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National Aerospace Laboratory NLR

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Summary

The Lidar Performance Analysis Simulator (LIPAS) simulates the Doppler Wind Lidar (DWL) ALADIN accommodated on the International Space Station (ISS) or on a free flying satellite. The paper describes backgrounds of the ADM, including its benefits for the meteorological community, and the DWL measurement technique. Furthermore it presents the objectives of the LIPAS study, and the way to come to a cost-effective simulator, that would be available on time. An overview is given for the instrument, carrier, and user interface related modules.

The LIPAS results will be used to assess the meteorological utility of the DWL, and to compare different instrument concepts. Furthermore results from the communication scenarios will give operational information. Re-using existing software in the EuroSim simulation environment has made it possible to quickly advance in the project. The LIPAS-simulator can be the basis for a framework simulator that can be tailored to a range of satellite applications.

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LIDAR PERFORMANCE ANALYSIS SIMULATOR - LIPAS

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1 Introduction

The Lidar Performance Analysis Simulator (LIPAS) simulates the Atmospheric Dynamics Mission (ADM) as presented in the assessment report of the European Space Agency ESA[1,2]. The National Aerospace Laboratory NLR, together with the Royal Netherlands Meteorological Institute KNMI, has developed the simulator under contract of ESA. National funding from the Netherlands Agency for Aerospace Programmes (NIVR) was available to cover part of the development cost.

As the LIPAS project started out, accommodation was still on the ISS. However, during the parallel phase A study it became clear that the instrument accommodated on the ISS would not meet the performance requirements of the mission, due to limitations such as facility size, mass, pointing stability and power.
It was concluded that a free flyer would be the preferred solution. The scope of LIPAS therefore widened to allow for any kind of carrier for the instrument.

The aim of this paper is to give an overview of the LIPAS study. Section 2 discusses the DWL mission as background to the LIPAS simulator. The ensuing section presents the objectives in developing, and finally using the simulator. Section 4 presents the development plan of the simulator, with emphasis on cost-effectiveness and timely delivery. Section 5 presents the functional breakdown of the simulator, and discusses the modules of the technical, scientific, and visualisation parts. The final section states the conclusions on the use (of results) of the simulator, its development, and its future use in other projects.

2 Background

The aim of the Earth Explorer ADM is to demonstrate improved three-dimensional atmospheric analyses by providing wind profile observations that fill a gap in the current (meteorological) operational observing network. Such analyses are useful for numerical weather prediction (NWP) and climate modelling. The mission is furthermore aiming to firstly demonstrate the instrument’s capability and technology, and the possibility of real-time data delivery. It is aimed to demonstrate the complete end-to-end data acquisition, processing, and dissemination process, thus paving the way for fully operational follow-on missions.

In the DWL concept a lidar, an acronym for light detection and ranging, emits a laser pulse into the atmosphere. As the pulse propagates through the atmosphere, part of the signal is scattered back by atmospheric particles that are moving with the wind velocity. These moving particles cause the frequency of the backscattered signal to be Doppler shifted w.r.t. the transmitted signal. The time lag between the transmitted and received signal determines the range of the particle to the instrument. Satellite characteristics (altitude, attitude, inclination angle, speed) and the lidar’s line of sight (LOS) determine the latitude and longitude position of the measured wind profile. In the proposed concept, a number of pulses (a cluster) are accumulated to increase the Signal to Noise Ratio (SNR). Clusters, where within wind variability is generally negligible, are nominally 50 km long, and about 200 km apart.

Atmospheric targets include molecules that are well distributed, and aerosols and cloud particles that have more irregular distribution in the atmosphere. The latter two exhibit generally a small variability of movement, typically 1 ms^{-1}, whereas molecules have greatly dispersed speeds by a few 100 ms^{-1}. This results in techniques using both relatively narrow and broad bandwidths of detection. Moreover, depending on atmospheric target and electromagnetic wavelength, either incoherent direct detection by interferometric dispersion, or coherent heterodyne detection by beating the measured signal with a local oscillator, can be used. These profound differences in principle of operation result in different performance characteristics.

Table 1: DWL scenarios

parameter	unit	Space Station			Free Flyer		
laser wavelength	µm	10.6/ 9.11	2.06	0.355	10.6/ 9.11	2.06	0.355
Laser energy	J	1.8	0.5	0.1	1.8	0.5	0.13
Telescope diam.	m	0.7			1.1		
Range gate	m	1000			1000		
Incidence angle	°	35			35		
PRF	Hz	8	10	100	8	20	100
Cluster length	km	50			50		
Accum. length	km	50	50	3.5	50	50	3.5
Orbit height	km	400			400		
Orbit inclination	°	51.6			97.2		

Table 1 shows all the DWL scenarios considered during the LIPAS project. The near-infrared (10.6/911 µm) scenarios use coherent detection, and the visual and UV (2.06 and 0.355 µm) use the direct detection principle. In the last stages the 0.355 µm Free Flyer concept was adopted, having higher laser energy and a larger telescope than the ISS concept.

3 Objectives

The objective of the LIPAS study was to develop an end-to-end framework simulator. It contains a number of relevant (sub-) systems and elements of the mission which are able to simulate the performance of the essential elements of the mission. These systems and elements are presented in section 5. Furthermore it is flexible so that models can be updated in accordance with more detailed information about the Lidar use on the ISS.

