Photonics in Telecom Satellite Payloads

Nikos Karafolas

with the kind contribution of colleagues in ESTEC and ESA's industrial & academic contractors

European Space Agency
European Space Research and Technology Centre
PO BOX 299
AG 2200 Noordwijk
The Netherlands
Nikos.Karafolas@esa.int





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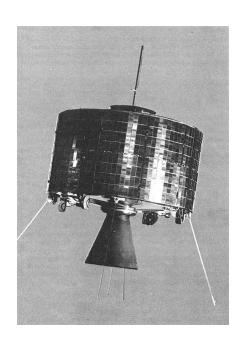
LECTURE-2

Optical Satellite Networking



History was written in parallel

- October 4 1957, Sputnik, the first Satellite is launched
- 16 May 1960, First working laser (Theodore Maiman Hughes RL)
- 19 August 1964, Syncom, the first GEO Telecom Satellite







Charles Townes

Charles H. Townes, who envisioned the laser, dies at 99

BY ROBERT D. MCFADDEN

Charles H. Townes, a visionary physicist whose research led to the development of the laser, making it possible to play CDs, scan prices at the supermarket, measure time precisely, survey planets and galaxies, and even witness

OBITUARY

the birth of stars, died on Tuesday in Oakland, Calif. He was 99.

His death was confirmed by his daughter Linda Rosenwein.

In 1964, Dr. Townes and two Russians shared the Nobel Prize in Physics for their work on microwave-emitting devices, called masers, and their light-emitting successors, lasers, which have transformed modern communications, medicine, astronomy, weapons systems and daily life in homes and workplaces.

One of the most versatile inventions of the 20th century, the laser amplifies waves of stimulated atoms that shoot out as narrow beams of light, to read CDs and bar codes, guide missiles, cut steel, perform eye surgery, make astronomical measurements and carry out myriad other tasks, from transmitting a thousand books a second over fiber optic lines to entertaining crowds with light shows.

The technological revolution spawned by lasers, laying foundations for much of the gadgetry and scientific knowledge the world now takes for granted, was given enormous momentum by the discoveries of Dr. Townes and — because almost nothing important in science is done in isolation — by the contributions of colleagues and competitors.

Thus, Dr. Townes shared his Nobel with Nikolai G. Basov and Aleksandr M. Prokhorov, of the Lebedev Institute for Physics in Moscow, whom he had never met. It was Dr. Townes and Dr. Arthur L. Schawlow who wrote the 1958 paper "Infrared and Optical Masers," describing a device to produce laser light, and secured a patent for it. A graduate student, R. Gordon Gould, came up with insights on how to build it, and named it a laser, for light amplification by stimulated emission of radiation. And it was Dr. Theodore H. Maiman, a physicist with Hughes Aircraft in California, who built the first operational laser in 1960.

Over six decades, Dr. Townes developed radar bombing systems and navigation devices during World War II, advised presidents and government

commissions on lunar landings and the MX missile system, verified Einstein's cosmological theories, discovered ammonia molecules at the center of the Milky Way and created an atomic clock that measured time to within one second in 300 years.

He moved easily from lab to classroom to government policy-making groups: with Bell Laboratories for nearly a decade when it was the most innovative scientific organization; with Columbia University for more than 20 years, when he achieved his most important breakthroughs; and with the Institute for Defense Analyses, a research center that advised the Pentagon on weapons and defense systems in the Cold War.

Like most scientific researchers delving into unknown realms, Dr. Townes had not aimed to invent devices that would become laser printers or supermarket scanners, let alone technologies that would put movies on discs or revolutionize eye surgery.

He was interested in molecular structures and the behavior of microwaves theoretically as a way to measure time with unprecedented accuracy, but more tangibly because the Pentagon, which partly funded his work at Columbia Uni-



SSOCIATED PRESS

Dr. Townes in 1955. He and two Russians shared the 1964 Nobel Prize in Physics.

versity's Radiation Laboratory, wanted better communications and radar systems using shorter wavelengths to reach greater distances.

He had an "a-ha!" moment. Sitting in a park in Washington in 1951, pondering how to stimulate molecular energy to create shorter wavelengths, he conceived of a device he called a maser, for microwave amplification by stimulated emission of radiation. It would use molecules to nudge other molecules, and amplify their thrust by getting them to

resonate like tuning forks and line up in a powerful beam.

He and two graduate students, James P. Gordon and H.J. Zeigler, built his maser in 1953 and patented their creation. It was the first device operating on the principles of the laser, although it amplified microwave radiation rather than infrared or visible light radiation.

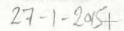
Five years later, Dr. Townes and Dr. Schawlow, who was his brother-in-law and would be awarded the 1981 Nobel Prize in Physics for work on laser spectroscopy, drew a blueprint for a laser. They called it an optical maser, a term that never caught on, and through Bell Laboratories they secured the first laser patent in 1959, a year before Dr. Maiman's first working model.

Despite their patent, they profited little. Both were bound to Bell Labs, Dr. Schawlow as an employee and Dr. Townes as a consultant. Dr. Gould, the former graduate student, was denied a laser patent in 1959, but in 1977 won a long court fight against the Townes-Schawlow patent and received some royalties. It was the entrepreneurs, however, who grew rich on laser products.

Daniel E. Slotnik contributed reporting.

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Communication Satellites – COMSATs

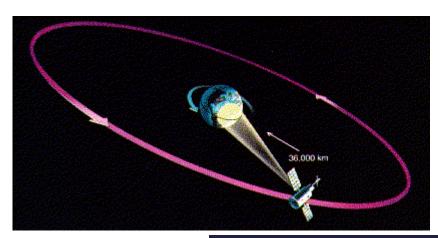


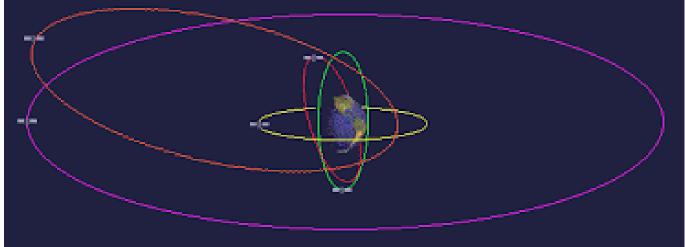


Eurostar 3000 platform



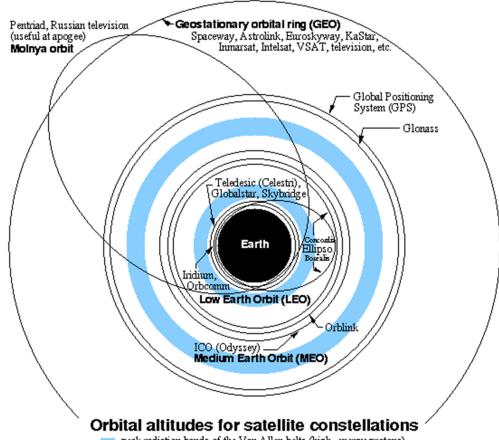
COMSATs are repeaters in the sky







Primarily in GEO but also in MEO and LEO

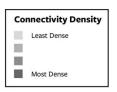


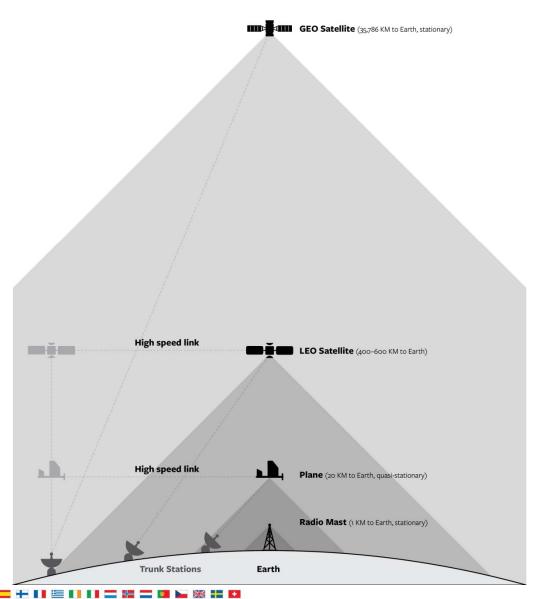
peak radiation bands of the Van Allen belts (high-energy protons)
orbits are not shown at actual inclination; this is a guide to altitude only
from Lloyd's satellite constellations. http://www.ee.surrey.ac.uk/PersonaVL.Wood/constellations/



Platforms at different altitudes

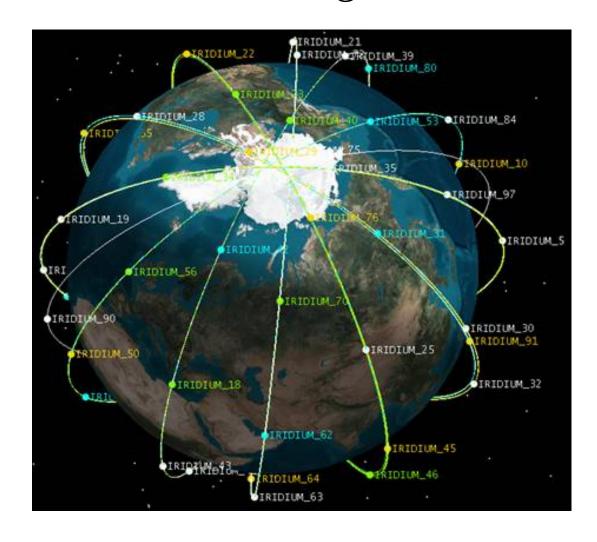
Higher altitudes generally means beams are more spread out on Earth, but giving more trunking opportunities far away from the sites of interest.





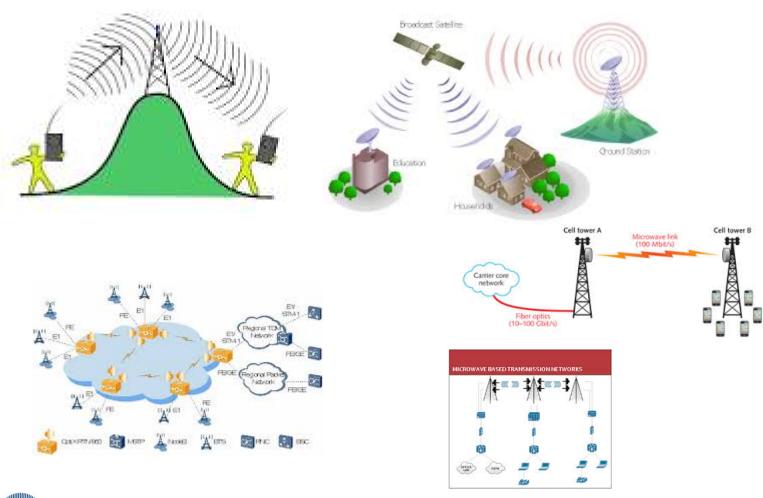


and can be nodes in a global network



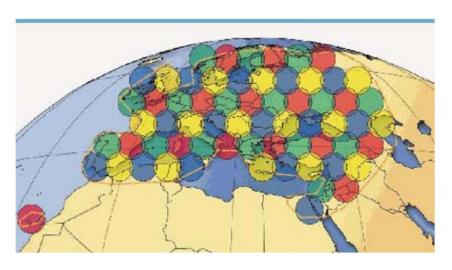


The functions within a COMSAT resembles the ones of ground repeater

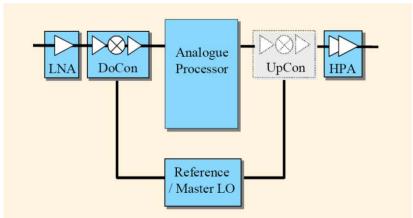


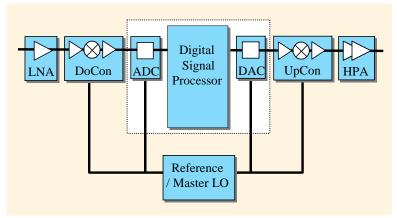


A COMSAT can vary from being a classical <u>Microwave Repeater</u> ("bent pipe transponder") to a full <u>Digital Exchange Centre</u> and can be a <u>Node of a Network</u>



