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ALADIN: an Atmospheric Laser Doppler Wind Lidar instrument for wind velocity measurements from space

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ABSTRACT

AEROSPATIALE, leading a European team, has just conducted a successful study, under ESA contract, to demonstrate the feasibility of a spaceborne Doppler Wind Lidar instrument meeting the scientific requirements of wind velocity measurements from space with high spatial resolution

A first parametric investigation, based upon the initial set of mission requirements, and supported by dedicated models and detailed trade-off studies, took account of capabilities of most promising signal processing algorithms and calibration/validation constraints: it yielded a large conically scanned instrument deemed technologically risky

A risk analysis was then carried out to propose a less challenging instrument meeting most key mission requirements. The fixed line-of-sight concept with return signal accumulation appeared as most attractive. A second set of requirements agreed upon by scientific users was therefore issued with relaxed constraints mainly on horizontal resolution, keeping roughly the same level of wind velocity measurement accuracy. A second instrument and subsystem trade-off was then performed to eventually produce an attractive instrument concept based upon a pair of small diameter telescopes each one associated to one scanning mirror rotating stepwise around the telescope axis, which drastically reduces the detection bandwidth.

Following the main contract, studies of accommodation on the international Space Station have been performed, confirming the interest of such an instrument for wind measurements from space.

Keywords: Doppler wind lidar CO₂ laser coherent detection signal processing

1. INTRODUCTION

ALADIN (standing for Atmospheric Laser Doppler Instrument) as a spaceborne Doppler wind lidar instrument, is intended to respond to the pressing need for an accurate wind field description at global scale for both meteorology and numerical weather prediction and climate applications. Such an active instrument will fulfill the gap existing between the present capability of sophisticated numerical models and the drastic lack of information they do require. It will also bring a full-size demonstration of the potential of spaceborne wind lidar in world meteorological and climate monitoring.

AEROSPATIALE, under ESA contract, has conducted the successful pre-feasibility study of a spaceborne CO₂ coherent Doppler lidar meeting the scientific requirements. The team led by AEROSPATIALE involved DRA (United Kingdom) for laser, calibration/validation and local oscillator, LMD (France) for numerical model and signal processing algorithms, SAT (France) for heterodyne receiver and signal preprocessing and conditioning, and TELDIX (Germany) for scanning mechanism and lag-angle compensator.

2. SCOPE OF THE STUDY

A first comprehensive parametric investigation, based upon the initial set of mission requirements, was supported by dedicated models at system and instrument level and in-depth system, instrument and subsystem trade-off studies. It took account of capabilities of most promising signal processing algorithms (Pulse Pair, Poly Pulse Pair, Adaptive Notch Filter) and on-ground and on-board calibration/validation constraints. It yielded an instrument conically scanned around the nadir axis and featuring a large telescope diameter; this concept was deemed technologically risky, especially as regards optical alignments and detection bandwidth.

A risk analysis was then carried out to propose a less complex, preferably smaller, therefore less challenging instrument that could however satisfy most key mission requirements, in particular wind velocity measurement accuracy. The fixed line-of-sight (LOS) concept with return signal accumulation appeared as most attractive at instrumental level: for a given SNR, it indeed allows a significant reduction in the telescope diameter that moreover decreases optical alignment constraints. A second set of requirements agreed upon by scientific users was therefore issued, with relaxed constraints mainly on horizontal resolution, keeping roughly the same level of wind velocity measurement accuracy.

A second instrument and subsystem trade-off was performed to produce an attractive instrument concept based upon a pair of head to tail small diameter telescopes, each one associated to one scanning mirror rotating around the telescope axis and halting on four predetermined positions, that can be changed in flight if necessary. The detection bandwidth is drastically reduced to a range that the detector can easily accommodate, since the platform Doppler shift is constant and can be compensated for by a fixed frequency offset in the electronics.

In the framework of the main contract, the implementation of the instrument has been studied on a Spacebus type platform (basically a telecommunication satellite developed by AEROSPATIALE). A follow-up study was afterwards requested by ESA for the implementation of such an instrument on the International Space Station: it led to a compact and ruggedised instrument allowing most of the performance to be met.