Final use of the simulator is to assess, and possibly trade-off, different instrument configurations, such as different transmitter (laser) wavelengths, detection technique, and mission related items such as the communication. The first objective is to give insight in the mission on user level for the meteorological community. User requirements relate to (1) the quality of measured wind profiles, (2) the coverage, and (3) the time of data delivery. The second objective is to give system-level information on the accommodation of the instrument, which includes the impact and constraints of the ISS and ISS operations on communication and instrument housekeeping. A different aspect is the use of the simulator to promote the DWL mission to the wider public. Therefore a 3D graphics module is required, producing animated images of the ISS, Earth, the instrument, and laser and communication signals.

4 Development plan

A major driver in the development of the simulator has been cost-effectiveness, and timely availability of a working simulator. Both have been facilitated by the extensive re-use (with necessary adjustments), and extension of available software at KNMI, ESA/ESTEC and NLR. EuroSim has been selected as simulation environment because it facilitates the re-use of the existing model software, which in many cases had already been applied in EuroSim.

4.1 Simulation environment

The EuroSim facility is a real-time simulation environment, which is especially well suited when model source code is already available, both in Fortran and C. EuroSim gives a framework where models can be combined in a structured manner (see Figure 1), and it takes care of communication between models using an Application Programming Interface (API)[7]. Other interesting features include:

- The dynamic scheduling and scheduling support
- The easy definition and submitting of discrete events using the Mission Definition Language (MDL)
- The easy definition of monitors, and recorders using the MDL
- The test analyser, using the PV-WAVE package.

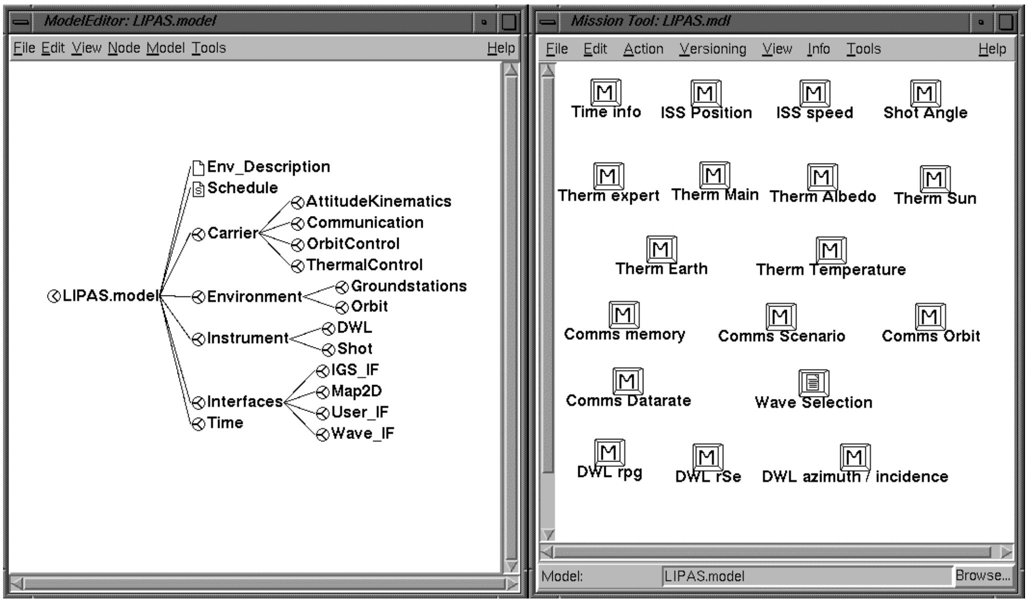


Figure 1: EuroSim Model Editor and Mission Tool with monitors and recorders

5 Functional break down

Figure 2 presents the top-level functional breakdown of the ADM as was used for the purpose of LIPAS. The important components are the instrument ALADIN, the carrier, the environment, the atmosphere and the ground segment (GS). The simulator itself uses a different breakdown as shown in Figure 3.