(Alcatel RT 2Q2006)







Photonics in COMSAT PLs today

We need Optical Communications <u>inside the Satellite</u> because the intra-satellite communication requirements can reach several Tbps Also because of the EMI, low mass, low volume and mechanical flexibility characteristics of fibers that are important in for a Spacecraft

We need free-space laser links <u>between satellites</u> because the higher directivity of the optical beam allows higher data/power efficiency (more Mbps for each Watt of power) This is critical to power-limited systems like a S/C. However it has higher Pointing Acquisition and Tracking requirements. We also need free space links that pass though the atmosphere and <u>link satellites to (optical) Ground Stations</u> to uplink or downlink in high bit rates



Photonics in COMSAT PLs tomorrow

Form a complete

"Optical Satellite Network"

interlinked with the terrestrial and submarine fiber optic networks



Intra-Satellite Photonics



Satellite Platform and Payload

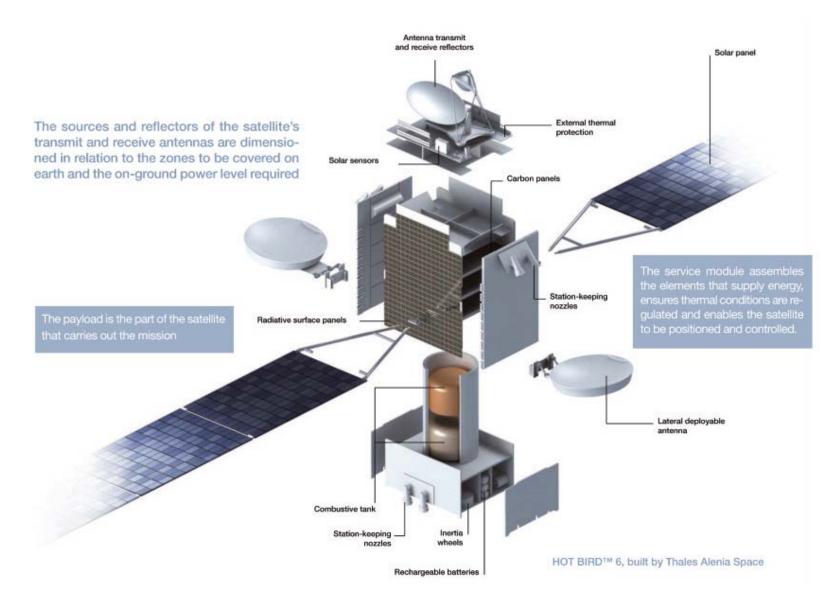
Any Satellite is composed by

- The Spacecraft (or Platform)
- The Payload

We need a "Spacecraft" to place the "value added" "Payload" to the right place, give it power and keep it protected from the space environment (radiation and thermal)

The target is always to maximise the Payload/Platform ratio









COMSAT Payloads can be massive...

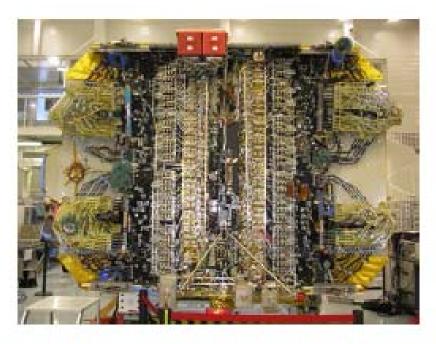


Fig. 4. Typical Payload Panel Equipment Layout (Eurostar E3000 Platform) Using Conventional RF Equipment

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APPLICATION OF PHOTONICS IN NEXT GENERATION TELECOMMUNICATION SATELLITES PAYLOADS

J. Anzalchi¹, P. Inigo², B. Roy²

¹ Airbus Defence and Space, Telecommunications Satellites Business Division, Stevenage UK.



Maximising the Payload output

Payloads will be restricted by an "envelop of available power-mass-volume"

In COMSAT the efficiency of the Payload is measured primarily in the

"cost of in orbit capacity delivery"

So we try to do things as efficiently as possible, i.e

Minimise the power consumption

Minimise the mass

Minimise the volume

Minimise the S/C AIT (Assembly-Integration-Testing) time



Why considering Photonics

PHOTONICS PROPERTIES

- Practically limitless bandwidth (BW) as fiber optics offer an exploitable capacity of several THz at the band around 1550 nm
- Practically lossless propagation in an optical fiber within a spacecraft (S/C)
- Transparency to any modulation/coding format
- Immunity to Electromagnetic Interference (EMI)
- Do not induce EMI
- Are light weight, low volume
- Are mechanically flexible
- Are galvanically isolated



In Telecom Payloads we want

- to reduce the mass-volume-power of the PL compared to the S/C
- to enable new functionalities such as dynamic allocation of the on board resources

Therefore

 we study the applicability of photonic technologies in the 5 main equipment of the "low-power" section of a Telecom PL

But

we do not consider them for the "high-power" section where photonics are not suitable



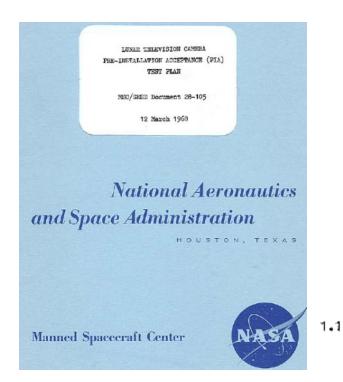
Analogue

Processor

UpCon

DoCon

First known use of fiber optics in space - 1968



Security Classification

The fiber optics portion of the camera is classified CONFIDENTIAL; however, it is incorporated within the camera case and is not visible from the outside. Personnel without security clearance are permitted to handle and operate the camera only under the surveillance of a person with a clearance. Performance data recorded during camera tests will not be classified. The camera must be kept in a secured area when not in use.



Where do we use Photonics in a COMSAT PL?

- Digital Links in Digital Payloads
- Analog Links in all types of Payloads
- Microwave Photonic Equipment mostly in Analog Payloads
 - Frequency Generation Units
 - Frequency Conversion Units
 - Switching Units
 - Beam Forming Units
 - RF filtering units



Digital communications

- Linking equipment with equipment
- Board to Board
- Chip to Chip in photonic PCBs

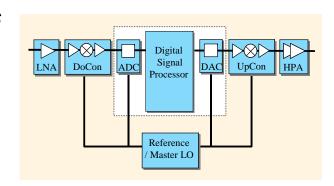
Coming Soon: Optical Interconnects 2-5 Years Optical communications will This approach to signal transfer is moving from longer-distance applications, enter the computer, connecting one circuit board to another. To day Optical connections between individual computers are commercially available. 5-10 Years Chilp-to-chilp communication

IEEE Spectrum August 2002



In Digital Processors Photonics are necessary to carry Tbps

- 100 beams with two polarizations
- 750 MHz per beam per polarization are fed to 200 ADCs
- Each ADC samples at 2 Gsps at 10 b plus extra coding
- Each ADC outputs about 25 Gbps
- 5 Tbps reach the DSP from the ADCs
- 5 Tbps leave the DSP for the DACs
- A DSP can be, for example, a 3-stages Clos Network
- Inside the DSP the traffic is multiplied by several times



Conclusion:

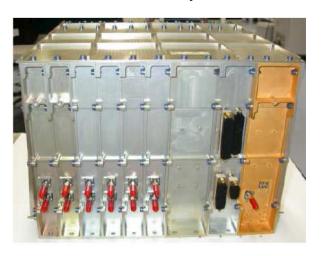
Modern Satellite Payloads carrying Digital Processors require optical communications to handle several Tbps with minimum power consumption

ESA targets <10mW/Gbps i.e <100 W for 10 Tbps



A Photonicaly interconnected 10 Tbps Digital Payload Demonstrator

TAS's DTP 2nd Generation can host 1000 fiber links at 10 Gbps each linked with an optical interconnection flexible plane



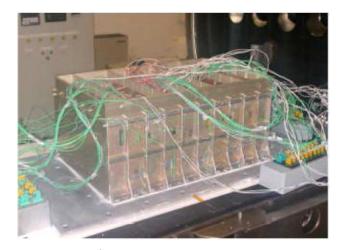


Fig. 2 : TAS Digital Transparent Processors of 2nd generation (DTP 2G)

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HIGH-THROUGHPUT OPTICAL INTER-BOARD INTERCONNECTS FOR NEXT-GENERATION ON-BOARD DIGITAL TRANSPARENT PROCESSORS

N. Venet¹, M. Sotom¹, H. Gachon¹, V. Foucal², M. Pez², V. Heikkinen³, T. Tuominen⁴, S. Pantoja⁵
¹Thales Alenta Space, France. ²D-Lightsys (Radiall), France. ⁴TT, Finland. ⁴Patria, Finland. ³Das-Photonics, Spain







The technological basis for digital communications

- Tx: VCSELs (850nm) (GaAs)
- Rx: Pin (850nm) (GaAs more rad-hard)
- Modulation: Direct modulation
- Fibers: GIMM
- Fiber Cables: Single and Ribbon Fiber
- Cable jackets: (no out gassing)
- Connectors: With anti-vibration mechanism for both parallel and single fiber
- No amplifiers are employed (max distance of 100 m for the ISS, typ. <10m)
- Parallel Tx/Rx Modules are currently preferred over WDM for reliability reasons



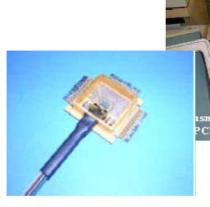
Single and Parallel Digital Optical Tx/Rx

ADC-DSP-DAC





Board to Board inside the DSP (N. Venet, ICSO 2004)





First operational use of fiber optic links in Space was in the International Space Station



decision taken in late 80's technologies of 90's

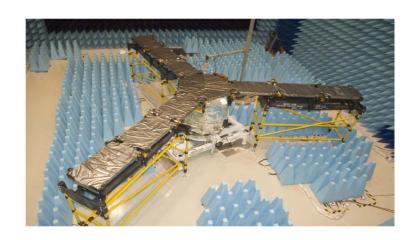
FO Tool Kit Development

HB AVIONICS/Electrical Systems (AES) ATP for OTDR Development 5/00 OTDR Requirements Developed 7/00 ATP for FO Tool Kit Development FO Tool Kit Requirements Developed 9/00 11/00 OTDR & FO Tool Kit Prototypes Completed 11/00 OTDR Outgas 10/00 OTDR Radiation Testing FO Tool Kit Prototype Testing Initiated FO Tool Kit Prototype Test Set PDGF Crew Walkdown with installation scenarios OTDR Burn-in Testing 01-01 OTDR Vibration Testing 01/01 OTDR Thermal Cycling Testing 12/00 - 3/01 FO Cable Functional ATPs 3/01 Electrical Cable (28VDC) Functional ATP 1-3/01 Other COTS tools and miscellaneous Outgassed 3/16/01 Kit Sharp Edge Inspection Kit Connector Fit Checks (IVA OTDR, Patch Cables, Reel, and all test adapters 3/20/01 Crew Walkdown and Bench Review 3/23/01 Stowage in MPLM Racks Crew Bench Review 3/20/01 3/26/01 Equipment Stowed in MPLM Development Equipment used in Flight-like System Level Testing (still ongoing as of 6/9/01) 3/26/01 4/19/01 6/12/01 Operations Training Session FO Tool Kit Deorbited FO Tool Kit Placed in KSC Stores



