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LIDAR Remote Sensing Concepts

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1) New Millennium Program

1.1 Introduction

The primary goal of the NASA New Millennium Program (NMP) is to develop technology for use on future operational missions. The Program consists of two thrust areas, one oriented towards developing technologies for Deep Space Probes and one oriented towards developing technology for Earth Observing Probes. Each thrust area intends to fly several technology demonstrator spacecraft designated DS-X and EO-X respectively where X is the mission number. Each mission has an ~$100 million cap on total mission cost. The EO-1 mission has been selected and is under development. The instrument discussed here was submitted by NASA MSFC as a potential candidate for the EO-2 or EO-3 missions due to launch in 2001 and late 2002 or early 2003 respectively. This report summarises and follows the format of the material provided to NMP.

1.2 Mission Objectives

1.2.1 Science:

To profile horizontal wind speed in the troposphere such that the measurement requirements identified by the NOAA Working Group on Space-Based Lidar Winds [1] are met. These requirements were recently adopted by the NOAA/DOD/NASA NPOESS Integrated Program Office as the (currently) unaccommodated EDR for winds and have subsequently been adopted, with some modification, by the New Millennium Program.To further the attainment of these science goals, the purpose of this instrument is to:

- Obtain accurate, unbiased line of sight (LOS) wind velocity estimates from the PBL, clouds, and regions of high backscatter in the mid-troposphere.

- Demonstrate the combination of various LOS velocity perspectives into horizontal velocity estimates.

- Assimilate horizontal wind measurements (and possibly LOS measurements) and demonstrate NWP and climate change benefit.

- Demonstrate accurate assignment of cloud top and bottom heights.

1.2.2 Technical:

To demonstrate the successful operation of a coherent Doppler lidar for the measurement of wind such that sufficient confidence is developed in the technique to enable the development and deployment of a wind sensor on NPOESS. The optimisation of the NPOESS wind sensor will also be enabled through analysis of this mission.

1.3 Mission Concept

The instrument will utilise Doppler analysis of coherently detected backscatter from entrained aerosols and cloud particles in the troposphere. The instrument design is based on a series of studies collectively known as AEOLUS (Figure (1.1)) that were conducted at NASA Marshall Space Flight Center.

The AEOLUS concept called for an instrument that could be mounted to any available platform and this concept was carried forward into this preliminary concept design for NMP. The obvious benefit of this approach is that any platform that satisfies the basic accommodation requirements can be utilised.

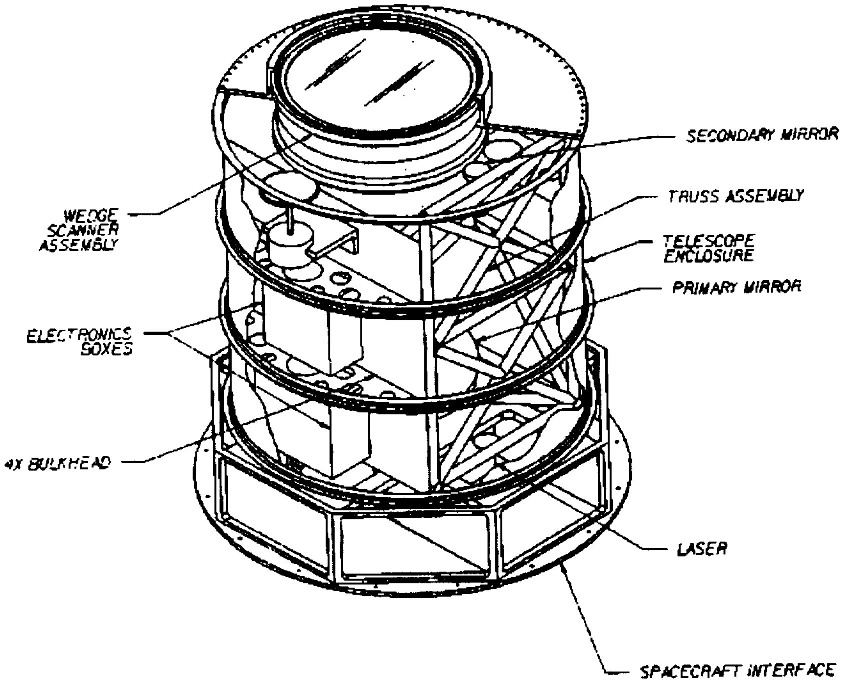


Figure (1.1) A schematic of the AEOLUS instrument from which the NMP design was derived.

A block diagram of the instrument subsystem is shown in Figure (1.2).

1.4 Description of Technology

A solid state transmit laser produces a 0.5 J, 0.2-0.5 μs long single mode pulse at a nominal wavelength of 2 μm and a nominal PRF of 10 Hz. The transmitted beam is expanded to a collimated beam by a 0.5 m diameter nadir-looking 3-element off-axis telescope and deflected 30 deg. from nadir by a rotating Si wedge. The wedge produces an elliptical beam transmitted into the atmosphere resulting in an effective telescope aperture of 0.46 m. A diffractive/holographic element

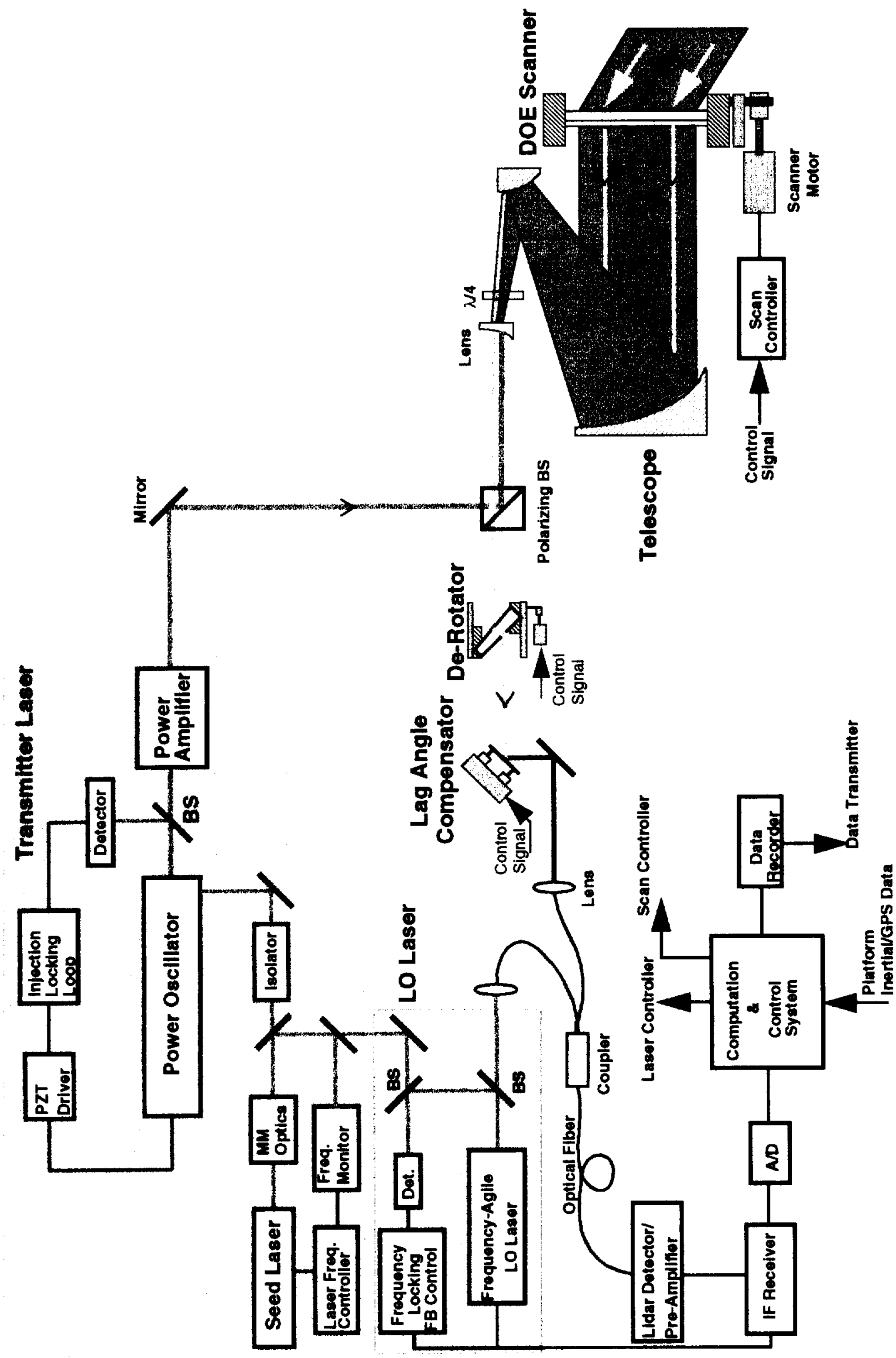


Figure (1.2) Instrument schematic showing the major subsystems.[2]

would be used in place of the wedge (with a considerable mass saving) if the technology matures sufficiently. As the beam is transmitted through the atmosphere, a small fraction is backscattered by aerosols and clouds. The backscattered signal is frequency shifted due to the relative velocity of the target and the spacecraft.

The backscattered signal is collected by the telescope and routed to the room temperature InGaAs signal detector using a Wang geometry optical receiver [3][4]. At the detector, the signal is mixed with an optical local oscillator (LO) signal. The local oscillator frequency is tuned to remove most of the Doppler shift due to the spacecraft motion. The electronic portion of the receiver uses a tunable electronic local oscillator to remove frequency shifts due components of the earth's rotational velocity seen by the instrument and to provide fine adjustment for potential errors in the optical local oscillator frequency. The signal is then split into I and Q components and digitised. The digitised signal is stored together with appropriate housekeeping and health and status data and at an appropriate time downloaded to the ground through the spacecraft supplied data link.

Finally, on the ground, the data is run through a velocity estimator to convert the signal frequency into a line of sight velocity vector. Velocity vectors from individual shots at different perspectives can be combined to produce vector(s) representative of the wind field.

1.5 Mission Benefits

1.5.1 Near-term:

This initial technology demonstrator mission will provide the scientific community with a significant amount of data to enable the optimisation of the impact that an operational wind lidar will have on climate change research and weather prediction.

1.5.2 Long-term:

An operational wind lidar will improve long term weather forecasting and this can result in cost savings for many industries (e.g. farming) that depend on weather forecasts. The instrument has potential for improved disaster prediction with a resultant reduction in deaths and injuries or of unnecessary evacuations. A review of the economic benefits of a space based wind lidar is contained in a report by J.J. Cordes.[5]

1.6 Justification for Space Flight

Coherent lidar has a long and varied history of providing atmospheric wind velocity measurements from the ground and from airplanes. The need for the measurement of winds from space has been well documented [6] but a coherent lidar has been perceived as technologically complex and risky to fly directly as an operational science instrument. The NMP provides an ideal opportunity to validate the technology from space and thereby deliver the technology for one of the significant unmet atmospheric parameters into the hands of the science and operational forecasting communities.

