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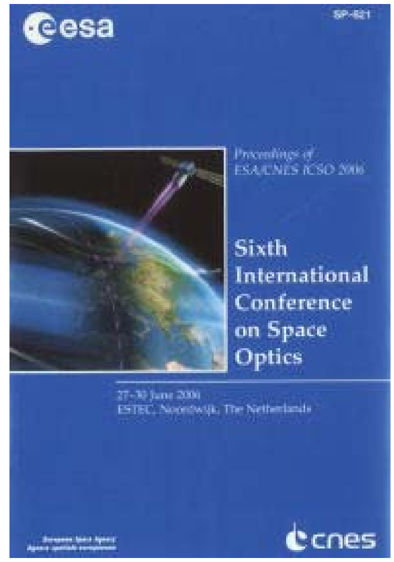

The ADM-Aeolus mission

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THE ADM-AEOLUS MISSION

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ABSTRACT

The Atmospheric Dynamics Mission ADM-Aeolus will make direct measurements of global wind-fields. The aim is to provide global observations of wind profiles with a vertical resolution that will satisfy the requirements of the World Meteorological Organization.

The only payload is the Atmospheric Laser Doppler Instrument (ALADIN), a direct detection Doppler lidar operating in the UV. It will determine the wind velocity component normal to the satellite velocity vector. These wind profile measurements will be assimilated into numerical forecasting models to improve the quality of the global three-dimensional wind fields. To make full use of the data, the global wind profile data must be made available to the weather prediction centers in near real time.

EADS-Astrium (UK and France) and their subcontractors develop Aeolus and ALADIN. Most subsystems have been completed, and the assembly of the Flight Model is well under way, and proceeding to a launch envisaged in late 2008. Details of ALADIN and several of its subsystems are reported in various papers of this conference.

1. INTRODUCTION

ESA's Atmospheric Dynamics Mission ADM-Aeolus will carry the first Doppler Wind Lidar into space for the observation of wind profiles on a global scale. Fig. 1 shows an artists view of Aeolus.

Presently, knowledge of the 3D wind fields over large parts of the Tropics and major oceans is quite incomplete. This leads to major difficulties both in studying key processes in the coupled climate system and in further improving the numerical forecast systems. Progress in climate modelling is intimately linked to progress in numerical weather prediction (NWP). The wind profile measurements provided by ADM-Aeolus are expected to demonstrate improvements in such atmospheric modelling and analysis. [1]

Fig. 1. Artist's view of Aeolus in orbit

This need for global wind profiles has led to a formulation of the measurement requirements by the World Meteorological Organization (WMO) [2]. Aeolus is designed to meet these requirements.

The need for global wind profiles has been recognized already in the '70's, and has led to investigations on use of a lidar technology from space [3, 4], and continued throughout the '80's [5]. Technology development initially concentrated on coherent reception techniques using CO_2-lasers with scanning capabilities to derive 2-D wind vectors. However, the studied instrument concepts proved too expensive to obtain full project approval.

Studies continued in the 90's and have led to a major simplification of the measurement concept: a study about the sampling requirements for a wind lidar indicated that the impact on forecasting skills is mainly determined by the quality and the number of the wind vectors, but stays nearly unaffected by their direction [6]. Thus it was concluded and later quantified that a major simplification of the wind lidar mission can be achieved when scanning is not used, and measurements are performed in a direction orthogonal to the satellite ground track velocity vector.

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The second simplification results from the advances in the technology of diode pumped Nd:YAG laser sources. Several diode pumped Nd:YAG lasers had been built in the 90's and demonstrated the maturity of this technology [7]. This laser source combined with direct detection methods [8 – 11] promised a sensitive wind lidar that allows determining winds with good accuracy also at high altitudes where essentially no aerosols are present.

