DAWN
Doppler Aerosol WiNd lidar

(hurricane)
Genesis and Rapid Intensification Processes (GRIP)
Science Team Meeting
El Segundo, CA

Michael J. Kavaya
NASA Langley Research Center

June 6, 2011

Acknowledgements

NASA SMD

Ramesh Kakar

AITT-07 “DAWN-AIR1”

GRIP

Jack Kaye $ Augmentation

NASA SMD ESTO

George Komar, Janice Buckner, Parminder Ghuman, Carl Wagenfuehrer

LRRP, IIP-04 “DAWN”

IIP-07 “DAWN-AIR2”

Airplane Change & Rephasing

NASA LaRC Director Office, Steve Jurczyk, *$ Augmentation*

NASA LaRC Engineering Directorate, Jill Marlowe, John Costulis, *$Augmentation*

NASA LaRC Chief Engineer, Clayton Turner, *1 FTE*

NASA LaRC Science Directorate

Garnett Hutchinson, Stacey Lee, and Keith Murray

Project Personnel (DAWN-AIR1, DAWN-AIR2, & GRIP)

*also were DAWN operators on GRIP flights

Dr. Michael J. Kavaya*	PI, LaRC	Overall project coordination including cost and schedule control and reporting. Lead, coherent lidar & data processing
Dr. Robert A. Atlas	Co-I, NOAA AOML Dir.	Science planning and data analysis
Dr. Jeffrey Y. Beyon*	Co-I, LaRC	Lead, data acquisition hardware and software
Garfield A. Creary*	LaRC	Project Manager
Dr. G. David Emmitt	Co-I, SWA Pres.	Science planning, data analysis, lidar attitude knowledge
Dr. Grady J. Koch*	Co-I, LaRC	Lead, lidar system overview, lidar receiver design, lidar remote sensing
Paul J. Petzar*	LaRC	Lead , electronics
Dr. Upendra N. Singh	Co-I, LaRC	Pulsed laser design, lidar remote sensing
Bo C. Trieu*	Co-I, LaRC	Lead, mechanical and thermal lidar subsystems
Dr. Jirong Yu*	Co-I, LaRC	Lead, pulsed laser design, lidar remote sensing
Dr. Yingxin Bai	SSAI	Laser alignment
Bruce W. Barnes	LaRC	Software
Frank L. Boyer	LaRC	Mechanical engineering
Dr. Joel F. Campbell	LaRC	Data processing
Dr. Songsheng Chen	LaRC	Laser alignment
Michael E. Coleman	AMA	Mechanical engineering
Larry J. Cowen	LaRC	Electronics technician
Joseph F. Cronauer	SSAI	Scheduling
Fred D. Fitzpatrick	LaRC	Electronics technician
Mark L. Jones	LaRC	INS/GPS software
Nathan Massick	SSAI	Mechanical engineering
Ed A. Modlin	LaRC	Mechanical technician
Anna M. Noe	LaRC	Aircraft accommodation
Don P. Oliver	LaRC	Aircraft accommodation
Karl D. Reithmaier	SSAI	Mechanical design
Geoffrey K. Rose	LaRC	Mechanical engineering
Teh-Hwa Wong	SSAI	Mechanical engineering
William A. Wood	LaRC	Software

Pulsed Coherent Lidar Wind Measurement - 7

Frequency Estimation Error

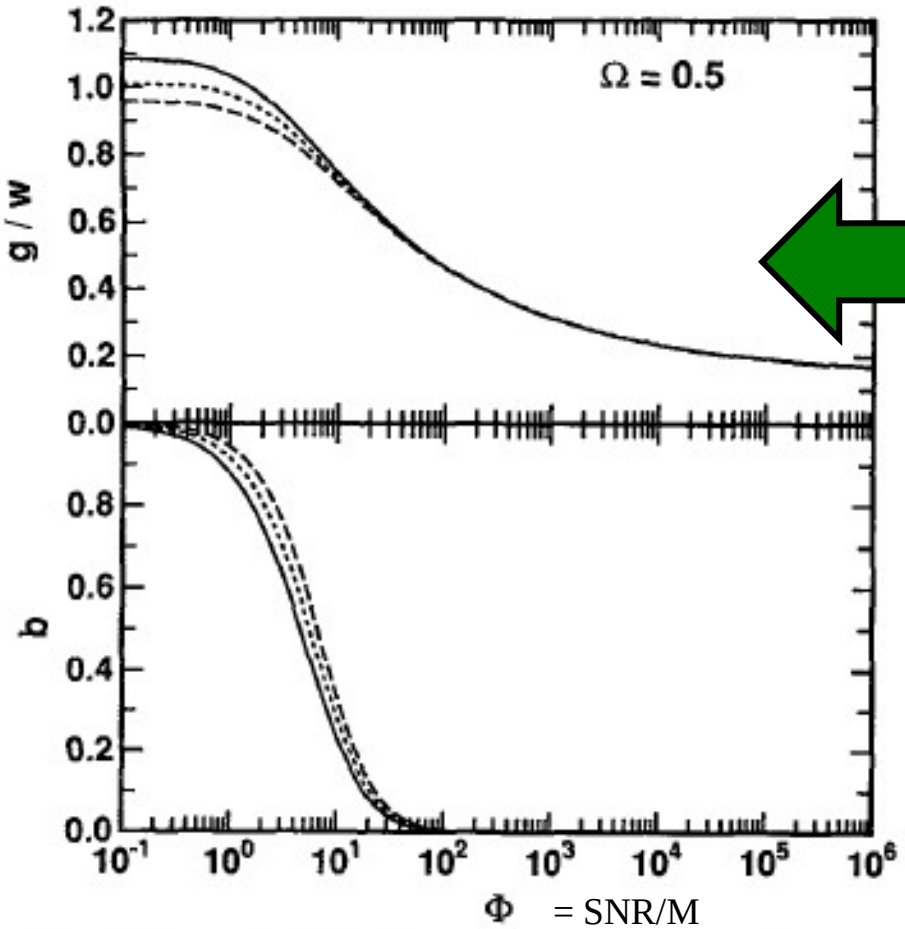


FIG. 8. The standard deviation g of the "good" ML estimates for mean frequency and the fraction b of "bad" estimates as a function of Φ for $\Omega = 0.5$. The results of the simulation are given by the best-fit empirical models [Eqs. (39) and (40)] for $M = 32$ (solid), 64 (dotted), and 128 (dashed).

- Abscissa is 7 orders of magnitude of SNR
- Upper ordinate is g/w [-]
- g – velocity error of "good" wind estimates [m/s]
- w is return signal spectral width [m/s]
- Wind turbulence σ_V [m/s] usually dominates value of w
- **g/w is constrained between 0.1 and 1.1, only 1 order of magnitude!**
- b – fraction of wind estimates that are bad
- **b is the deciding parameter!**
- Ω – 0.19 range gate length / pulse length
- M – number of data samples

1218 JOURNAL OF ATMOSPHERIC AND OCEANIC TECHNOLOGY VOLUME 11

OCTOBER 1994 FREHLICH AND YADLOWSKY 1217

Performance of Mean-Frequency Estimators for Doppler Radar and Lidar

R. G. FREHLICH AND M. J. YADLOWSKY*

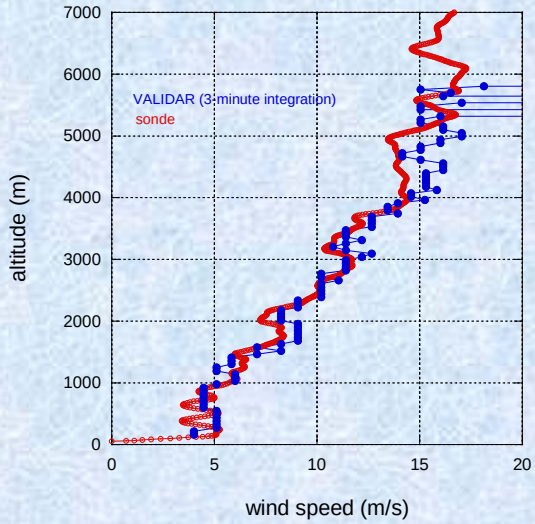
Cooperative Institute for Research in the Environmental Sciences (CIRES), University of Colorado, Boulder, Colorado

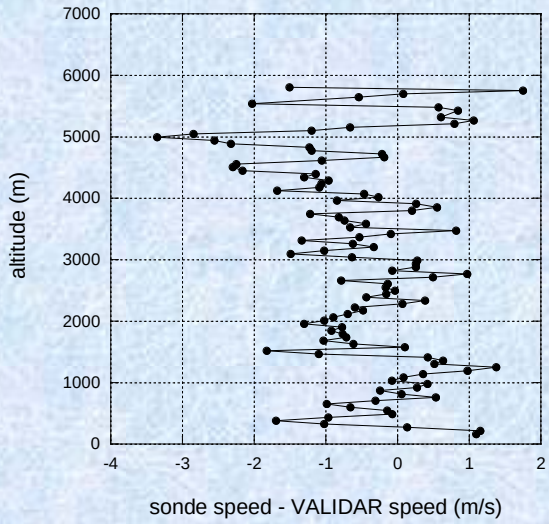
(Manuscript received 20 May 1993, in final form 14 January 1994)

DAWN Ground-Based Wind Performance

at Howard University, Beltsville, MD

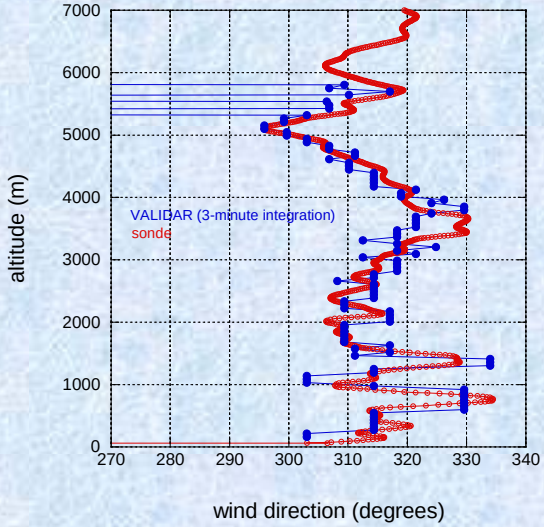
sonde on February 24, 2009 at 17:59 local

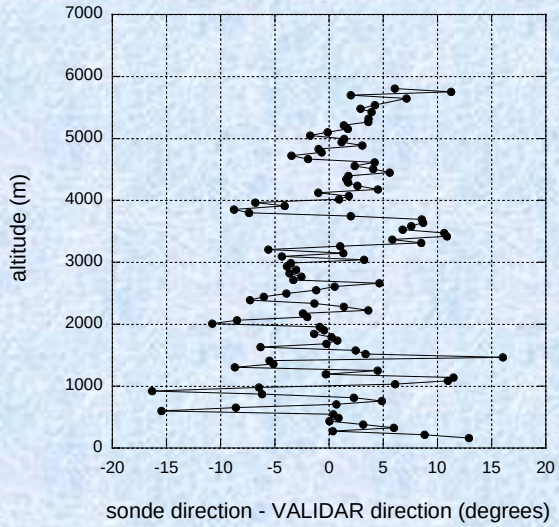




Wind Speed

- root-mean-square of difference between two sensors for all points shown = **1.06 m/s**





Wind Direction

- root-mean-square of difference between two sensors for all points shown = **5.78 deg**

Nominal Scan Pattern: DAWN During GRIP Campaign

5 different azimuth angles from -45 to + 45°

2 sec shot integration; 2 sec scanner turn time

Example:

1 pattern = 22 s = 3,168 m

Along-Track & Temporal Resolution

Swath Width Depends on Flight

And Measurement Altitudes

e.g., Flight Altitude = 10,586.4 m

Measurement Altitude = 0 m

Swath Width = 8,688 m

Trade Off

Fast revisit time to less azimuth angles

vs.

