Atmospheric Measurements for Flight Test at NASA’s Neil A. Armstrong Flight Research Center

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Background:

1987 Graduate of the University of Utah (B.S. Meteorology)

1993 Graduate of the University of Nevada-Reno (UNR)
(M.S. Atmospheric Physics)
Desert Research Institute 1990-1993

NASA Atmospheric Science 29 years

Who’s interested in Good high Altitude Atmospheric Data?

- Advance DoD Hypersonics
- Commercial Space
- NASA Hypersonics
- NASA/DOD Space
- NASA Flight Opportunities
- NASA Aeronautics
- NASA Science Mission (Earth Sciences)
- Actually Everyone!

How does weather impact flight research?

Flight safety

Mission planning

Flight on-condition

Post-flight engineering

Flight Safety

Avoid hazardous weather conditions

Thunderstorms (hail and lightning)

Turbulence

High winds

Clouds and/or precipitation

Range safety

People and property in local communities

Mission Planning

Flight objectives

Decisions based on forecasts and observations (crew briefings)

Criteria for Go/No Go

Weather limits/constraints

Operational guidelines (flight cards)

Primary and secondary objectives

Post-flight engineering

Atmospheric reference for air data calibrations

Determine errors in aircraft measurements

- Air pressure
- Pressure altitude
- Mach number
- Airspeed

Use weather balloon observations to measure pressure, temperature and wind

Post-flight engineering (continued)

Interpolate for flight time and trends during the day

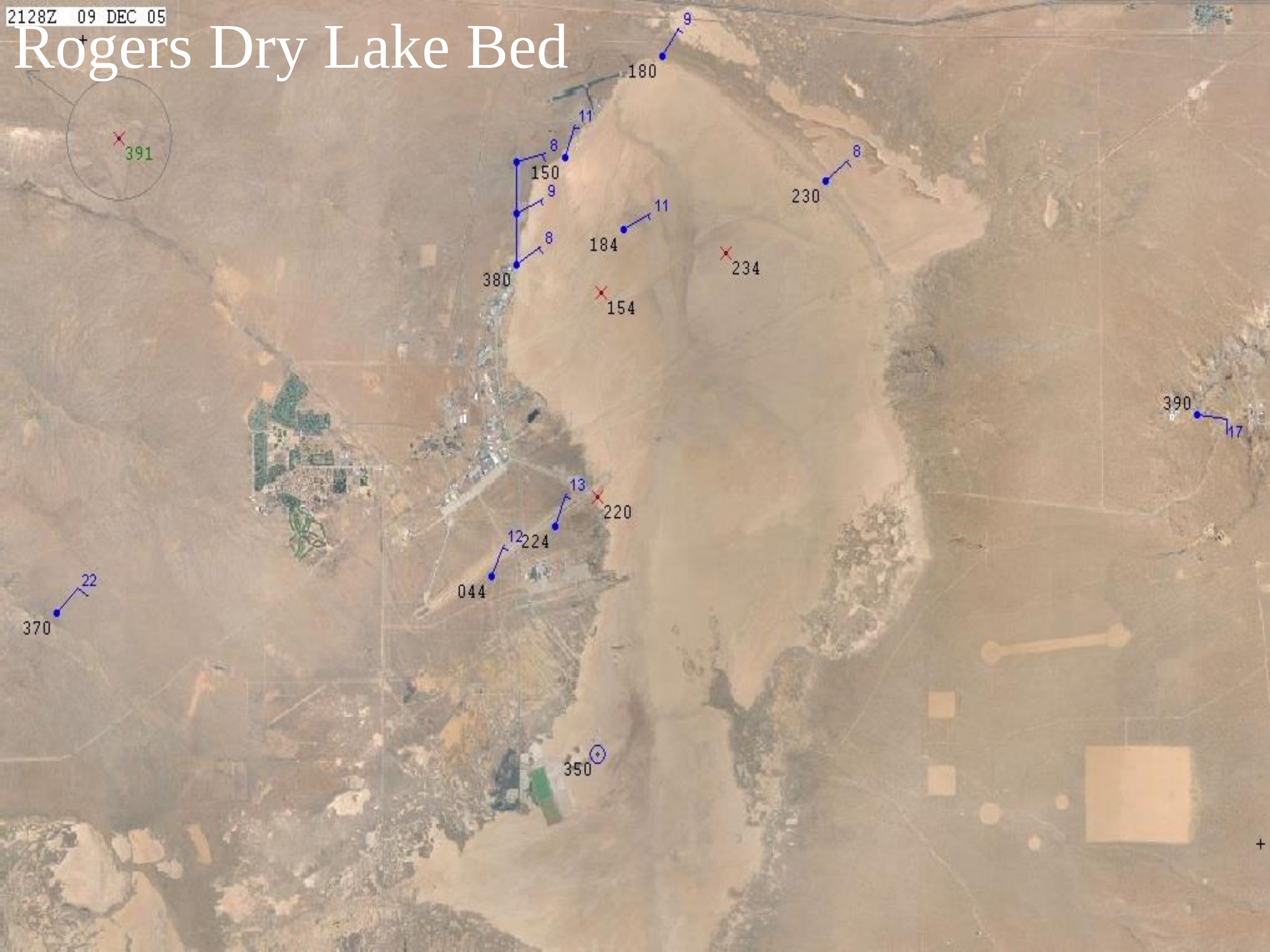
Correct RADAR measurements for atmospheric refraction

Weather Tools

- Rawinsonde Balloons
- Jimspheres
- Tethered Sondes
- Wind Towers
- NAM, RAP, GFS, Global Ensemble, GEOS-5 models
- LIDARs
- RADARs
- SODARs

Where are we Located?

Rogers Dry Lake Bed



NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: EC01−0264−14 Date: July 25, 2001 Photo By: Carla Thomas

NASA's Dryden Flight Research Center is situated immediately adjacent to the compass rose on the bed of Rogers Dry Lake at Edwards Air Force Base, Calif.

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC91-485-1 Date: 5 Sep 1991

Main Building (4800) at Dryden FRC

Discovery
United States

Shaped Sonic Boom Demonstration Aircraft (SSBD)

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: EC03–0210–1 Date: August 2, 2003 Photo By: Carla Thomas

Northrop–Grumman Corporation's modified U.S. Navy F–5E Shaped Sonic Boom Demonstration (SSBD) aircraft.

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC85-33297-23 Date: 1985 Photo by: NASA

X-29 in Flight from Above

Stratospheric Observatory for Infared Astronomy (SOFIA)

NASA Earth Science

ERAST Helios

Phantom Eye Liquid H2

NASA’s IKHANA Predator B

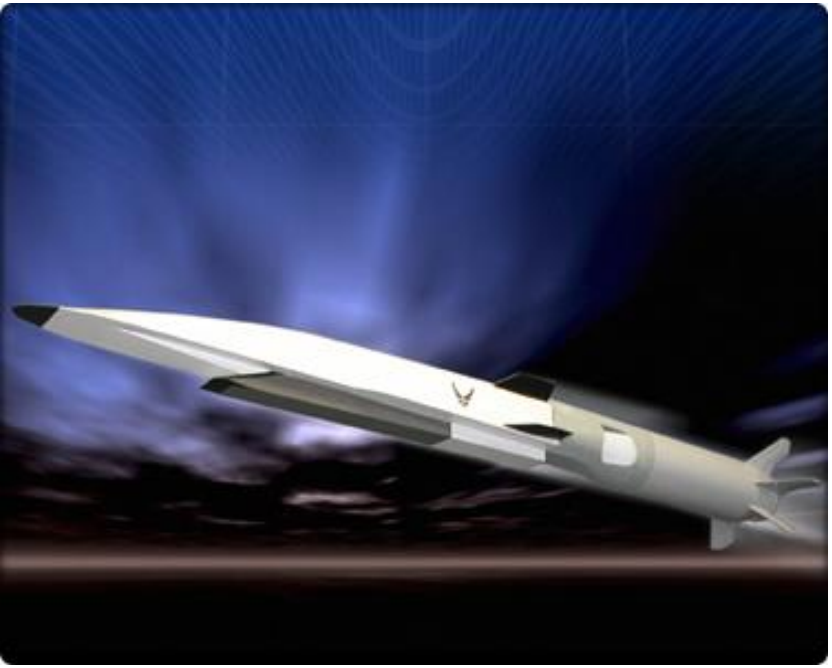
Hypersonic Research   Mach 9.6 (7000mph)

Dryden Flight Research Center ED98-44824-1
X-43/Hyper -X aircraft.   NASA/Dryden Illustration by Steve Lighthill

