Quantum Communications along Space Channels

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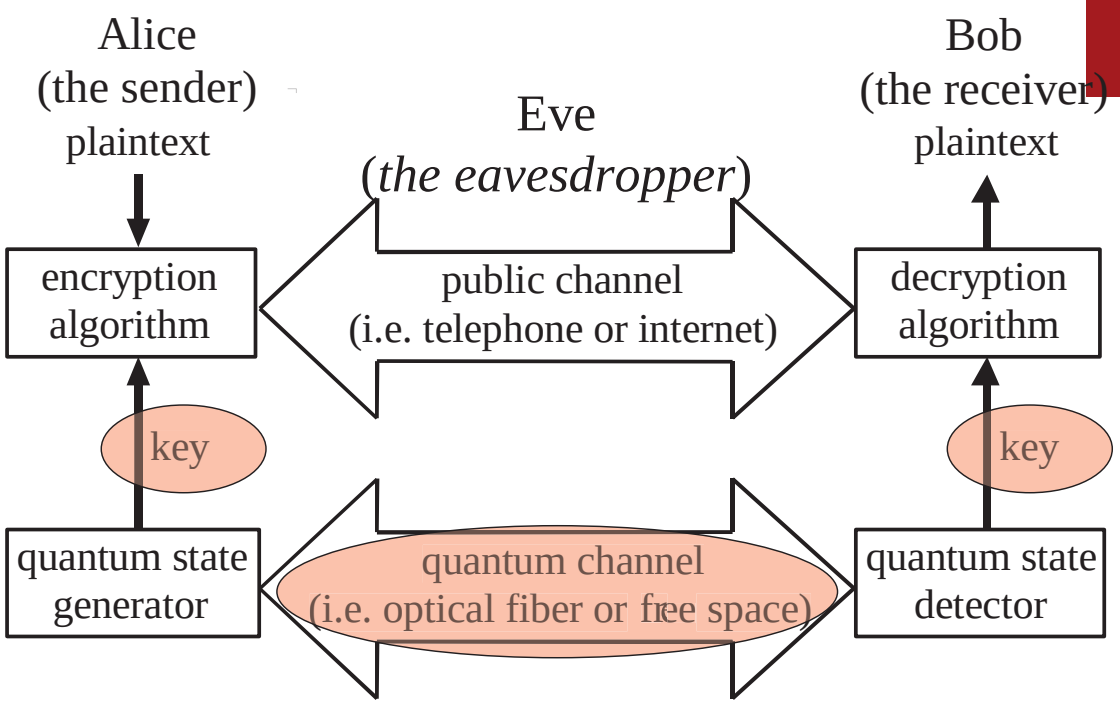
Expanding Quantum Communications

The paradigm shift that Quantum Communications represent vs. classical counterpart allows to envisage the application of global cryptographic key distribution as well as the extension to Space of quantum technologies.

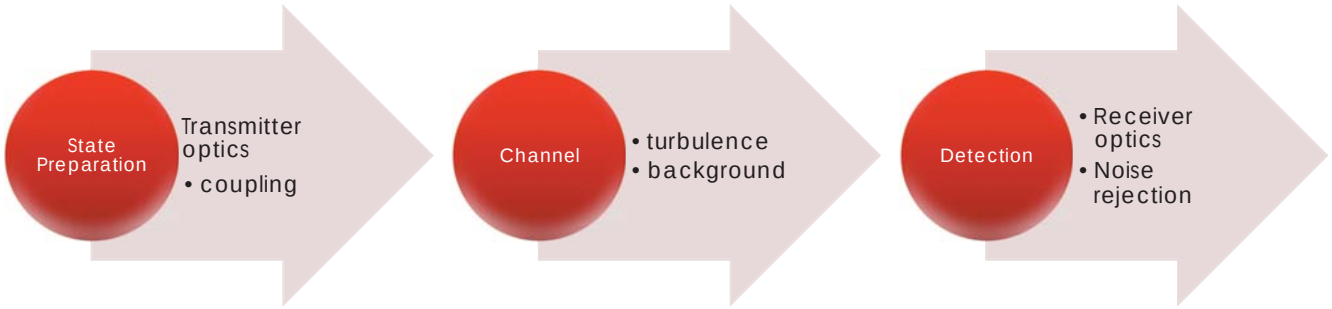
Topics of the talk

- Introduction to Space Quantum Communications (SQC) and Quantum Key Distribution (QKD) in Space
- Ground-ground exploratory links
- Ground-Space experiments and modeling
- Space-space link initial investigations
- Conclusions

Quantum Key distribution

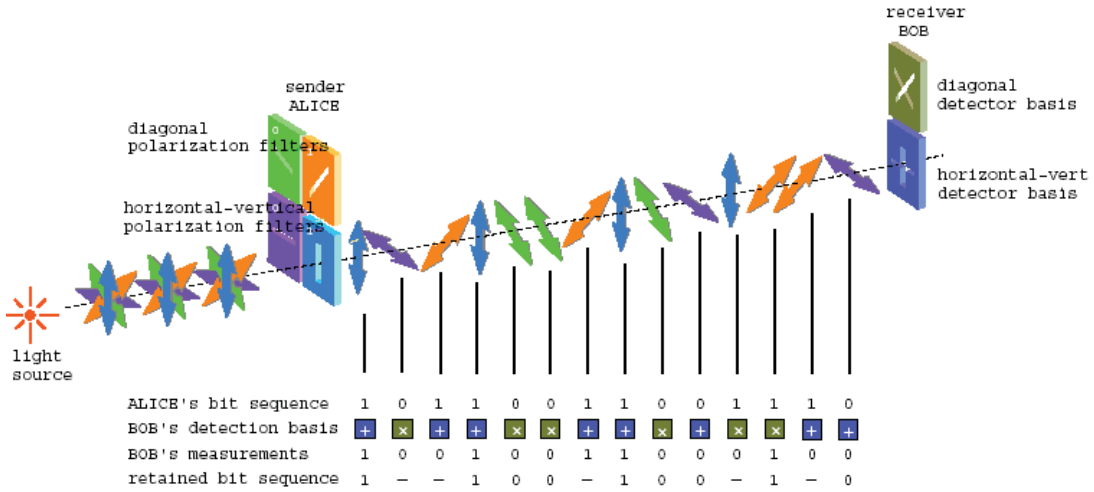


Photonics QC blocks for free space



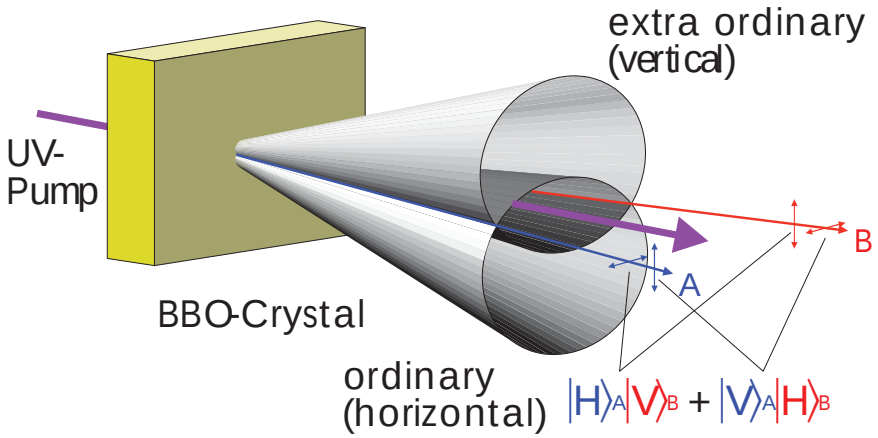
QKD Protocol BB84

- Bennett and Brassard 1984
- 4 photon states:
  - Two orthogonal polarization states
  - Two non-orthogonal reference frames



Quantum entanglement

Maximal knowledge of a total system does not necessarily include total knowledge of all its parts.

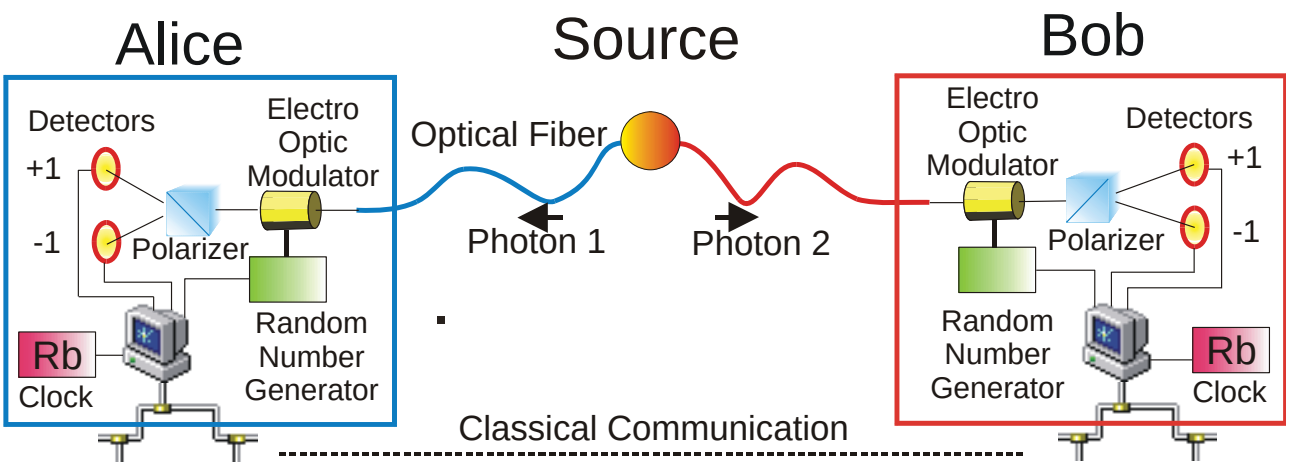


E. Schrödinger
(1935)

Entanglement QKD

Proposal: A.K. Ekert 1991

Laboratory Implementation: **T. Jennewein** et al. 2000



Padova QuaKE setup

- Free space link
- B92 protocol
- Demonstrating the integration of all components: from optics to physical layer to network layer.

QuAKE

Quantum Advanced Key Exchanger is our QKD working system based on B92 (*Bennet - Brassard*) protocol.

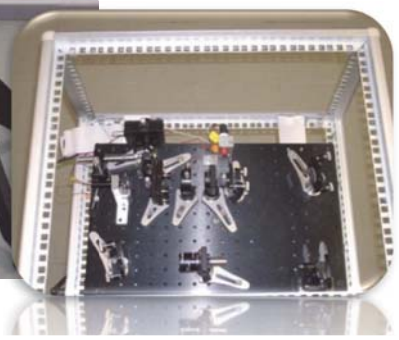
The system consists of a transmitter (*Alice*) and a receiver (*Bob*) that are connected through a free-space quantum channel over a distance of approximately 50 m, and both are driven by a field-programmable gate array (*FPGA*).

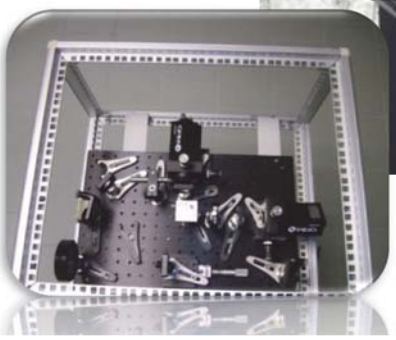
Alice
Quantum transmitter

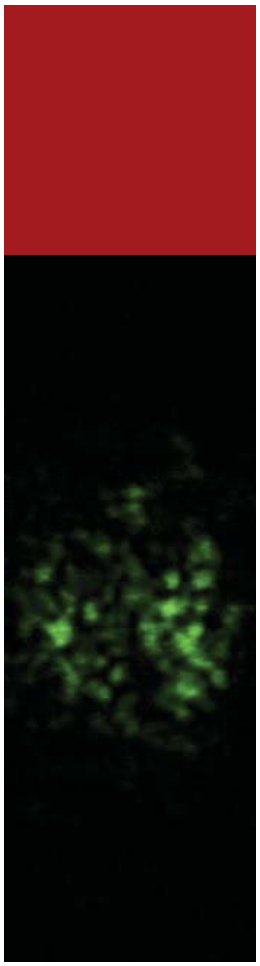
Alice uses three laser diodes: two attenuated laser (@ 850 nm) for the key generation, and the third one for the synchronization (@ 808 nm) .

Bob employs two SPADs to detect the incoming photon

Bob
Quantum receiver







Transmission parameters

Packet rate	12.5 pck/s
Raw key rate	72 k bit/s
Sifted key rate	4.6 k bit/s

Channel parameters

Overall loss rate	$6.4\ 10^{-2}$
Quantum bit error rate	$2.1\ 10^{-2}$
Undetected eavesdropper rate	< 0.41

Security parameters

Secret key rate	600 bit/s
Information leakage rate	< 0.2 k bit/s
Prob. of failed reconciliation	< 0.02
Prob. of higher leakage	$< 5\ 10^{-3}$

Printed message

OTP demo

Hello QuAKE..!

Message written by users

Hello QuAKE..!

Decrypted data

Quantum Key exchange

Kth3@pqxvno6aj

Encrypted data with OTP

Data sent in insecure classical channel

Kth3@pqxvno6aj

Data received

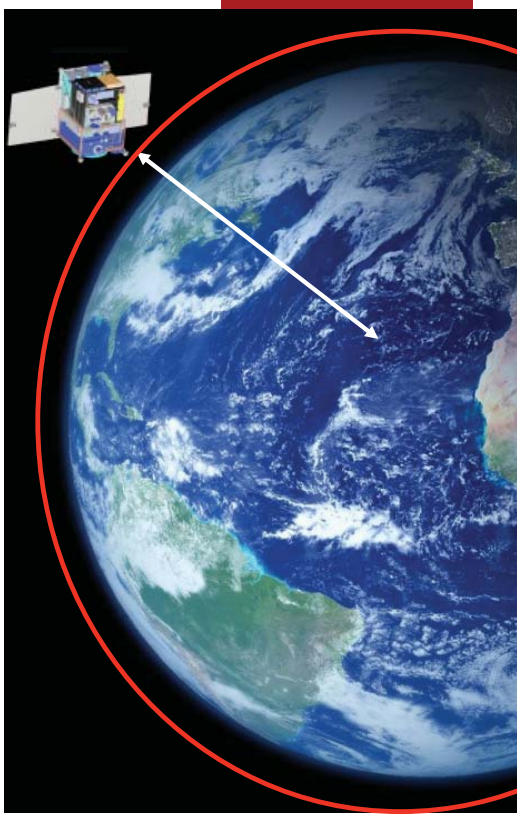
AES Demo

Quantum Key exchange

Image sent in insecure classical channel (e.g. Internet)

Challenges in QC with photons

- Losses, pointing & background
- Photon statistics transformation (from poissonian to log-normal)
- Optimization of optical design for coupling optimization
- *Space qualification of orbital payload.*



Space optical communications

- Very significant results were obtained in the optical classical communications.
- ESA ARTEMIS - Advanced Relay and Technology Mission Satellite – had demontrated link with:
  - OGS telescope at Tenerife
  - With satellite LEO KIRARI, the Japanese Optical Intersatellite Communications Engineering Test Satellite (2005).
  - With airplane Mystère 20, with LOLA ((Liaison Optique Laser Aéroportée) payload, at 40 000 km (2006).
  - NFIRE – multi-Gbs - 2011
- TerraSAR-X and the U.S.-Satellite NFIRE: 5.5 Gb/s

Topics of the talk

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- **Ground-ground exploratory links**
- Ground-Space experiments and modeling
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G-G free-Space Link Features

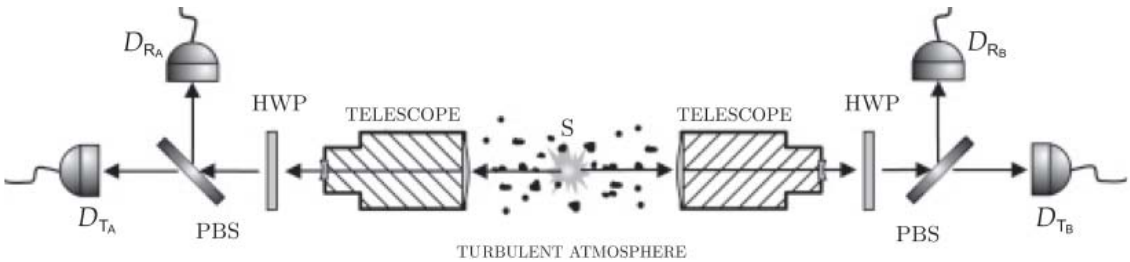
- Photons are weakly interacting – unlikely massive particles.
- Polarization is maintained in propagation.
- Increasing effect of turbulence with the link length, thus limited to about 250 km for Earth curvature.
- Qcomm uses temporal bins of few ns
- Target: to analyze the turbulent channel dynamics wrt qubit timescale

Lossy QComm blues

The propagation of very weak beams - single photon trains or CV - along long links has been initially extrapolated from the classical communication body of knowledge

- V. Tatarskii, The Effect of the Turbulent Atmosphere on Wave Propagation (1971);
- R. L. Fante, Proc. IEEE 63, 1669 (1975);
- P. Diament and M. C. Teich, J. Opt. Soc. Am. 60, 1489 (1970);
- The statistics of polarization encoded single photon beam in 10 km propagation was studied by P. W. Milonni et al., J. Opt. B: Quantum Semiclass. Opt. 6, S742 (2004) and theoretically by G. P. Berman and A. A. Chumak, Phys. Rev. A 74, 013805 (2006).
- Recent advancements in the CV entanglement distillation of deterministically prepared light pulses entangled in continuous variables that have undergone non-Gaussian noise were shown by R. Dong et al. Experimental entanglement distillation of mesoscopic quantum states, Nature Phys. 4, 919 (2008).
- Recent studies in the uplink feasibility: E. Meyer-Scott et al. PRA 84, 062326 (2011)

The turbulent quantum channel



- In a Bell measurement scenario
- The input state is

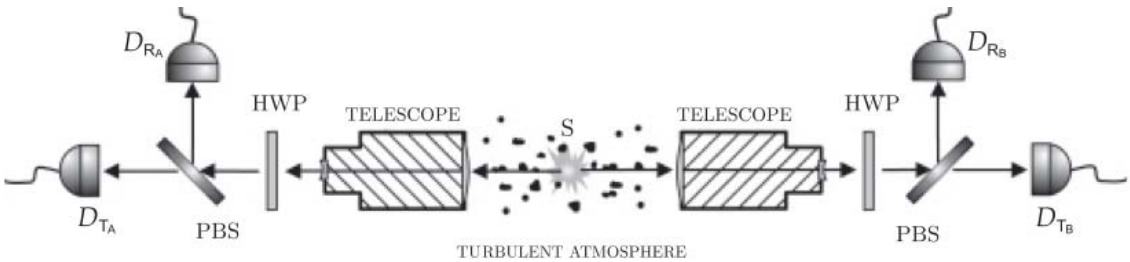
$$\hat{\varrho}_{\text{in}} = \hat{\varrho}_{\mathcal{B}} \equiv |\mathcal{B}\rangle\langle\mathcal{B}|$$

$$\begin{aligned}|\mathcal{B}\rangle &= \frac{1}{\sqrt{2}}(|1\rangle_{\mathrm{H}_A}|0\rangle_{\mathrm{V}_A}|0\rangle_{\mathrm{H}_B}|1\rangle_{\mathrm{V}_B} \\ &\quad + e^{i\varphi}|0\rangle_{\mathrm{H}_A}|1\rangle_{\mathrm{V}_A}|1\rangle_{\mathrm{H}_B}|0\rangle_{\mathrm{V}_B}) \\ &\equiv \frac{1}{\sqrt{2}}(|\mathrm{H}\rangle_A|\mathrm{V}\rangle_B + e^{i\varphi}|\mathrm{V}\rangle_A|\mathrm{H}\rangle_B)\end{aligned}$$

- At the two receivers, the density operator results as

$$\hat{\varrho} = p_0\hat{\varrho}_0 + p_{\mathrm{H}_A}\hat{\varrho}_{\mathrm{H}_A} + p_{\mathrm{V}_A}\hat{\varrho}_{\mathrm{V}_A} + p_{\mathrm{H}_B}\hat{\varrho}_{\mathrm{H}_B} + p_{\mathrm{V}_B}\hat{\varrho}_{\mathrm{V}_B} + p_{\mathcal{B}}\hat{\varrho}_{\mathcal{B}}$$

The turbulent quantum channel



- $\hat{\varrho} = p_0\hat{\varrho}_0 + p_{\mathrm{H}_A}\hat{\varrho}_{\mathrm{H}_A} + p_{\mathrm{V}_A}\hat{\varrho}_{\mathrm{V}_A} + p_{\mathrm{H}_B}\hat{\varrho}_{\mathrm{H}_B} + p_{\mathrm{V}_B}\hat{\varrho}_{\mathrm{V}_B} + p_{\mathcal{B}}\hat{\varrho}_{\mathcal{B}}$
- Where the probabilities are

$$p_0 = \langle (1 - |T_A|^2)(1 - |T_B|^2) \rangle$$

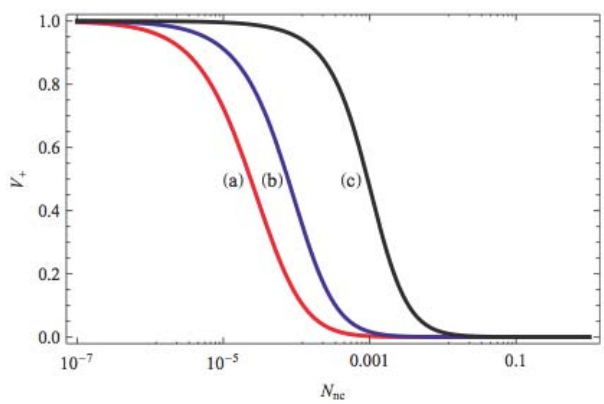
$$p_{\mathrm{H}_A} = p_{\mathrm{V}_A} = \tfrac{1}{2}\langle |T_A|^2(1 - |T_B|^2) \rangle$$

$$p_{\mathrm{H}_B} = p_{\mathrm{V}_B} = \tfrac{1}{2}\langle |T_B|^2(1 - |T_A|^2) \rangle$$

$$p_{\mathcal{B}} = \langle |T_A|^2 |T_B|^2 \rangle$$

Prediction for the *weakly* turbulent Qchannel

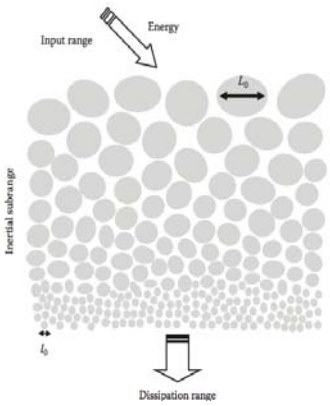
The visibility in the presence of loss-fluctuating channels – of increasing variance from a) to c)- attains higher values compared with similar standard-loss channels.
This fact can be explained by contributions of random events **with losses less than the average value.**
In the presence of postselected measurements, this plays a significant role.



