

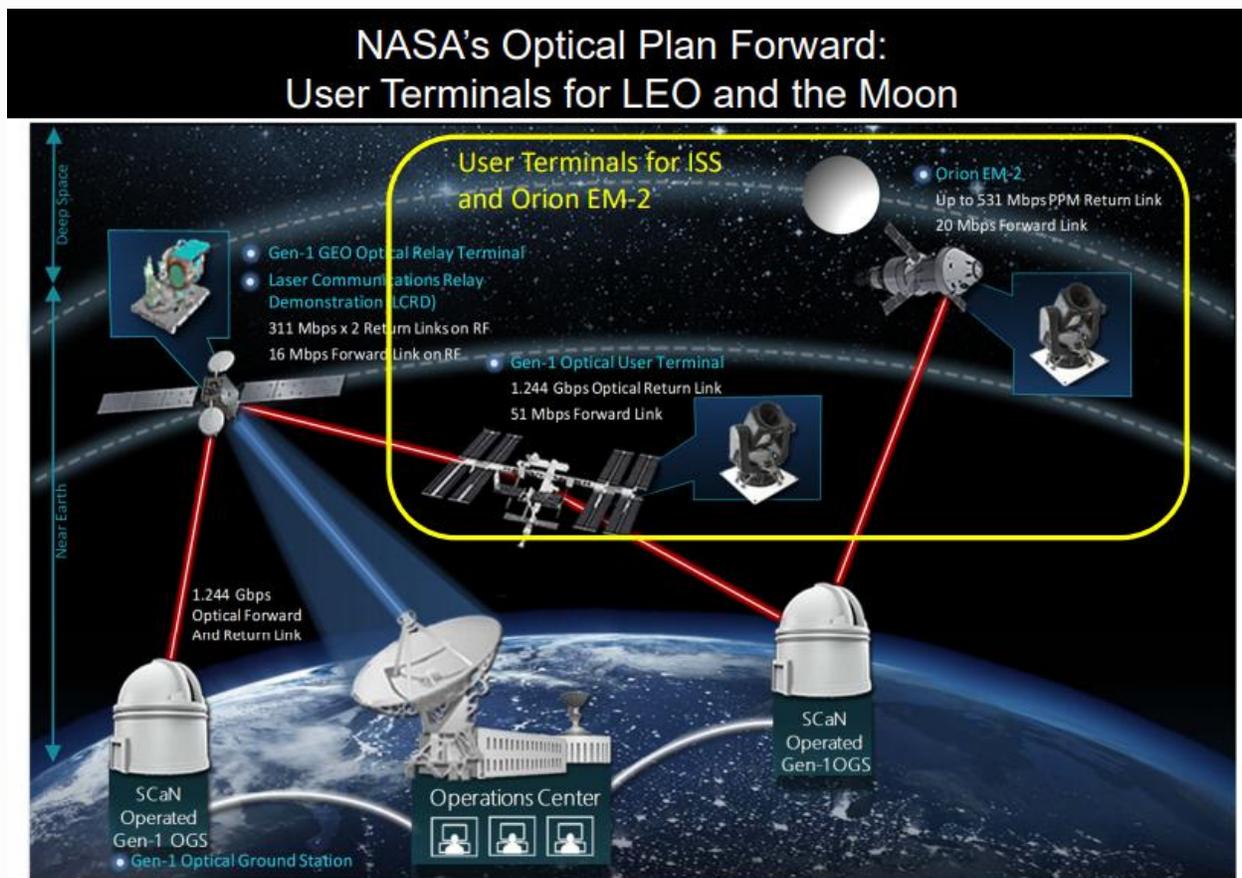
## Topic: On Laser Communications Development of Photonic Technology: Past, Present, Future

From the Editor-in Chief

In the effort to maintain relevancy of the Communicator, assumptions had to be made: 1. The readership diversity spans subject matter experts of different knowledge domains and degrees of expertise; 2. The different sub-specialties of space operations in the readership constrains the forum of SpaceOps for which our educational outreach in general comprehensiveness may be limiting; and 3. Topical rigor in the forum content was best assessed from the workshops and conferences many in the readership attend and contribute. The assumptions may not be truly reflective of the Communicator's readership. And for that reason, please take the time to complete the enclosed survey so that Communicator rightly be responsive for what you deem of journalistic value.

With great appreciation

Ronald H. Freeman, PhD



Although radio-frequency (RF) - based communications currently are the most reliable form of space communications, radio and microwave portions of the electromagnetic spectrum are getting close to capacity. RF wavelengths are longer, and the transmission beam covers a wider area size (about 100 miles). So, capture antennas for RF data transmissions must be very large. In contrast, optical laser wavelengths are 10,000 times shorter, allowing data to be transmitted across narrower, tighter beams. Laser beams deliver the same amount of signal power to much smaller collecting antennas. In other words, laser communications enable NASA to work within a

