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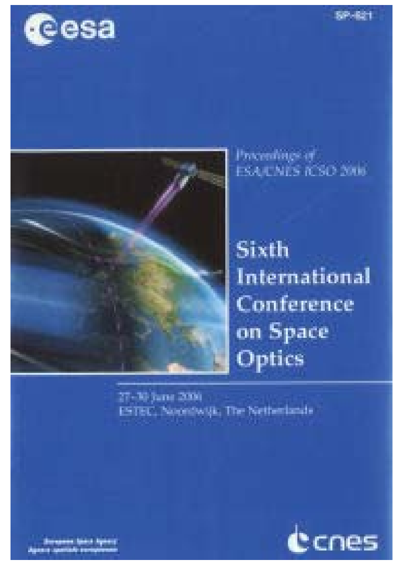


## *LOLA: a 40.000 km optical link between an aircraft and a geostationary satellite*

*Vincent Cazaubiel, Gilles Planche, Vincent Chorvalli,*
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# LOLA: A 40.000 KM OPTICAL LINK BETWEEN AN AIRCRAFT AND A GEOSTATIONARY SATELLITE

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## ABSTRACT

The LOLA program aims at characterising a 40.000 km optical link through the atmosphere between a high altitude aircraft and a geostationary platform. It opens a new area in the field of optical communications with moving platforms. A complete new optical terminal has been designed and manufactured for this program. The optical terminal architecture includes a specific pointing subsystem to acquire and stabilize the line of sight despite the induced vibrations from the aircraft and the moving pattern from the received laser signal. The optical configuration features a silicon carbide telescope and optical bench to ensure a high thermoelastic angular stability between receive and transmit beams. The communications subsystem includes fibered laser diodes developed in Europe and high performance avalanche photo detectors. Specific encoding patterns are used to maintain the performance of the link despite potential strong fading of the signal. A specific optical link model through the atmosphere has been developed and has been validated thanks to the optical link measurements performed between ARTEMIS and the Optical Ground Station located in the Canarian islands. This model will be used during the flight tests campaign that is to start this summer.

## 1. INTRODUCTION

In Europe, the in-orbit success of the SILEX (Satellite Interlink EXperiment) program has demonstrated the feasibility to establish long distance optical links between a LEO remote sensing satellite, namely SPOT4 and a GEO relay spacecraft ARTEMIS. Urgent images taken far away from Europe can be sent in real time to processing centres.

Europe has continued to invest in optical communication technologies. The European Space Agency has promoted several Optical Intersatellite Link technology developments. The DLR is funding the LCT program (Laser Communication Terminal) to be flown on board the Terrasar satellite. The European Community is supporting the Campanina project to develop High Altitude Platforms inter-connected with optical links.

End 2003, the decision of the French MOD to initiate the LOLA program opens new perspectives for free space optical communications through the atmosphere. Flight tests are about to start.

## 2. LOLA PROGRAMME OBJECTIVES

LOLA stands for Liaison Optique Laser Aéroportée (Airborne Atmospheric Laser Link). The main objective of this prospective program is to characterise the performance of an optical link between an airborne demonstrator and the ARTEMIS geostationary existing spacecraft (cf. fig.1.) Some specificities of the aircraft environment and of the atmosphere are a clear challenge for the establishment of the link. The airborne dynamic perturbations are about ten times more stringent than on a satellite. The atmosphere affects significantly the propagation of the light not only in terms of transmission but also in terms of direction of propagation and wavefront error of the beam.

The ultimate goal of this programme is not only to demonstrate the feasibility of such links but also to determine its operational availability for unmanned aerial vehicles or high altitude platforms.

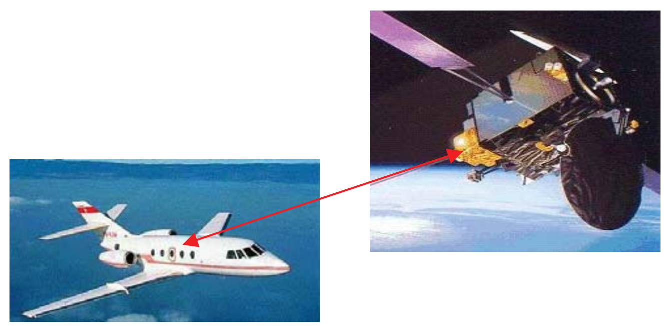

Fig.1. The LOLA bi-directional link.