Slower revisit time to more azimuth angles (less cloud blockage?, wind variability studies, measure w)

Note: weather models assimilate LOS winds

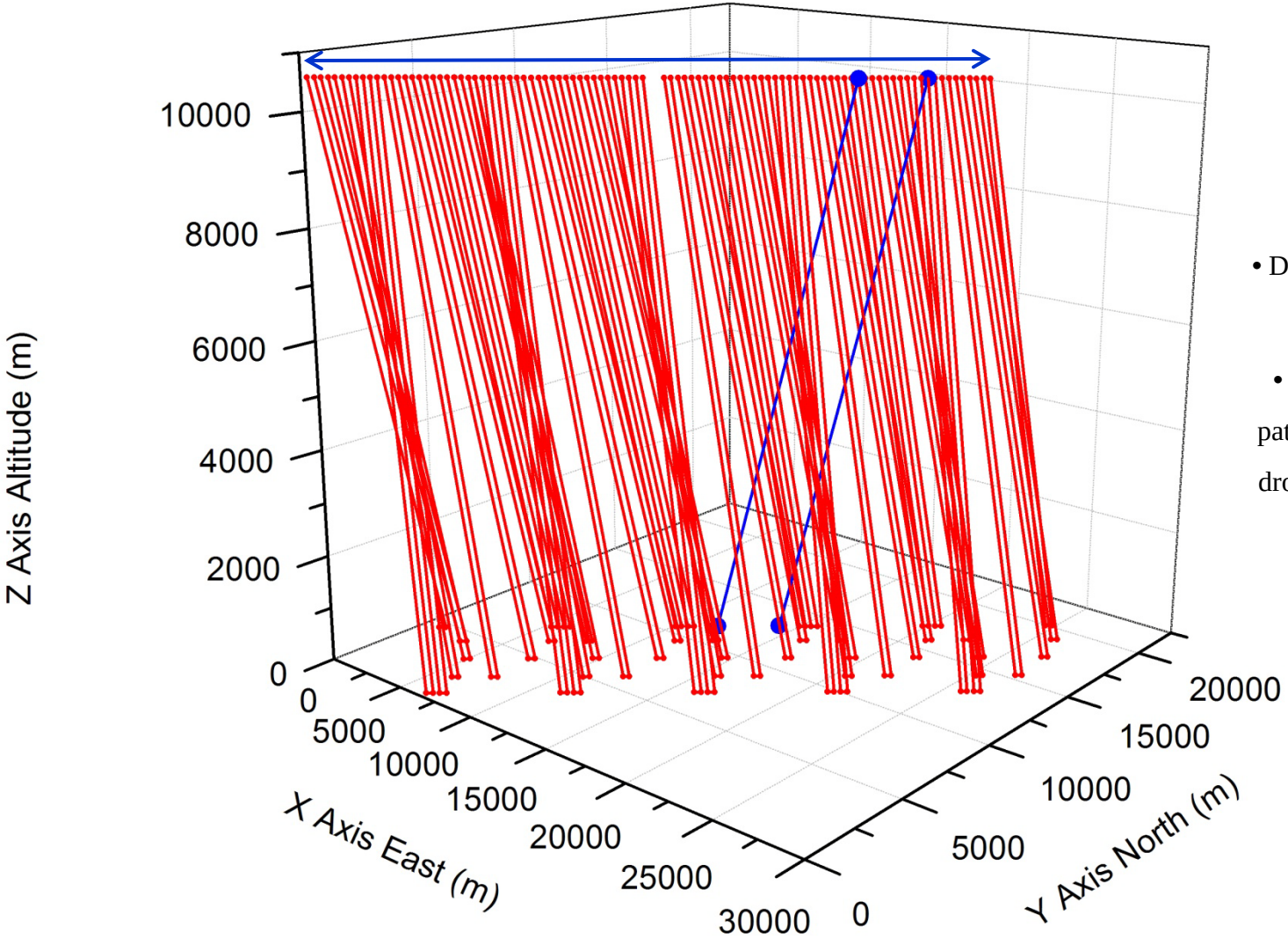
Nominal Scan Pattern: DAWN During GRIP Campaign

Actual DC-8 and dropsonde trajectories for 9-1-2010

Dropsonde launched at 17:20:15.49 Zulu

Dropsonde hit water 17:33:36.5 Zulu. Fall time = 201 sec

196 seconds = 3 min, 16 sec = 28,224 m



Same dropsonde shown for two arbitrary launches relative to lidar scan pattern

- DC-8 forward motion = 29 km
- 1 scan pattern = 22 sec
- Several different lidar scan patterns may collocate with the dropsonde at different altitudes

DAWN Data Products
All vs. Along-Track Dimension

Near Term

1. 5 LOS wind profiles vs. altitude
2. 5 LOS relative aerosol backscatter profiles vs. altitude
3. Profile of u, v, and w vs. altitude (MAIN PRODUCT)

Farther Term

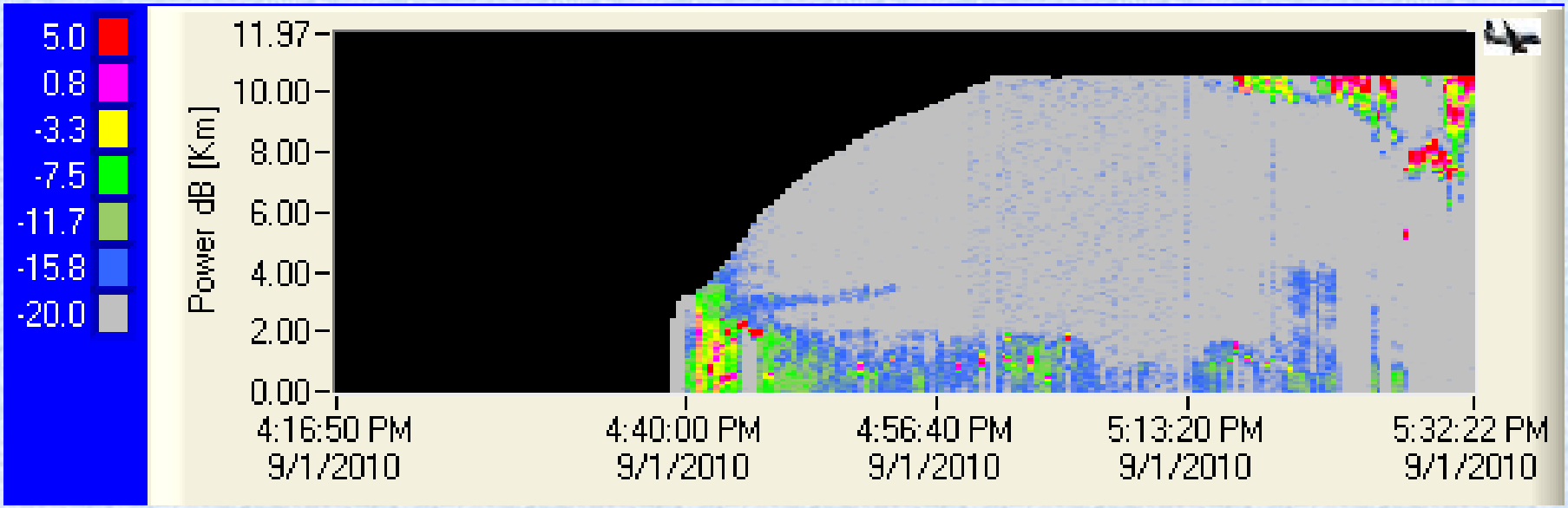
4. Wind turbulence profiles vs. altitude
5. Correlations of wind, wind turbulence, and aerosol backscatter
6. Assimilation of wind data into NWP models (NOAA)
7. Study of near ocean surface velocities (wind, spray, wave, current)
8. Multiple profiles of u, v, and w vs. altitude for investigating wind spatial variability (3 out of 5)

GRIP Science Team

9. Fusion of wind data with other GRIP or non-GRIP data for hurricane research (GRIP science team)

DAWN Vertical Coverage During GRIP

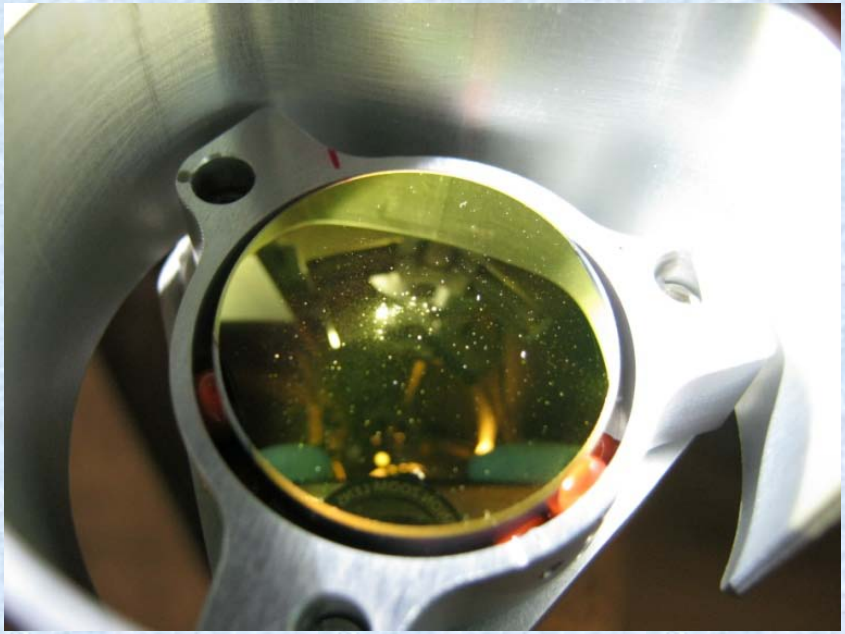
Strong Function of Cloudiness



- DC-8 taking off from Fort Lauderdale to fly into Earl
- Signal return affected by aerosol backscatter, atmospheric extinction, and$1/R^2$ (DC-8 altitude)
- Solid gray not measured
- Note almost complete profiles from 5:00 – 5:13 pm Zulu!
- Integration is 20 shots or 2 sec. (showing azimuth 0 deg only of 5 azimuths)
- Will measure entire profile next time …

Why Entire Profiles Next Time

- Post-GRIP: Discovered burn on telescope secondary mirror likely entire GRIP ~ 10 dB loss. Already fixed 4/28/11.
- Post-GRIP: Discovered slight lidar misalignment, at altitude had to cool laser to keep it working. This cooling misaligned the receiver ~ 3 dB loss for most of GRIP. Already fixed.
- Planned 250 mJ, 10 Hz laser but actually 200 mJ, 10 Hz. Already fixed.
- So we effectively flew a 200/10/2 = 10 mJ, 10 Hz laser
- Next time will be 250 mJ, 10 Hz



For GRIP data, we still need to:

- Implement best noise whitening
- Implement zero padding for multiple shot frequency registration
- Get 5-axis processing working
- Combine several scan patterns by altitude bins for handoff to science team

DAWN Horizontal Coverage During GRIP

Science Flight	DC-8 Flight Minutes	DAWN Data Minutes	DAWN to DC-8 Fraction
8/17 Zulu	281.2	176.0	0.63
8/24	437.4	368.9	0.84
8/29-30	502.8	427.4	0.85
8/30	399.9	380.6	0.95
9/1-2	478.1	469.15	0.98
9/2	466.5	444.3	0.95
9/6-7	441.2	407.6	0.92
9/7-8	420.8	395.5	0.94
9/12-13	500.4	463.6	0.93
9/13-14	500.6	421.8	0.84
9/14-15	410.8	334.8	0.82
9/16-17	486.4	475.5	0.98
9/17	485.8	422.3	0.87
9/21	443.9	399.6	0.90
9/22	456.2	400.1	0.88
Total	6711.9	5987.1	0.89

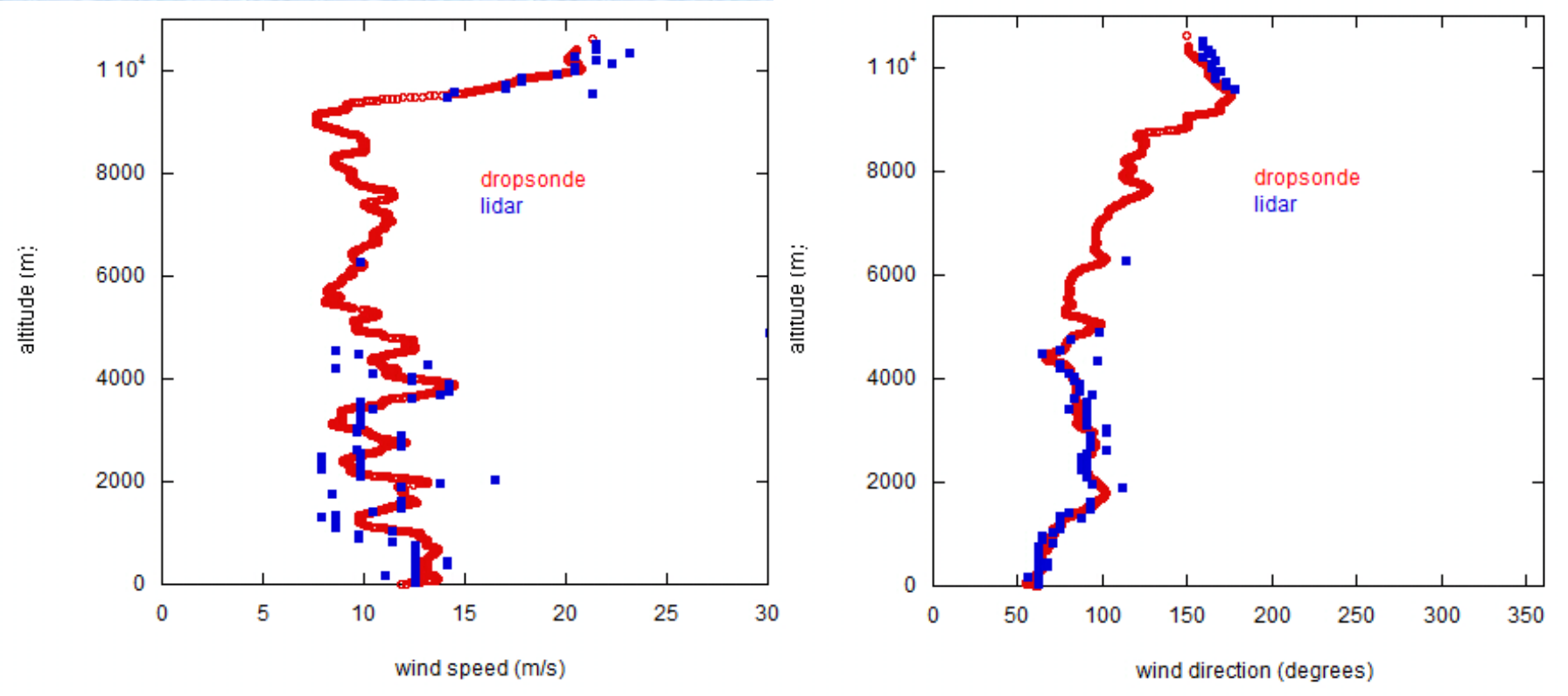
Note: Shutter 7 open minutes < flight minutes, DAWN fractions a little higher