1.7 Instrument Characteristics

Table (1.1) summarises the basic instrument characteristics requested by the New Millennium Program.

Characteristic		Value	Comments
Spacecraft	Type	Any	Will consider any platform satisfying accommodation requirements
	Orbit type	No preference	
	Orbit altitude	300 - 400 km	Prefer low orbit to maximise SNR
	Orbit inclination	as close to 90 as possible	Maximise coverage of earth's surface
Laser	material	Ho:YLF or Th,Ho:YLF	
	wavelength	2.02 or 2.06 μm	
	pulse energy	500 mJ	Maximise within spacecraft power and available technology constraints
	pulse width	200 - 500 ns	Must be shorter than minimum range gate.
	L.O. tuning range	± 4 GHz	to remove Doppler shift induced by spacecraft motion wrt target
Optical	Diameter	0.5 m	
	Scanning type	30 deg conical	Provides coverage, biperspective wind views
	Scanner	Si wedge	Will use HOE/DOE if wavefront/efficiency requirements can be satisfied
Mass		358	Includes 20 % contingency and some contingency at the subsystem level
Power		625/289/162	Operational/ warm-up/ standby; includes 20% contingency
Data	Peak Rate	~6 MB/s	See text for assumptions
	Volume	~50 MB/day	Assuming 10% duty cycle
Overall envelope		1.22 (D) x 1.35 (L) m^3	Cylindrical shape
Technology Readiness Level		3/4	

Table (1.1) Instrument Characteristics requested by NMP.

1.8 Data Plan

1.8.1 Strategy:

Two basic mission profiles are being considered for an operational instrument, the first assumes continuous data collection and rapid provision of that data to the Numerical Weather Prediction (NWP) community at all times. The second uses hindcasting [7] and requires operation ~10% of an orbit but at times specified by the NWP community. At this time it is not clear how large the resources available to a lidar on the converged DOD/NOAA platform will be.

The first option uses a nominally 10 Hz laser prf to provide a reasonable shot pattern density (see Figure (A.9) in Appendix A for typical shot patterns) throughout an entire orbit. This requires considerable resources from the platform as the instrument is continously consuming ~650 W and producing raw data at the rate of ~6 MB/s or ~500GB/day.

The second operational scenario recognises two basic facts. The first is that for a significant fraction of the time, the output from the current global climate models is generally adequate. The second is that an active remote sensor such as a coherent Doppler lidar consumes a lot of spacecraft resources (power) and is thus expensive to support. Recognising these facts the science community is investigating the feasibility of using hindcasting to determine the optimum locations for collecting data with a coherent Doppler lidar. This technique relies on running numerical weather prediction models and looking at divergences in the output results from different models (or the same model with slightly perturbed input conditions). These divergences are indicative of a breakdown in the model and can frequently be traced back to some set of localised starting conditions. In an operational sense, when a region of inadequate atmospheric data has been identified, an orbiting lidar could be programmed to collect data in that region during the next several passes over the region. These regions are likely to be associated with unstable atmospheric conditions and thus need to be well sampled in order to extract useful wind data. This leads to the requirement of a higher PRF from the laser and the 20 Hz currently identified is probably close to a bottom limit on the acceptable PRF. It is currently estimated that there will be several such regions each orbit leading to the lidar being operational ~10% of the time. This results in a significant reduction in the average power consumption for the lidar - although the peak power consumption during operation will increase.

It should be noted that at this time there is insufficient evidence to assess the value of the hindcasting approach and a series of Observing System Simulation Experiments (OSSEs) needs to be conducted by the NWP community in order to provide suitable data for evaluating the potential of the technique.

The mission proposed to the New Millennium Program requested an orbit duty cycle of ~10% as it was felt that this was high enough to provide sufficient data volume to validate the concept of using lidars to generate meaningful wind data but low enough to not have the platform data link become a significant cost driver. In a final operational system the data recorded would be subject to compression techniques and it is felt that the lidar data (particularly from higher altitudes) will be amenable to some simple but effective (lossless) compression schemes.

1.8.1.1 On Orbit:

Operation required for ~ 10% of each mission cycle; occasional real-time downlink for system diagnostics at ~6 Mb/s (assuming no data compression).

1.8.1.2 Calibration/Validation Plan:

Intercomparison against land-based and airborne wind lidars. At least two overflights of a land-based station desired. Intercepts with airborne instruments and NSCAT are also anticipated.

The NPOESS IPO has expressed interest in supporting calibration and validation of any demonstration mission. NOAA has also expressed interest in supporting calibration and validation activities as well as the possibility of existing support from within NASA Code Y. It was anticipated that the Marshall DAAC (which has subsequently been closed) would have been made available for data processing.

1.8.1.3 Post-Mission:

One of the goals of the mission would be to demonstrate the feasibility of the timely delivery of data to the NWP community. In this respect considerable work will be carried out prior to mission completion. However it is anticipated that 8 months of post-processing and reconciliation with data from the calibration and validation program will be required. A statement of goals met/not met would be provided 12 months from end of mission.

1.9 Accommodation Requirements

In addition to the information given in Table (1.1) the control, stability, knowledge and data requirements listed in Table (1.2) - (1.5) were also provided to the NMP.

The data in Table (1.2) - (1.5) assume a 300 km orbit height. It should be noted that the transmitter/receiver boresight alignment requirement in Table (1.2) is a stability requirement over the signal round trip time (ie 2.3 ms) only and is not equivalent to a "Hubble" type staring specification where the boresight must be effectively held for some considerable time period.

Specification	Value	Driving Requirement	Comments
S/C horiz. velocity	15 m/s	Budget for received signal spectrum shift	
Laser nadir angle at S/C	0.1 deg (360 arcsec)	Budget for received signal spectrum shift	GLAS ~90 arcsec
Laser azimuth angle at S/C	0.1 deg (360 arcsec)	Budget for received signal spectrum shift	GLAS ~90 arcsec
XMTR/RECR boresight alignment over echo time	3.2 µrad (0.671 arcsec) over 2.3 ms	3 dB SNR loss	GLAS < 2 arcsec over 1 s

Table (1.2) Control/stability requirements provided to NMP.

Specification	Value	Driving Requirement	Comments
S/C horiz. velocity	0.6 m/s	0.3 m/s LOS velocity error	
S/C vert. velocity	0.35 m/s	0.3 m/s LOS velocity error	
Nadir angle at S/C	45.5 µrad (9.4 arcsec)	0.3 m/s LOS velocity error	GLAS ~ 5 arcsec
Azimuth angle at S/C	74.1 µrad (15.3 arcsec)	0.3 m/s LOS velocity error	GLAS ~ 5 arcsec
S/C altitude above local earth surface	50 m	Max. 50 m target height error	
Round trip time of light	0.4 µs	Max. 50 m target height error	
Freq. diff. XMTR at t=0 to LO at t= 2.3 ms	300 kHz	0.3 m/s LOS velocity error	
Local horiz. direction relative to a perfect sphere	~ 4 deg.	0.3 m/s error in converting LOS velocity to horiz. velocity; 100 m/s max. horiz. velocity	

Table (1.3) Knowledge requirements provided to NMP.

Parameter	Value	Notes
nominal maximum wind velocity any direction	±100 m/s	Permits observation of some jets. This is not the bandwidth for the purpose of calculating SNR.
error in nadir angle	+/- 0.1 degs	Increasing the nadir angle increases the signal capture bandwidth required.
transmitter/lo frequency offset error	10 MHz	Accounts for failure to exactly tune the optical local oscillator to the correct frequency.

Table (1.4) Assumptions used in assessing the data requirements.

Parameter	Value	Notes
Sampling rate above Nyquist	1.1X	
Digitiser resolution	12 bit	Could possibly manage with 10 bit (reduces data storage) but restricts dynamic range available.
Aerosol target altitude range	0 - 20 km	
Guard band range	1 km	This represents additional digitising time outside of the 0-20 km window listed above and ensures capture of data in the event of a timing error.
Electronic Receiver type	Complex	Splitting the electronic receiver lowers the bandwidth required from the A/D converters but increases the number of A/D converters required.
Duty cycle	10%	Based on the proposed data plan for this demonstration mission.
Ancillary data	240 bits	A nominal allocation of 20x12 bit words for ancillary data is included in the data requirement estimates.
Data compression	None	Worst case scenario - in reality there is likely to be potential for considerable data compression.

Table (1.4) Assumptions used in assessing the data requirements.

Parameter	Value	Notes
Peak sample rate	149 Msamples/s	A simple analysis without accounting for the frequency errors listed in Table (1.4) reduces this to ~100 Msamples/s.
Digitisation time for each pulse	163.2 μs	This is the time for the optical pulse to travel through the atmospheric sample to the ground and back out again.
Data collected on one shot	583,242 bits	
Data collected in one orbit/ one day	3.2 GB/ 50.4 GB	10% duty cycle

Table (1.5) Data requirements

1.10 Sensitivity Analysis

An analysis of the performance of the instrument was carried out using the UAH/NASA MSFC lidar simulation model. Appendix A contains screen shot prints of the analysis carried out for this particular mission.

The velocity estimator used for coherent Doppler lidar has a probability density function (PDF) associated with it [8] This PDF expresses the likelihood that the velocity measured is the true wind velocity and not a random noise spike. The performance of coherent Doppler lidar is generally characterised by the aerosol backscatter value at which the probability of the velocity estimate being closely grouped near the true velocity value is 0.5.

Given this situation then, on a single shot basis the instrument will have a worst case backscatter sensitivity (for a mid-latitude summer atmosphere) of $\sim 1\mathrm{x}10^{-7}$/(m-sr) in the boundary layer with a 250 m vertical resolution range gate. In the troposphere the instrument will have a single shot backscatter sensitivity of $\sim 1\mathrm{x}10^{-8}$/(m-sr) for a 2 km vertical resolution range gate. These backscatter estimates include allowances for 6dB of SNR loss due to instrument degradation.

Without these performance degradation margins the (ideal) performance of the instrument on a single shot basis is $\sim 3\mathrm{x}10^{-8}$/(m-sr) in the boundary layer and $\sim 3\mathrm{x}10^{-9}$/(m-sr) in the troposphere. The use of shot averaging [9] over n shots can produce an ~sqrt(n) or better reduction in the minimum detectable backscatter value. The instrument contribution to the velocity error will be < 1 m/s on a single shot.

It should be noted that for backscatter values less than those listed above, the instrument will still produce a velocity estimate but the liklihood that the estimate will be grouped near the correct value will be less than 0.5.

Nevertheless, the combination of velocity estimates from over a grid cell (100 km x 100 km in the boundary layer and 500 km x 500 km in the mid/upper troposphere) can still extract the mean wind velocity in the cell (under certain conditions) by looking at the distribution of the individual velocity estimates.