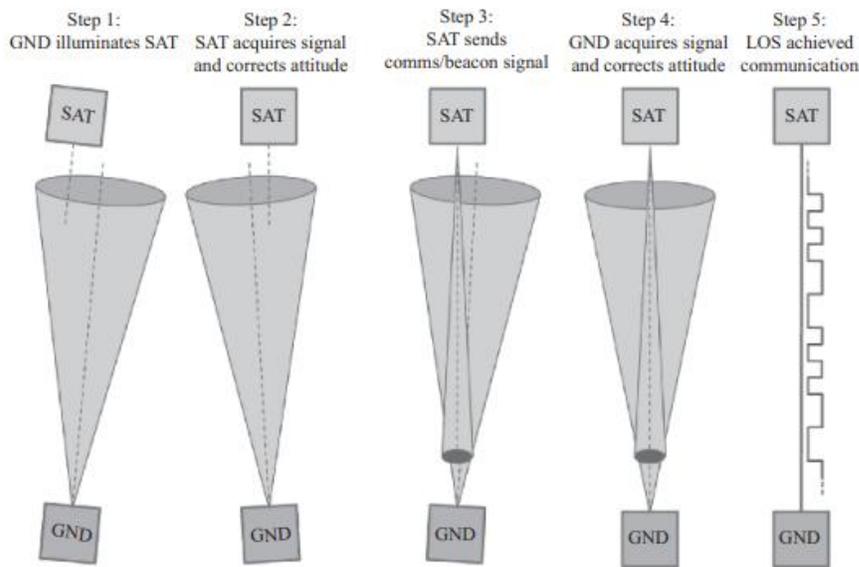
new, less crowded section of the electromagnetic spectrum to develop more efficient, cost-effective space communications equipment.

Space-ground signals cross mostly cloud-free zones, wherein atmospheric turbulence causes sudden drops of signal (or “fades”) lasting for many milliseconds. And, the extremely narrow divergence of the beams challenges Pointing, Acquisition, and Tracking (PAT) across the vast distances of space. Deep Space Network (DSN) has developed a new hybrid RF and optical antenna, capable of doing both RF and optical spacecraft passes with the same aperture [1].

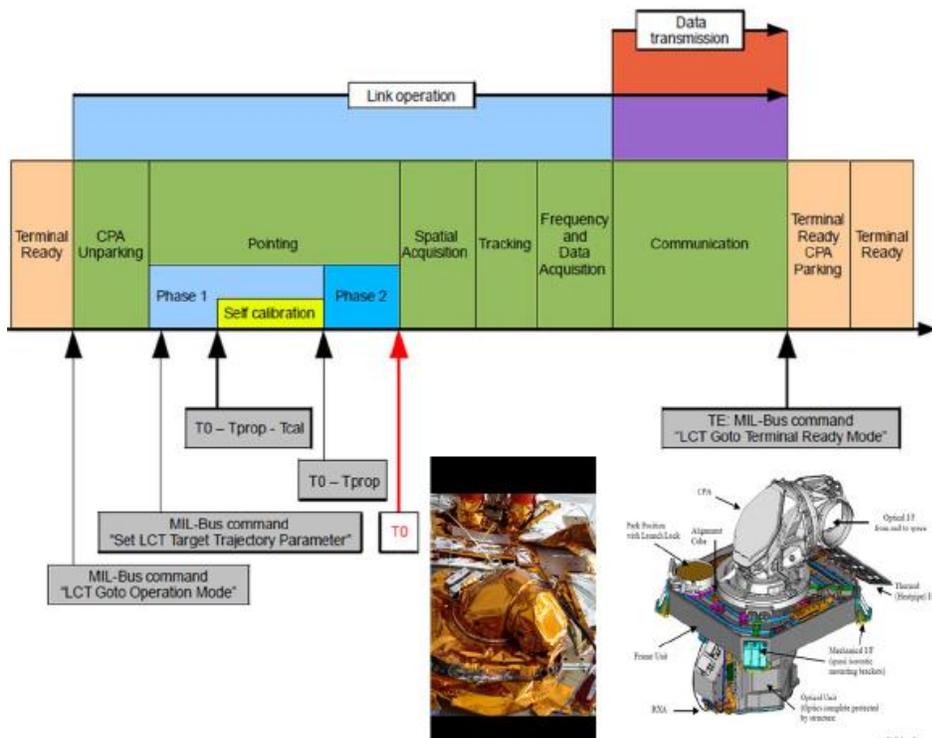
### **Lunar Reconnaissance Orbiter (LRO)**

Last year, China Aerospace Science and Technology Corporation (CASC) built a constellation of 300 small satellites in low Earth orbit for global communications and other services. Satellite broadband startup OneWeb through a joint venture with Airbus Defence and Space, will build only 600 satellites instead of 900 after ground tests of the first satellites demonstrated better than expected performance. OneWeb has added back ups for all major components on the satellites, including redundant computers and four reaction wheels per satellite, to improve the reliability of each spacecraft. And Satellogic, a small satellite startup in Montevideo Uruguay, is on its way to orbiting a constellation of 300 Earth Observation (EO) satellites to provide near - real time imagery of the Earth.