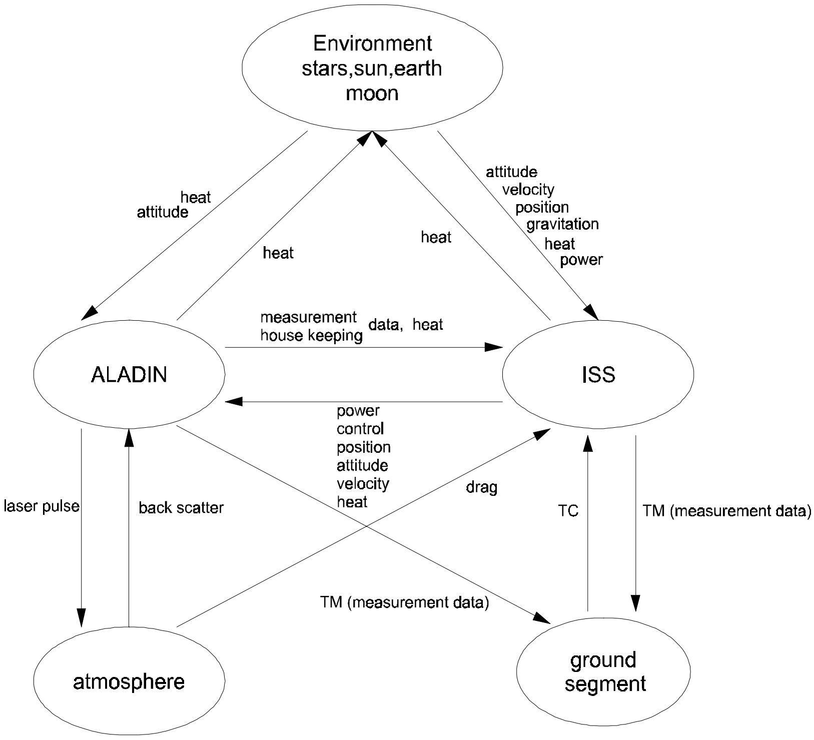


Figure 2: Functional breakdown of the ADM

We distinguish scientific, technical and visualisation parts. The scientific part is the responsibility of KNMI, whereas the technical and visualisation parts are the responsibility of NLR. The scientific issues focus (1) on properties of the atmosphere and instrument that are directly related to wind measurements (e.g. cloud coverage, laser wavelength, atmospheric back scatter, pulse repeat frequency), and (2) the overall performance of the instrument and the carrier (i.e. the impact of DWL measurements on NWP and climate studies). Technical issues relate to the accommodation of the instrument on the ISS such as communication, housekeeping (e.g. of power and heat), operational modes of the ISS, and the performance and constraints of the envisaged hardware of the ISS, instrument and communication infrastructure.

Various other simulator functionalities take care of the proper running of the simulation. These include tasks and schedule, the data dictionary, and missions.

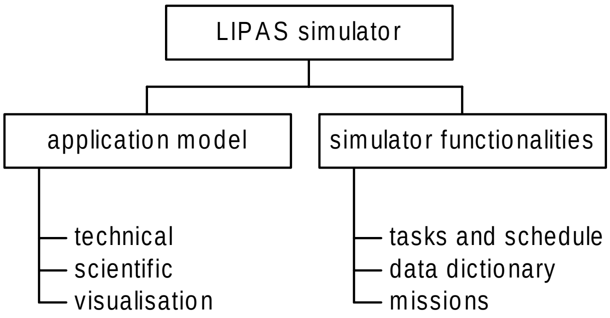


Figure 3: Functional breakdown of the LIPAS simulator

The basic simulator works as follows (see also Figures 4 and 5). At the instant that the lidar emits a laser pulse, the position of the carrier is determined in the technical part using an orbit model. Combined with the attitude, and the user-defined Line of Sight (LOS), the location of the observation is determined. Furthermore, velocity, position and attitude restitution errors are determined. With the observation location, the scientific module extracts a wind profile and other atmospheric characteristics from an atmospheric data base. These data are processed, together with restitution errors, to obtain the Horizontal Line of Sight (HLOS) winds, and the wind profile quality. Processing also determines the amount of measurement data per cluster. The technical part uses the measurement data to model the data handling on board, and the downlink to the ground station and the user.

5.1 Technical modules

Figure 4 presents the important components of the technical part. They include the:

- Laser schedule, which determines the exact time when laser pulses are fired, and when measurement cell centroids are encountered. This module can be used to jump from cell to cell, to quickly simulate a day or week. This information is for instance needed to analyse the communication needs.
- ISS orbit, which contains ESOC’s Position and Environmental Model[5,6] (PEM) for orbit determination, position of Sun and Moon, and visibility of ground stations and Data Relay Satellites (DRS)
- ISS attitude, which includes a kinematic attitude model of ISS[4]. Attitude variations influence the shot pattern, restitution error and thermal model.
- Shot pattern, which determines the location on the surface of separate laser pulses and cluster centroids. The result is used to extract the required profile from the atmospheric data base
- Communication (comms), which includes 2 scenarios: one for standard communication via DRS, and one for direct transmission to ground stations. Important input is the data rate,

which depends on the laser wavelength and detection technique. Important results are the required data buffer, processing power, and delay in data delivery.

- Restitution errors, which include velocity, position and attitude errors. These errors determine in part the overall accuracy of the wind data.
- Thermal model, which gives a first estimate of the thermal loading by radiation and instrument heat dissipation