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## 3. LOLA OPTICAL TERMINAL ARCHITECTURE

The LOLA optical terminal features an aerial part and deported communication and control electronics
The aerial part includes a coudé telescope mounted on top of a bi-axis wide angular mechanism and a focal plane that combines the optical receive and transmit paths. The receive beam is split between the acquisition & tracking path and the communication receive channel. An inertial measurement unit provides the reference axes during the open loop phase(Cf. Fig.2)
The laser Rx and Tx communication electronics modulates the laser diode with the 50 Mbits/s transmit digital signal and demodulates the 2 Mbits/s receive optical signal .
The terminal control electronics ensures the management of the Pointing Acquisition and Tracking sub-system.
Various metrology equipment ensure the proper monitoring of the environment as well as the performance of the terminal ( TEB, timings…).
Requirements & expected performance are provided Fig.3 and Fig.4.)

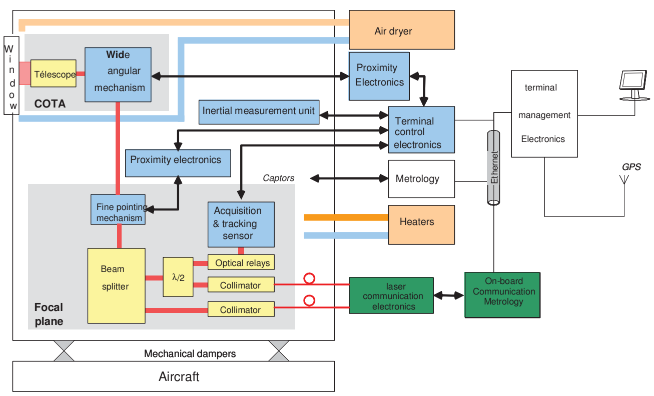


Fig. 2 :.LOLA functional diagram.

| Parameter | Spec | Typical performance | performance |
|---|---|---|---|
| Rallying duration | 30 s | 10 s | |
| Detection, centring, tracking convergence duration | 0,3 s | 0,28 s | |
| Probability of success of acquisition | 0,97 | 0,99 | |
| Power at Window output | [80 – 116] mW | 104 mW | |
| Waist diameter | 73 mm | 73 mm | |
| WFE at emission | λ/10 rms | λ/16,7 rms | |
| Pointing error in beacon tracking | 3,5 µrad | 1,6 µrad | |
| Pointing error in communication tracking | 2,5 µrad | 1,5 µrad | |
| Polarisation ratio | 5 % | 4 % | |
| Wavelength | [843-852] nm | 848 nm | |
| WFE at reception | λ/8 rms | λ/10 rms | |
| Communication performance | See figure | | |
| Synchronisation duration | 1ms | 1ms | |

