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Expected Characteristics of Global Wind Profile Measurements with a Scanning, Hybrid, Doppler Lidar System

Michael J. Kavaya

NASA Langley Research Center
Mail Code 468, Hampton, Virginia, 23681, USA

Abstract

Over 20 years of investigation by NASA and NOAA scientists and Doppler lidar technologists into a global wind profiling mission from earth orbit have led to the current favored concept of an instrument with both coherent- and direct-detection pulsed Doppler lidars (i.e., a hybrid Doppler lidar) and a step-stare beam scanning approach covering several azimuth angles with a fixed nadir angle. The nominal lidar wavelengths are 2 microns for coherent detection, and 0.355 microns for direct detection. The two agencies have also generated two sets of sophisticated wind measurement requirements for a space mission: science demonstration requirements and operational requirements. The requirements contain the necessary details to permit mission design and optimization by lidar technologists. Simulations have been developed that connect the science requirements to the wind measurement requirements, and that connect the wind measurement requirements to the Doppler lidar parameters. The simulations also permit trade studies within the multi-parameter space. These tools, combined with knowledge of the state of the Doppler lidar technology, have been used to conduct space instrument and mission design activities to validate the feasibility of the chosen mission and lidar parameters. Recently, the NRC Earth Science Decadal Survey recommended the wind mission to NASA as one of 15 recommended missions. A full description of the wind measurement product from these notional missions and the possible trades available are presented in this paper.

MISSION GEOMETRY

The lidar signal falls as the square of the range to the target. A Low Earth Orbit (LEO) height of 400 km minimizes the range to the target while retaining sufficient mission lifetime. A polar sun-synchronous dawn-dusk orbit maximizes the sun's illumination of the solar panels to provide the required power for the active sensors. The satellite velocity is 7.7 km/s and the earth surface point beneath the satellite advances at 7.2 km/s. The rotation of the earth between two successive orbits is 23 deg. or 2570 km at the equator and 2050 km at 37 deg. latitude. The hybrid lidar system scanner would be capable of 45, 135, 225, or 315 deg. azimuth angle with 0 deg. defined as the spacecraft flight direction. The scanner nadir angle is a constant 45 deg. as a compromise between the range to the target and the alignment with the desired horizontal wind. Because of the curved earth, the nadir angle at the earth's surface increases to 48.7 deg and any lidar LOS wind error is magnified by a factor of 1.33 into the horizontal plane. The laser's pulse strikes the earth's surface a distance 414 km from the point beneath the spacecraft. The along-track and cross-track components of this distance are each 292 km. Azimuth angles 45 and 135 comprise a fore and aft pair of LOS wind profiles to the right of the satellite ground track. Azimuth angles 315 and 225 deg comprise a fore and aft pair to the

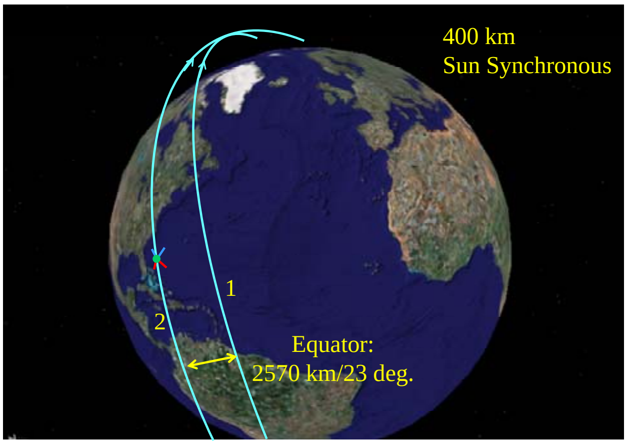

Figure 1**: Two consecutive orbits**

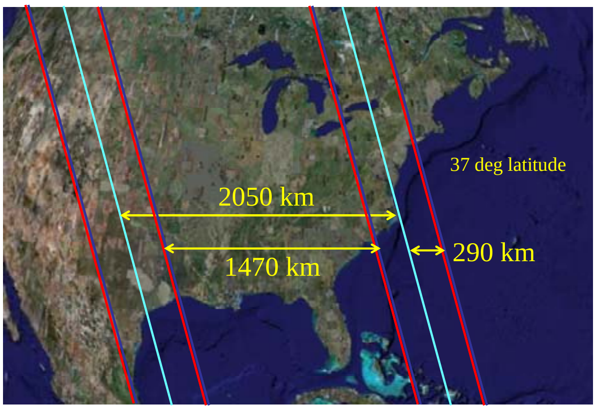

Figure 2**: Geometry of two ground tracks and their left and right vector wind track positions**