Number of noise counts

A. A. Semenov and W. Vogel, Entanglement transfer through the turbulent atmosphere Phys. Rev. A 81, 023835 (2010)

Stochastic refractive index



- The refractions index is related to pressure (in Bar) and temperature (in K)

$$n(R) - 1 \approx 7.9 \times 10^{-8} \frac{P(R)}{T(R)}$$

$$D_n\left(n(\mathbf{R})\right) = \left\langle [n(\mathbf{R}_1) - n(\mathbf{R}_2)]^2 \right\rangle = \left\langle [n(\mathbf{R}_1) - n(\mathbf{R}_1 + \mathbf{R})]^2 \right\rangle = C_n^2 R^{2/3}$$

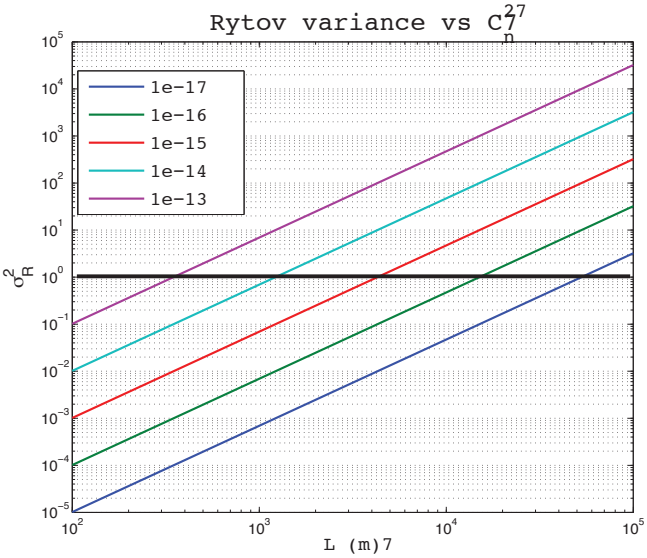
$$C_n^2 = \left(\frac{78p}{T^2} \times 10^{-6} \right)^2 C_T^2$$

- The refraction index has a random term

$$n(R) = n_o + n_1(R) \qquad n_0 \cong 1 \qquad \left\langle n_1(R) \right\rangle = 0$$

Strength of the perturbation

- The effect of the propagation of a beam with wavenumber k along a distance L is classified as weak or strong according the Rytov variance



$$\sigma_R^2 = 1.23 C_n^2 k^{7/6} L^{11/6} \gtrless 1$$

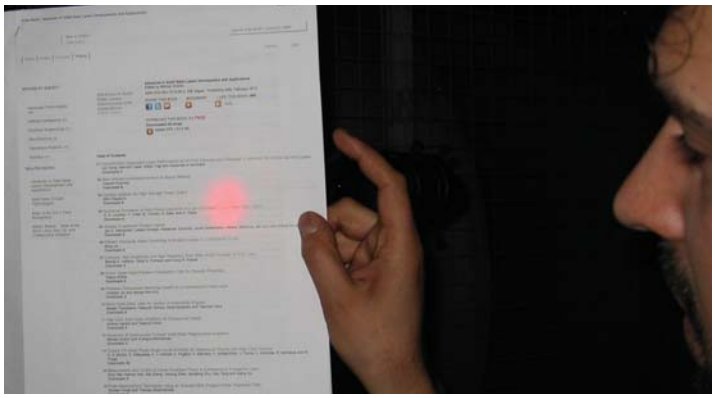
C_n^2 takes values in $10^{-17} \div 10^{-13}\, m^{-2/3}$

$k \approx 10^7\, m^{-1}$

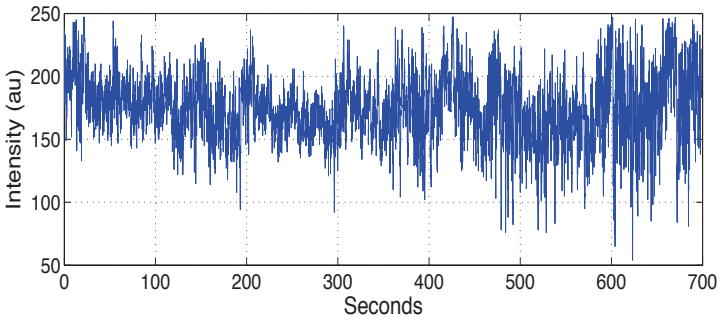
L takes values in $10^2 \div 10^7\, m$ (in space)

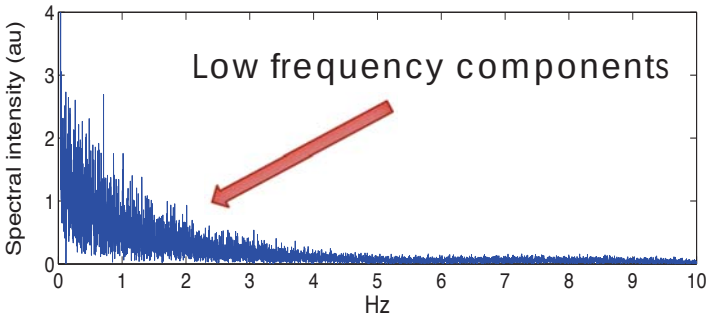
for λ=532 nm

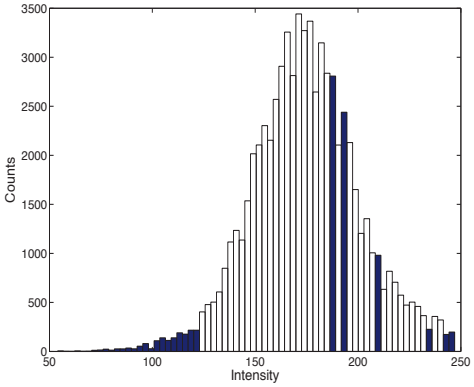
Weak turbulence



Specola-DEI intensity and spectrum





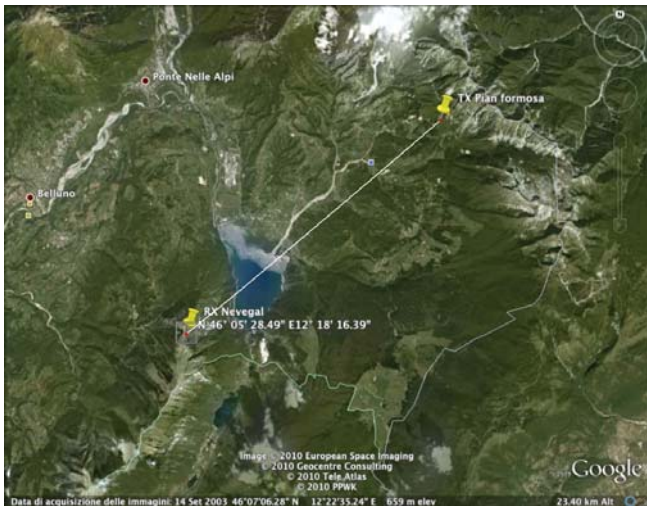


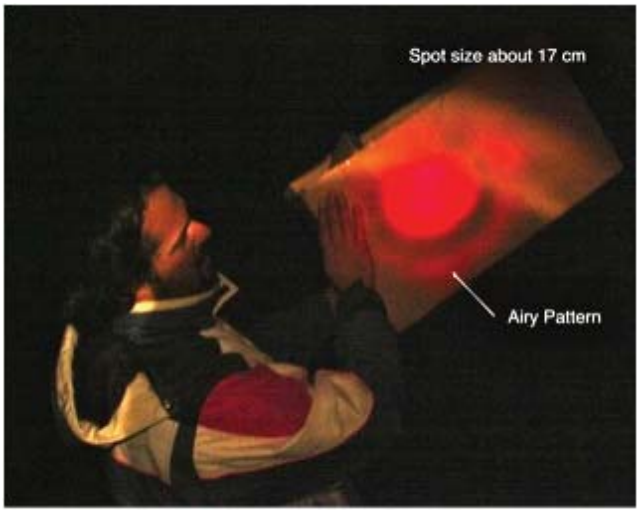
Mean s1=176+/-26

Clearly not Log-normal !!

Alpago – Lake St. Croce link

- 13.3 km
- Result: diffracted limited spot – dia 170 mm
- Airy rings – significant wandering

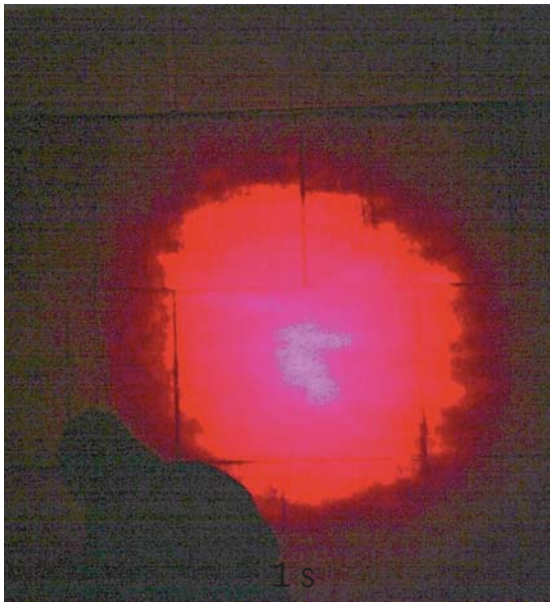


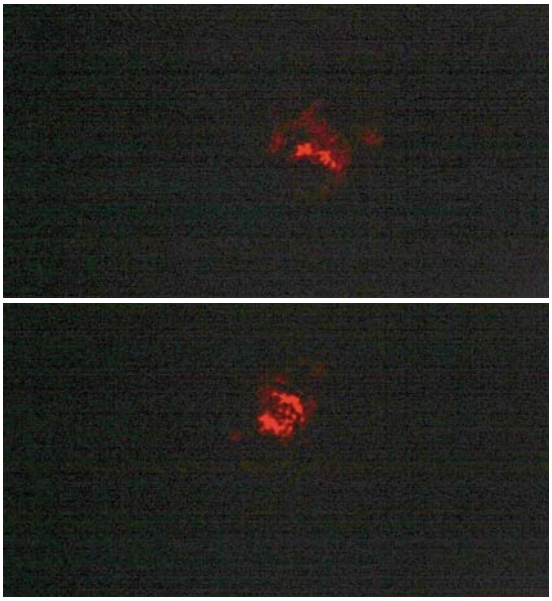


Strong turbulence
Cima Ekar-Mt. Grappa link 18 km

Onset of strong turbulence

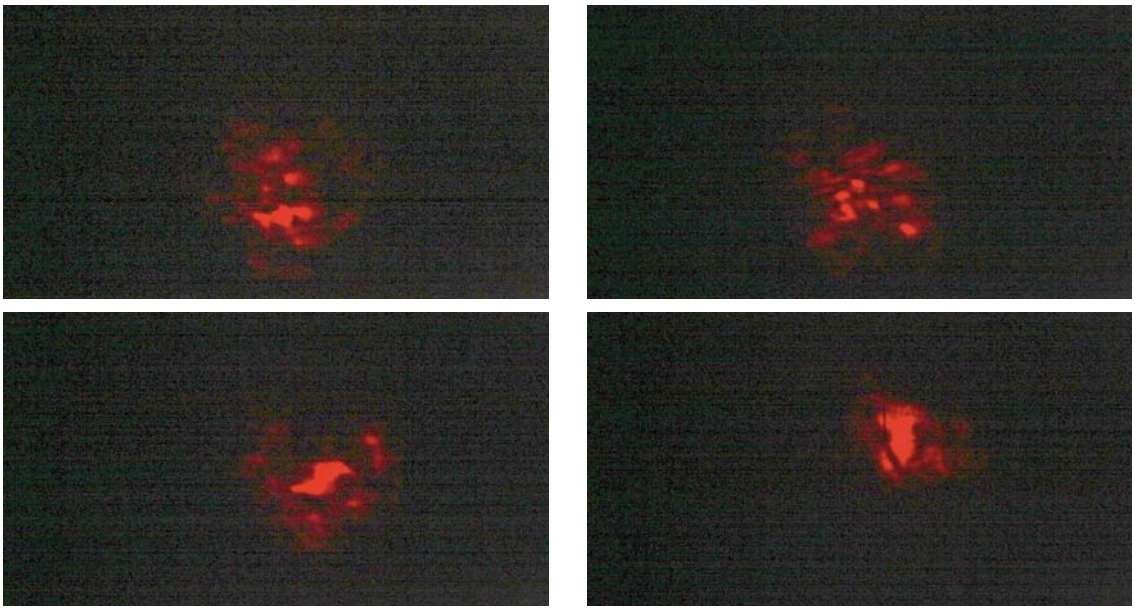
The scintillation effect is evident, due to strong perturbation of the wavefront.
The apparent spot size is the result of a superposition of bright flashes.



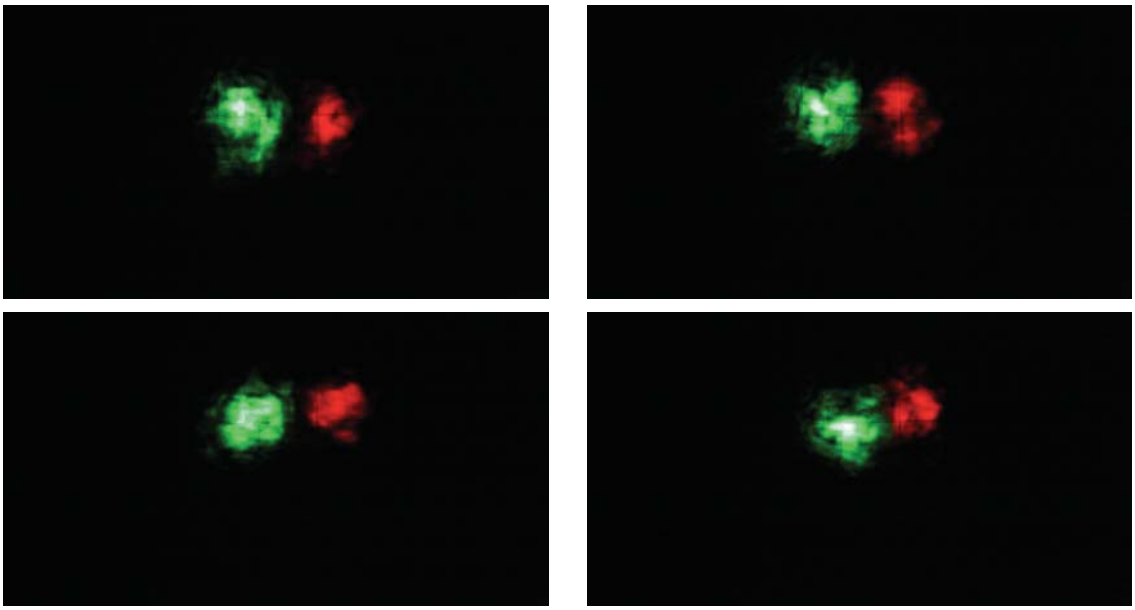


1 ms

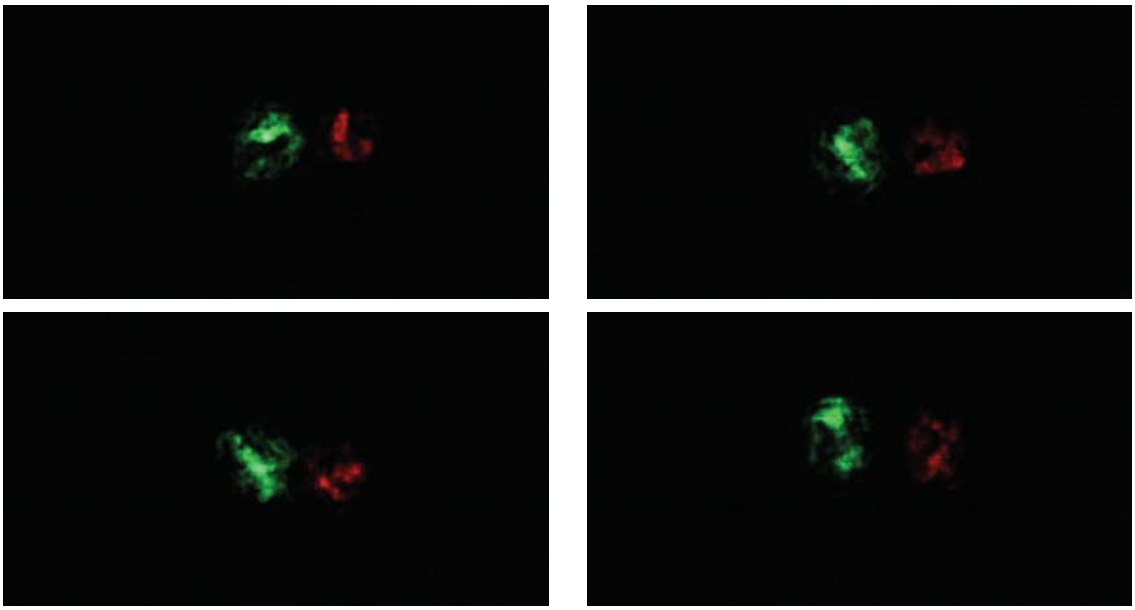
16 ms



And it’s lambda dependent
20 ms

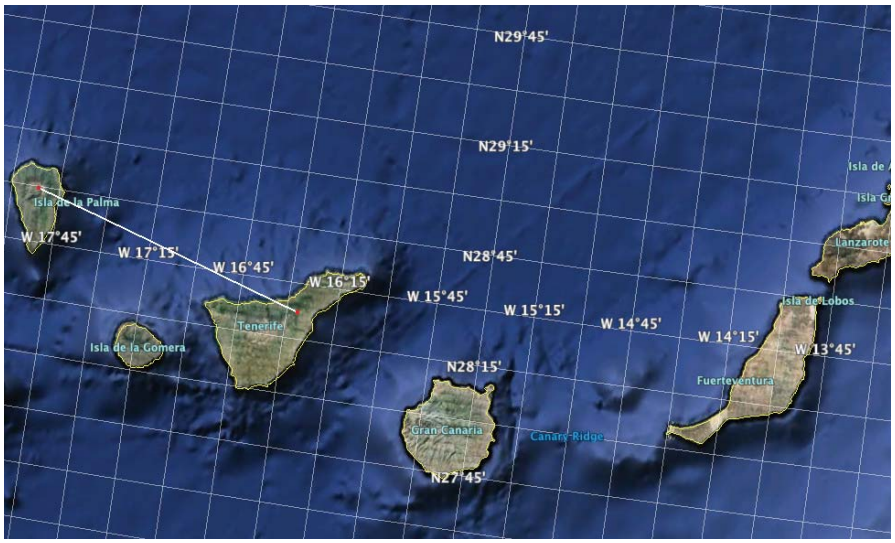


And it’s lambda dependent
5 ms



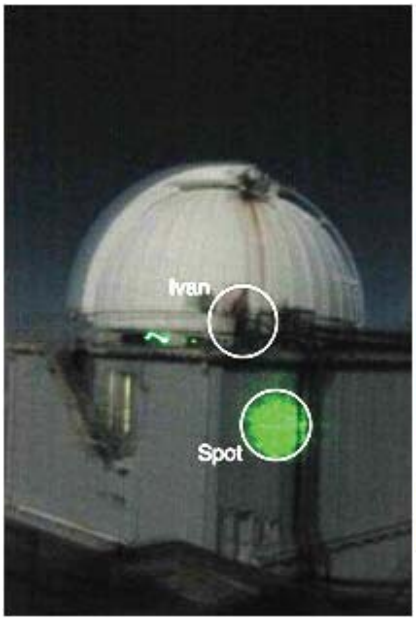
Strong turbulence

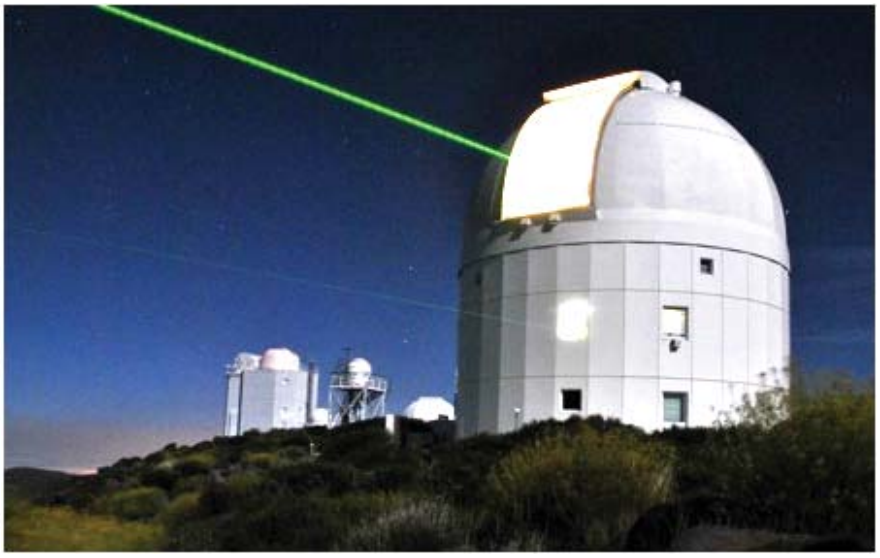
144 km – direct link at 2400 m over Atlantic Ocean
OGS - Observatorio del Teide – Tenerife
Johan-Kapteyn Observatory – Roque de los Muchachos – La Palma



