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ABSTRACT

For over 20 years researchers have been investigating the feasibility of profiling tropospheric vector wind velocity from space with a pulsed Doppler lidar. Efforts have included theoretical development, system and mission studies, technology development, and ground-based and airborne measurements. Now NASA plans to take the next logical step towards enabling operational global tropospheric wind profiles by demonstrating horizontal wind measurements from the Space Shuttle in early 2001 using a coherent Doppler wind lidar system.

Keywords: wind velocity, Doppler lidar, coherent detection

1. THE SPARCLE MISSION

The goals of SPARCLE are:

1) to demonstrate that coherent Doppler wind lidar (CDWL) technology can provide the desired global wind measurements,
2) to validate wind measurement performance prediction models for use in assessing proposed future follow-on missions, and
3) to measure characteristics of the atmosphere, clouds, and earth surface for optimum design of future missions.

SPARCLE is primarily a technology demonstration mission, which is consistent with its selection as NASA's New Millennium Program (NMP) second Earth Orbiter (EO-2) mission. The mission will be managed by the Marshall Space Flight Center (MSFC), which will provide project management, mission and science requirements, instrument engineering, instrument integration, and space qualification. The mission will include key partnerships with the NASA Langley Research Center (LaRC) for the pulsed solid state laser technology, the NASA Jet Propulsion Laboratory (JPL) for tunable continuous wave (CW) solid state laser technology, the University of Alabama in Huntsville (UAH) for optomechanical design, Coherent Technologies, Inc. (CTI) for the flight laser subsystem, and Simpson Weather Associates (SWA) for science guidance. The authors are the co-principal investigators for the instrument and the science, respectively. SPARCLE will utilize the Hitchhiker (HH) program, managed by the NASA Goddard Space Flight Center (GSFC) for riding on the space shuttle. The instrument will be contained in two pressurized HH canisters, each about 50 cm in diameter and 72 cm long, mounted on the sill (wall) of the shuttle payload bay, as shown in Figure 1. The shuttle will turn upside down with its

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payload bay facing the earth during instrument operation. The schedule consists of instrument delivery to GSFC/HH in 33 months, followed by launch 6 months after that in early 2001.

2. THE COHERENT DOPPLER WIND LIDAR

Total mission hardware consists of the lidar instrument, the HH canisters, and ground support equipment (GSE). The lidar instrument for a space mission consists of the coherent Doppler lidar subsystem with its lasers, optics, and structure; the control and data acquisition computer; the software; the thermal subsystem; and so forth. Only the CDWL will be discussed here. The optical schematic is shown in Figure 2. (Note that system attributes are still being finalized and the specifications mentioned herein are preliminary.)

The heart of the CDWL is the pulsed transmitter laser. The Tm,Ho:YLF solid state laser technology developed at LaRC will be transferred to CTI, where it will be combined with CTI's extensive experience in packaging and fielding durable CDWL systems.[1] The side diode-pumped laser will have nominal specifications of 2.051 micron wavelength, 100 mJ pulse energy, 180 ns pulse duration, and 6 Hz pulse repetition frequency (PRF). This yields a total transmitted optical power of 0.6 W, which will be sufficient to demonstrate vector wind velocity measurement due to the very good photon efficiency of the coherent detection technique. A polarizing beamsplitter and a quarter wave plate comprise a transmit/receive switch to allow the received photons to propagate to the optical detector, and not to reenter the pulsed laser. The T/R switch converts the linearly polarized light from the laser into circularly polarized light. The Gaussian cross section laser beam is then expanded using an innovative, compact, diffraction limited telescope having approximately a 25 cm diameter primary mirror.[2] This is done since the signal-to-noise ratio (SNR) for this measurement is proportional to the area of the primary mirror, for optimum matching of the transmitted beam size, the receiver's effective beam size, and the mirror. For data collection, the direction of this expanded beam, before reaching the scanner, will be straight down at earth, or nadir. The silicon wedge scanner deflects the expanded beam 30 deg. from the nadir position. This angle represents a compromise between the desire to align with the horizontal wind as much as possible, and the loss of signal at larger angles due to slant range and atmospheric extinction.[3]

By rotating the scanner about the optical axis of the transmitted beam leaving the telescope, a set of possible lidar pointing directions forming a cone of half angle 30 deg. about the nadir direction is enabled. Horizontal wind measurements are then possible by measuring the line of sight (LOS) wind of a parcel of air from two different perspectives. For example, if the shuttle direction of flight is considered the 0 deg. position of the scanner's azimuth angle, then a wind measurement taken at 45 deg. azimuth may be combined with a later wind measurement at 135 deg. into approximately the same parcel of air. For a Space Shuttle orbit altitude of 300 km and an air parcel altitude of 1 km, the laser pulse will travel 348 km from the lidar to the air parcel. The round trip time of light will be 2.3 ms. The shuttle will be traveling 7730 m/s, and the location of the illuminated spot on the earth's surface will be traveling forward 7385 m/s. It will take 33 sec. for the 135 deg. view to approximately coincide with the same target volume as the earlier 45 deg. view.