Hypersonics

HTV-2 4/2010 & 8/2011

X-51 5/2010, 3/2011, 8/2012, 5/2013

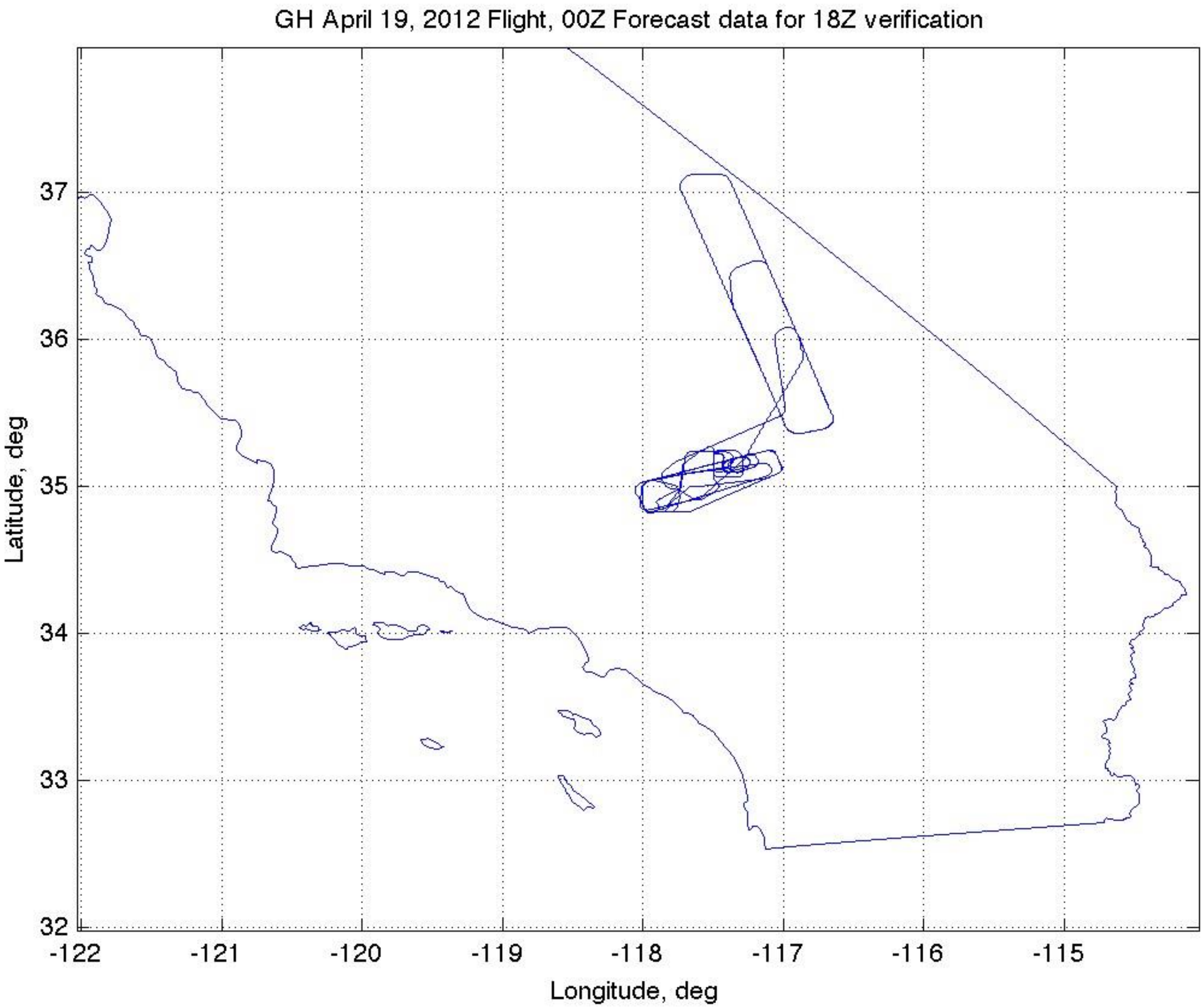


AHW 11/2011

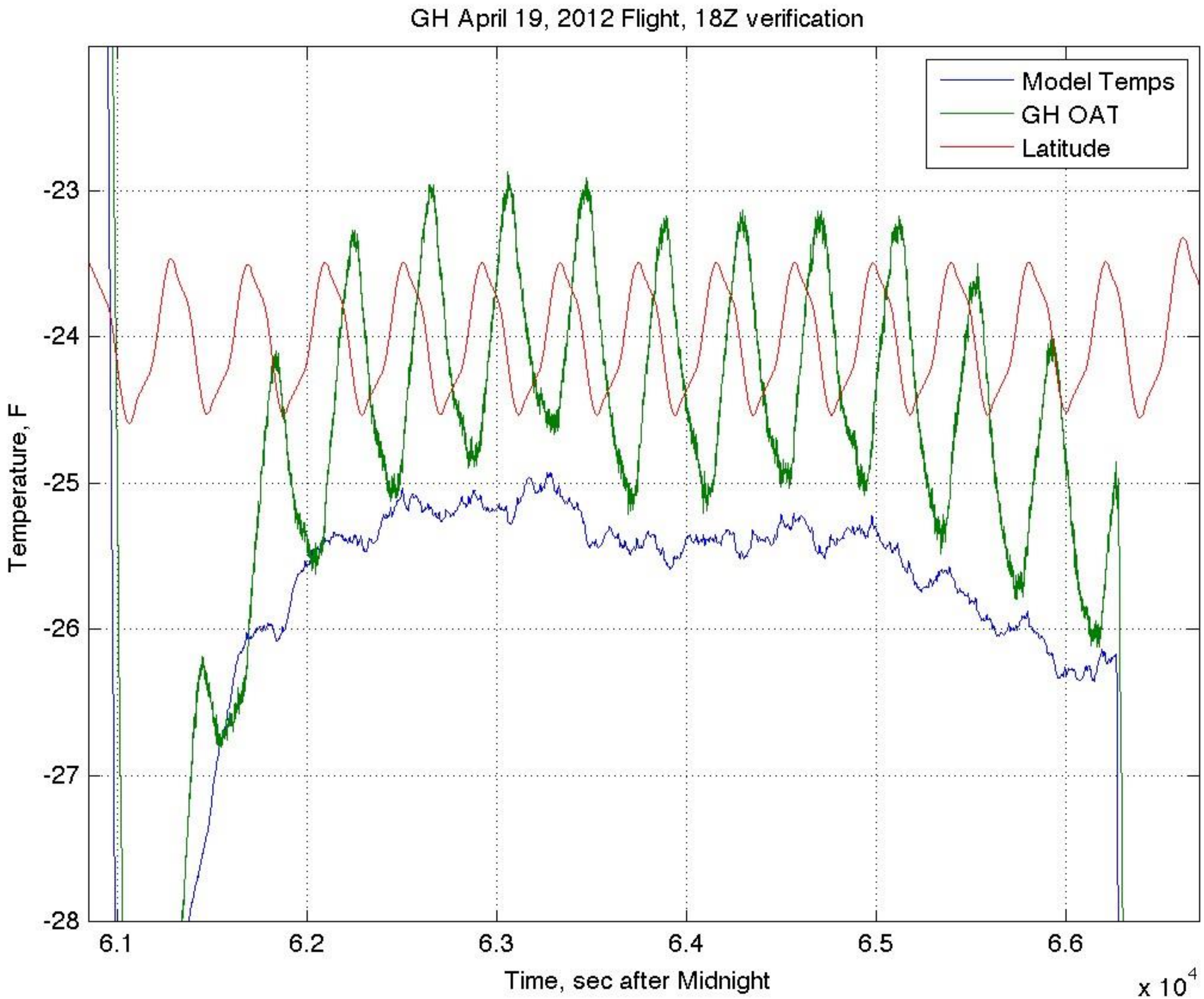
Global Hawks

18 Jan 2010

Global Hawk Flight Area for KQX Refueling

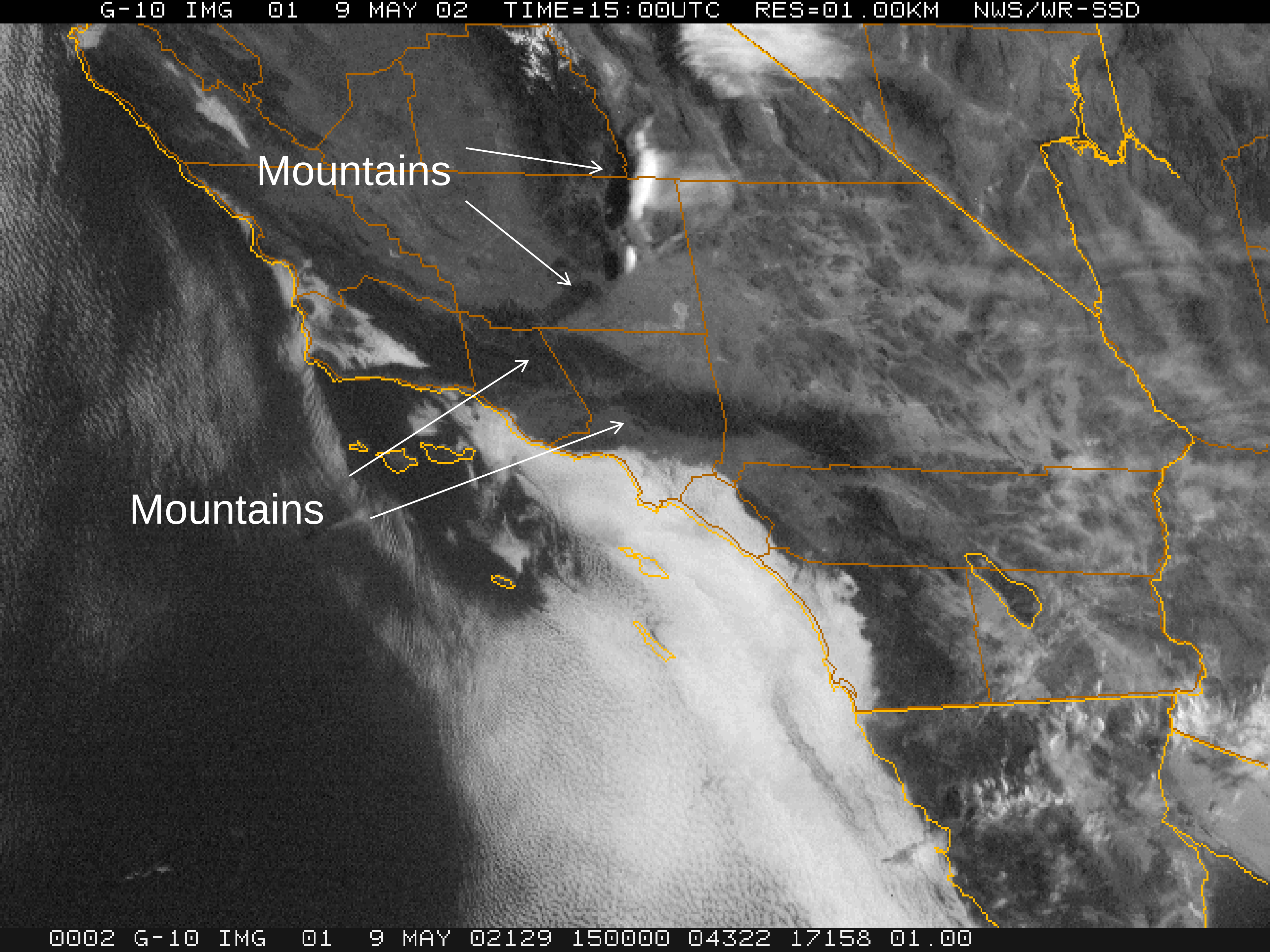


Global Hawk "Poor Man's Calibration"