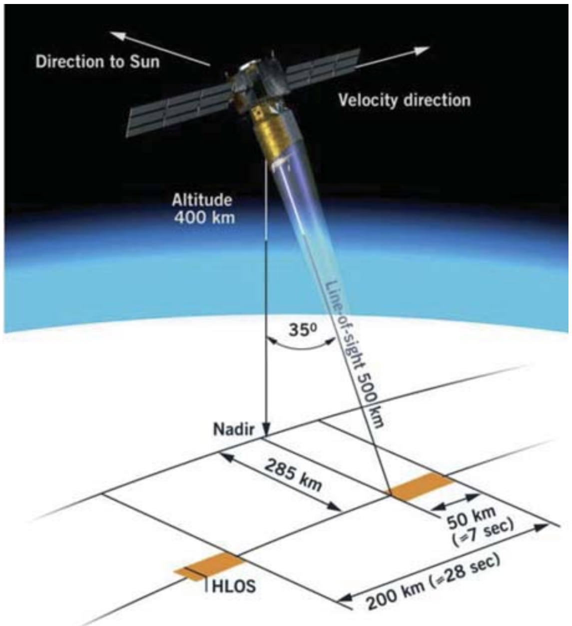

Fig. 2. Schematic view of the ADM-Aeolus measurement geometry.

2. AEOLUS MISSION OVERVIEW

The Aeolus mission requirements have been used to derive a feasible mission concept during the Phase A study [12] which was the basis for the mission selection. Although the original concept has evolved in all areas, the basic facts still remain valid.

The measurement geometry of Aeolus is shown in Fig. 2. ALADIN (the Atmospheric Laser Doppler Instrument) will emit a light pulse in the UV (355 nm). This wavelength has been selected due to the strong backscatter from the atmospheric molecules (Rayleigh scatter), as well as due to the good eye safety. In addition, the 355 nm wavelength is obtained by frequency-tripling of Nd:YAG lasers, which represent the best developed solid-state lasers and provide the best basis for development of a complex spaceborne laser system as required for a Doppler wind lidar.

To pick up the Doppler shift from horizontal winds, the laser pulse is fired at a slant angle into the atmosphere. For Aeolus, it is an angle of 35° to Nadir, orthogonal to the Aeolus ground-track velocity vector. Due to Earth curvature, the incidence angle at the measurement track is 37°.

The backscatter signal diminishes with the square of the measurement distance. Thus a low orbit height is desirable to obtain a comparatively strong backscatter signal. However, for low orbits the air drag becomes high and a large amount of propellant would be required for orbit maintenance. For Aeolus, an orbit height of about 400 km gives the best compromise between measurement capability and propellant need.

The received light is collected by a telescope and is directed onto a receiver subsystem. The receiver samples the signal in the time domain in order to determine its arrival time and hence the distance to the atmospheric layer. For each layer the spectral distribution of the return signal is analysed through a high-resolution spectrometer. Direct detection is used to measure the spectrum, requiring low-noise (quasi photon-counting) detectors; ALADIN uses CCD's with an on-chip signal accumulation with very low excess noise and high quantum efficiency (> 80 %).

Fig. 3 shows the return signal spectrum. It is the sum of a wide-bandwidth Rayleigh signal (about 3340 MHz FWHM in the upper troposphere) and a narrow-bandwidth Mie signal due to aerosol scattering (less than 90 MHz typically). Various techniques are available to measure the Mie and Rayleigh spectrum central frequency and they fall into two categories: fringe-imaging and edge techniques. An extensive

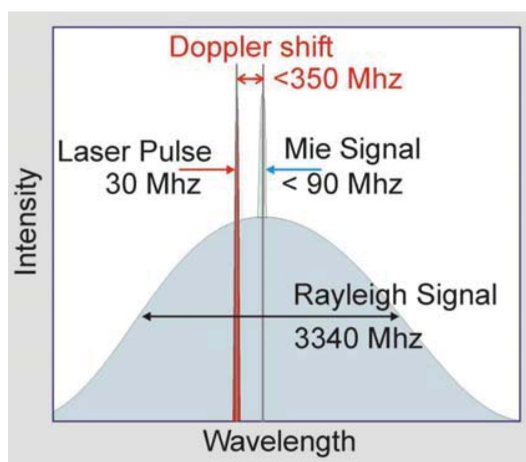

Fig. 3. Schematic view of the backscatter spectrum of scattering from the air molecules (Rayleigh scattering), and from aerosol and cloud particles (Mie-scattering), as compared with the outgoing laser pulse.