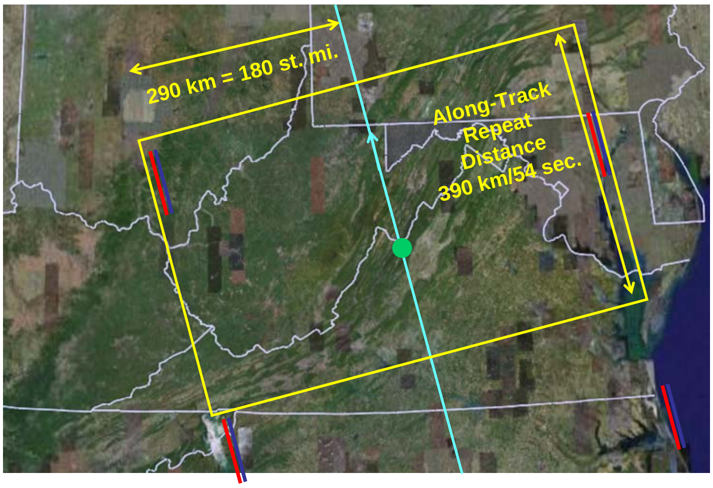

Figure 3**: Left and right vector wind profiles repeat every 390 km**

left of the track. The angle between the fore and aft views in the horizontal plane is the optimum 90 deg. angle. The cross-track positions of the right and left LOS profile pairs are separated by about 584 km. There is a 1470 km distance between the left measurements of one orbit and the right measurements of the next orbit at 37 deg. latitude. The scanner dwells at each azimuth angle for 12 s while each Doppler lidar fires multiple laser shots to obtain one vertical profile of the line-of-sight (LOS) wind velocity in the direction of the laser beam. Firing at 5 and 100 Hz, the coherent and direct lasers