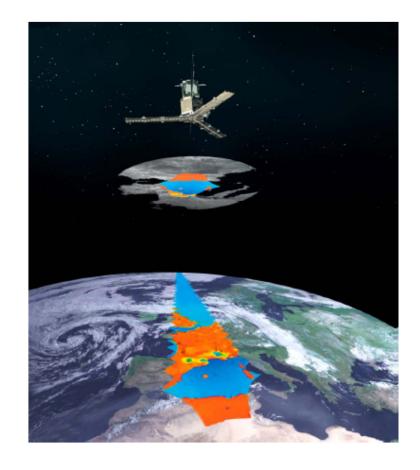
(BOEING

SMOS (Soil Moisture and Ocean Salinity): first Satellite Payload to rely critically on fiber optics (in orbit since 11/2009)



144 links at 110 Mbps (72 to and 72 from antenna elements)

- very low EM emission levels (from Tx/Rx)
- galvanic isolation
- mechanically flexible and lightweight
- better phase stability when bended





Optical Analog Links

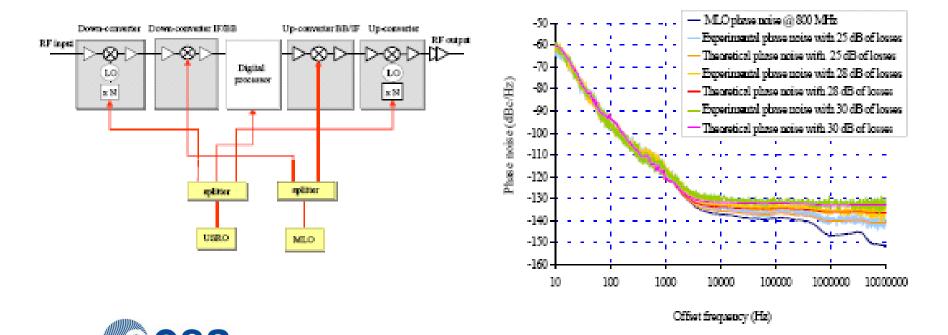
communications:

- Distribution of a LO (with minimal added phase noise) between the Frequency Generation Unit to Frequency Converter
- Analog links between
 - INPUT LNA -Frequency Converter
 - Frequency Converter SWITCH
 - SWITCH FILTERS or OUTPUT TWTA



Photonic LO distribution

- Optical distribution of a microwave LO requires extremely low phase noise analog transmission of signals (from some MHz to some GHz)
 - The use of EDFA is mandatory for a splitting ratio more than 100 (B. Benazet et.al, ICSO 2004)



First flight demonstration of an analog link

In February 2000, the Space Shuttle "Endevaour" flew for 11 days a 5.3 GHz fiber optic link linking an antenna on a 60 m boom to equipment in the shuttle bay

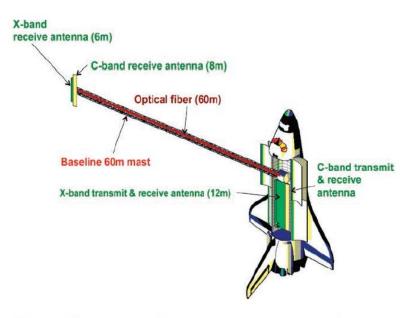


Figure 10. Schematic diagram of interferometric synthetic aperture radar deployed on Shuttle Endeavour during SRTM in 2000. (*Courtesy JPL*)

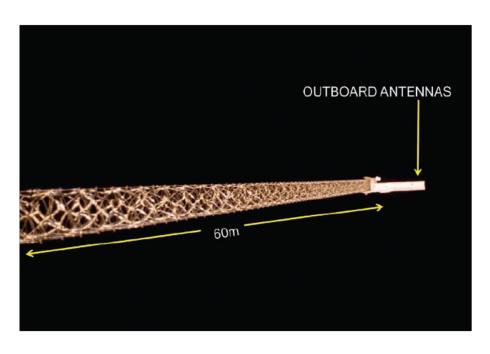


Figure 11. Shuttle boom deployed in orbit. (Courtesy JPL)

IEEE A&E SYSTEMS MAGAZINE

SEPTEMBER 2014

Ultra-Stable RF-Over-Fiber Transport Enables NASA Ground-Based Deep Space Tracking Antenna Arrays and Space-Borne Earth Mapping Radar

Kamy: Lau

Laiversity of California

Berkeley, CA USA

George F. Lutes
NASA Jet Propulsion Laboratory

Pasadena, CA USA

In Analog Payloads Photonics are considered for:

Frequency generation, conversion and distribution&switching

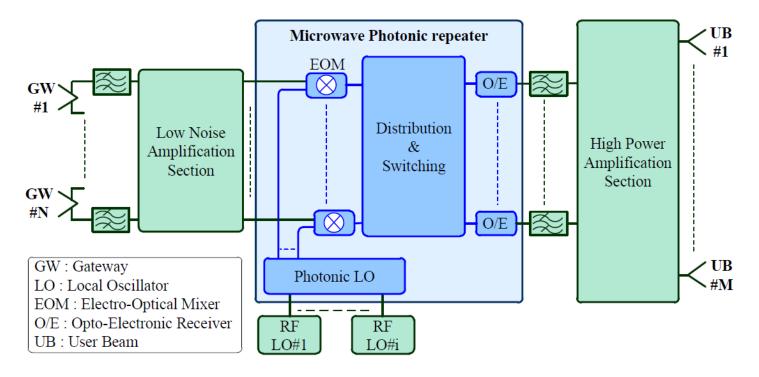


Fig. 1. Simplified block diagram of a microwave photonic repeater

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RECONFIGURABLE MICROWAVE PHOTONIC REPEATER FOR BROADBAND TELECOM MISSIONS: CONCEPTS AND TECHNOLOGIES



And extend to more elaborated architectures

with photonic Beam Forming Networks and photonic RF filtering

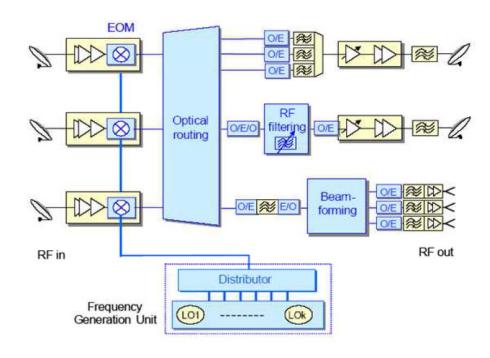


Fig. 4. Conceptual block diagram of photonic analog telecom payloads in the long-term perspective

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TOWARDS TELECOMMUNICATION PAYLOADS WITH PHOTONIC TECHNOLOGIES



Frequency Generation Unit

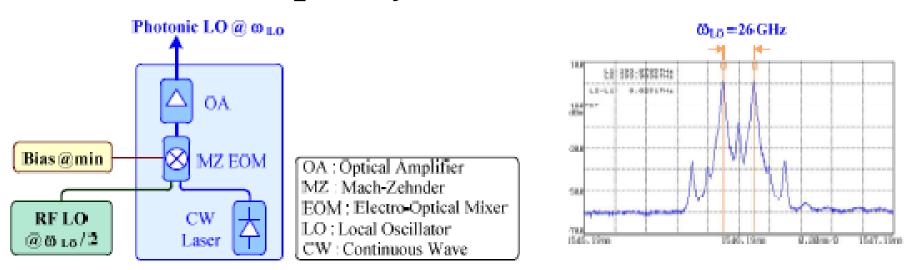
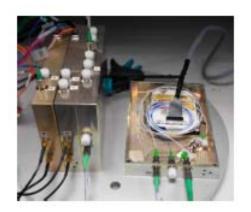


Fig. 4. Microwave Photonic Local Oscillators : principle (left) and typical optical spectrum (right)



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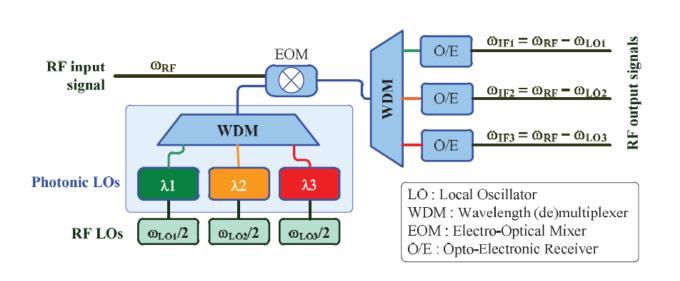
RECONFIGURABLE MICROWAVE PHOTONIC REPEATER FOR BROADBAND TELECOM MISSIONS: CONCEPTS AND TECHNOLOGIES

M. Aveline¹, M. Sotom¹, R. Barbaste¹, B. Benazet¹, A. Le Kernec¹, J. Magnaval¹, P. Ginestet¹, O. Navasquillo², M.A. Piqueras²

¹Thales Alenia Space – France, ²DAS Photonics (Spain)



Frequency Conversion Unit



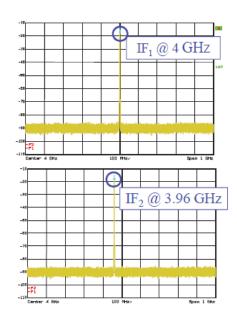


Fig. 5. Multiple-LO photonic RF frequency conversion: principle (left), IF output spectra (right)

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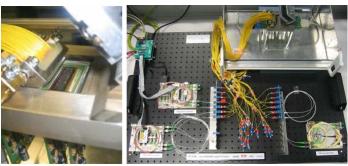
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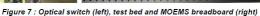
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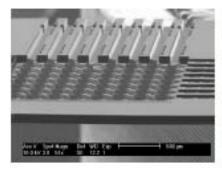
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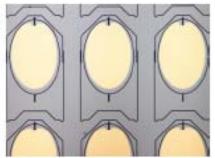


Circuit Switch Unit

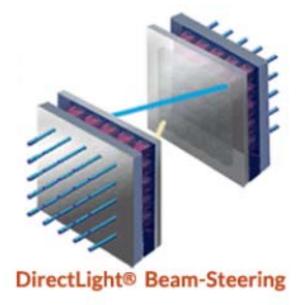












POLATIS TECHNOLOGY - DirectLight® Beam-Steering All-Optical Switch



Beam Forming Network

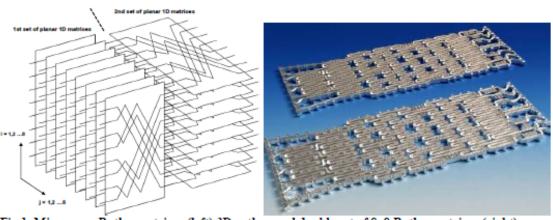


Fig 1. Microwave Butler matrices (left) 3D orthogonal double set of 8x8 Butler matrices (right) example of a 8x8 RF matrix (≈15x8 cm² at 30 GHz)