1.11 Status

After submission of the instrument design, a request was made from the NMP as to the feasabiliy of cutting the mission further and they were informed of an ongoing effort to attempt to fit a coherent lidar within Hitchhiker canisters. The status of this design is covered next.

2) Hitchhiker Instrument Design

2.1 Introduction

A series of conceptual designs for fitting a coherent Doppler lidar into Hitchhiker canisters was conducted. A Hitchhiker canister is a standardised cylinder for STS (space shuttle) payloads provided by the Shuttle Small Payloads Project Office at Goddard Space Flight Center. The canisters can be pressurised and are available either sealed or with a motorised opening door. Table (2.1) summarises the basic parameters of these canisters, detailed specifications are provided in the Hitchhiker Customer Accommodation and Requirements Specification (CARS) documentation available from GSFC.[10] It should be noted that the Hitchhiker platform provides no thermal interfaces, all instrument generated heat must be radiated by the instrument. Figure (2.1) shows both sealed and open-lid canisters together with the GSFC supplied Hitchhiker support avionics mounted on the side of the STS payload bay (Hitchhiker-S). The canisters can also be mounted on a cross-bay bridge structure (Hitchhiker-C). Programmatic requirements are that at least 24 months prior to flight, the customer delivers complete documentation on the payload to GSFC and the flight hardware must be delivered to GSFC ~6 months prior to flight.

Parameter	Value
Interior length	31.25" (28.25" for user)
Interior diameter	20" (19.75" for user)
User mass	200lbs (160lbs for motorised door canister)
Misc interfaces	Four (three for motorised lid can) 28V bi-level or pulse commands (10mA max) for driving relays) IRIG-B format serial time code One pulse/minute square wave signal 3 channels for temperature sensors (sealed cans only) Analog 0-5V channel, converted to 8 bit values, 15 Hz sample rate.

Parameter	Value
Power	Nominally two 28V DC 10 Amp lines
Max. total power	1600 W (HH-C - 8 customers) 1300 W (HH-S 3 customers)
Max. total energy	10kWh/day (HH-C) 4kWh/day (HH-S)
Data	Asynchronous 1200 baud downlink 1-1400 kb/s downlink (split payloads) 50Mb/s downlink by request
Command	Asynchronous 1200 baud uplink channel

Table (2.1) Basic specifications for a Hitchhiker canister.

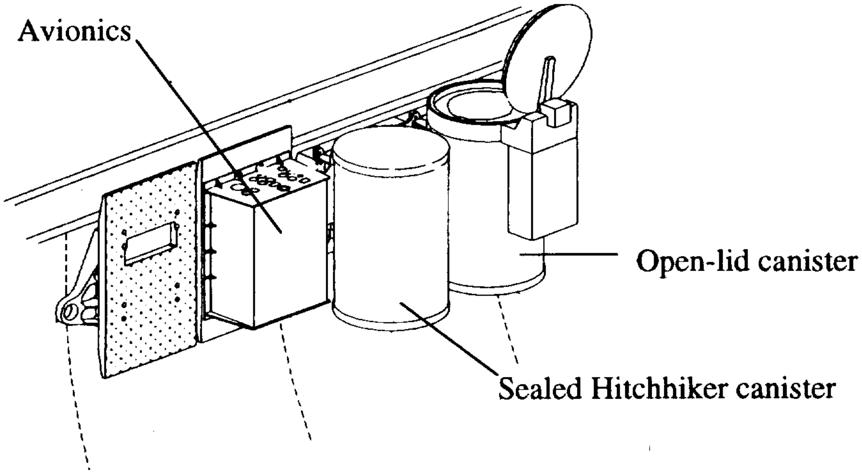


Figure (2.1) Representation of Hitchhiker canister payloads mounted to STS wall.

2.2 Design Concepts

A preliminary design was developed to assess the feasibility of using an existing 100 mJ, 6 Hz 2 μm flashlamp pumped laser, 25 cm diameter telescope [11] and Si wedge scan element available at MSFC. The design concept followed that of the Shuttle Laser Altimeter (SLA) and attempted to use two Hitchhiker canisters, one for the lasers and optics and one for the electronics and controls. The design concentrated on ensuring that all the laser and optical components would fit in one canister. A summary of the preliminary mass properties for this instrument is given in Table (2.2). This table (and the others associated with this design) are not complete because it quickly became clear that there were several problems associated with accommodating the flashlamp pumped laser. These included, but were not limited to, a power draw in excess of what the Hitchhiker carrier could provide, an associated heat dissipation problem and the need to redesign the laser resonator to permit packing within the constraints of a Hitchhiker canister volume. Of these three concerns, the power and thermal constraints were the most problematic.

Table (2.3) lists the preliminary estimate for power consumption among the various subsystems of the instrument. The pulsed laser power estimate is based on a 6 Hz pulse rate with 185 J of energy deposited into the flashlamps for 100 mJ of single mode Q-switched output energy. From the table it is clear that the inefficiency of the flashlamp laser drives the power consumption outside of that available from the Hitchhiker platform. Further compounding the problem is the fact that the lidar is an earth-observing instrument. This means that during operation the STS bay is oriented towards the earth and consequently the ability to reject heat is severely limited. For this instrument, essentially all of the power consumed in Table (2.3) has to be radiated as heat.

This analysis showed that the existing 6 Hz flashlamp pumped laser could not be used as the laser source for a Hitchhiker packaged instrument and the possibility of using a diode pumped laser was investigated. The subsequent conceptual design used conduction cooled diodes to pump the laser and Figure (2.2) shows the difference in power consumption between the flashlamp pumped laser design and the conduction-cooled-diode pumped laser design. The use of conduction-cooled

MASS		**Can 1 (lbs)**	**Can 2 (lbs)**	**Total (lbs)**
Lasers		31.0	75.1	106.1
	Local Oscillator	8.0	10.0	18.0
	Master Oscillator	1.0	3.0	4.0
	Pulsed Laser	22.0	62.1	84.1
Optical subsystem		129.5	35.0	164.4
	Window	13.0	0.0	13.0
	Scanner	76.5	20.0	96.4
	Telescope	30.0	0.0	30.0
	De-Rotator	5.0	5.0	10.0
	Lag-angle compensator	0.0	10.0	10.0
	Miscellaneous Optics	5.0	0.0	5.0
Electronics		0.0	64.0	64.0
	Receiver	0.0	20.0	20.0
	Computer	0.0	44.0	44.0
Thermal		20.5	5.0	25.5
	Pump	2.5	0.0	2.5
	Bypass Valve	18.0	0.0	18.0
	Radiator	0.0	0.0	209.1
	Controller	0.0	5.0	5.0
Misc. Cabling etc.		10.0	10.0	
Structure		32.0	20.0	52.0
Total (Cans)		223.0	209.1	432.0
Radiator				209.05
Max acceptable		160.0	200.0	

Table (2.2) Mass properties of the flashlamp pumped laser Hitchhiker instrument concept.

diodes enabled the elimination of the fluid loop required for the flashlamp pumped system and the adoption of heat pipes for conducting the heat to the outside of the canister. Although the mass in can 1 was still over the 160 lbs outlined in the Hitchhiker documentation, a conversation with the Hitchhiker project office indicated that this did not necessarily prevent a mission from moving forward as there was considerable margin built into the Hitchhiker design. -A preliminary

POWER		Can 1 Power (W)	Can 2 Power (W)	Total Power (W)
Lasers		1165.0	472.4	1637.4
	Local Oscillator	16.0	14.0	30.0
	Master Oscillator	9.0	5.0	14.0
	Pulsed Laser	1140.0	453.4	1593.4
Optics		32.0	28.0	60.0
	Window	0.0	0.0	0.0
	Scanner	15.0	15.0	30.0
	Telescope	0.0	0.0	0.0
	De-Rotator	5.0	5.0	10.0
	Lag-angle compensator	12.0	8.0	20.0
	Miscellaneous Optics			0.0
Electronics		0.0	135.0	135.0
	Receiver	0.0	40.0	40.0
	Computer	0.0	95.0	95.0
Thermal		175.0	15.0	190.0
	Pump	175.0	0.0	175.0
	Bypass Valve	0.0	0.0	0.0
	Radiator	0.0	0.0	0.0
	Controller	0.0	15.0	15.0
Misc. Cabling etc.		10.0	10.0	
Structure				0.0
Total		1382.0	660.4	2042.4

Table (2.3) Power requirements of the flashlamp pumped laser Hitchhiker instrument concept.

Subsystem	Can 1	Can 2	
Local Oscillator	16.0	14.0	
Master Oscillator	9.0	5.0	
Slave Oscillator	90.3	62.9	
Window	0.0	0.0	
Scanner	15.0	15.0	
Telescope	0.0	0.0	
De-rotator	5.0	5.0	
Other Optics	12.0	8.0	
Receiver	0.0	40.0	
Computer	0.0	95.0	
Thermal	0.0	0.0	
Misc. cables, wiring etc.	10.0	10.0	
Structure	0.0	0.0	
Total	157.3	254.9	412.2
Goal			1000.0

Table (2.4) Power requirements of the conduction-cooled-diode pumped laser Hitchhiker instrument concept.

estimate of the instrument volume indicated that it would fit.

Subsystem	Can 1	Can 2	Other
Local Oscillator	8.0	10.0	
Master Oscillator	1.0	3.0	
Slave Oscillator	25.0	3?	
Window	13.0	0.0	
Scanner	76.5	20.0	
Telescope	30.0	0.0	
De-rotator	5.0	5.0	
Other Optics	5.0	10.0	

Table (2.5) Mass properties of the conduction-cooled-diode pumped laser Hitchhiker instrument concept.

Subsystem	Can 1	Can 2	Other
Receiver	0.0	20.0	
Computer	0.0	44.0	
Thermal	12.5	12.5	0.0
Misc. cables, wiring etc.	10.0	10.0	
Structure	32.0	20.0	
Total	218.0	157.5	0.0
Goal	160	200	

Table (2.5) Mass properties of the conduction-cooled-diode pumped laser Hitchhiker instrument concept.

For can 1 the ability to fit all the components within the canister envelope was verified from a preliminary engineering drawing of the packaging concept and for can 2 an initial estimate was made by totalling the known volume currently asigned to the can (5500 in^3) and comparing with the can volume (8600 in^3) - provided that there was considerable room left (as there was) it ws not unreasonable to assume that the electronics could be repackaged as necessary to fit.