Very roughly 0.367 min/DAWN scan … total 16,000 scans … 328 dropsondes

September 1, 2010

Lidar scan number 120 of data folder 16:17:36

17:20:11 – 17:20:31; 2-axis



Latitude = 29.95 N

Longitude = 75.75 W

GPS Altitude = 10,611 m

Over Atlantic Ocean

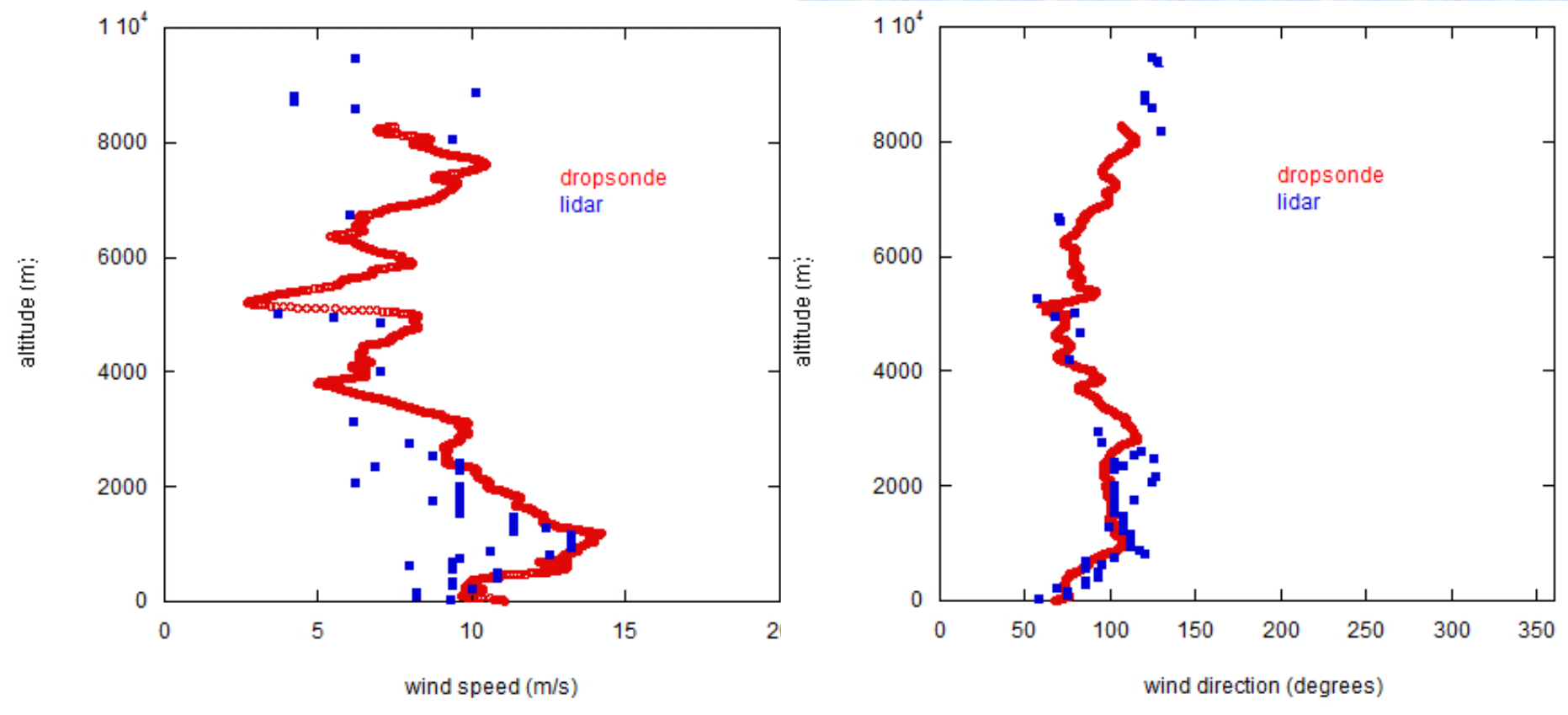
Ground Speed = 224.6 m/s

True Heading = 146 degrees

September 7, 2010

Lidar scan number 74 of data folder 18:30:23

19:24:14 – 19:24:34; 2-axis



Latitude = 20.418 N

Longitude = 65.7 W

GPS Altitude = 9,673 m

Over Atlantic Ocean

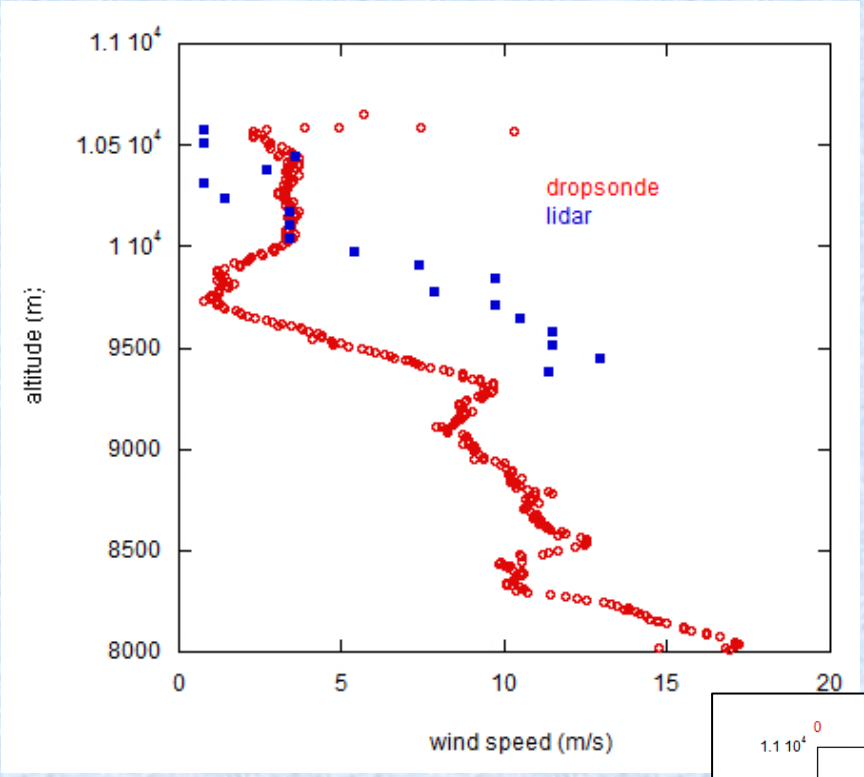
Ground Speed = 218 m/s

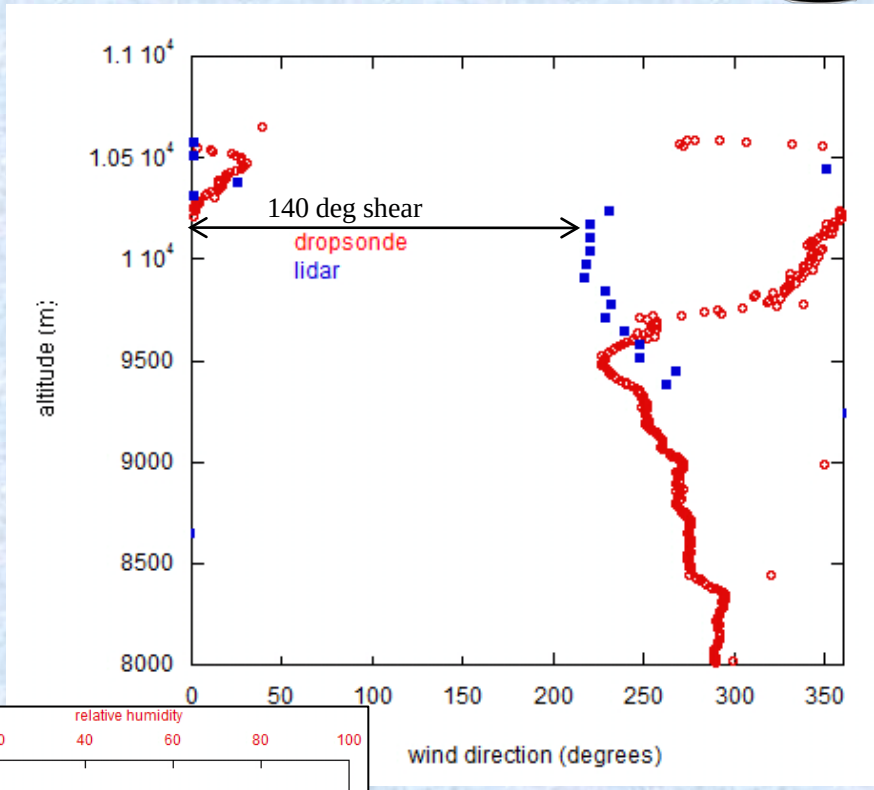
True Heading = 88.7 degrees

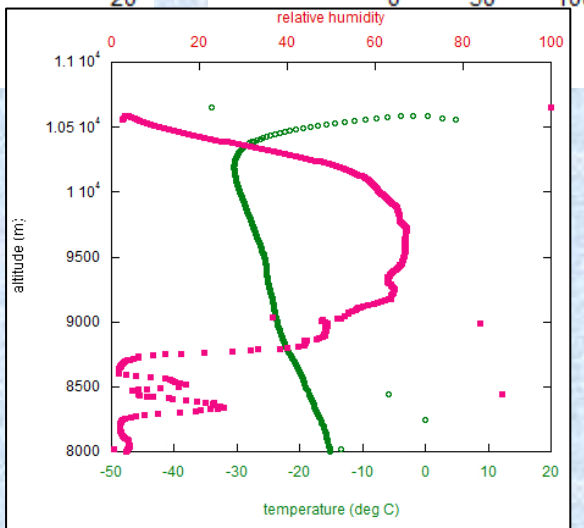
September 2, 2010

Lidar scan number 99 of data folder 16:11:47

16:55:14 – 16:55:33; 2-axis







Latitude = 31.34 N

Longitude = 77.74 W

GPS Altitude = 10,650 m

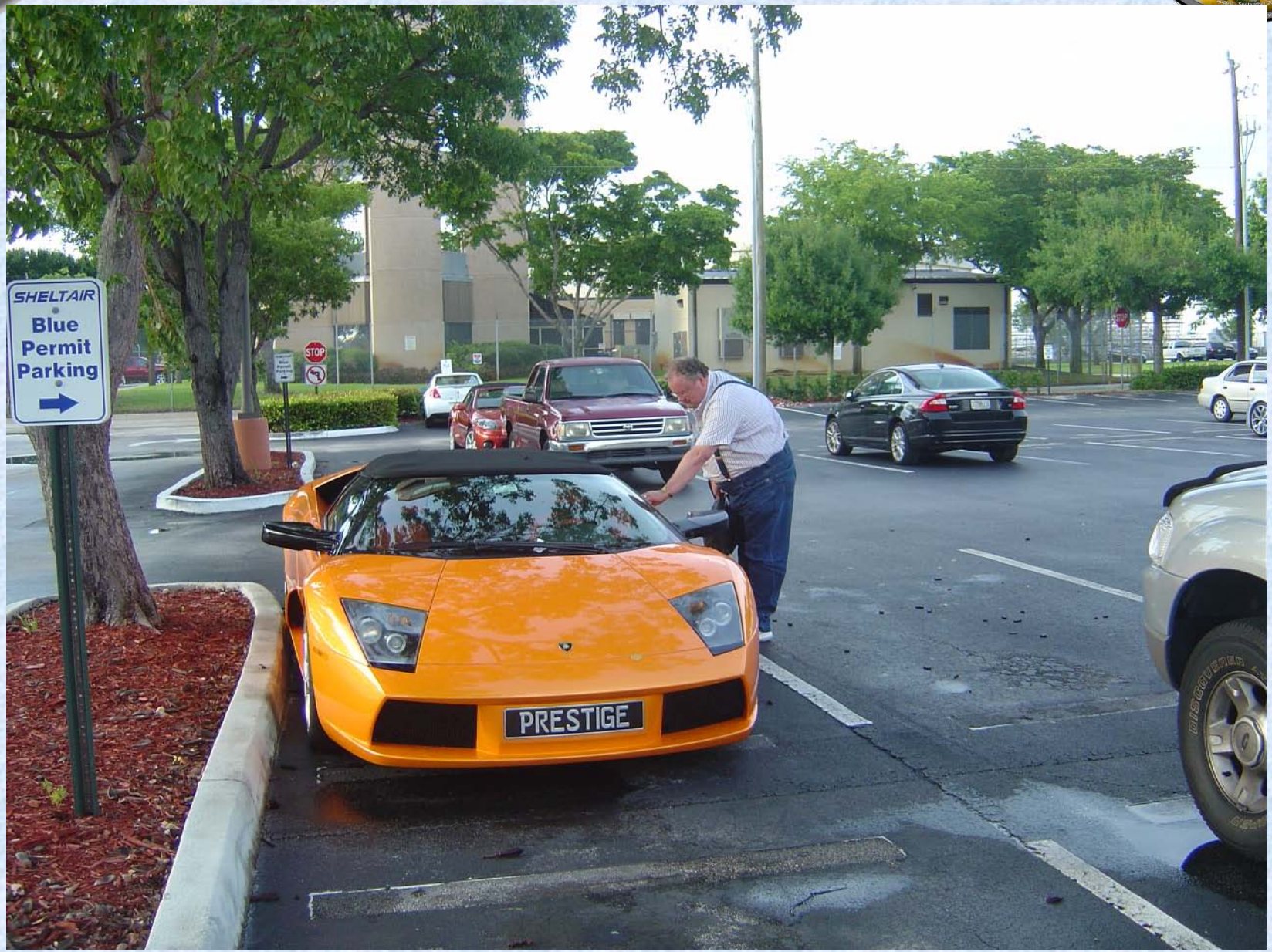
Over Atlantic Ocean

Ground Speed = 240.5 m/s

True Heading = 76.5 degrees

T and RH, Not quality controlled

Didn’t Know Flight Campaigns Were So Fun



Back Up Slides

DAWN
Doppler Aerosol WiNd lidar

Fiscal years 2008 – 2010