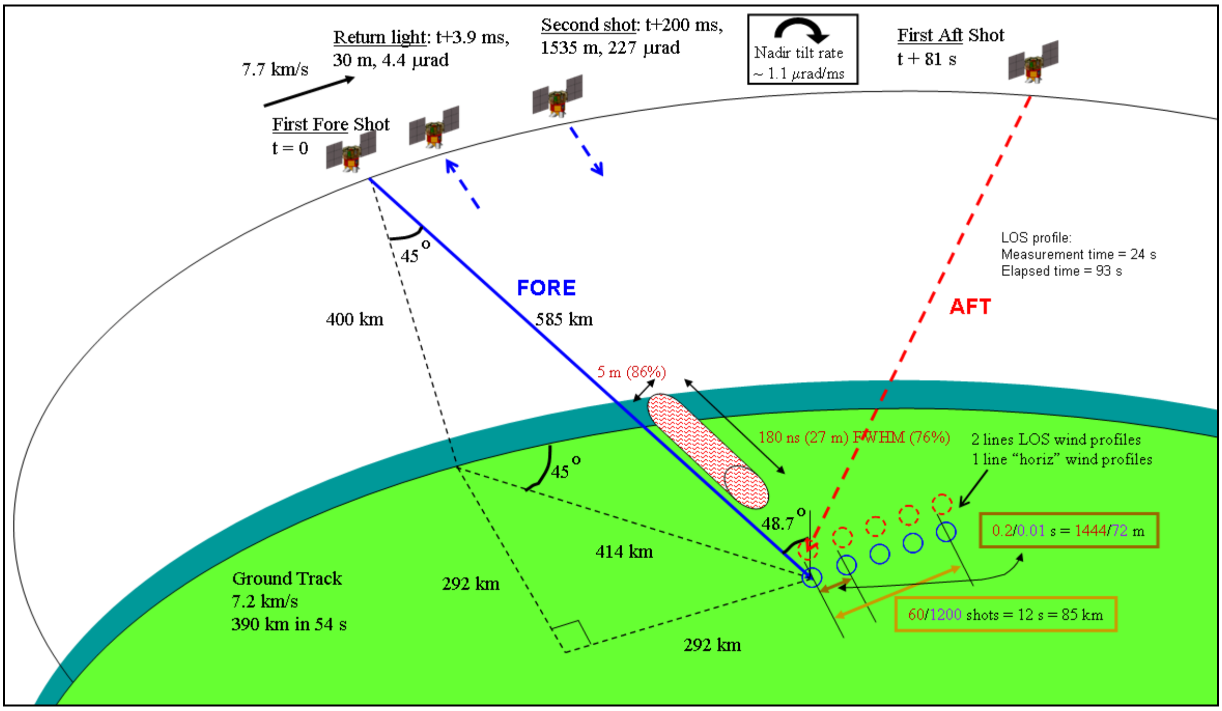

Figure 4**: Depiction of lidar shot accumulation for a collocated pair of LOS wind profiles ("vector wind profile")**

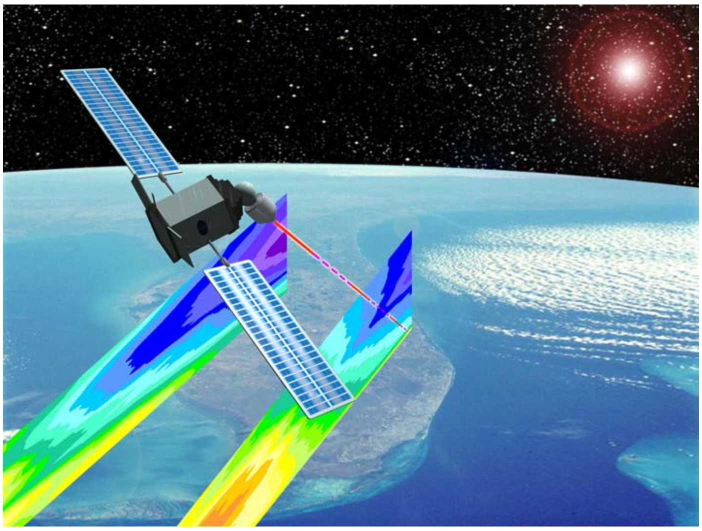

Figure 5**: Depiction of color coded horizontal wind magnitudes for left and right measurement tracks of one orbit**

accumulate 60 and 1200 shots for the LOS profile, respectively. The surface distance between successive laser shots is 1444 and 72 m, respectively. During the 12 s of shot accumulation, the surface position advances 85.2 km. A time interval of 1.5 s is allotted to change from one azimuth angle to the next. Each azimuth angle requires 12 + 1.5 = 13.5 s. A full pattern of four azimuth angles requires 54 s. During this time the surface position advances 390 km. This is the measurement repeat distance in the along-track direction. The aft LOS shot accumulation is timed to closely overlay the fore

LOS shot accumulation. Figures 2, 3, and 4 show the 85 km long shot sequences as blue and red for fore and aft, respectively. The duty cycle of each azimuth angle is 25%. This is also the duty cycle for the fore and aft LOS wind profile pairs for both the right and left sides of the ground track. The artist concept in Figure 5 shows the two vertical planes of vector horizontal wind measurements made by one orbit; however the 25% duty cycle in the along track direction is not depicted. For overlap, the first shot in the aft direction needs to occur about 81 s after the first shot of the fore direction. The measurement time for the LOS and vector profiles is 12 and 24 s, respectively. The total elapsed time is 12 and 93 s, respectively. Together, physically overlapped fore and aft pair of LOS wind profiles approximately contains the information in a horizontal vector wind profile. However, it is planned to provide the data user with the pairs of LOS wind profiles appropriately labeled with measurement time, location, and laser beam angle, and quality flag.