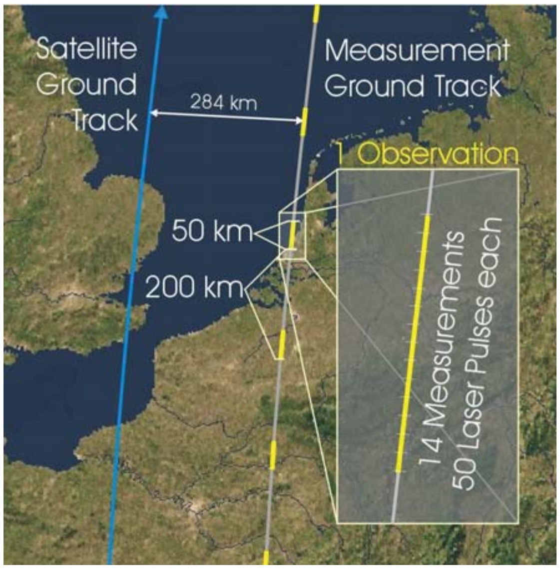

Fig. 4. Ground pattern of wind observations covering a 150 s flight segment of Aeolus. The division of one wind observation into individual measurements is indicated.

trade-off has been performed between these two options during earlier development phases, both in terms of performance and technical implementation.

The fringe imaging technique will be used for the Mie receiver. This concept was preferred over the edge technique as the latter is too sensitive to the Rayleigh background in the ultraviolet. It is intended to sample the received spectrum with a resolution compatible with the spectrum width. A lineshape fitting computation then provides the location of the spectrum centre. The fringe width obtained is set by the spectrometer resolution. After multi-channel sampling, the fringe spreads over a few spectral intervals. The fringe is superimposed on the Rayleigh and atmosphere radiance spectra, which provide additional noise. This noise is kept negligible by making use of blocking spectral filters.

The double edge technique is used for the Rayleigh receiver. This concept was preferred over the fringe imaging technique, that has a similar performance but whose implementation imposes tighter alignment and detector requirements. Two filters are placed symmetrically from the centre wavelength position in order to perform a differential measurement. The filter outputs (A and B) are used directly as the estimator for the frequency shift.

The receiver concept proposed for ALADIN is capable of using both measurement principles simultaneously.

Aeolus will provide input data for Numerical Weather Prediction (NWP) models. These models assimilate wind averages over the resolution grid, measurements with higher spatial resolution than the grid size lead in general to data representativity errors. For global NWP models in the next few years, a grid size of about 50 km can be expected; thus ideally, Aeolus should deliver average wind profiles of 50*50 km^2 areas. This is approximated by averaging measurements along the flight over 50 km, some spatial representativity error for the cross dimension is remaining. For measurements from Aeolus, the 50 km averaging distance corresponds to 7 s measurement duration.

NWP models have a correlation radius of about 200 km; if information with higher resolution is fed into the model along a single track, instabilities in the cross direction can occur. Thus it was decided to measure average winds over 50 km with a spacing of 200 km. This results in a burst measurement cycle, where the lidar operates over 50 km stretches and then is switched off for the next 150 km. With the average orbital velocity of 7.2 km/s, the lidar is measuring for 7 s during a 28 s burst cycle. Fig. 4 visualizes the resulting measurement track of Aeolus.