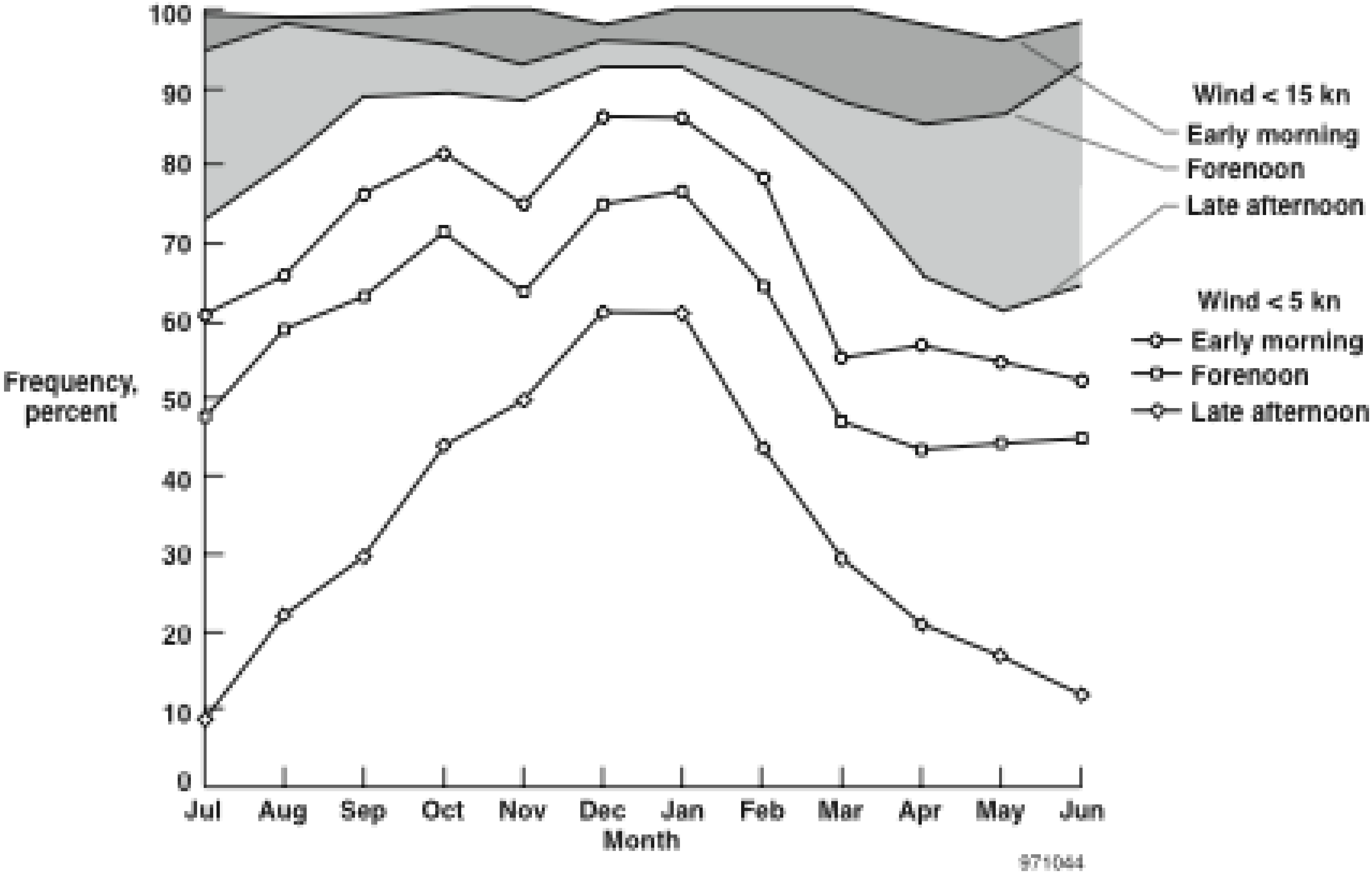


Climatology

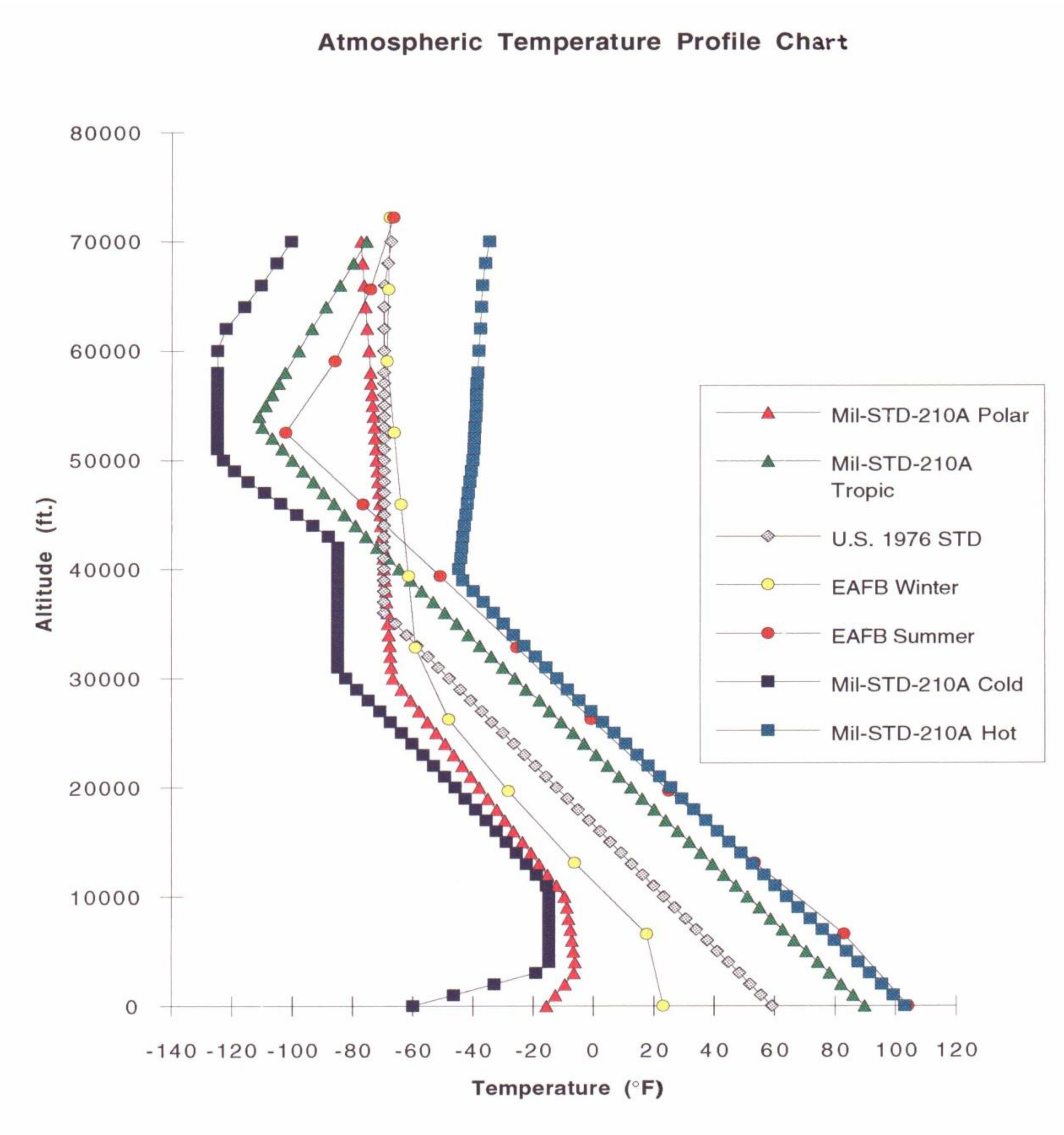
- Understanding the Atmosphere
  - Surface behavior
    - Seasonal vs time of day
      - Temperature
      - Winds
      - Precipitation
  - Upper Air profile
    - Seasonal
      - Temperature
      - Winds
      - Moisture


G-10 IMG 01 9 MAY 02 TIME=15:00UTC RES=01.00KM NWS/WR-SSD
Mountains
Mountains
0002 G-10 IMG 01 9 MAY 02129 150000 04322 17158 01.00