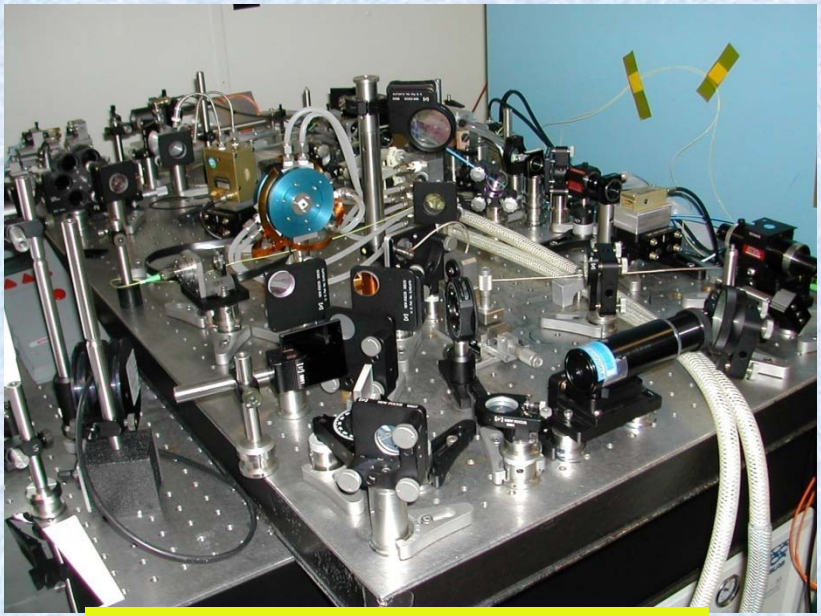
Compactly and robustly package the 2-micron, Ho:Tm:LuLiF, pulsed laser technology developed at Langley for eventual global wind measurements from earth orbit (Jay's section)

Langley has previously demonstrated a world record 1200 mJ of pulse energy with this technology

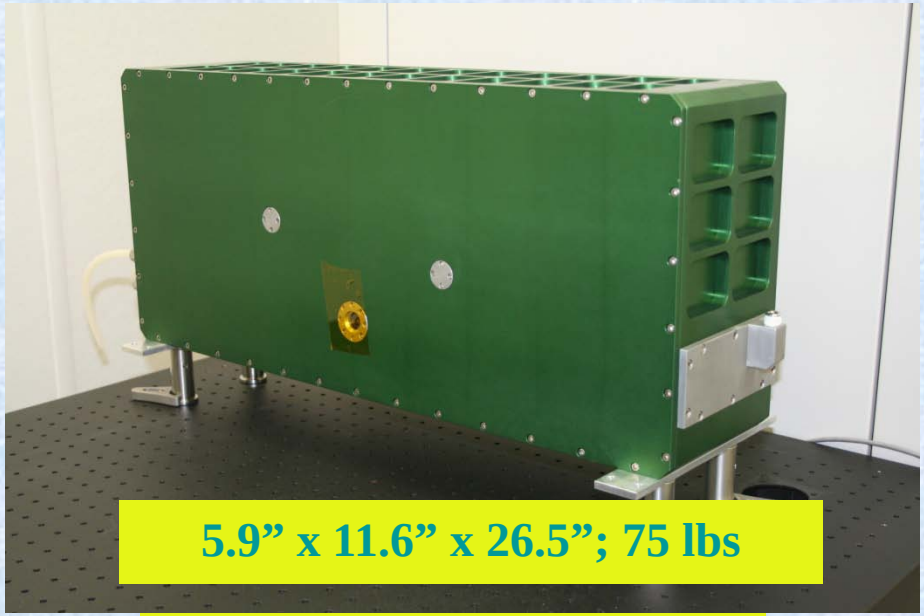
Simulations of the winds space mission indicate a requirement of 250 mJ pulse energy at 5 Hz

Laser derating of technology is wise for space missions

DAWN Transceiver (Transmitter + Receiver)
250 mJ/pulse, 10 pulses/sec.
5.9" x 11.6" x 26.5", 75 lbs.; 15 x 29 x 67 cm, 34 kg

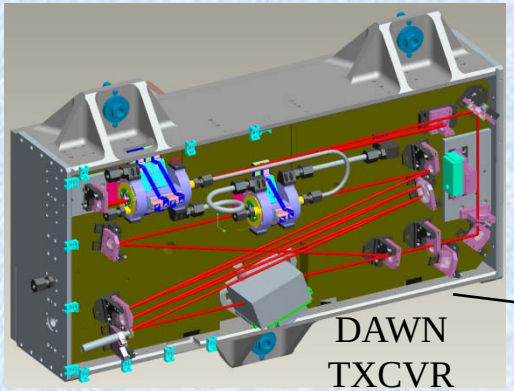


Previous implementation
90 mJ per pulse

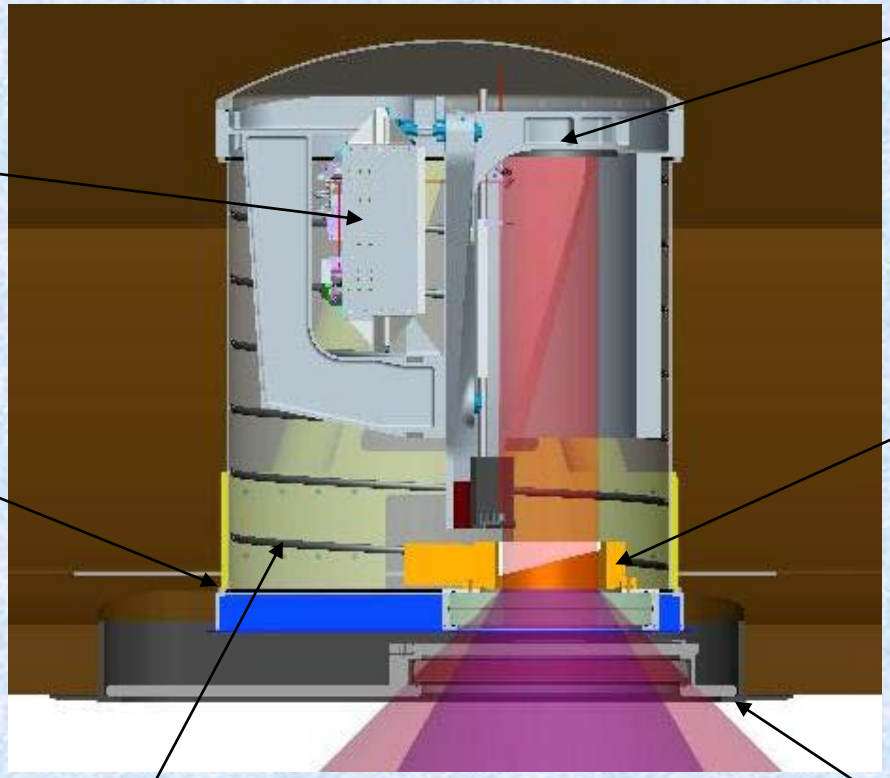


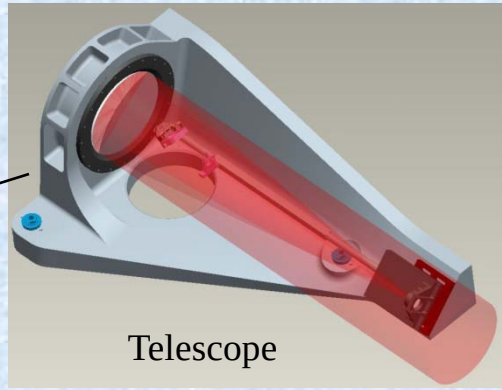
Completed DAWN package
Small, Robust, **250 mJ per pulse**

DAWN System Integration

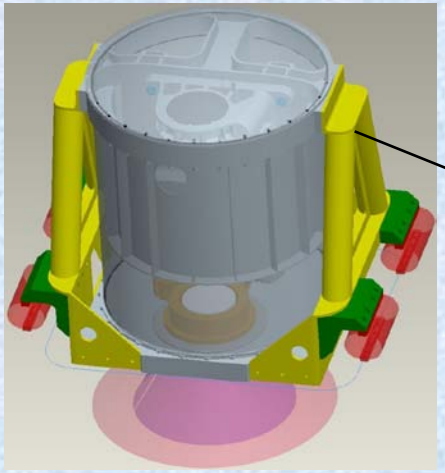


DAWN TXCVR





Telescope

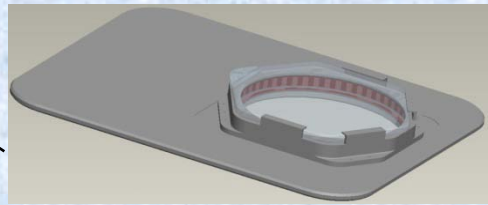


29” x 36” x <37” Tall

Sealed Enclosure & Integrated Lidar Structure

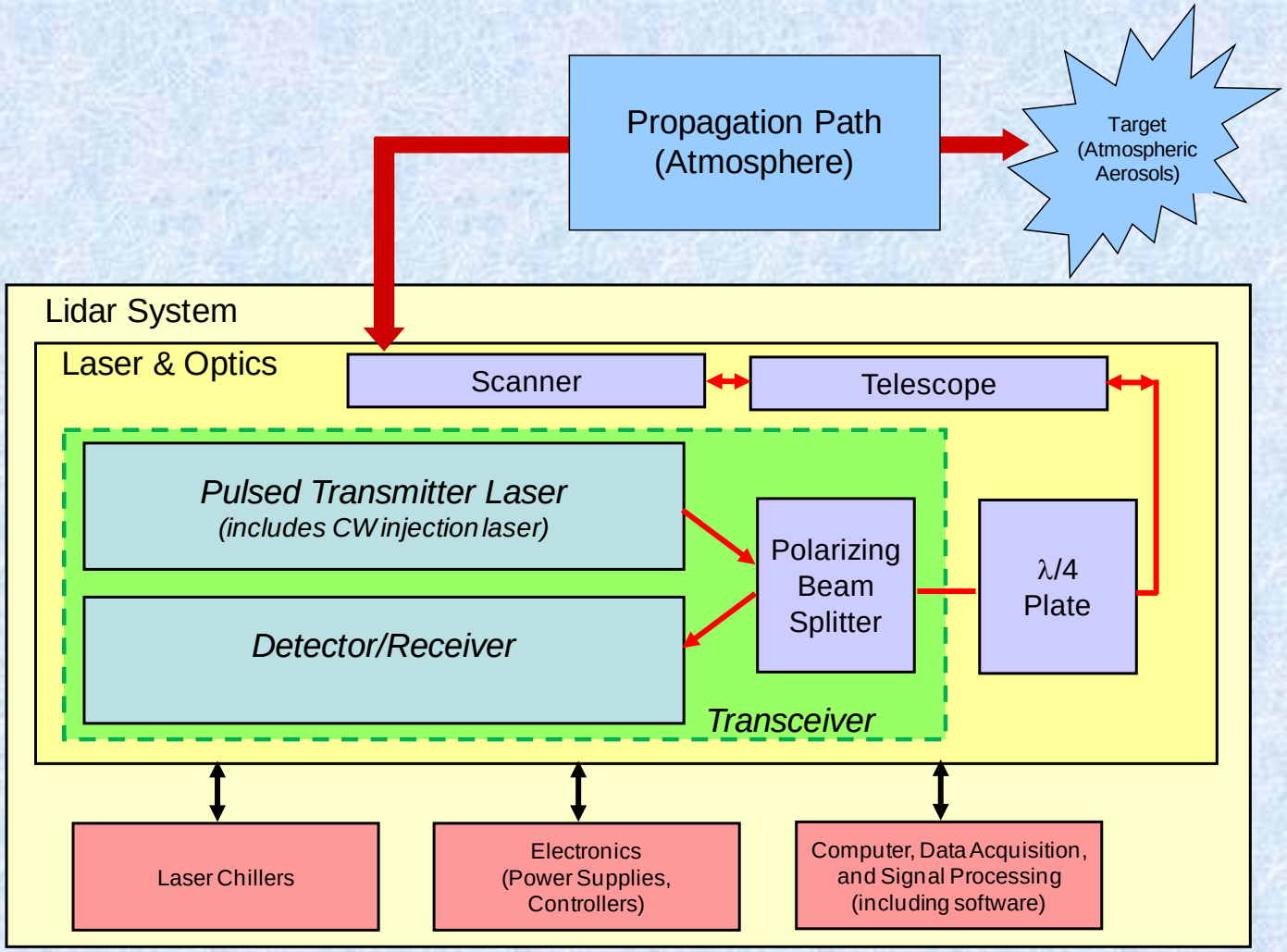
Newport Scanner (RV240CC-F)