3. THE ALADIN WIND LIDAR

Fig. 5 shows the arrangement of the key optical

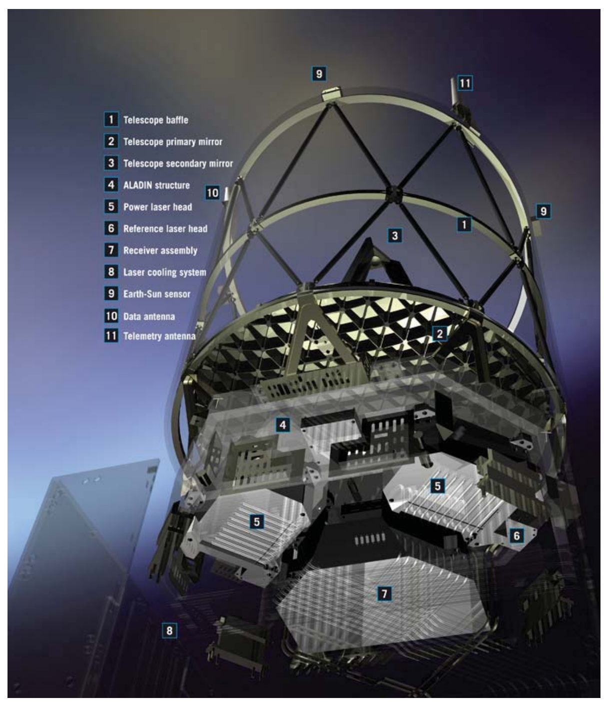

Fig. 5. ALADIN with a 1.5 m diameter receiving telescope and the redundant transmitter laser heads, as well as the receiver on the ALADIN structure below the telescope

subsystems in ALADIN in an artist's view. The key performance parameters of this novel instrument are summarized in Tab. 1.

Tab.1. Key parameters of ALADIN

Parameters	Value
Transmit-receive Telescope	
Telescope diameter	1.5 m
Telescope magnification	41.67
Telescope transm. (incl. obscuration)	> 80 %
Transmitter beam divervence (full angle)	12 µrad
Receiver Field-of-View (full angle)	19 µrad
Receiver	
Fizeau interferometer (Mie)	
Free Spectral Range	2.2 GHz
Useful Spectral Range	1.5 GHz
Fringe width (FWHM)	145 MHz
Double Fabry-Perot (Rayleigh)	
Free Spectral Range	10.9 GHz
Spacing	5.5 GHz
Detector quantum efficiency	> 80%
Signal Processing	
Altitude range (Mie + Rayleigh)	-1 to +30 km
Vertical resolution	0.25 to8 km

A mono-static concept has been selected, i.e. the transmitter laser uses the same telescope to send the light pulse to Earth as the receiver. This concept has the advantage to relax the alignment tolerance of the transmitter with respect to the receiver sufficiently to avoid any active beam pointing alignment tools.

There are two redundant transmitter laser assemblies mounted in ALADIN. Tab. 2 summarizes the demanding requirements imposed on these lasers.

Tab. 2. Key performance requirements for the ALADIN transmitter lasers

Parameter	Value
Type	Solid-state laser
Laser cooling	Conductively, via cold plate
Emission wavelength	355 nm
Pulse energy	120 mJ
Pulse repetition rate	100 Hz
Burst mode operation	7 s on, 28 s repeat cycle
Burst warm up	< 5 s
Pulse width	30 ns
Spectral width (FWHM)	< 30 MHz
Frequency jitter	< 4 MHz rms
Output beam diameter	7.5 mm
Output beam divergence	< 0.4 mrad full angle
Pointing jitter	< 0.04 mrad
Output wavelength tunable	± 7.5 GHz
Lifetime in space	39 months
Burst-mode cycles	3.6 Mega-bursts
Total laser pulses	2.6 Giga-shots

The transmitter laser is a diode pumped, injection seeded Nd:YAG master oscillators with about 10 mJ energy, which is amplified by two slab amplifiers to about 420 mJ in the fundamental wavelength (1064 nm). Lithium-Borate crystals are used to triple this fundamental output to the required 355 nm wavelength with an efficiency of about 30 %.

These transmitter lasers are completely new developments for spaceborne technology – naturally the development is technologically very challenging. In particular the long lifetime demands on the laser diode which are used for the pumping of the Nd:YAG crystals, as well as the lifetime of the coatings used to direct the high energy pulses reaches into many unknown areas.

The received light is collected by a Silicon-Carbide light-weight telescope of 1.5 m diameter and is directed onto a receiver subsystem. An asymmetrical baffle reduces the stray-light. The baffle also carries antennas and sensors for the Aeolus satellite. Fig. 6 show the test model of the telescope during integration in 2005. The Flight Model is presently being assembled.