3. MISSION ANALYSIS AND INSTRUMENT TRADE-OFF

The instrument was to be based upon a CO₂ laser transmitter emitting in the 9-11 μm range and to operate in heterodyne mode. The basic initial and reviewed (after the risk analysis) requirements were:

- single LOS wind component observation, in arbitrary direction
- wind velocity measurement accuracy (for a wind velocity range of ± 100 m/s):
 - 2 m/s in lower troposphere
 - 2-6 m/s in medium/upper troposphere (initial); up to at least 10 km height (reviewed)
 - 5-10 m/s in lower stratosphere (initial); < 10 m/s up to 15 km height (reviewed)
- measurement cell size: 50 x 50 km (target, initial); 200 x 200 km (minimum, initial; typical, reviewed)
- vertical resolution: 0.5 km (target, initial); 1 km (minimum, initial; typical, reviewed)
- measurement reliability:
 - > 90% (target), > 50% (minimum) (initial)
 - > 80% up to 10 km, > 50% in higher troposphere (reviewed)
- Earth coverage: global (initial); swath width 800 km (target), 600 km (minimum) (reviewed)
- sampling for each cell, 3 components (initial), 2 components (reviewed), separated by at least 30° (target), 1 component (minimum)

The following study drivers were selected:

- valuable wind measurements (good accuracy) up to 15 km
- wide analysis of mission options (coverage, shot distribution)
- confidence in technical feasibility.

The parametric analysis was supported by dedicated numerical models:

- orbital model;
- scanning model (computation of shot distribution on ground), for five types of scanning strategies: conventional conical scanning around the nadir axis, fixed LOS, spinning satellite (Quick LAWS type), pair telescopes contrarotating around their optical axes, biconical scanning (involving two rotation devices);
- wind velocity measurement performance models (analytical and time instrument model);
- preliminary mass and power models

Mission aspects:

The near polar orbit was eventually selected since:

- it is the only orbit providing global Earth coverage;
- in the case of sun-synchronous orbit, less constraints are imposed onto the platform (fixed solar arrays can be used) and eclipse duration and occurrence can be limited.

A 450 km altitude was selected, taking account of:

- instrument constraints (lower laser energy preferred) requiring lowest altitude;
- platform constraints (ergol mass to minimise) requiring lower limit close to 450 km

Signal processing aspects:

Signal processing was considered as a key element in the elaboration of the instrument requirements and relaxation of subsystem requirements. Detailed modelling and simulations proved that:

- ◊ The laser pulse characteristics have no determining effect on the performance provided the pulse duration stays higher than 1 μ s and the chirp stays lower than 1 MHz.
- ◊ Accumulation shows a high potential for improvement.
- ◊ ANF yields best accuracy, under the condition of initialisation at the true frequency for optimal convergence.

Instrument aspects:

The high performance instrument featured a conically scanned 1.2 m diameter telescope, a 12 J and 4 Hz laser, and a 1.5 GHz detection bandwidth; optical misalignment requirement was 3 μ rd. The concept was mainly driven by the initial Earth coverage requirements. This concept was not deemed unfeasible, but technologically very demanding. An investigation of risk reduction actions led to propose two safer, hence more attractive concepts:

- conical scanning with smaller telescope diameter (0.8 m);
- fixed LOS instrument with small telescope(s) (0.5 m).

Only the second concept, compliant with reviewed Earth coverage requirements (imposing only shots along different LOS in four cells along a 800 km swath), offered the possibility of shot accumulation. This concept was therefore selected.