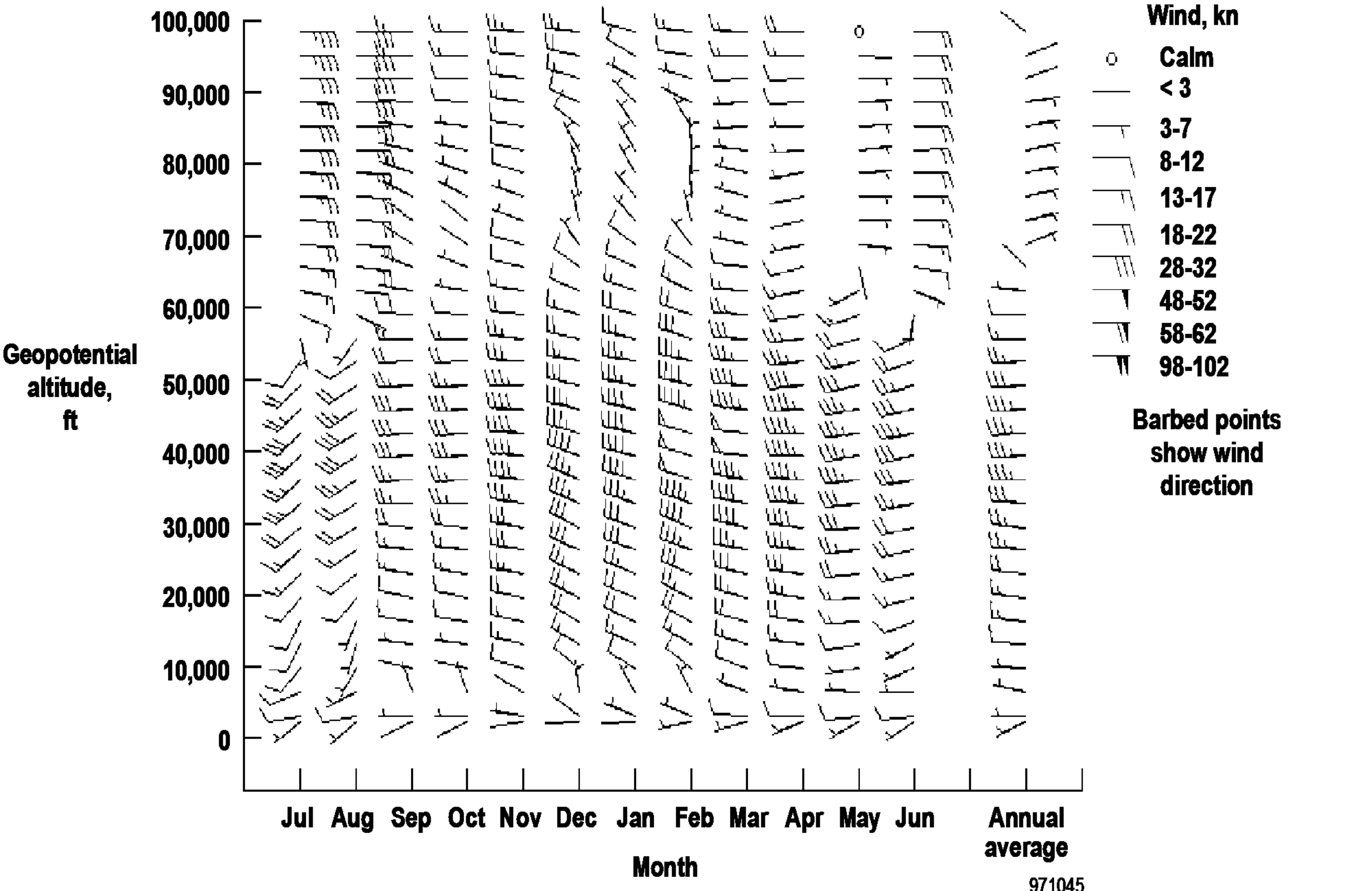
Surface Winds at Edwards AFB

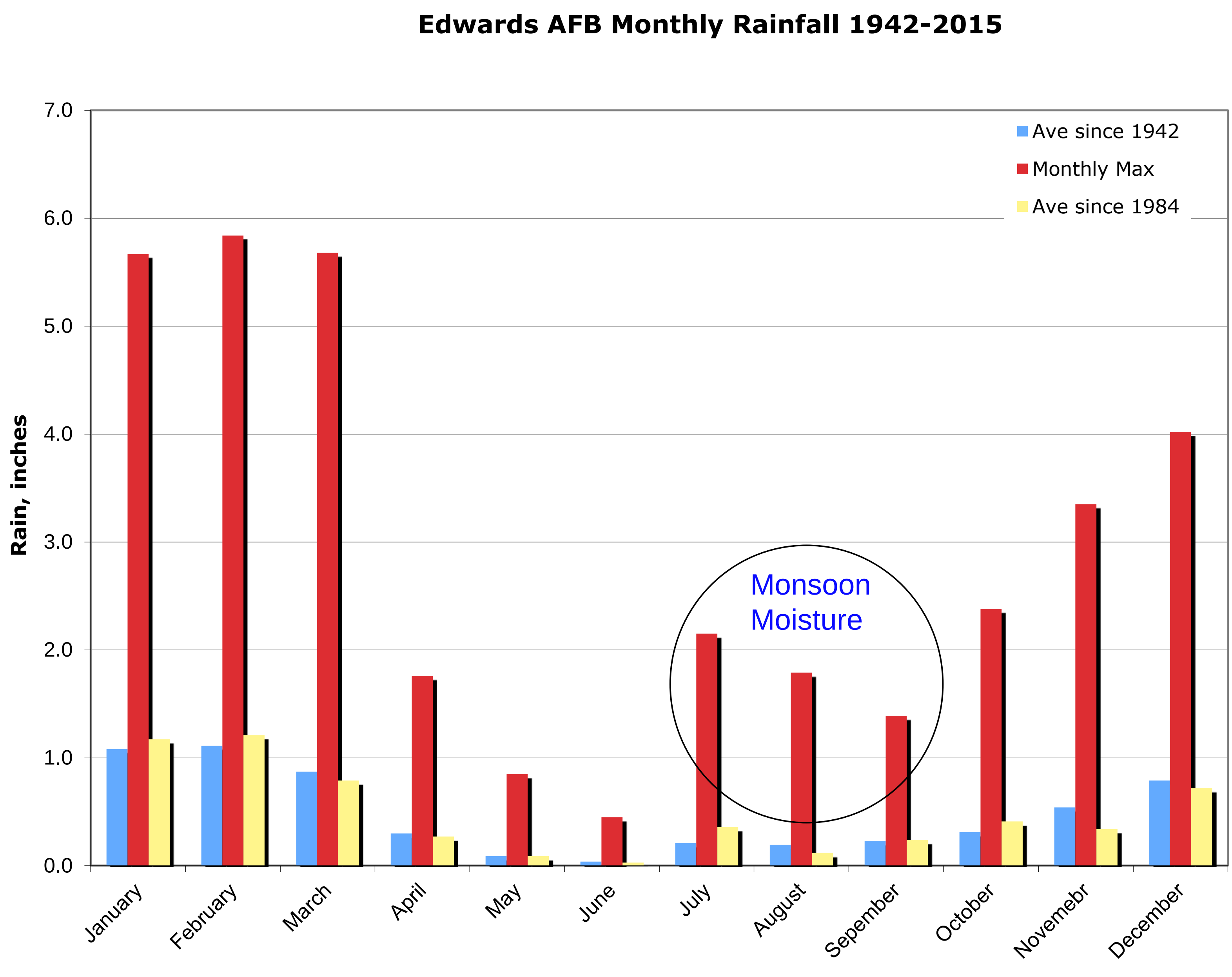


Temperature Standards



EDW Monthly Upper Atmospheric Winds





Edwards AFB Monthly Rainfall 1942-2015
Rain, inches
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Ave since 1942
Monthly Max
Ave since 1984
Monsoon
Moisture
January
February
March
April
May
June
July
August
Sepember
October
Novemebr
December