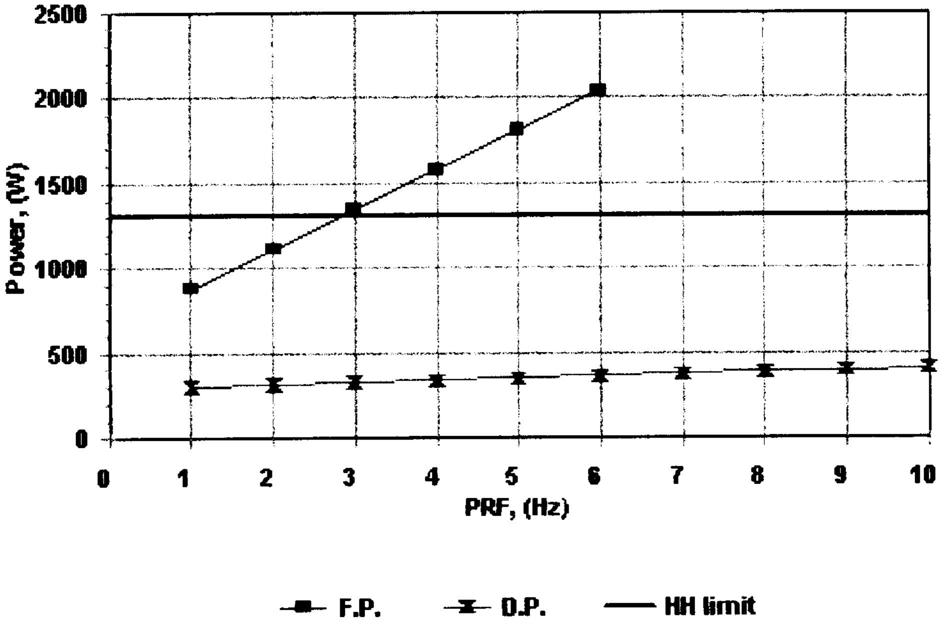


Figure (2.2) A comparison of the power consumption of the flashlamp pumped system (F.P.) and the diode pumped system (D.P.) as a function of laser prf. The red line represents the total simultaneous power available from a HH-S mount.

This preliminary conduction-cooled concept design was subsequently presented to NASA headquarters.

It should be noted that the design hinges upon the use of conduction-cooled-diodes to eliminate a bulky, inefficient fluid loop and that subsequent discussions with potential laser sources found a reluctance to commit to conduction-cooled-diodes. The thermal issues that this raises have not been adequately addressed by MSFC at the time of this report.

2.3 Performance Related Issues

This instrument is primarily a scaled down version of the one discussed in the previous section of this report. The primary difference from a sensitivity point of view arises from the reduced laser pulse energy and telescope diameter. One benefit of the decision to use a diode pumped laser was that this enabled the laser to be chosen with an optimum wavelength in terms of laser efficiency and atmospheric attenuation.

2.3.1 Wavelength selection

There are several issues to consider in choosing the laser wavelength:

- Laser efficiency

There are limited thermal dissipation capabilities within the Hitchhiker can and this will likely lead to a laser selection based on the most power efficient material.

- Atmospheric transmission at line center

The following table shows the two-way atmospheric transmission for some of the wavelengths discussed by laser suppliers. The transmission was calculated using Fascode for a 30 deg slant path from space to the ground using a tropical maritime atmosphere. This atmosphere was chosen as the most likely target for this instrument will be tropical marine aerosols. It can be seen that there is little difference between the two favoured laser hosts, Tm,Ho:YLF and Tm:YLuAG.

Two- way transmission			
Tm,Ho:YAG 2.091282 μm	Tm,Ho:YLF 2.065479 μm	Tm:YLuAG 2.021842 μm	Tm:YAG 2.012552
0.64	0.54	0.52	0.18

Table (2.6) Two way atmospheric transmission from 100 km to ground at a 30 degree nadir angle through a tropical marine atmosphere with 23 km visibility for four common 2 μm laser materials at line center.

- Change of atmospheric transmission with azimuth angle.

The relative velocity between the spacecraft and the earth results in a Doppler frequency shift of the return signal. The magnitude of the Doppler shift seen is a function of the azimuth angle and varies between ~+/- 4 GHz of the laser centre frequency. Ideally we would like the atmospheric attenuation to be constant over the Doppler shift range so that the SNR is not dependent on the azimuth angle. With the exception of Tm:YAG, this is not a concern for the wavelengths under consideration. From Figure (2.3) - (2.6) we see that, except for Th:YAG, the atmospheric transmission only varies by small amounts over the bandwidth and the variation from material to material is insignificant. This means that, with the exception of Th:YAG, atmospheric attenuation is not a major driver on the selection of laser wavelength and the choice will be dominated by laser considerations ie primarily efficiency.

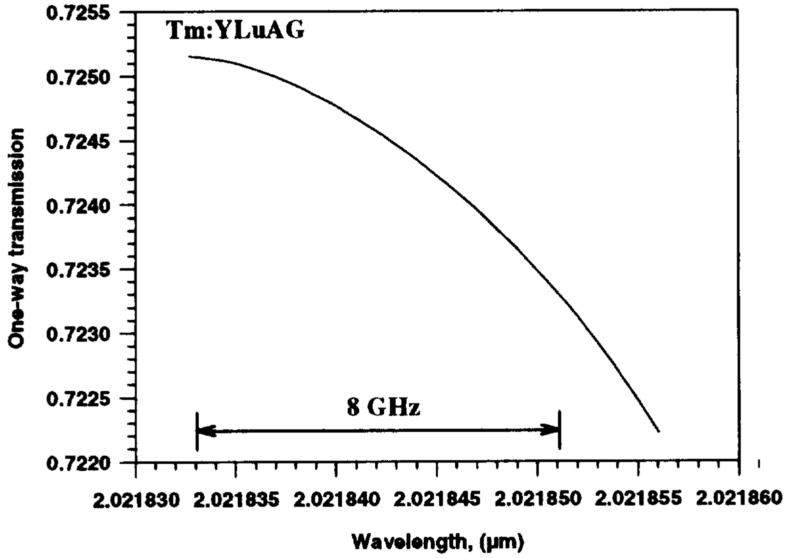


Figure (2.3) Atmospheric transmission from 100 km to the ground for Tm:YLuAG in a tropical maritime atmosphere with 23 km visibility and a 30 deg. nadir angle.

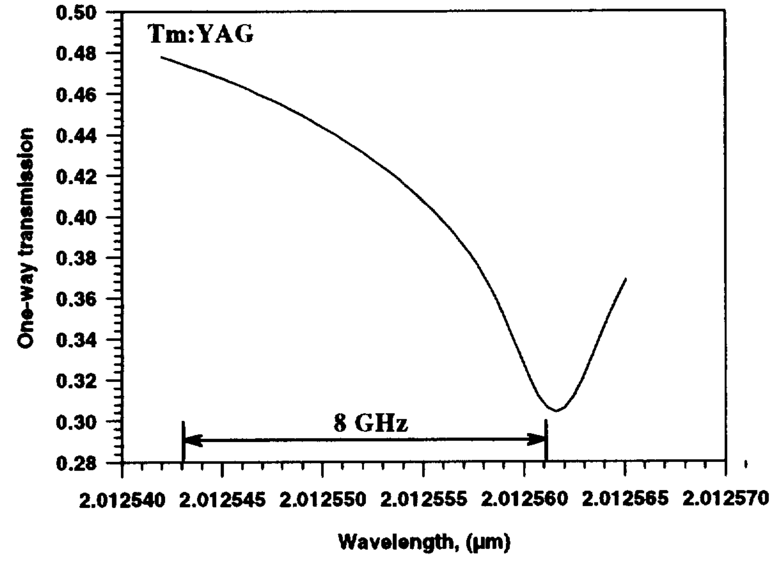


Figure (2.4) Atmospheric transmission from 100 km to the ground for Tm:YAG in a tropical maritime atmosphere with 23 km visibility and a 30 deg. nadir angle.

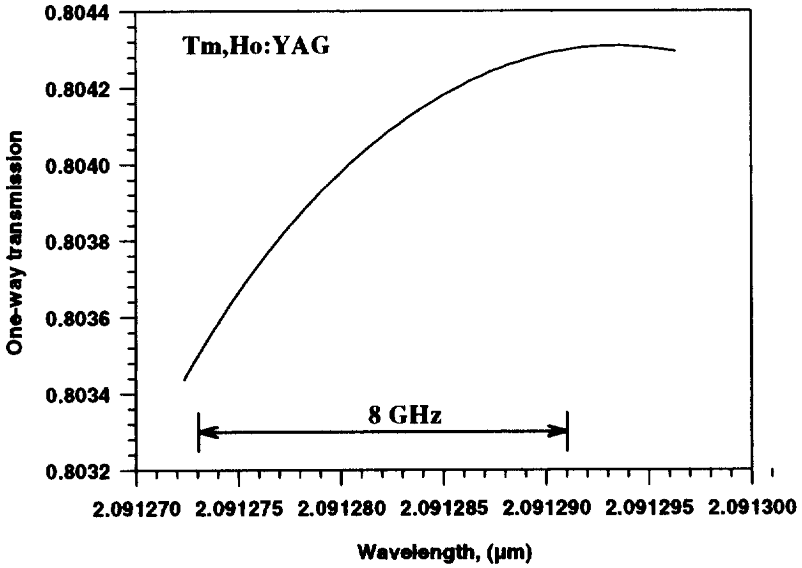


Figure (2.5) Atmospheric transmission from 100 km to the ground for Tm,Ho:YAG in a tropical maritime atmosphere with 23 km visibility and a 30 deg. nadir angle.

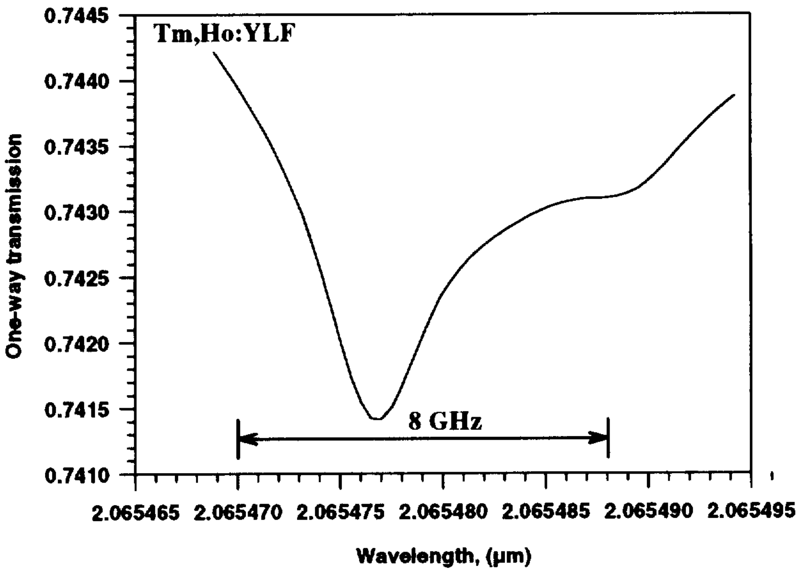


Figure (2.6) Atmospheric transmission from 100 km to the ground for Tm,Ho:YLF in a tropical maritime atmosphere with 23 km visibility and a 30 deg. nadir angle.