Planned constellations of hundreds communication satellites will benefit from the use of optical communication’s ability to transmit the increasingly higher data rates with compact, low-mass terminals, while avoiding interference problems and radio frequency band saturation. Near Earth Network (NEN) provides telemetry, commanding, ground-based tracking, and data and communications services to a wide range of customers. NEN provides these services to customers with satellites in low Earth orbit (LEO), geosynchronous orbit (GEO) highly elliptical orbit, lunar orbit and missions with multiple frequency bands. One of the NEN’s assets, the 18.3m “WS1” antenna at White Sands, New Mexico, provides Ka-band communication for the LRO mission. The first United States mission to the Moon in over ten years, LRO, launched on June 18, 2009, orbits the **Moon** locating potential resources on the Moon and characterizes the radiation environment. NASA’s Space Network (SN) provides tracking and data acquisition services (TDRS) to spacecraft below GEO orbit (22,236 miles above the surface of the Earth) connecting customer spacecraft with 100% coverage of the customer's orbit, nearly 8 million minutes of S/Ku/Ka-band communications services per year. TDRS satellites 8, 9, and 10 support Ka-band communication, as will the TDRS-K and -L satellites under construction. Designed to support multiple missions at the same time, each satellite has S band, Ku band (1st Gen only), and Ka band (2nd gen only) electronic communication systems hardware that operate at different carrier frequencies and support various data rates. The primary system design goal was to increase the amount of time that the spacecraft were in communication with the ground and improve the amount of data that could be transferred. All radioed commands and received telemetry go to and from TDRS satellites via two TDRS satellite ground terminals at the White Sands Complex. The process comprises five steps. In step 1, the ground terminal illuminates the satellite with a high divergence beacon laser. The satellite acquires the signal and corrects its attitude in step 2. In step 3, the satellite points the transmit communications beam to the ground station. In step 4, the ground station acquires the satellite signal using it as a tracking beacon and corrects its pointing direction accordingly, thus both partners obtain line of sight. In step 5, communication is performed and line of sight is maintained via optical tracking.



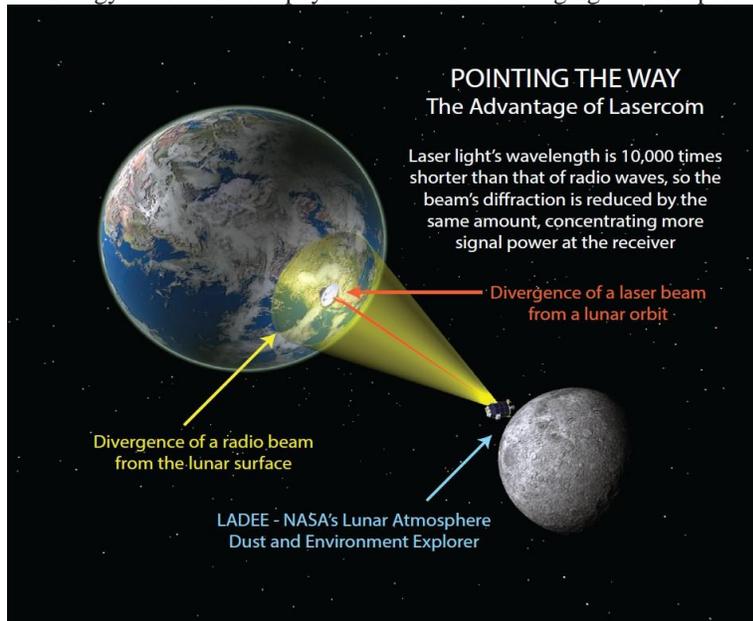
The PAT process addresses the opto-mechanical system of a laser communication terminal to obtain line of sight. The first step, pointing, relates to the transmit beam steering towards the counter terminal. In the case of a satellite link, this would be orbit data of the satellite and GPS location data of the ground station. Depending on the accuracy of the a priori data and the accuracy of the opto-mechanical system (gimbal accuracy, jitter reference calibration), an angular uncertainty area can be defined. If the uncertainty area exceeds the transmit beam cone, scanning algorithms must be applied. In the next step, acquisition, the beam is detected by the counter terminal using an acquisition sensor, and a control mechanism is activated that steers the beam into the tracking sensor's field of view. Finally, the beam displacement measurement by the tracking sensor continuously creates an error signal used by the control loop to maintain the link lock [2].



Multiple earth-science missions send data from low-Earth orbits to ground stations at 1-3 Gbps, to achieve data throughputs of 5-40 terabits per day, exceeding the capabilities of S-band and X-band frequency allocations used for science probe downlinks in the past [3]. The scheduling of NASA's deep space antennas to meet the communications and tracking needs of more than 40 missions can be extremely complex requiring increased antenna availability.

### Lunar Atmosphere and Dust Environment Explorer (LADEE).

The NASA lunar exploration and technology demonstration mission launched on a Minotaur V on September 7, 2013, orbited around the Moon's equator to study lunar exosphere and dust. LADEE mission scientific objectives were: (1) determine the composition of the lunar atmosphere, investigate processes controlling distribution and variability - sources, sinks, and surface interactions; and (2) characterize the lunar exospheric dust environment, measure spatial and temporal variability, and influences on the lunar atmosphere. Impacts on the lunar surface from meteoroid streams resulted in enhancements in both the lunar atmosphere and dust environment. The Earth-Moon system frequently encounters debris trails from short- and long- period comets (as well as asteroids), referred as *meteoroid streams*. The meteoroids in these streams have similar velocities and are on near-parallel trajectories, resulting in what appears as shooting stars. Meteor (and meteoroid) rates vary as a function of the Earth's position in its orbit, with an activity curve that increases to a peak and then decreases. Unlike at the Earth, all of the stream meteoroids incident at the Moon will impact its surface and create ejecta clouds and release species into the exosphere [4a]. Since they move on near-parallel trajectories, their observed asymmetries show effects on the lunar environment. Therefore, it is necessary to know the locations where the streams are normally incident on the lunar surface. Instruments included a dust detector, neutral mass spectrometer, and ultraviolet-visible spectrometer, as well as a technology demonstration consisting of a laser communications terminal [4]. NASA Ames was responsible for the day-to-day functions of LADEE while the Goddard Space Flight Center operated the sensor suite and technology demonstration payloads as well as managing launch operations.