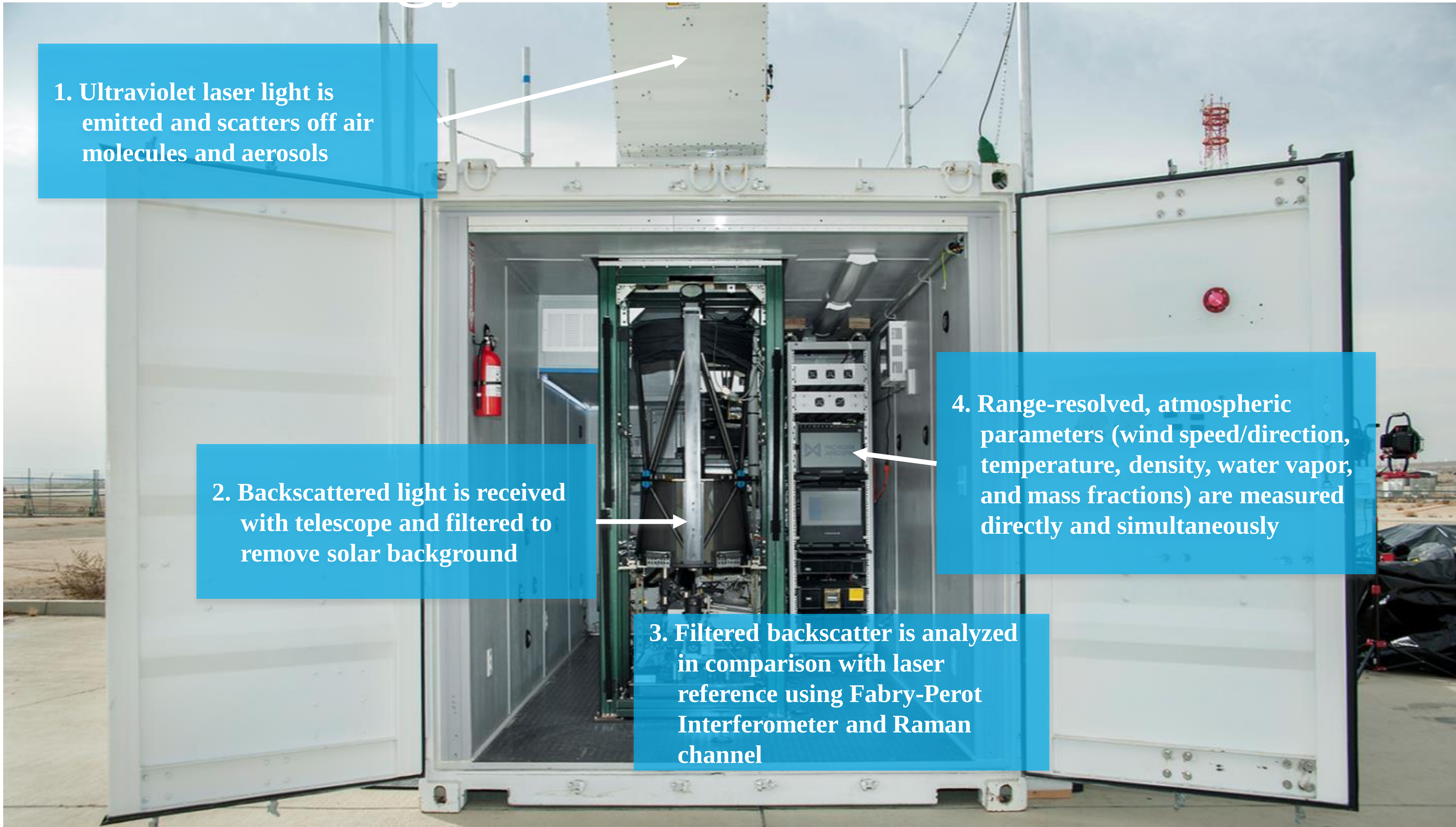
Tools of the Trade

High Altitude Lidar for Atmospheric Sensing (HALAS) Overview at NASA Armstrong

Testing Locations – NASA-Armstrong


HALAS
HIGH ALTITUDE LIDAR ATMOSPHERIC SENSING
TEST & EVALUATION
HSST
HIGH SPEED SYSTEMS TEST
SCIENCE & TECHNOLOGY
MICHIGAN AEROSPACE
F 18 IRONBIRD

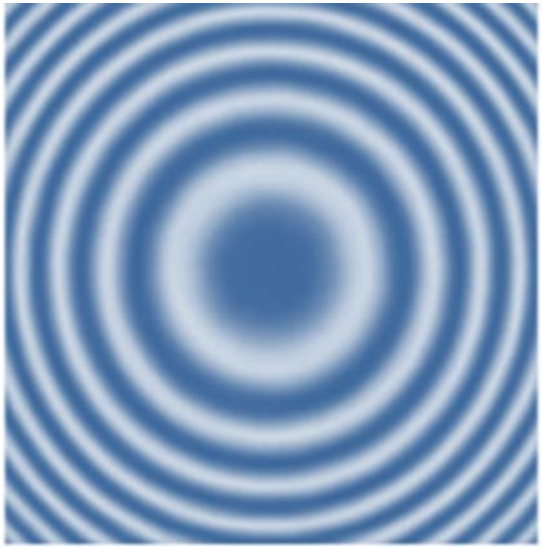
HALAS Overview

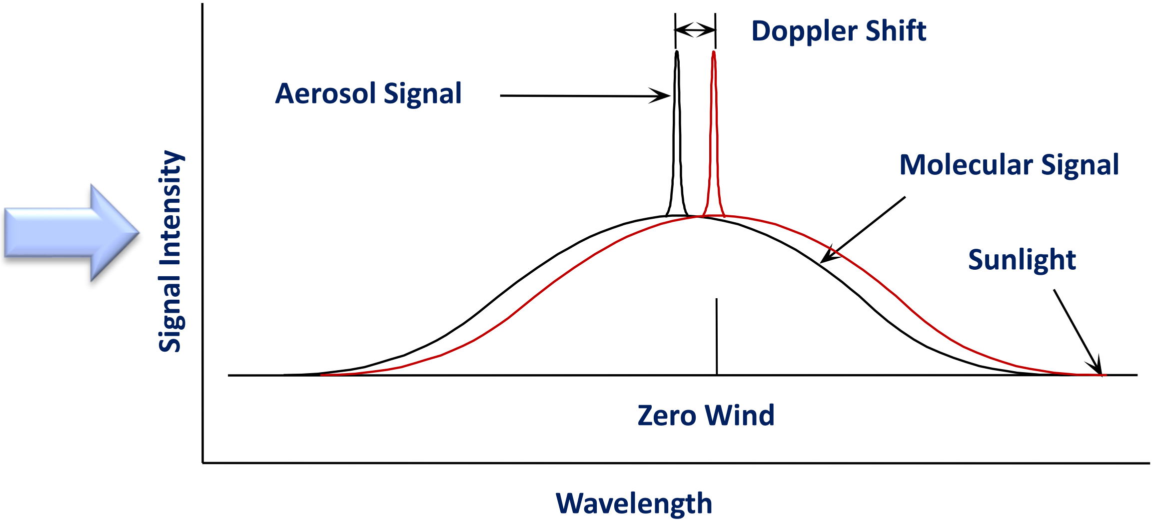


Data Product Retrieval

UV LIDAR makes direct measurements of wind speed, temperature, and density

Parameter	Atmospheric Phenomenon	Effect on Scattered Signal	Effect on Output
Wind Speed	Change in wind speed	Wavelength of return shifts	Etalon ring (fringe) radii shifts
Density	Density of air mass increases	Scattering of laser increases	Area under the fringe increases
Temperature	Temperature of air mass increases	Wider spectrum return	Fringe broadens – width increases





Rayleigh and Raman Scattering

Rayleigh scattering*:

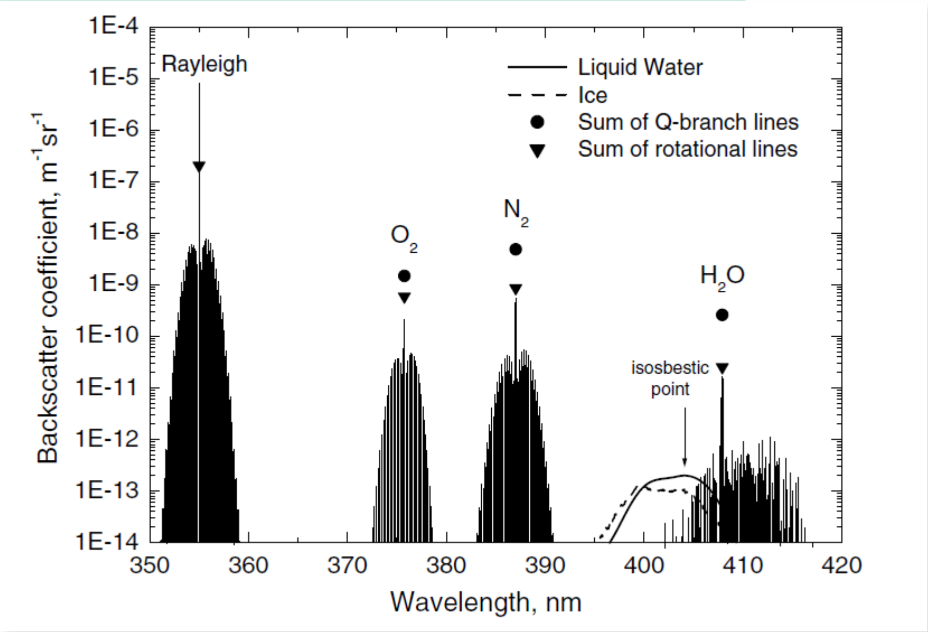
- Sum of Cabannes line (0.03 cm^{-1} wide), rotational Raman and vibrational Raman scattering (weak contribution compared to the Cabannes lines)

Raman scattering:

- The scattered light is shifted by an amount specific to the species and elastic scattered light is filtered out

Species identified by the Raman shift.