2.3.2 Instrument Sensitivity

As mentioned previously this instrument concept is a scaled down version of the one used for the NMP proposal and similar analyses were conducted to determine the instrument performance. Table (2.7) lists the instrument and orbit input parameters used by the model and Table (2.8) lists

LASER			ORBIT		
Wavelength	2.0654790	µm	Orbit height	300	km
Pulse energy	0.1	J	Inclination angle	50	deg
Pulse length	0.2	µs	Max. nadir angle at this height	72.75	deg
Duty cycle	1				
P.R.F.	10	Hz	**RECEIVER/DETECTOR**		
Additional spectral width (FWHM)	0	MHz	Type	Complex	
Gaussian spectral width	0.937	MHz	Geometry	Wang	
Frequency	145144277.91	MHz	Mixing efficiency	0.420	

Table (2.7) Parameters used to assess the Hitchhiker instrument performance.

Min. vertical range resolution	25.54	m	Heterodyne quantum efficiency	0.6	
			Detector truncation efficiency	1	
OPTICS			Detector shot noise efficiency	1	
Telescope diameter	0.25	m	Detector nonlinearity efficiency	1	
Nadir angle	30	deg	System efficiency	0.401	
Transmit intensity fraction	0.955		Total detection efficiency	0.071	
Transmit optics	0.8				
Receive optics	0.8		**SCANNING**		
Polarisation efficiency	0.97		Scan type	Wedge	
Wavefront aberration loss	0.95		Min. beam diameter	0.217	m
Receive/lo misalignment angle	6.765	μrad	Effective beam diameter	0.233	m
Misalignment Loss	3.000	dB	Plot duration	1	mins
Misalignment efficiency	0.501		Telescope rotation rate	10	rpm
SYSTEM					
Margin for unexplained loss	0.5				

Table (2.7) Parameters used to assess the Hitchhiker instrument performance.

the atmospheric, signal processing and other miscellaneous parameters used. Note that as the desired vertical range resolution changes, the signal processing parameters will also change.

TARGET			**SIGNAL PROCESSING**		
Atmospheric Model	Midlat Summer		Horiz. velocity search space	+/-20	m/s
Aerosol Model	Clear		LOS velocity search space	+/- 10.47	m/s
Aerosol altitude	0	m	Probability of a good estimate	0.5	
backscatter (lambda)	5.212E-07	/(m-sr)	Line of sight range resolution	1173.710	m
Max. horizontal wind	+/-100	m/s	Observation time	7.830	μs

Table (2.8) Atmospheric, signal processing and other miscellaneous parameters.

Horizontal wind velocity uncertainty	0	m/s	Effective time between samples	0.0493	µs
Vertical wind velocity uncertainty	0	m/s	Effective digitisation frequency	20.278	MHz
Wind variance between shots	0	m/s	Effective no. samples / obs.	158.779	
Vertical range resolution	1000	m	Phi	4.895	
Target nadir angle	31.570	deg	Signal width	0.937	MHz
Line of sight range to this altitude	349.173	km	Omega	7.337	m/s
Coherence length	4.037	m	Sigmav/w	0.874	
One way Intensity Transmission	0.788		No. of shots/ wind estimate	1	
Maximum line of sight velocity	+/- 52.35	m/s	Bandwidth (wide band)	101.389	MHz
			Bandwidth (narrow band)	0.937	MHz
MISCELLANEOUS PARAMETERS			Bandwidth (search band)	20.278	MHz
Satellite velocity	7733.138	m/s	MLE row no.	32	
ground track velocity	7385.390	m/s			
Earth rotation velocity at equator	463.3360	m/s			
Nadir angle at ground	31.570	deg	**RESULTS**		
Slant range to ground	349.173	km	Wideband SNR	-22.100	dB
Time for one orbit	5420.452	s	Narrowband SNR	-1.758	dB
Swath radius (conical/wedge scan)	174.608	km	Searchband SNR	-15.110	dB
Optimum mirror flip time (line scan)	33.433	s	P(bad)	0.500	
Solid angle subtended at target	3.487E-13	sr	P(good)	0.500	

Table (2.8) Atmospheric, signal processing and other miscellaneous parameters.

The results from the model are summarised in Figure (2.7) - Figure (2.9). When looking at the

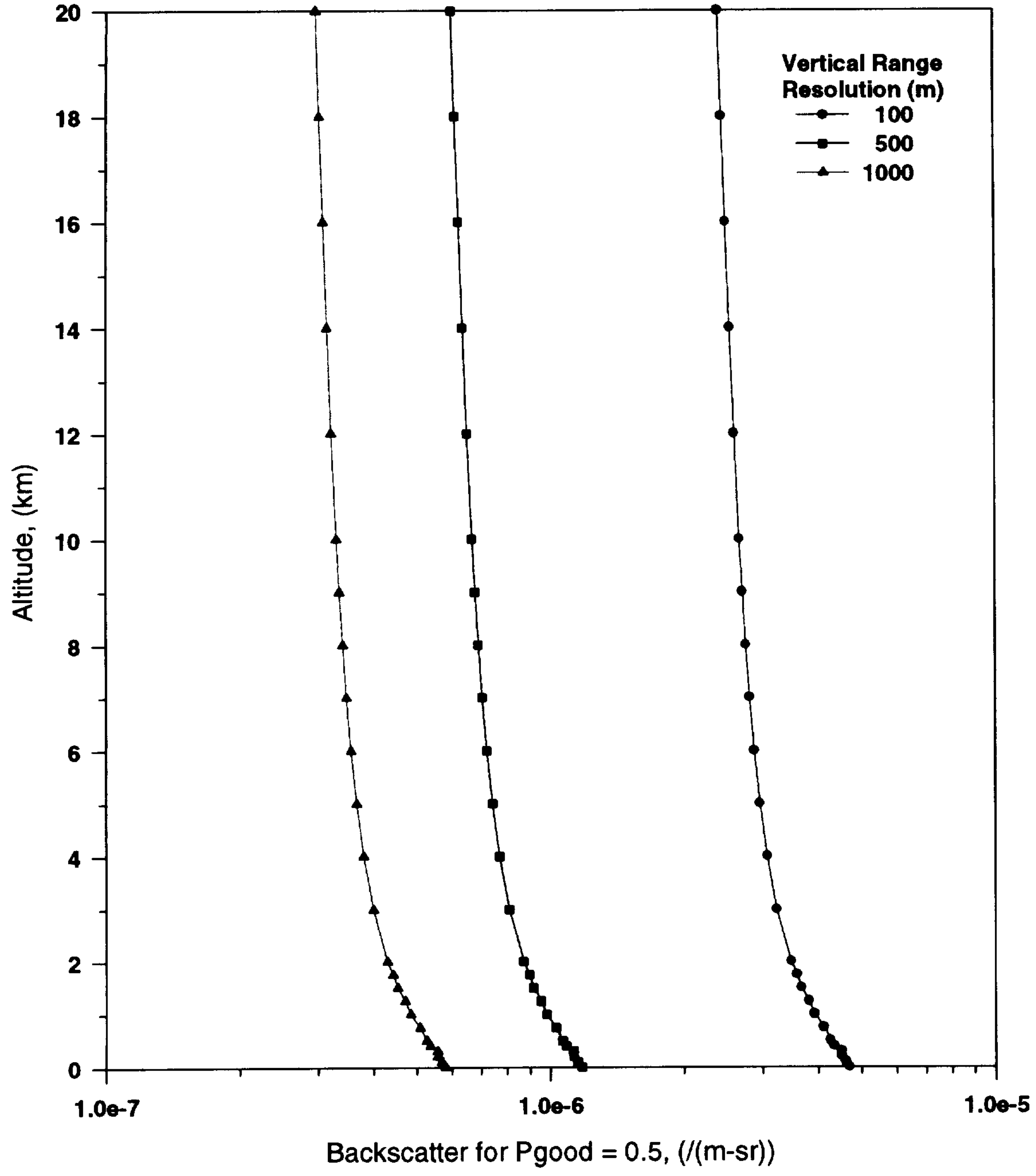


Figure (2.7) Single shot backscatter sensitivity as a function of altitude for range resolutions of 100 m, 500 m and 1000 m.

performance of the instrument by comparison with Figure (2.9) it must be remembered that this performance parameterisation carries at least 6dB of sensitivity degradation due to instrument effects. Additionally the instrument is likely to be run in a shot accumulation mode to improve the sensitivity.

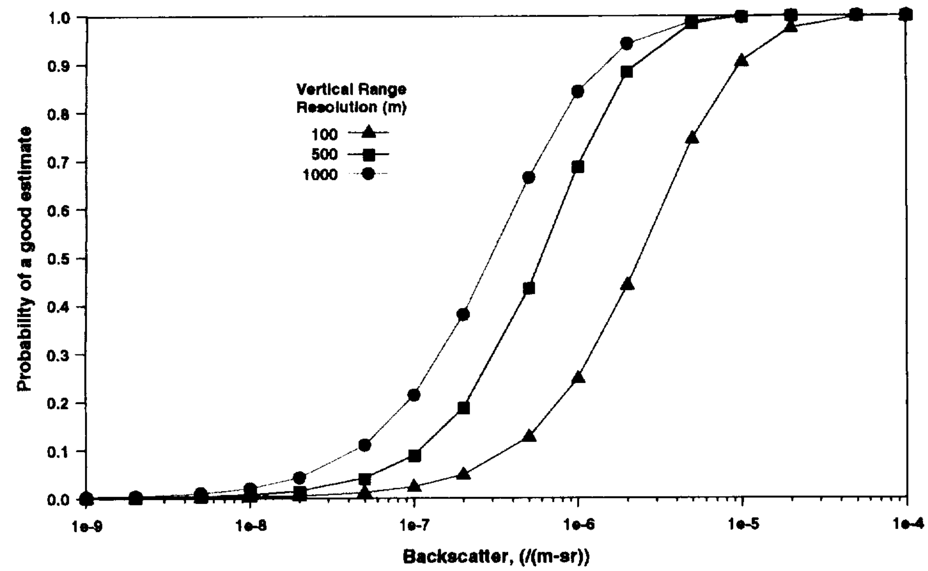


Figure (2.8) Performance of the maximum liklihood velocity estimator as a function of vertical range resolution and backscatter.