### Lunar Laser Communications Demonstration (LLCD) mission (2013)

The benefits of air-to-ground, air-to-air and air-to-space photonics relate to transmission speed, low *Size Weight and Power* (SWaP) systems, spectrum regulation, as well as immunity to electromagnetic interference. Airborne communication platforms can be used for near real-time up/down-linking of time-critical information to ground stations or spacecraft in low or geostationary orbits. Inter-UAV or UAV to high-altitude platforms such as pseudo-satellites can be used to set-up low-latency, high-speed data networks. Moreover, using free-space laser communications in the aerospace & defense sector is motivated by the establishment of secure and reliable high-

speed links in RF-denied environments for intelligence, surveillance and reconnaissance (ISR). Laser-based data links show immunity to jamming and spoofing; and, transmission cannot be detected in contrast to traditional RF technology. Space-based laser systems rely on 1064- or 1550-nm wavelength windows to establish high-capacity networks from satellites on the low Earth or geostationary orbits [5]. As NASA works to upgrade and enhance current network assets, the search has begun for more capable and effective solutions for future space communication. One solution for NASA is to look beyond the radio and microwave portions of the electromagnetic spectrum towards the near-infrared and in the realm of light photons. Light photons are small packets of electromagnetic waves, and when many are transmitted together “in synch,” they form what is commonly known as a *laser beam*. [6]

LLCD established the ability to encode data onto a beam of laser light and validated a new form of communications from space, “optical communications.” The main goal of LLCD was to use highly reliable infrared lasers, similar to those used to bring high-speed data over fiber-optic cables into our workplaces and homes. With a transfer data rate of up to 622 Mbps, it demonstrated a two-way, high-rate laser communications from lunar orbit aboard LADEE. The LLCD mission achieved the following milestones:

***Longest-range dedicated optical communications link*** (error-free data downlink from the moon at a distance of some 400,000 km, overcoming a link loss greater than 100 times and operating error-free through turbulent atmosphere.

***High data rates*** (100 Mb/s, higher than the best Ka-band radio system flown to the moon on the 2009 LRO)

***High-definition video link***. ( 20-Mb/s error-free high-definition video uplink to and from the moon)

***Pinpoint ranging***. (simultaneous centimeter-class precision ranging to the spacecraft),

Data was imparted with pulse-position modulation (PPM) of an amplified single-frequency laser, then transmitted across the vast distance to the ground receiver through narrowband spectral filtering, in front of a state-of-the-art photon-counting detector, consisting of 16 superconducting nano-wire detector arrays (SNDAs), detecting every error-free bit per two received photons. The code words re-assembled at the receiver, where the decoder found and corrected the parts of the code word lost in fade.

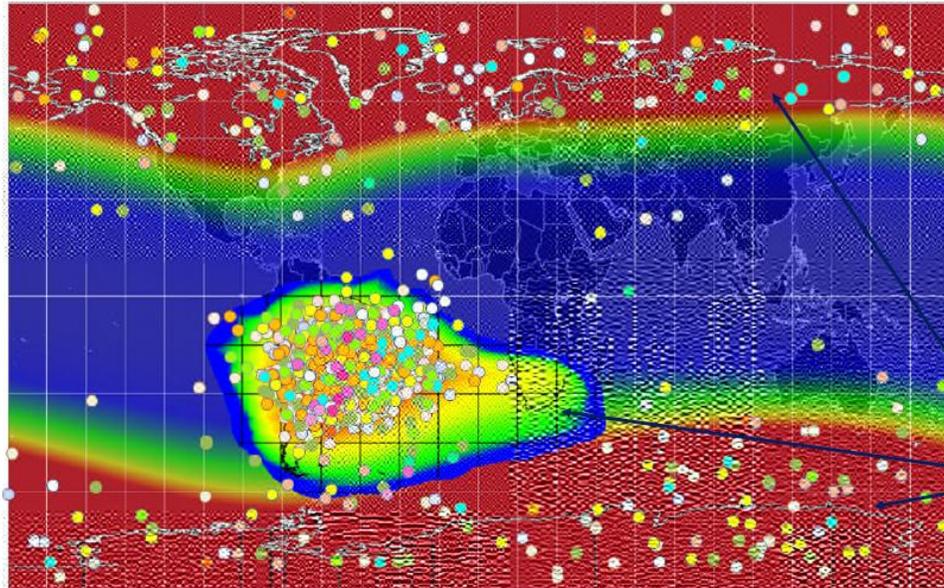
Commercial companies seeking to improve Internet bandwidth worldwide have a significant interest in free-space optical communication (FSOC). World governments have invested in the initial infrastructure while retiring the technical risks on this technology. Integrated photonics drove the costs of FSOC to well below those of RF systems in order for commercial networks of “fiber-in-the-sky” to realize another communications revolution. Vital photonic components for realizing the fiber optic transmitter and receiver subsystem included lasers, electro-optic modulators, amplifiers and photon detectors for the generation, coding, amplification and reception of light, respectively. The photonic components deployed in space required additional performance quantitative evaluation --- the performance degradation of space photonic hardware against the different types of radiation.