DC8 Port/Window/Shutter



3/8” Cooling Tube

Pulsed Coherent-Detection 2-Micron Doppler Wind Lidar System



DAWN Arriving Palmdale
In VALIDAR Trailer

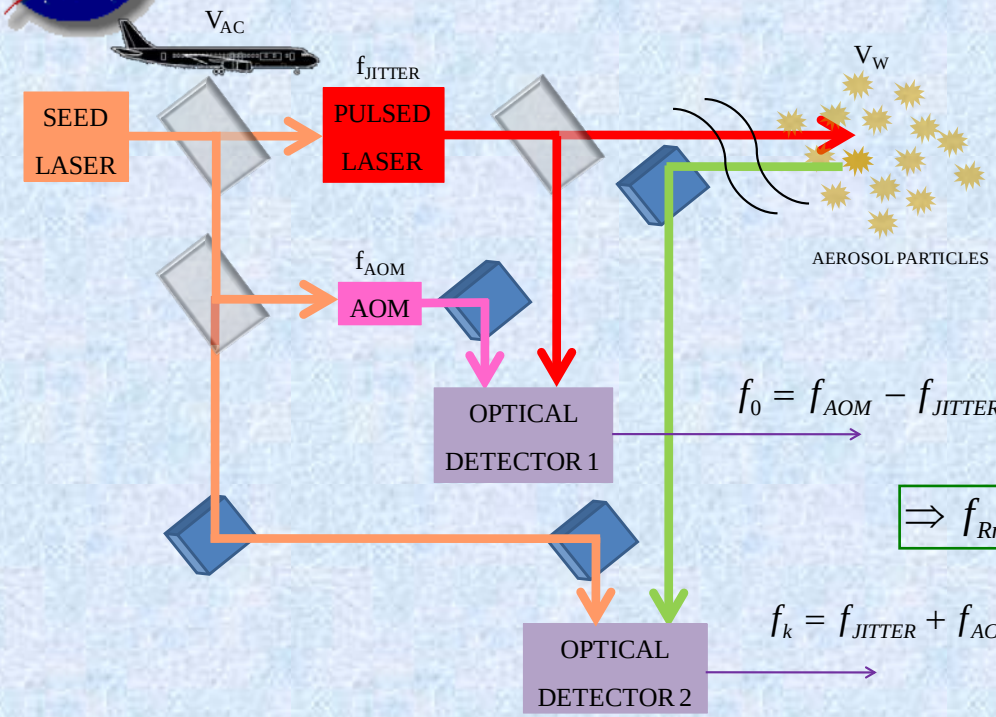
DAWN Optics Mounted in DC-8 Cargo Level

Three Cabin Stations with 2 or 3 Operators

1. Laser Control (L) 2. Data Processing (R)

3. 3 Laser Chillers

Frequencies, Angles, and Velocities

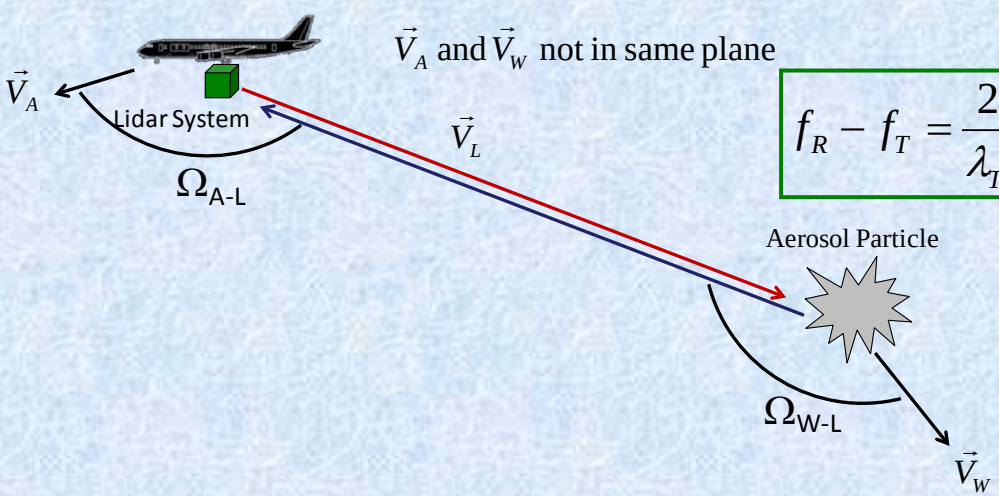


$$f_0 = f_{AOM} - f_{JITTER} \qquad \left[f_{AOM} > 0; \text{assume } f_{AOM} > \left| f_{JITTER} \right| \right]$$

$$\Rightarrow f_{Rn} - f_{Tn} = f_{AIRCRAFTn} + f_{Wn} = f_{0n} + f_{kn} - f_{AOM}$$

$$f_k = f_{JITTER} + f_{AC} + f_W \qquad \left[\text{assume } \left| f_{AC} \right| > \left| f_{JITTER} + f_W \right| \right]$$

$\vec{V}_A$ and $\vec{V}_W$ not in same plane



$$f_R - f_T = \frac{2}{\lambda_T}\left[\left| \vec{V}_A \right| \cos\Omega_{A-L} - \left| \vec{V}_W \right| \cos\Omega_{W-L} \right]$$

$$\cos\Omega_{A-L} = \sin\theta_A \sin\theta_L \cos\left(\phi_A - \phi_L\right) + \cos\theta_A \cos\theta_L$$

$$\cos\Omega_{W-L} = \sin\theta_W \sin\theta_L \cos\left(\phi_W - \phi_L\right) + \cos\theta_W \cos\theta_L$$

Juggling 4 Coordinate Systems

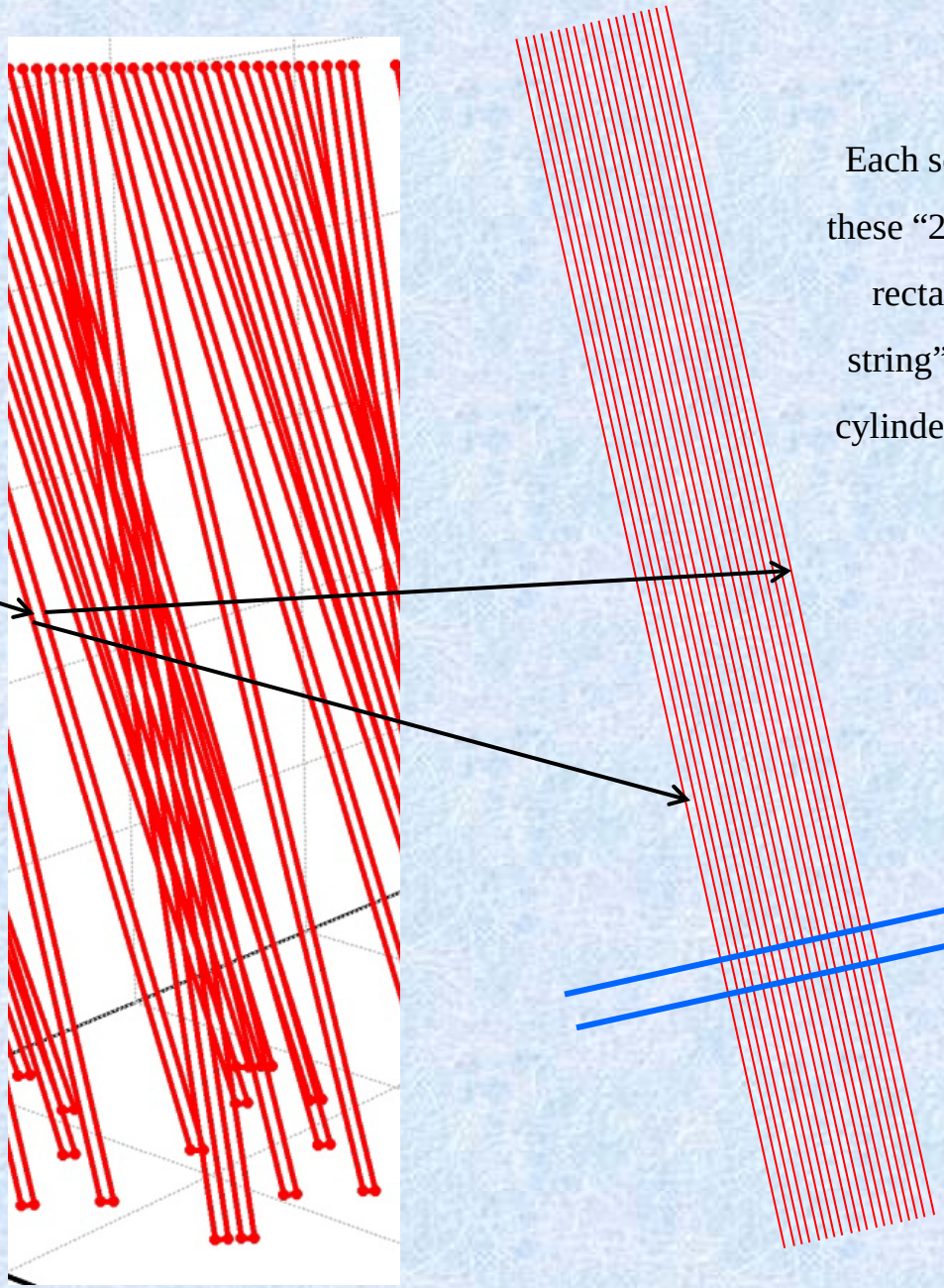
	1	2	3	4
Coordinate System	Aircraft Body Coordinates Forward-Right-Down FRD	North-East-Down Coordinates NED	East-North-Up Coordinates ENU	NED Except "Air Coming From"* "SWD"
Right-Hand, Perpendicular Axes	Axes glued to aircraft body	Axes fixed in air wherever you are	Axes fixed in air wherever you are	No such axes
2 Laser Beam Direction Angles	θ_L, ϕ_L from optics offsets and lidar scanner			
3 Aircraft Rotations		Yaw = Heading, Pitch, Roll from INS/GPS		
3 Aircraft Velocity Components			V_{AE}, V_{AN}, V_{AU} from INS/GPS	
3 Desired Wind Components			V_{WU}	V_{WN}, V_{WE}
Equations	Down = Belly Direction	$V_{AN} = V_{AE}$ $V_{AE} = V_{AN}$ $V_{AD} = -V_{AU}$		$V_{AN*} = -V_{AN}$ $V_{AE*} = -V_{AE}$ $V_{AD*} = V_{AD}$

Use INS/GPS yaw, pitch, roll to go between these two coordinate systems

Simple equations go between these pairs of coordinate systems

Nominal Scan Pattern: DAWN During GRIP Campaign

Each pair of lines drawn represents shot accumulation consisting of 2 sec and 20 laser shots



Each scan pattern has 5 of these “20 string harps” tilted rectangles. Each “harp string” is approximately a cylinder of 20 cm diameter.

