Space-borne Backscatter Lidar an operational tool for weather forecast and climate Research

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Introduction

First ideas as well as proposals to put an optical radar on board a spacecraft have been published in the late sixties. A first attempt to develop a Backscatter - or MIE-Lidar was started by the European Space Research Organisation - the precursor of the today's ESA - in 1974 within the Spacelab - program.[1] A feasibility study was performed and a number of predevelopments were initiated [2]. Finally the program did not succeed by a couple of technical but also political reasons. (ESA publication) Immediately after this negative decision NASA established an Atmospheric LIDAR Advisory group and tried to develop a Shuttle LIDAR with a growth capability to application of differential absorption technique to measure atmospheric temperature, surface pressure, water vapour etc. A total of about 30 different measurement goals were discussed and classified with respect to technical risks and scientific needs.[3] Also this project did not succeed and was finished after a feasibility study which had demonstrated the feasibility. It was September 1994 that the first space-borne LIDAR, the Laser in Space Technology Experiment LITE was performed on board the shuttle [4]. This experiment was performed together with numerous correlative ground-based LIDAR measurements demonstrated surprisingly good performance and also agreement. In the meantime two additional backscatter LIDARs have been brought on board the manned Russian orbiter MIR, the Russian BALKAN-System and ALISSA the result of a Russian - French cooperation. These space vehicles are operating at a lower orbit than future satellites and therefore are promising better S/N ratios. On the other hand they are or were equipped with conventional Nd:YAG-lasers optically pumped by flashlamps. With the development of diode pumped lasers providing about an order of magnitude more average power at the same electrical power consumption, the disadvantage of more distant orbits is compensated. The results from the LITE experiment can be taken as examples what will be achieved from orbits used by operational satellites.

While for quite a couple of years European Space Agency has been pushing the development of the ATmospheric LIDar ATLID, a Backscatter LIDAR planned for a polar orbiting satellite with some but limited success [5], we have to realise that there are well placed plans in Japan to put a MIE-LIDAR on an orbiter within the next seven or eight years

Scientific Rational for an orbiting Backscatter LIDAR

The application of a wide variety of passive optical sensors on satellites has improved our knowledge about the behaviour of the atmosphere and improved our observation possibilities in a way which was unbelievable 35 years ago to most of meteorologists and atmospheric physicists. This technical revolution had tremendous impact on weather forecast and the meteorological services all over the world as well as on climate research. There is very low probability that the Antarctic Ozone Hole would have been detected without a polar orbiting atmospheric sounder like TOMS. Passive sounders are receiving radiation originating from any source within the field of view. The angular resolution is generally high but in many cases still limited by technical reasons (size of the aperture, size and number of receiving elements, data rate). One basic disadvantage common to all passive sounding systems is the fact that the photons arriving at the sensor do not carry any information, where they are coming from. Any range information has to be deduced by secondary information or á priori knowledge. Limb sounders achieving an altitude resolution around 3 km at the best are integrating over some hundred km range interval thus loosing horizontal resolution.

The range resolution of a backscatter LIDAR is physically limited by the pulse length of the emitted laser pulse, the output power, the suppression of background noise, the electronic bandwidth of the receiving system, the quantum efficiency and the noise characteristics of the receiver. In practice range resolution needed for atmospheric research is not a problem of major concern. Due to their ranging capability, simple Backscatter LIDARs are able to detect multilayer cloud structure and even optically thin aerosol layers which hardly can be detected by passive systems. Lasers used in LIDARs are emitting in an extremely narrow spectral band. Within this band and due to the small beam divergence they are brighter than any natural light source and make measurements feasible, where passive sensors fail. On the other hand the limited electrical power on board of a spacecraft will never allow to operate an imaging LIDAR competitive to an imaging radiometer with respect to field of its view. Therefore a satellite borne LIDAR is in no way a candidate to substitute any present passive sounder. But the right design of a package combining both active and passive sensors will highly improve the quality of remote sensing data to be used for weather forecast, studies with respect to climate change.

Climate as well as weather is governed by many different parameters, involving many feedback processes. Besides the earth's atmosphere, its chemical composition and its radiative behaviour, the presence of clouds and aerosols, their formation and disappearance at all levels have a strong impact on our living conditions and the stability of our present ecological system. Due to their strong scattering coefficient clouds and aerosol particles are the primary targets of any backscatter Lidar.

Clouds

A cloud parameter needed for climate applications and weather forecast which easily can be retrieved with an accuracy of some ten meters is the cloud top height. Passive sensors must relay on indirect methods and far from achieving comparable accuracy. Consecutive shots allow to measure the altitude distribution, the horizontal extent and also the mean cloud top height. For clouds with an optical depth < 2 -3 the lower boundary can be detected with somewhat decreasing accuracy due to a lower S/N and multiple scattering with increasing optical depth. LIDAR - simulations and especially the past LITE experiment have demonstrated that often different cloud decks can be penetrated and sometimes the ground return from below a dense stratus layer can be detected. Airborne correlative LIDAR measurements which tried to sound the same volume as LITE showed for highly variable cirrus clouds astonishing good agreement as long as the time shift between the measurement are taken within 15 minutes and the spatial offset is below a couple of miles [5]. The inversion of space-borne LIDAR returns into optical thickness had the tendency to underestimate this quantity compared to the airborne measurements.

This is not unexpected and can be explained by the stronger multiple scattering effect for the space-borne LITE-system. By application of a multiple scattering scheme to the inversion algorithm the results could definitely be improved.

Depolarization capabilty of the detection chain will allow to discriminate liquid and frozen particles which is an essential additional information from an energetic point of view. The knowledge of the optical depth, the upper boundary of a cloud deck and the radiation temperature measured by a collocated IR-sounder will allow to improve the present temperature profiling via broad weighting functions by converting a measured radiation temperature into absolute temperature and attributing it to a well defined altitude.

Polar Stratospheric Clouds

Polar stratospheric clouds are believed to play a key role in a chemical reaction scheme which finally leads. to ozone depletion in the stratosphere. Due to their appearance at altitudes between 16 and 28 km in polar regions which are not easily accessible there is need to know more about not only their formation, chemical nature and heterogeneous reactions taking place at the surface of PSC particles but just statistics about the vertical and horizontal distribution and a discrimination in the generally used classification into Type Ia, Ib and II. Schemes to detect PSCs by means of present passive sounders are under development. Some of them make use from a visible channel. This is not applicable at very high latitudes in mid winter. A backscatter LIDAR on a polar orbiting space platform passing the pole any 1 1/2 hour would cover a reasonable grid north or south of 70°. From recent measurements using an airborne LIDAR we can deduce, that Polar Stratospheric Clouds of Type Ib (Moderate Backscatter ratio no depolarisation and Type II, with high Backscatter ratio and high depolarisation, which seem to be the predominant types are detectable with reasonable spatial resolution.

Aerosols

Aerosols particles are present throughout the atmosphere. The typical number densities vary from 10 thousand /cm³ in the troposphere down to a few/cm³ in the stratosphere. At an altitude of 30 km the return signal from aerosol particles is negligible compared to the return from molecules. Therefore often the return signals from that region are taken to calibrate LIDARs.

Aerosols are interacting with any kind of electromagnetic radiation. Due to their size distribution, this interaction is most effective between the near UV and the near to mid IR. Between about 60 % and 95 % relative humidity particles are growing with humidity and rapidly changing their optical properties. Aerosol particles are involved in the formation of clouds and may act as condensation nuclei. Aerosols may reduce the visiblity at ground level by more than two orders of magnitude. In that sense they are masking the results of remote sensing instruments while they are not easily detectable by passive instruments (besides limb sounders). Strong effect on stratosphere have been reported after the major vulcano eruptions of El Chichon and Mount Pinatubo in the past which were transporting enormous amounts of SO_2 and particles into the stratosphere. A correlation with stratospheric ozone depletion and stratospheric aerosol concentration was found by several authors. The impact of upper tropospheric aerosol on global atmospheric circulation was shown to be effective assuming increased aerosol concentration following major vulcano events applying the Hamburg General Circulation Model ECHAM [7] In a paper by Hirono [8] even the triggering of the El Nino effect by enhanced aerosol concentration was taken into consideration.

The LITE data again show that enhanced stratospheric aerosols layers as they appear after a major vulcano eruption can be detected for the following two or three years with reasonable horizontal and vertical resolution during night-time. Background conditions need integration over thousands of kilometres.

Typical boundary layers can be detected during daytime and night-time from a space borne Backscatter LIDAR. A typical marine boundary layer can be seen in the LITE results after having passed a cirrus cloud with an optical density around 1.

References

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"Application of a space-borne backscatter LIDAR based on airborne LIDAR measurements."