The pulsed laser light will impinge on the aerosol particles occurring naturally in the air, and which move with the air's velocity. The laser beam, although converted from circular cross section to elliptical cross section by the wedge scanner, will be approximately 4 m in diameter at the aerosol target. Since the laser's pulse length in the atmosphere is about 27 m, the instantaneous interaction volume of the laser light with the atmosphere is cylindrically shaped. The efficiency with which the aerosol particles scatter the laser light back in the direction of the lidar is defined by the parameter β. The amount of backscattered photons is proportional to the length of the atmospheric interaction volume, and to the solid angle subtended by the photon detector back at the lidar. Therefore, the units of β are $m^{-1}sr^{-1}$. The laser light impinging on the aerosol particles is circularly polarized, and the T/R switch of the CDWL is designed to most efficiently receive light that is circularly polarized in the opposite direction. This would be the case if the target were an on-axis mirror. The effect on the polarization is in general defined by the 16 elements of the 4x4 Mueller scattering matrix of the aerosol target. Aerosol particles very likely do not match the Mueller matrix of an on-axis mirror. However, published values of β which are used to assess the performance of missions such as SPARCLE were measured with similarly polarized coherent lidar systems. Some of these lidars used circular polarization, and some used linear polarization. This difference will not affect β significantly if the 12, 21, 14, 41, 22, and 44 Mueller matrix elements are small compared to the 11 element.[4] Also, as long as the aerosol particles are randomly oriented in space, the Mueller matrix elements will not depend on the laser beam approach direction. Therefore, the published values of β should produce reasonable performance predictions for SPARCLE.

A few of the backscattered photons return to the CDWL system and reenter the 25 cm diameter telescope. The beam expanding telescope works in reverse and reduces the diameter of the received "beam". The T/R switch directs the photons to the receiver. Figure 2 shows the use of optical fibers to combine the received photons with photons from the tunable (frequency-agile) local oscillator (LO) laser. An alternative is to eliminate the fiber coupler and mix the beams in free space. The tunable LO laser was developed by JPL researchers, and the technology has been transferred to CTI for the flight unit fabrication.[5] The total Doppler shift of the backscattered photons is due to the total relative motion of the shuttle and the air parcel. This consists of the wind, the shuttle velocity, and the earth's rotation. The Doppler shift from the shuttle's velocity is greatest when the scanner is aimed in the fore (0 deg.) and aft (180 deg.) positions, when it is ± 3.8 GHz. Since it is not feasible to consider receiver components (optical detector, amplifiers, analog to digital converters, data storage devices) to handle this range of frequencies, the tunable LO laser was developed to have a ± 4 GHz tuning range. For each laser shot, the gross Doppler shift is predicted, and the LO laser is tuned to dramatically reduce the range of signal frequencies. This leads to several pointing requirements. First, the pointing direction must be controlled sufficiently to allow the tunable LO to do its job. Second, the pre-shot pointing knowledge must be adequate to set the tunable LO to ensure the heterodyned signal is within the receiver's capture range. Third, the pointing stability during the round trip time of the photons must allow the receiver to remain pointed in the direction of the transmitted photons to within the allowed budget. We currently budget about 7 microradians (1.5 arcsec) over the 2.3 ms interval which represents a budgeted 3 dB lowering of SNR. Fourth, the post-mission knowledge of the pointing direction must allow wind velocity accuracies on order of 1 m/s.

The nadir angle compensator (NAC) is an optical element designed to correct for the predicted misalignment between the transmitter and receiver directions due to the continuous orbiting of the shuttle about the earth during the round trip time of the light. For SPARCLE, this angle is only 2.7 microradians, which would cause a loss of 0.4 dB in SNR if uncorrected. SPARCLE is currently baselined to not have a NAC element.

The backscattered photons are combined with the LO laser photons on the surface on an InGaAs detector using either a fiber optic coupler (as shown), or using free space combining. The detector output signal occurs at the difference frequency between the backscattered photons and the LO photons, which is arranged to be in the radio frequency (RF) range for the benefit of the receiver components that follow the detector. The signal is digitized and processed to estimate LOS wind velocity. The velocity estimation algorithms may be envisioned as performing a Fourier Transformation on a particular time interval of the detector signal, and locating the frequency (velocity) of the resultant spectrum's peak.