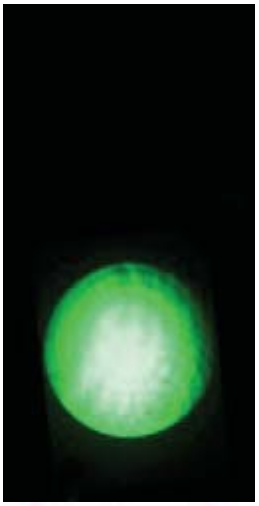
Canary Islands link

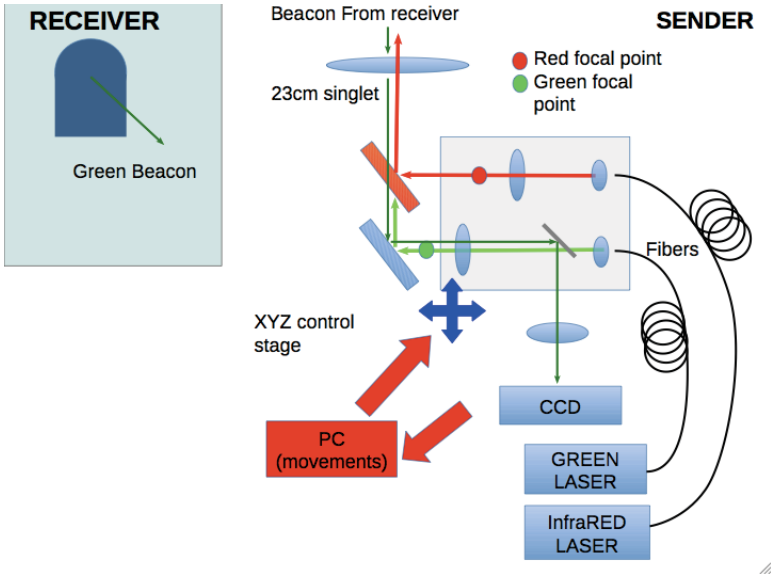
- Spot in good atm condition: diameter long-term about 2 m



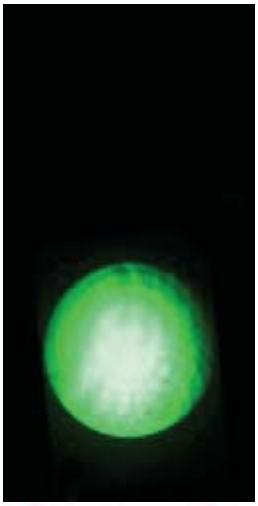


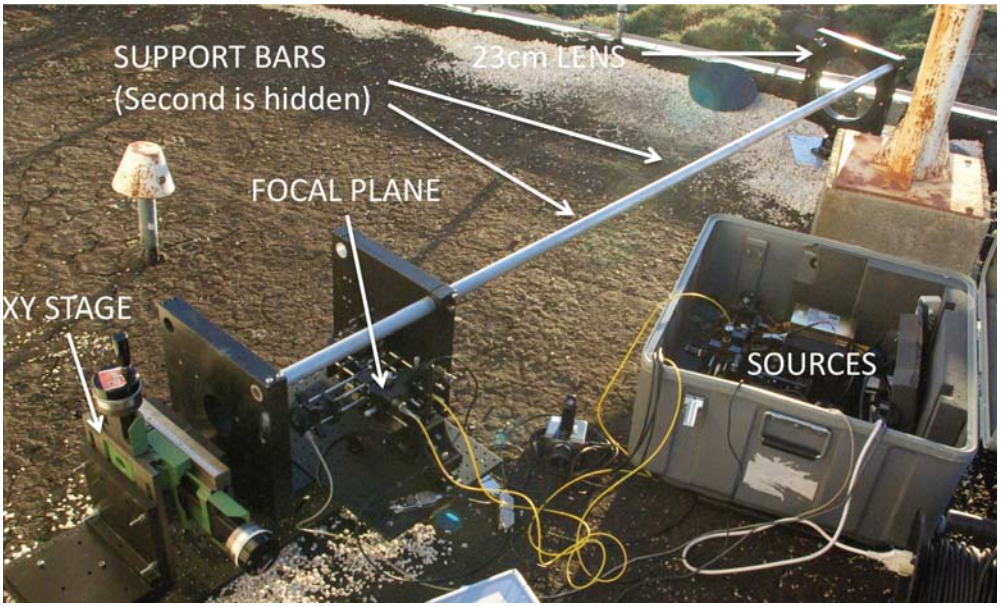
La Palma Tx setup

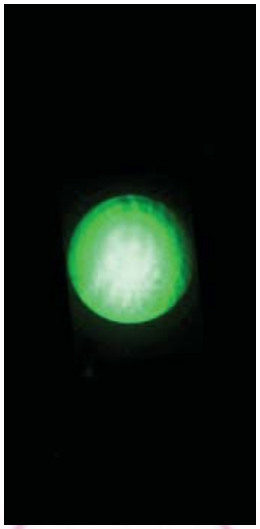




La Palma Tx setup

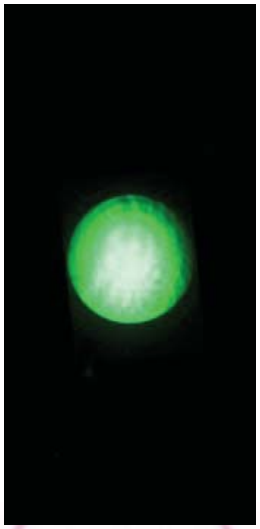






Phenomenological divergence

- **In the best case, the full angle subtended by this spot is of 14 μrad.**
- The diffraction limited full angle of a collimated beam may be calculated from and estimate of the beam waist at the transmitter of w0 = 60 mm, as follows: $2\theta = 2\lambda / \pi\omega_0 = 5.6\mu$rad.
- **the observed spot in optimal conditions is less than a factor three of the diffraction limit** (for a collimated beam)



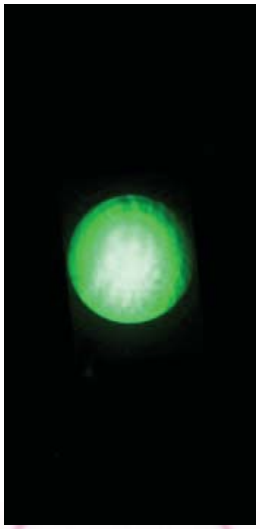
Observations - 1

- In the optimal condition for the propagation, the value of $_0$ that results is of 28 mm.
- From this estimate, we may note that the propagation corresponds to the fourth case described by Fante, as

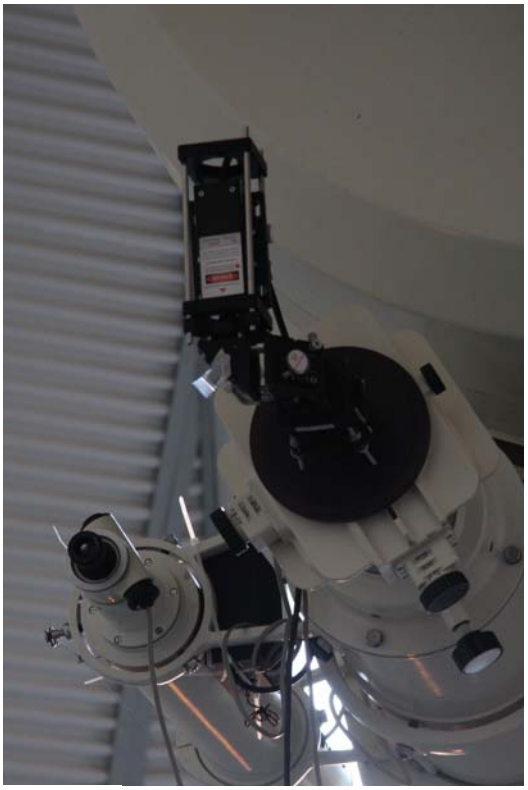
$$k \quad _0^2 \ll x$$

and it effectively corresponds to a beam that at the receiver plane breaks up in multiple spots.

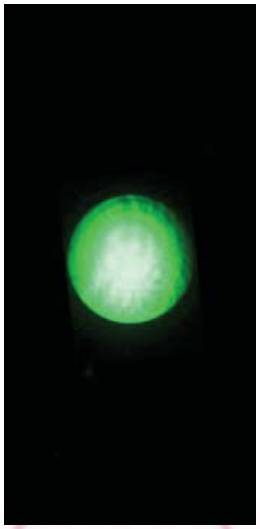
Observations - 2



- The dependence of L on the radius of curvature F of the beam at the transmitter has been verified in the experiment by varying the position of source of telescope from the front focal length.



$$\langle \rho_L^2 \rangle \simeq \frac{4x^2}{k^2 D^2} + \frac{D^2}{4}\left(1 - \frac{x}{F}\right)^2 + \frac{4x^2}{k^2 \rho_o^2}$$

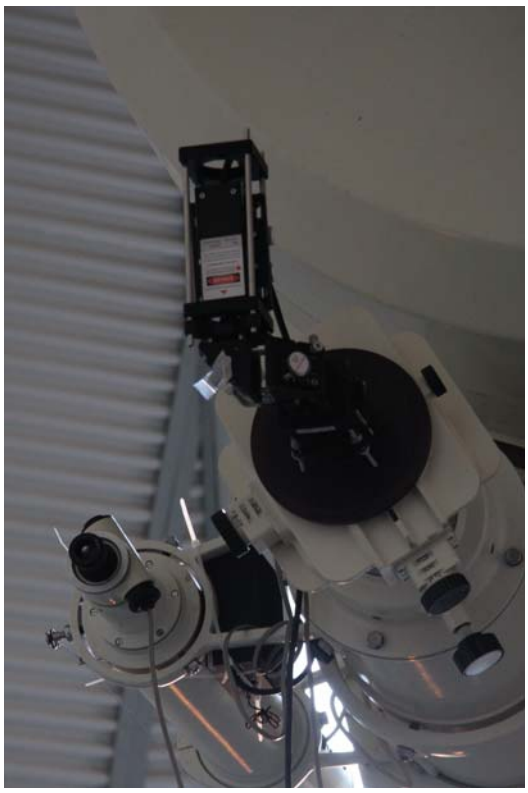


Observations - 2

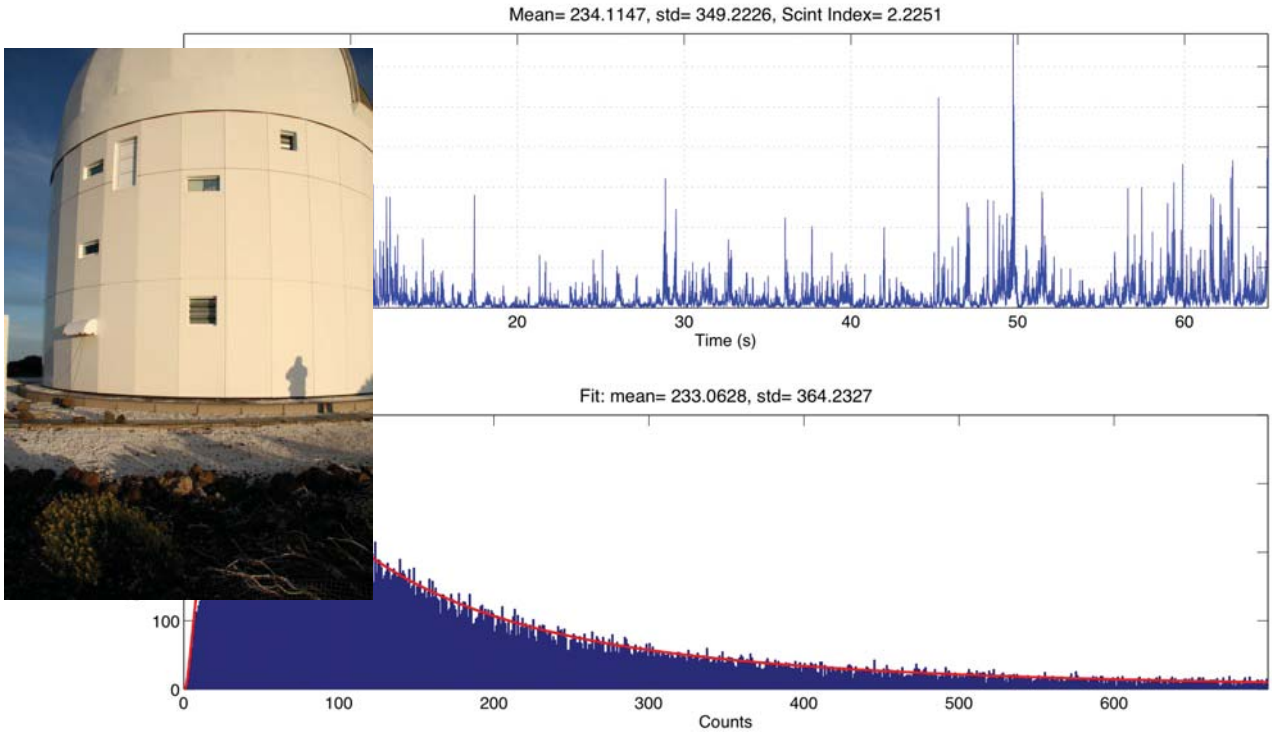
- By observing the back-scattering of the beam with an auxiliary telescope 100mm diameter - f/10 mounted beside the n. 2, it was possible to assess the actual focal position. The feedback from the observer at the receiver end allowed to optimize the focal position in order to minimize

  L·

- This condition was observed in the experiment corresponding to the focus at the path end, and corresponds to the minimum of the term



JKT → OGS – Single Photons



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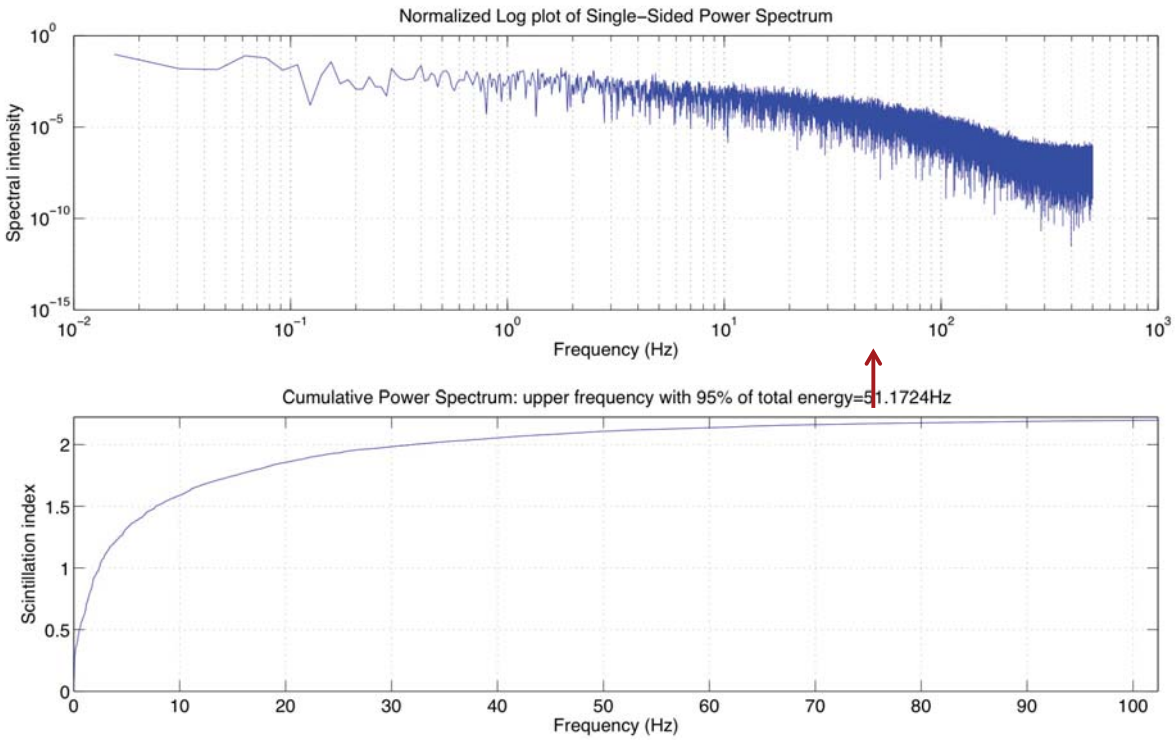
JKT → OGS – Single Photons spectrum



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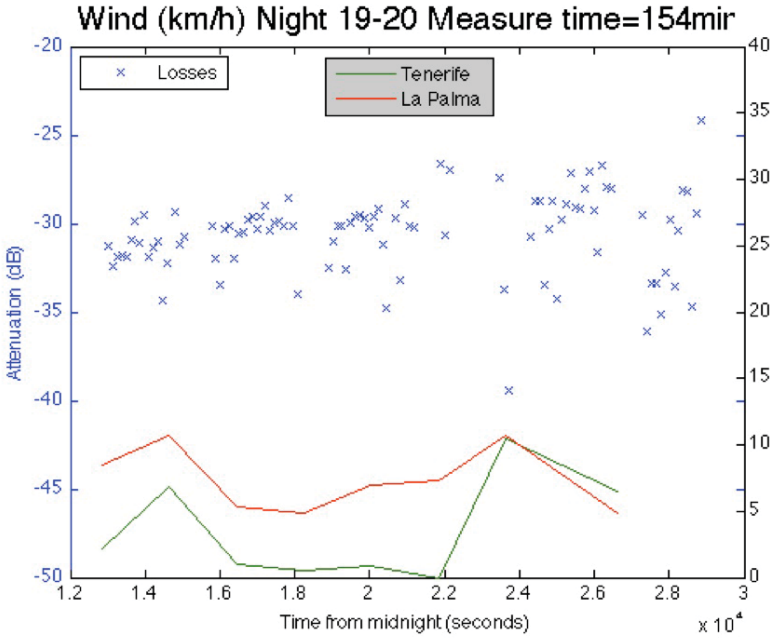
JKT → OGS – Single Photons best link – weak wind



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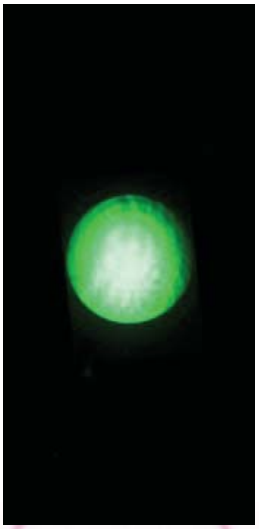
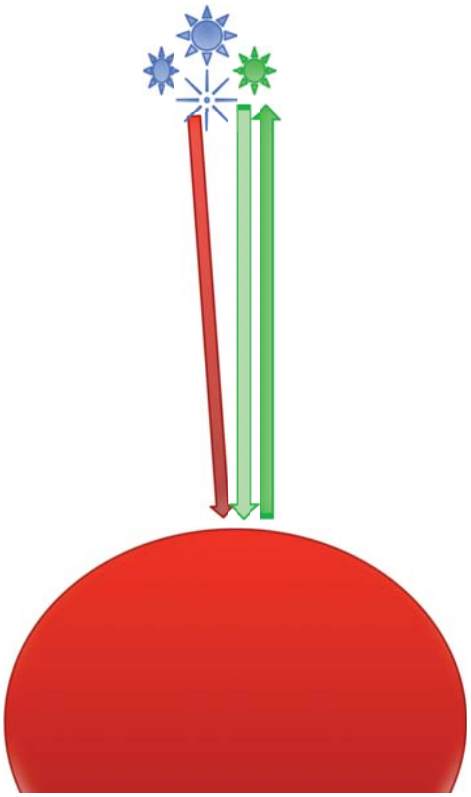
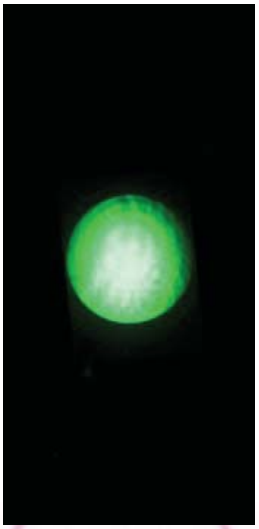
Twin Beam-propagation



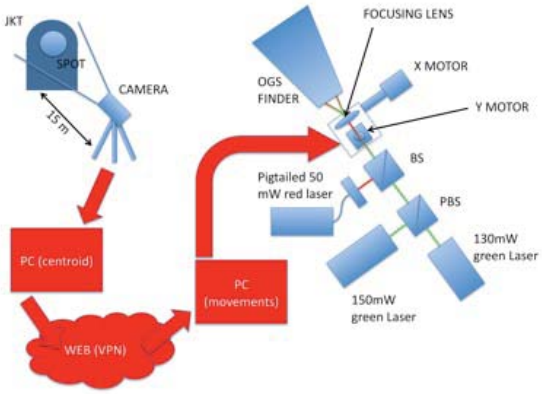
- How are related two nearly-copropagating beams?
- The pointing and aiming stabilization is relevant if the “main” beam is single photon!
- Analogous with AO wavefront correction using artificial stars.