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International Workshop on Spaceborne LIDAR 1966/ Hakone JP

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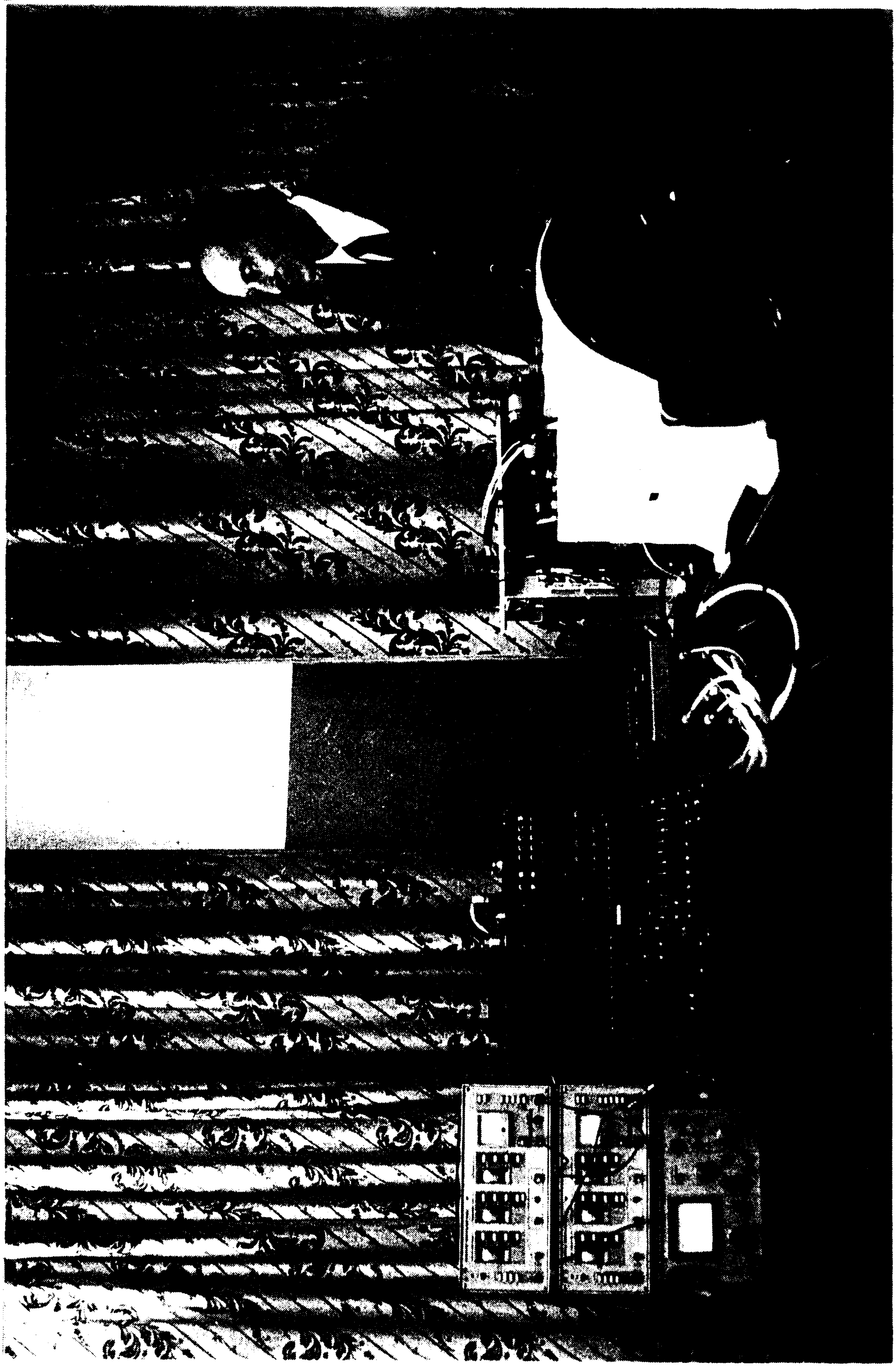

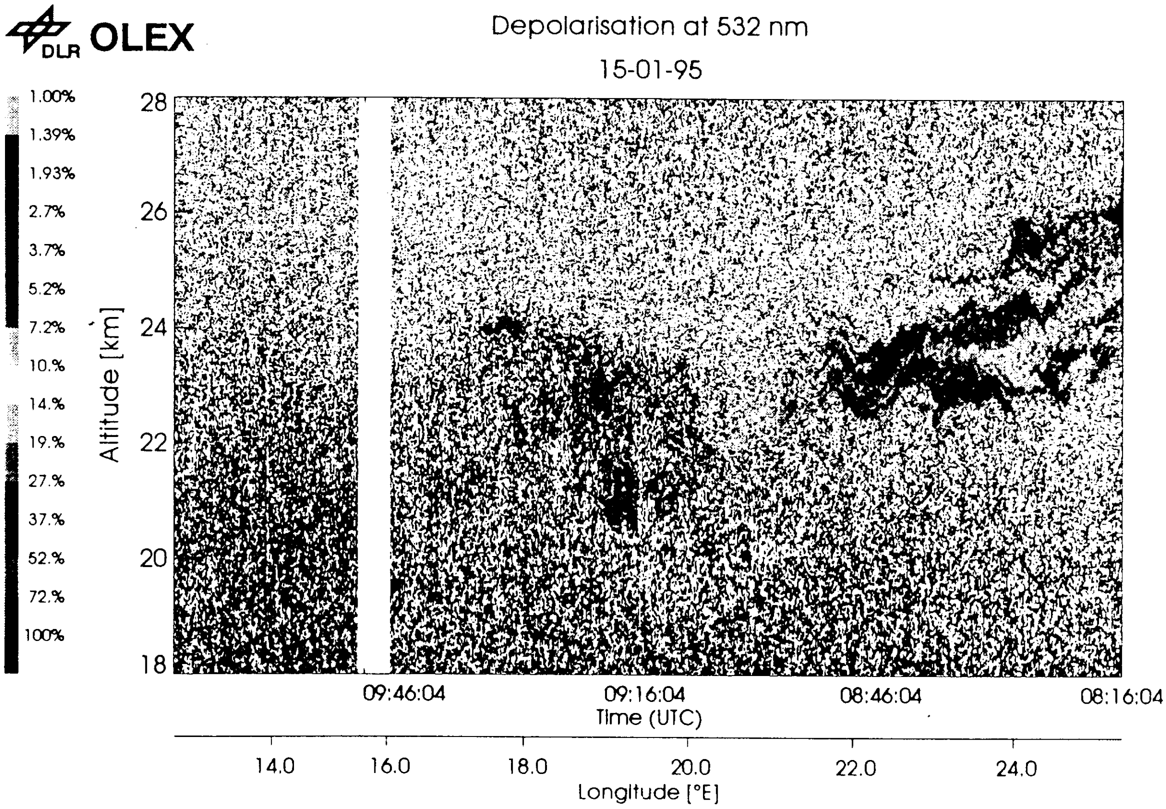

OLEX
DLR
Depolarisation at 532 nm
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1.00%
1.39%
1.93%
2.7%
3.7%
5.2%
7.2%
10.%
14.%
19.%
27.%
37.%
52.%
72.%
100%
Altitude [km]
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22
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18
09:46:04
09:16:04
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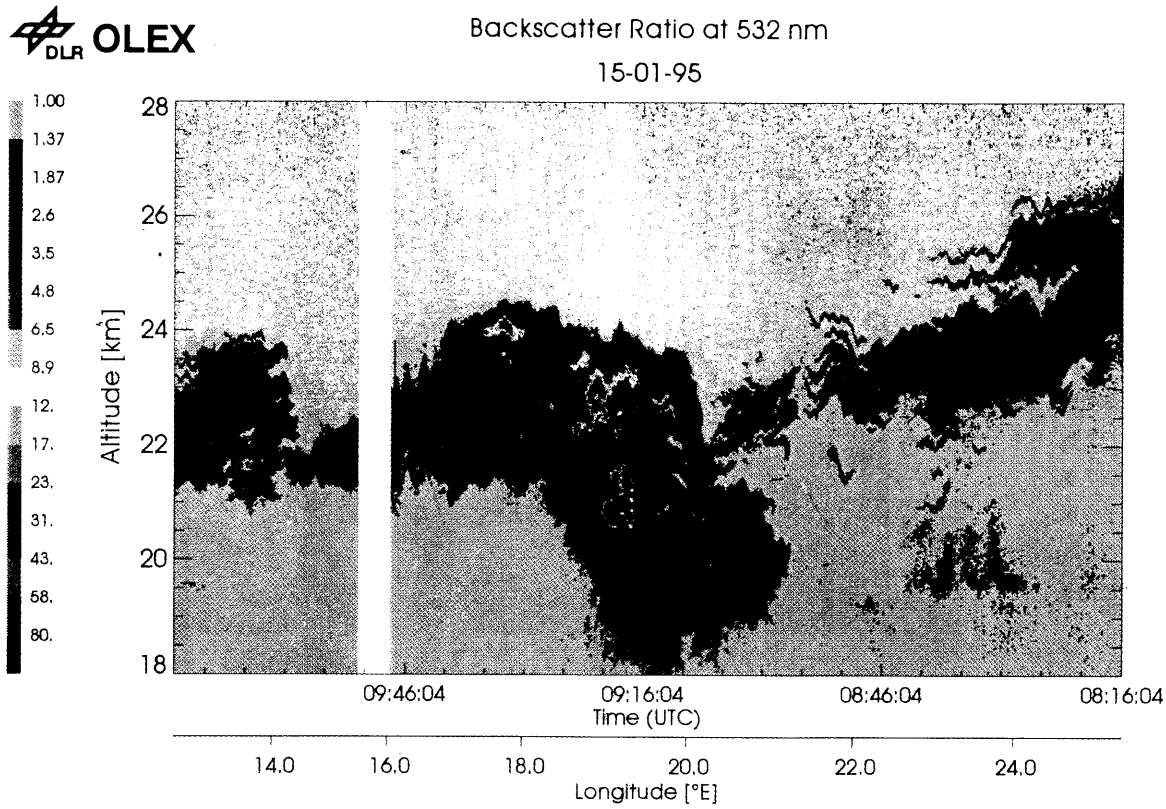