Fig. 6. ALADIN telescope test model during integration

The ALADIN structure carries the laser heads and the optical bench assembly on the one side, and the telescope on the other one. The laser heads are coupled via heat-pipes to the large radiator on the side of the spacecraft, used to control the temperature of the

Fig. 7. ALADIN structure with laser heads and receiver during integration of the test model

lasers. Fig. 7 shows the arrangement of the laser heads and the receiver on the test model.

The optical bench assembly is a stiff carbon-fiber bench carrying the transmit-receive optics as well Mie- and Rayleigh spectrometers, and the detection front-end units (DFU) for each receiver, with the signal detectors: special charge-coupled devices (CCDs) with on-chip storage cells to allow signal accumulation. With accumulation, the detection can approach the shot-noise limit, the ultimate detection sensitivity.

The ALADIN electronics units are mounted in the Aeolus satellite: the detector outputs are digitized and formatted for downlink in the Detection Electronics Unit (DEU). The Transmitter Laser Electronics handles the power conditioning of the lasers as well as overall laser thermal and logical control.

Autonomous star trackers are mounted on the ALADIN structure used for attitude determination, which is used for the satellite attitude control and, in the case of no available ground echo, for the Doppler retrieval. They are mounted on the instrument structure in order to minimize misalignment errors.

ALADIN is a rather complex and large instrument. The telescope determines its dimension of 1.5 m diameter. Due to the powerful laser package, its average power consumption is 850 W (1030 W peak), which is driving the platform design. The mass of ALADIN (including electronics boxes and harnesses) is about 470 kg. This is about half of the complete Aeolus satellite dry mass.

4. THE AEOLUS SATELLITE

The Aeolus satellite is placed in a sun synchronous dusk-dawn orbit of about 400 km altitude, as shown in Fig. 8. The orbit altitude has been selected as best compromise between lidar measurement performance and fuel requirements for orbit maintenance over the 3 year mission lifetime, while the dusk/dawn orbit provides the most sun illumination and the most benign thermal environment. The wind lidar measures towards the night side to reduce the background signal. Still, a fully illuminated background exists on the summer or winter side.

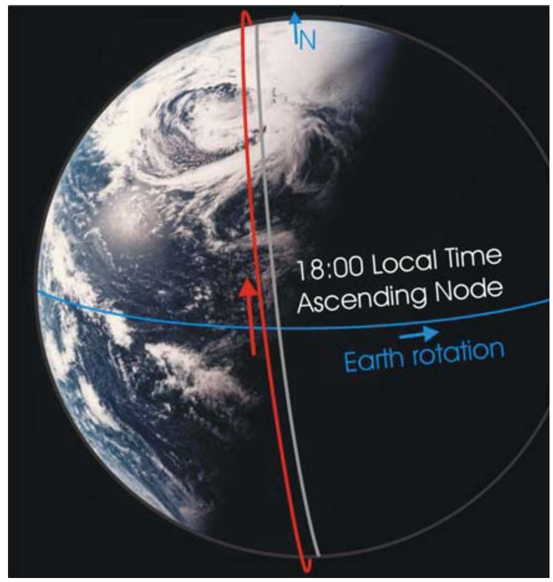

Fig. 8. The Aeolus dusk-dawn orbit of about 400 km altitude (red), and the measurement ground track (grey).

The Aeolus satellite is shown in Fig. 9 as artist's view, and Fig. 10 show the actual structure model during its tests in 2005.

It has a mass of about 1.1 t (plus about 100 kg fuel). The payload envelope limits its size. The solar arrays of 13 m span have three panels on each side. With GaAs cells, they will provide over 2 kW power, to supply an orbital average power of about 1.4 kW.

The comparatively low mass of Aeolus allows the launch with a comparatively cheap launcher, like Vega, Rockot or Dnjepr. Aeolus is designed to be compatible with any of these three launchers.