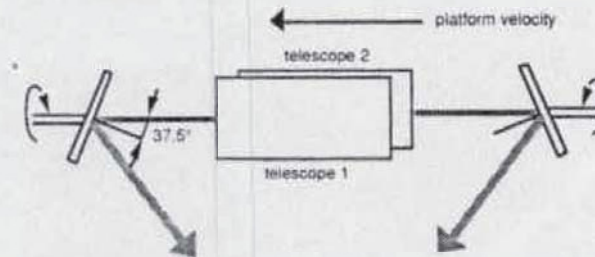
4. OVERALL DESIGN AND PERFORMANCE

Overall concept description:

The fixed LOS process can be achieved either by several telescopes or by one or two telescopes associated to one step by step scanning mirror. We selected the second option, for reasons of mass and volume, and also of reliability and flexibility. The proposed concept features two head to tail fixed telescopes associated each one to a scanning mirror rotating around the telescope axis in a stepwise motion: four LOS are defined for each telescope, along which 20 shots are performed.

Instrument architecture: The instrument features

- A 12 J energy per pulse and 10 Hz pulse repetition frequency laser transmitter, with a reduced duty cycle (no firing during the rotation of the scanning mirrors).
- A heterodyne detection chain with two redundant local oscillators used as injection seeders for the laser; bank filters reduce the bandwidth to 10 MHz, increasing SNR in on-board signal processing; a 10 bit - 25 MHz ADC is compliant with a signal dynamics ranging from 15 km to 3 km; for lower altitudes, saturation occurs without hampering frequency retrieval.
- Two 50 cm pupil diameter telescopes with a magnification of 10 associated each one to a slant scanning mirror rotating around the telescope axis.



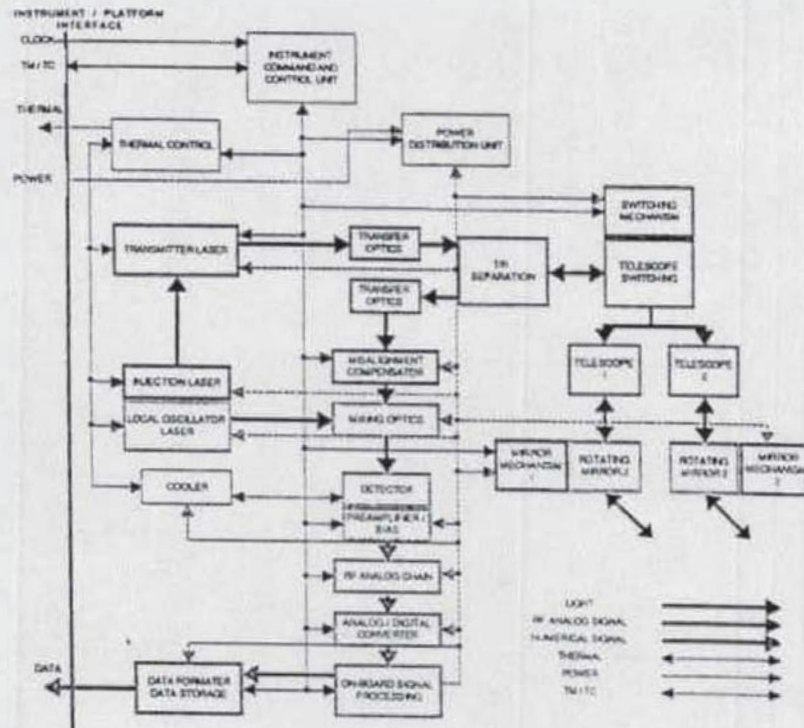
Separation of emitted and return beams is ensured through polarisation: the emitted beam is polarised linearly at laser output, then circularly (anti-clockwise) at telescope output through a quarter wave plate; the return beam is polarised circularly, but in the opposite sense (clockwise), then linearly at telescope output; emitted and return beams at detector thus present crossed polarisation states, and a Brewster plate can thus separate both transmitter and receiver paths. The optical receiving chain also includes a misalignment compensator devoted to correction of low frequency perturbations and a switching device rotating at 600 rpm (synchronous with laser emission) for distributing the laser beam on each telescope.

The rotation axis of the scanning mirror has been chosen to be parallel to the platform velocity: this creates a constant platform Doppler shift of 370 MHz, which the detector bandwidth can easily accommodate and which is offset by electronics in the PreProcessing chain.