OLEX
DLR
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31.
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58.
80.
Altitude [km]
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Time (UTC)
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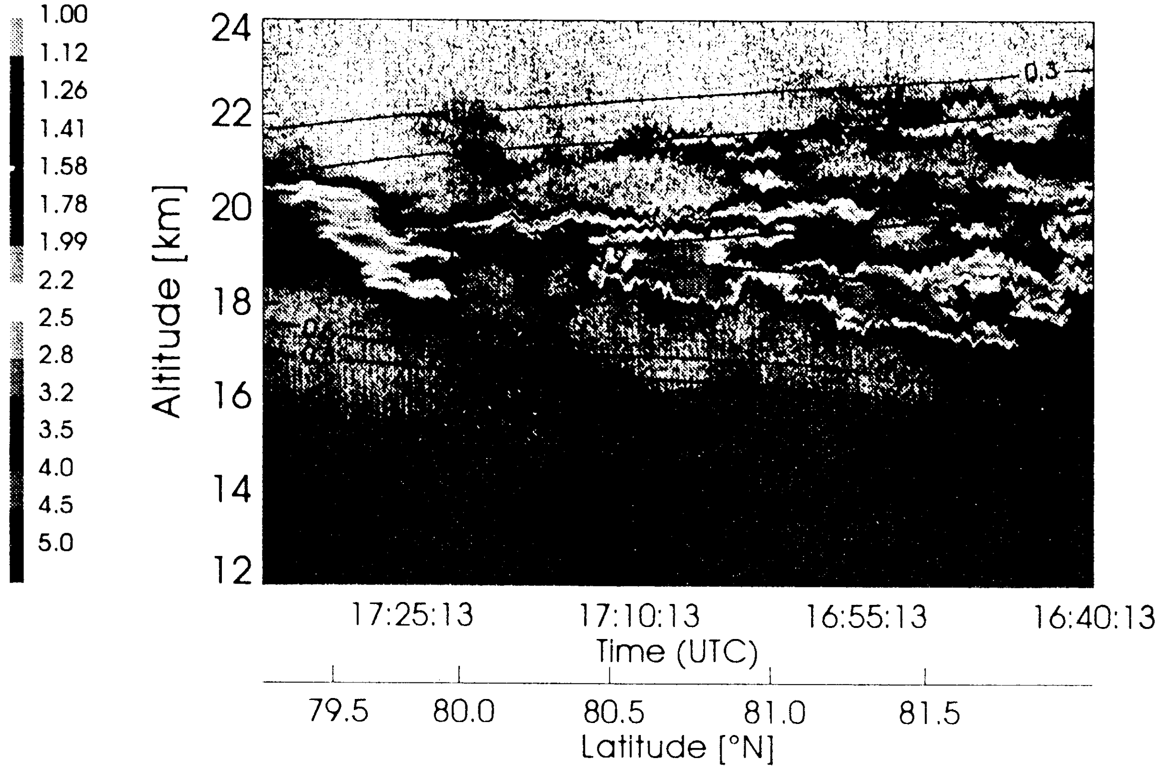
24.0
Longitude [°E]

OLEX

Backscatter Ratio at 532 nm

17-12-94



Depolarisation at 532 nm

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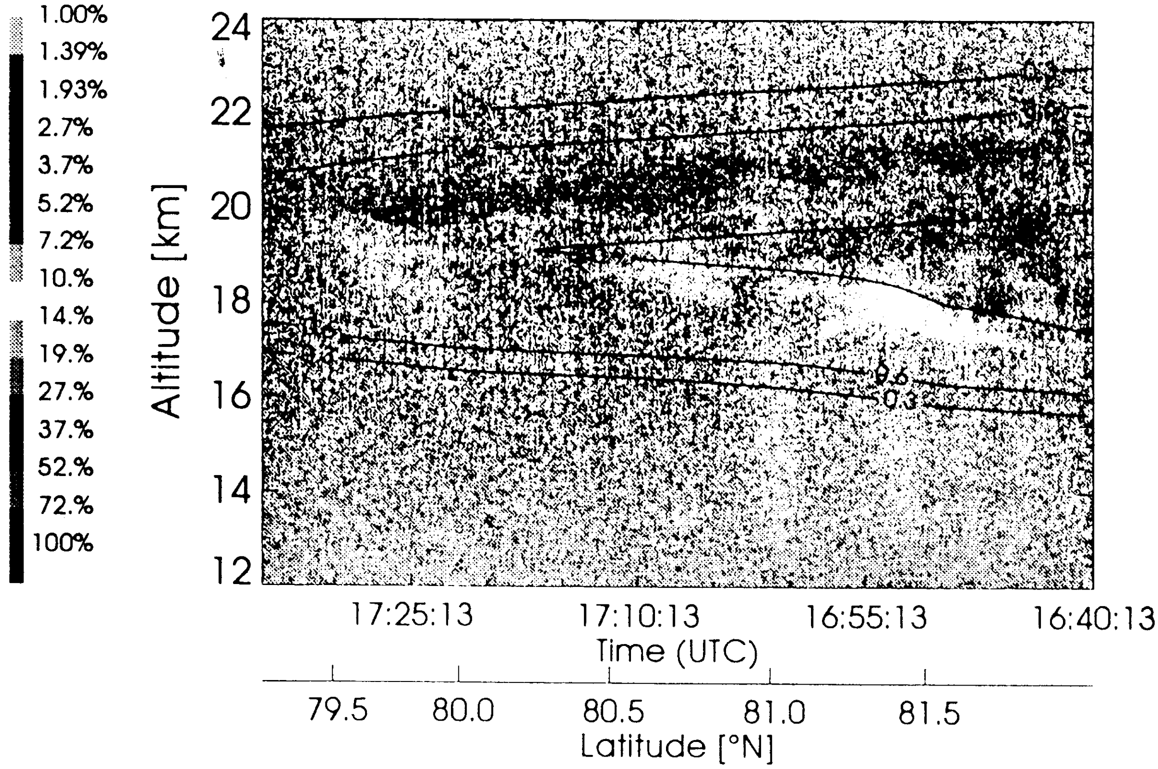

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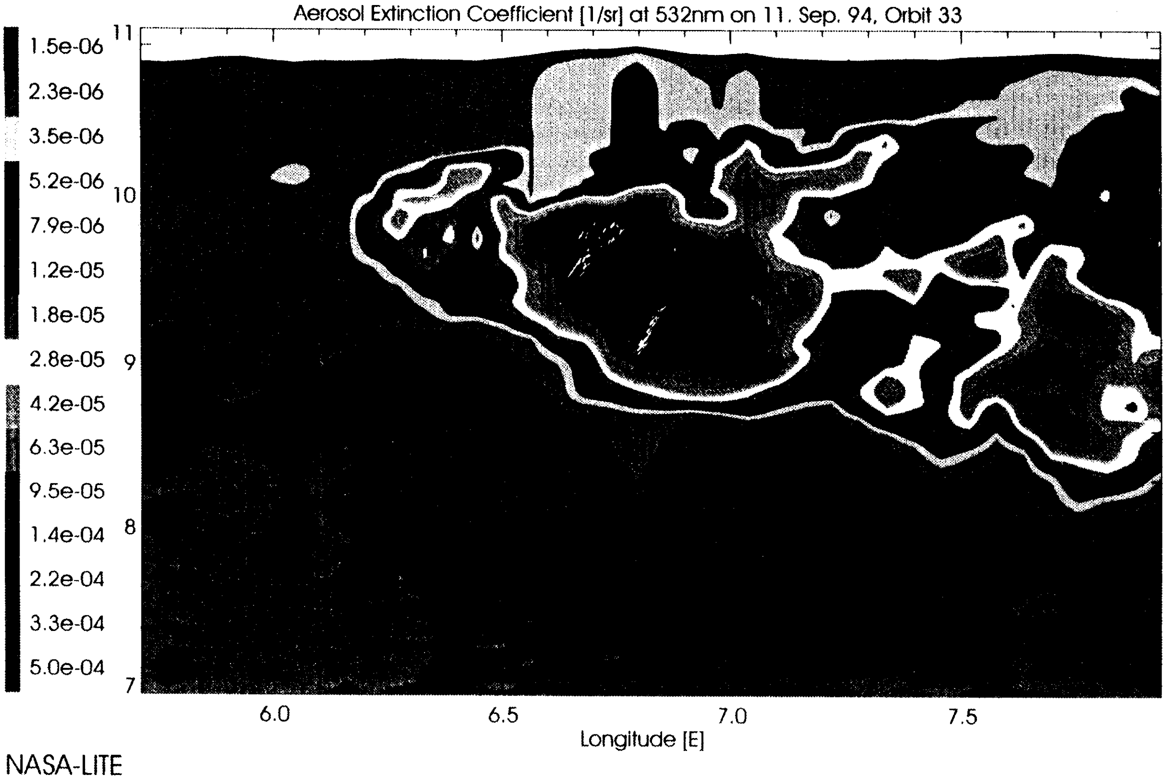