### **Developing Photonics Technology-based Space Communications**

**Milestone1.** The Engineering Test Satellite-VI (ETS-VI) was developed by the National Development Agency of Japan (NASDA). Pointing and tracking of narrow beams were transmitted over great distances while overcoming cloud cover, turbulence and other hurdles introduced by the atmosphere. Japan’s 1-Mb/s laser link to ground from the ETS-VI in GEO successfully demonstrated pointing, acquisition and tracking of narrow laser beams directly between spacecraft and Earth stations in 1994. A Gaussian approximation on downlink volume availability was derived from more than 3000 consecutive days of recorded cloud coverage data available for a pre-selected number of sites at preferred locations. [7]

**Milestone2.** Altitude distributions of electron and proton fluxes and spectra were obtained on ETS-VI dosimeter. Electronic devices damaged by radiation belt particles impacted space operations. Satellites orbit the planet within or close to the inner and outer Van Allen belts when they are deployed in the low Earth and geostationary orbits, respectively. Due to the Earth’s magnetic field, transit galactic and solar cosmic radiation of electrons, protons and heavier ions, is trapped. G. Galet at CSA’s SpaceOps Workshop (2019) illustrated the following,

## Illustration : LEO in-flight feedback



Mainly SEU / SET linked to protons captured in the belts + cosmic rays

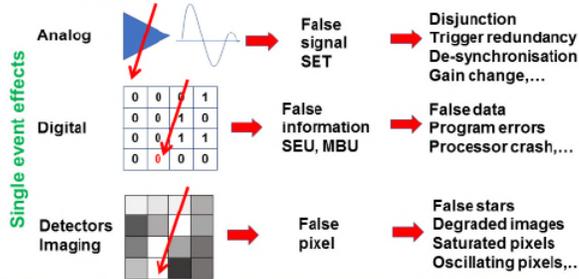
No direct link with solar flares

Hazard zones

Technical Data Acquisition Equipment (TEDA) measured the space environmental effects on the devices to determine causes for spacecraft operational anomalies.

### Radiation effects on electronics

Non destructive

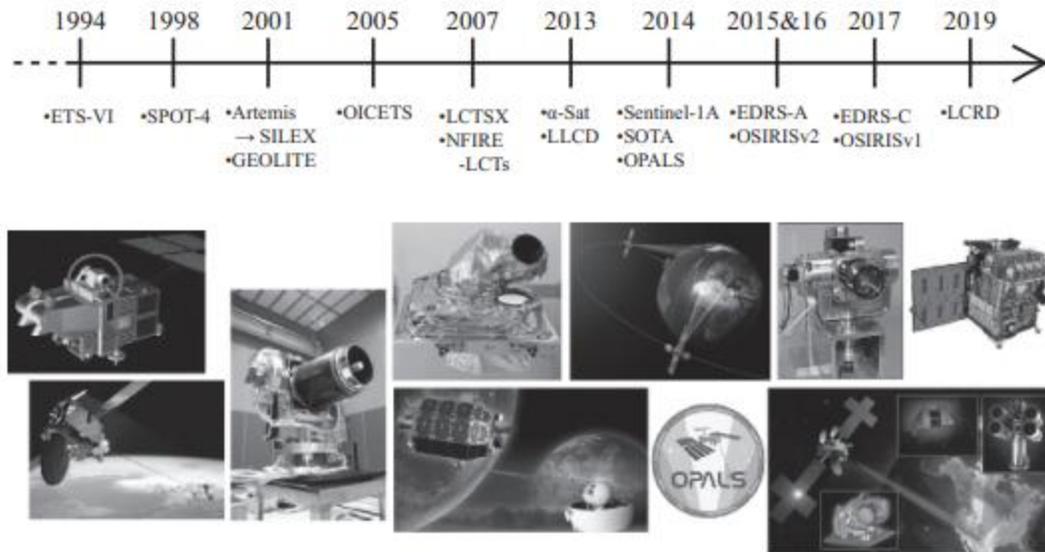


Many on-board events leading to memory errors, dialogs, algorithms corruptions ...

Events often foreseen in design => Estimation of impact on availability => OK with or without Specific on-board protections => Acceptable mission impacts / req. availability

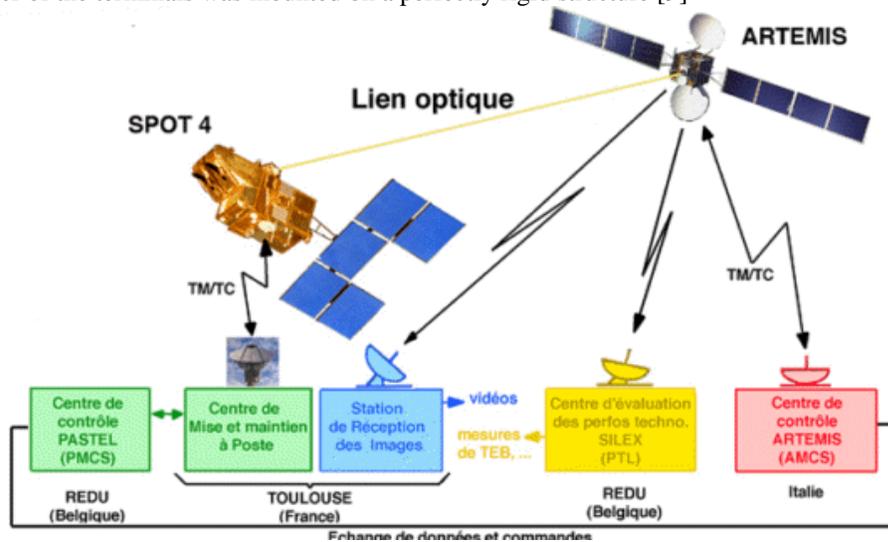
Priority is to trace all events => Counting & geolocalization done on ground for environment experts to perform off-line analysis