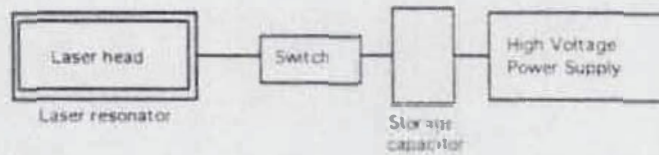
Star sensors are also foreseen for acquisition of reference LOS, with a requested accuracy of 25 μ rd.

The scanning cycle features 2 x 4 measurement periods of 2 s each, the overall duration, taking account of reset time for the mirrors, is 28 s (corresponding to the cell size of 200 km on ground).

Instrument block diagramme:



Laser transmitter configuration:

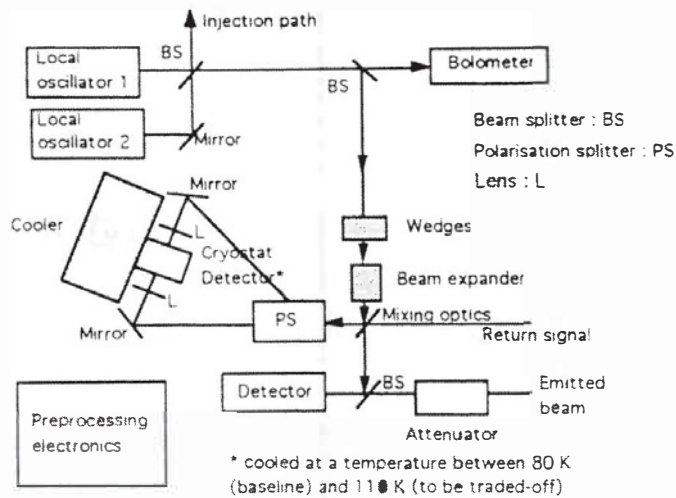


Optical configuration:

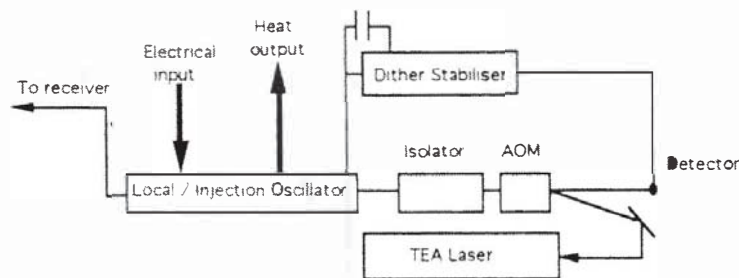
- confocal positive-branch unstable resonator with a supergaussian-profiled output coupler
- control of chirp by use of a large spot size and a sufficiently long cavity
- rotational line selection with a blazed plane diffraction grating and intracavity positive lens
- selection of linear polarisation by the diffraction grating
- single longitudinal mode selection by CW injection of about 1 W off grating zero order and piezoelectric length control

The discharge technology retained as baseline is the pulser-sustainer, for reasons of mass and high discharge-optical efficiency, as well as good reliability/redundancy.

Heterodyne receiver configuration:



Local oscillator:



Scanning mechanism: It features

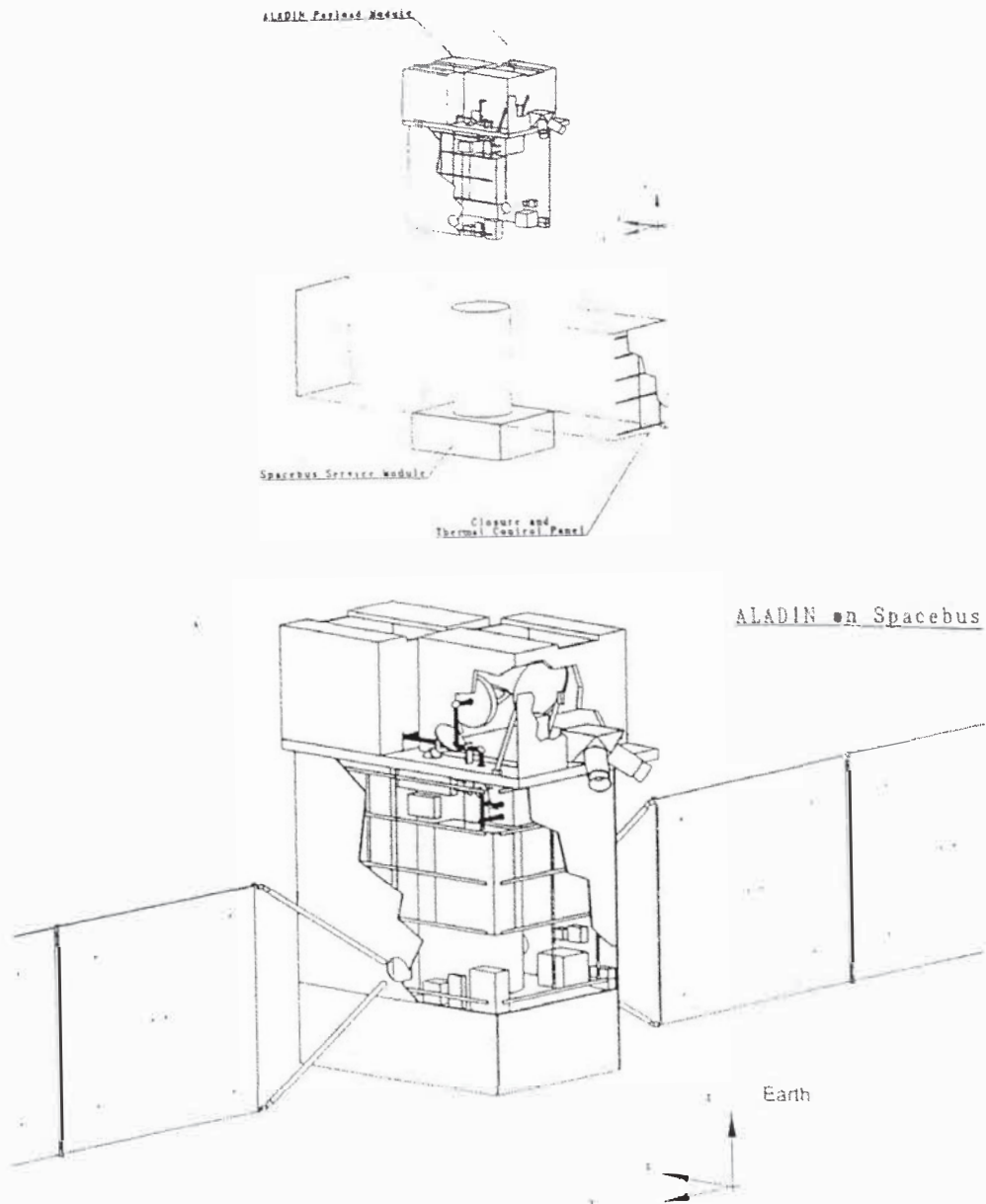
- a magnetic bearing unit with transverse axis vernier gimbaling capability;
- a single stage direct drive DC motor with microprocessor-controlled current shaping;
- a dual stage angular position sensing using a low resolution optical encoder combined with high resolution capacitive or inductive linear sensors for small displacements about the rotation axis and the axes perpendicular to it.

Single mirrors balanced with corotating counterweight and antiphase rotation of both mirrors ensure momentum compensation

Platform accommodation:

The instrument is proposed on a Spacebus type satellite: this platform has been developed by AEROSPATIALE for telecommunication purposes and would be adapted to low altitude orbit

On the following illustration, the first drawing represents the payload module prior to its integration onto the service module, the second one provides a detailed view of the payload on the platform