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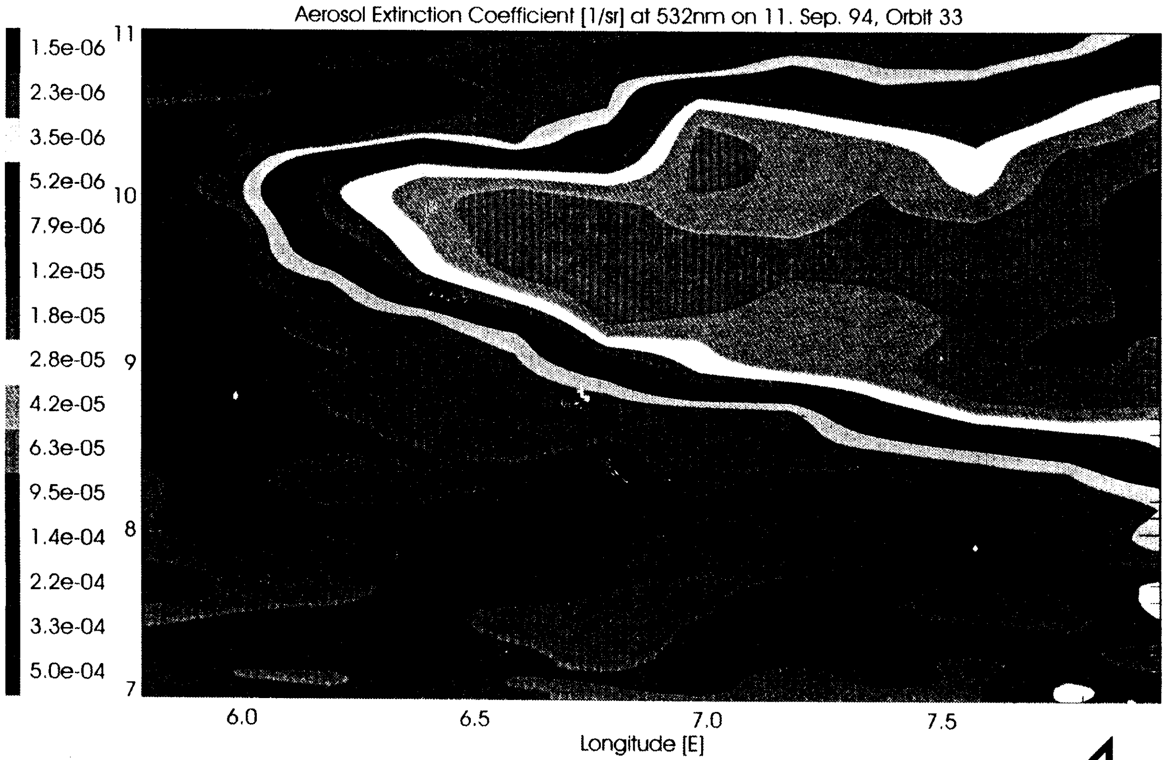

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18th ILRC, Berlin 1996

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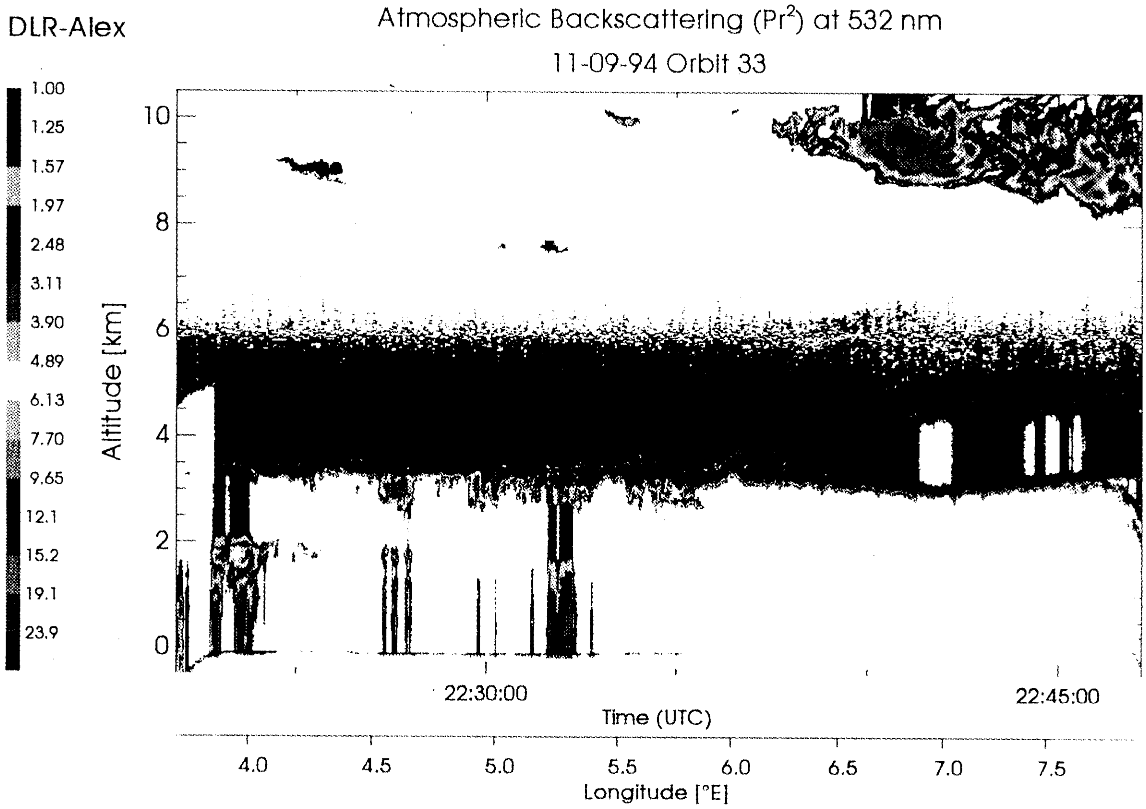
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Altitude [km]
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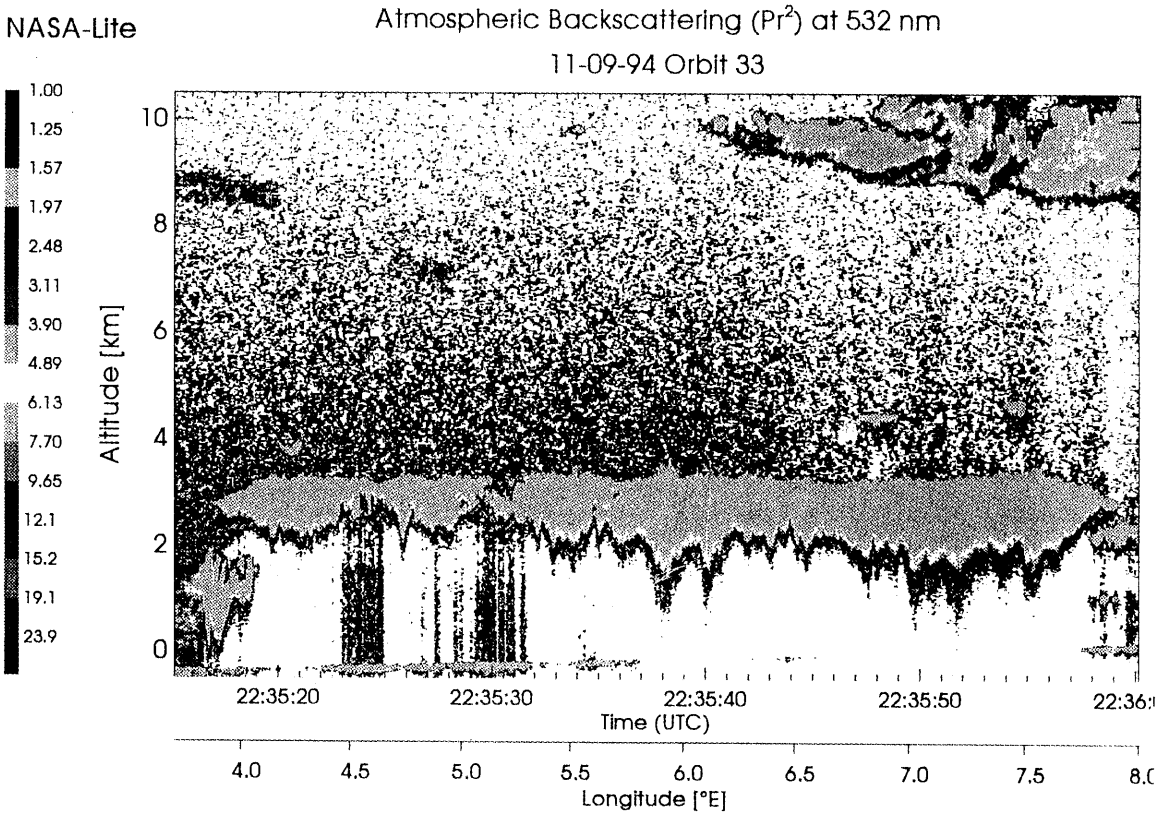
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Altitude [km]
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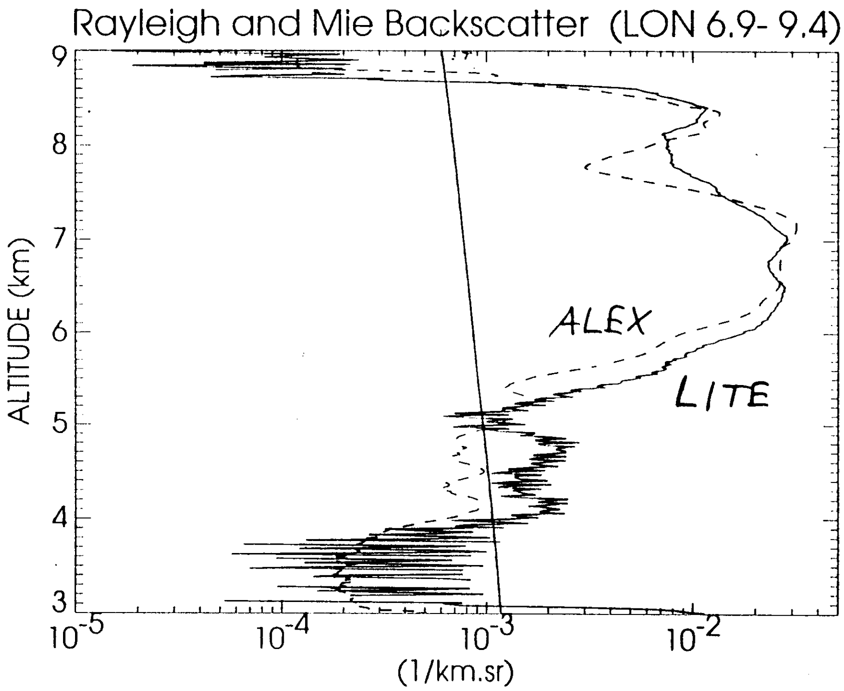
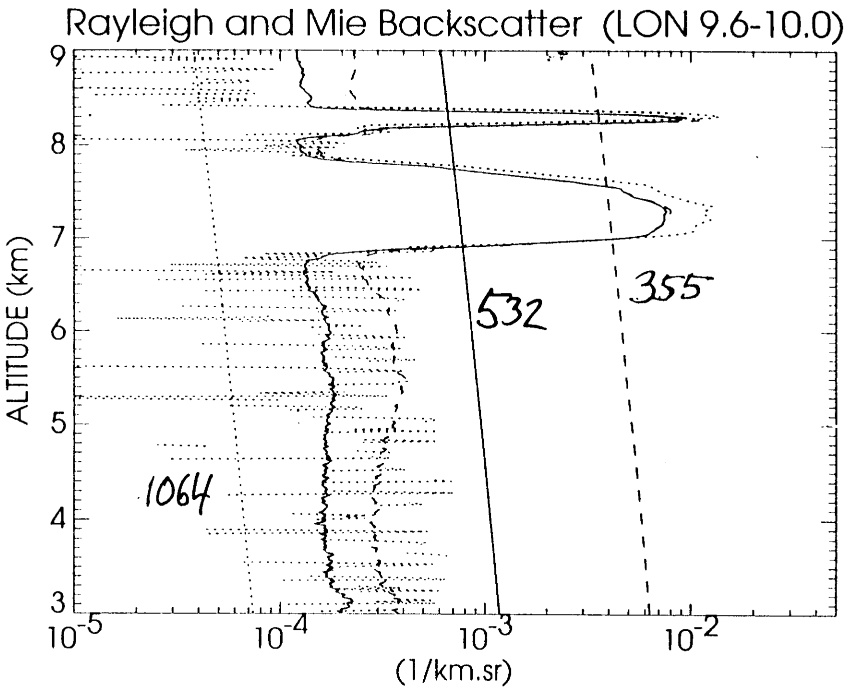
ORBIT 32