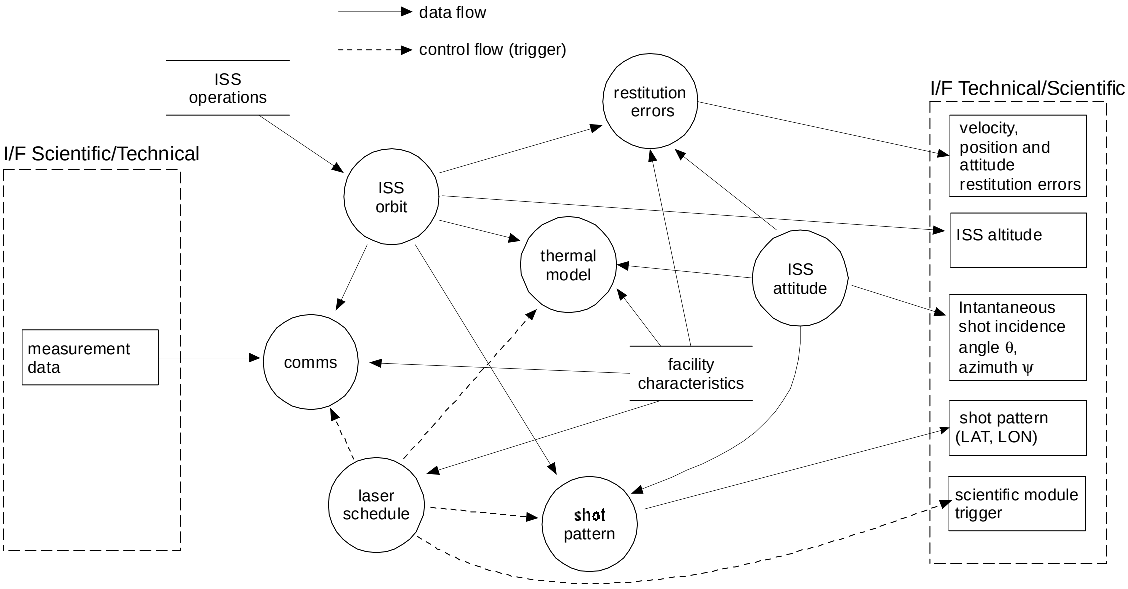


Figure 4: LIPAS technical modules

5.2 Scientific modules

Figure 5 shows the scientific modules. Realistic atmospheric conditions will be used in the simulator. They are obtained from a data base of the European Centre for Medium-range Weather Forecasts (ECMWF), which contains profiles of horizontal winds, humidity (q), pressure (P), cloud coverage (Cc) and cloud liquid water (Clw) content. These profiles are formatted in the general meteorological format BUFR. Depending on the latitude and longitude of a cluster a profile is extracted from the data base and decoded (AtmDataBase). Temperature (T) and density (ρ) profiles are derived from a reference climatological database (AtmRef). The atmospheric environment is further defined by the aerosol backscatter (β) characteristics, obtained from experimental databases (AtmScatProf). Having defined the atmospheric state, transmission τ of the emitted laser pulse through the atmosphere is determined (AtmTrans). Part of the signal is absorbed (AtmAbsorb) or scattered (AtmScat) by molecules, aerosols and clouds (AtmCloud). Several concepts at different laser wavelength are available according to the scenarios studied in the ALADIN design phase. These include coherent detection at 2 and 10 μm and direct (incoherent) detection at 0.355 μm. The SNR of the atmosphere return signal on the detector telescope differs depends on detection technique and is parameterized as a function of backscatter, transmission, telescope diameter, laser wavelength, range and the number of accumulated shots. Signal processing (SigProc) of the detected signal provides, for each cluster, the HLOS wind profile and accuracy characteristics in terms of the Probability Density Function (PDF) of DWL errors.