Several different scanning patterns are planned for SPARCLE to allow many aspects of the CDWL hardware, the atmosphere, and velocity estimation to be investigated. Figures 3 and 4 show two of the planned scan modes. Pattern 2A will demonstrate horizontal wind measurement by probing air parcels from two perspectives as discussed above. The unbroken line represents the ground track of the shuttle, and the dashed lines show the coincident locations of the fore (45 deg.) and aft (135 deg.) lidar shots. It will also demonstrate lidar shot accumulation, which is the use of multiple lidar shots of the same perspective to obtain LOS velocity measurements in atmospheric regions having an aerosol backscatter coefficient β too low for single lidar shot velocity measurement. The true wind for a single shot LOS wind measurement is defined as the linear average of the actual LOS wind velocities within the cylindrically shaped LOS measurement volume. The true wind when using shot accumulation is defined as the linear average of the actual LOS wind velocities within the volume obtained by sliding the LOS measurement volume along the flight direction to encompass all the involved laser shots and the volume between the laser shots. In both cases the true wind is defined using the location, height, angle, and time attributes assigned to the LOS velocity measurement. Pattern 4B will most closely approach the scan pattern envisioned for future operational wind missions. The wedge scanner will perform a step-stare pattern of 16 different azimuth positions, yielding 8 cross-track regions (4 to the right, and 4 to the left) which are probed from two perspectives. Therefore, vector winds can be obtained in 8 target areas across the ground swath.

3. THE PHOTON GAUNTLET

It is interesting to review the instrument operation discussed above from the point of view of the photons. (The numbers below represent the lowest acceptable level of single shot lidar performance. Every effort will be made to achieve even greater single shot sensitivity to the aerosol backscatter coefficient β. Other paths to greater sensitivity will include shot accumulation, and relaxation of the vertical resolution.) Each 100 mJ laser pulse contains about 10^{18} photons leaving the laser. Because of obscurations, transmission coefficients, and reflection coefficients, about 7×10^{17} photons leave the lidar into space. After passing through the atmosphere in a slanting path, about 6×10^{17} photons impinge on the aerosol particles at 1 km altitude. The single shot performance of the lidar is required to be equal to or better than an aerosol backscatter coefficient β sensitivity of $5 \times 10^{-6}\ m^{-1}sr^{-1}$ (defined here as "β_{50}", with "50" indicating 50% as will be explained below). This requirement assumes that the interval of signal used for a velocity estimate corresponds to 250 m of vertical extent in the atmosphere (290 m extent in range, 2 μs in duration). The cylindrically shaped LOS measurement volume is identical in diameter but is much longer than the approximately 27-m long instantaneous laser-atmosphere interaction volume. The β sensitivity requirement also assumes that the post-mission data processing will utilize adjacent lidar wind information and contextual atmospheric information to allow the final search bandwidth for the velocity, referenced to the horizontal direction, to be limited to ± 10 m/s or 20 m/s total. Using these values of β and signal interval length, about 9×10^{14} photons per sr scatter backwards towards the lidar. Since the 25 cm diameter telescope mirror represents a very small solid angle at the slant range of 348 km, only about 230 photons will enter the telescope. About half of these photons will reach the optical detector through the receiver optics, but not all of the photons that reach the detector contribute to the heterodyne signal. In order to contribute to the heterodyne signal, the photons must be phase coherent with the LO photons across the active area of the detector. Only about 7 photons are expected to contribute. The optical detector then converts the heterodyne photon signal into an electrical current. The detector's efficiency at doing this depends on the RF frequency. Using a detector heterodyne quantum efficiency (HQE) of 0.6 at the largest (worst case) RF frequency, about 4 photoelectrons contribute to the wind velocity estimate. In this threshold case, the true wind would be sensed for 50% of the shots.

4. VELOCITY MEASUREMENT PERFORMANCE

When $\beta = \beta_{50}$, with about 4 contributing or "coherent" photoelectrons, employing velocity estimators to the detector output signal yields "good" LOS wind velocity estimates about half (50%) of the time.[6] This "good" estimate percentage rises above 99% of the time for about 25 contributing photoelectrons. The velocity estimates from each LOS measurement volume (i.e., 290 m or 2 μs of data) for each lidar shot are subject to these statistics. To understand this behavior, one can visualize that the highest signal in the Fourier Transform signal spectral domain corresponds to the frequency bin containing the true velocity. These estimates are tightly grouped about the true LOS wind velocity with a spread or error that is only slightly larger than the spread or second moment of the atmospheric LOS wind velocities within the LOS measurement volume. The error contribution due solely to the CDWL is typically less than 1 m/s. The other half of the velocity estimates at this particular value of β will be uniformly spread over the 20 m/s wide search bandwidth. This corresponds to a noise spike in the signal spectral domain rising higher that the true wind signal. For higher values of β, the percent of good estimates will be larger. For lower values of β, the percentage of good estimates will be smaller, but the remaining good estimates will be very accurate. The theory linking CDWL SNR to velocity measurement had been found to agree with experimental data to within 5%[7].