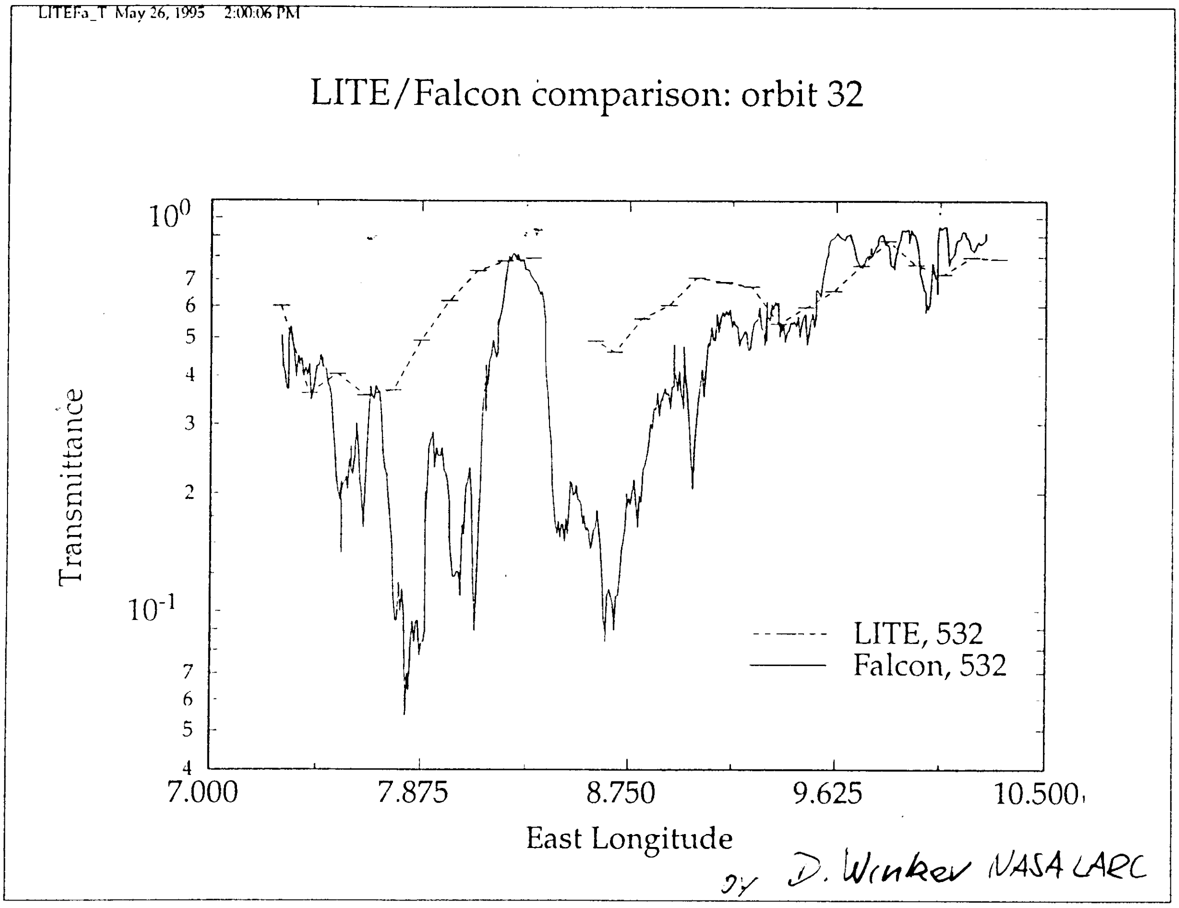
532 nm



ORBIT 32

ALEX

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LITE/Falcon comparison: orbit 32
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Falcon, 532
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8.750
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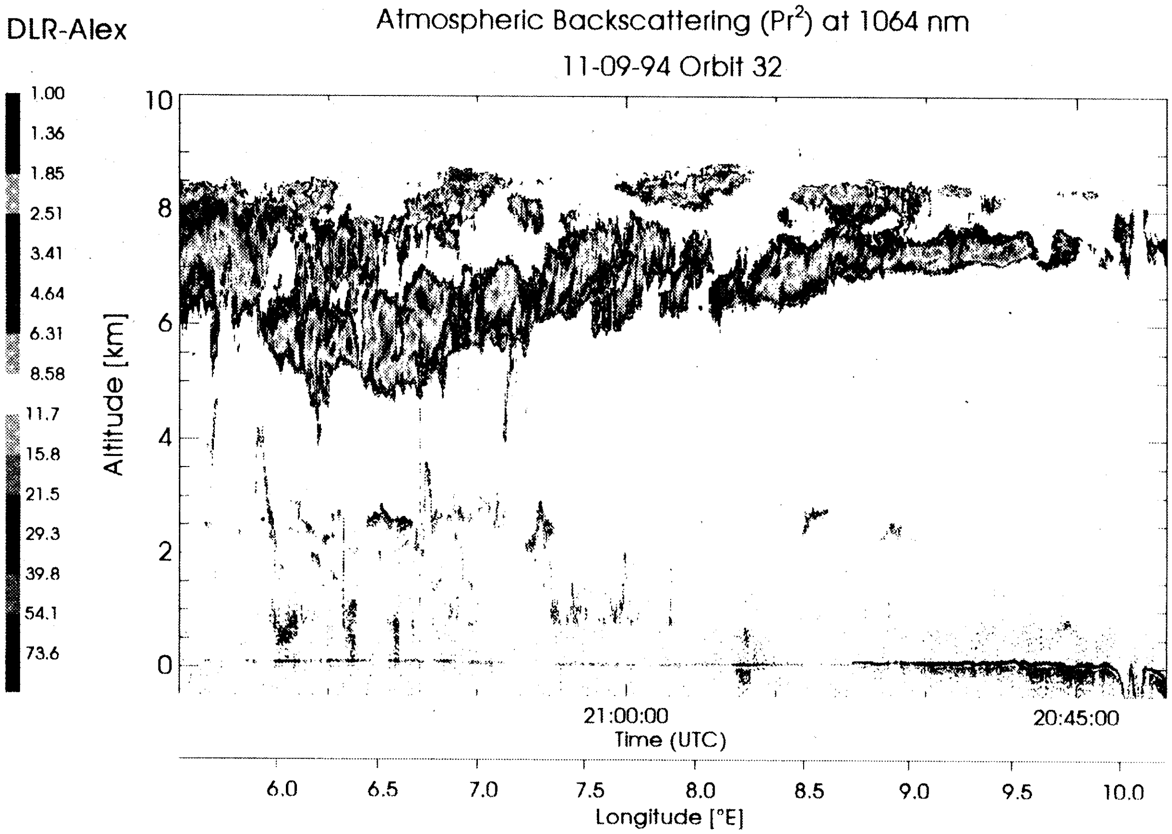
10.500
by D. Winker NASA LARC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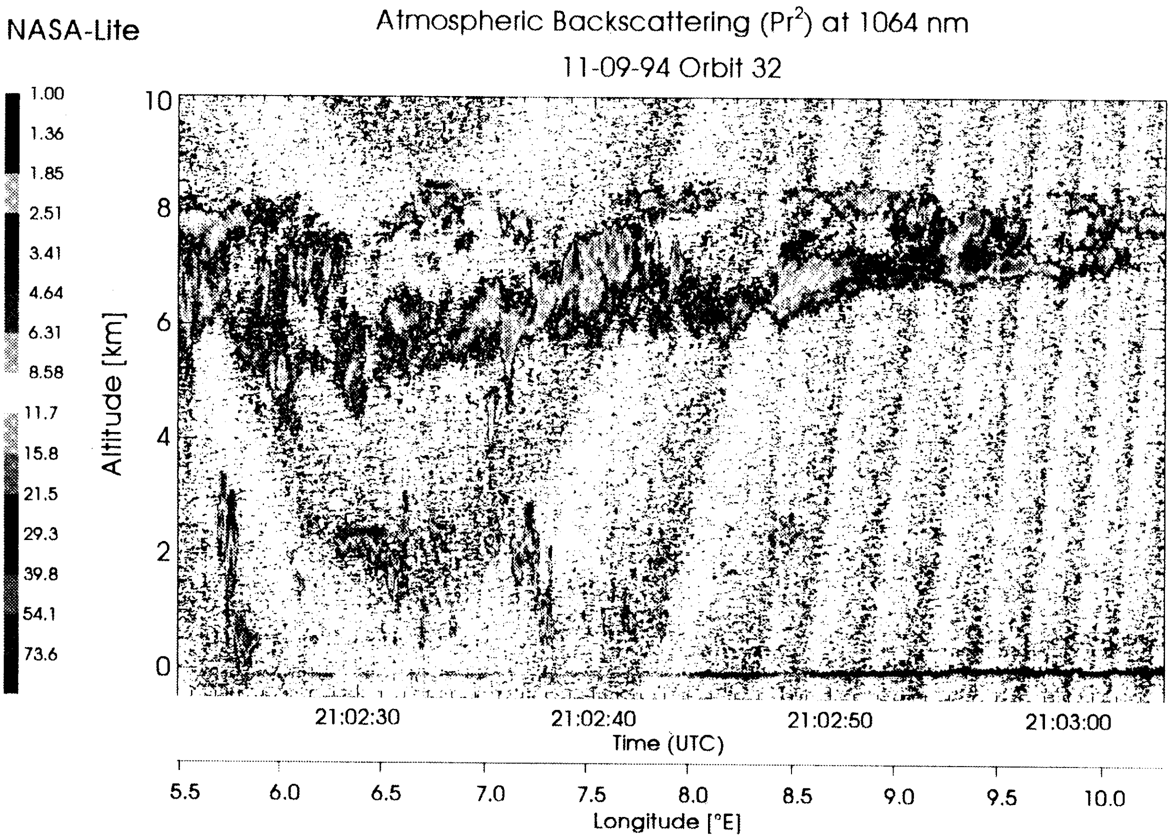
