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# Tropospheric Wind Measurements From Space:

# The SPARCLE Mission And Beyond

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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.

## THE SPARCLE MISSION

The goals of SPARCLE[1] are:

1) to demonstrate that coherent Doppler wind lidar (CDWL) can provide the desired global wind measurements,
2) to validate performance 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) and 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. The shuttle will turn upside down with its 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.

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## THE COHERENT DOPPLER WIND LIDAR

The heart of the CDWL is the pulsed transmitter laser[2]. 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. The Gaussian cross section laser beam is expanded using an innovative, compact, diffraction limited telescope having approximately a 25 cm diameter primary mirror.[3] A silicon wedge scanner deflects the expanded beam 30 deg. from the nadir position[4].

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.

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 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 $\beta$, the aerosol backscatter coefficient.

A few of the backscattered photons return to the CDWL system and reenter the 25 cm diameter telescope. 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.. For each laser shot, the gross Doppler shift is predicted, and a frequency tunable local oscillator (LO) laser[5] is tuned to dramatically reduce the range of signal frequencies.

The backscattered photons are combined with the LO laser photons on the surface on an InGaAs detector using either a fiber optic coupler, 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. These scan patterns differ in: 1) the number of scanner azimuth positions, and therefore locations, in cross-track coordinates, that are probed from two or more perspectives; 2) in the number of perspectives (usually two) that an air parcel is probed from; and 3) in the time spent in a single perspective to allow multiple laser shots to accumulate. Lidar shot accumulation is the use of multiple lidar shots of the same perspective to obtain LOS velocity measurements in atmospheric regions having an aerosol backscatter coefficient $\beta$ too low for single lidar shot velocity measurement. The aerosol backscatter sensitivity that yields a fixed velocity estimation performance is expected to improve proportionally to the square root of the number of shots accumulated.

## 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 $\mu$s 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 $\beta$ will be uniformly spread over the 20 m/s wide search bandwidth planned for use in post-mission data processing (PMDP). This corresponds to a noise spike in the signal spectral domain rising higher that the true wind signal. For higher values of $\beta$, the percent of good estimates will be larger. For lower values of $\beta$, 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].

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.

## GENERAL 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 LOS wind velocity accuracy consists of factors selectable during PMDP as well as factors fixed at the time of measurement. 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 currently planned to be 20 m/s). 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. 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.

## ROADMAP TO FUTURE MISSIONS

SPARCLE is the next stepping stone towards enabling future science and operational tropospheric wind profiling missions. In parallel with SPARCLE, NASA is continuing the advance the CDWL technology so that it will be ready when needed. Future missions will likely be at orbit heights of 400-833 km and nadir angles of 30-45 degrees, compared to 300 km and 30 degrees for SPARCLE. Mission lifetimes will be 1-7 years. The desired data product will be horizontal vector wind accuracies of 1-2 m/s coupled with an aerosol backscatter sensitivities of $1\text{-}2 \times 10^{-10}$ $m^{-1}$ $sr^{-1}$ at 2 micron wavelength. This leads to required CDWL parameters of approximately 1-2 J pulse energy, 10-20 Hz PRF, 5% transmitter laser electrical to optical efficiency, 0.75 - 1 m optics diameter, lidar system efficiencies near 10%, and shot accumulation of 10-100 pulses. MSFC, LaRC, and JPL continue to collaborate to achieve these advances.

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