This discussion has centered on the behavior of the CDWL instrument. Two other very important factors in the final velocity measurement performance are: 1) the representativeness of the calculated horizontal wind velocity, using measured LOS velocities, to the actual horizontal velocity of the atmospheric horizontal measurement volume of interest, and 2) non-lidar engineering contributions to velocity error. Representativeness can be understood by imagining the error due to measuring the wind very well in only one corner of a 100 km x 100 km horizontal measurement volume, and then assigning the answer to the entire volume. This error depends on the variations of the wind over the horizontal measurement volume. The representativeness issue is more important in planning future operational wind missions than for SPARCLE. However, scan patterns are planned to confirm current thinking and to design future sampling strategies.[8] The non-lidar engineering contributions to velocity error are discussed in the next section.

5. SPACE ACCOMMODATION REQUIREMENTS

The measurement of vector winds from space with a laser involves complex interactions of the lidar instrument, the space platform, the atmosphere, and the earth. The metrics of a space-based wind profiling mission consist of horizontal wind velocity accuracy and other factors (e.g., spatial coverage, horizontal measurement volume dimensions). The horizontal wind velocity accuracy arises from: 1) the LOS wind velocity accuracy, 2) parameters of the LOS velocity measurement set: quantity, positions, angles, times, 3) the correlated variance in the wind field, and 4) the choice of the horizontal measurement volume. The LOS wind velocity accuracy consists of factors selectable during post-mission data processing (PMDP) as well as factors fixed at the time of measurement (including post-mission calculations from recorded ancillary data). The LOS wind velocity accuracy factors selectable during PMDP are shot accumulation quantity, the vertical integration length of data used in a velocity estimate, the velocity estimation algorithm, and the horizontal velocity search processing bandwidth (a priori limit on possible velocities). The LOS wind velocity accuracy factors fixed at the time of measurement consist of contributions from the coherent lidar (CL) system, the spacecraft/platform, the atmosphere, and the earth. Both the spacecraft/platform and atmosphere contribute to LOS wind velocity accuracy by: 1) lowering the SNR, and 2) by non-SNR effects. The spacecraft/platform contributes to lowered SNR by contributing to the misalignment angle of the CL receiver after the round trip of the photons to and from the atmosphere. Knowledge errors in the spacecraft/platform horizontal and vertical velocity, horizontal and vertical location, and angular orientation comprise the non-SNR effects. The atmosphere contributes to lowered SNR through laser beam extinction on the transmit and receive paths, spatial coherence length reduction of the reflected light due to the random locations and spatial extent of the illuminated aerosol particles, and spatial coherence length reduction of the reflected light due to refractive turbulence. (The latter phenomenon may usually be neglected for space-based scenarios.) The non-SNR contribution of the atmosphere to the LOS velocity accuracy comes through the signal spectrum broadening from the instantaneous wind velocity variations in the LOS measurement volume. The earth only contributes through the non-SNR effects of knowledge error of its radius and local horizontal direction. (Making an accurate LOS wind measurement, but assigning it to the wrong location and/or angle constitutes an error.) A third possible earth contribution would come from the assumption that the earth surface return represents a zero velocity target if in fact there is motion (e.g., water, vegetation). The CL effects on LOS wind velocity accuracy also divide into SNR and non-SNR factors. Non-SNR contributors are knowledge error of the transmitted laser beam direction, and signal spectrum broadening from the transmitted laser pulse's spectrum. An attempt to graph the velocity error tree is shown in Figure 5.

A list of accommodation requirements can be calculated by assuming a desired goal of approximately 1 m/s wind accuracy overall, and assigning 10% of a root sum square (RSS) budget, which is 0.3 m/s, to each effect. This simplistic approach leads to requirements of approximately: 300 kHz knowledge error (KE) of the difference frequency between the transmitted light and the LO laser light at signal reception; 0.35 m/s KE in the lidar vertical velocity; 0.6 m/s KE in the lidar horizontal velocity; 45 microradian KE in the laser beam nadir angle; 78 microradian KE in the laser beam azimuth angle; and 5 degree KE in the local horizontal direction of the earth below the wind measurement. The latter requirement arises from assuming that the desired data product is velocity referenced to the local horizontal direction. A similar set of accommodation requirements arises from the need to locate the wind measurement in x, y, and z position. Some of these knowledge requirements may be derived from post-mission analysis of the lidar and housekeeping data; thereby relieving the lidar hardware. A more sophisticated wind accuracy budget is currently under development.