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Altitude [km]
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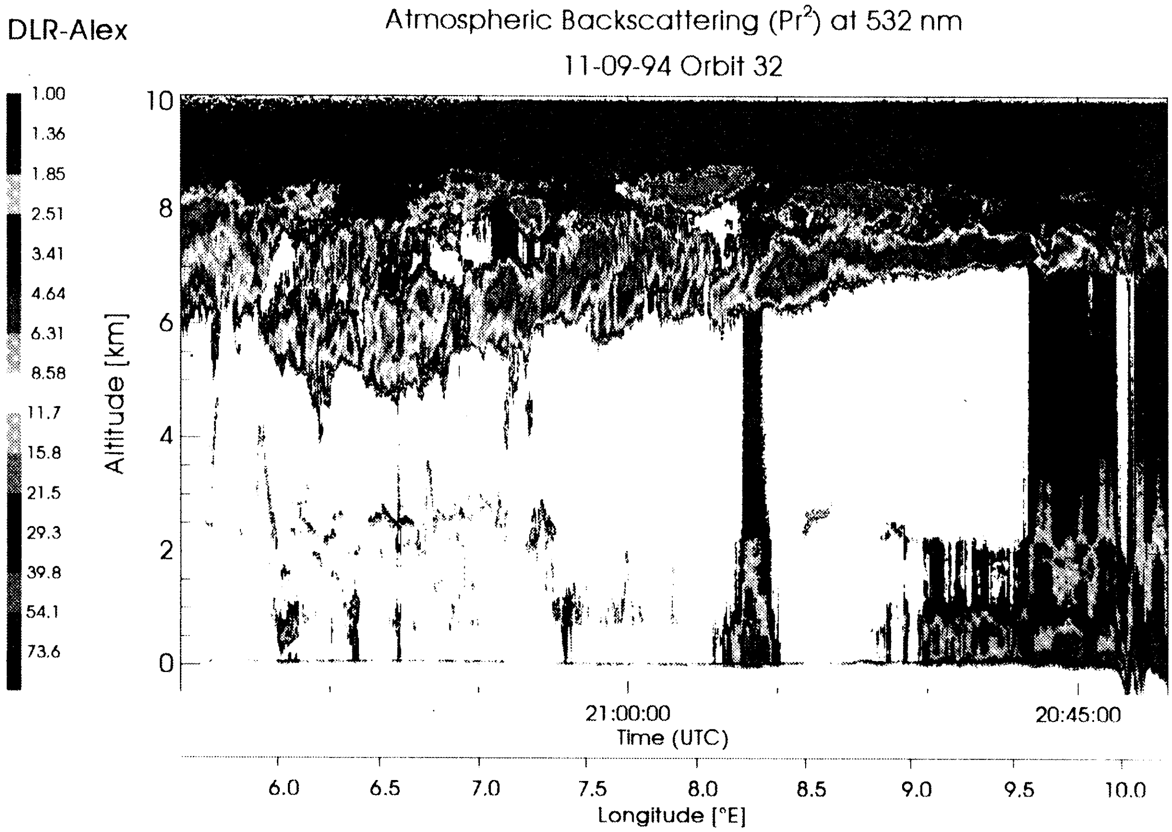
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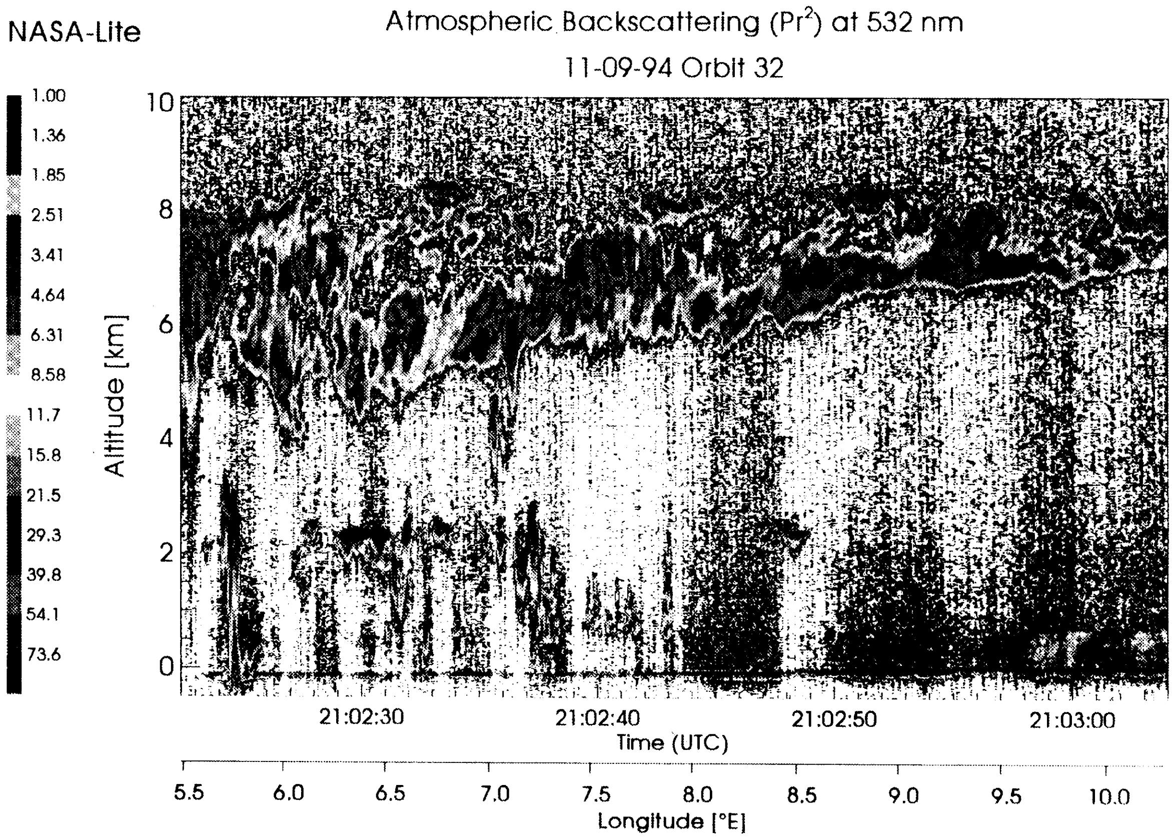
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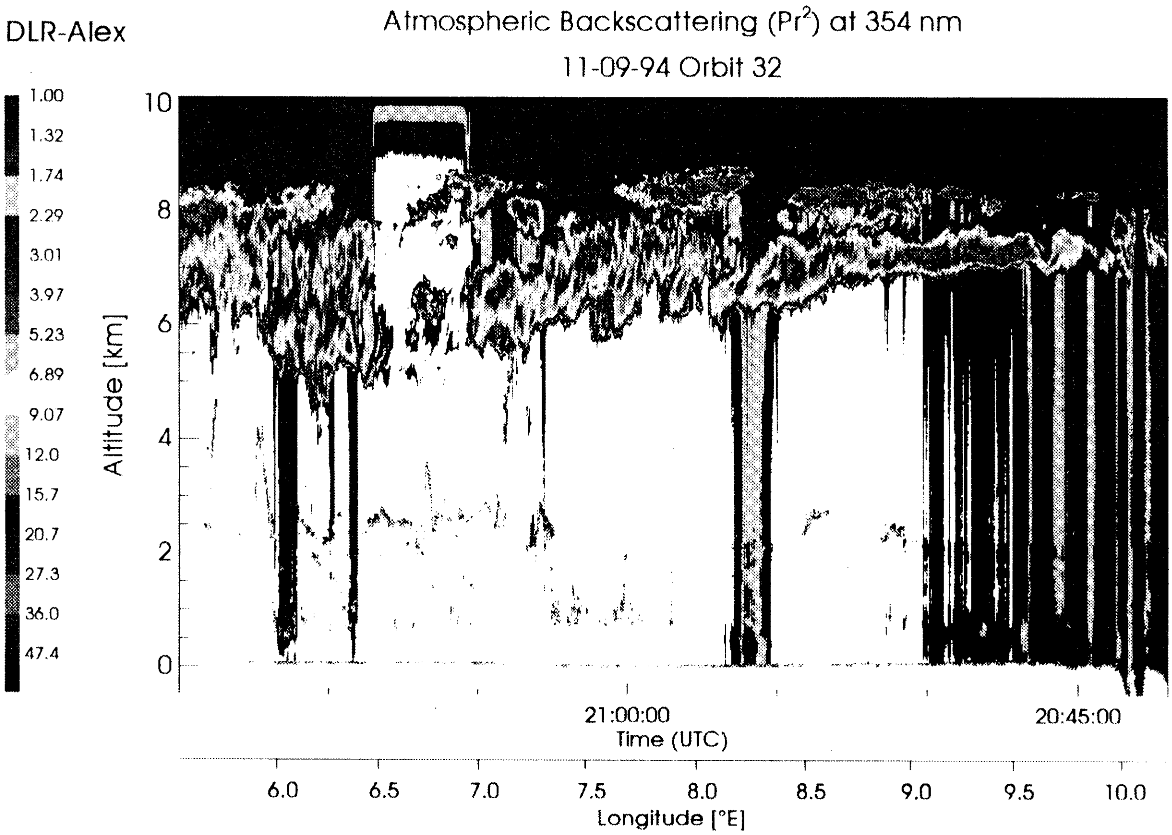
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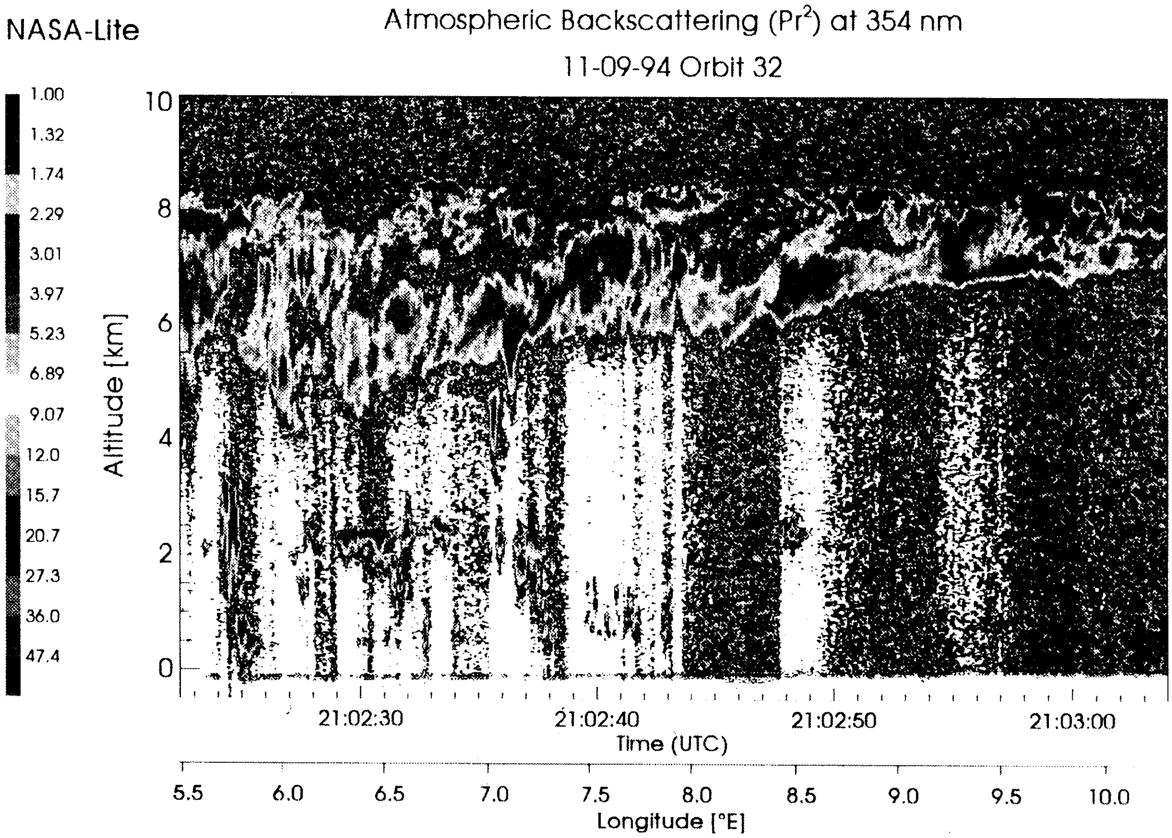