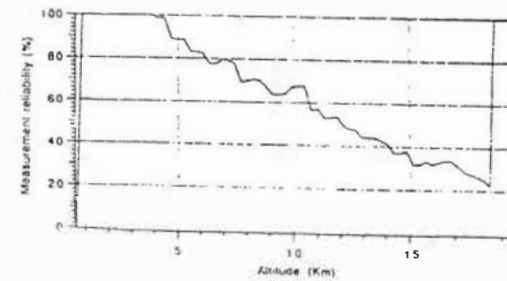
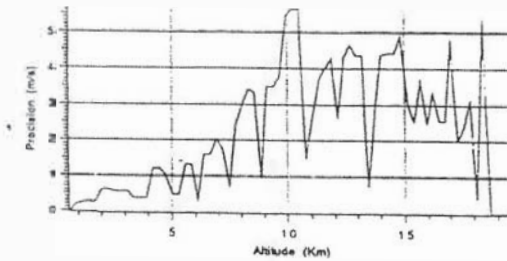
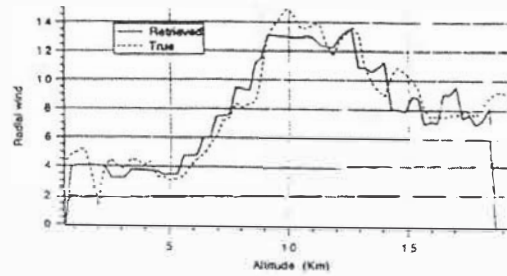


Functional performance:

- Wind velocity error (average, for 80% reliability):

in PBL:	< 2 m/s
at 10 km:	< 6 m/s

The following curves provide wind velocity simulated performance as a function of the altitude; as expected, the accuracy stays pretty good within the troposphere, only the reliability is progressively degraded as the SNR decreases at higher altitudes.



- Vertical resolution: 1 km
- Instrument mass (including 10% contingencies): < 700kg
- Instrument power (including 10% contingencies): ≈ 2 kW
- Data rate: ≈ 2.2 Mbit/s

5. IMPLEMENTATION ON THE INTERNATIONAL SPACE STATION

The International Space Station (ISS) offers a unique opportunity for an instrument like ALADIN. Starting from the baseline concept as presented in the previous sections, detailed studies were performed to investigate the possibility of implementing ALADIN on a dedicated location on the Integrated Truss Assembly (ITA), which can accommodate attached payloads, preferably through Attached Payload Attach Structures (APAS); the latter can accommodate up to six different small payloads, provided they are limited in mass, volume and power.

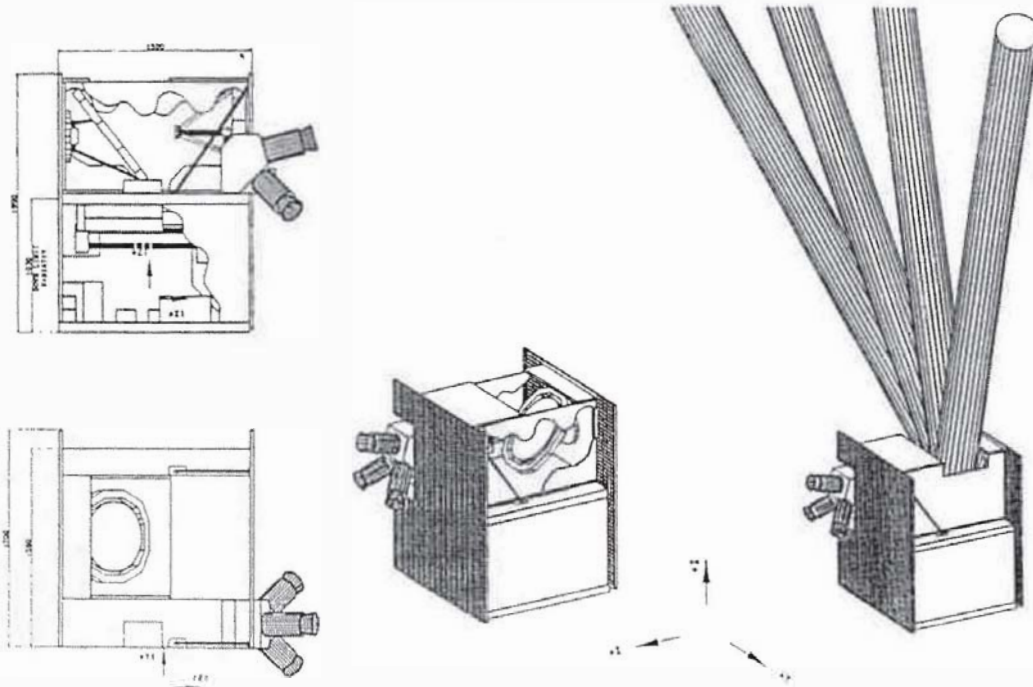
Some specific constraints had to be accounted for:

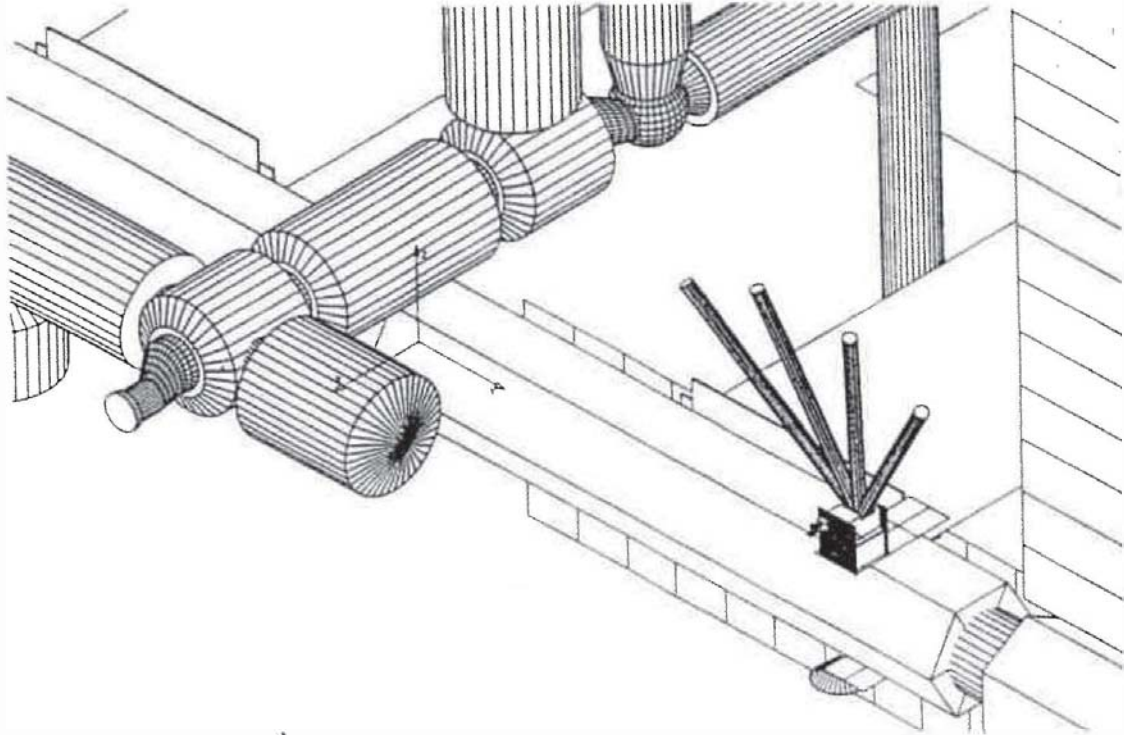
- the instrument shall have its own radiators, since no thermal bus is provided at ITA level;
- the interface with the APAS shall be equivalent to the one provided with two small payloads;
- the ISS solar arrays shall not be hit by the laser beams.

Those constraints yielded a more compact instrument with one telescope instead of two. In addition to mass and volume limitation, the reason of using one telescope only is linked to power limitation: the needed power has to stay close to 1 kW, which can be realised either by decreasing the laser power, or by reducing the duty cycle:

- the first option was not selected essentially because of the reduction of the SNR incurred (≈ 3 dB);
- the second option allows to drop one telescope, which offers significant advantages in mass and volume reduction; in this case, a single LOS per cell is provided, but this is still in line with the minimum requirement (§ 3).