DOPPLER LIDAR REMOTE SENSOR

The wind sensor is envisioned to be a combination of a coherent-detection and direct-detection pulsed Doppler wind lidar. The combination is called a hybrid Doppler wind lidar. The direct-detection lidar uses optical components that are very sensitive to the exact wavelength of the backscattered lidar

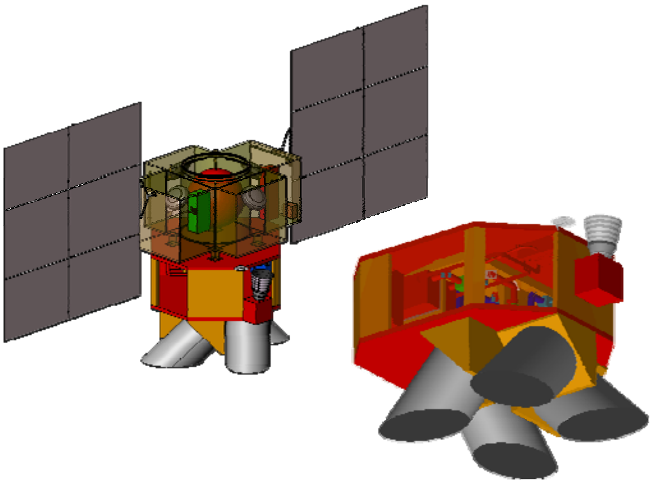

***Figure 6*: Depiction of the instrument and integrated spacecraft with four fixed telescopes**

signal. Optical intensities are carefully measured to calculate the wind-caused Doppler shift of the light. The coherent-detection lidar uses a single element optical detector both as a photon to electron converter as does the direct lidar, and as a mixer. A separate continuous-wave (CW) local oscillator (LO) laser illuminates the detector and translates the entire backscattered light's optical spectrum from THz frequencies to MHz frequencies. The translated optical spectrum is then digitized and processed in a computer to find the wind-caused Doppler shift. The nominal lidar wavelengths are 2 microns for coherent detection, and 0.355 microns for direct detection. Tables 1 and 2 provide some comparisons of the two Doppler lidars and some of the benefits of having both types of lidars in the sensor. The wind measurement requirements for the first science demonstration space mission only require two tracks of vector horizontal wind profiles. This is doable with four azimuth angles as discussed above. Rather than a moving large scanner for this first mission, we baseline a set of four fixed position telescopes of 50 cm diameter each. A moving optic much smaller than 50 cm chooses which azimuth angle to use.

	Coherent Detection	Direct Detection
Laser Wavelength (microns)	2.053	0.355
Doppler Shift (MHz/m/s)	0.976	5.63
Primary Target	Aerosols	Molecules
Target Spectral Width (m/s)	0.006 from Brownian motion; Dominated by approx. 10% of mean wind	300 from Brownian motion
Use of Optical Detector	Convert photons to electrons and use LO to translate optical spectrum to much lower frequencies	Convert photons to electrons
Method to Eliminate Background Light	Digital signal processing in computer	Narrowband optical filter
Low Signal Disadvantage	Declining probability of a wind measurement	Increasing velocity error
Low Signal Advantage	Successful wind measurements are very accurate	Always make a measurement

***Table 1*: Comparison of coherent and direct detection Doppler lidars**

Overall sensor power, mass, volume, and development risk is reduced
Natural redundancy
Coherent lidar works better as altitude goes down
Direct lidar works better as altitude goes down
Altitudes where both lidars measure wind provide intercomparisons
Knowledge of direct lidar measurement can extend coverage of coherent lidar
Coherent lidar surface returns can calibrate attitude of both lidars
Coherent lidar can measure winds below a cloud deck by poking though the holes

***Table 2*: Benefits of the hybrid Doppler wind lidar concept**

WIND MEASUREMENT REQUIREMENTS

The formulation of the wind measurement requirements has been ongoing since the 1970's. In 2001, NASA sponsored a gathering of NASA, NOAA, university, and industry scientists to update and improve the requirements. In particular, Doppler lidar technologists worked with the scientists to ensure that the requirements addressed the tradeoffs faced by the design of an earth-orbiting wind sensor and mission. The result was a sophisticated set of requirements with accompanying definitions, comments, and design atmospheric parameters vs. height, laser wavelength, and conditions. Figure 7 shows what is covered by the requirements. Table 3 presents a selection of the requirements for the envisioned first and second space missions. A recent NASA report devotes 24 pages to document the complete NASA-NOAA requirements [A. Valinia, J. Neff, S. Ismail, M. J. Kavaya, U. N. Singh, et al, "Lidar Technologies Working Group Report," Final Report of the NASA Earth Science Technology

Office (ESTO) Laser/Lidar Technology Requirements Working Group (June 2006); available at http://esto.nasa.gov/adv_planning.html]. Since that report, some terminology changes and upper atmosphere vertical resolution changes have occurred and are depicted in Table 3.