Longitude [°E]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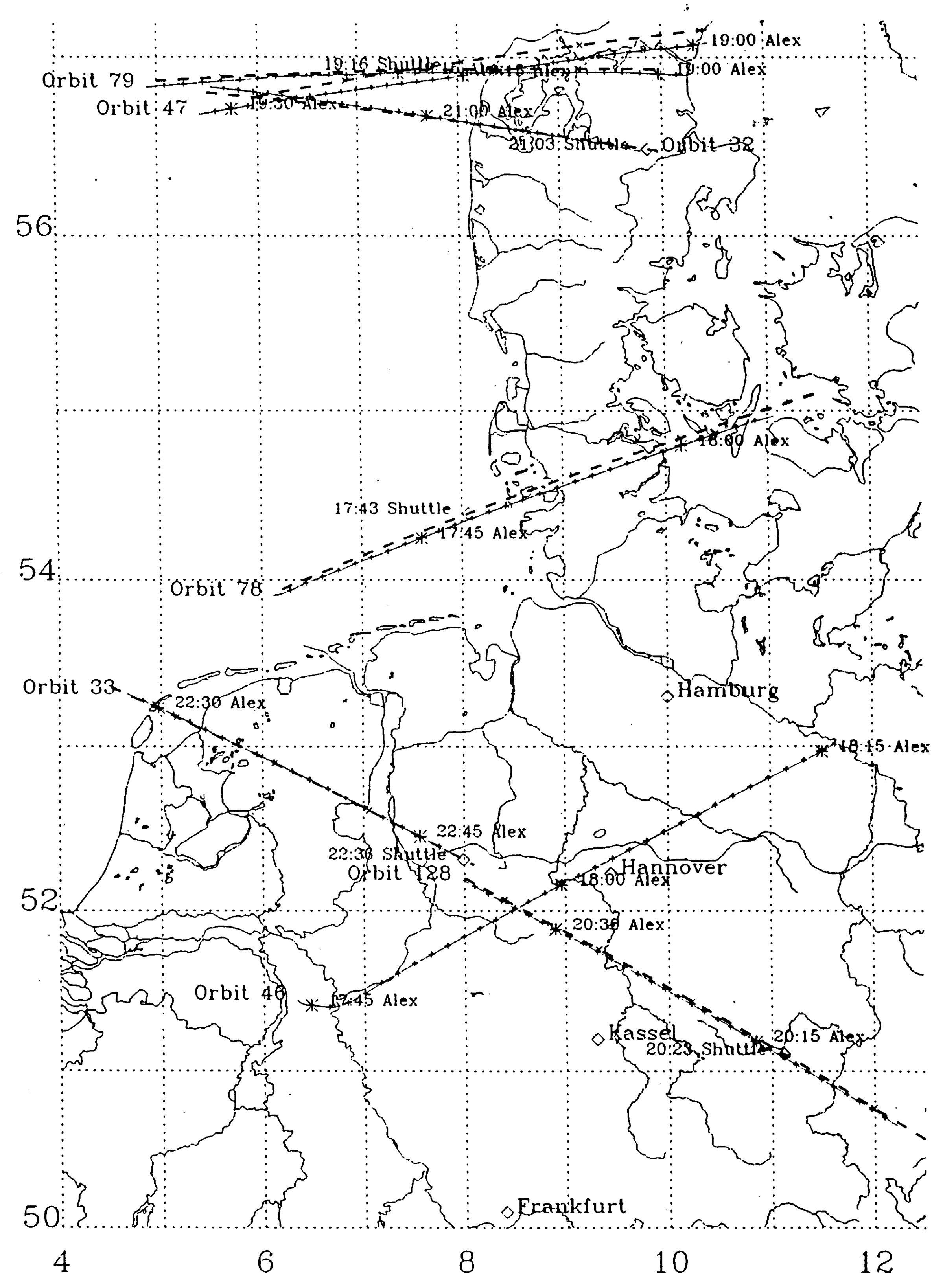
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54
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Orbit 33
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Hamburg
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Orbit 128
Hannover
18:00 Alex
52
Orbit 46
17:45 Alex
Kassel
20:15 Alex
20:23 Shuttle
50
Frankfurt
4
6
8
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12