- N_2: 2,331 cm^{-1}
- O_2:1,556 cm^{-1}
- H_2O: 3,657 cm^{-1}

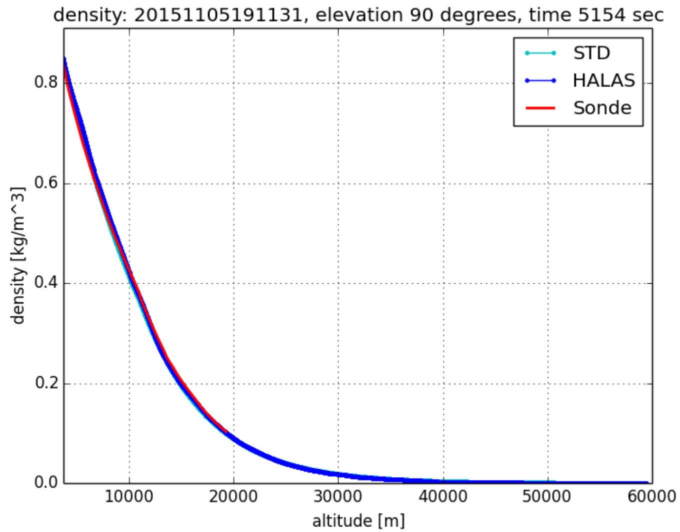


* R.B. Miles, W.R. Lempert, J.N. Forkey, “Laser Rayleigh Scattering,” Meas. Sci. and Technol. 12 (2001)

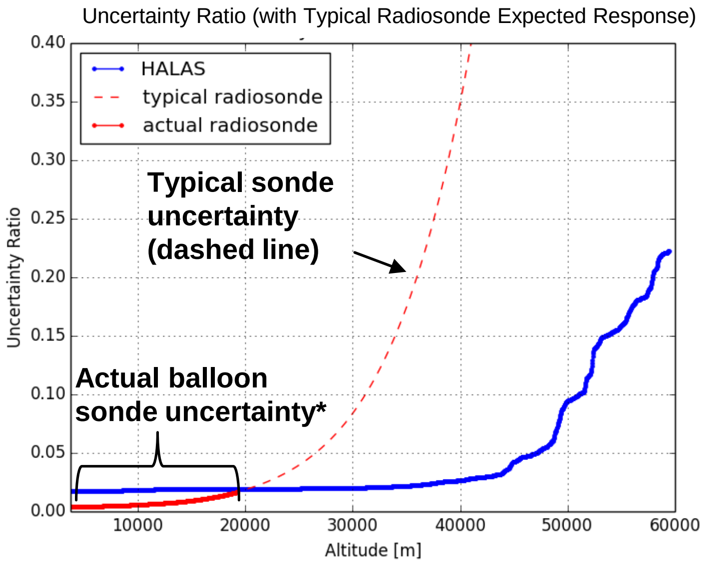
Why HALAS vs Weather Balloons

Parameter	Balloon	HALAS
Measurement location	Dictated by the prevailing winds and ascent rate	Selectable
Timeliness of profile	Typically takes 1-2 hours to reach altitude and only provides single altitude per data point	Simultaneously provides full range profile in seconds to minutes (dependent on accuracy and range)
Data products	Winds, pressure, temperature and humidity (depends on radiosonde)	Winds, density, mass fraction (O_2, N_2 & H_2O), temperature and humidity
Uncertainty	Adequate uncertainty at low altitudes but suffer at high altitudes	Better uncertainty at higher altitudes. Comparable at lower elevations.
Environmental impact	Non-retrievable and not biodegradable	Only light is emitted from the system
Autonomous operation	Typically requires 1-2 people to launch and/or track a balloon	Can be made to run remotely with sufficient safety protocols
Operational coverage	Limited in number of profiles per day or night	Can run continuously 24/7
Spatial resolution	Dictated by hardware and ascent rate	Limited by detector update rate
Operational constraint	Land or sea-based. Can operate in adverse weather.	Land-and aircraft based (upon completion of Phase 3). Limited by heavy cloud cover from land.

Representative High Altitude Density



Parameter	Value
Date/time (UTC)	
Azimuth/Elevation	0° /90°
Integration time	59.7 min
Balloon launch (UTC)	
Balloon Max Altitude	19.3km (63,320ft)
CCD gain	200
CCD shift rate	500ns
Laser power	11.5W

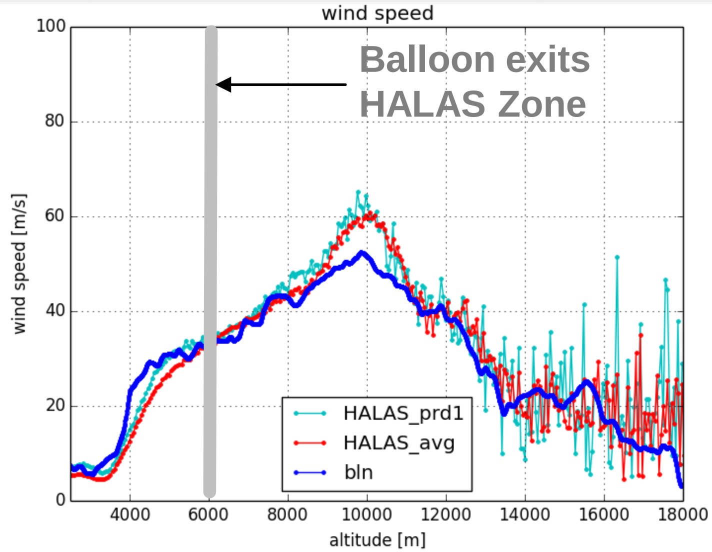


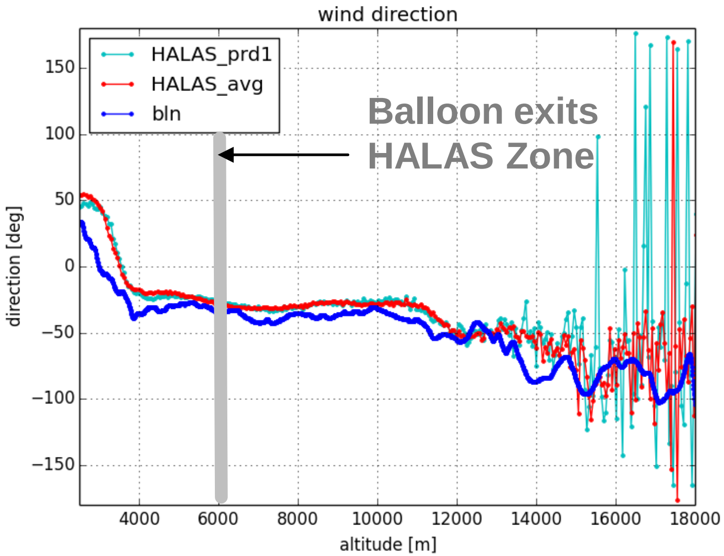
- **Typical balloon uncertainty at 40km (131kft) is ~30% vs HALAS uncertainty of ~2%**

*** Balloon burst at 19.3km; typical high altitude balloons burst at 40km**

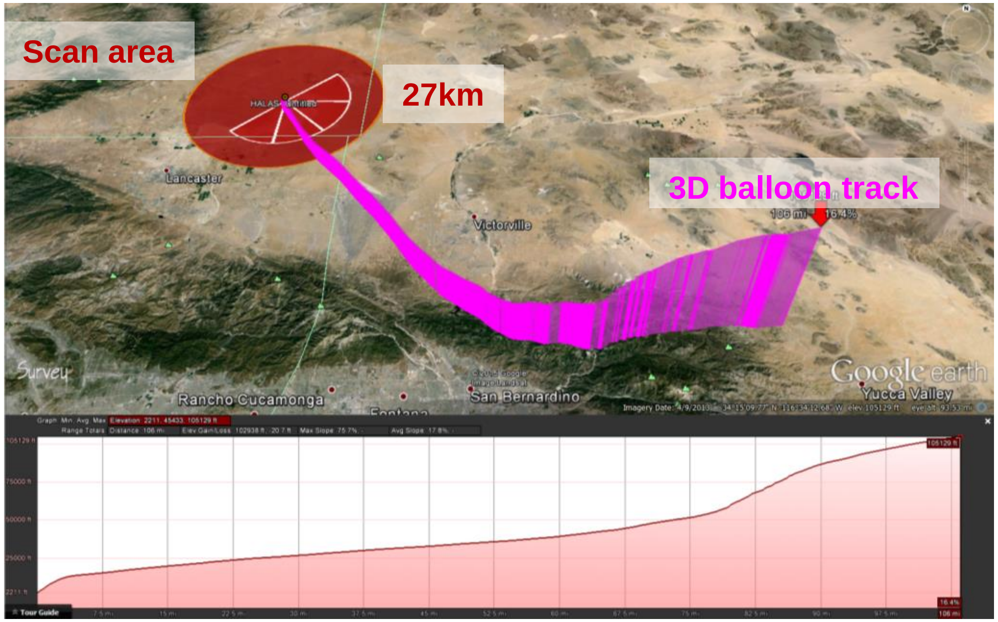
Representative Standoff Winds
Set 384

Average is over 20 Azimuthal views (40 min total)