Example of range gate length, 153.5 m in range, 133 m in height

Wind Measurement Volume and Time

Assume DC-8 at 10.6 km or 34.7 Kft; going 144 m/s or 280 knots

Single Laser Pulse

- Light travels 12.242 km slant range to surface in 40.8 microsec (light in atmosphere)
- Beam diameter grows from 15 cm at DC-8 to 30 cm at surface
- Illuminated measurement volume ~ π x $(0.1\ m)^2$ x range gate length ~ 5 m^3
- DC-8 flies forward 6 mm
- Repeats every 100 ms or 14.4 m; along-track duty cycle = 0.04%

LOS Wind Profile

- Consists of 20 laser shots evenly spaced over 2 s and 288 m
- Light in atmosphere time = 20 x 40.8 microsec = 817 microsec
- Illuminated measurement volume = 20 x 5 m^3 ~ 100 m^3
- Repeats every 4 s and 576 m along track distance; along-track duty cycle = 0.02% or 50%

u,v,w Wind Profile

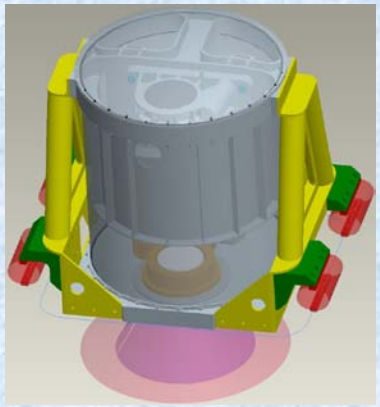
- Consists of 5 LOS wind profiles at different azimuth angles
- Light in atmosphere time = 5 x 817 microsec = 4.1 ms
- Illuminated measurement volume = 5 x 100 m^3 ~ 500 m^3
- Repeats every 22 s and 3168 m along track distance
- Along-track duty cycle = 0.02% or 50% or 100%

DAWN Compared to Commercial Doppler Lidar Systems

Coherent detection wind lidar figure of merit*

$$\left(\text{Minimum Required Aerosol Backscatter}\right)^{-1} \propto E\sqrt{PRF}\,D^2$$

Lidar System	Energy	PRF	D	FOM	FOM Ratio
Lockheed Martin CT WindTracer	2 mJ	500 Hz	10 cm	4,472	40
Leosphere Windcube	0.01	20,000	2.2	7	25,400
LaRC DAWN	250	10	15	177,878	1



29” x 36” x <37” Tall

The LaRC DAWN advantage in FOM may be used to simultaneously improve aerosol sensitivity, maximum range, range resolution, and measurement time (horizontal resolution).

*SNR is not a good FOM for coherent detection wind

DAWN Lidar Specifications

Mobile and Airborne

NASA DC-8

LaRC VALIDAR Trailer

Lidar System

15-cm diameter off-axis telescope

Dual balanced heterodyne detection

InGaAs optical detectors

Integrated INS/GPS

Pulsed Laser

Ho:Tm:LuLF, 2.05 microns

2.8 m folded resonator

~250 mJ pulse energy

10 Hz pulse rate

180 ns pulse duration

Master Oscillator Power Amplifier

Laser Diode Array side pumped, 792 nm

~Transform limited pulse spectrum

~Diffraction limited pulse spatial quality

Designed and built at LaRC

Lidar System in DC-8

Optics can in cargo level

Centered nadir port 7

One electronics rack in cargo level

Two electronics racks in passenger level

Refractive optical wedge scanner, beam deflection 30.12 deg

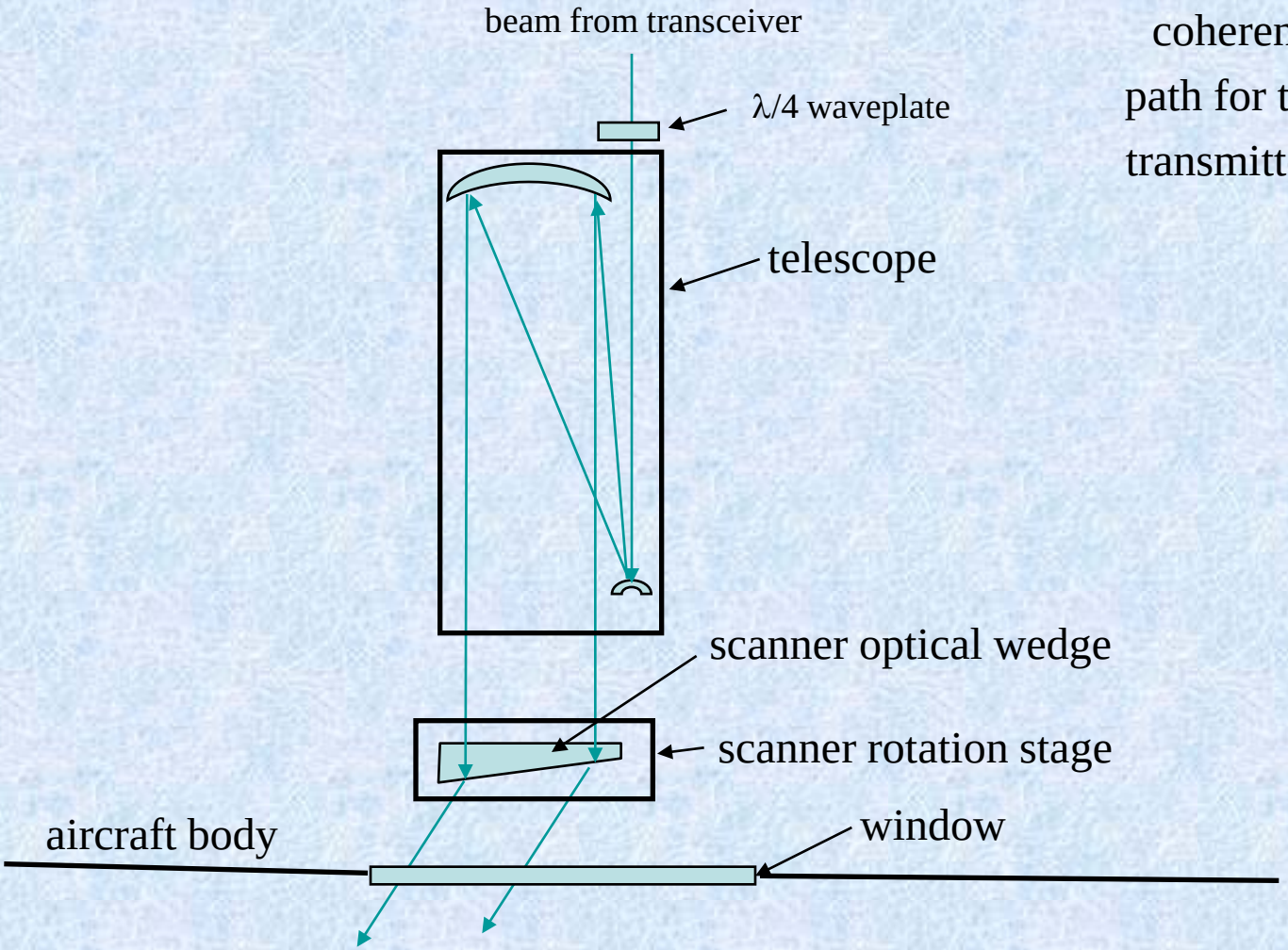
Conical field of regard centered on nadir

All azimuth angles programmable

DAWN Operation in GRIP

- DAWN was completed and shipped to Palmdale on 7/15/10 as required, much earlier than the AITT and IIP completion dates of 3/31/11 and 11/30/11
- DAWN operated and collected data for a large fraction of the 25 DC-8 flights (3 shakedown, 1 checkout, 6 ferry, and 15 science flights), and of the 139 total flight hours (113 science hours)
- Many of the flight hours were over or in thick clouds, which blocked the laser beam
- The laser pulse energy decrease from unplanned cooling at altitude was quickly mitigated, and workarounds implemented by the science flights
- Cloud layers revealed in the laser signal were frequently corroborated with the LASE display
- Post GRIP examination revealed a burned telescope secondary mirror which may have cost 10 dB or more in SNR
- Coverage of the atmosphere vertically was probably reduced due to the SNR loss
- Data analysis is proceeding and has already revealed lidar agreement with dropsonde when SNR is high

Telescope & Scanner

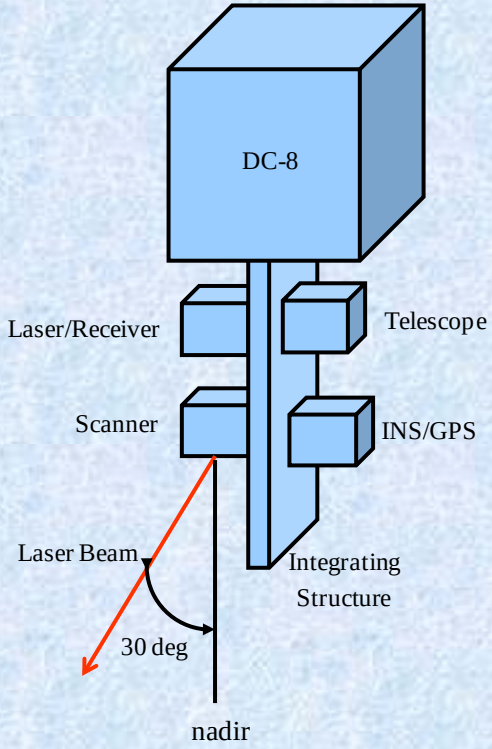


coherent lidar uses the same path for transmit and receive—transmitted path is shown here.