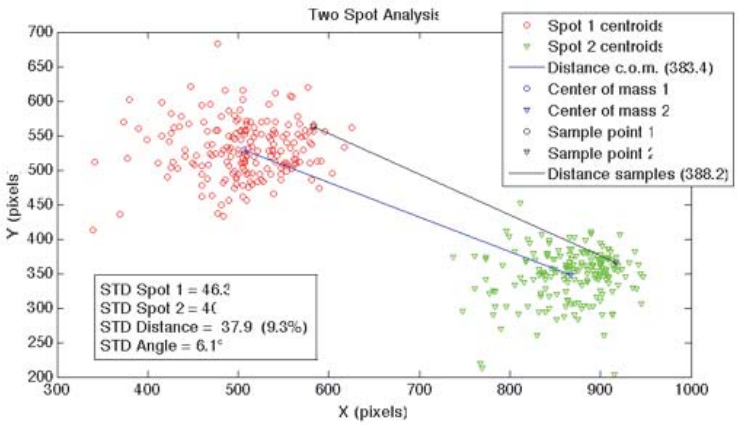
Twin Beam-propagation



- We have analyzed the propagation of two beams along the same path, to study the correlation of the beam centroids.
- The application of this technique would be to use one beam for the quantum channel - thus for the single-photon exchange - and the other with a weak laser beam to be used as beacon for the beam steering, in the same direction of propagation.

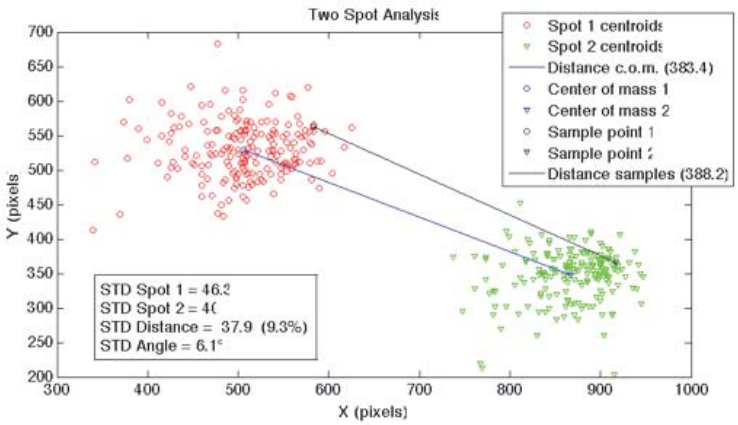


Twin Beam-propagation

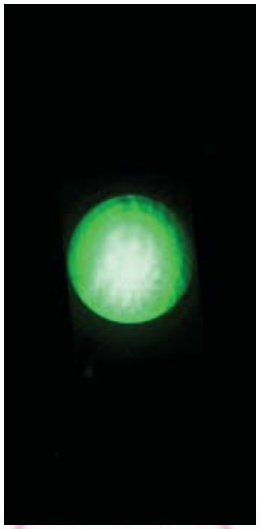


- JKT building with the two green beams, while on the right the dispersion of the two beam centroids is reported for an extended measurement.
- The average separation is of 7.7 ± 0.5 meters, corresponding to a subtended angle of $\theta = 53\ \mu$rad.

Twin Beam-propagation



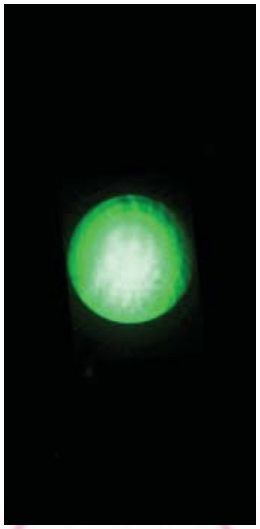
Beams movements are correlated with a standard deviation of 37.9 pixels, equivalent to 0.75 m.
At this separation θ, the two beams are correlated at least in a common mode that involve the wander of both beams.



Twin Beam-propagation

- This results is **not** valid for the higher order spatial fluctuations.
- Indeed, the separation angle is compared with the set of reference values introduced in adaptive optical corrections of phase front, as the isoplanatic angle θ_0 and the independence angle θ_{ind}.

- D. L. Fried, "Anisoplanatism in adaptive optics," J. Opt. Soc. Am. A 72, p. 61, 1982.
- A. Louthain, Integrated Approach to Airborne Laser Communication. PhD thesis, Air Force Institute Of Technology, 2008.
- J. A. Louthain and J. D. Schmidt, "Anisoplanatism in airborne laser communication," Opt. Express 16, pp. 10769–10785, Jul 2008.
- L. Bolbasova and V. P. Lukin, "Modal phase correction for large aperture ground-based telescope with multi- guide stars," in Mitigation of Atmospheric Effects and System Performance II: Techniques and Application, SPIE, ed., 7476, p. 74760M, 2009.



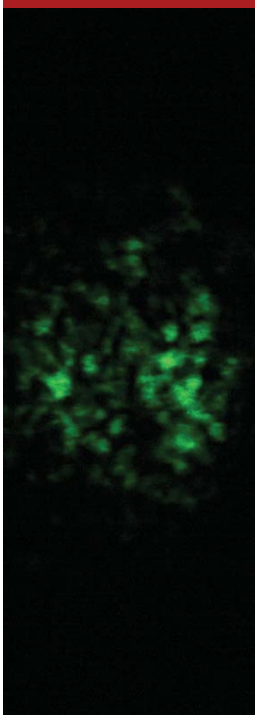
Twin Beam-propagation

- Direct calculation using:
  - wavelength λ = 532 nm,
  - link length L = 144 km,
  - $C_n^2 = 2 \times 10^{-17}\ m^{-2/3}$,
  - transmitting aperture D = 200 mm,
  - wind speed V = 10 m/s,
  - outer scale L0 = 70 m and
  - inner scale li = 7.5 mm, where for the turbulence parameters we extracted the values from the various meteo stations of IAC.

$$\theta_0 = 0.18\,\mu\text{rad} \qquad \theta_{ind} = 3.1\text{mrad}$$

☞the separation angle is greater than the isoplanatic angle. This can be deduced from the different scintillation patterns and the centroid relative motion.

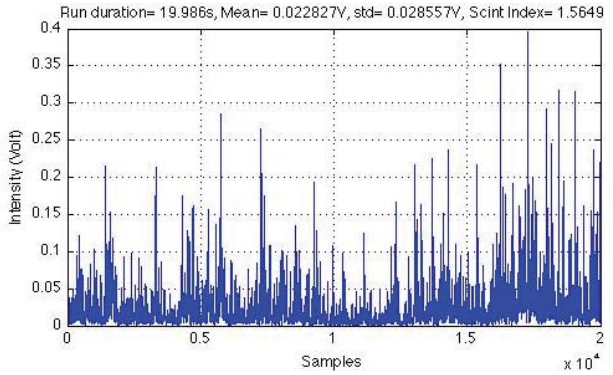
☞However the separation is significantly lower that the independence angle, thus attesting the feasibility of the above described type of control.

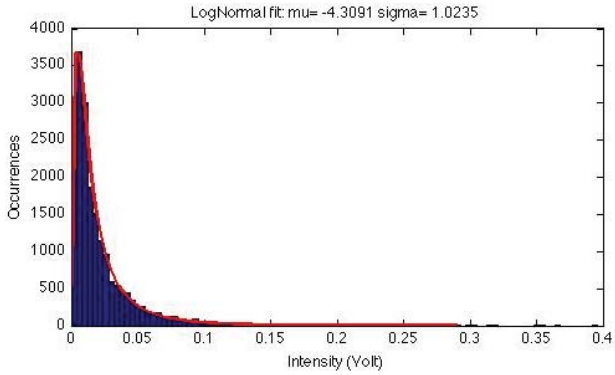


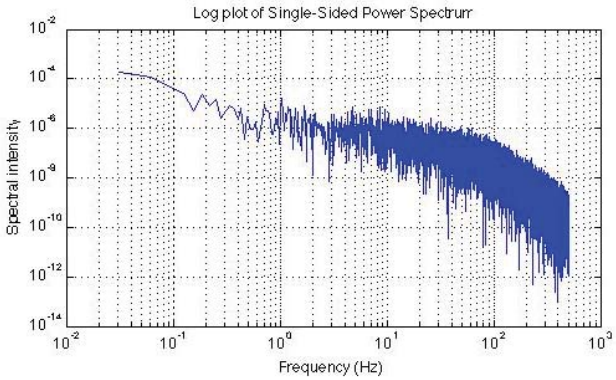
Exploiting the fluctuation in the link loss

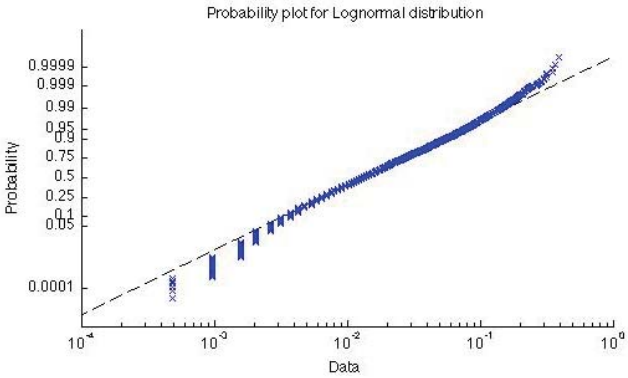
- By looking at the classical beam, the evidence of the scintillation is a series of peak
- During qubit transmission this is not evident, due to ns-scale time integration.
- Can we combine classical pulses with the Q bits?
- This requires a good synchronization in order to reject the strong flash in the SPADs
- The convolution of the scintillation with an aperture is slowing the rise and fall of the gathered beam.

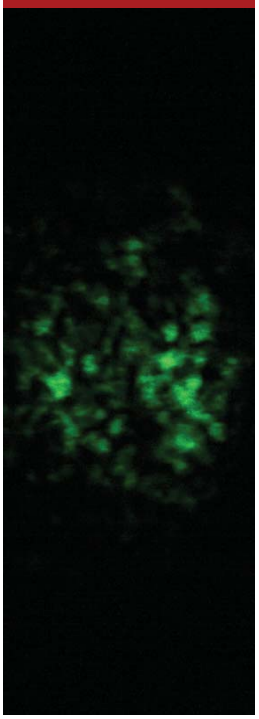
Turbulence distribution&spectrum





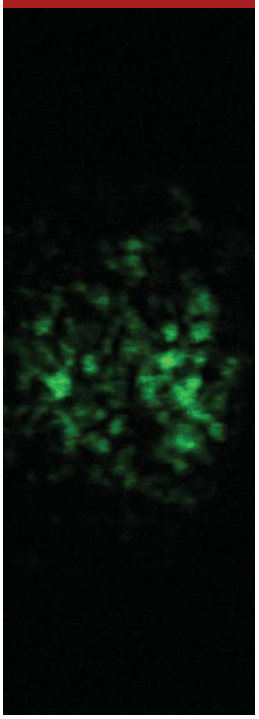






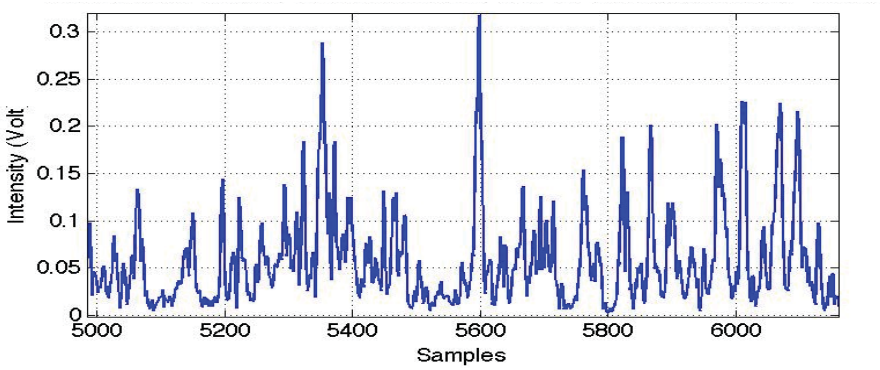
Scintillation, or bright glimpses in the dark

- With strong turbulence the distribution of the intensity is changed, from poissonian (ideally) to log-normal.
- The theoretical methods cannot describe further details.

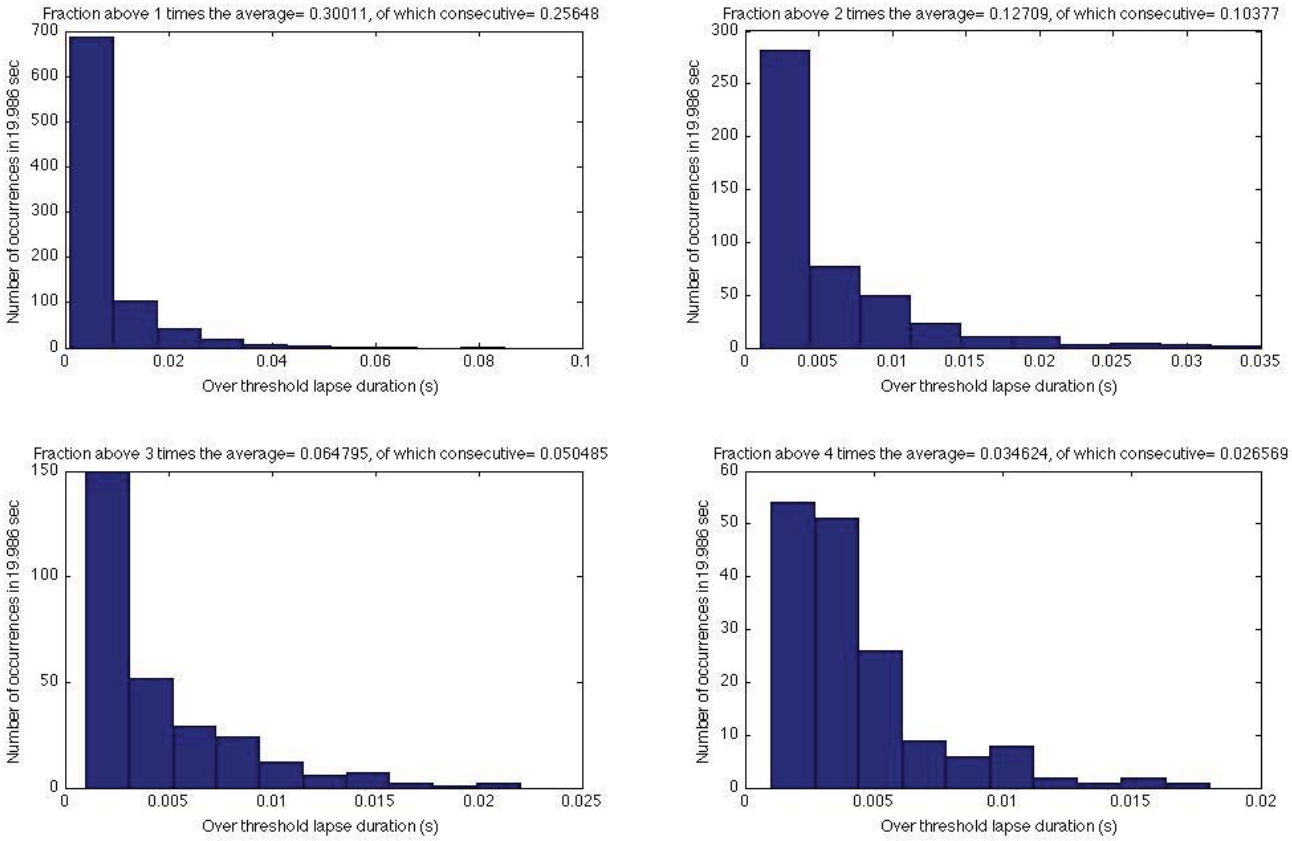


Scintillation, or bright glimpses in the dark

- In the experiment we have observed the presence of evidence of peaks that are long-lasting wrt the photon bin time.
- We computed the fraction of the link time above the average value (first moment of the phenomenological lognormal distribution)



Above-average persistence



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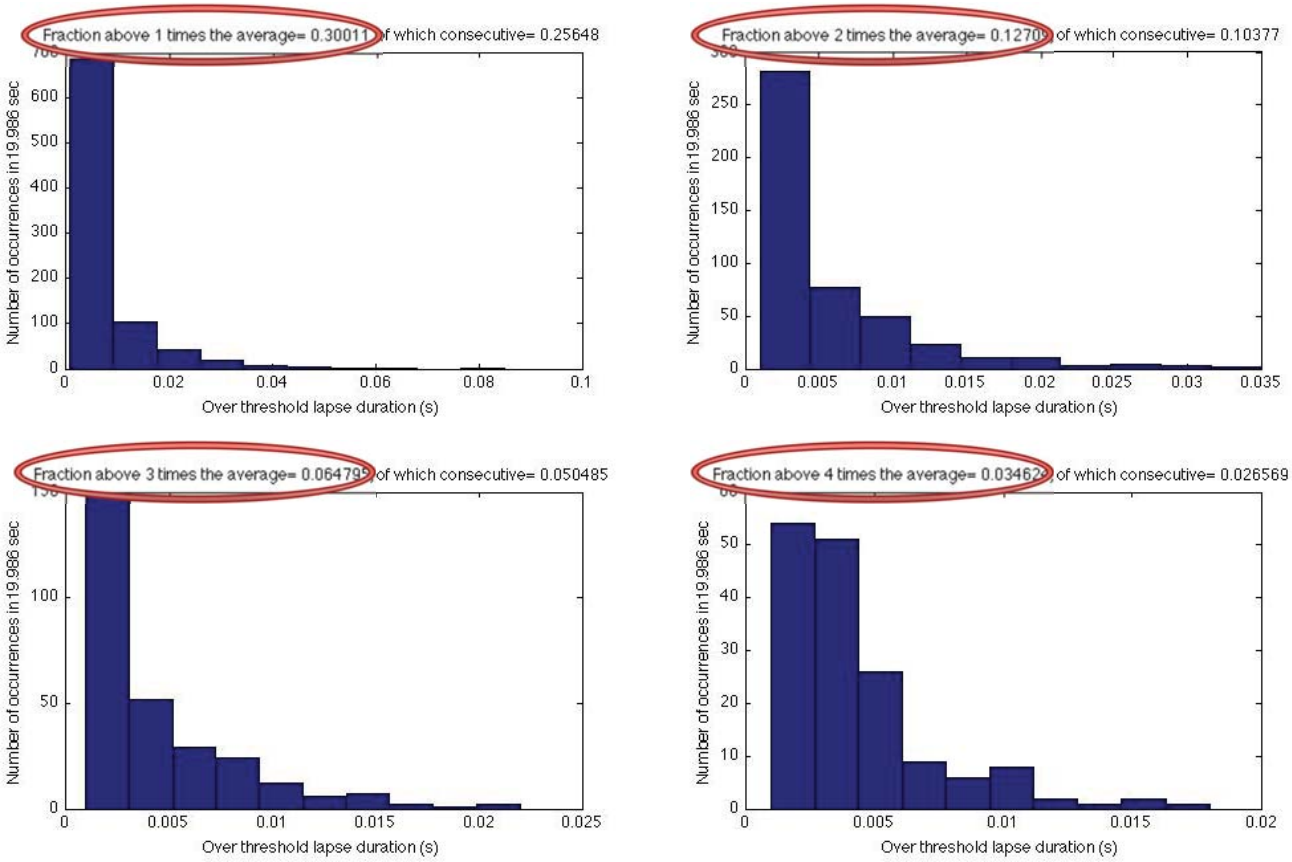
Above-average persistence