Fig .3 : Optical terminal requirements and performance

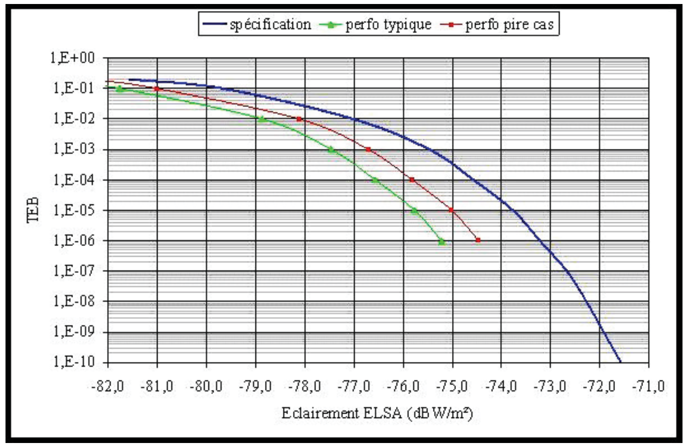


Fig.4 : Communication performance

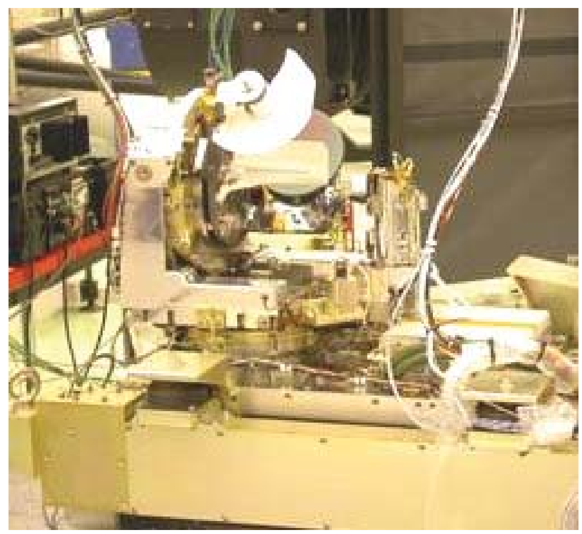

Fig.5: LOLA optical terminal during modal survey

## 4. TERMINAL OPTOMECANICAL CONFIGURATION

The selected aerial design is a Coudé off axis telescope. The optical beam is folded through the azimuth and elevation articulations. The focal plane is located beneath the azimuth elevation motor. This design enables to point the optical beam over a 2π steradiant angular range. It minimises the mobile mass and the optical straylight can be baffled easily. (Cf..Fig5 )

**Pointing stability**

When pointing requirements below 1 µrad are required, thermoelastic stability becomes a clear design driver for the opto-mechanical architecture.
The telescope and the focal plane are thus made out of stiff and stable silicon carbide material (cf.Fig.6 & Fig.7).
Solar flux entrance has been reduced thanks to specific thermal shield on the telescope and a rejection filter on the optical window. The overall terminal is installed inside a thermal enclosure and the focal plane itself is protected by a specific thermal hood;
Finally, optical fibres enable to move away from the optical head, dissipative elements, like the laser diodes or the communication receiver.

**Filtering**

Isolation between the receive and transmit paths is another stringent requirement as the emitted power is typically 100 mW whereas the receive power can be as low as a few pW.
The filtering is ensured by selected electro-bombarded dielectric multilayer coatings.

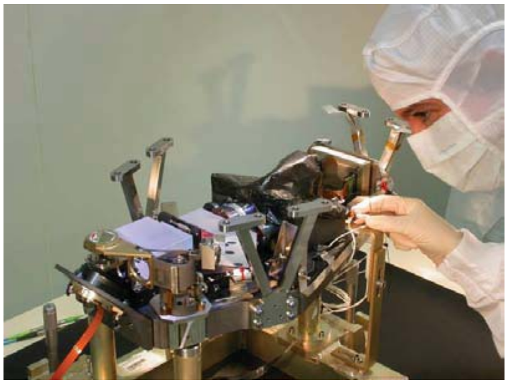

Fig.6: LOLA focal plane

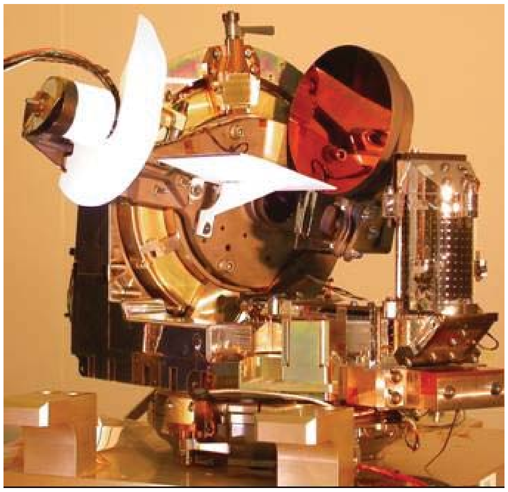

Fig.7: LOLA telescope

## 5. POINTING ACQUISITION AND TRACKING

Rejection of the dynamic perturbations and the distortion of the optical beam through the atmosphere has been a major design driver of the pointing acquisition and tracking subsystem.
The low frequency reference attitude and position is provided by a gyro-stabilised inertial central unit coupled to a GPS information sensor.
The bandwidths of the tracking control loops have been increased significantly up compared to SILEX (capability up to several hundred Hz).
Mechanical dampers filter the high frequency content of the dynamic perturbations. (Cf.Fig.8)

The wide angular mechanism combines a full hemispherical range with high bandwidth (50 Hz) and high accuracy pointing capabilities (few tenth of µrad). This mechanism is therefore able to perform the whole acquisition by steering the telescope, from accurate open-loop pointing to fast GEO beacon spot centring into the small tracking window. This allows to simplify the acquisition sequence and to largely relax the range requirements on the fine pointing mechanism while maintaining fast acquisition duration (about 10s).
The wide angular mechanism uses a brushless DC torque motor with low friction ball-bearing guiding and high resolution optical encoder.