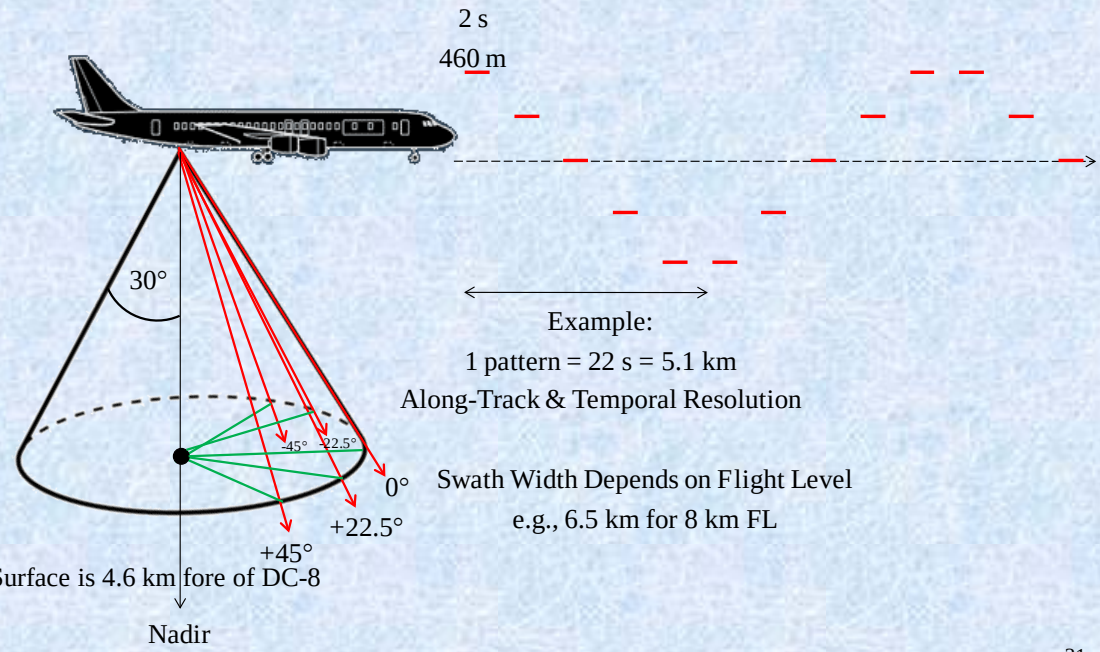
DC-8 Accommodation

DAWN depicted in DC-8

DAWN Assembly for Optical Alignment, and Pointing Control & Knowledge



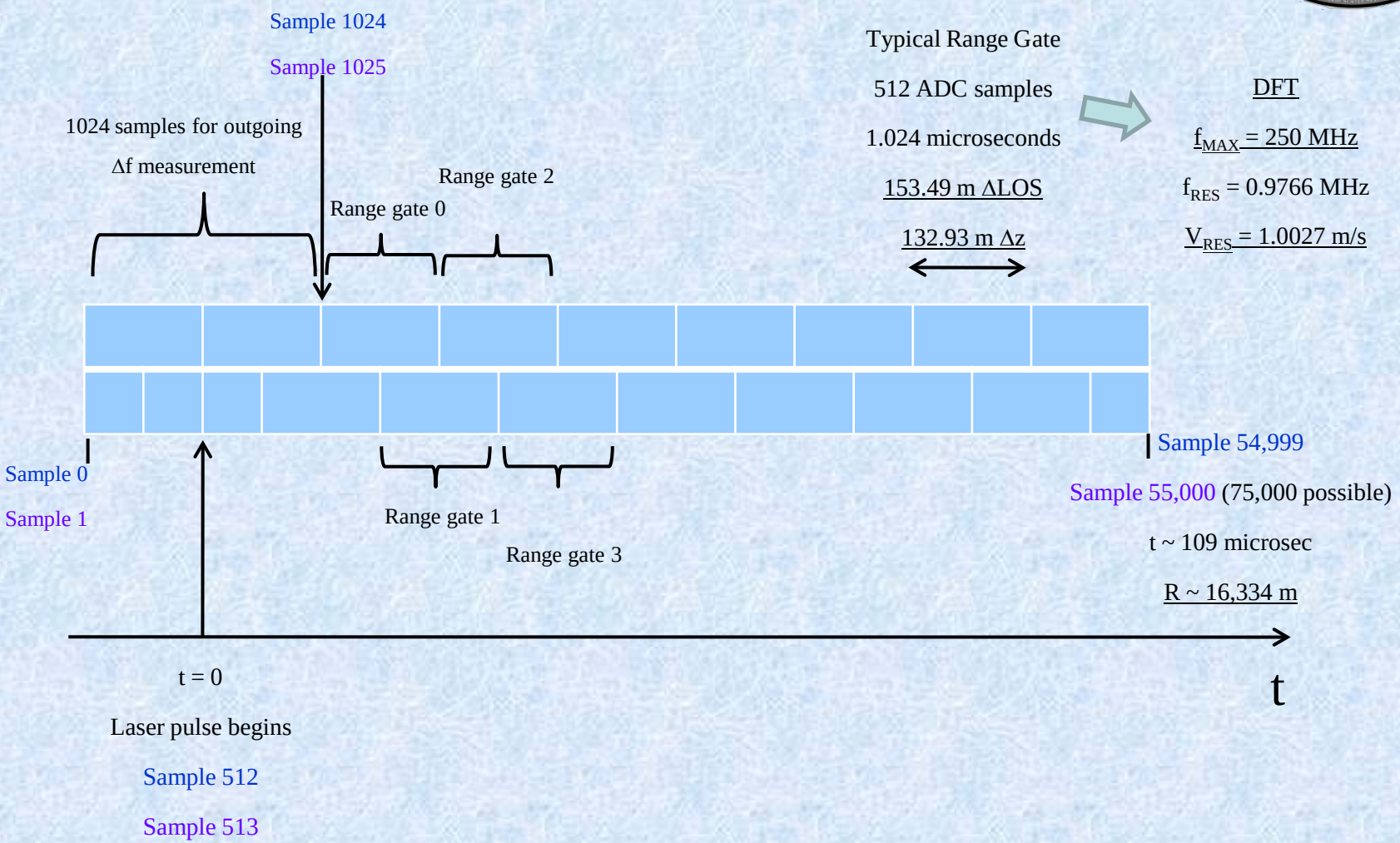
Scan Pattern During GRIP



Not in the INS/GPS Manual

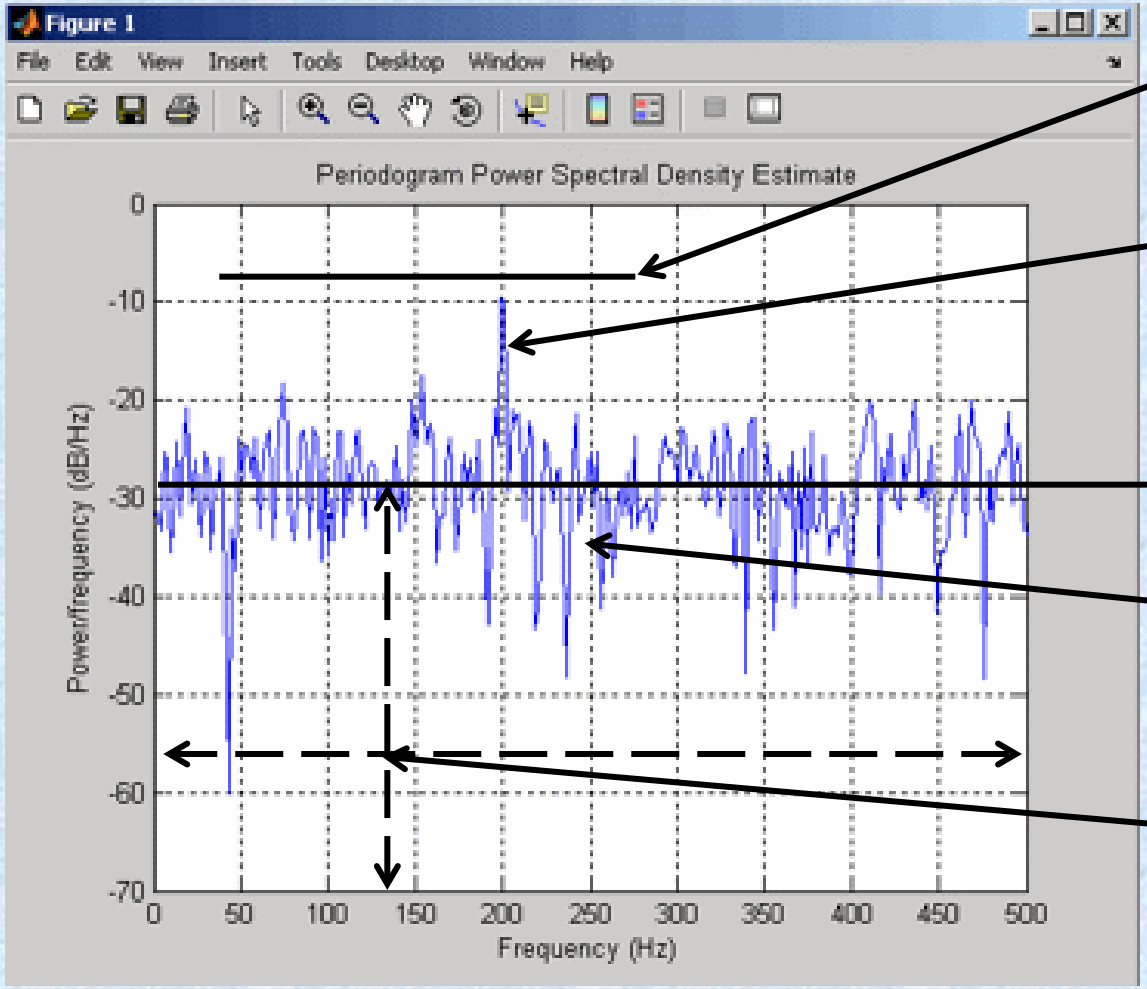
- Assumes sequence of rotation is yaw, then pitch, then roll
- Assumes sense of rotation is rotating axes rather than rotating vector
- Assumes true north, not magnetic north

1 Direction, 1 Laser Shot
Nominal Data Capture Parameters



ADC = 500 Msamples/sec, λ = 2.0535 microns, zenith angle = 30 deg., round-trip range to time conversion = c/2 = 149.896 m/microsec

Periodogram: Estimating Signal Frequency After N_P Shot Accumulation One Range Gate, One Realization



Mean Data Level = L_D

Data Fluctuations = $\sigma_D = L_D/\sqrt{N_P}$

Mean Signal Power = area under mean signal bump but above mean noise level. $P_S = A_S = [(L_D - L_N) \bullet \Delta f \bullet 1]$ (if signal in one bin)

Mean Noise Level = L_N

Noise Fluctuations = $\sigma_N = L_N/\sqrt{N_P}$

Mean Noise Power = area under mean noise level = $P_N = A_N = L_N \bullet \Delta f \bullet$ (# Noise Bins)

$$\Phi = (L_D - L_N)/L_N$$

Data = Signal + Noise, D = S + N

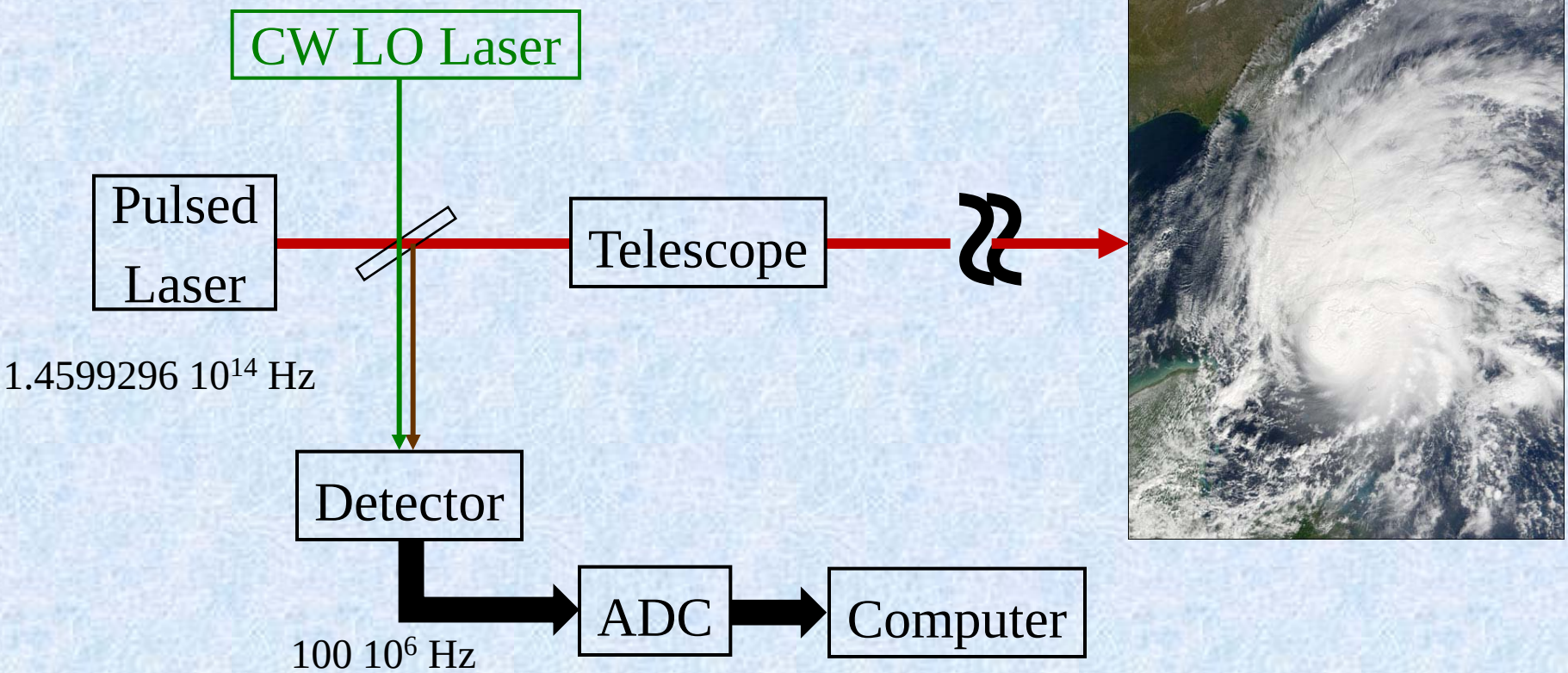
$$\int_0^\infty (Mean\ Periodogram)\, df = Ave.\ (Signal + Noise)\ Power$$

Coherent or Heterodyne Lidar

Fractional wavelength or frequency change ~ 7×10^{-7} ~ 0.7 ppm

$1.4599306\ 10^{14}$ Hz or

$1.4599286\ 10^{14}$ Hz



DAWN Pulsed Coherent Doppler Wind Lidar
Engineering/Science Parameter Tradeoffs

(Hold each expression constant for parameter trades)

1. Before Lidar Design and Fabrication

$$\frac{z_{AIRCRAFT}^2\,\Phi_{MIN}^{1,1,1}\left[C_1\ln\left(V_{SEARCH}\Delta z 4/\left(c\lambda\cos(\theta)\right)\right)+C_2\right]}{ED^2T^2\left[\cos(\theta)\right]^{1.5}\beta_{MIN}}\sqrt{\frac{N_{AZIMUTHS}V_{H,AIRCRAFT}}{(PRF)\Delta x\,\Delta z}} \qquad (1)$$

2. After Fabrication, Before Data Collection

$$\frac{z_{AIRCRAFT}^2\left[C_1\ln\left(V_{SEARCH}\Delta z\right)+C_3\right]}{T^2\beta_{MIN}}\sqrt{\frac{N_{AZIMUTHS}V_{H,AIRCRAFT}}{\Delta x\,\Delta z}} \qquad (2)$$

Trade: aircraft height and velocity, vertical and horizontal resolution, minimum detectible aerosol level, atmospheric transmission, number of measured azimuth directions, and velocity search space

3. After Data Collection, Before Dissemination

$$\frac{\left[C_1\ln\left(V_{SEARCH}\Delta z\right)+C_3\right]}{\beta_{MIN}\sqrt{\Delta x\,\Delta z}} \qquad (3)$$

Trade: vertical and horizontal resolution, minimum detectible aerosol level, and velocity search space

z = altitude [m] $z_{AIRCRAFT}$ = aircraft altitude

R = range of lidar to target [m] $R_{MAX} = z_{AIRCRAFT}/\cos(\theta)$

θ = laser beam nadir angle [radians] $[30°]$

Φ = detected coherent photoelectrons per shot per range gate [-]

$C_2\Phi_{MIN}^{1,1,1}$ = minimum usable Φ for 1 shot & 1 m range gate & 1 frequency bin search BW $(N_{SEARCH}=1)$ $\left[\sqrt{m}\right]$

$N_{SEARCH} = 4\Delta R V_{SEARCH}/(c\lambda)$ [–]