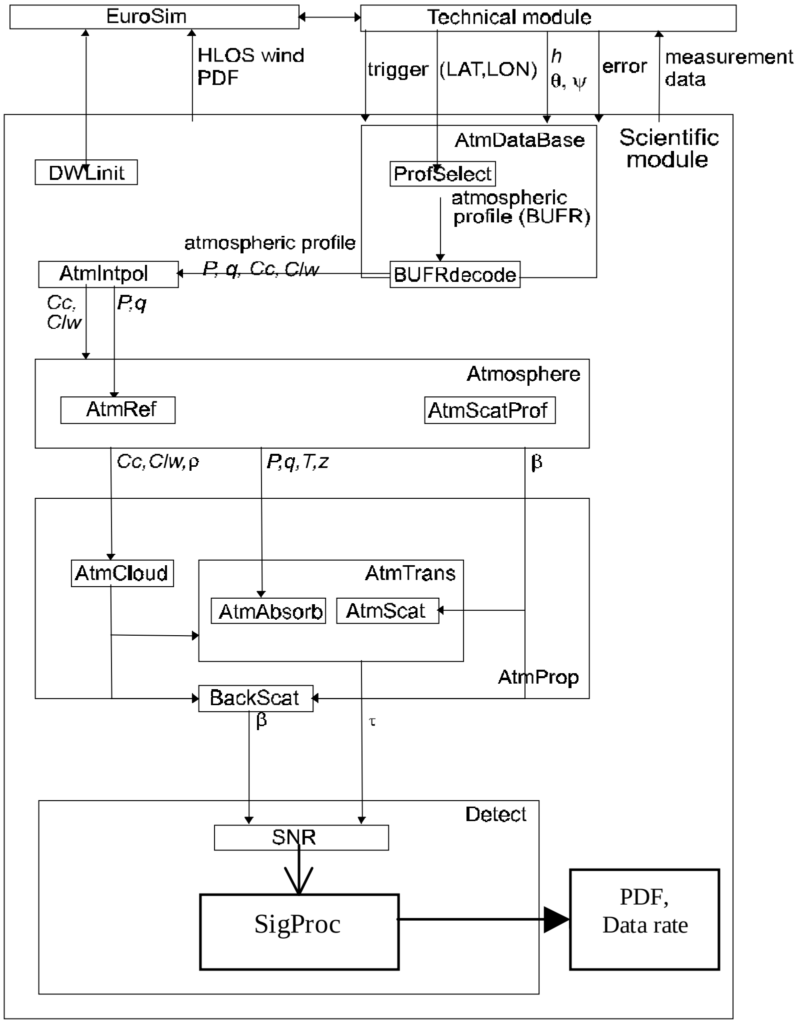


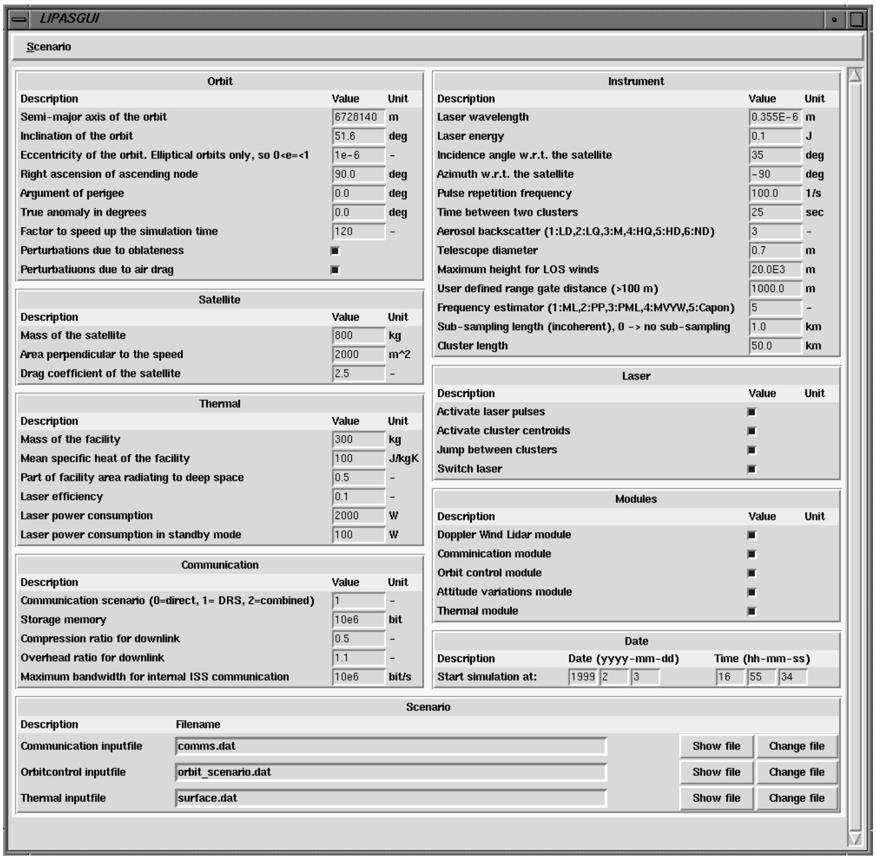
Figure 5: LIPAS scientific modules (notations in text)

5.3 User interfaces

The user interface consists of 4 parts:

- The LIPAS graphical user interface
- The scientific results display
- The two-dimensional map
- The three-dimensional visualisation

The graphical user interface (GUI) shown in Figure 6, parses the data to a dedicated input file for each separate module. This data is read during initialisation of the simulator.



Orbit

Description	Value	Unit
Semi-major axis of the orbit	6728140	m
Inclination of the orbit	51.6	deg
Eccentricity of the orbit. Elliptical orbits only, so 0<e=<1	1e-6	-
Right ascension of ascending node	90.0	deg
Argument of perigee	0.0	deg
True anomaly in degrees	0.0	deg
Factor to speed up the simulation time	120	-
Perturbations due to oblateness	■	
Perturbatiuons due to air drag	■	

Satellite

Description	Value	Unit
Mass of the satellite	800	kg
Area perpendicular to the speed	2000	m^2
Drag coefficient of the satellite	2.5	-

Thermal

Description	Value	Unit
Mass of the facility	300	kg
Mean specific heat of the facility	100	J/kgK
Part of facility area radiating to deep space	0.5	-
Laser efficiency	0.1	-
Laser power consumption	2000	W
Laser power consumption in standby mode	100	W

Communication

Description	Value	Unit
Communication scenario (0=direct, 1= DRS, 2=combined)	1	-
Storage memory	10e6	bit
Compression ratio for downlink	0.5	-
Overhead ratio for downlink	1.1	-
Maximum bandwidth for internal ISS communication	10e6	bit/s

Instrument

Description	Value	Unit
Laser wavelength	0.355E-6	m
Laser energy	0.1	J
Incidence angle w.r.t. the satellite	35	deg
Azimuth w.r.t. the satellite	-90	deg
Pulse repetition frequency	100.0	1/s
Time between two clusters	25	sec
Aerosol backscatter (1:LD,2:LQ,3:M,4:HQ,5:HD,6:ND)	3	-
Telescope diameter	0.7	m
Maximum height for LOS winds	20.0E3	m
User defined range gate distance (>100 m)	1000.0	m
Frequency estimator (1:ML,2:PP,3:PML,4:MVYW,5:Capon)	5	-
Sub-sampling length (incoherent), 0 -> no sub-sampling	1.0	km
Cluster length	50.0	km

Laser

Description	Value	Unit
Activate laser pulses	■	
Activate cluster centroids	■	
Jump between clusters	■	
Switch laser	■	

Modules

Description	Value	Unit
Doppler Wind Lidar module	■	
Comminication module	■	
Orbit control module	■	
Attitude variations module	■	
Thermal module	■	

Date

Description	Date (yyyy-mm-dd)			Time (hh-mm-ss)		
Start simulation at:	1999	2	3	16	55	34

Scenario

Description	Filename
Communication inputfile	comms.dat
Orbitcontrol inputfile	orbit_scenario.dat
Thermal inputfile	surface.dat

Figure 6: The LIPAS graphical user interface

The standard EuroSim Mission Tool supplies a number of monitors and recorders, as in Figure 1. A drawback of the of the EuroSim monitors is that they are always time-dependent

For displaying the measurement results this was inconvenient. An additional client-server has been established between EuroSim and PV-WAVE, so that scientific measurement results can be displayed in real-time (Figure 7).