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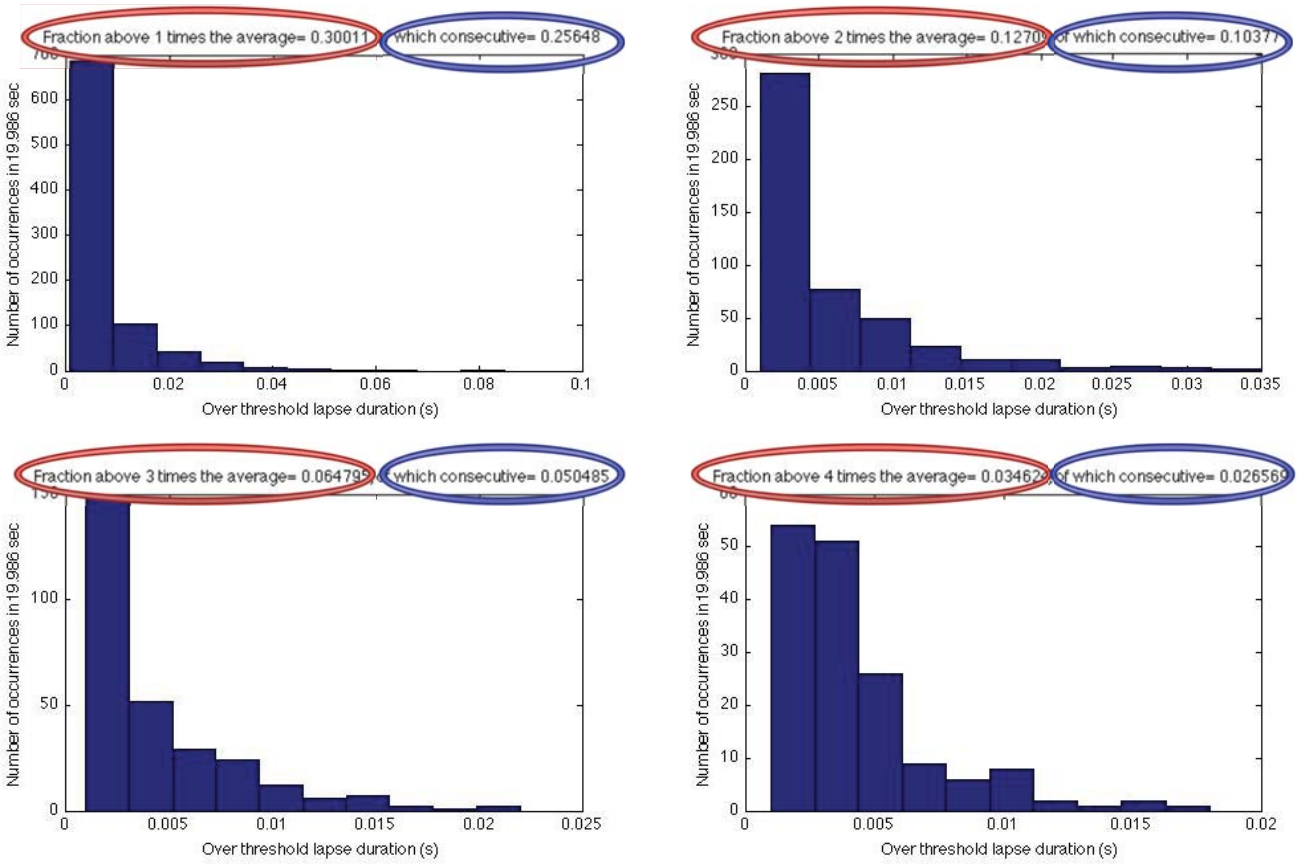
Above-average persistence



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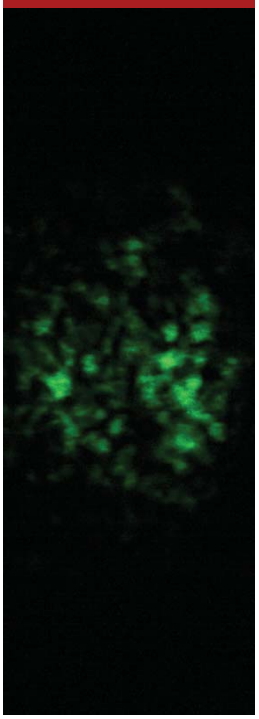
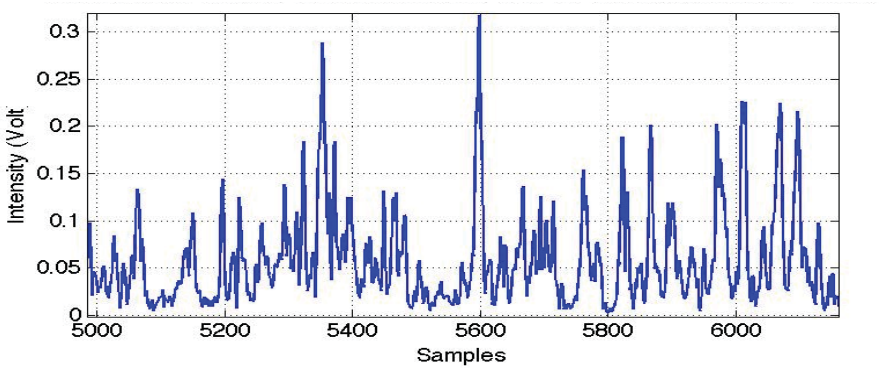


Scintillation exploitation

- This persistence may be exploited in ordet to use the channel for a fraction of time with significant lower losses.
- Experimentally, it needs a copropagating short and strong pulse.

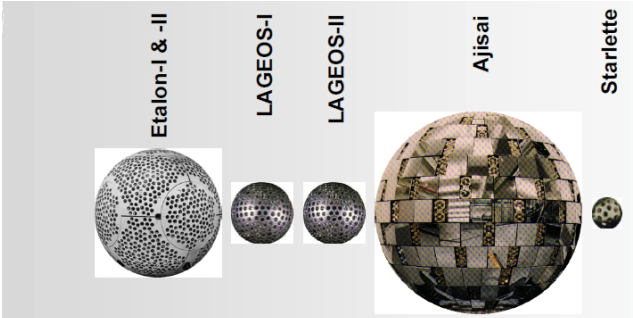


Topics of the talk

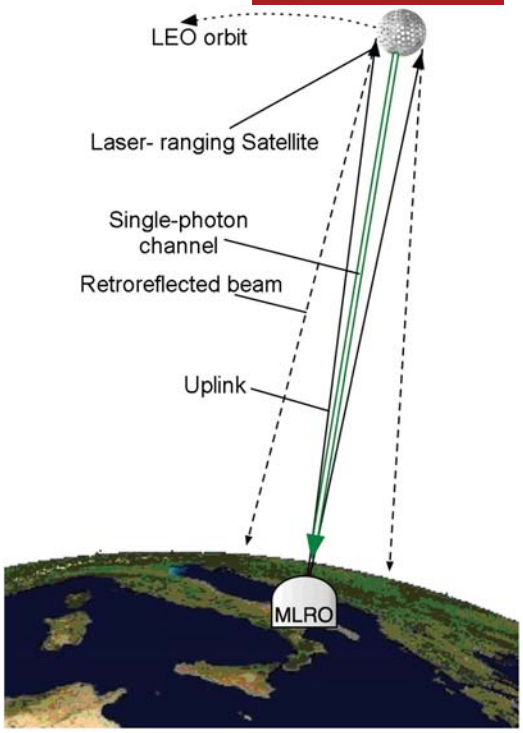
- Introduction to Space Quantum Communications (SQC) and Quantum Key Distribution (QKD) in Space
- Ground-ground exploratory links
- **Ground-Space experiments and modeling**
- Space-space link initial investigations
- Conclusions

First demonstration of single-photon exchange from a orbiting sender

- The source is realized using orbiting retroreflectors.
- These belong to the network of the geodetic satellites for Satellite-Laser-Ranging (SRL).
- A station on Earth will send the pulse up and the satellite sends it back.

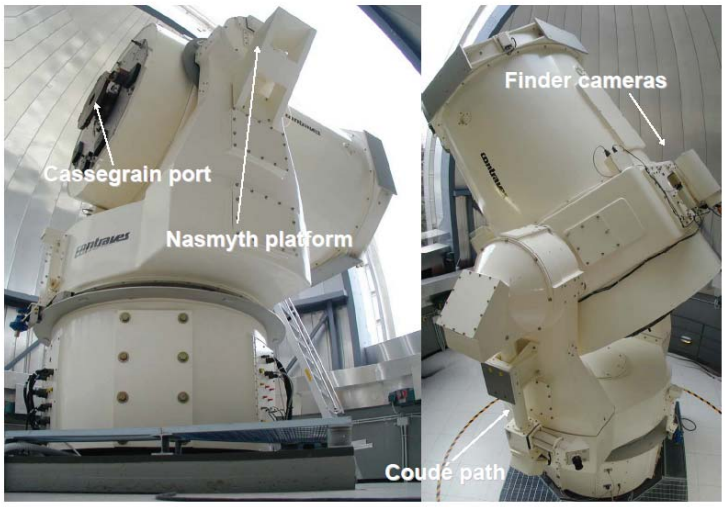


	Etalon-I & -II	LAGEOS-I	LAGEOS-II	Ajisai	Starlette
Inclination	64.8°	109.8°	52.6°	50°	50°
Altitude (km)	19,120	5,860	5,620	1,490	810
diameter (cm)	129.4	60	60	215	24
mass (kg)	1415	411	405.4	685	47.3

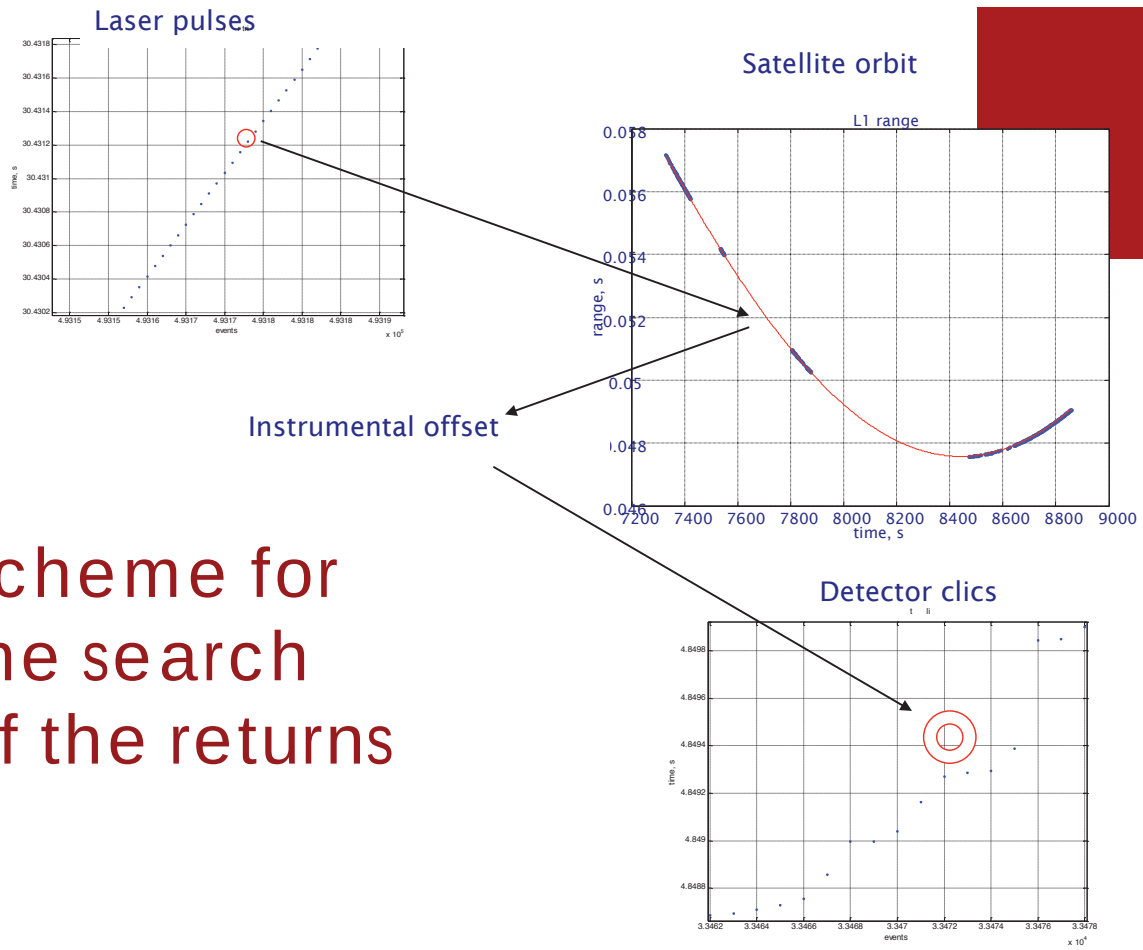


The ground station: Matera ASI-MLRO

- *Giuseppe Colombo* Space Geodesy Centre of Italian Space Agency.
- Direttore Dr. G. Bianco
- Matera Laser Ranging Observatory (MLRO).
- World highest accuracy in SLR: mm-level!

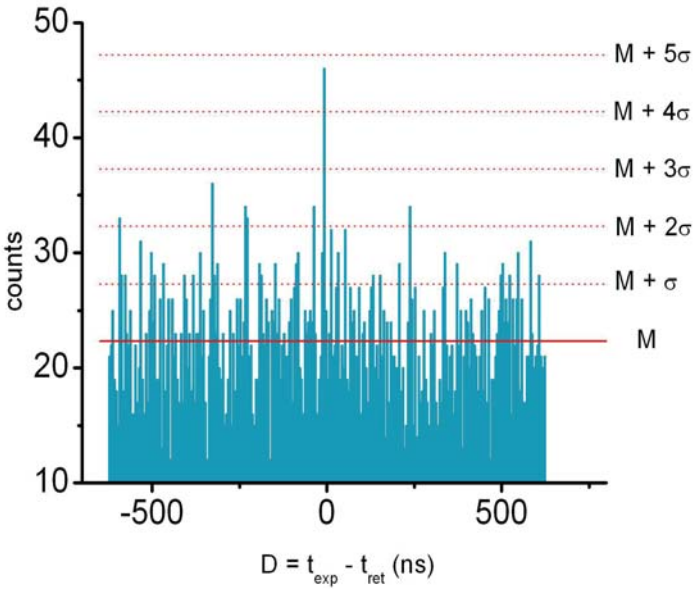


Scheme for the search of the returns



Single-photon link with Ajisai

- A peak of 5 cps was observed at D=0 above the background.
- The peak height exceeds 4 times the rms of the background.
- **Total losses are of -157 dB.**
- In the downlink channel, μ = 0.4, and **so clearly in the single-photon regime**.
- DCR = 17 kHz X p(click) 3 10-4 per pulse.
  - Integration 5 s
  - Bin-size 5 ns
  - FOV 30″
  - Filter 10 nm BW



P. Villoresi et al. New J. Phys. **10** 033038 (2008)

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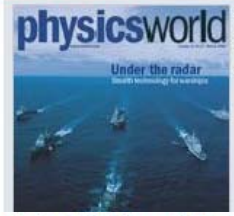

Physics World
Volume 21 No 3
March 2008

FREE OF CHARGE! MULTIPHYSICS PRESENTATIO

HEADLINE NEWS

Single photons make the trek from space

Mar 20, 2008

Quantum communications via satellite might soon be feasible

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Robotic pen guides the hand of

Satellites could keep your secrets safe in space

31 March 2008
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It is a quantum leap of sorts: wireless quantum encryption over very long distances just got a step closer.

Quantum communication relies on sending entangled photons, each carrying a bit of information. It is secure because it will be obvious if anyone intercepts the photons, since doing so will disrupt the entanglement. Safely received bits are then used as

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SECURE COMMUNICATIONS VIA SPACE

The exchange of information between distant sources is the basis of all communications, but quantum mech open up this distant exchange as never before. Quantum key distribution, for instance, would allow for absol encryption of information exchange by encoding information keys on single photons. These photons are so s that there is physically no way to undetectably tamper with them as they travel from sender to receiver. Tele quantized states is another possible application. This would allow future quantum computers to be interconn the properties of individualized photons or other quanta.

To achieve this type of technology, an exchange of single quanta between a sender and a remote receiver r Already, some companies have explored ways of achieving quantum key distribution over fiber optics, but it been done using satellites. Paolo Villoresi and his colleagues at the University of Padova in Italy, in collabor the group of Anton Zeilinger in Austria, have taken the first step to establishing quantum communications in

CLEO QELS 08

Conference on Lasers and Electro-Optics
Quantum Electronics and Laser Science Conference

Technical Conference: May 4-9, 2008
Exhibit: May 6-8, 2008
San Jose McEnery Convention Center
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cmorri@osa.org

FISICA

Crittografia quantistica

Singoli fotoni su e giù dallo spazio

L'esperimento rappresenta un passo molto importante per la crea sistema di comunicazione quantisticamente criptata a scala globa

Hanno "sparato" singoli fotoni nello spazio e per poi ricaptarli dopo che erano stati riflessi dal satellite giapponese Ajisai in orbita attorno alla Terra a 1500 chilometri di quota. L'impresa, la prima di questo genere, è stata compiuta dal gruppo di ricerca dell'Università di Pad Paolo Villoresi and Cesare Barbieri, che la illustrano in un articolo p sull'ultimo numero della rivista New Journal of Physics.

PAROLE CHIAVE

singolo fotone
crittografia qu

News

Quantum channel links Earth and spa

by Anna Canale-Parola

Cosmos Online

SYDNEY: Scientists have managed to establis 'quantum link' between the Earth and space by refle laser pulses off a satellite, a technique that might the way to quantum communication on a global scale

According to the researchers, information encrypte packages of light could one day be bounced off sate and transmitted around the world. Banks, governm and intelligence agencies would welcome this adva since quantum-encryption is a theoretically uncrack system for encoding information.

Padova SpaceQ team

Right to left: Cr. Bonato, A. Tomaello, V. Da Deppo, I. Capraro, G. Naletto, C. Barbieri, P. Villoresi

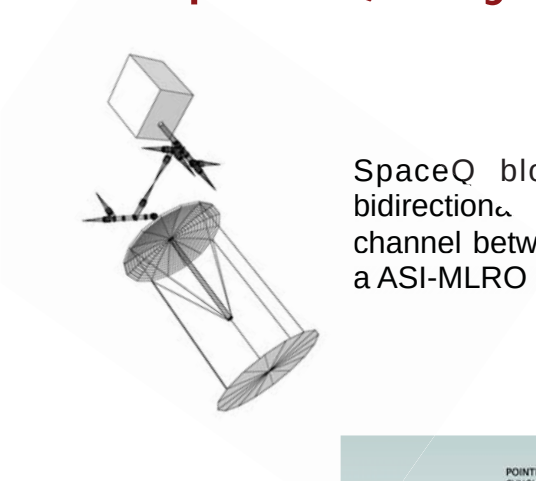
Not in the photo: G. Anzolin, T. Occhipinti, F. Tamburini

DEI, CISAS and D. Astronomy, University Padova, ITALY and INFM-CNR LUXOR

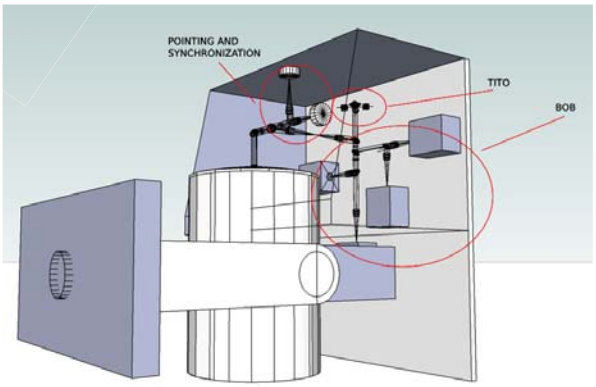
Industrial partner: Thales-Alenia Space Torino

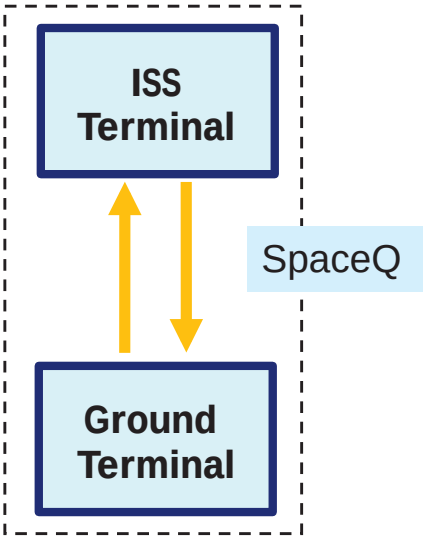
Scientific collaboration with:
IQOQI and University of Vienna, Prof. A. Zeilinger,
Center EUDOXOS (Kefallinia, Greece), Prof. N. Solomos.