6. ACKNOWLEDGEMENTS

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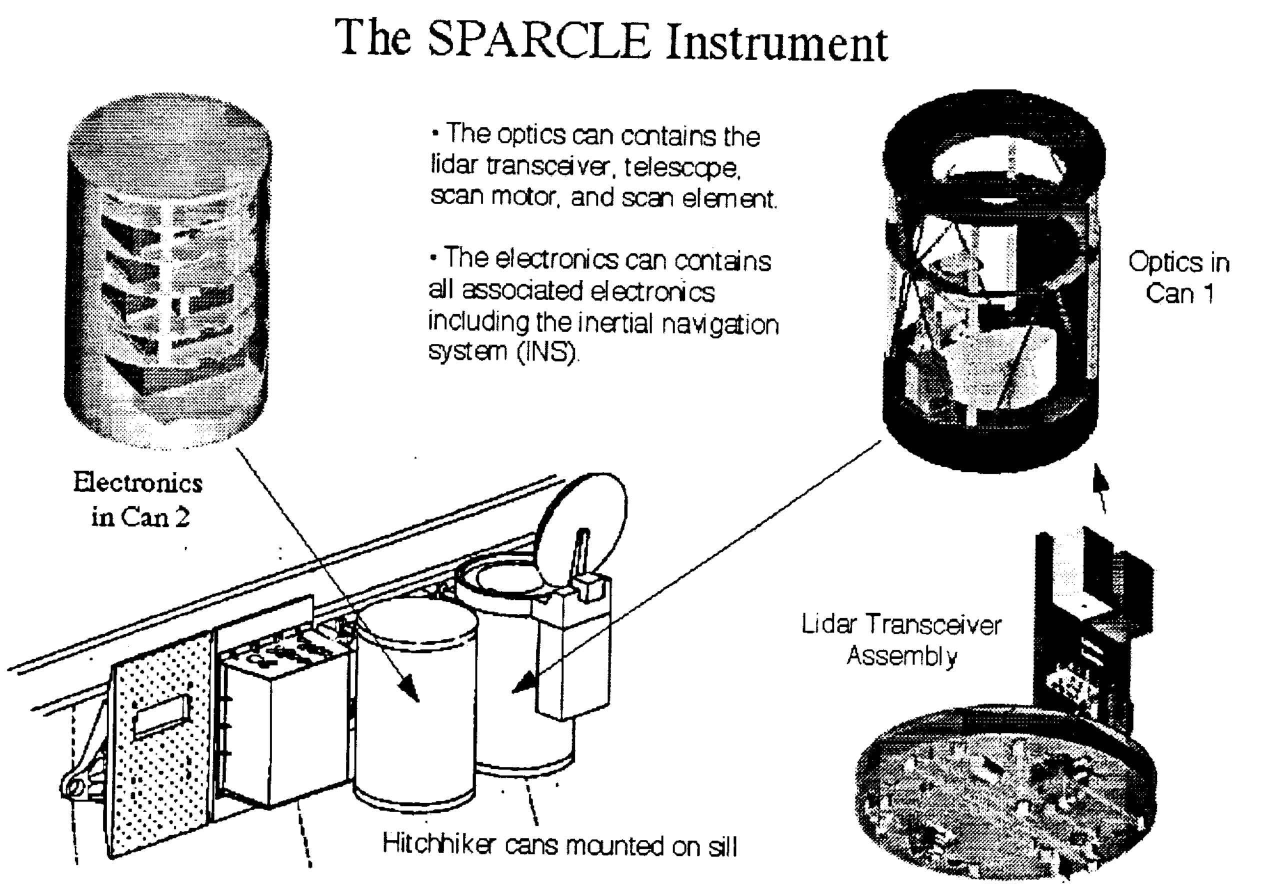