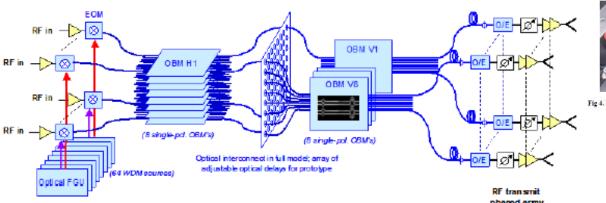


Fig 3. Schematic of the baseline architecture of a transmit Optical Beamformer Network (OBN), that features the full-scale optical beam-former, the E/O and O/E conversion interfaces and all the associated optical links



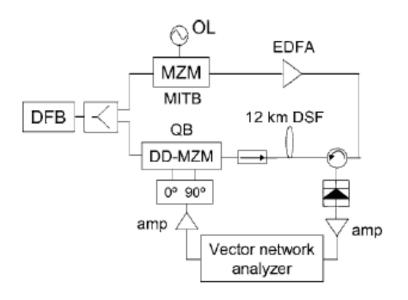
Fig 4. Picture of the optical Butler matrix chip in the characterization set-up before packaging

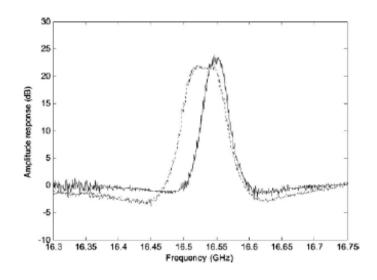


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RF filtering Unit









Photonic Technologies Basis

MZI optical modulators as used as "mixers" for downconversion MOEMS as the crossconnect switch EDFAs for high splitting ration in LO distribution











The benefits of introducing Photonics in COMSAT PL

Table 2. Summary Comparison of Photonic vs. Conventional Payload

Parameter	Unit	Conventional Payload	Photonic Payload	% Change	Photonic Payload Comments
Mass	kg	2078	1553	-25.3%	25.3% less mass
Power	kW	25.1	22.9	-8.7%	8.7% less power consumption
Thermal dissipation	kW	14.8	12.5	-15.5%	15.5% less thermal power diss.

Table 3 provides a summary comparison of mass budget in Kg per equipment type for the conventional vs. photonic repeater.

Table 3. Summary Comparison of Photonic vs. Conventional Repeater by Equipment Type

Equipment Type	Conventional Payload (kg)	Photonic Payload (kg)	% Change
Filters	485	415	-14.4%
LNAs	77	79	+2.6%
MPMs	487	487	0%
Converters	147	70	-52.4%
Waveguide & Coax Cables	611	353	-42.2%
Switches & Misc.	271	149	-45.2%
TOTAL	2078	1553	-25.3%

ICSO 2014 International Conference on Space Optics Tenerife, Canary Islands, Spain 7 - 10 October 2014



Which results in significantly increased revenue

Savings in mass

can be converted in extra fuel

for extra years of operation

which can lead to <u>hundreds of Meuros extra revenue</u> for an operator

A TRANSPONDER IS THE UNIT OF CAPACITY

The payload of a communications satellite consists mainly of transponders which operate like magnifiers. They receive signals from earth and retransmit them back to earth after changing their frequency and / or polarisation and amplifying them. Transponders operate in entirely transparent mode to all technologies, which means that they relay analogue or digital signals of varying bit rates, compression and encryption formats.



The average cost of a 36 MHz transponder is 1.62 Meuro/year

A satellite can have several tens of transponders A year of operation offers tens/hundreds of Meuros in revenue



COMSATs is a multibillion business

...and a small investment in a new technology in satellite manufacturing can lead to a big return in revenue from value-adding-services...

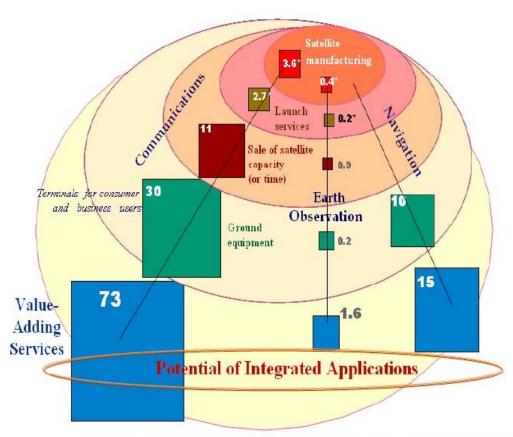


Figure 7: The three value chains in the commercial satellite applications.

Source: World Market Survey - Euroconsult 2009, in 2008 figures in billion \$



Extra-Satellite Laser Communications

- Inter-satellite Links
- Space-Ground-Space optical Links
- Demonstrations

main reference spurce:

"ESA's Optical Ground Station & Laser Communication Activities" Plenary Talk by Zoran Sodnik at ICSO 2014 www.icsoproceedings.org



Inter-satellite Optical Communications



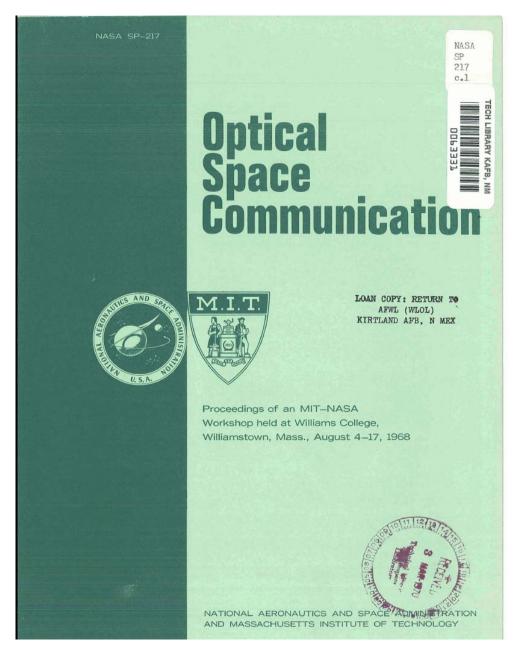


What was first?

- Waveguided (fiber optics)
- Atmospheric
- Space

Optical Communications?







Optical Communications—A Decade of Preparations

NILO LINDGREN

Abstract—This paper, an introduction to this first Special Issue on Optical Communications, follows some of the arguments that have prevailed for and against optics as a viable communications medium for terrestrial and space applications, and assesses the present state of the art of optics devices, systems, and theory, based on discussions with scientists and engineers who have been specializing in the optical field. It also attempts in a small way to give some appreciation of the special problems the traditional communications engineer faces in readjusting his thinking and his "physical intuition" in going from the world of electrons to the world of photons.

Co., held their first excited press briefing in New York in 1960 to announce the successful development of an experimental ruby laser, one of the future possiat all. The great promise is to develop techniques that one can use with state-of-the-art devices to get hold of the very large optical bandwidth." But this has been difficult so far.

Today, after a decade of slow work, despite the development of many more types of lasers, of more powerful, more efficient, more extraordinary and reliable lasers, despite a growing spectrum of possible laser applications, it is hardly an exaggeration to say that there is, as yet, no practical optical communication system in existence.

Moreover, the best judgement today is that practical optical communication systems lie still far in the future.

Despite the persistent work of a preciously small community of researchers, the past decade has produced so far,



"...fiber optic losses...would amount to thousands of dBs per mile" –

"by 1973...at least one satellite would be...carrying laser comms experiments.."

The major drawback, however, at the present time is that the glass used in fiber optics is very lossy, amounting to a decibel per meter at the very best. In actuality, with present glasses, the losses would amount to thousands of decibels per mile, which makes the material clearly unsuitable for long-distance communication.

The present work, then, going on principally in the United States, in Britain, and in Japan, aims at the development of very pure glass fibers. If pure enough fibers are successfully developed, dielectric waveguides might eventually be used between switching exchanges a few miles apart within cities and towns.

The transmission medium is, of course, only one aspect of the Bell program in optical communications. Separate that required nonexistent technology."

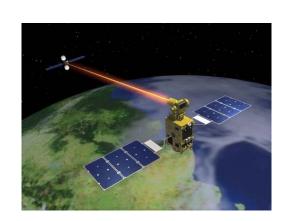
At long last, however, the optics community is getting its chance at a real demonstration. By 1973, if all goes well, at least one satellite will be put aloft carrying laser communication experiments, put up by NASA. It will have taken a full decade to bring this about. In one way or another, many companies and groups have had a hand in giving impetus to these experiments. But even yet, there has been some expression of fear by people in the optics community that if these experiments should not succeed, or should fail in some significant way, optical communications could be held back for an indefinitely longer period. The simplistic promises of a decade ago, which were not made good, have not been forgotten.



"Free-Space" Optical Communications

Require 2 Laser Communication Terminals each composed of:

- Optical Antennas (i.e telescopes)
- Pointing, Acquisition and Tracking mechanism (opto-mechanics)
- Telecommunication transmit/receive opto-electronic boards





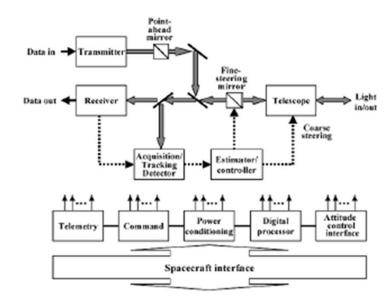


Fig. 6. High-level block diagram of an optical space communication system.



The mathematics of free-space optical links - 1

Using optical frequencies in long distance inter-satellite links (ISLs) allows higher directivity since this depends on the emission wavelength, λ , the transmitter and receiver antenna diameters, D_{Tx} and D_{Rx} respectively, and the pointing loss, L_P :

$$P_{Rx} \propto \left(\frac{D_{Tx} D_{Rx}}{\lambda}\right)^2 L_P$$





The mathematics of free space optical links - 2

Electromagnetic radiation does not propagate in a straight line. If the transmitter system is perfect, diffraction will increase the beam size if transmitted over distance.

Diffraction limited beam divergence angle: $\phi \approx \lambda / D$

EXAMPLE:

Radio Ka-band wavelength: λ =12000 μ m (25 GHz)

Laser wavelength: $\lambda=1.5 \mu m$

Divergence angle ratio: $\phi_{Ka} / \phi_{I} \approx 7742$

Illuminated area ratio: $(\phi_{Ka} / \phi_I)^2$ ---> $A_{Ka} / A_I \approx 59\ 000\ 000 = 78\ dB$

Laser communication can deliver (concentrate) 59 Millions times more power than a Ka communication from a transmit to a receiv terminal of same diameters.

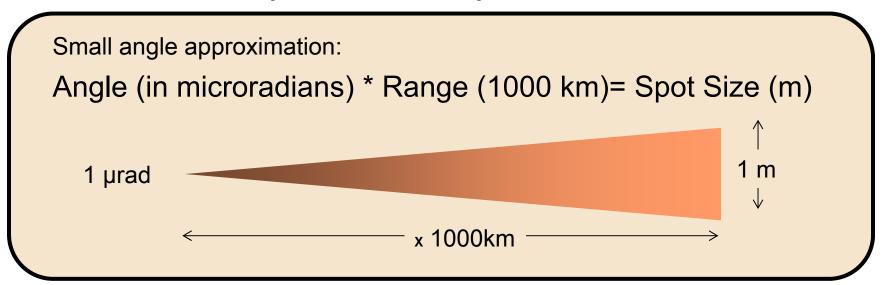
But laser communication terminal needs to <u>point</u> 7742 times more accurately than a Ka-band terminal of same diameter.