Fig. 9. Aeolus satellite in flight configuration

Fig. 10. Aeolus structure model during testing in 2005

demanding requirements to keep ALADIN pointing very close to the normal of the satellite ground track velocity vector (to minimize the Doppler shift due to the satellite velocity), and to keep its pointing as constant as possible (to avoid uncorrectable velocity biases). In order to achieve the required performance, a careful design of the attitude control system combined with the use of state-of-the-art sensors and actuators is necessary.

The satellite is tilted 35^{o} to the night side for all nominal measurements. However, for the spectral calibration of the receiver, as well as for validation activities of the wind data, the satellite can be commanded to point at Nadir with small offset angles to generate a deterministic Doppler shift from the satellite velocity vector.

The measurement data must reach the meteorological processing centers as fast as possible, with a maximum latency of 3 hours allowed, but 0.5 hours actually desired for regions of high interest. Thus the data have to be down-linked at least once per orbit, with the possibility to down-link the data to various stations along the orbit. The primary ground station selected is Svalbard, located at Spitzbergen at high latitude of 78^{o}13'N, and thus having a line-of sight to most orbits crossing close to the North Pole. Additional ground stations receiving the data in the X-band can be used, as long as the receiving dish has at least 2.4 m diameter.

Aeolus should be seen as a pre-operation satellite, leading the way for later operational wind satellite. For this reason, it is designed to provide a high autonomy and low operating cost. The orbit has been selected to have a 7-day repeat cycle, so the operational timeline is fully repetitive. The satellite will receive commands only once per week, and requires no continuous monitoring, even in case of single failure situations.

5. PERFORMANCE EXPECTATION

The Aeolus design is driven by the need to achieve excellent performance of global wind profile measurements. The performance of Aeolus has been simulated, based on the assumption of a reference atmosphere (as derived as the median conditions from various aerosol observations, and the US-Standard atmosphere for the molecular scattering). Fig. 11 shows the results of the simulation of the wind noise error (rms) for an altitude up to 30 km. It meets the specifications and thus expectations for the impact of the Aeolus data are very high. The simulation includes all known ALADIN deficiencies – of course, reality is

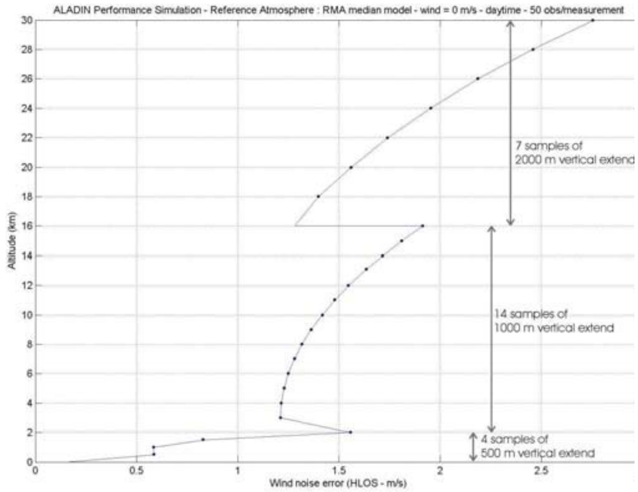

Fig. 11. Aeolus wind error throughout the altitude range for a 'normal' atmosphere without clouds. Wind error stays below 2 m/s up to 16 km, and remains still below 3 m/s up to 30 km altitude.

bound to invade when more experimental results become accessible.

The predictions for all specified parameters show that the mission is likely to be very successful. The performance expectations for the stratosphere are particularly important as there is hope to improve long-term weather forecasts with better knowledge of stratospheric wind patterns.

6. CONCLUSIONS

The need for the global wind profiles for improve weather forecast has long been established, but so far technological difficulties have prevented to realize a spaceborne wind lidar. For Aeolus, some of the key problem areas like beam scanning or development of new laser technologies have been avoided. Still, Aeolus makes a large step into new optical technologies for space applications. Aeolus with its novel ALADIN wind lidar is well under development, and launch is envisaged for late 2008.

Aeolus is a precursor for operational wind observers. The global coverage can be improved by adding more spacecraft in the same orbit, but at different phases. The development of Aeolus is carried out by a team of about 60 industrial partners, lead by the prime contractor EADS-Astrium. The planned development leads to a launch in late 2008.

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