Another innovation introduced in the LOLA PAT system is the Acquisition & Tracking Sensor combining three functions:

- Detection within the terminal field of view (+/-2.5 mrad) of the weak signal resulting from the illumination of the GEO beacon
- Compensation of the point-ahead angle (offset between emission & reception directions due to the velocity of the terminals) by biasing the

tracking reference, i.e. replacing the Point Ahead Mechanism

- Tracking the spot position with a sub-microradian accuracy by and a high sampling frequency..

Such a multi-function sensor is made possible by the flexible windowing offered by Active Pixel Sensor technology, which allows rapid switching from full-frame readout to high frequency acquisition of a small window at any position in the matrix. The LOLA sensor is a 750x750 pixel CMOS matrix with 8 Mpixel/s readout rate.

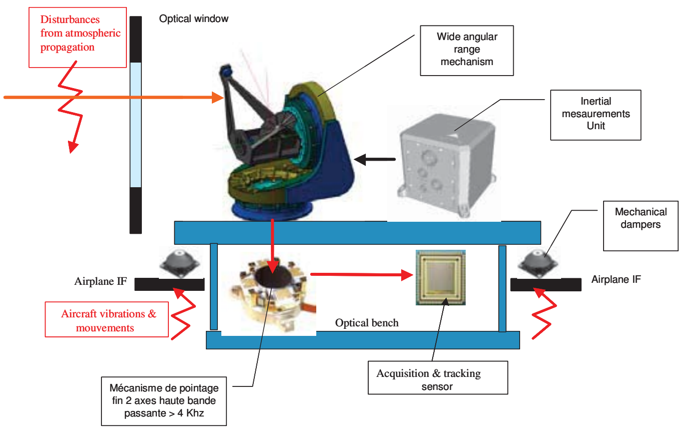


Fig.8: Pointing, Acquisition & tracking architecture

## 6. COMMUNICATION CHAIN

The communication chain is compatible with ARTEMIS up and down links: ie 2Mb/s BPPM forward link and the 50 Mbits/s OOK downlink.

This 0.8µm flight proven technology is based on PM fibered single mode laser diode components and Slick APD avalanche photodiodes. Fibre Bragg grating is used to stabilize the emitted optical spectrum down to 1 nm. (Cf. Fig.9).

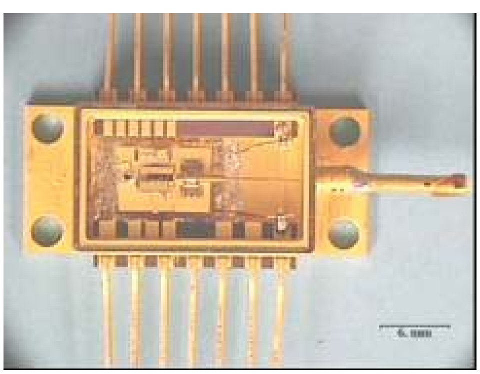

Fig.9: LOLA European 0.8µm laser diode

The laser communication unit includes a single stage current driver for the Tx laser diode and a Rx photodiode an with integrated pre-amplifier. (Cf.Fig10)

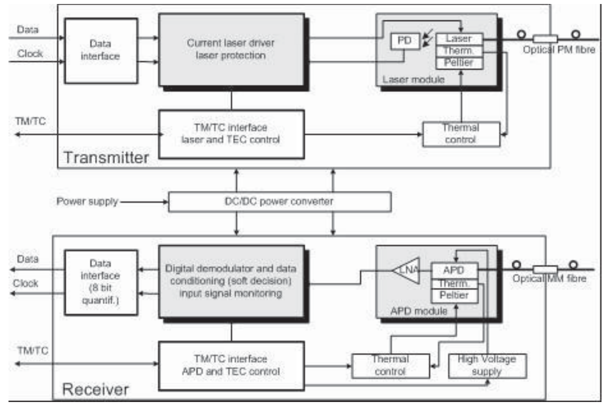


Fig.10: Laser communication unit

The atmosphere is a fading propagation channel for optical beams. To increase the robustness of the transmission to potential error bursts a specific coding of the data stream is implemented. The LOLA communication chain features scrambling, bit integrity framing, frame interleaving, and DVBS2 error correcting code. (Cf.Fig.11). It provides quasi error free transmission despite the disturbances of the propagation channel.