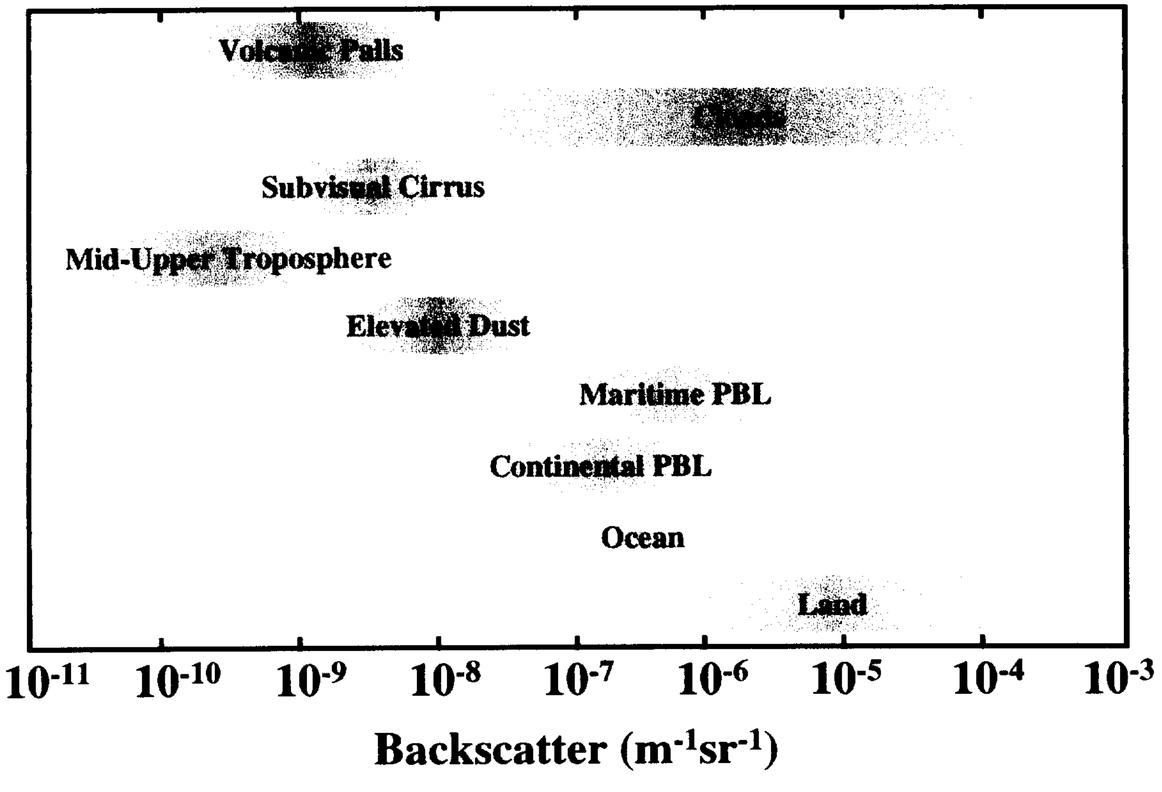


Figure (2.9) Natural Variability of 2 μm Backscatter. [12]

2.4 Current Status

The instrument design is currently under further study to ensure that the design is feasible. From an engineering point of view the major tasks are to develop an adequate thermal design and to reduce the mass in the optics can. From the science point of view the major task is to extract the maximum benefit from a short duration mission with a limited sensitivity instrument.

3) References

[1] http://eo.msfc.nasa.gov/general/require.html

[2] Figure courtesy of Dr. Farzin Amzajerdian, Center for Applied Optics, University of Alabama in Huntsville, Huntsville, AL 35899.

[3] J.Y. Wang, Appl. Opt. 27, 4470-4474 (1988).

[4] B.J. Rye et al., Appl. Opt. 31 (15), 2891-2899 (1992).

[5] J.J. Cordes, "Economic Benefits and Costs of Developing and Deploying a space-based Wind Lidar", Final Report, D-9502, Contract No. 43AANW400223, National Weather Service, March 1995.

[6] see for example: W.E. Baker, G.D. Emmitt, F. Robertson, R.M. Atlas, J.E. Molinari, D.A. Bowdle, J. Paegle, M.J. Post, J.R. Anderson, A.C. Lorenc and J. McElroy,"Lidar-measured winds from space: A key component for weather and climate prediction", Bull. Amer. Meteor. Soc. 76(6), 869-888 (1995).

[7] Private Communication Dr. G.D. Emmitt, Simpson Weather Associates, Jan. (1997).

[8] see for example R.G. Frehlich et al., J. Atmos. & Oceanic Tech. 11(5), 1217-1230 (1994).

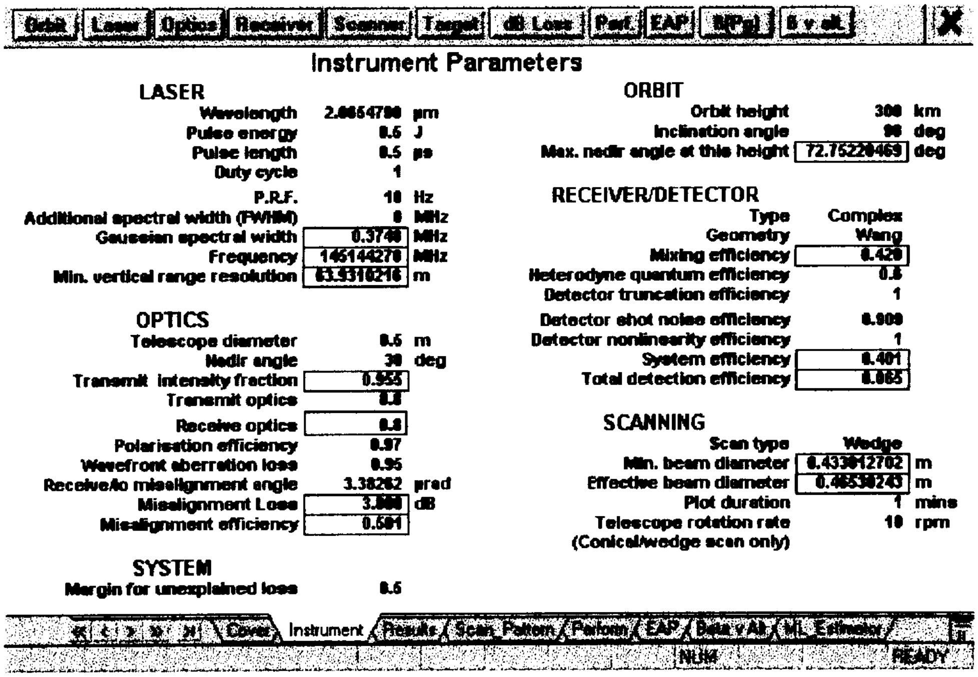
[9] R.G. Frehlich, J. Atmos. & Oceanic Tech. 13(3), 646-658 (1996).

[10] Goddard Space Flight Center, "Hitchhiker Customer Accommodations & Requirements Specifications", HHG-730-1503-07 (1994).

[11] Anees Ahmad, Farzin Amzajerdian, Chen Feng and Ye Li, "Design and fabrication of a compact lidar telescope", SPIE Vol. 2832, 34 - 44 (1996).

[12] Figure provided by Dr. Jeffry Rothermel, NASA MSFC and Mr. David Bowdle, University of Alabama in Huntsville, 23rd. April 1997.

Appendix A Model outputs for the NMP Parameters



Instrument Parameters

LASER

Wavelength	2.0654790	µm
Pulse energy	0.6	J
Pulse length	0.5	µs
Duty cycle	1	
P.R.F.	10	Hz
Additional spectral width (FWHM)	0	MHz
Gaussian spectral width	0.3740	MHz
Frequency	145144270	MHz
Min. vertical range resolution	63.9310216	m

OPTICS

Telescope diameter	0.5	m
Nadir angle	30	deg
Transmit intensity fraction	0.955	
Transmit optics	0.8	
Receive optics	0.8	
Polarisation efficiency	0.97	
Wavefront aberration loss	0.95	
Receive/lo misalignment angle	3.38262	µrad
Misalignment Loss	3.000	dB
Misalignment efficiency	0.501	

SYSTEM

Margin for unexplained loss	0.6	

ORBIT

Orbit height	300	km
Inclination angle	98	deg
Max. nadir angle at this height	72.75220469	deg

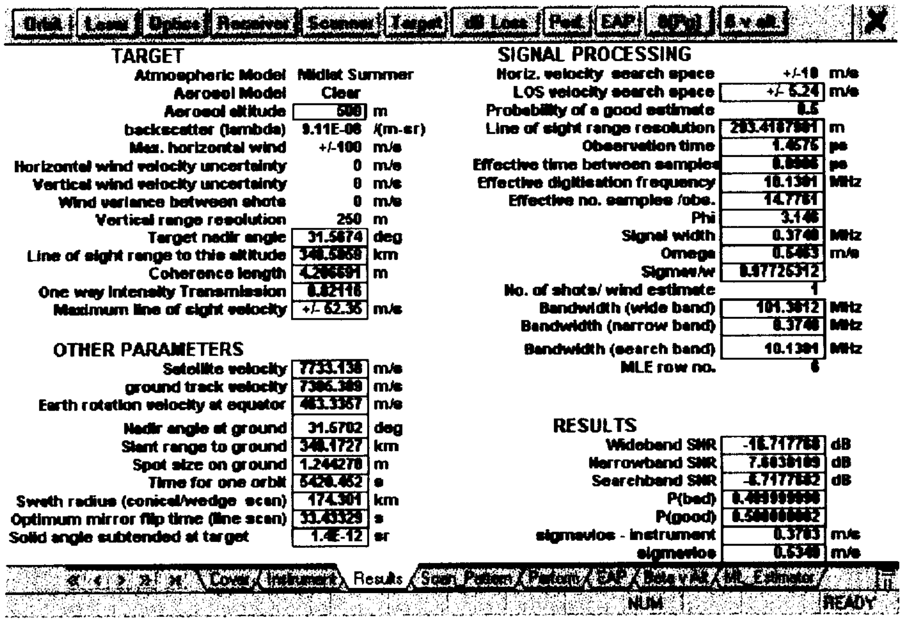
RECEIVER/DETECTOR

Type	Complex
Geometry	Wang
Mixing efficiency	0.420
Heterodyne quantum efficiency	0.8
Detector truncation efficiency	1
Detector shot noise efficiency	0.909
Detector nonlinearity efficiency	1
System efficiency	0.401
Total detection efficiency	0.065

SCANNING

Scan type	Wedge	
Min. beam diameter	0.433012702	m
Effective beam diameter	0.46530243	m
Plot duration	1	mins
Telescope rotation rate (Conical/wedge scan only)	10	rpm

Figure (A.1) Instrument and orbit parameters



TARGET

Atmospheric Model	Midlat Summer	
Aerosol Model	Clear	
Aerosol altitude	500	m
backscatter (lambda)	9.11E-08	/(m-sr)
Max. horizontal wind	+/-100	m/s
Horizontal wind velocity uncertainty	0	m/s
Vertical wind velocity uncertainty	0	m/s
Wind variance between shots	0	m/s
Vertical range resolution	250	m
Target nadir angle	31.5874	deg
Line of sight range to this altitude	348.5858	km
Coherence length	4.266691	m
One way Intensity Transmission	0.82116	
Maximum line of sight velocity	+/- 62.35	m/s

OTHER PARAMETERS

Satellite velocity	7733.138	m/s
ground track velocity	7306.309	m/s
Earth rotation velocity at equator	463.3367	m/s
Nadir angle at ground	31.6702	deg
Slant range to ground	348.1727	km
Spot size on ground	1.244270	m
Time for one orbit	5420.462	s
Swath radius (conical/wedge scan)	174.301	km
Optimum mirror flip time (line scan)	33.43329	s
Solid angle subtended at target	1.4E-12	sr

SIGNAL PROCESSING

Horiz. velocity search space	+/-10	m/s
LOS velocity search space	+/- 5.24	m/s
Probability of a good estimate	0.5	
Line of sight range resolution	293.4187981	m
Observation time	1.4576	µs
Effective time between samples	0.0986	µs
Effective digitisation frequency	10.1381	MHz
Effective no. samples /obs.	14.7781	
Phi	3.146	
Signal width	0.3740	MHz
Omega	0.5403	m/s
Sigmav/w	0.97726312	
No. of shots/ wind estimate	1	
Bandwidth (wide band)	101.3812	MHz
Bandwidth (narrow band)	0.3740	MHz
Bandwidth (search band)	10.1381	MHz
MLE row no.	6	

RESULTS

Wideband SNR	-16.717768	dB
Narrowband SNR	7.6038109	dB
Searchband SNR	-6.7177682	dB
P(bad)	0.499999998	
P(good)	0.500000002	
sigmavlos - instrument	0.3703	m/s
sigmavlos	0.5340	m/s

Figure (A.2) Target, signal processing and other miscellaneous parameters.