Fundamental Concepts

Small Angles - Divergence & Spot Size

 1° ≈ 1700 µrad \rightarrow 1 µrad ≈ 0.0000573°



Divergence	Range	Spot Diameter
1 μrad	40 x 1000 km	~ 40 m
10 μrad	40 x 1000 km	~ 400 m



Pointing

Each terminal needs

<u>first</u>



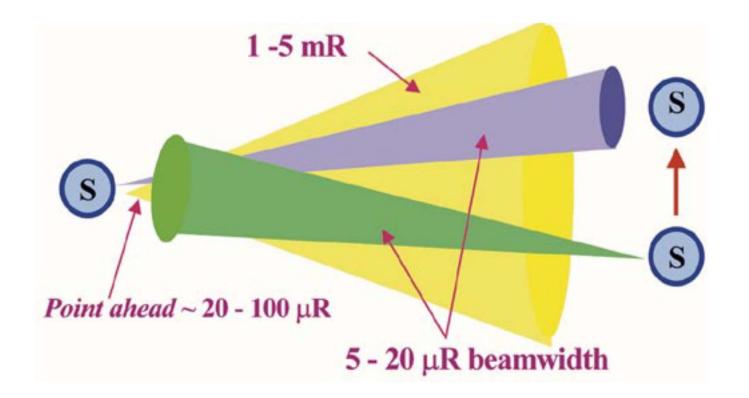
- to know where the counter-terminal is using
 - -uploaded ephemeris data of corresponding satellite,
 - -GPS

(this is uploaded by telemetry to each S/C)

then it applies

- Pointing- Acquisition & Tracking (PAT) of the counter-terminal
 - Course PAT
 - Fine PAT





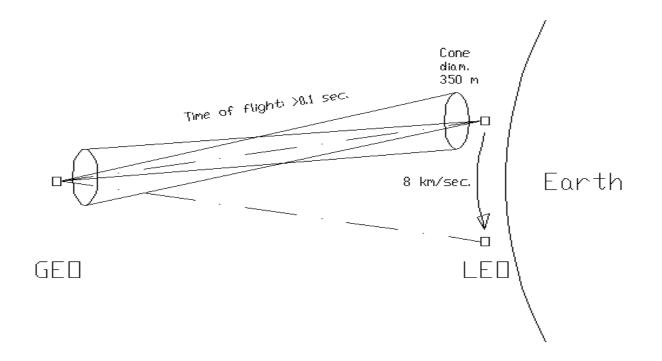
JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 21, NO. 11, NOVEMBER 2003

Optical Satellite Networks

Vincent W. S. Chan, Fellow, IEEE, Fellow, OSA



Pointing Acquisition and Tracking point ahead!

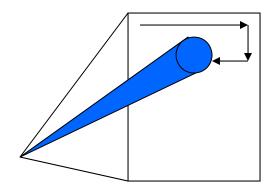




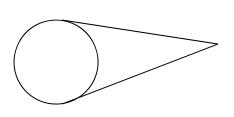


SILEX Acquisition Strategy (1)

ARTEMIS



OGS (or LEO satellite)



Scan FOV: 5796 x 5472 μrad Rx FOV (diam): 2327 μrad

Scan interval: 316 μrad

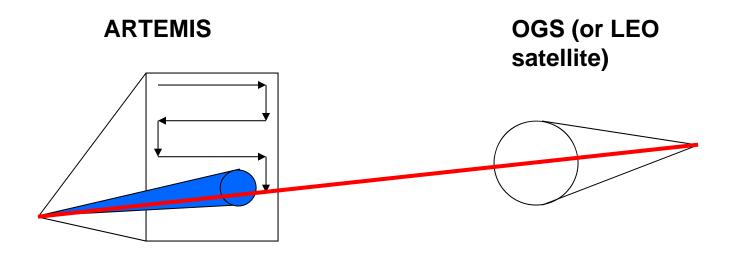
Rx FOV: 1050 x 1050 μrad

Beacon FOV: diam. 750 μrad

Beacon wavelength: 801 nm



SILEX Acquisition Strategy (2)

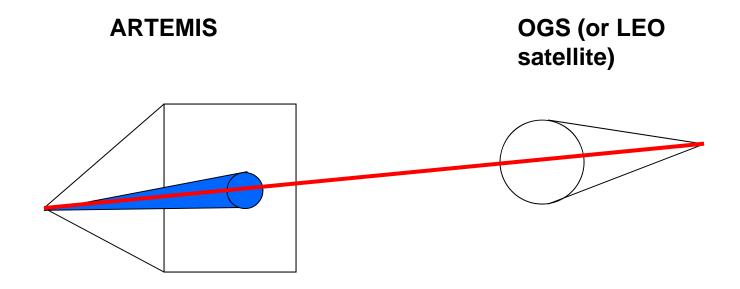


Scan duration: 208 s
Beacon FOV (diam): 750 μ rad
Far-Field illumination: 0.75 s
Beacon wavelength: 801 nm
Max. beacon power: 19 x 900 mW

Response time: <0.35 s Laser FOV (diam): $27 \mu \text{rad}$ Laser wavelength: 847 nm Laser power: 3 W



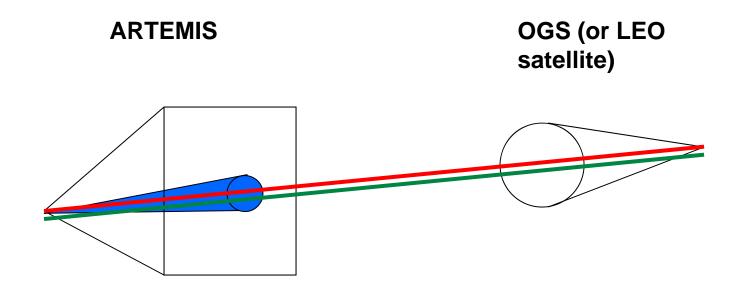
SILEX Acquisition Strategy (3)



Alignment optimization: 27 sec. Laser FOV (diam): 27 μrad Beacon wavelength: 801 nm Laser wavelength: 847 nm Beacon polarisation: Laser polarisation: LHC



SILEX Acquisition Strategy (4)



Comms laser FOV (diam): 10 μrad Comms laser: 819 nm

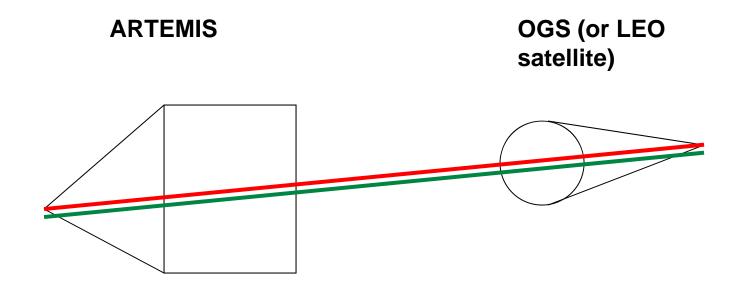
Comms polarisation: LHC

Beacon switch-off: after 2 s

Laser FOV (diam):27 μradLaser wavelength:847 nmLaser polarisation:LHC



SILEX Acquisition Strategy (5)



Comms laser FOV (diam): 10 μrad Laser FOV (diam): 27 μrad Comms wavelength: Wavelength: 847 nm 819 nm Comms polarisation: Laser polarisation: LHC LHC Comms power: 37 mW Laser power: 3 W



And all this in less than

1 sec!



The telecommunication link

Optimise

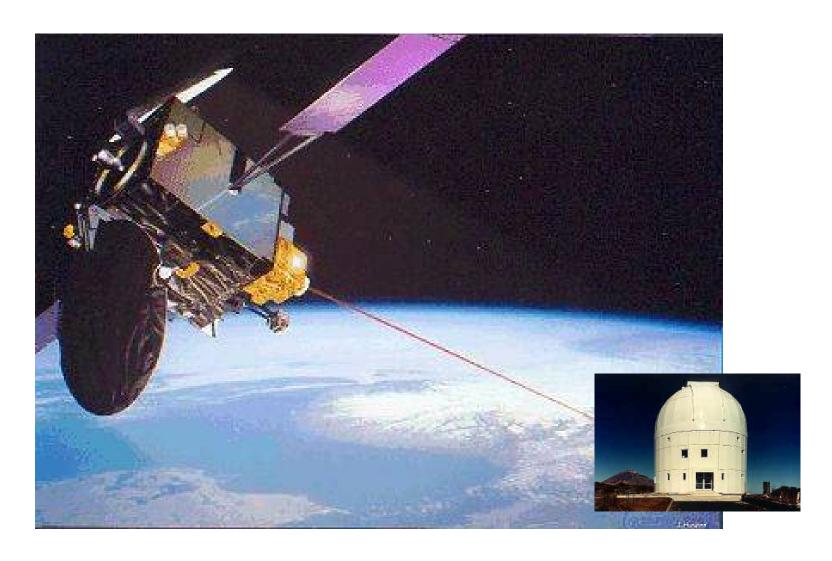
- Modulation scheme
- Reception scheme
- Coding

Remember in free-space there is nor fiber-induce phenomena

- No dispersion i.e we can use very high data rate
- No non-linearities i.e we can use very high data rate

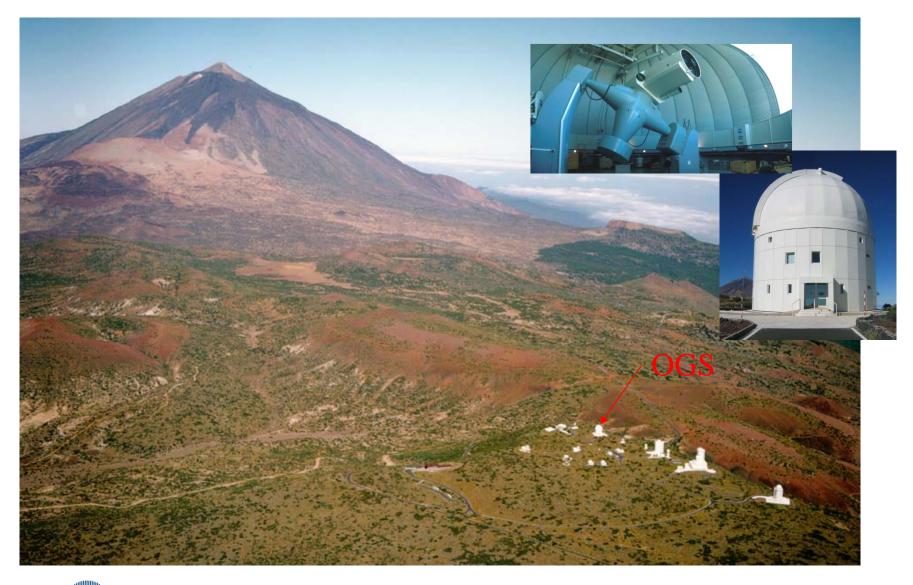


Ground-Satellite-Ground Optical Communications





Observatorio del Teide in Izaña, Tenerife, Spain

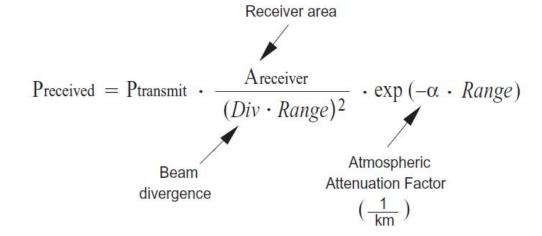




Inter-satellite link

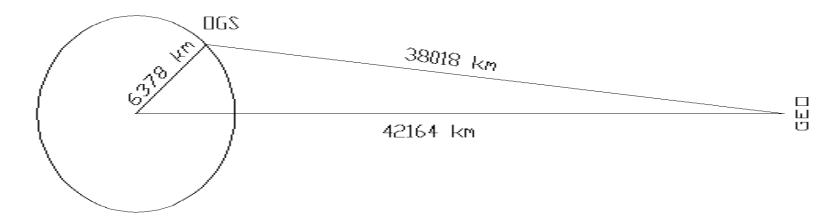
$$\begin{array}{c} \text{Receiver area} \\ \hline \\ \text{Preceived} &= \text{Ptransmit} \\ \hline \\ \hline \\ \hline \\ (\textit{Div} \cdot \textit{Range})^2 \end{array}$$