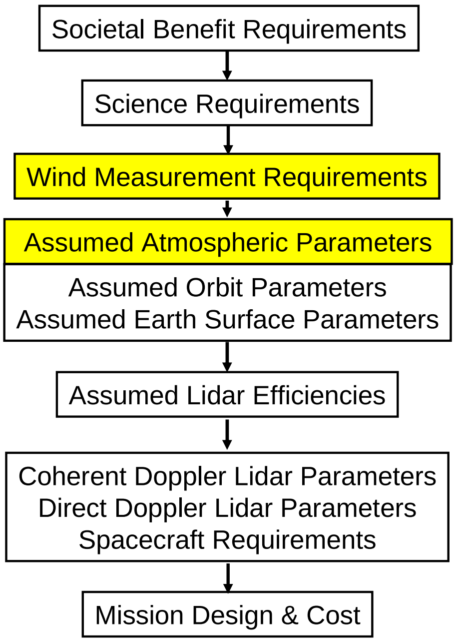

***Figure 7*: Mission areas specified by the NASA-NOAA wind measurement requirements**

	Science Demonstration	**Operational**	
Minimum Vertical Depth of Regard (DOR)	0-20	0-20	km
Maximum Vertical Resolution: Tropopause to Top of DOR Top of BL to Tropopause (~12 km) Surface to Top of BL (~2 km)	 4 2 1	 3 1 0.5	 km km km
Maximum Horizontal Resolution[A]	350	350	km
Minimum Number of Horizontal[A] Wind Tracks[B]	2	4	-
Minimum Number of Collocated LOS Wind Measurements for Horizontal[A] Wind Calculation	2 = pair	2 = pair	-
Maximum Velocity Error[C] Above BL In BL	3 2	3 2	m/s m/s
Minimum Wind Measurement Coverage[D]	50	50	%

[A] Horizontal winds are not actually calculated; rather two LOS winds with appropriate angle spacing and collocation are measured for an "effective" horizontal wind measurement. The two LOS winds are reported to the user. [B] The 4 cross-track measurements do not have to occur at the same along-track coordinate; staggering is OK. [C] Error = 1σ LOS wind random error, projected to a horizontal plane; from all lidar, geometry, pointing, atmosphere, signal processing, and sampling effects. The true wind is defined as the linear average, over a 100 x 100 km box centered on the LOS wind location, of the true 3-D wind projected onto the lidar beam direction provided with the data. [D] Scored per vertical layer per LOS measurement not counting thick clouds

***Table 3*: Key subset of wind measurement requirements**

COMPARISON OF FIRST MISSION TO GLOBAL RAWINSONDE NETWORK

It is interesting to compare the measurement output of the first envisioned “Science Demonstration” space mission to that of the worldwide rawinsonde network. With about 850 worldwide rawinsonde launch locations and 2 launches per day, the rawinsonde network provides 1700 vector wind profiles per day. The first hybrid Doppler lidar space mission would make 2 vector wind profiles every 350 km (see Table 3) or every 48.5 seconds. This results in 3566 vector wind profiles per day or a factor of 2.1 more profiles than the rawinsonde network. The orbiting Doppler lidar measurements would also have the benefits of 1) true vertical profile compared to rawinsonde path, 2) more even distribution of measurements around the earth including oceans and lakes, 3) more consistent delivery and data latency, and 4) greater calibration and quality knowledge.