ΔR = Data processing range gate length [m]

V_{SEARCH} = search band for wind velocity [m/s]

Δz = height resolution $= \Delta R\cos(\theta)$ $[m]$

c = speed of light [m/s] λ = laser wavelength [m] $\left[2.05\ 10^{-6}m\right]$

$c\lambda/4 \approx 150$; $c\lambda/(4\Delta R) \approx 150/\Delta R$

E = lidar laser pulse energy [J] [250 mJ]

D = circular receiver collection diameter [m] [0.15 m]

T = 1-way atmospheric intensity transmission [-]

β = aerosol backscatter coefficient $\left[m^{-1}sr^{-1}\right]$

$N_{AZIMUTHS}$ = number lidars scanner azimuths per repeated pattern [-]

$V_{H,AIRCRAFT}$ = Aircraft horizontal velocity [m/s]

Δx = along-track horizontal resolution (pattern repeat) [m]

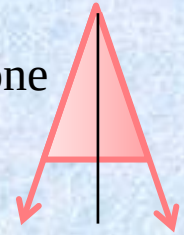
GRIP science team input requested for stages 2 & 3.
Send comments to michael.j.kavaya@nasa.gov

Wind Measurement Performance

Data Products		Vertical profiles of u, v, w wind field from aircraft to surface, clouds permitting. Profiles of wind turbulence. Profiles of relative backscatter. Wind spatial variability.
Velocity accuracy (m/s)		< 1-2
Vertical resolution (km)		Selectable, typically 133 m
Horizontal integration per LOS (s)		Selectable, typically 2 s (~460 m)
Nadir Angle (deg)		30
Scan Pattern		5 azimuth angles/pattern (selectable) 1 pattern/22 s (~ 5000 m) (processing speed limited)
Range of regard (km)		0 – 12 (DC-8 to surface)

	DAWN on DC-8	3-D Winds Decadal Survey Space Mission
Pulse Energy	0.25 J	0.25 J
Pulse Rate	10 Hz	5 Hz
Receiver Optical Diameter	0.15 m	0.5 m
# Telescopes	1	4
Scanner	Wedge	N/A
Nadir Angle	30 deg	45 deg

Pulsed Coherent Lidar Wind Measurement - 1

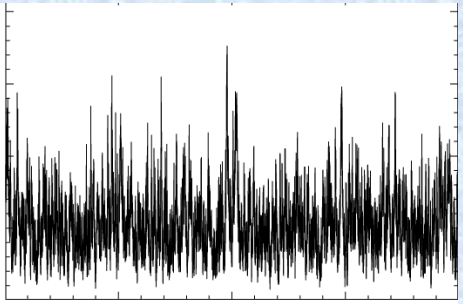


- 2-micron Tm:Ho:LuLF laser pulse ~ τ = 180 ns duration ~ 54 m long in atmosphere
- Rotating optical wedge scanner provides possible laser directions on surface of a cone with 30-degree half angle
- Axis of cone is nominally nadir, but changes with aircraft attitude (roll, pitch), and exact mounting
- Location of wind measurement determined by 1) aircraft position, 2) direction of laser, and 3) distance away along laser beam
- If t = 0 is firing of pulse, then return signal at t is from ranges $c(t/2 - \tau/2)$ to $ct/2$. For example, τ = 180 ns, t = 10 microseconds, signal is from 1471.98 to 1498.96 m (27 m). The entire 54 m laser pulse contributes to this signal
- Time from firing pulse gives distance away, leading to measurement position

Pulsed Coherent Lidar Wind Measurement - 2

- Laser pulse optical frequency = 1.4599296 10^{14} Hz (Tm,Ho:LuLiF at 2.053472 microns)
- Return signal Doppler shifted by line-of-sight (LOS) lidar platform and wind velocities (+973,960 Hz per m/s of closing velocity, neglecting relativity)
- Optical detector surface mixes return signal with local oscillator (LO) beam to lower signal frequency by 8-14 orders of magnitude
- Maximum design horizontal wind (e.g., 100 m/s): horizontal wind bandwidth = 200 m/s or 194.792 MHz; LOS wind bandwidth = 97.396 MHz (at 30 deg. nadir)
- Pulsed laser to LO frequency offset and/or platform velocity designed to position 0 m/s wind signal at freq. f_0; possible signal freq. go from $f_0 - 48.7$ to $f_0 + 48.7$ MHz
- Return signal digitized at rate high enough to capture highest frequency, $f_0 + 48.7$ MHz, for example f_S = 500 Msample/second. Sample spacing = 2 ns
- Also mix LO with outgoing laser pulse, digitize, determine pulse-LO frequency difference, determine t = 0, and store these numbers for each pulse

Pulsed Coherent Lidar Wind Measurement - 3



periodogram

- Now the data are in a computer ☺
- Locate correct t = 0 position in data
- Return signal divided into end-to-end time chunks of duration Δt for processing
- Range gate length is $\Delta R = (c\Delta t)/2$. For example, Δt = 1.024 microseconds, ΔR = 153.5 m

  [Height resolution is ΔR * cos(beam nadir angle) ~ ΔR * 0.866 at 30 deg.]
- On each range gate, perform a 1024 ns/2 ns = 512 point FFT and calculate periodogram

  (periodogram is energy content vs. frequency)
- Periodogram output frequency spacing = $1/\Delta T$ = 0.976562 MHz (1.003 m/s); highest

  frequency = $f_S/2$ = 250 MHz (256.7 m/s); number of output complex numbers = 250/0.976562 = 256; number of real output numbers = 2 * 256 = 512
- Repeat for multiple laser pulses and build up an average periodogram for each range gate

Pulsed Coherent Lidar Wind Measurement - 4

- Perform frequency estimation routine on accumulated periodogram for each range gate

  (e.g., determine frequency of highest peak in periodogram = “peak finding”)

- Correct frequency estimate by pulse-LO frequency difference

- Correct frequency estimate by platform (DC-8) velocity projected to LOS direction

- You now have a range (or height) profile of the wind velocity projected to the LOS direction ☺

- Later probe the same air mass from a different azimuth direction and repeat all of the

  above for second, different perspective profile of the LOS wind (e.g., first

  azimuth = 45 deg. and second azimuth = 135 deg.; equal cross-track distances)

- Choice A: assume zero vertical wind and combine the two LOS profiles into a horizontal vector wind profile (magnitude and direction vs. altitude) or
- Choice B: Use a third azimuth direction; assume the wind at the new cross-track distance is the same; calculate the horizontal vector and vertical wind profiles

- You now have a horizontal wind profile ☺

Heterodyne (Coherent) Detection

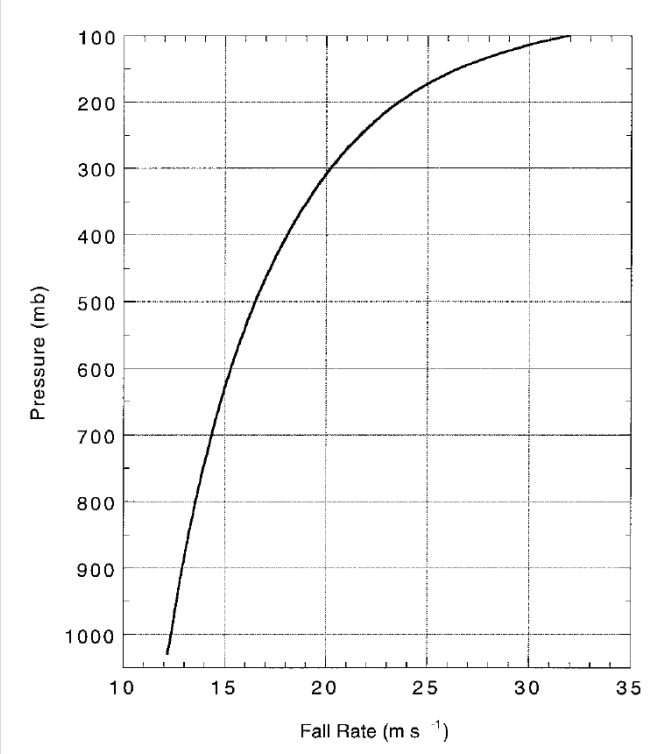
"heterodyne detection can allow measurement of the phase of a single-frequency wave to a precision limited only by the uncertainty principle"

Michael A. Johnson and Charles H. Townes

Optics Communications 179, 183 (2000)

Dropsondes

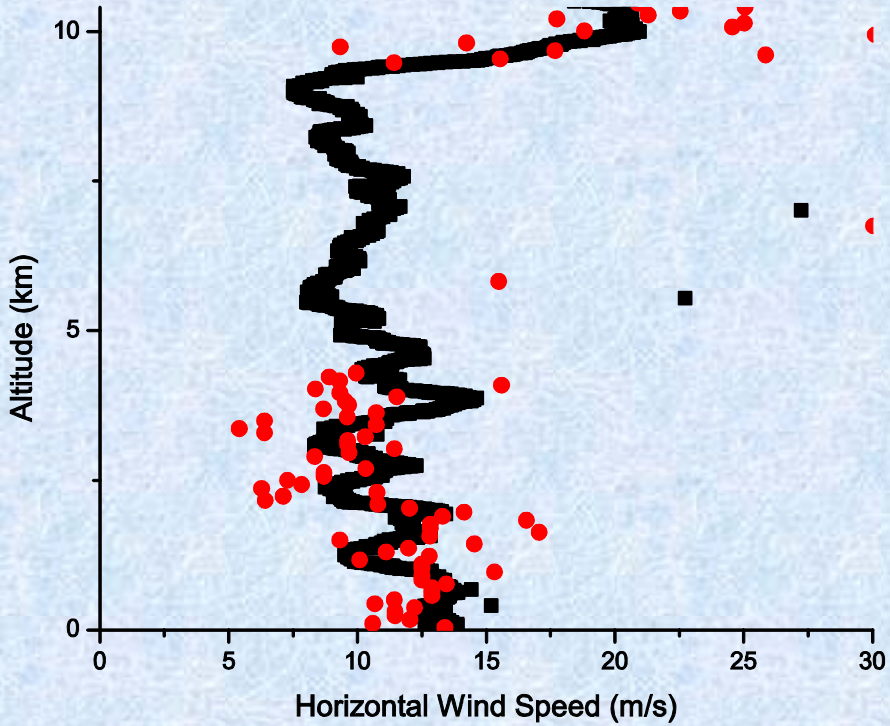
- Airborne Vertical Atmospheric Profiling System (AVAPS)
- Vaisala
- Wind data every 0.5 sec
- < 400 g
- 7-cm diameter x 41-cm long
- Square-cone parachute
- Fall velocity = 12 m/s at sea level

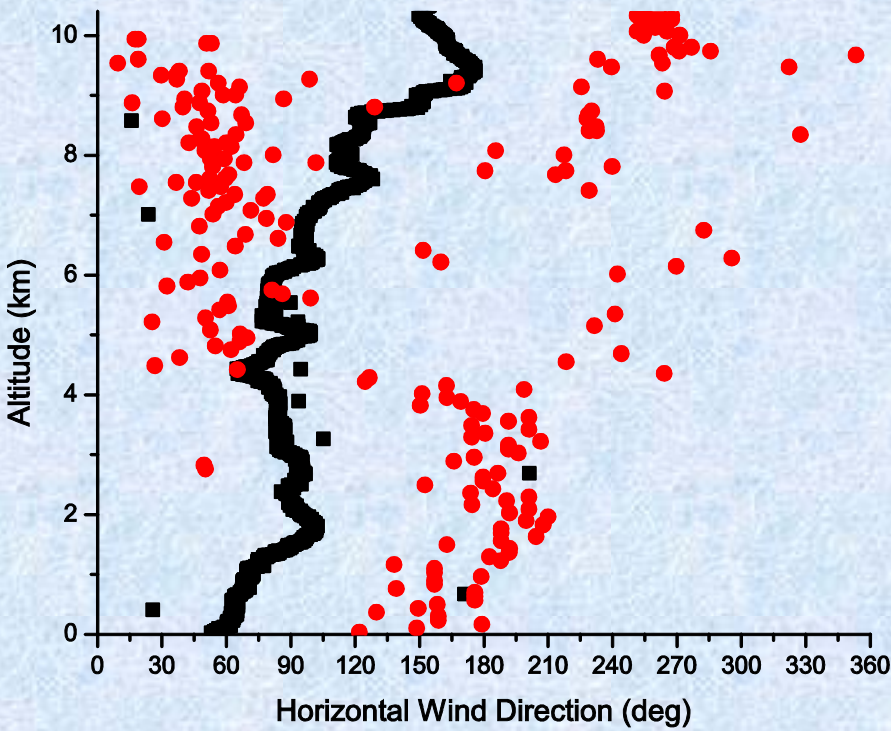


September 1, 2010

Lidar scan number 118 of data folder 16:17:36

17:19:27 – 17:19:47; 5-axis





Latitude = 29.95 N

Longitude = 75.75 W

GPS Altitude = 10,611 m

Over Atlantic Ocean

Ground Speed = 224.6 m/s

True Heading = 146 degrees