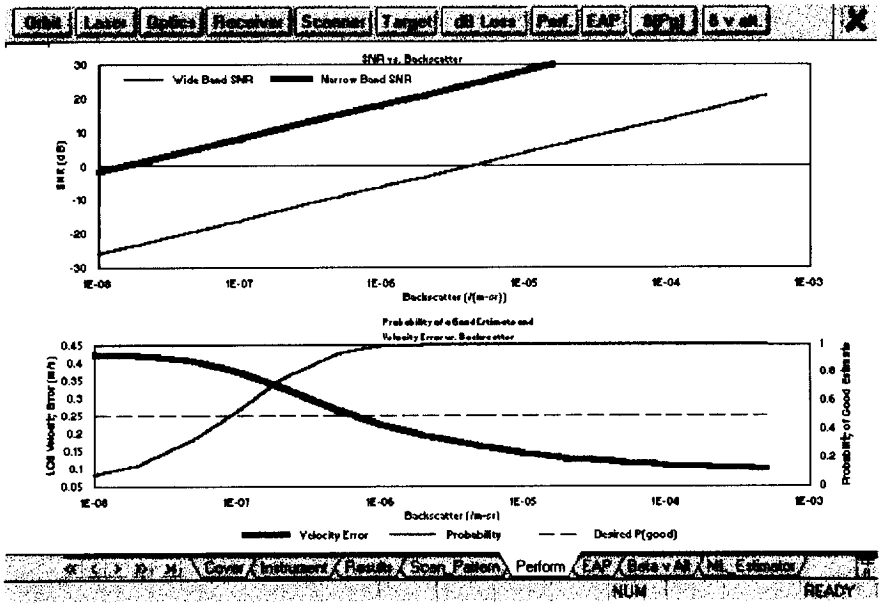


Figure (A.3) Signal to noise ratio and velocity estimator performance.

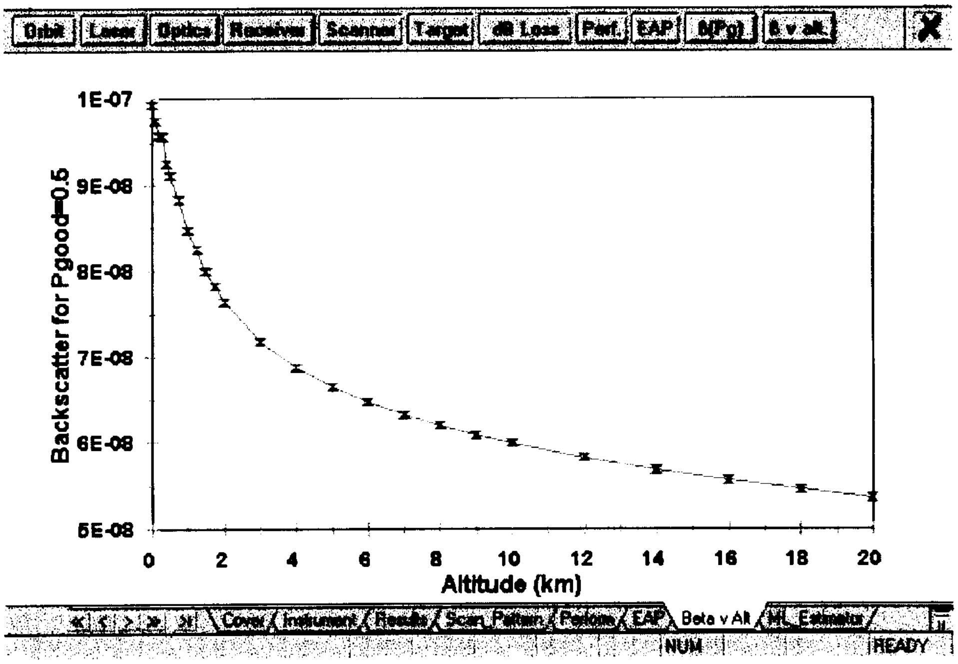


Figure (A.4) Sensitivity as a function of altitude for a 250 m range gate and a mid-latitude summer atmosphere.

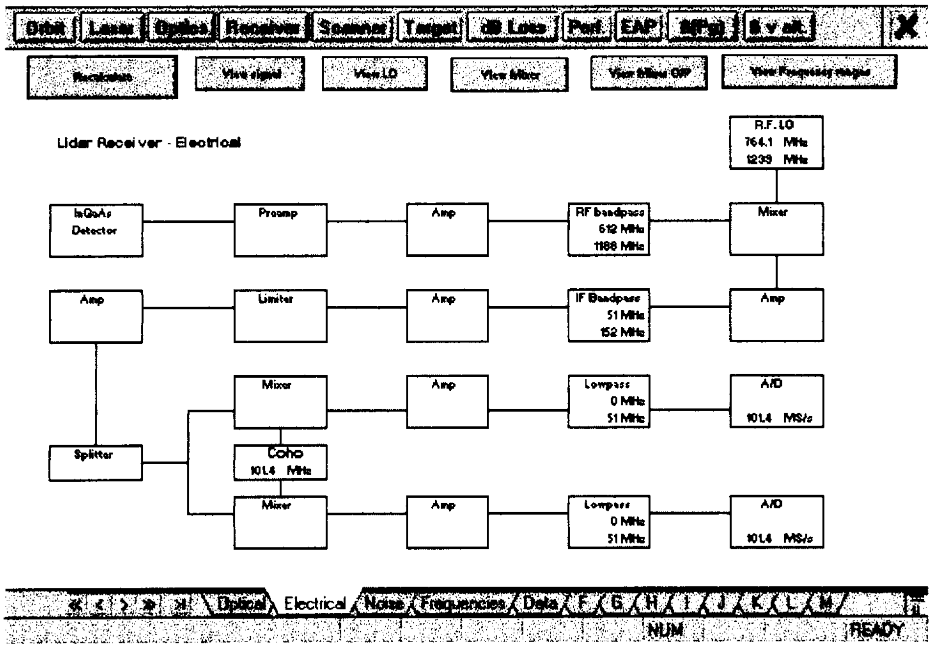
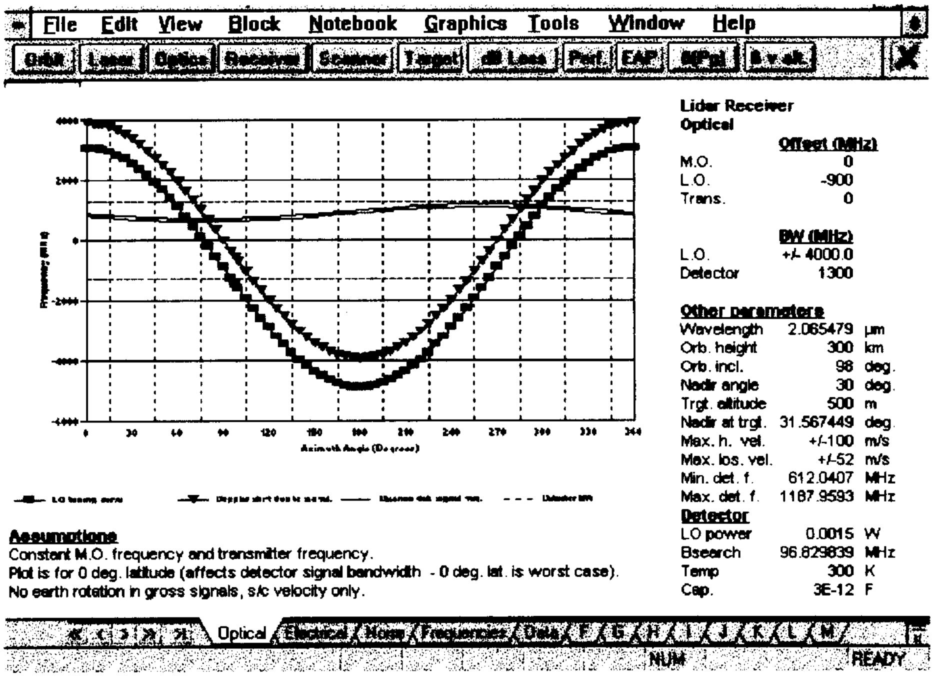


Figure (A.5) Receiver block diagram.



Lidar Receiver
Optical

	Offset (MHz)	
M.O.	0	
L.O.	-900	
Trans.	0	
	BW (MHz)	
L.O.	+/- 4000.0	
Detector	1300	
Other parameters		
Wavelength	2.065479	µm
Orb. height	300	km
Orb. incl.	98	deg.
Nadir angle	30	deg.
Trgt. altitude	500	m
Nadir at trgt.	31.567449	deg.
Max. h. vel.	+/-100	m/s
Max. los. vel.	+/-52	m/s
Min. det. f.	612.0407	MHz
Max. det. f.	1187.9593	MHz
Detector		
LO power	0.0015	W
Bsearch	96.829839	MHz
Temp	300	K
Cap.	3E-12	F

Assumptions
Constant M.O. frequency and transmitter frequency.
Plot is for 0 deg. latitude (affects detector signal bandwidth - 0 deg. lat. is worst case).
No earth rotation in gross signals, s/c velocity only.

Figure (A.6) Optical frequencies as a function of azimuth angle.