Figure 1: The SPARCLE Instrument Mounted On The Shuttle Bay Sill

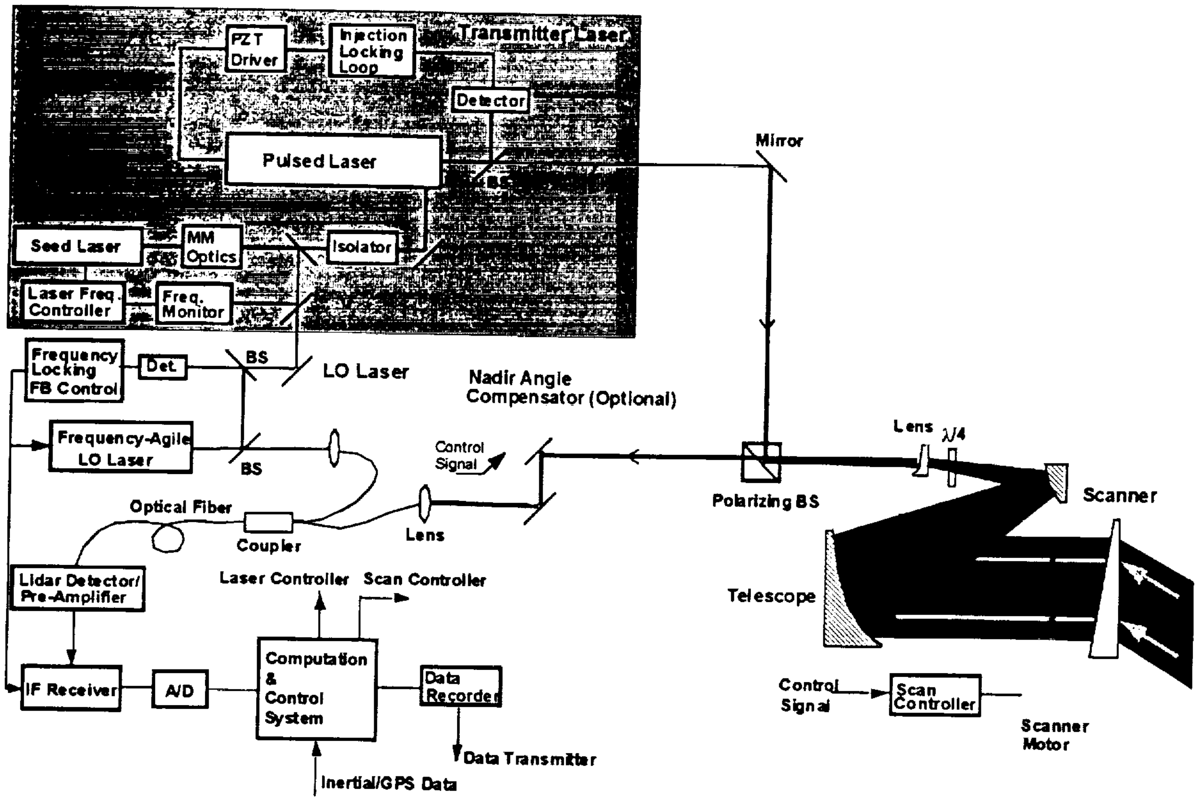

Figure 2: SPARCLE Optical Schematic