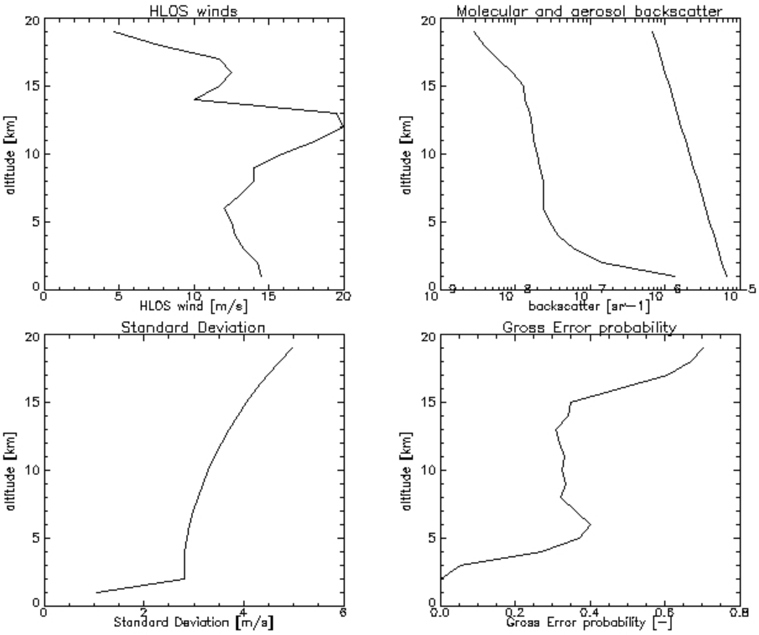


Figure 7: Real time display of scientific results

Furthermore a 2D and 3D representation of the mission is available. Both interfaces have been based on the Proba software of ESA-ESTEC, but have been extended for the LIPAS simulator to display communication scenario's and shot patterns.

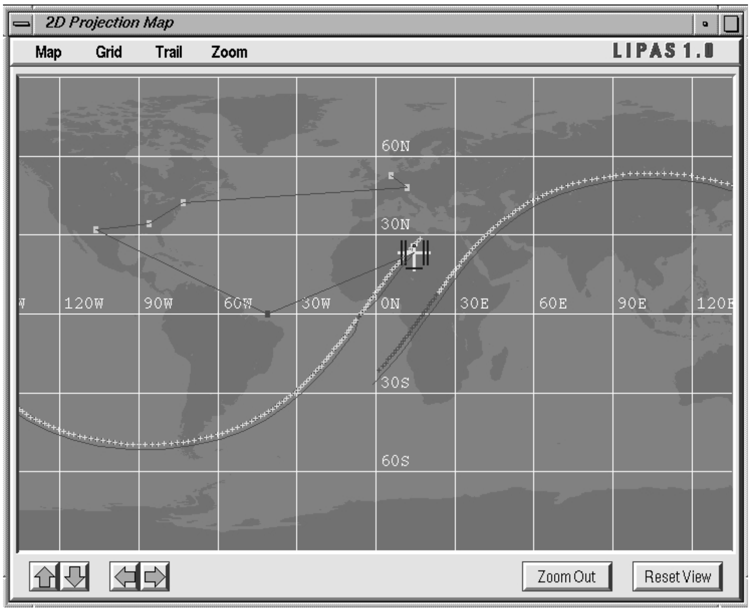


Figure 8: The Map2D interface

The 2D dimensional interface is based on the X-forms library. The 3D interface is based on EuroSim's Image Generation System IGS. IGS makes use of Vega Lynx to tie simulator variables such as position and attitude to a 3D scene. The scene will include the ISS orbiting the Earth, the communication links, and the shot pattern.

Figure 9: 3D presentation of the LIPAS mission. ISS model courtesy of Spacebel/Trasys

6 Results and evaluation

This section will give brief examples of ADM user performance analysis using results of the scientific part, and using results of the communications module for analysing and comparing the different missions.

Scientific results

For each cluster of shots, relevant information of atmospheric state, HLOS winds and accuracy (PDF) are saved in BUFR format and stored in a database for post-processing purposes. A tool has been developed to perform some simple statistical analysis on the database. This includes the performance of the DWL in clear air, *i.e.* without clouds (Figure 10). Moreover, histogram plots are generated, using PV-WAVE, that show the impact of clouds on the DWL performance (Figure 11).