Milestone3. Since the 1990s, reliability and economics of photonic components have combined with the need for more bandwidth. The U.S. government launched the GeoLite laser communications mission in 2001. GeoLite was the second in the series of technology demonstration satellites by National Reconnaissance Organization (NRO), launched on 18 May 2001. Besides the GeoLite Laser Terminal (GeoLite), the other payload unit was GLOM (Radiometer) that measured intensity fluctuations and polarizations of the laser beam transmitted from Earth through the turbulent atmosphere to GeoLite satellite. The *lasercom* experiment provided NRO information on high data rate as well as data for further research and development of models and system design. [8]

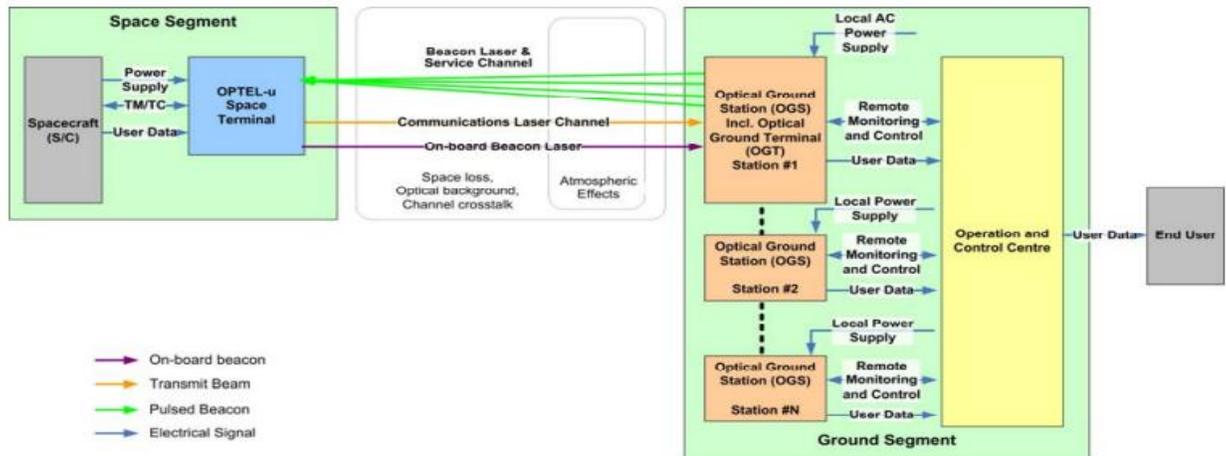


Milestone4. The SILEX system was developed for the European Space Agency by Matra Marconi Space, providing a laser link between the Passenger SPOT de Télécommunication Laser (PASTEL) optical terminal on SPOT 4 satellite and the Optical PAYload for Inter Satellite Link Experiment (OPALE) optical terminal, mounted on the geostationary communications satellite ARTEMIS, which had been placed in orbit in 2001. The SPOT-4 imagery information carried between PASTEL and OPALE was modulated at 50 Mbits/sec and relayed to the ground (Toulouse) by the K-band payload on ARTEMIS. Aligning and stabilizing two terminals were about 38,500 km away from each other, with a pointing error of less than 2 micro-radians. Pointing was difficult because:

- SPOT 4 was in a low-earth orbit, whereby the relative velocity of the two satellites was considered,
- of the time needed for light to travel between PASTEL and OPALE,
- of dynamic perturbations generated on board the satellites (activation of mechanisms, etc.) indicating that neither of the terminals was mounted on a perfectly rigid structure [9]