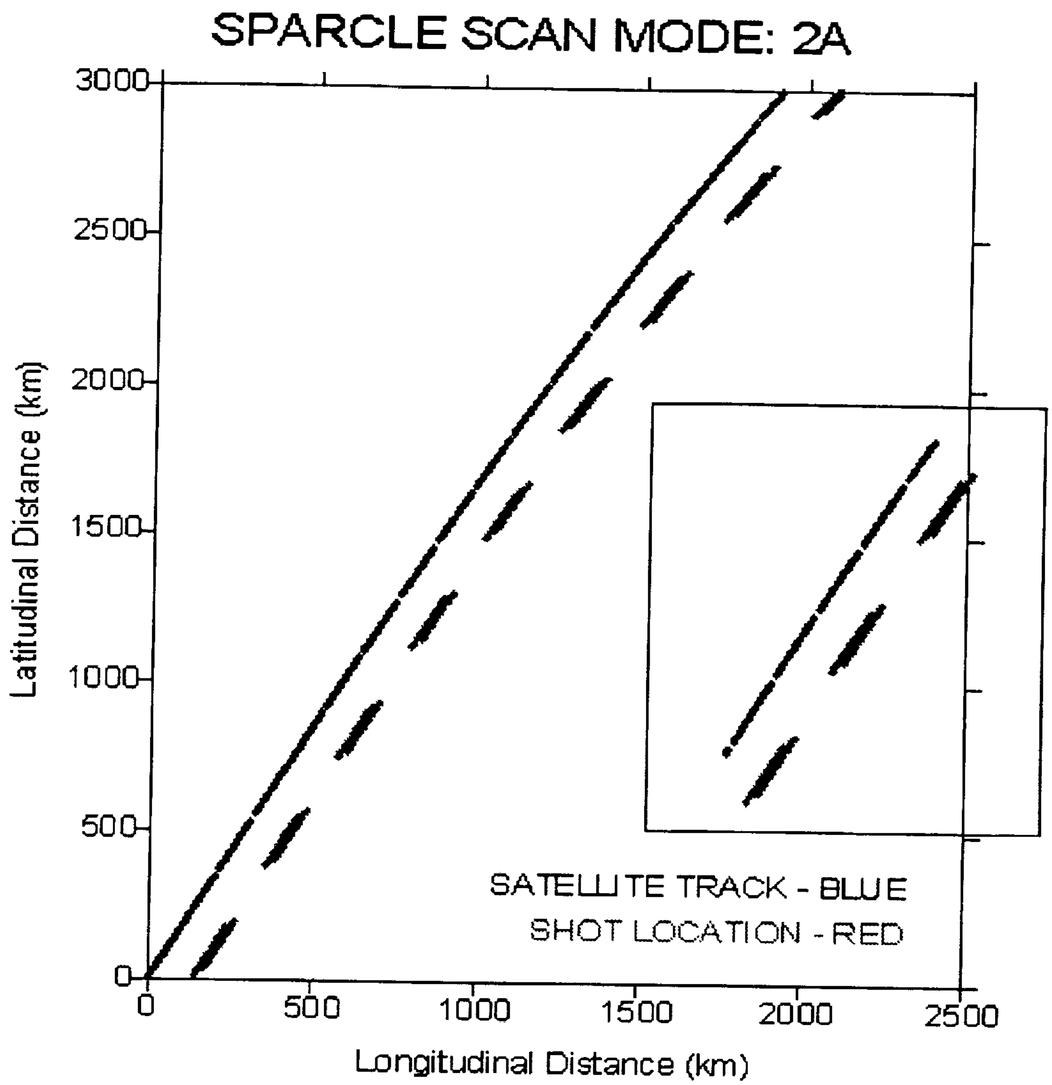

Figure 3. SPARCLE Scan Pattern 2A

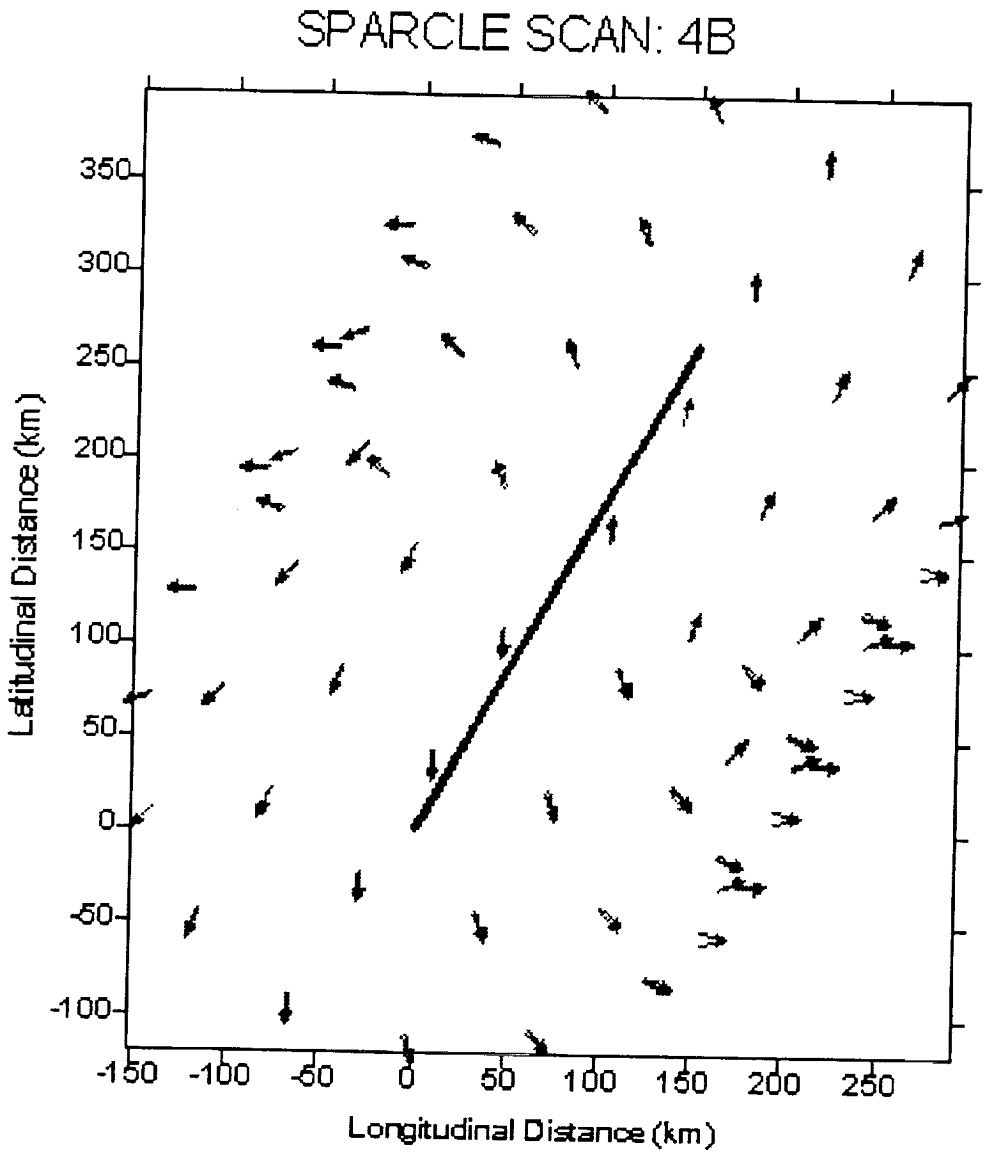

Figure 4. SPARCLE Scan Pattern 4B

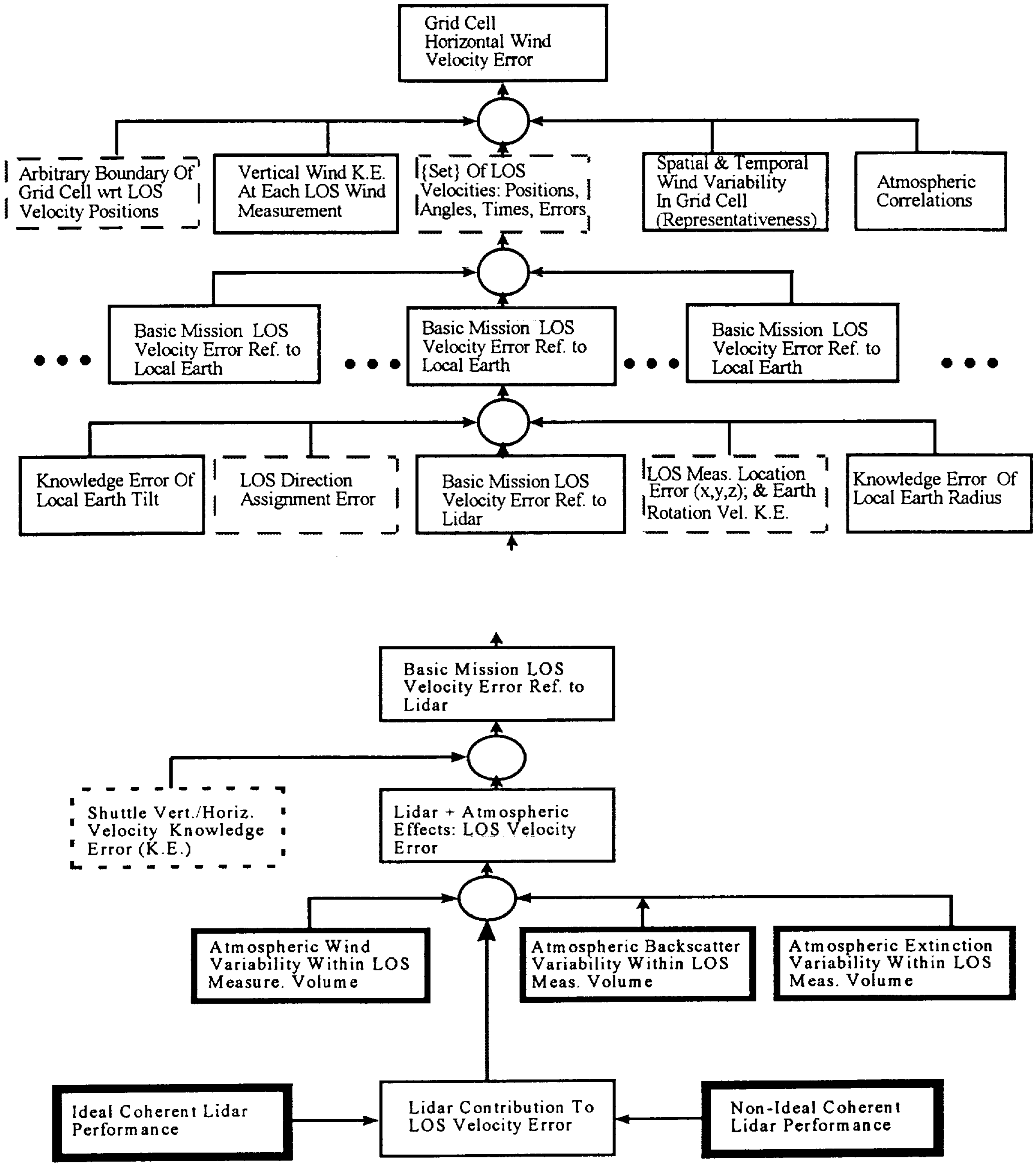

Figure 5. SPARCLE Wind Velocity Error Tree
(Solid dark-primary lidar influence, solid medium-secondary lidar influence, dashed-mission influence)