Design of Quantum Space terminal: ASI SpaceQ Project – Phase A



SpaceQ blocks: to establish a bidirectional polarization quantum channel between a LEO satellite and a ASI-MLRO ground station.

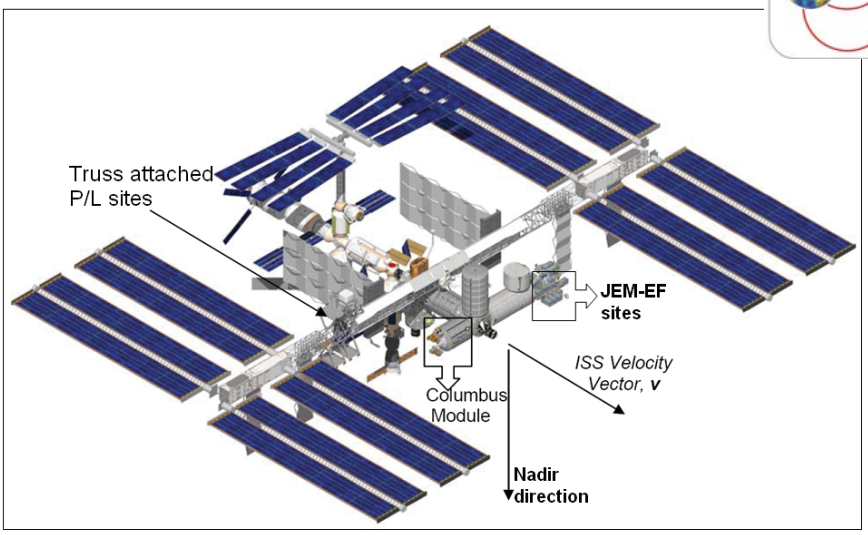




SpaceQ possible accommodations on ISS

The ISS more important provisions to accommodate P/L's are:

- 4 Express Pallet Adapters on the Columbus Exposed Facility (CEF)
- 10 Japanese Exposed Modules Exposed Facility (JEM-EF) sites.
- Cupola (for pressurised instruments).
- Nadir Research Window (for pressurised instruments)
- EXPRESS pallet
- The possible future Small Payload External Robotic Facility (SPERO)

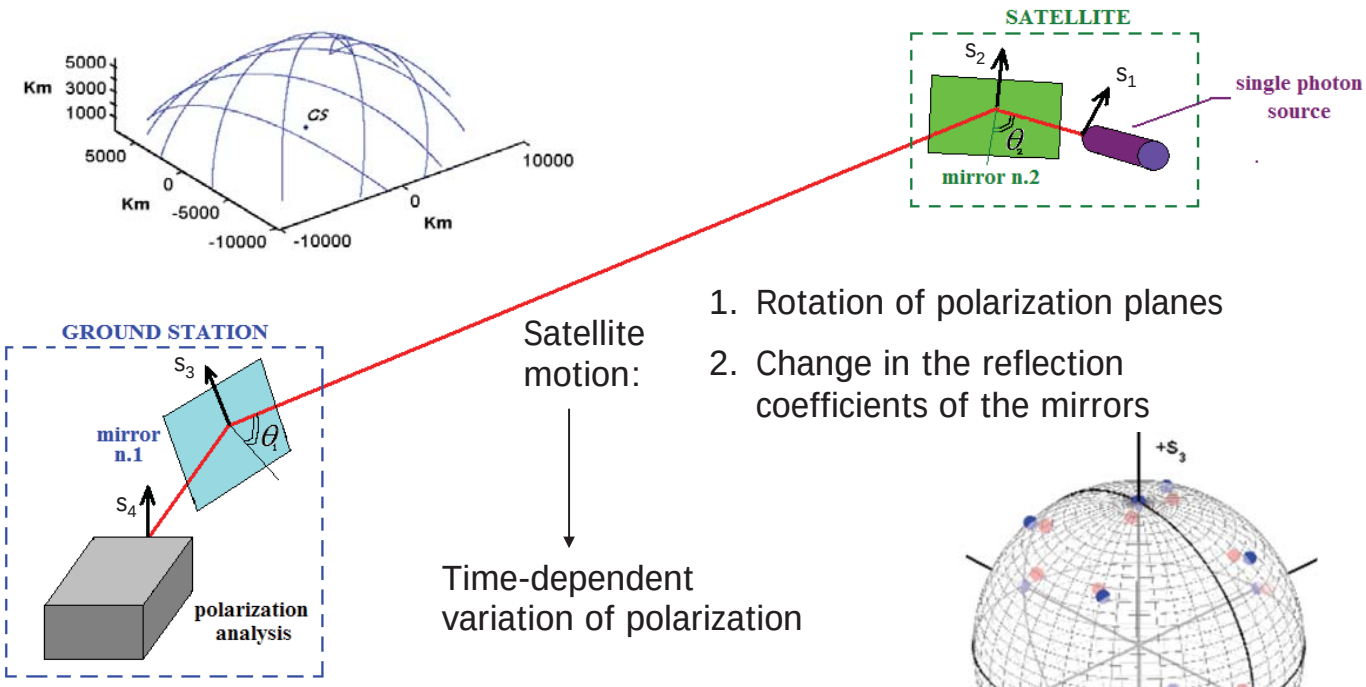


OPERATING MODE	EARTH HARDWARE INVOLVED	ON ISS HARDWARE INVOLVED
1)BB84-QKD	ROSY	TITO
2)BB84-QKD DECOY	ALICE	BOB
3)ENTANGLED BASED QKD	· E N T A N G L E D SOURCE ·ROSY	BOB
4) Q U A N T U M TELEPORTATION	TELEPORTATION MODULE	BOB

MLRO facilities and Nasmyth platform

- 1.5 meter telescope with astronomical quality optics, Cassegrain configuration f/212, long Coudé path
- ranging laser: active hybrid Nd:YAG, 40 ps pulses @ 523 nm, 100 mJ/pulse; 10 Hz repetition rate, range accuracy less than 2 mm
- the transmitted beam divergence is "diffraction limited" and can be tuned in a continuous way from around 1" to 20".
- a Hydrogen Maser atomic clock is used to synchronize all operations to better than 10 ps
- radar safety device aircraft detection

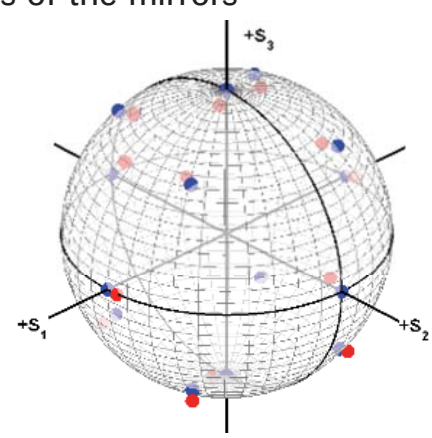
Polarization alignment with orbiting terminal
Mueller matrix for the Space channel



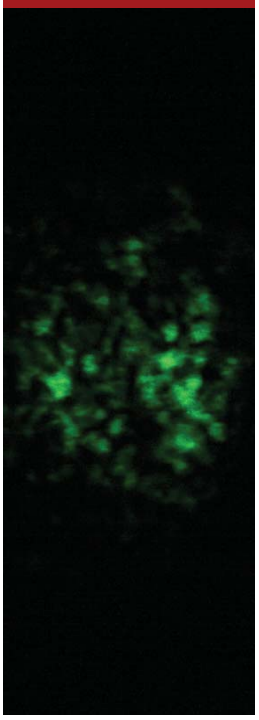
Satellite motion:

1. Rotation of polarization planes
2. Change in the reflection coefficients of the mirrors

Time-dependent variation of polarization

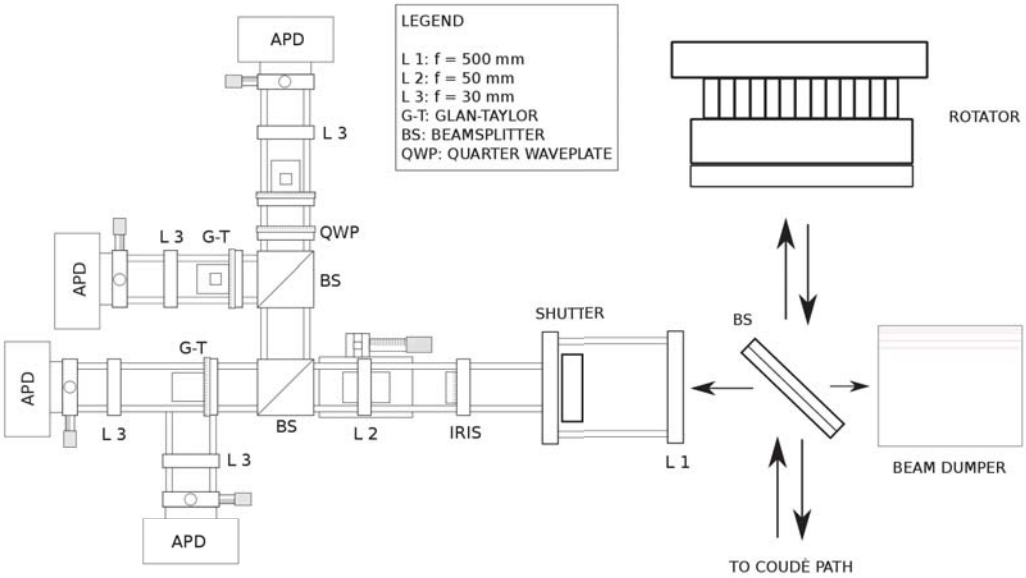


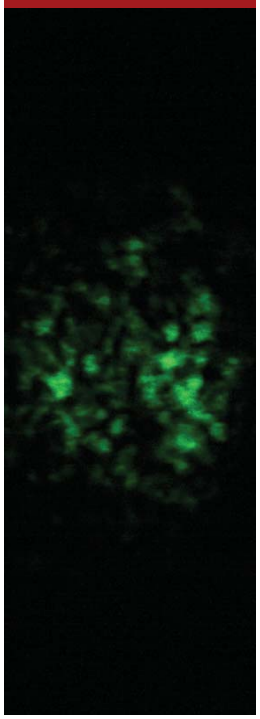
C. Bonato et al., *Influence of satellite motion in a Space-Earth quantum communication link*, Optics Express **14**, 10050-10059 (2006)



Spolar-M experiment

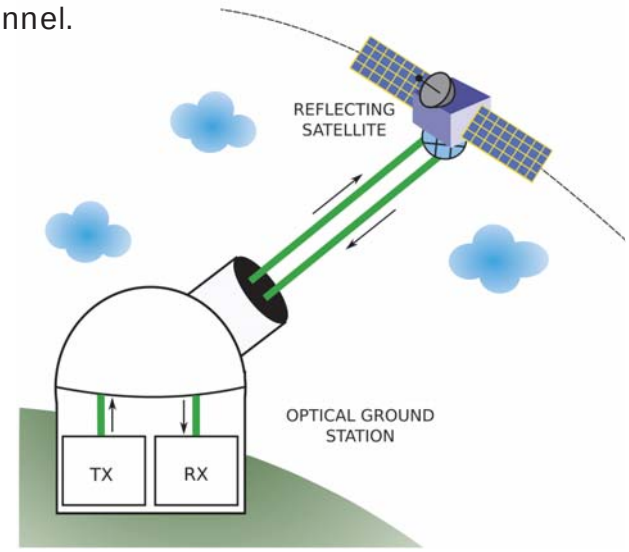
Stokes Polarimeter for the measurement of polarization changes induced in an Space to Earth Quantum Channel

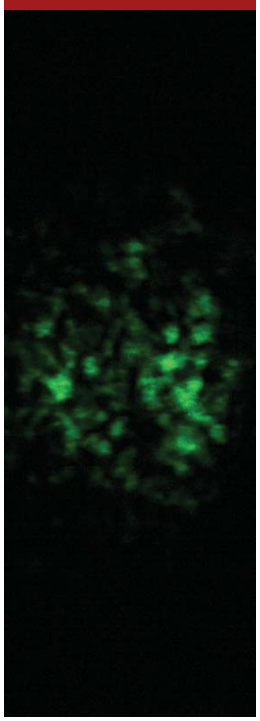




Round-trip channel analysis

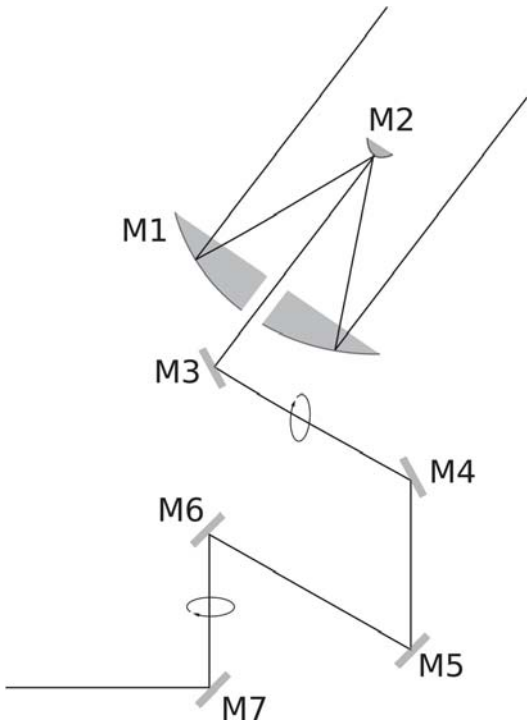
- We generate a polarization state by the use of a linear polarizer and a rotating quarter waveplate and send it through the telescope to an orbiting satellite.
- After the reflection of the corner-cube array placed on the satellite the state is collected by the telescope again and guide to the polarimeter to measure its polarization.
- Taking into account the received and the transmitted state we are able to reconstruct all the polarization changes induced by the entire channel.





Influence on the transmitted and received polarization states

Telescope rotates the incident polarization states depending on its orientation

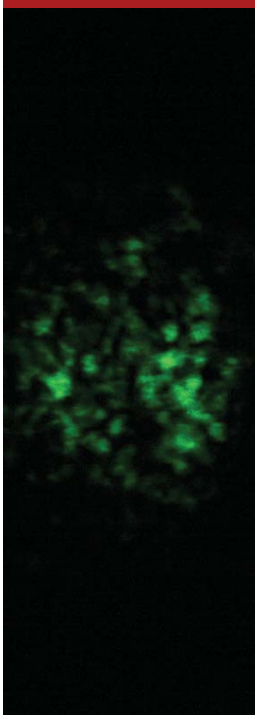


- Mirror matrix

$$M(\phi) = \begin{bmatrix} 1 & 0 \\ 0 & e^{-i\phi} \end{bmatrix}$$

- Rotation matrix

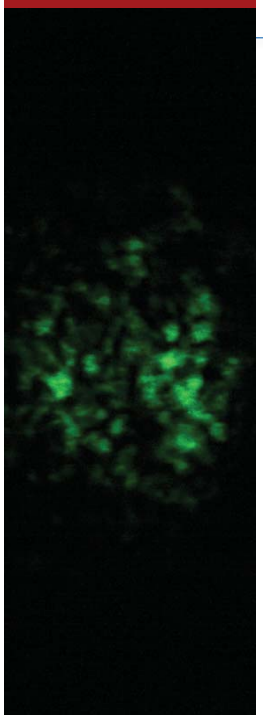
$$R(\theta) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}$$

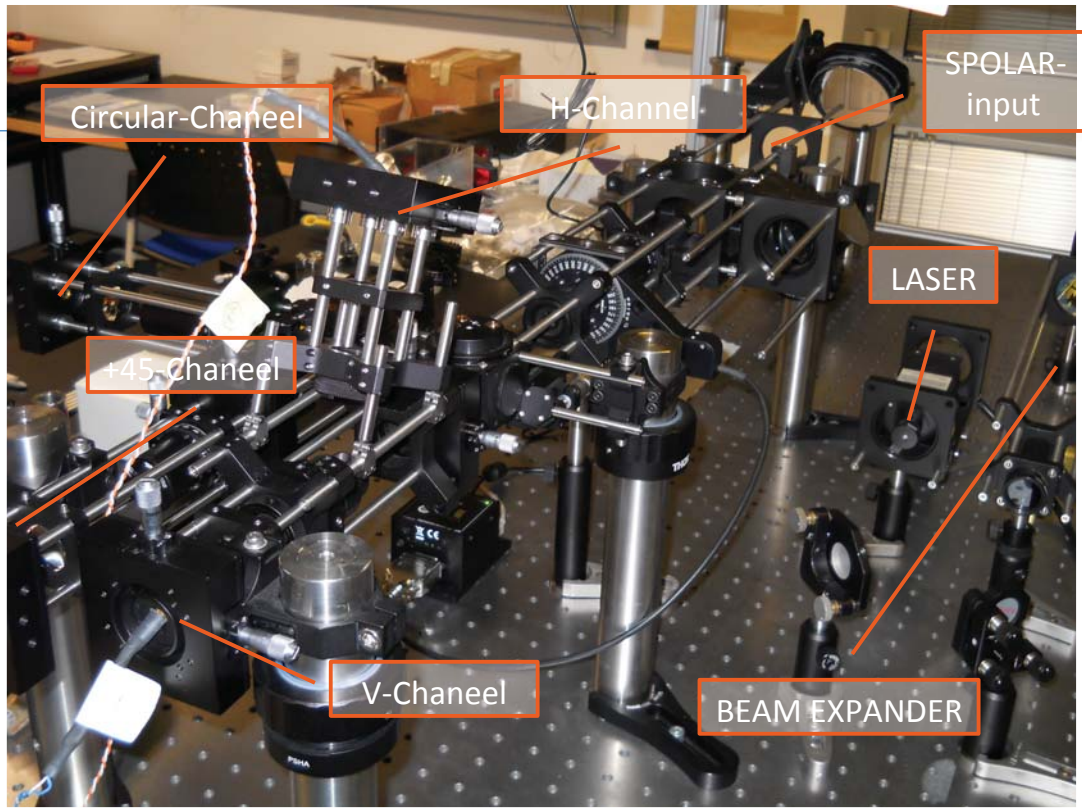


Influence on the transmitted and received polarization states

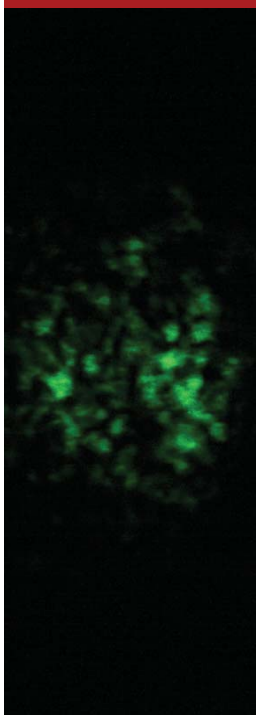
- We send a right circular polarization state back forward the telescope using a reflecting corner cube placed in the second-last mirror.
- We measured it with the Spolar-M for different position of the telescope
- What we obtained is a circular shift of the polarization state upon the Poincaré sphere.