POSSIBLE MISSION TRADEOFFS

Table 1 showed that coherent detection Doppler lidar always makes accurate wind measurements but is coverage challenged when the aerosol backscatter coefficient of the atmosphere becomes too small. Conversely, direct detection Doppler lidar always makes a wind measurement (coverage) but is accuracy challenged when the number of received photons becomes too small. This shortage of photons may be due to cloud and atmospheric absorption at lower altitudes, a short measurement range gate (for good vertical resolution), or a short shot accumulation time (for good horizontal resolution or more cross-track measurement locations). For trade studies, the wind measurement figure of merit (Velocity Performance VP) must be different for the two types of Doppler lidar. It must be the minimum required aerosol backscatter coefficient for coherent lidar, and the wind measurement velocity error for direct detection. Figure 8 shows the lidar and science requirement parameter dependencies for the two cases. R is the range to the target, E is the laser pulse energy, PRF is the laser pulse repetition frequency, D is the lidar receiver diameter, Vert Res is the required vertical resolution (VR), λ is the laser wavelength, and θ_{MISAL} is the transmitter-receiver misalignment angle during reception of the backscattered photons.

<u>Coherent Detection Doppler Wind Lidar</u>

Minimum Required Aerosol Backscatter Coefficient

$$\propto \frac{R^2}{\mathrm{E} \times \sqrt{\mathrm{PRF}} \times \sqrt{\mathrm{Vert\,Res}} \times \mathrm{D}^2 \times e^{-\left[\frac{1.1\mathrm{D}\theta_{\mathrm{MISAL}}}{\lambda}\right]^2}}$$

<u>Direct Detection Doppler Wind Lidar</u>

Velocity Error

$$\propto \frac{\mathrm{R}}{\mathrm{D}\sqrt{\mathrm{E} \times \mathrm{PRF} \times \mathrm{Vert\,Res}}}$$

***Figure 8*: Velocity performance parameter dependencies for both types of Doppler lidar**

There is another key concept required before trades can be discussed. The expressions in Figure 8 do not directly include the along-track measurement repeat distance (horizontal resolution, HR) or the number of wind tracks (NWT) parameters. The way to include these parameters is to realize that making the horizontal resolution better by a factor of 2 (dividing HR by 2) has the main effect of cutting the available measurement time by a factor of 2. One way to compensate for this is to double the PRF. The equation is HR x PRF = constant. Similarly, increasing the number of wind tracks by a factor of 2 means that the time available for each wind track is decreased by 2. One way to compensate is to double the PRF. The equation is PRF/NWT = constant. Note that smaller values for VP, VR, and HR are better.

	Coherent	Direct
Science Requirement vs. Science Requirement	VP^2 x VR x HR / (NWT x R^4) = constant	VP^2 x VR x HR / (NWT x R^2) = constant
Lidar Parameter vs. Lidar Parameter	PRF x E^2 x D^4 = constant	PRF x E x D^2 = constant
All Parameters	VP^2 x VR x HR x PRF x E^2 x D^4 / (NWT x R^4) = constant	VP^2 x VR x HR x PRF x E x D^2 / (NWT x R^2) = constant

***Table 4*: Parameter tradeoff rules**

Table 4 shows the parameter trade rules for science requirements, geometry, and lidar parameters. The equations for science requirements vs. science requirement are almost the same for coherent and direct detection. The exception is the range to target which is categorized here as a science requirement because of its effect on mission lifetime and cross-track field of regard. For both types of lidars the VR and HR may be inversely traded, and the VR x HR product may be proportionately traded with NWT. For example, if VR is improved (reduced) by 2, then HR may be relaxed (increased) by 2 to compensate. If NWT is doubled, then the product VR x HR may be relaxed by 2 to compensate. If it is desired to improve VP by 2, then the product VR x HR may be relaxed by 4, or NWT may be reduced by 4. Changes in R cause large ramifications, more so for coherent lidar. The equations for trading lidar parameter vs. lidar parameter are quite different for the two lidars. The influence of pulse energy and optical diameter is much greater for coherent. For example, a desire to reduce PRF by 2 may be balanced by reducing E by 1.4 or 2 for coherent and direct, respectively; or by reducing D by 1.2 or 1.4 for coherent and direct, respectively. The last row of Table 4 shows the combined science requirement and lidar parameter equations. It is desired to minimize all the parameters in the numerators for reasons of science value and engineering ease. It is desired to maximize NWT for science value.

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