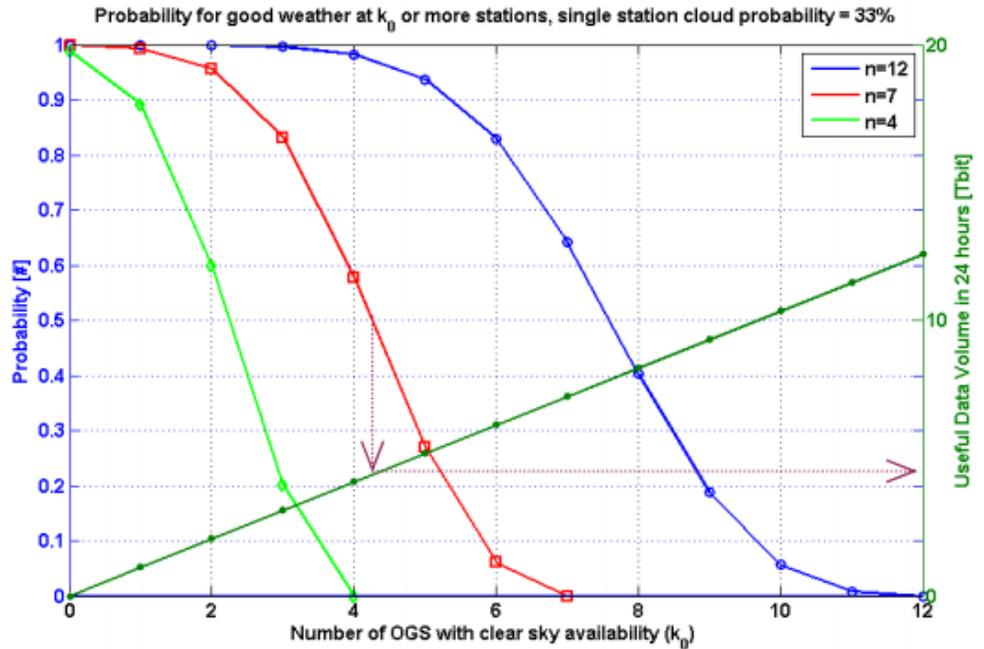
Milestone5. Constellations of hundreds communication satellites planned for the future will benefit from the use of optical communication's ability to transmit increasingly higher data rates with compact, low-mass terminals, while avoiding interference problems and radio frequency band saturation. The OPTEL- $\mu$  system operated laser communications downlinks from low earth orbit to ground in the 1550nm band. An optical space terminal (ST) performed downlinks to a network of optical ground stations, containing an optical ground terminal (OGT) to match the space counterpart ST that was dimensioned to ensure sufficient cloud-free line-of-sight access to collect downlink data. Potential site locations of the optical ground network had been carefully pre-selected based on historical analysis over 8 years of cloud coverage conditions using the cloud depiction and forecast system (CDFS-II). The baseline ground system consists of a global network of cost-efficient, eye-safe OGTs that can be remotely controlled. In summary, the use cases will demonstrate (1) "eye-in-the-sky", to provide profitability from high data rates up to 2Gbits/s; (2) Add-on-RF system, doubling data volumes with +25% on-board resources; and (3) payload data download for site diversity [10].



For a commercially acceptable probability of 95% clear sky availability, an OGT network of seven optimal selected sites can achieve an aggregated data volume per day of about 6 Tbit (750 Gbyte) per space terminal. A comprehensive evaluation of cloud measurement data from the years 2002-2008 was used to derive clear sky condition statistics of 7 pre-selected ground station locations. The study involved analysis of daily contact time for all selected locations, assuming a strawman mission on a 700km sun-synchronous LEO satellite.

The operational concept for an optical link needs to consider the full strategy of getting the on-board data to the satellite owner processing facility or directly to customer, taking into account the specific characteristics of the link. Down-linking onboard sensor data by radio frequency (RF) links in X-band (8 GHz), using antennas in the 5-13m range, establishes a reliable link at a bit rate of 300-1200 Mbps. Satellite owners use ground network services for their communications, where an external provider has a set of multi-mission antennas at different strategic locations around the world. The satellite owner interacts with the provider by requesting passes for their satellites whereby the time the satellite will be over a particular ground station is predicted, and this information together with the predicted. Ground station resource scheduling is usually established in a preliminary version a week in advance of a satellite pass, and then a firm schedule is set a few days in advance [11].

- $p_0$  = Probability for clouds (no link) at a station
- $n$  = Number of stations
- $k$  = Number of stations with cloud blockage
- $P_{n,k}$  = Probability that exactly  $k$  out of  $n$  stations have line-of-sight contact



### Laser Communications Relay Demonstration (LCRD) mission (2020)

The next step for NASA will be a longer-term demonstration of FSOC in space, LCRD. Designed to demonstrate high-bandwidth, bidirectional optical communications relay services between GEO and Earth, the payload consists of two independent laser communication terminals, connected via a new electronic switch to provide high-speed frame switching and routing between the two optical space terminals (OSTs) while also serving as the interface to the host spacecraft.

LCRD’s goals over its multiyear operation are to measure and characterize the system performance across a variety of atmospheric conditions, while developing new software and operational procedures to adapt to them. These may include buffering data via the disruption-tolerant network (DTN) protocol for short outages, or performing fast handoffs between the two ground stations to mitigate longer outages due to passing clouds that might block the beam. The system will also provide an on-orbit capability to test and demonstrate new modulation schemes, as each modem is software defined and thus reprogrammable in orbit [12].

The culmination of the LCRD mission will be a demonstration of a “space relay” communications link from a spacecraft LEO up through LCRD in GEO and then down to the ground. Specifically, NASA is developing a new optical terminal to demonstrate on the international space station (ISS) in 2020 that is interoperable with LCRD for future space users in LEO or higher. This next-generation terminal will leverage recent developments in integrated photonics, which should lower SWaP and cost of the flight modem by an order of magnitude relative to RF systems. The new terminal may even replace the current LCRD terminal design for GEO if radiation requirements can be met [13].

Powered by recent developments in nanostructures, meta-materials, and silicon waveguides, integrated photonics could significantly impact evolution of space-based laser communication. The lithographic techniques to create a photonic integrated circuit (PIC) will realize hundred-fold reductions in size, mass, power, and importantly, cost. The need for a lower footprint optical interconnects and transmission in data centers, drives current PIC

development. NASA's Integrated LCRD LEO User Modem and Amplifier (ILLUMA) will include an embedded PIC, thus leveraging access to custom device fabrication with public-private partnerships and allowing the technology to become ubiquitous in future space data links [14].