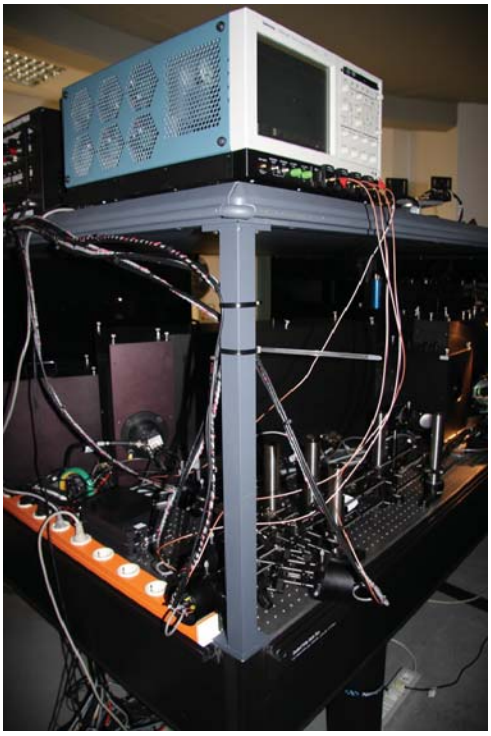
SPOLAR – M optical scheme

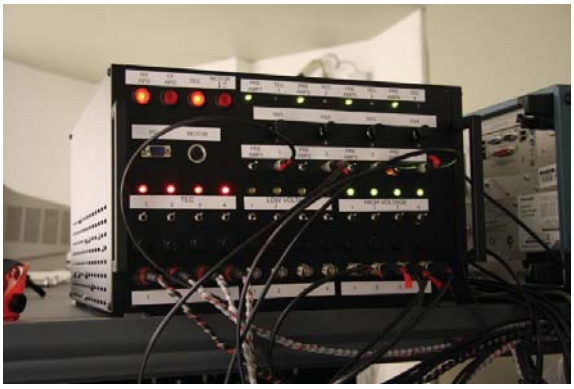


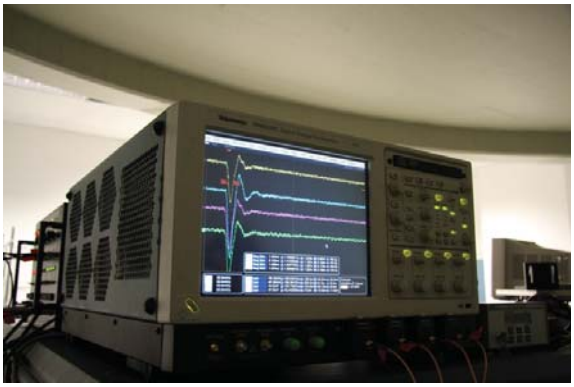


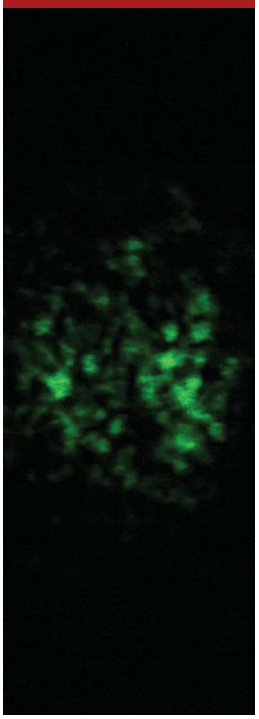
Polarimeter @ Matera



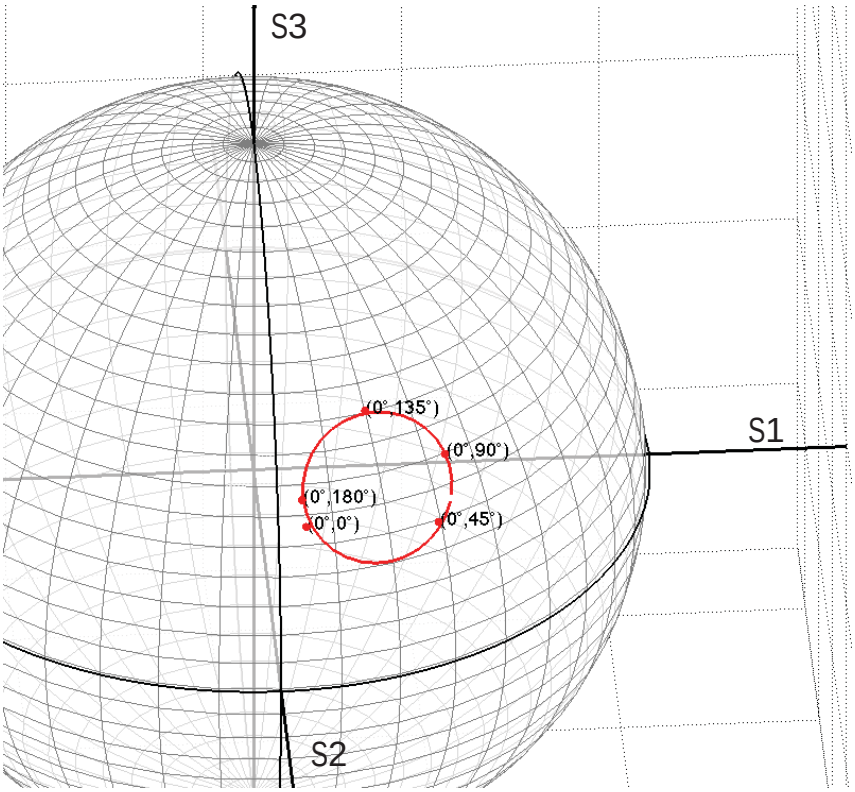








Characterization of Matera Telescope

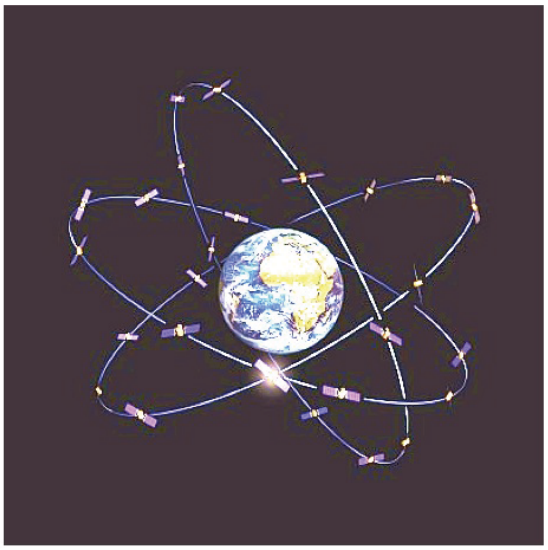


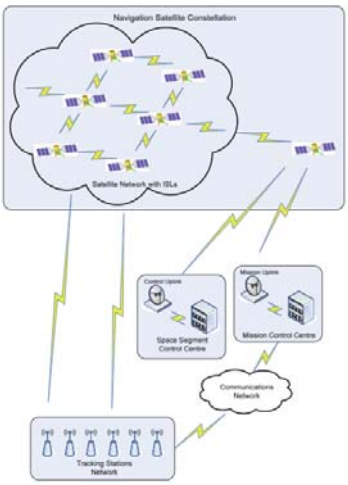
Topics of the talk

- Introduction to Space Quantum Communications (SQC) and Quantum Key Distribution (QKD) in Space
- Ground-ground exploratory links
- Ground-Space experiments and modeling
- **Space-space link initial investigations**
- Conclusions

Intersatellite Q-Comm network

- number of satellites: 27
- number of planes: 3
- number of satellites per plane: 9
- inclination: 56°
- orbit radius: 29600 km
- node spacing: 120°
- satellite minimum distance: 19000km
- satellite maximum distance: 59000km





Issues addressed:

1. Communications with very high diffraction losses
2. Synchronization of time reference.
3. QKD networking.

Possible application of the Conveyor Belt Synchronization, V. Giovannetti et al. Phys. Rev. A 70, 043808 (2004)

Intersatellite link

- **The long distances** involved and the fast relative motion **are severe constraints**, **partially compensated by the absence of beam degradation due to the propagation in the atmosphere** as well as the relatively low background noise level.
- We address the conception of the optical terminal and the predicted performances in the case of constellations of LEO and MEO satellite including the quantum communications and quantum teleportation.

Motivation

- The estimate of the value of a parameter in a microscopic system using a suitable preparation of the probe according to QM may enjoy an advancement in the accuracy of the estimate.
- **By introducing quantum strategies, the accuracy scaling law may be significantly increased to be proportional to 1/N, with an improvement of $\sqrt{N}$.**
- Due to high level of optical losses, a restricted amount of probes is expected to be available for the metrology: advantage of using QM!
- **Quantum-inspired probes** have been envisaged for applications like the dispersion cancellation using ultrashort chirped laser pulses: may also play here.

Limitations

- Standard Quantum Limit

  $Dp_0 > h/(4\pi\ Dx_0) \Rightarrow Dp_0\ (t/m)^2$ large mass

  - large satellite mass
  - Other sources or fluctuation

- Margolus-Levitin theorem: limit in the number of orthogonal states that a system may pass through in a unit time

$$v_\perp \leq \Delta E_{max}/h.$$

  - by using optical photons and with a temporal reference for the oscillator or clock accuracy of tens of picosecond, the energy per qubit is appropriate.

Synchronization of a pair of distant clocks

- In general, a nonfungible – unspeakable – operation.
- Eddington and Einstein procedures
- Valencia et al 2005 – entangled photons - second order correlation function.
- The conveyor-belt scheme proposed by the MIT group that can be considered as very attractive in the present scenario. The advantage of this technique is, as in the case of the Eddington procedure, the insensitivity on the separation of the two terminals.

  V. Giovannetti, S. Lloyd, L. Maccone, J. H. Shapiro, and F. N. C. Wong, "Conveyor-belt clock synchronization," Phys. Rev. A **70** 043808 (2004).

Attenuation without turbulence

- Example: portrait of Prof. Planck with dim illumination - from the Saleh-Teich book

Link model

- In an intrasatellite quantum link the communication scheme can be essentially simplified in a vacuum optical link: between a transmitter and a receiver hosted into satellites.
- The propagation of a Gaussian beam in vacuum has minimum divergence θ wrt beam waist w_0

$$\theta \simeq \frac{\lambda}{\pi w_0}$$

Attenuation in vacuum

- The propagation equation for a Gaussian beam in vacuum enjoy the absence of the broadening effects due to atmosphere

$$w_{LT}^2 = w_0^2 \left(1 + \frac{L^2}{Z_0^2}\right) \qquad Z_0 = \frac{\pi w_0^2}{\lambda}$$

- L is the propagation (link) distance, leads us to the estimation of the power P collected by a receiver of radius R:

$$P = 2\pi I_0 \int_0^R \rho e^{-2(\rho^2/w_{LT}^2)} d\rho$$

Attenuation in vacuum

- To get a quantitative idea of the link energy-transfer we introduce η, defined as the ratio between the transmitted over received energy as:

$$\eta = \eta_0 \left(1 - e^{-2R^2/w_{LT}^2}\right)$$

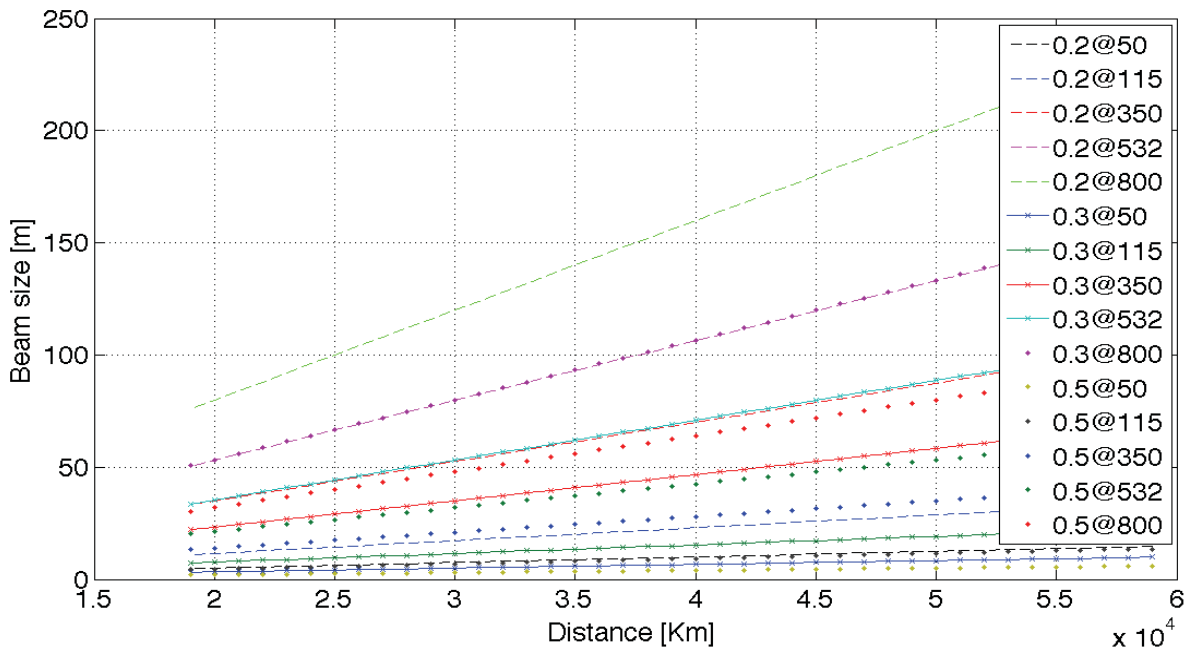
- In a real scenario we have to consider all the involved non-idealities: such as the optical efficiency and the pointing losses.
- All these unwanted quantities are combined in the factor η_0, set to 0.1 in our simulations.

W_0 *vs.* D criterias

- We have also to consider that to achieve a beam waist of w_0 as expressed above, the effective telescope diameter D has to be significantly larger.
- However, the most effective criteria is maximum on-axis irradiance, introduced in the Prof. Siegman book (Ch. 18), with the waist-to-aperture-radius rate at 0.89, while the optimal ratio for reducing tail clipping require a waist-to-aperture-radius rate of $\pi/2$.

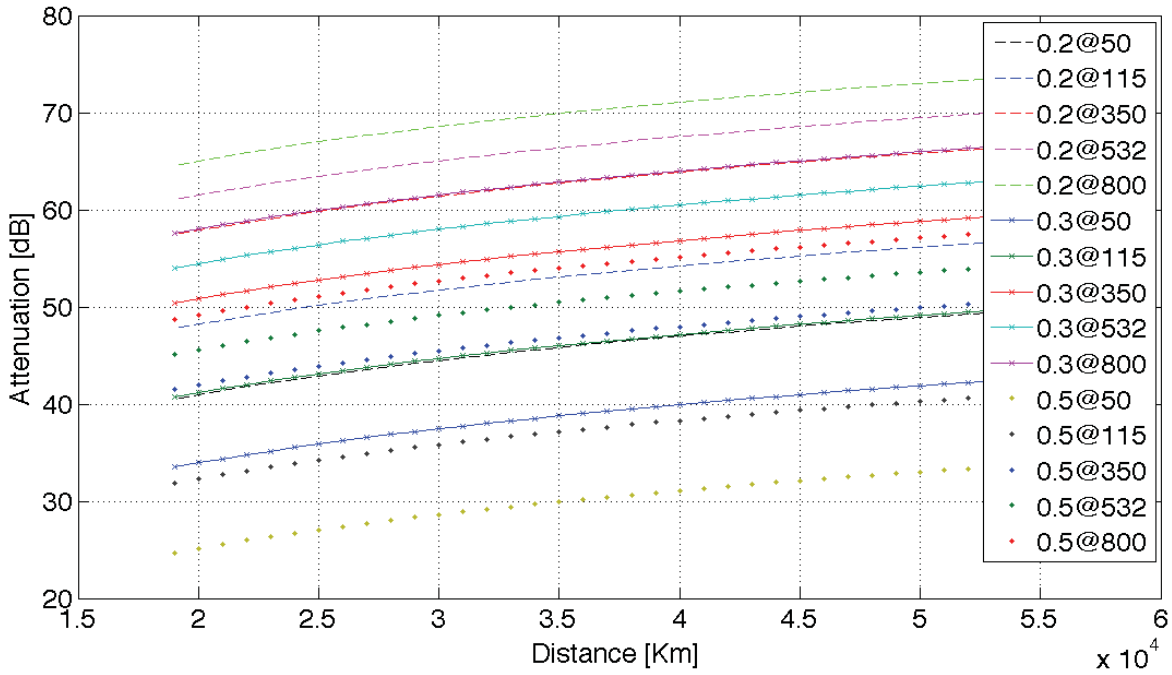
Beam Size for different transmitter diameters

- Link lengths from Low Earth Orbit (LEO) to Medium Earth Orbit (MEO) satellites.



Attenuation results
20, 30 and 50 cm collectors

- Link lengths from Low Earth Orbit (LEO) to Medium Earth Orbit (MEO) satellites.



Signal to noise ratio

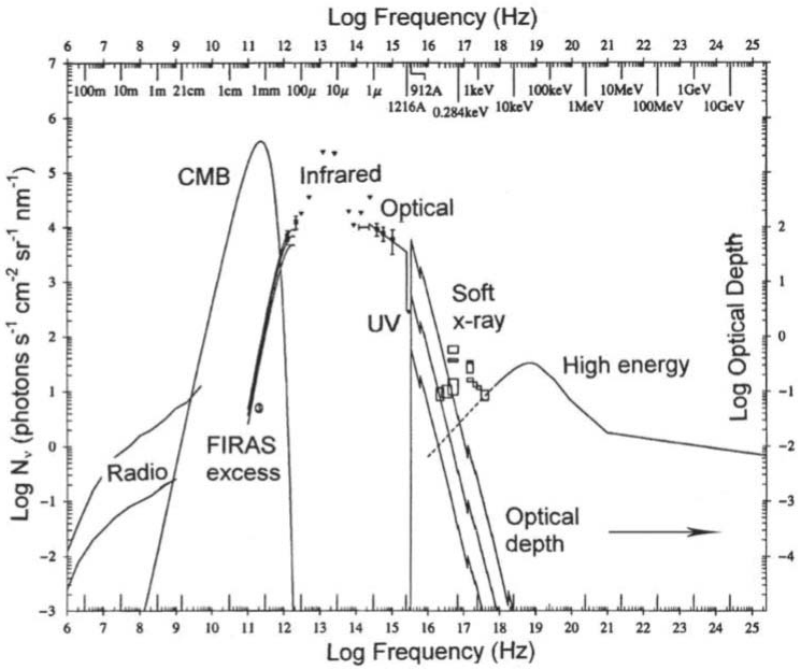
- To communicate with single photons the receiver must be able to distinguish between signal photons and noise photons

$$SNR = \frac{\eta}{\epsilon_N}$$

- The number of noise photons ε_N of an optical quantum receiver with field of view Ω_{fov} and that aims a satellite **that in the background has a portion of space**, by taking a detection time Δt and a bandwidth $\Delta \lambda$, is

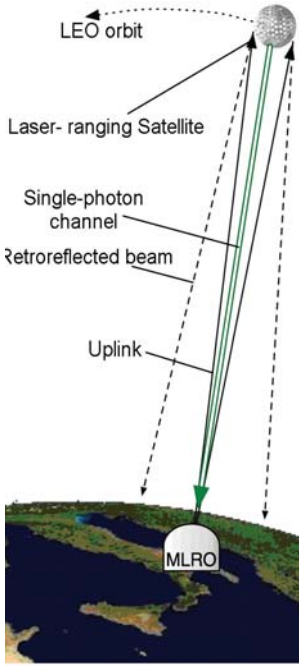
$$\epsilon_N = H_b \Omega_{fov} \pi R^2 \Delta\lambda \Delta t$$

Background signal: cosmic radiation



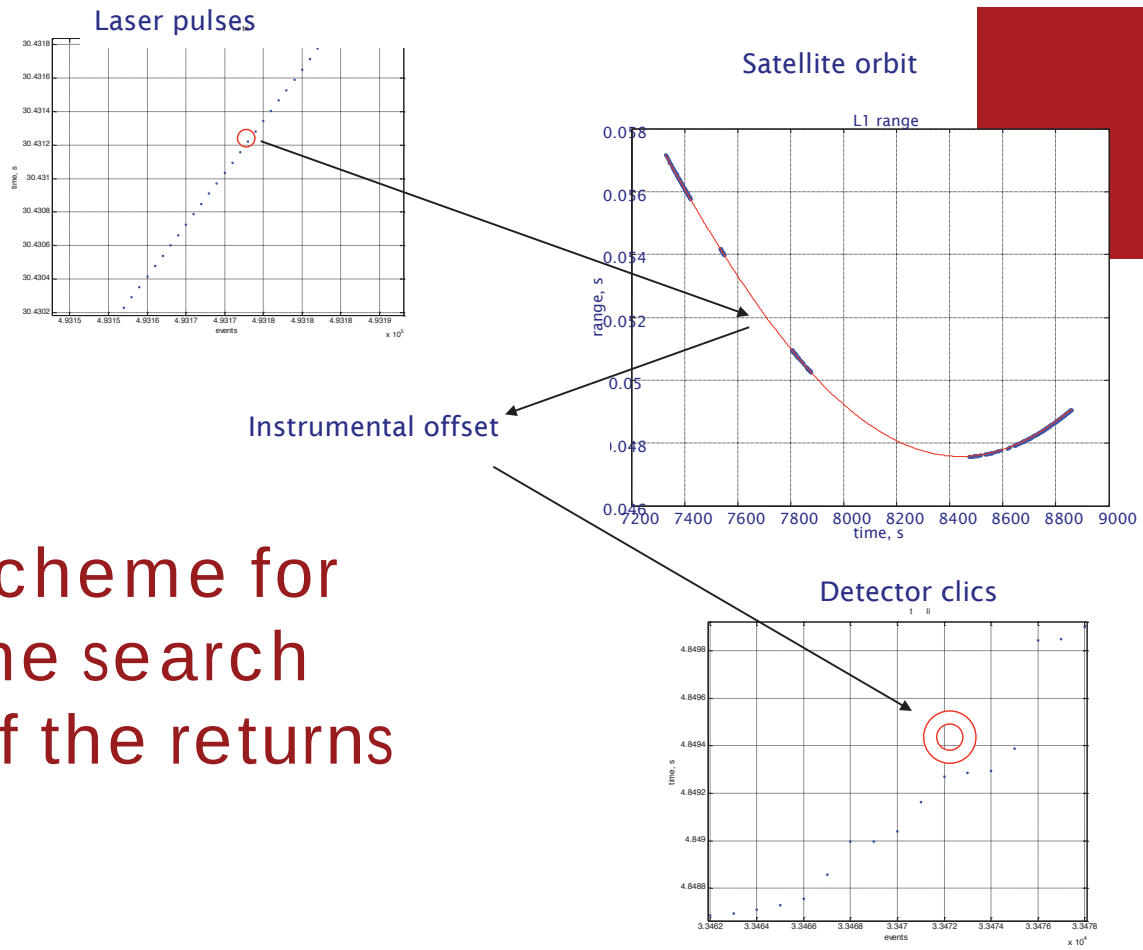
M. V. Zombeck, Handbook of Space Astronomy and Astrophysics, Cambridge University Press, 3rd ed., 2006.