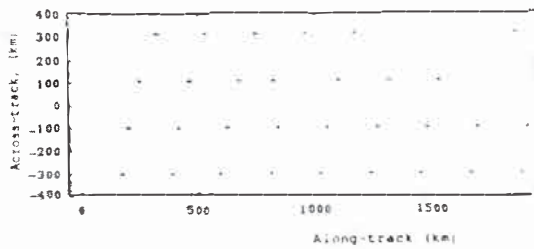
The configuration of the instrument is provided hereafter (on the right side are drawn the four laser beams), followed by its representation on the ISS



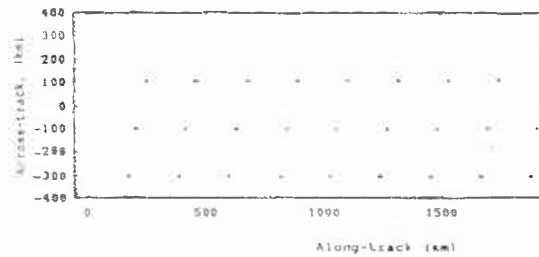


Overall performance:

Shot sampling on ground (taking account of shot cancelling to avoid ISS solar arrays):



0° solar array position, 460 km altitude
among 800 shots per orbit:
38 shots of the extreme LOS are cancelled

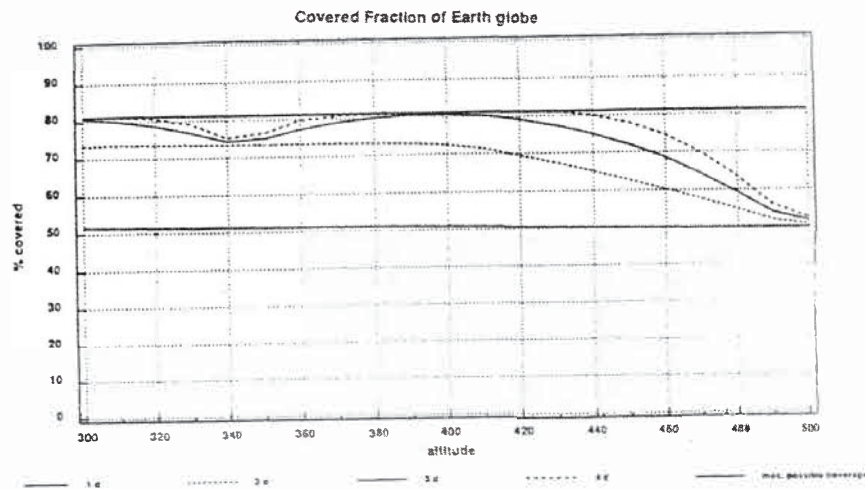


75° solar array position, 460 km altitude
among 800 shots per orbit:
4 shots of the extreme LOS are cancelled
2 shots of the medium LOS are cancelled

- Sampling: accumulation, along each LOS, of
in each horizontal cell
- Swath coverage

20 shots
200 x 200 km
800 km

Earth coverage (ISS altitude range: 335-460 km, inclination: 51.6°):



- Wind velocity error (average, for 80% reliability) and vertical resolution: similar to the ones provided by the two-telescope instrument.
- Instrument mass (including 10% contingencies): < 600kg
- Instrument power (including 10% contingencies): ≈ 1.3 kW
- Data rate: ≈ 1.1 Mbit/s

6. CONCLUSIONS

The proposed ALADIN instrument, be it the baseline two-telescope option or the most compact one-telescope option ideally suited for the implementation on the ISS, is based upon a ruggedised concept which offers the minimum level of risk development, while meeting the core of scientific requirements, especially as regards wind velocity measurement accuracy and measurement reliability.

In terms of reliability and flexibility, this innovative concept offers conclusive advantages with respect to more conventional fixed LOS concepts with switching device(s) behind the telescope:

- In case of failure of one scanning mechanism or the laser switching device, the laser power remains used in its entirety, making still valid measurements possible along a lower number of LOS.
- The number of cluster areas and the LOS angles can be adapted at will, even in flight if need be (for instance to avoid cloudy areas), provided the on-board software is designed accordingly and the possible scanning mirror positions are predefined on ground.

7. ACKNOWLEDGEMENTS

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