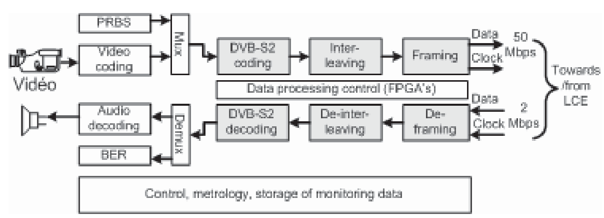


Fig.11: Coding / Decoding scheme

## 7. LINK MODEL

The optical link model has been developed to assess the performance of the link through the atmosphere and to establish the link availability over the world and the year. It has enabled to confirm during the design phase the design of the LOLA optical terminal and will be used for test predictions during the flight test campaign. This model

This model includes (Cf.Fig.12)

- the link parameters such as distance, elevation angle, turbulence amplitude, cloud coverage, plane altitude..
- Constant parameters determined by the design of both optical terminals (pupil diameter, source power, optical transmissions…)
- Statistical parameters such as the pointing performance of each terminals, atmospheric scintillation

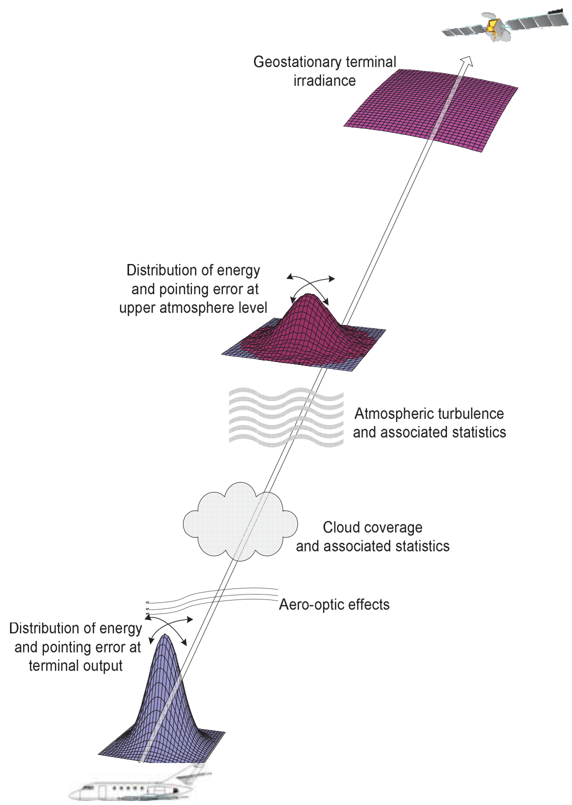


Fig.12: The link model.

This model provides a time x frequency (> 2500 Hz) domain simulation that combines the contributions of each parameters. The output is the received beam in the time domain.

Fig.13 depicts the upward propagation of the wavefront error of the Gaussian beam from the aircraft towards the satellite.

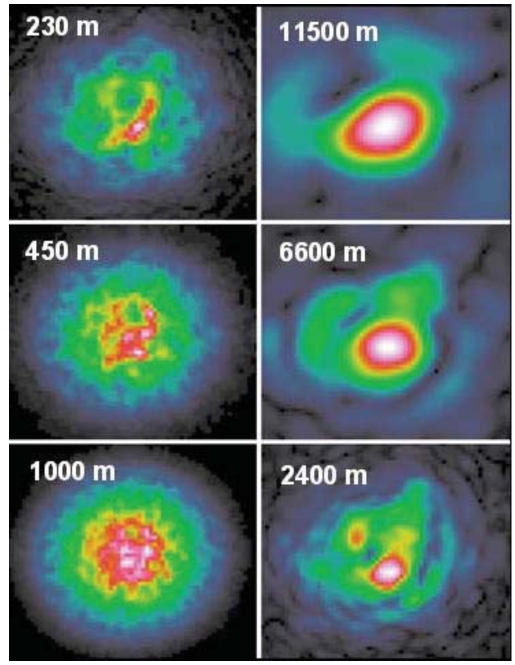


Fig.13:Wave front error propagation.

This model has been correlated with optical link measurements performed thanks to the European Space Agency between ARTEMIS and the Optical Ground Station in Teide (Canarian Islands). A very good match between test results and performance predictions has been achieved (Cf.Fig.14).