**Laser Communications Relay Demonstration (LCRD) for 2020**

**Scheduled launch: August 2020**

**Mission duration:**  
Two year ops demo  
Six years ops

**Hosted payload: US Air Force's Space Test Program Satellite – 6 (STPSat-6)**

**Ground stations:**  
California  
Hawaii

**Partnership:**  
NASA Goddard Space Flight Center  
NASA Jet Propulsion Laboratory  
MIT Lincoln Laboratory  
STMD/Technology Demonstration Missions

**Flight payload:**

- Two 10.8 cm Optical Modules and Controller Electronics Modules
- Two software-defined DPSK Modems with 2.88 Gbps data rate (1.244 Gbps coded user rate)
- 622 Mbps Ka-band RF downlink
- New High Speed Switching Unit to interconnect the three terminals

**Key for NASA's Next-Gen Earth Relay**

### Deep-Space Optical Communications (DSOC) mission (2022)

The 2013 success of LLCD also provided new impetus to laser communications in another realm: deep space. NASA's Space Technology directorate and Space Communications and Navigation (SCaN) program are now teaming to bring the agency's DSOC effort to "Technology Readiness Level 6"—meaning a prototype unit fully ground-tested to space environmental levels, a.k.a., "shake and bake"—by the end of fiscal 2017, as a precursor to flight of a working laser communication system on the upcoming Discovery mission scheduled for 2020 [15].

### References

- [1] Lichten, S., Hoppe, D., Mohageg, M., Piazzolla, S., Amy Smith, A., & Soldan, H. (2019). Operational Concepts and Challenges for Optical communications in NASA's Deep Space Network, *In SpaceOps Workshop 2019, Montreal, Quebec*.
- [2] Lambert, S. & Casey, W. (1995). *Laser communications in space*. Artech House, Norwood, MA.
- [3] McCarthy, K., Stocklin, F., Geldzahler, B., Friedman, D., & Celeste, P. (2010, April). NASA's evolution to Ka-band space communications for near-earth spacecraft. *In SpaceOps 2010 Conference Delivering on the Dream Hosted by NASA Marshall Space Flight Center and Organized by AIAA* (p. 2176).
- [4] Stubbs, T., Glenar, D., Wang, Y., Hermalyn, B., Saranto, M., Colaprete, A., & Elphic, R. (2014). The impact of meteoroid streams on the lunar atmosphere and dust environment during LADEE mission. *In 45th Lunar and Planetary Science Conference; March 17, 2014 - March 21, 2014; The Woodlands, TX*.
- [5] Cornwell, D. (2016). Space-based laser communications break threshold. *Optics and Photonics News*, 27(5), 24-31.
- [6] Cornwell, D. (2016). Space-based laser communications break threshold, *Optics and Photonics*.
- [7] Goka, T., Matsumoto, H., & Fukuda, T. (1996), Space environment and effects measurements from ETS-VI

satellite. *Environment Modelling for Space-based Applications, Symposium Proceedings (ESA SP-392)*. ESTEC Noordwijk, 18-20 September 1996. Editors: W.Burke and T.-D. Guyenne, p.51

- [8] Robson, K. (2016). *NYO experimental satellites*. National Reconnaissace Office, Chantilly, VA.
- [9] Tolker-Nielsen, T., & Oppenhauser, G. (2002, April). In-orbit test result of an operational optical intersatellite link between ARTEMIS and SPOT4, SILEX. In *Free-Space Laser Communication Technologies XIV* (4635, 1-15). International Society for Optics and Photonics.
- [10] Roth, C. (2016). *OPTEL- $\mu$ : Optical terminal for small satellite LEO applications*. 83230910-DOC-S-EN-003 10/11/2016 Ref.: DLR OLEODL Workshop
- [11] Dreischer, T., Thieme, B., Bacher, M., Buchheim, K., & Hyvönen, P. (2012). OPTEL  $\mu$ : a compact system for optical downlinks from LEO satellites. *Proc. 12th SpaceOps, Stockholm, Sweden*.
- [12] Wang, R., Wu, X., Wang, T., & Taleb, T. (2009, December). Experimental evaluation of delay tolerant networking (dtm) protocols for long-delay cislunar communications. In *GLOBECOM 2009-2009 IEEE Global Telecommunications Conference* (pp. 1-5). IEEE.
- [13] Schoolcraft, J., & Wilson, K. (2011). Experimental characterization of space optical communications with disruption-tolerant network protocols. In *2011 International Conference on Space Optical Systems and Applications (ICSOS)* (pp. 248-252). IEEE
- [14] Cromwell, D. (2019). NASA's optical communications program for 2017 and beyond. In *Space Tech Annual Conference: Securing Your Place in Space: Accelerating System Development Through New Partnerships and Innovative Technologies, May 21, 2019 - May 22, 2019*. Pasadena, CA.
- [15] Roberts, W. (2017, February). Discovery deep space optical communications (DSOC) transceiver. In *Free-Space Laser Communication and Atmospheric Propagation XXIX* (Vol. 10096). International Society for Optics and Photonics