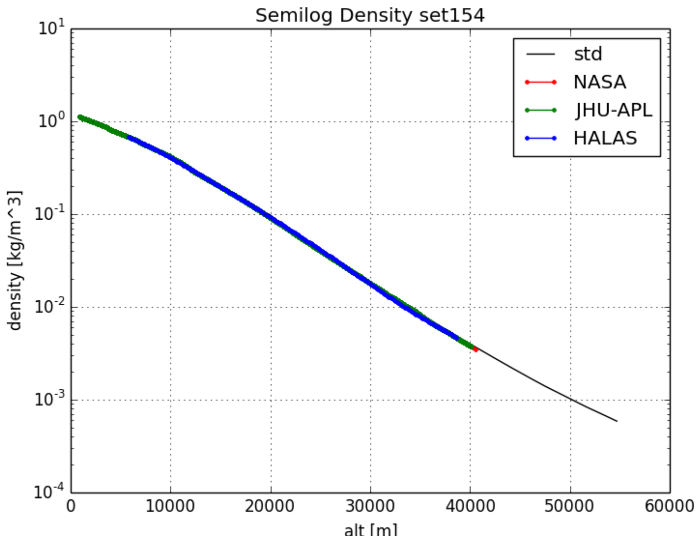


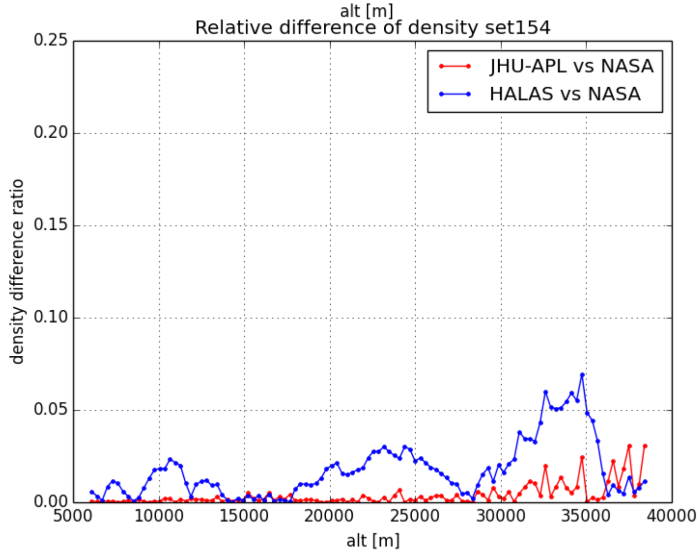


Parameter	Value
Date/time (UTC)	
Azimuth/Elevation	(45,90,135,180,225)˚ /45˚
Integration time	2 min/azimuth
Balloon launch (UTC)	
Balloon distance; max altitude	170.6km; 32km (559,711ft; 104,987ft)
CCD gain	200
CCD shift rate	500ns
Laser power	11.5W



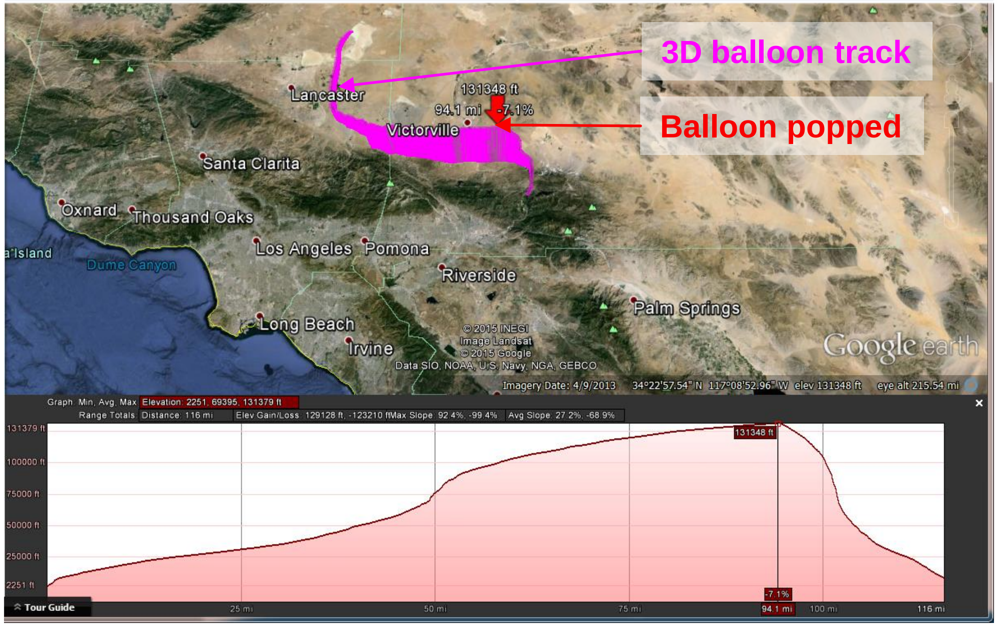
Representative Density



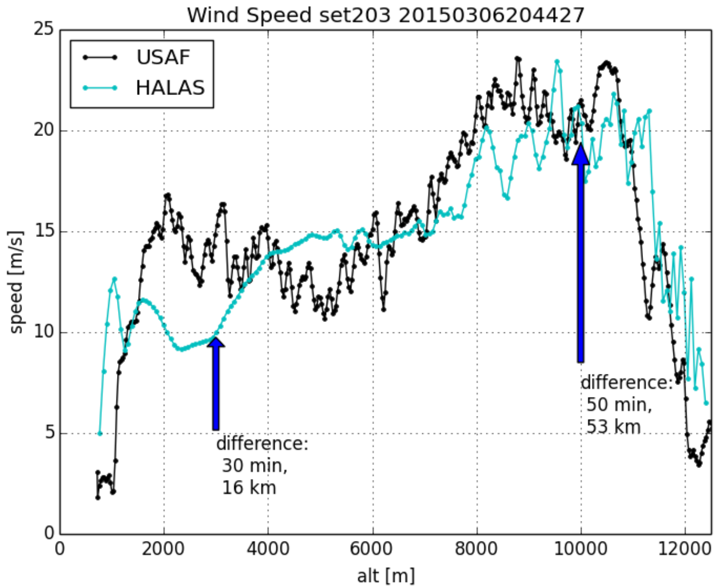


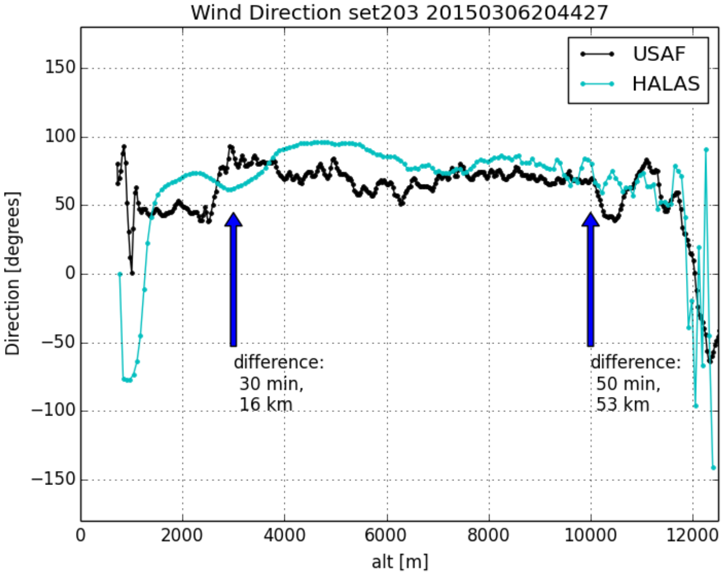
Plot shows the relative difference between the balloon and the HALAS data, not uncertainty

Parameter	Value
Date/time (UTC)	3/4/2015 (04:49)
Azimuth/Elevation	0°/90°
Integration time	18 min
Balloon launch (UTC)	3/4/2015 (05:00[NASA] / 0:00[AF])
Balloon distance / max altitude	58mi / 131,348ft
CCD gain	95
CCD shift rate	900ns
Laser power	11.7W



Representative Wind Speed/Direction

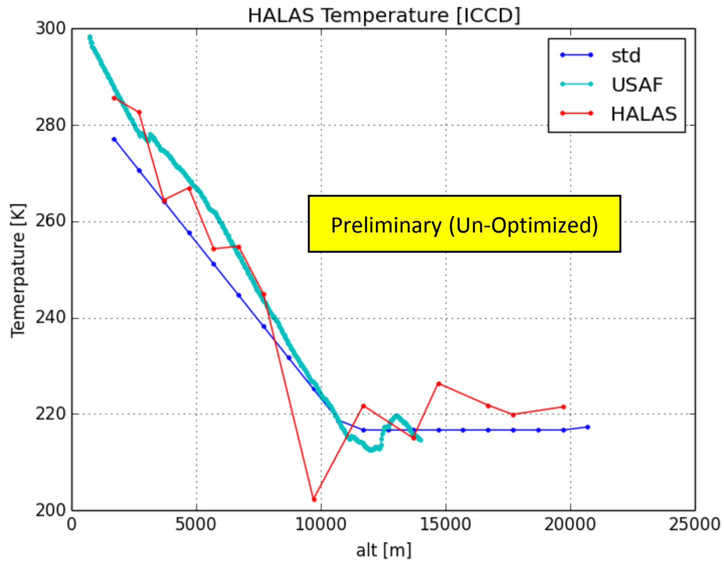


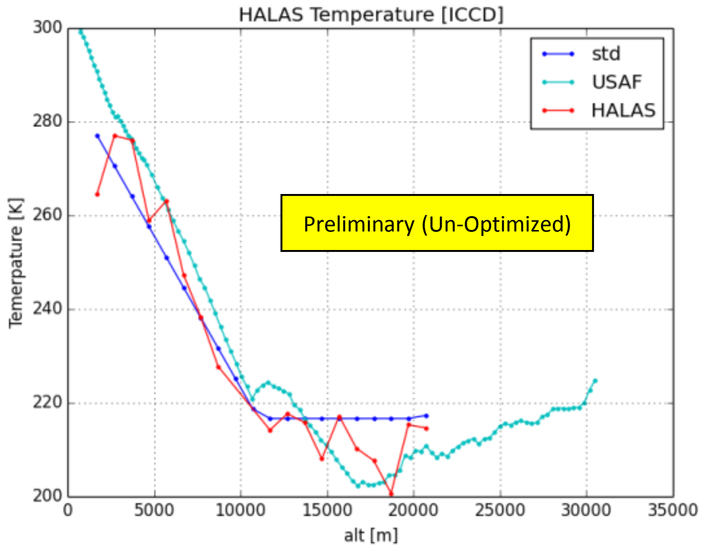


Parameter	Value
Date/time (UTC)	3/6/2015 (20:44)
Azimuth/Elevation	(0,90,180,270)˚ /65˚
Integration time	6 min/azm
Balloon launch (UTC)	3/6/2015 21:00[AF]
Balloon distance / max altitude	37mi (estimate)/ 82,100ft
CCD gain	95
CCD shift rate	500ns
Laser power	11.2W