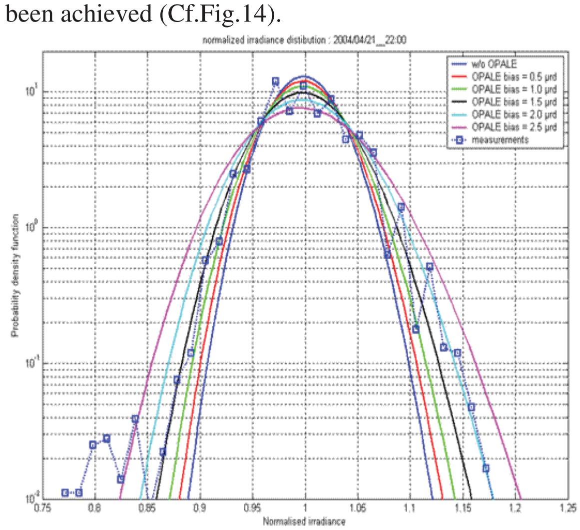


Fig.14: Model correlation with ARTEMIS-OGS test results

## 8. LINK PERFORMANCE

The link performance have been first established for reference conditions (An airplane altitude of 20.000 ft, a fairly turbulent atmosphere (2 sigma value) corresponding to an average altitude wind of 27 m/s, a cirrus thickness of 1 km, a 15° sun aspect angle, as well as typical pointing performance of both LOLA and ARTEMIS optical terminals). (Cf.Fig.15)

| | Uplink | Downlink |
|---|---|---|
| Max channel data rate | 2 Mbits/s | 50 Mbits/s |
| Useful data rate | 1,64 Mbits/s | 29 Mbits/s |
| TEB after decoding | $> 10^{-7}$ | $>10^{-7}$ |
| Link Margin | 2.7 dB | 6.9 dB |

Fig.15: Link performance and margin

A sensitivity analysis on the main link parameters has then been performed to assess the robustness of the performance to various conditions. As anticipated, the uplink performance is more sensitive to parameters fluctuation. On the down link the turbulences create mainly scintillation of the incoming signal whereas for the uplink the atmosphere affects the wave front error of the uplink Gaussian beam causing not only scintillation but also an erratic fluctuation of the direction and shape of the emitted pattern. This is the well known "shower curtain effect"
Figures 16 & 17 synthesise this sensitivity analysis. The link budgets show positive margins in all cases.

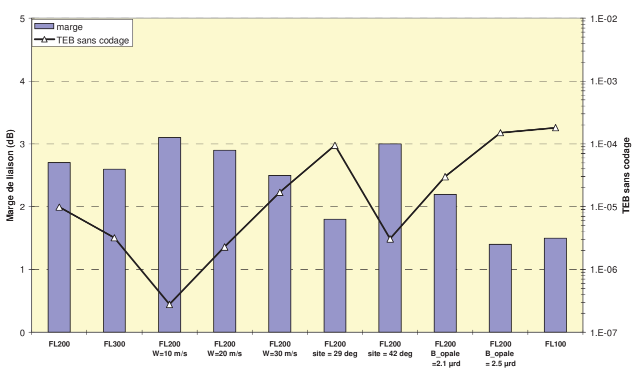


Fig.16: Downlink sensitivity analysis

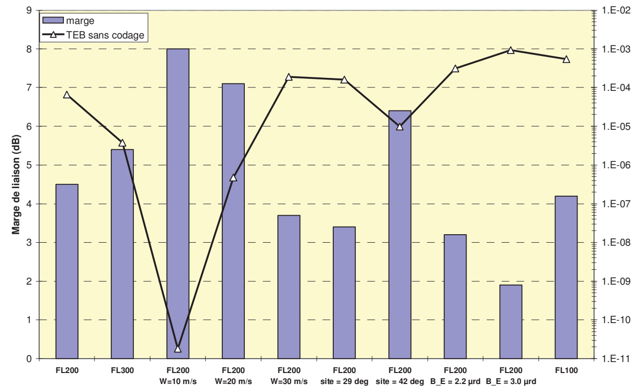


Fig.17: Uplink sensitivity analysis

## 9. FIRST FLIGHT

A first flight was successfully performed on April 13rd to qualify the optical window. (Cf.Fig.18). During this flight the air tightness of this specific window was demonstrated up to the maximum cruise altitude of the aircraft 33.000 ft.


Fig.18: Aircraft with specific optical window above wing

## 10. CONCLUSION

The development of the airborne LOLA optical terminal is proceeding nominally with the final performance check on the ground. The flight test campaign starts this summer until April 2007.