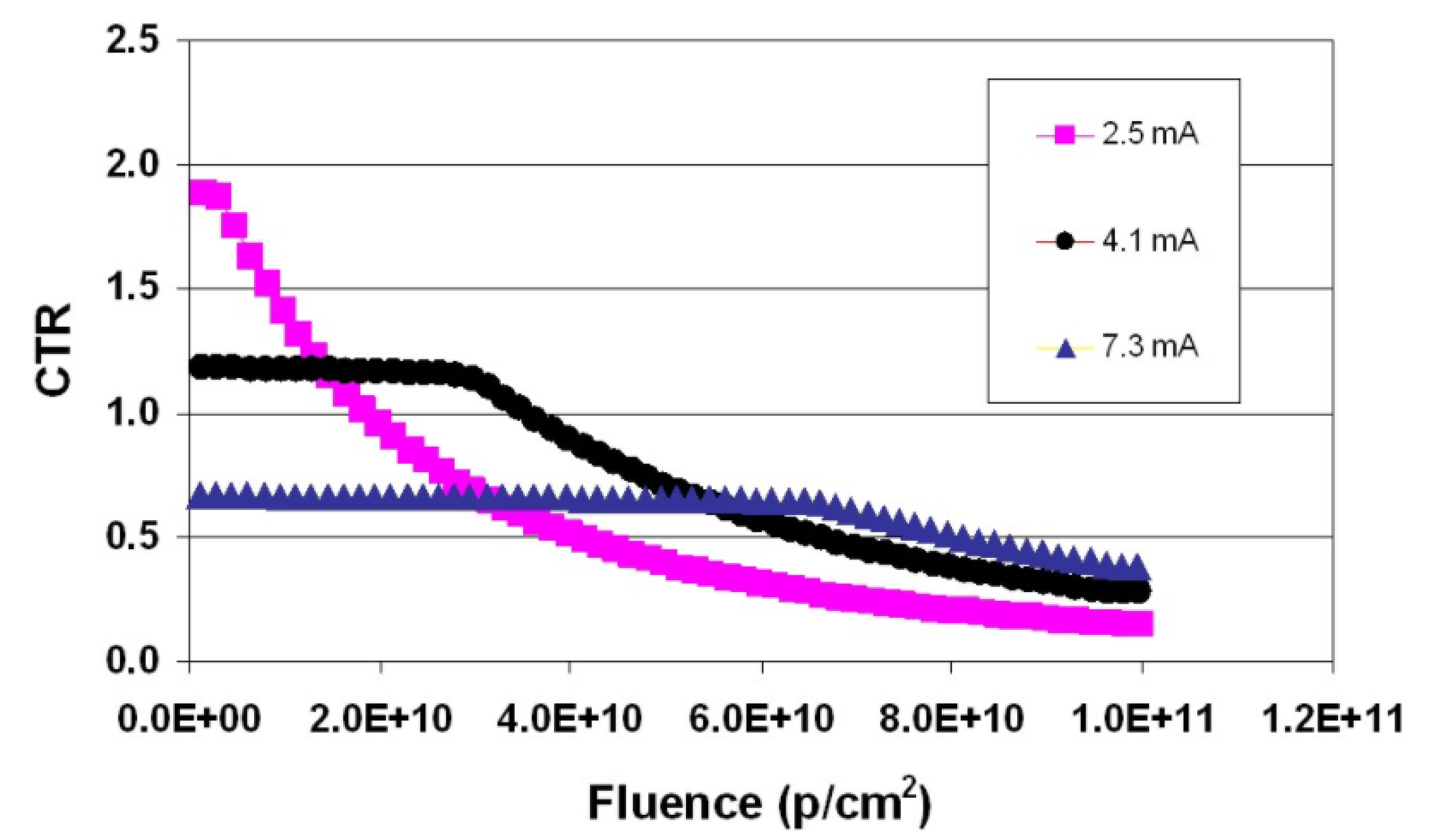
LED Proton Degradation

- LED Light-current and current-voltage before/after irradiation





Optocoupler Current Transfer Ratio Degradation with Proton Fluence



R. Reed, “Radiation effects in Active Optical Components”