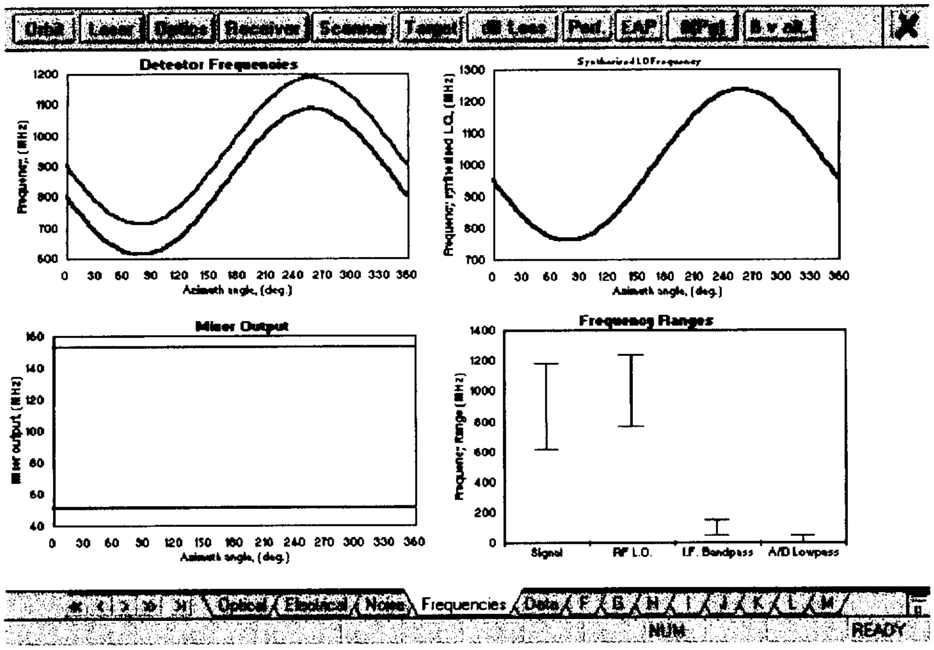
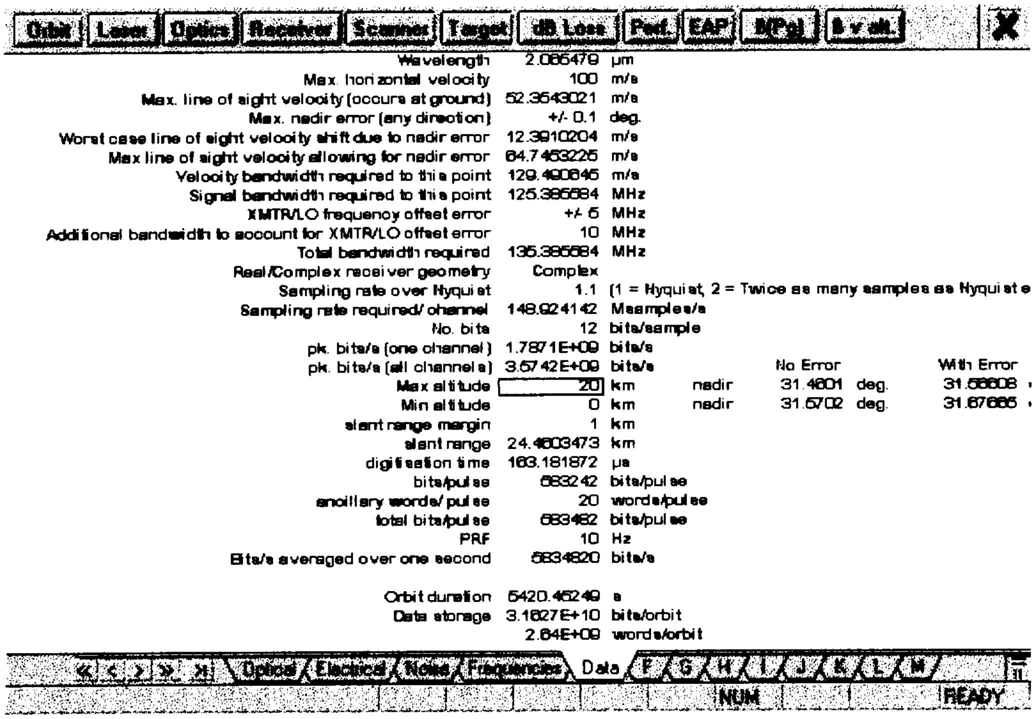


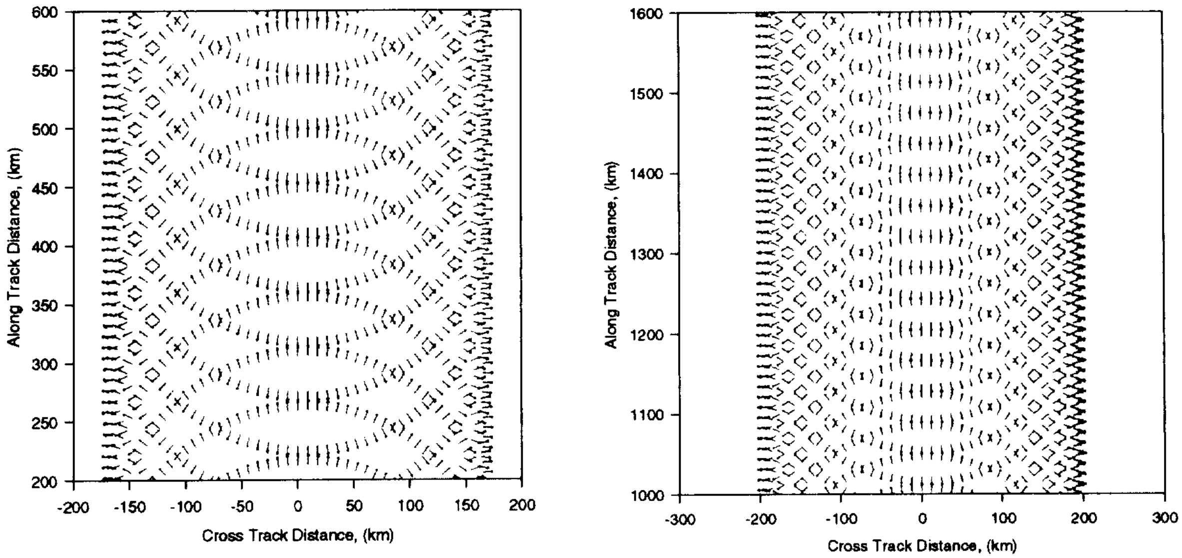
Figure (A.7) Plots of the minimum and maximum frequencies out of the detector (top left), the tuning curve for the electronic local oscillator (top right), the mixer output (bottom left) and the frequency bandwidths required in various stages of the receiver (bottom right).



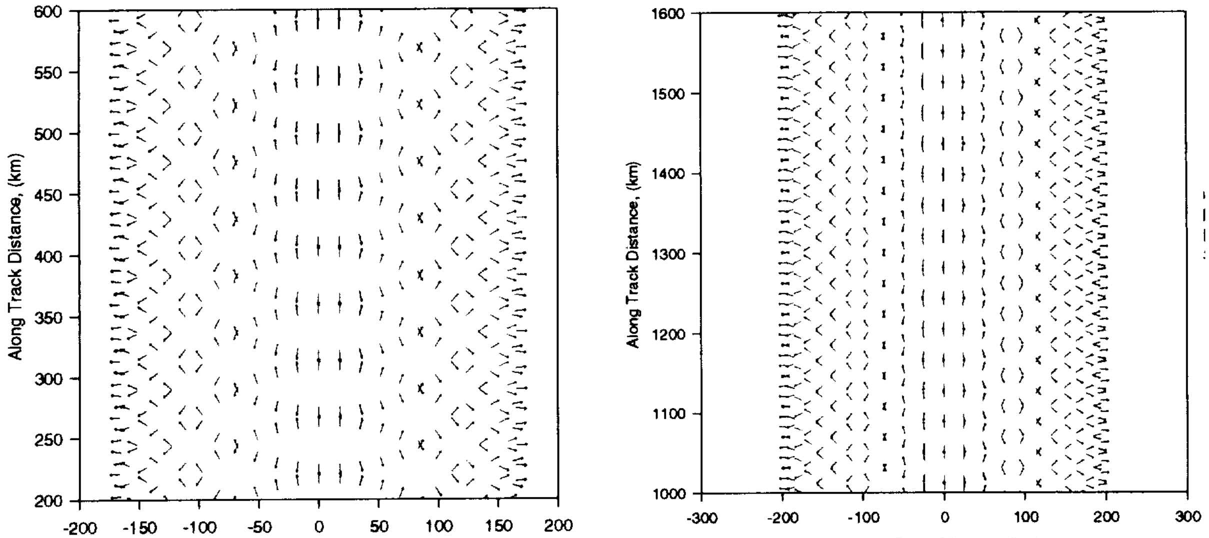
Wavelength	2.065479	µm				
Max. horizontal velocity	100	m/s				
Max. line of sight velocity (occurs at ground)	52.3543021	m/s				
Max. nadir error (any direction)	+/- 0.1	deg.				
Worst case line of sight velocity shift due to nadir error	12.3910204	m/s				
Max line of sight velocity allowing for nadir error	64.7453225	m/s				
Velocity bandwidth required to this point	129.490645	m/s				
Signal bandwidth required to this point	125.385684	MHz				
XMTR/LO frequency offset error	+/- 5	MHz				
Additional bandwidth to account for XMTR/LO offset error	10	MHz				
Total bandwidth required	135.385684	MHz				
Real/Complex receiver geometry	Complex					
Sampling rate over Nyquist	1.1	(1 = Nyquist, 2 = Twice as many samples as Nyquist e				
Sampling rate required/ channel	148.924142	Msamples/s				
No. bits	12	bits/sample				
pk. bits/s (one channel)	1.7871E+09	bits/s				
pk. bits/s (all channels)	3.5742E+09	bits/s		No Error		With Error
Max altitude	20	km	nadir	31.4601	deg.	31.56608
Min altitude	0	km	nadir	31.5702	deg.	31.67665
slant range margin	1	km				
slant range	24.4603473	km				
digitisation time	163.181872	µs				
bits/pulse	583242	bits/pulse				
ancillary words/ pulse	20	words/pulse				
total bits/pulse	583482	bits/pulse				
PRF	10	Hz				
Bits/s averaged over one second	5834820	bits/s				
Orbit duration	5420.46249	s				
Data storage	3.1627E+10	bits/orbit				
	2.64E+09	words/orbit				

Figure (A.8) Data requirements.

Appendix (A.I) Shot Patterns



A) 300 km altitude, 10 rpm, 20 Hz PRF, 30 deg. nadir B) 350 km altitude, 12 rpm, 20 Hz PRF, 30 deg. nadir



C) 300 km altitude, 10 rpm, 10 Hz PRF, 30 deg. nadir D) 350 km altitude, 10 rpm, 10 Hz PRF, 30 deg. nadir

Figure (A.9) Shot density plots for both 10 Hz (bottom) and 20 Hz operation (top) at both 300 km altitude (left) and 350 km altitude (right). Each arrow is a line of sight vector pointing in the direction the shot was fired. Pairs of vectors that are close to each other but orthogonal in direction are considered to be most optimal for resolving the wind vectors. These vectors are represented by the green arrows while the red arrows represent vector pairs that have too little angular seperation to be regarded as useful. It should be noted that the scanner rotation rate was adjusted slightly for each satellite altitude to improve the grouping of the vector pairs.