Synchronization issues in orbit



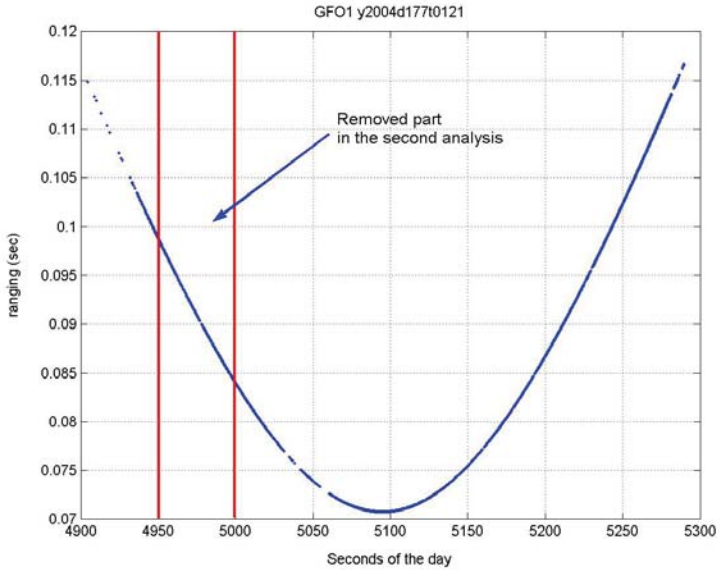
- QComm requires to point out the instant of measure – about 1 ns or less.
- The satellites are rapidly moving.
- the Earth gravitational field is influencing the orbit at the level of tens of meters or more.

Scheme for the search of the returns



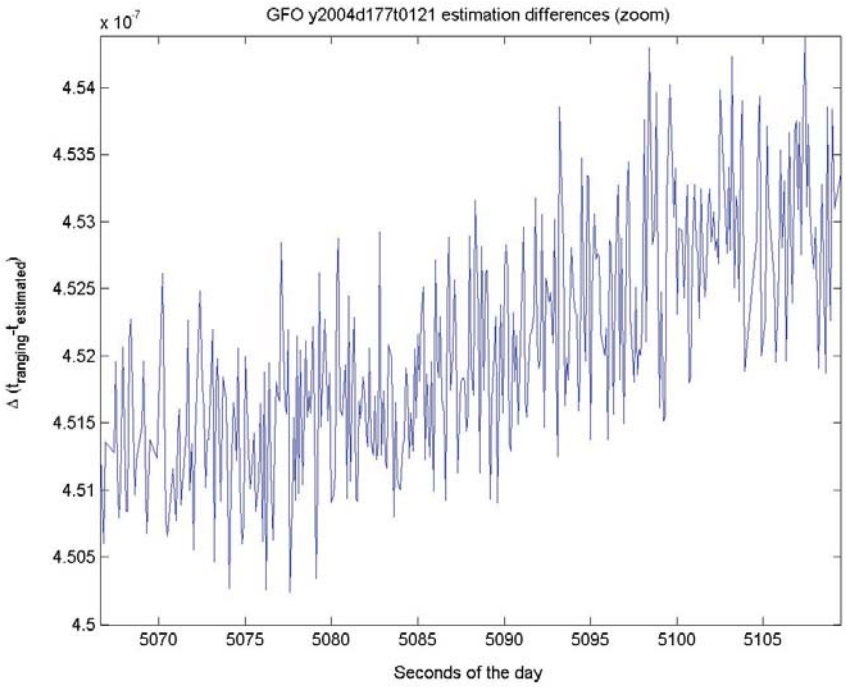
the GFO orbital data y2004d177t0121

- The full orbit have a “best fit” polynomial interpolation of degree 67

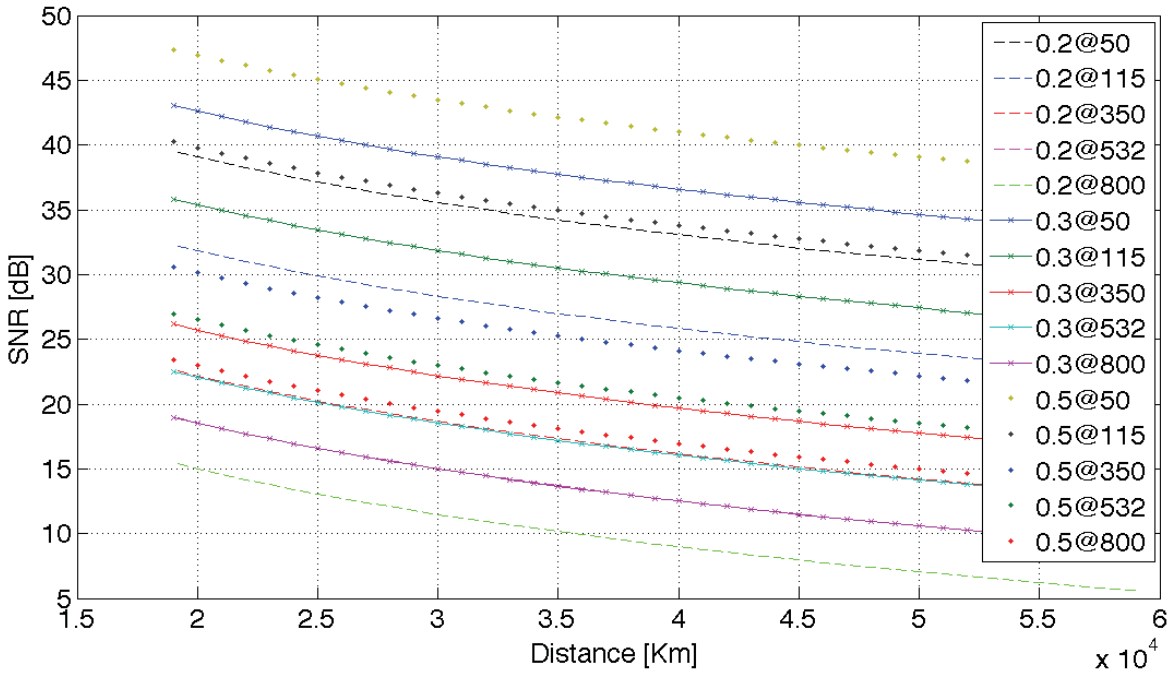


the GFO orbital data y2004d177t0121

Hundreds of ns of offset: need of a multipole model

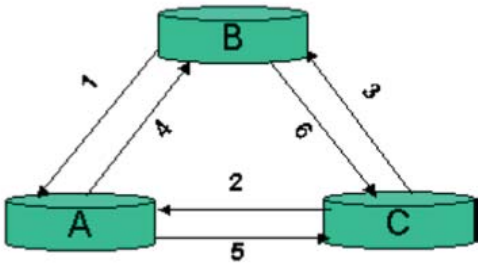


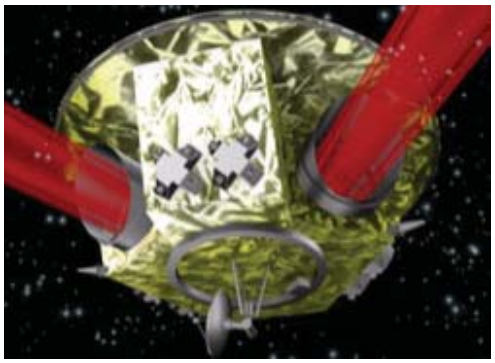
SNR for the two diameters



Very accurate pointing has been conceived already

- LISA: Laser Interferometer Space Antenna mission is a planned gravitational wave detector consisting of three spacecraft in heliocentric orbit.
- Aims to measure distance fluctuations between test masses aboard each spacecraft to the picometre level over a 5 million km separation.





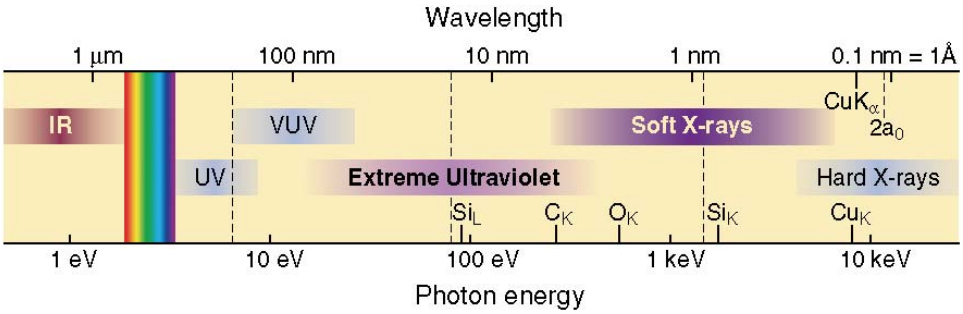
A big drawback: it uses a strong coherent beam

- For QComm we need to reduce the attenuation, as the signal is a single photon.

- Shrink the wavelength to reduce diffraction?

The outer space is, indeed, vacuum

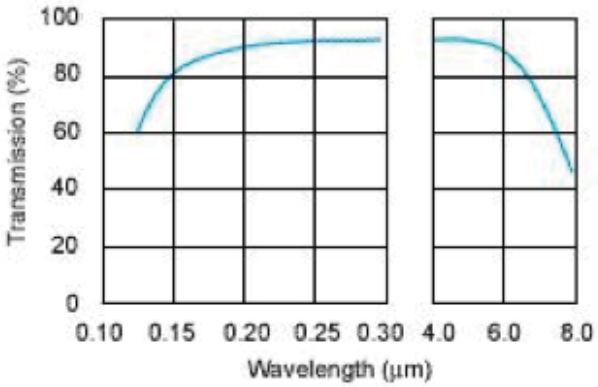
- Vacuum ultraviolet Astronomy is a mature space subject.



- See smaller features
- Write smaller patterns
- Elemental and chemical sensitivity

Up to 120 nm, transmission optics is available

- Single photon detector are available.
- Magnesium fluoride allows to make lenses and polarizers



Topics of the talk

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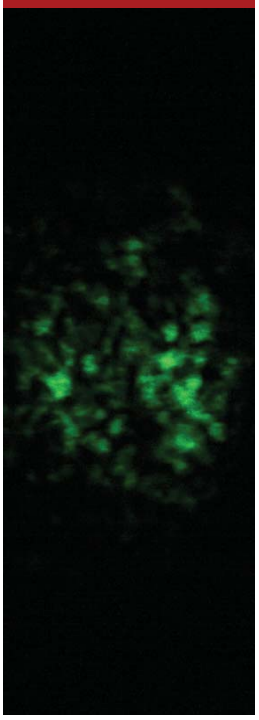
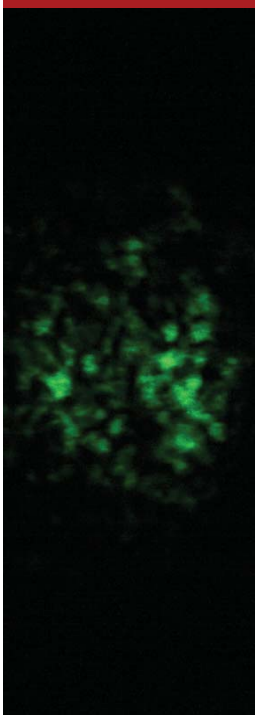
- Ground-Space experiments and modeling
- Space-space link initial investigations
- **Conclusions**



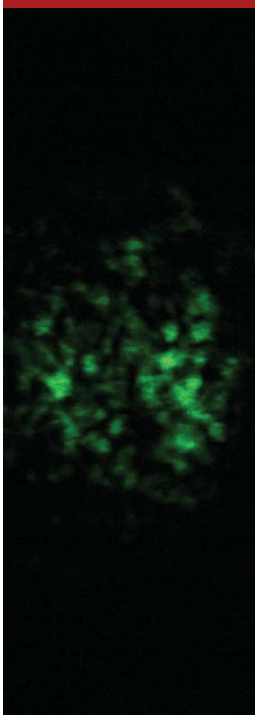
Conclusions on ground-ground links (G-G)

- Advanced and dedicated Optics is necessary for long distance Qcomm.
- Turbulence modifies significantly the beam properties and statistics. Eg. 3x diffraction.
- The Experiments show features not predicted that a suitable to be exploited.
- Quantum beam guiding is feasible even to ultimate distances.



Conclusions on ground-ground-Space Links

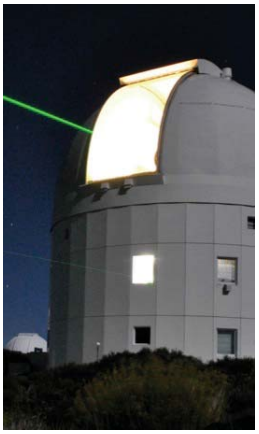
- The single photon link has been explored.
- The present technologies are mature enough.
- Polarization encoding protocols: space link telescope under characterization.



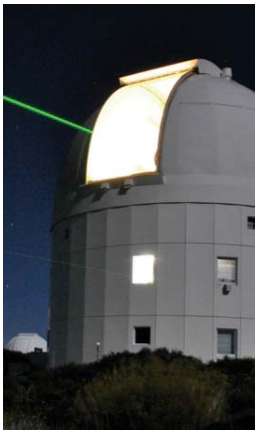
Conclusions on intersatellite networks

- Challenging scenario: more losses&no turbolence.
- Short wavelength accessible, with promising scaling.
- Novel quantum techniques und study.

Perspectives: G-G



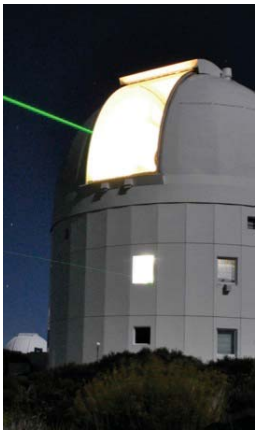
- To extend the QKD protocols to exploit the channel specific features.



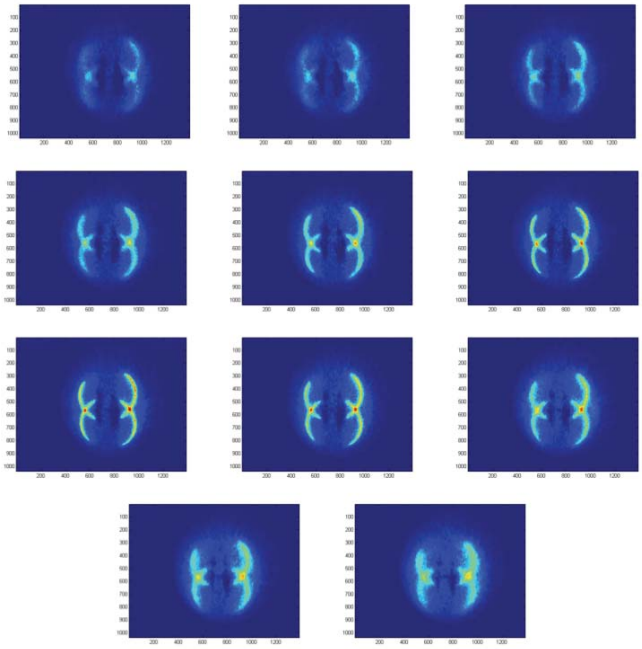
Perspectives: G-G

- To extend the QKD protocols to exploit the channel specific features.
- To investigate the control on the propagation of quantum correlation.

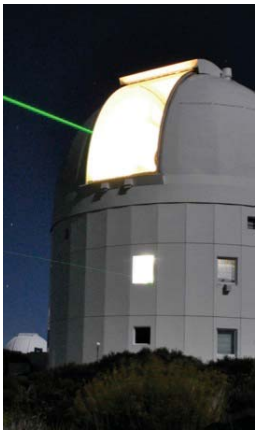
Perspectives: G-G



- To investigate the control on the propagation of quantum correlation.
- Adaptive control of bi-photon wavefront.
- Collaboration with IQC, Prof. Jennewein.
- Recent visit in Padova of Chris Pugh.
- Welcome further strengthening with IQC.

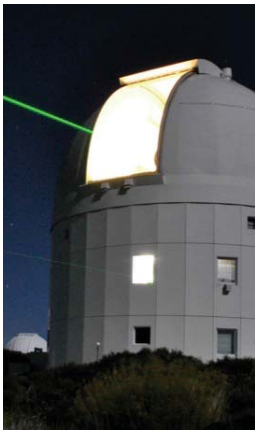


Perspectives: G-G



- To extend the QKD protocols to exploit the channel specific features.
- To investigate the control on the propagation of quantum correlation.
- “Exploitation” of turbulence.

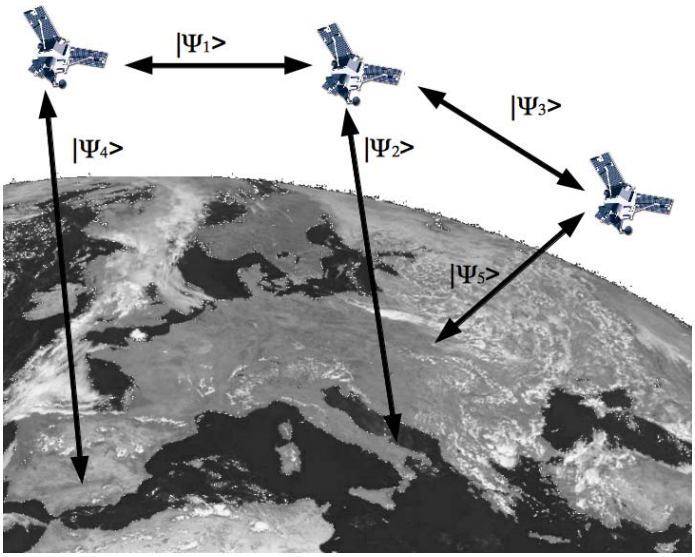
Perspectives: G-Space



- To extend the characterization of the Mueller matrix of a Space-to-Ground channel.
- To implement a QKD protocol along space channel.
- Fostering the international collaboration.

Perspectives: Intersatellite Quantum links

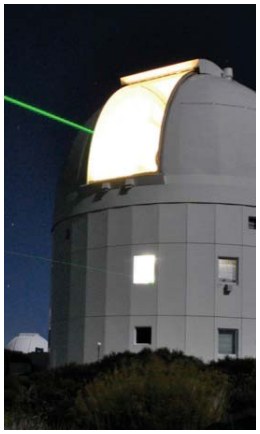
- ESA study under way to envisage the quantum resources to exploit in the intersat single photon channels.
- To investigate the ultraviolet extension of the quantum communications.
- Searching for the promising Quantum protocols, other than QKD, in this new scenario.



Projects and collaborations

- Funds form:
  - University of Padova: progetti di ricerca di Ateneo
    - 2004-2007, 2009-2011
  - Fondazione CARIPARO – 2004-2007
  - Agenzia Spaziale Italiana – 2008-2009
  - Consortium Galileo satellite network 2007-2008
  - University of Padova – Progetti Stategici 2009-2012
  - ESA – Intersatellite quantum network 2011/2013
- Main collaborations
  - Italian Space Agency - ASI – Matera
  - Austrian Academy of Science
  - NICT – Tokyo Japan
  - ICFO - Institut de Ciències Fotòniques – Barcelona
  - Boston University

Padova QuantumFuture Collaboration



Interdisciplinary research group – UniPD 2009-2013

- Quantum and Classical Optics (6)
- Quantum communications engineering (4)
- Quantum Control theory(2)
- Quantum Astronomy(3)
- 10 PhD stud. + PDoc.

QComm: not limits but horizons