Correlaive Measurements in Support of LITE Using the Airborne LIDAR ALEX

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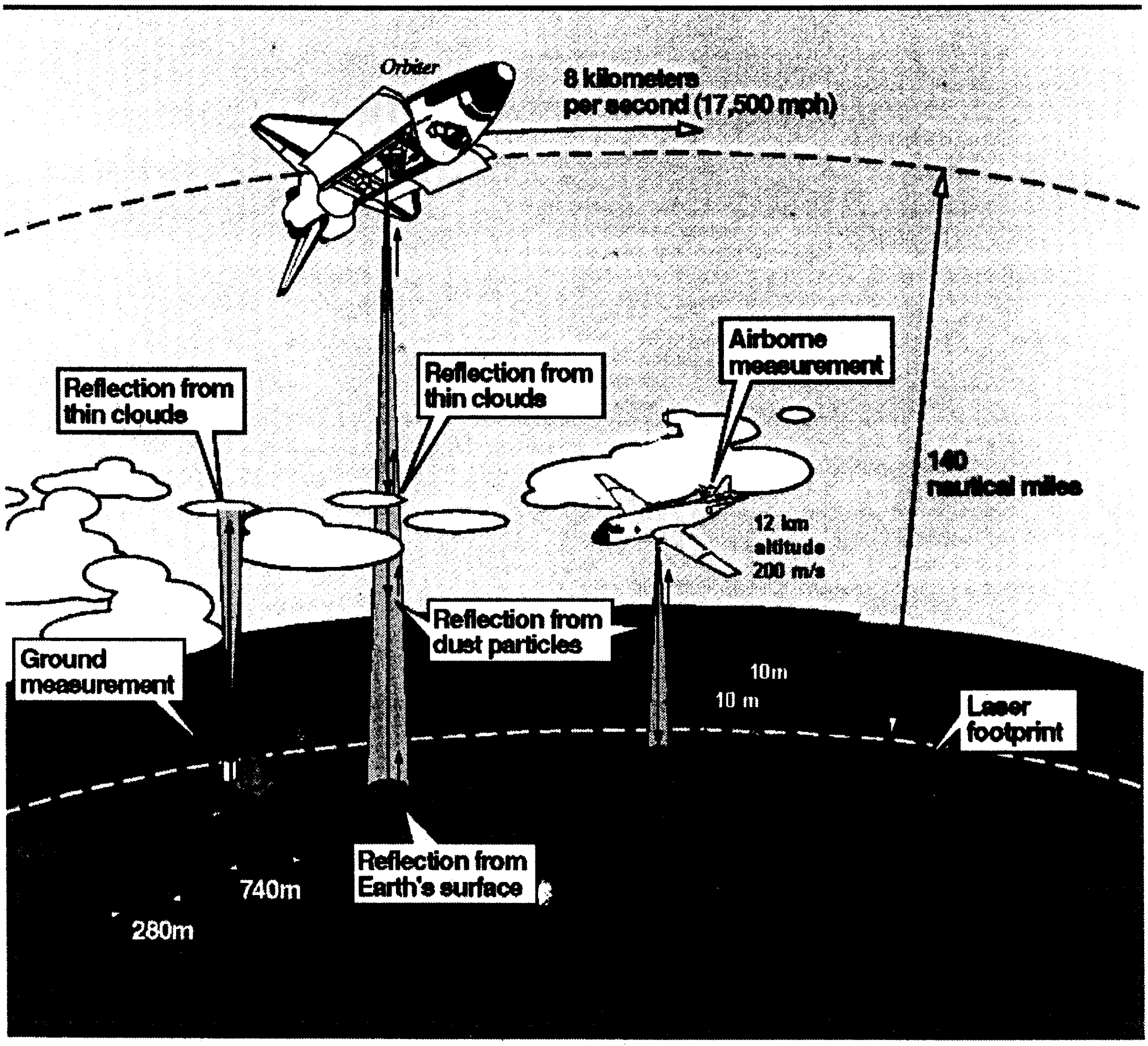

Cartoon: Copy from arbs8.larc.nasa.gov

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Table 2. User Requirements

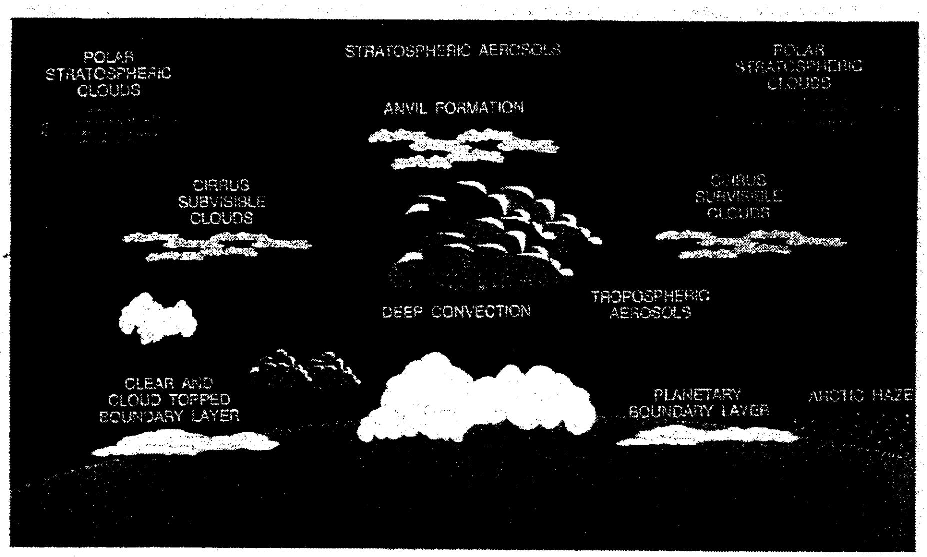
Resolutions and Priorities

Atlid Parameter	Meteorology Horizont. Resolution	Meteorology Vertic. (km)	Meteorology Priority	Environmental Research Horizont. Resolution	Environmental Research Vertic. (km)	Environmental Research Priority
Cloud top height	<50	0.1 (Ci 0.5)	A	500	0.1 (Ci 0.5)	A-B
Vertical extent of cloud	<50	0.1 (Ci 0.5)	A-B	500	0.1	B
Optical depth of thin cloud	100	0.5	C	100	0.5	A
Planetary boundary layer height	100	0.1	A	500	0.1	B
Tropopause height	100	0.5	B	–	–	D
Tropospheric aerosols	100	0.5	C	500*	0.5	A-B
Stratospheric aerosols	–	–	D	100	1.0	C

(Ci = cirrus   * 200 for optical depth boundary layer)

Frequency of Observation

System Requirements	Meteorology	Environmental & Climate Research
Area of coverage	Global } every day	Global } may be achieved over several days
Frequency of observations	6-hourly	6-hourly
Duty Cycle	100%	Selective
Reliability	High	High
Lifetime	3 + years	3 + years



ALEXIS (Atmospheric Lidar EXperiment in Space)

Improvements by a combination of operationall passive sensors with a backscatter lidar compared to present passive sounders

Parameter	Improvement	Importance for	present aocuracy
Cloud top height	Temperature at cloud top Temperatureprofile above clouds Humidity at this level	Weather forecast	> 1 km, 1 K
Radiation properties of clouds	Ice–/ Waterdiscrimation Liquid water content ? Temperature profile	Weather forecast Cloud physics	not detectable
Tropopause height	Temperature profile above and below the tropopause	Weather forecast	> 1 km, 3 K
Height of the PBL (Planetary boundary layer)	PBL stability Flux of sensible heat ocean to atmosphere	Climatology Weather forecast Pollution monitoring and forecast	not resolved
Subvisible clouds height assignment and opt. Thickness	Total temperature profile Humidity at cloud level Surface temperature	Climatology Wettervorhersage	not detectable
Aerosol layers in troposphere and stratosphere	Surface temperature Global radiation at ground level Radiation budget	Climatology	sometimes detectable no height assignment

DFVLR NE–PA
1988 – LIDAR/spa