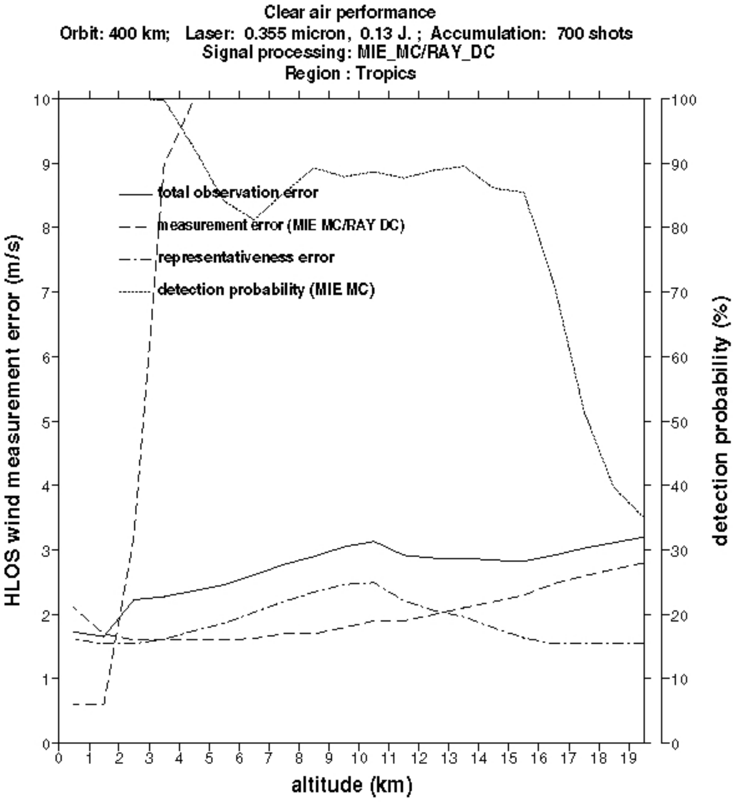
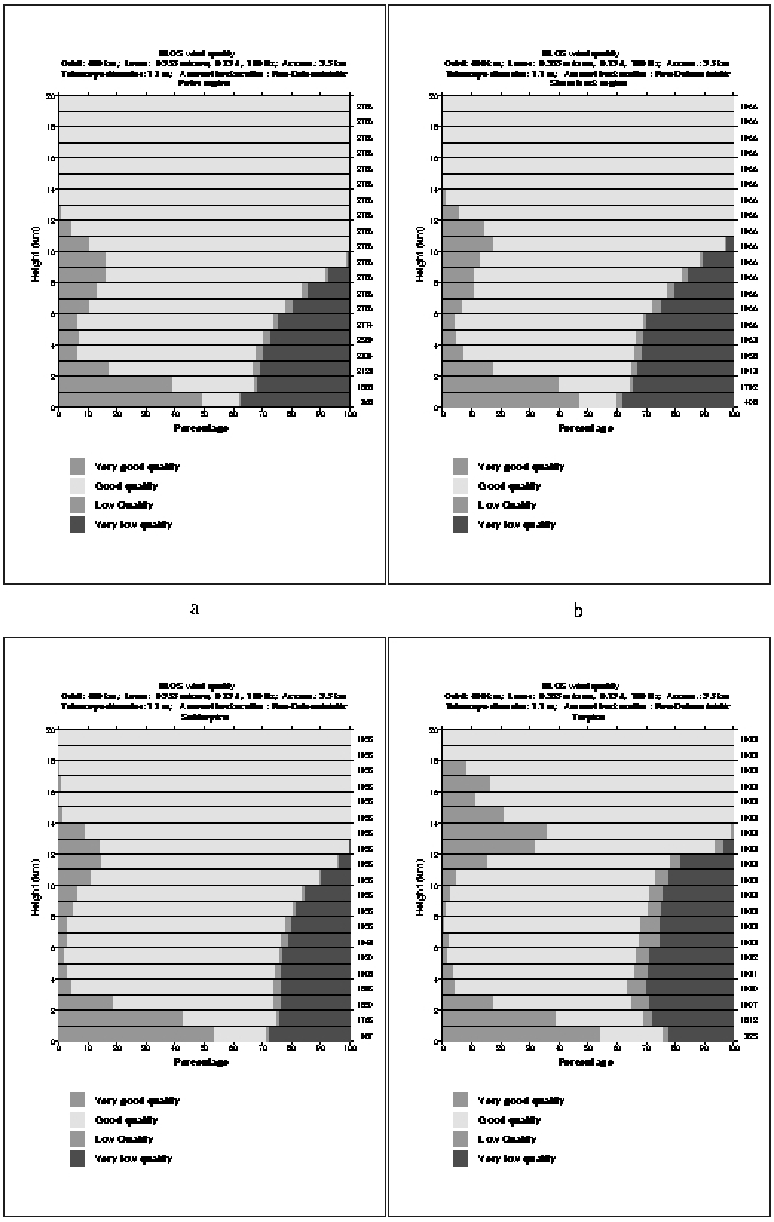


Figure 10: Clear air performance for a 0.355 micron lidar concept. In the lower part of the atmosphere up to 2.5 km, the detected return signal originates mainly from aerosols. Aloft, aerosol concentration decreases fast and the best return signals originate from molecules.



a

b

c

d

Figure 11: Quality of detected return signals. Very good returns above (below) 2.5 km originate from clouds (aerosols). Good quality returns originate mainly from molecules. Low and very low quality returns originate from parts in the atmosphere that are obscured by clouds.

