A Space-Based Point Design for Global Coherent Doppler Wind Lidar Profiling Matched to the Recent NASA/NOAA Draft Science Requirements

Michael J. Kavaya
NASA Langley Research Center
Mail Code 468, Hampton, VA 23681 USA
(757) 864-1606, (757) 864-8828 (fax)
m.j.kavaya@larc.nasa.gov

G. David Emmitt
Simpson Weather Associates

Rod G. Frehlich
University of Colorado

Farzin Amzajerdian
Upendra N. Singh
NASA Langley Research Center

ABSTRACT

An end-to-end point design, including lidar, orbit, scanning, atmospheric, and data processing parameters, for space-based global profiling of atmospheric wind will be presented. The point design attempts to match the recent NASA/NOAA draft science requirements for wind measurement.

INTRODUCTION

The global measurement of vertical profiles of horizontal winds throughout the troposphere continues to be a highly desired, unmet need of NOAA, the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office (IPO), NASA, DOD, and other organizations[1]. Recent global wind measurement activities by the joint NASA/NOAA Global Tropospheric Winds Sounder (GTWS) program have included the formation of a Science Definition Team (SDT), the formulation by the SDT of draft science requirements with public release for comments[2], the generation of point designs[3] for both coherent-detection and noncoherent-detection (direct) Doppler wind lidar systems in space matched to the draft science requirements, and both space instrument designs and space mission designs for both lidar types, based on the point designs. The instrument and mission designs were performed, respectively, by the Instrument Synthesis and Analysis Lab (ISAL)[4], and Integrated Mission Design Center (IMDC)[5] at NASA Goddard Space Flight Center. The purpose of this paper is to present the coherent-detection Doppler wind lidar point design results.

DRAFT SCIENCE REQUIREMENTS

The joint NASA Earth Science Enterprise (ESE)/NOAA National Environmental Satellite Data and Information Service (NESDIS) "draft Global Tropospheric Winds Sounder (GTWS) Science and Operational Data Specification" was released on 16 October 2001. The wind measurement requirements, the atmospheric environment parameters, and the spatial resolution and coverage requirements were defined since Doppler wind lidar measurements involve a close interdependence of these areas. Two complete sets of numbers representing "threshold" and "objective" wind missions were listed. The “threshold” requirements were deemed to represent the minimum data requirements that would result in a meaningful impact on science and operational weather prediction. An orbit height was not specified. The GTWS chose to concentrate on the “threshold” mission, and to specify a 400-km orbit height for internal consistency. The full requirements document may be accessed on the Internet[2]. A brief synopsis is presented in Table 1, but the entire document is needed for full specification. The locations directly under the orbiting satellite on the earth’s surface are referred to as the track.

Table 1. Draft NASA/NOAA Threshold Wind Data Product Requirements

Vertical depth of regard of wind measurements (DOR)	km	0-20
Vertical resolution: Tropopause to top of DOR Top of BL to tropopause Surface to top of boundary layer (BL) (BL specified = 2 km)	 km km km	 Not required 1 0.5
Vertical location accuracy of line-of-sight (LOS) wind measurements	km	0.1
Horizontal location accuracy of LOS wind measurements	km	0.5
Number of collocated LOS wind measurements for horizontal[A] wind calculation	-	2 = pair
Allowed angular separation of LOS wind pair, projected to a horizontal plane	degree	30-150
Maximum allowed horizontal separation of LOS wind pair	km	35
Maximum horizontal extent of each horizontal[A] wind measurement	km	100
Maximum along-track horizontal spacing of horizontal[A] wind measurements	km	350
Minimum horizontal cross-track width of regard of wind measurements	km	±400
Minimum number of cross-track locations for horizontal[A] wind measurements[B]	-	4
Maximum cross-track spacing of adjacent cross-track locations	km	350
Maximum design horizontal wind speed: Above BL Within BL	 m/s m/s	 75 50
Maximum 1σ LOS wind random error, projected to a horizontal plane; from all lidar, geometry, pointing, atmosphere, signal processing, and sampling effects[C]	m/s	3
Design 1σ wind turbulence level	m/s	1.2
Maximum LOS wind unknown bias error, projected to a horizontal plane	m/s	0.1
Minimum design a priori velocity knowledge window, projected to a horizontal plane (using nearby wind measurements and contextual information)	m/s	26.6
Design cloud field: Layer from 9-10 km, extinction coefficient Layer from 2-3 km, 50% of lidar shots untouched, 50% blocked	 km^{-1} %	 0.14 50, random
Aerosol backscatter coefficient: 2 vertical profiles provided	m-1sr-1	Provided
Aerosol backscatter: Probability density function (PDF) PDF width	 m sr m-1sr-1	 Lognormal Provided
Atmospheric extinction coefficient: 2 vertical profiles provided	km^{-1}	Provided
Minimum wind measurement success rate, referenced to these requirements, including two specified cloud layers	%	50
Orbit latitude coverage	degree	80N to 80S
Downlinked data	-	All raw data
Mission life	year	2

[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]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.