Ground-satellite link





The effect of propagation through the atmosphere



Extension of turbulent atmosphere:

≈20 km -> (is smaller than the line-width of the drawing)

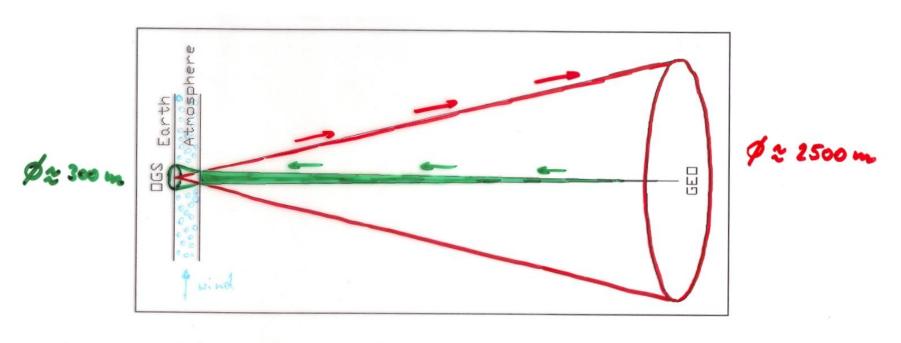
Atmospheric turbulence effects on the propagation of a coherent laser beam decrease with height above ground.

SCINTILLATION

- Beam spreading and wandering due to propagation through air pockets of varying temperature, density, and index of refraction.
- Results in increased error rate but not complete outage
- Almost exclusive with fog attenuation.



The beam broadens and it is distorted in phase "Shower Curtain Effect"



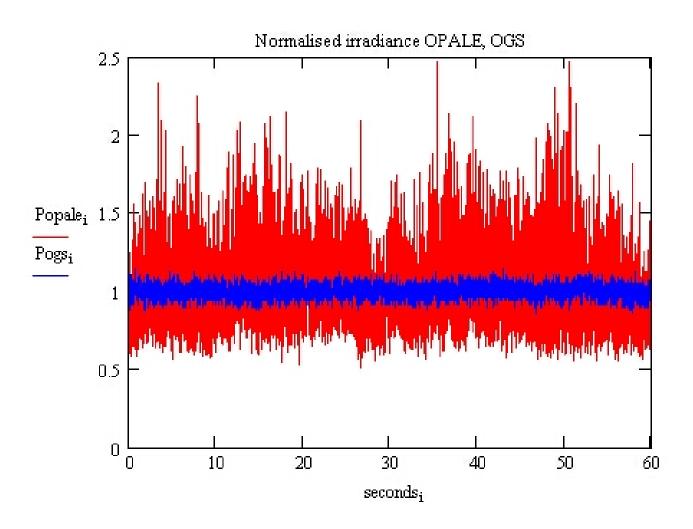
turbulent eddies -> "SHOWER CURTAIN EFFECT"

Transmit Laser Power:

OGS->ARTEMIS
6 Watt

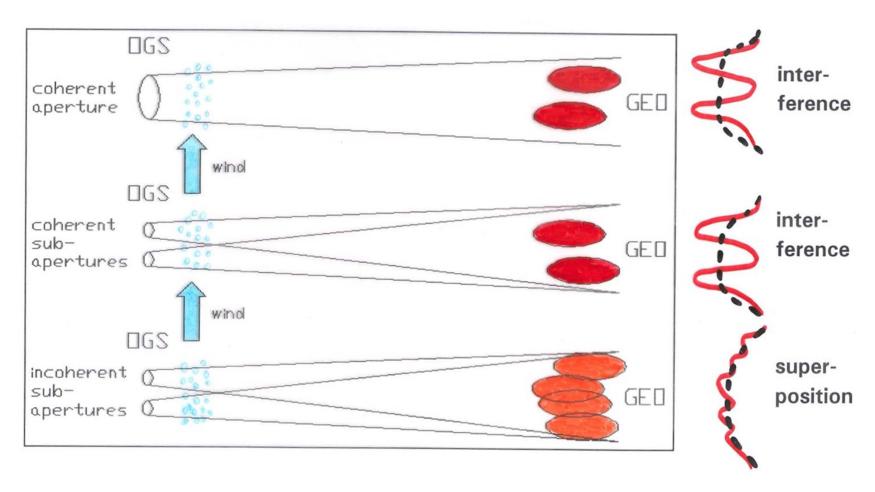
ARTEMIS-> OGS 60 mWatt

The signal at the Satellite terminal is distorted far more than the one in the Ground terminal



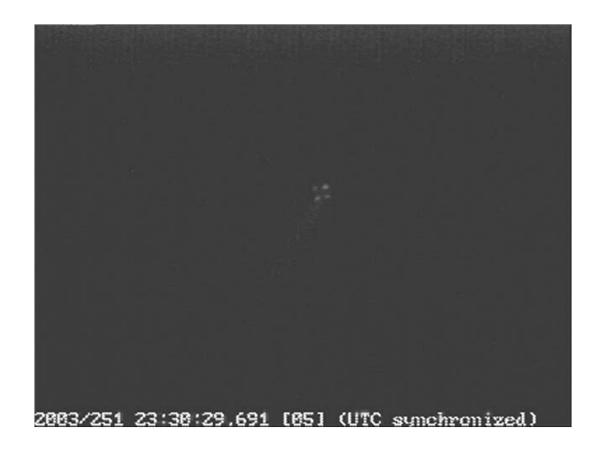


Mitigate scintillation by multiple incoherent transmitters





Video OGS – ISS link





Applications of ISLs

- 1. **Data Relay** (like the Tracking and Data Relay Satellites that serve the Space Shuttle) (Mbps from a LEO/GEO satellite or aircraft to earth via another GEO satellite)
- 2. For **Space Science Links** (Mbps or Kbps over millions of kms) (between Lagrange Points or Interplanetary Probes Space to OGSs or GEO)
- 3. For **Broadband** (multigigabit) links (over thousands of Kms) in Telecom Constellations among S/C in LEO/MEO/GEO

Technologies

- Europe: First Generation of terminals were in 800-850nm band-ASK(PPM)-Direct Detection
- Europe: Second Generation were in 1064nm-BPSK-Coherent Detection
- In USA: 1550nm-ASK-Direct Detection has been studied and demonstrated



History: ESA's 40 years developments on laser ISLs

1977 First project on laser ISLs technologies initiated by ESA

Mid 80's SILEX (Semiconductor laser Inter-satellite Link

Experiment) is decided

90's ISL terminals are developed using

direct detection @ 1550 nm

coherent detection @ 1061 nm

2001 onwards Flight demonstrations

ARTEMIS-SPOT-4 ARTEMIS-OICETS ARTEMIS-Airplane TerraSAR - NFIRE

2017 EDRS: The first operational satellite system using Laser

ISLs



Flying S/C equipped with ISL terminals

ETS (JAXA) in GTO (1 Mbps-DD)

• SPOT-4 (CNES) in LEO (50Mbps-850nm-DD)

ARTEMIS (ESA) in GEO (50Mbps-850nm-DD)

GeoLITE (USA) in GEO (military - confidential)

OICETS (JAXA) in LEO (50Mbps-850nm-DD)

TerraSAR-X (DLR) in LEO (5.5Gbps-1064nm-CD)

NFIRE (USA) in LEO (5.5Gbps-1064nm-CD)

ESA maintains an Optical Ground Station in Tenerife, Spain to support experiments for Ground-Space links

IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 16, NO. 5, SEPTEMBER/OCTOBER 2010

1051

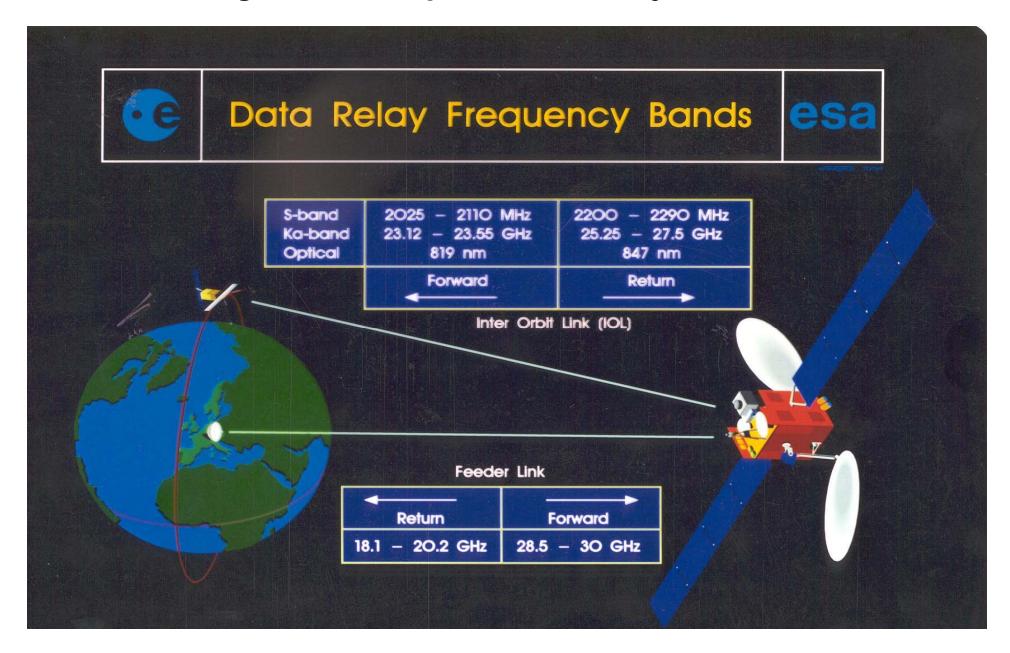
Optical Intersatellite Communication

Zoran Sodnik, Bernhard Furch, and Hanspeter Lutz

(Invited Paper)



SILEX First generation optical data relay



SILEX Parameters



	ARTEMIS	SPOT-4
Antenna diameter Rx:	250 mm	250 mm
Beam diameter Tx (1/e²):	125 mm	250 mm
Transmit power:	5 mW	40 mW
Transmit data rate:	2 Mbps	50 Mbps
Transmit wavelength:	819 nm	847 nm
Transmit modulation scheme:	2-PPM	NRZ
Receive data rate:	50 Mbps	none
Receive wavelength:	847 nm	819 nm
Receive modulation scheme:	NRZ	none
Link distance:	<45000 km	
Beacon wavelength:	801 nm	none
Optical terminal weight:	160 kg	150 kg



ARTEMIS to OGS to ARTEMIS VIDEO!