<u>Communication results</u>

Figure 12 and 13 show an example of direct link communication. Figure 12 shows delays for a 12-hour interval of a polar orbit, using a direct link to the Spitsbergen satellite station. Almost each orbit the satellite is insight of the ground station because of its high latitude. However, depending on the location (in time) of the 12-hour interval, there can be areas that have delays of more than one hour, with a maximum of about 1 orbit period, as shown in the figure. Figure

13 shows an approach to obtain decreased delays in the tropics by using an additional ground station. The additional station has a longitude shifted by about 90° as compared to the first station. We see that the delays in the tropics decrease, but that still a sizeable area exists with delays up to 1 orbit period. However, each orbit the satellite can link at least to one of two ground stations.

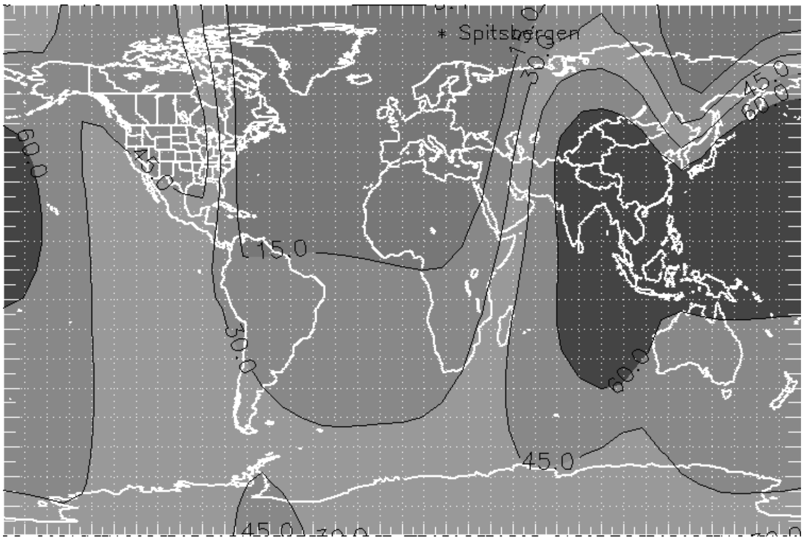


Figure 12:Delays in minutes for a 12-hour interval of a polar orbit using the Spitsbergen ground station

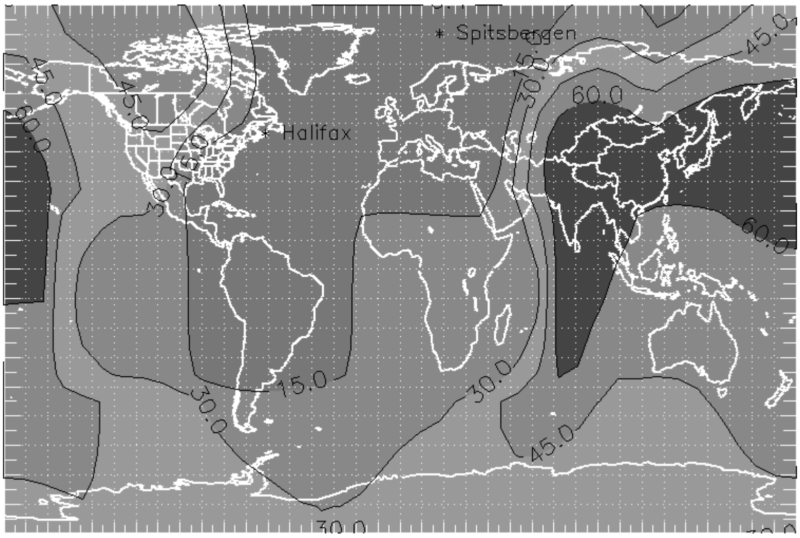


Figure 13:Delays in minutes for a 12-hour interval of a polar orbit using the Spitsbergen and Halifax ground stations

7 Conclusions

Results of the LIPAS-simulator have contributed to the phase A study on laser wavelength selection and type of detection (i.e. coherent or incoherent). Furthermore results from the communication scenarios will give additional information to establish operational scenarios.

Users should be aware of the explicit assumptions in LIPAS, specifically tailored to the ADM. In most cases an expert consultation will be necessary to perform scientific trade-off studies.

Re-using existing software has made it possible to quickly advance in the project. EuroSim made it possible to integrate scientific Fortran code, with the more technically oriented C code. Drawbacks of re-use include (non-) availability of reference documentation, selection and isolation of the appropriate models from earlier simulators, and the often conflicting naming conventions of different models.

In the meteorological domain, the LIPAS-simulator, integrated with meteorological models, could be used to generate new data bases for DWL impact studies.

Finally, the LIPAS-simulator is flexible enough to analyse a polar platform for the envisaged operational DWL system. In fact it is a basic simulator of a satellite platform, that can be tailored to a range of satellite applications, by combining it with the appropriate instrument modules.

Acknowledgements

We would like to acknowledge the support of the ESTEC simulation department, in particular Peter van der Plas, for making available part of the Proba simulator. Furthermore we thank ESOC for providing the PEM models, and Spacebel/Trasys for providing the ISS visualisation model. Finally we would like to thank Ed Kuijpers and Johannes van Es for their efforts on the communication and thermal models.

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