SPACE-BASED COHERENT DOPPLER WIND LIDAR POINT DESIGN

The specifications in the draft science requirements, probably the most comprehensive ever done, eliminated much of the usual trade space in generating a point design. We chose a step-stare lidar scanner capable of pointing anywhere on the surface of a cone with a half angle of 45 degrees, and centered in the nadir direction. Combined with the required 400 km orbit height, the possible intersection points of the lidar beam with the earth was a circle with a great circle radius of 414 km. (We neglect here the variation in earth's radius with location. Many important and perhaps subtle aspects of lidar wind measurement from space have been published elsewhere[6-11].) The slant range to the earth surface was 585 km, the nadir angle in the troposphere varied slightly with altitude about 48.6 degrees, and the delay time from laser firing to receiving return signal varied slightly with altitude about 3.8 ms. The horizontal wind velocity was reduced by a nadir angle factor 0.75 for the LOS wind measurement, but the total LOS wind measurement error was amplified by a nadir angle factor 1.33 for projection into the horizontal.

Table 2. Coherent Lidar Point Design Parameters

Orbit height	km	400
Orbit inclination angle: (sun-synchronous)	degree	97.03
Scanner type: rotating telescope, step-stare		
Lidar scanner nadir angle	degree	45
Number of scanner azimuth angles	-	8
Azimuth angle sequence: 114, 73.8, -18.4, -155, -109, -64.2, 25.3, 152	degrees[A]	
Optical wavelength	micron	2.0518
Pulse energy	J	5
Pulse repetition rate	Hz	12
Pulse duration (Gaussian temporal shape)	ns	180
Telescope diameter	m	0.75
Lidar system efficiency: Optics transmission terms = 0.63 Optics aberration terms = 0.88 Coherent detection terms = 0.29 Budgeted lidar contribution to return signal misalignment = 0.71	-	0.12
Budgeted non-lidar contribution to return signal misalignment	-	0.71
Each LOS wind measurement: Number of lidar shots combined Along-track measurement length of combined shots	 - km	 60 36
Sampling error combined with lidar error	m/s	0.7
Assumed occurrences in nature of background and enhanced aerosol modes	%	75, 25
Aerosol backscatter profile percentile used (percent of atmosphere with higher backscatter)	%	70
Coherent lidar statistical wind measurement success rate	%	≥72
Combined aerosol backscatter and lidar statistics success rate (0.7 x 0.72)	%	≥50

[A]Azimuth is measured CCW from forward for positive values

Although the satellite tangential velocity was 7680 m/s, the sub-satellite position on the earth advanced at 7220 m/s. The allowed 350 km horizontal spacing of the wind measurements was traveled in 48.5 s. This represents the maximum allowed time to make wind measurements at all 4 cross-track locations; hence the maximum time to make 8 LOS wind measurements at 8 scanner azimuth angles. We allocated 5 s for each LOS wind measurement and 1.06 s for each scanner direction change. The 2-micron, solid-state pulsed laser development program at NASA LaRC is obtaining results favorable to a 12 Hz laser pulse firing rate. Therefore, we chose the accumulation or combination of 60 laser shots for each LOS wind measurement. For coherent lidar wind measurement with likely frequency estimation algorithms, this shot accumulation improves the sensitivity of the wind measurement (lowers the required aerosol backscatter coefficient at a given performance level) by the square root of the number of accumulated shots[12]. In our case the sensitivity improved by 9 dB. This permitted our laser pulse energy and/or optical diameter to be smaller compared to a single shot wind measurement case. The early work on space-based lidar winds, such as the Laser Atmospheric Wind Sounder (LAWS), all assumed single-shot wind measurement.

The point design parameters of the coherent lidar and mission are given in Table 2. The azimuth angles and their sequence provided the required collocation of the fore and aft LOS wind pairs at the equator. Slight adjustments to the angles will be needed at other latitudes. The vertical profiles of velocity error for both the background and enhanced aerosol backscatter cases are shown in Figure 1. The vertical profile of the coherent lidar probability of successful wind measurement for the assumed occurrence probabilities of the two aerosol cases is shown in Figure 2. Note in Table 2 that the overall wind measurement success rate is the required 50%. Discussion of these and other results will be presented.