ARTEMIS TO SPOT-4



IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 16, NO. 5, SEPTEMBER/OCTOBER 2010

Optical Intersatellite Communication

Zoran Sodnik, Bernhard Furch, and Hanspeter Lutz



(Invited Paper)

First Image Transmitted by SILEX data relay





30 November 2001 17:45 Lanzarote, Canary Islands, in the Atlantic ocean west of Africa, the first image transmitted via optical intersatellite link from SPOT4 to ARTEMIS and then to SPOTIMAGE in Toulouse, France via ARTEMIS' Ka-band feeder link





ARTEMIS and the OICETS Link

Dec. 2005: First bi-directional optical inter-satellite link







Fig. 5. LUCE LCT on top of the OICETS spacecraft.

The OICETS laser terminal during Integration and Testing





Fig. 4. ARTEMIS (left) and SPOT-4 (right) LCTs during assembly at Astrium SAS (former Matra Marconi Space) France.

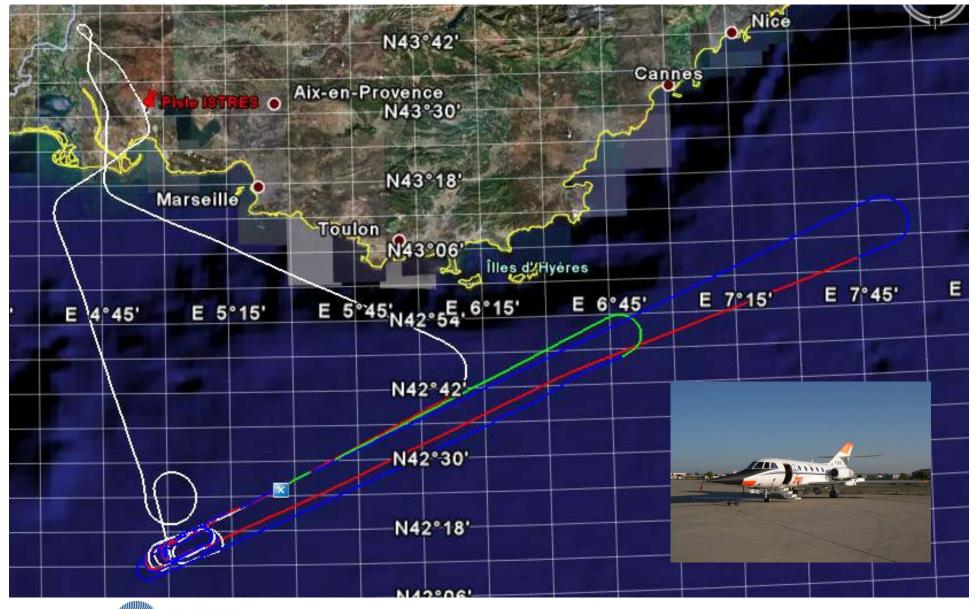
DLR OGS - OICETS Optical Communications



Fig. 2 Image of receiver telescope in June 2009, hosted by an astronomical clamshell dome (left) and Instrument setup in the 2009 campaign (right). The beam is guided to the tracking camera, receiver frontend and measurement instruments [5]



ARTEMIS and the Airplane links (flying over Cote d'Azur)



Summary of first generation optical ISL terminals

	ARTEMIS	SPOT-4	OICETS	LOLA
Orbit and launch date:	GEO - 2001	LEO - 1998	LEO - 2005	NA - 2006
Antenna diameter Rx:	250 mm	250 mm	260 mm	125 mm
Beam diameter Tx (1/e²):	125 mm	250 mm	130 mm	73 mm
Transmit power (ex aperture):	5 mW	40 mW	70 mW	104 mW
Transmit data rate:	2 Mbps	50 Mbps		
Transmit wavelength:	819 nm	847 nm	847 nm	847 nm
Transmit modulation scheme:	2-PPM	OOK - NRZ	OOK - NRZ	OOK - NRZ
Receive data rate:	50 Mbps	none	2 Mbps	2 Mbps
Receive wavelength:	847 nm	819 nm	819 nm	819 nm
Receive modulation scheme:	OOK - NRZ	none	OOK 2-PPM	OOK 2-PPM
Link distance:	<45000 km			
Beacon wavelength:	801 nm	none	none	none
Optical terminal mass:	160 kg	150 kg	160 kg	50 kg



2nd generation commercial small & Gbps terminals

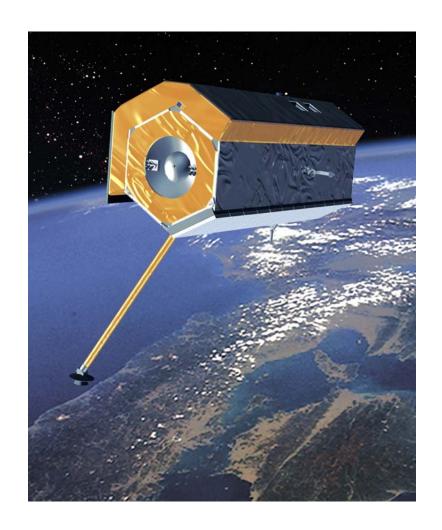


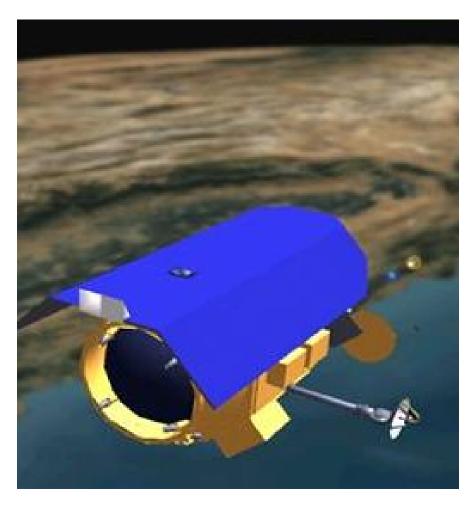
Figure 1: TESAT LCT for 45,000 km LEO-GEO links at 1.8 Gbps

Fig. 6. Engineering model of the SROIL terminal

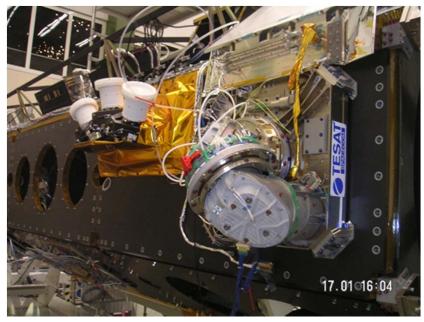


Broadband Links Applications TerraSAR-X and NFIRE Link



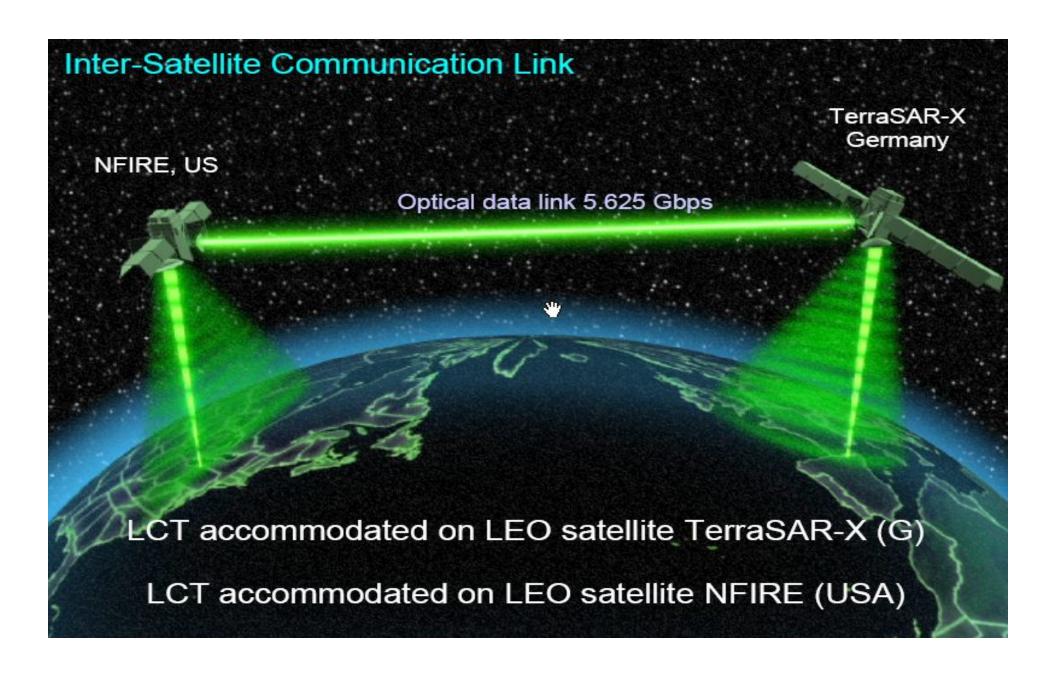














TerraSAR-X (TSX) – NFIRE Parameters

	TSX	NFIRE
Antenna diameter Rx:	125 mm	125 mm
Antenna diameter Tx (1/e²):	125 mm	125 mm
Transmit power:	<1000 mW	<1000 mW
Transmit data rate:	5500 Mbps	5500 Mbps
Transmit wavelength:	1064 nm	1064 nm
Transmit modulation scheme:	BPSK	BPSK
Receive data rate:	5500 Mbps	5500 Mbps
Receive wavelength:	1064 nm	1064 nm
Receive modulation scheme:	BPSK	BPSK
Link distance:	<8000 km	
Beacon wavelength:	none	none
Optical terminal weight:	35 kg	35 kg



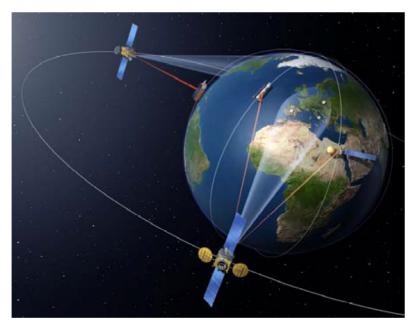


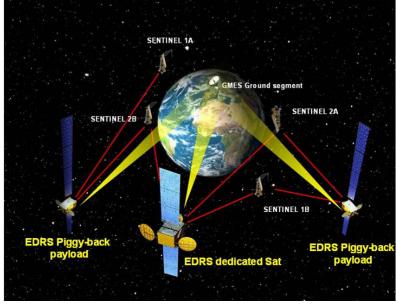
TABLE I
TECHNICAL DATA OF LCTs FOR SPACECRAFT DESCRIBED IN THIS PAPER

	ARTEMIS	SPOT-4,	TerraSAR-X,	Alphasat,
		OICETS	NFIRE	Sentinel 1+2
Rx diameter:	250mm	250mm,	125mm	135mm
		260mm		
Rx data rate:	50Mbps	None,	5.6Gbps	2.8Gbps
		2Mbps		
Rx wavelength:	847nm	819nm	1064nm	1064nm
Rx modulation:	NRZ	None,	BPSK,	BPSK,
		OOK-2PPM	BPSK	BPSK
Tx diameter (1/e ²):	125mm	250mm,	125mm	135mm
		130mm		
Tx power:	35mW	70mW,	1 Watt	5Watt
		100mW		
Tx data rate:	2Mbps	50Mbps	5.6Gbps	2.8Gbps
Tx wavelength:	819 nm	847 nm	1064 nm	1064nm
Tx modulation:	None	OOK-NRZ	BPSK	BPSK
Beacon wavelength:	801nm	None	None	None
Link distance:	<45000km	<45000km	<6000km	<45000km
Mass of terminal:	157kg	150kg,	35kg	45kg
		170kg		
Power consumption:	200W	150W	120W	140W
Launch date:	12.07.2001	24.03.1998	15.06.2007,	2013,
		23.08.2005	24.04.2007	2012
Orbital location:	GEO 21.5°E	LEO 825 km	LEO 508 km,	GEO 25°E
		LEO 610 km	LEO 350 km	LEO 800 km