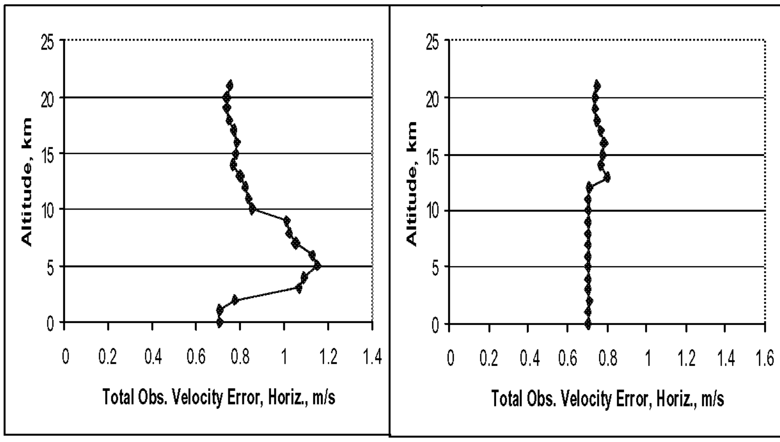

Figure 1. Background (L) and Enhanced (R)

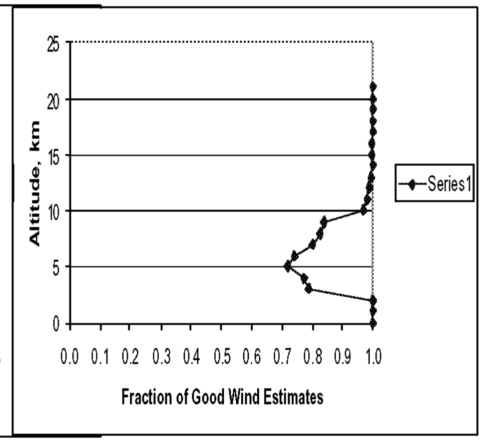

Figure 2

REFERENCES

1. http://npoesslib.ipo.noaa.gov/Req_Doc/IORDII_011402.pdf, p.40
2. http://nais.msfc.nasa.gov/cgi-bin/EPS/synopsis.cgi?acqid=99220
3. K. Miller, "GTWS Reference Designs," Meeting of the Working Group on Space-Based Lidar Winds, Key West, Florida (Jan. 2002), http://space.hsv.usra.edu/LWG/Index.html
4. http://isal.gsfc.nasa.gov/
5. http://imdc.gsfc.nasa.gov/
6. M. J. Kavaya, G.D. Spiers, E.S. Lobl, J. Rothermel, and V.W. Keller, "Direct global measurements of tropospheric winds employing a simplified coherent laser radar using fully scalable technology and technique," Proc. SPIE Vol. 2214, pp. 237-249 (6 April 1994).
7. M. J. Kavaya and G.D. Emmitt, "The Space Readiness Coherent Lidar Experiment (SPARCLE) Space Shuttle Mission," Proc. SPIE Vol. 3380, pp. 2-11, (14-16 April 1998).
8. V.S.R. Gudimetla and M. J. Kavaya, "Special Relativity Corrections for Space-Based Lidars," Appl. Opt. 38(30), 6374-6382 (1999)
9. M. J. Kavaya, G. D. Spiers, and R. G. Frehlich, "Potential Pitfalls related to space-based lidar remote sensing of the Earth with an emphasis on wind measurement," Proc. SPIE 4153, pp. 385-393 (2001)
10. R. Frehlich, "Errors for Space-Based Doppler Lidar Wind Measurements: Definition, Performance, and Verification," J. Atmospheric and Oceanic Technology 18, 1749-1772 (2001)
11. M. J. Kavaya and G. D. Emmitt, "Characteristics and Trade-Offs of Doppler Lidar Global Wind Profiling," Proc. 82^{nd} AMS Annual Meeting, 18^{th} International Conf. on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology, pp. 215-217, Orlando, FL (13-17 Jan. 2002)
12. J. Yu, M. Petros, U. N. Singh, N. P. Barnes and J. C. Barnes, "An All Solid-State 2-μm Laser System for Space Coherent Wind Lidar", IEEE 2000 Aerospace Conference proceeding, volume 3 of 7, 27-33 (2000)
13. R. Frehlich, "Simulation of Coherent Doppler Lidar Performance for Space-Based Platforms," J. Appl. Meteorology 39, 245-262 (2000)