EDRS: The first operational use of Laser ISLs (remember ARTEMIS-SPOT4/OICETS 10 years earlier)







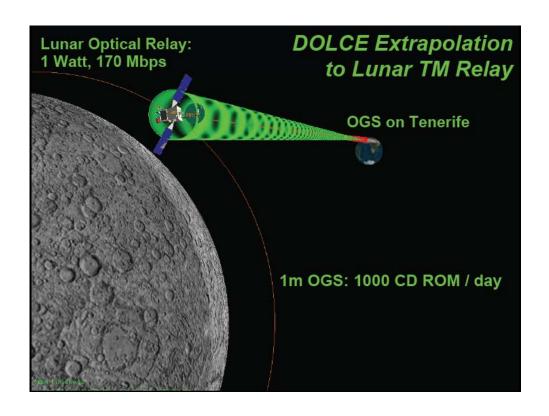
Optical links serving Space Science Missionsbeyond GEO

- Moon Links
- Links at the L2 point
- Interplanetary links



the Moon link 400.000 Kms

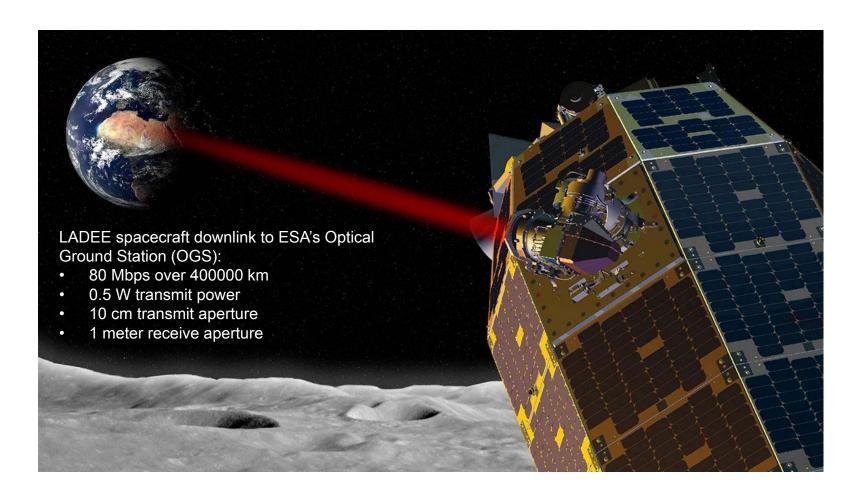
Moon-Earth (OGS) simulated link by RUAG in ESA's DOLCE project





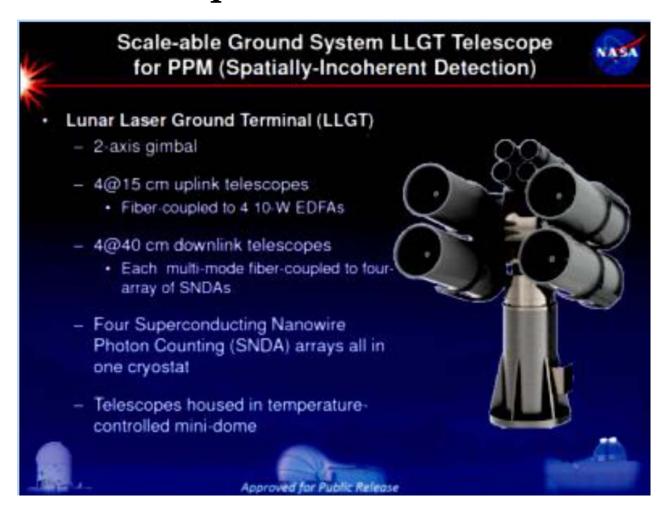
the LADEE-OGS Moon Link

(September 2014)



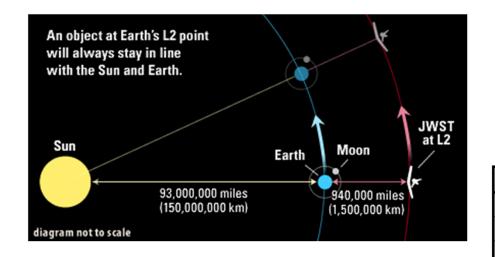


Multiple smaller telescopes to compensate for atmospheric turbulence





The L2 point (1.5 million kms): a parking place for Space Science Telescopes



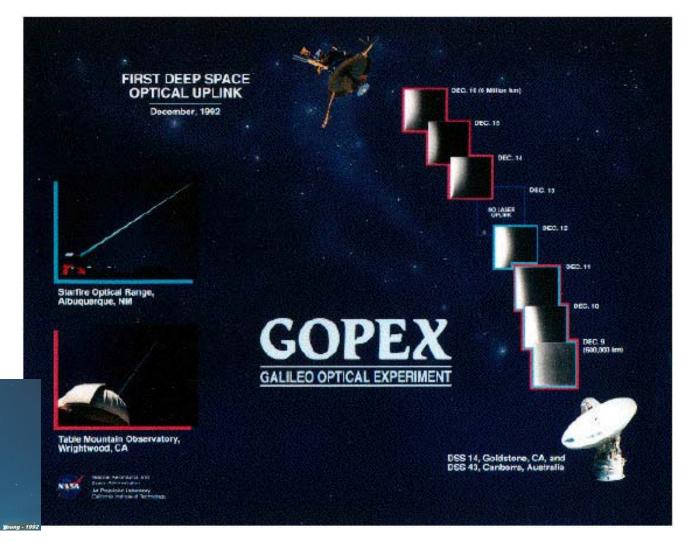
Parameter	Value
User data rate	10 Mbit/s
Communication wavelength	1060 nm
Transmitter architecture	Master oscillator, power amplifier
Average transmit power	1 W
Transmit aperture diameter	10 cm
Modulation format	Pulse position modulation
Link distance	1'500'000 km
Receive aperture diameter	1.016 m
Receiver field of view	> 90 µrad
Target receiver sensitivity	60 photons/bit
Link features	Forward error correction, interleaving

RUAG, CH.



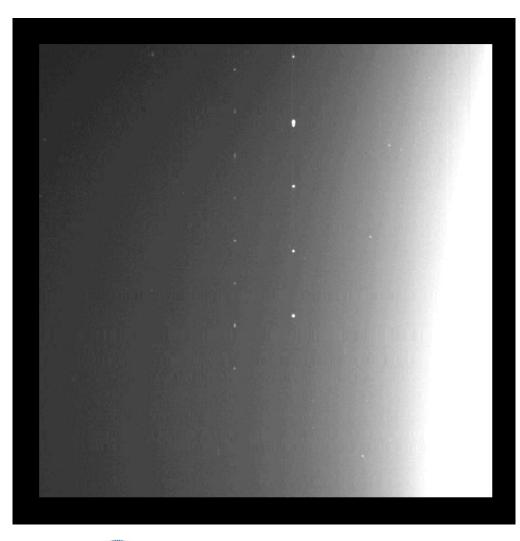
GOPEX: Galileo Optical Experiment

In December 1992 optical links experiments were performed between OGSs in the US and the Galileo Spacecraft (which was on its way to Jupiter). At its longing span the link was 6 Million kms





GOPEX: Galileo Optical Experiment



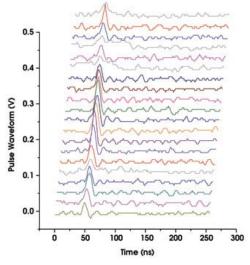
Two sets of laser pulses transmitted from Earth to a spacecraft over a distance of 1.4 million kilometers (870,000 miles) in a communications experiment are shown in this long-exposure image made by the Galileo spacecraft's imaging system. In the image, taken on Dec. 10 1992, second day of the 8-day experiment, the sunlit part of the planet (west central United States) is to the right, the night side to the left. The camera was scanned from bottom to top of the frame (approximately south to north), smearing terrain features but showing individual pulses. The five larger spots in a vertical column near the predawn centerline of the frame represent pulses from the U.S. Air Force Phillips Laboratory's Starfire Optical Range near Albuquerque, NM, at a pulse rate of 10 Hz. Those to the left are from the Jet Propulsion Laboratory's Table Mountain Observatory near Wrightwood, CA, at a rate of 15 Hz. Spots near the day/night terminator to the right are noise events not associated with the laser transmissions. The experiment, called GOPEX (Galileo Optical Experiment), is demonstrating a laser "uplink" from Earth to spacecraft. Laser "downlinks" may be used in the future to send large volumes of data from spacecraft to Earth. The experiment was operated by JPL's Tracking and Data Acquisition Technology Development Office for NASA's Office of Space

Communications Advanced Systems Program.



The Mercury Messenger Link - 24 million km!





Laser pulses emitted from the Mercury Laser Altimeter aboard the Messenger spacecraft, 24 million kilometers from Earth, were detected at the observatory

Laser tests were successful despite the clouds at the NASA Goddard SFC Geophysical and Astrophysical Observatory on May 31, 2005

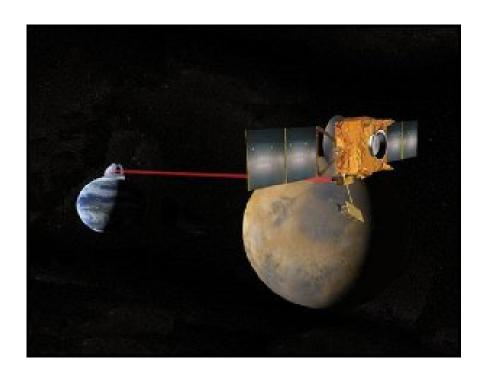
The LIDAR calculated the distance of about 24 million km with an <u>accuracy of 20cm!</u> 23.964.675.433.9 m +/- 20 cm



The Mars Link - 400 million kms

MTO: Mars Telecom Orbiter
The cancelled (due to budget constraints) NASA
2010 mission for a Mars Telecom Orbiter

The Mars horizon with Earth at the sky seen by a Mars rover







Summary in Extra-Satellite Optical Links

- Intersatellite links have been demonstrated offering Gbps communications
- ISL terminals are commercially available
- The EDRS is the first operational system
- Space to Ground links have been demonstrated
- Space to Ground Links suffer from the atmospheric propagation effects
- Spatial Diversity of OGS can increase substantially the link availability
- Inter-linking a number of satellites and OGS with ISLs and GSLs can enable the use of a <u>global optical space network</u> either self-sustained or linked with the terrestrial and submarine fiber optical network.



Summary of Photonics in COMSAT PLs

A portfolio of photonic technologies and techniques have matured to high TRL in

- intra-satellite communication links
- photonic equipment for a number of functions
- inter-satellite links
- satellite to ground to satellite links

The combination of these technologies/techniques enable a number of COMSAT Payload scenarios and Systems. The most advanced of these Systems make use of ISLs with On-board Optical Switching enabling the establishment of:

Optical Satellite networks