- Plots marks time and location difference between balloon and HALAS
- 3D ground track not available from Air Force data stream. Distances are estimated from average of multiple balloon launches before and after this launch

Temperature Estimations

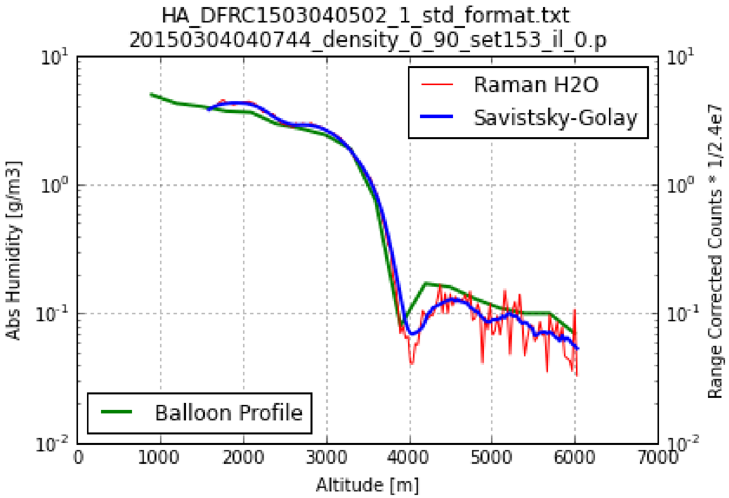


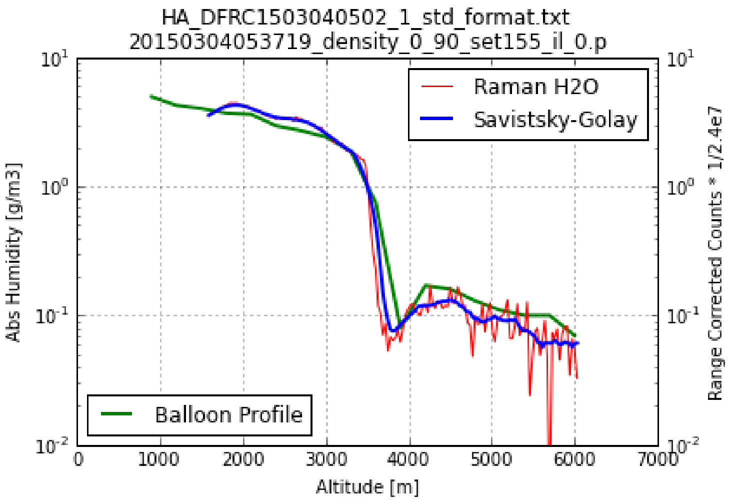


Initial (Not Optimized) HALAS Temperature Estimates: Night [left], Day [right]

- Initial temperature results do not reflect the full capability of HALAS
- Upgrades are being implemented to enhance the temperature measurement capability under Phase 3 of HALAS
  - Upgrades will allow higher spectral resolution and better uncertainties

Water Vapor





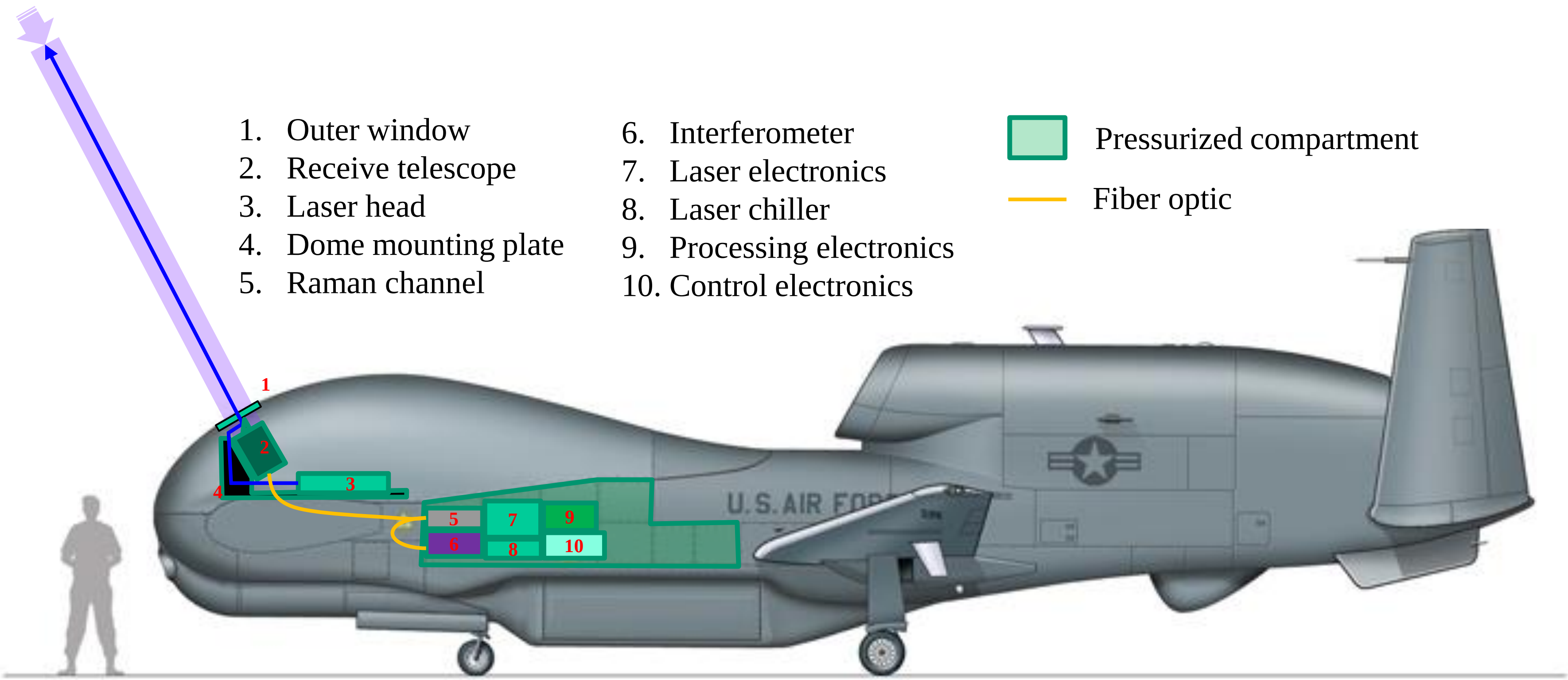
Parameter	Value
Date/time (UTC)	3/4/2015 (04:07 and 05:37)
Azimuth/Elevation	0°/90°
Integration time	18 min
Balloon launch (UTC)	3/4/2015 05:00[NASA]
Balloon distance / max altitude	58mi / 131,348ft
Bin size	30m
Laser power	11.5W

- Water vapor not part of original effort but were added due to interest from current and future customers
- Water vapor measurements show great promise for future implementation
  - Tracks well with balloon and provides greater resolution (30m)

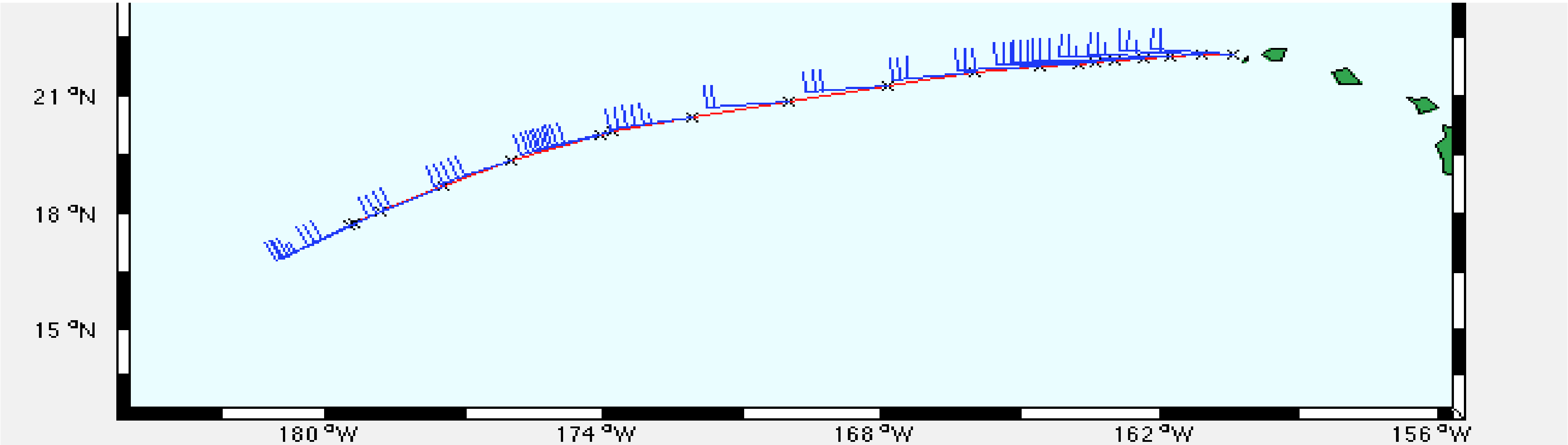
HALAS on aircraft

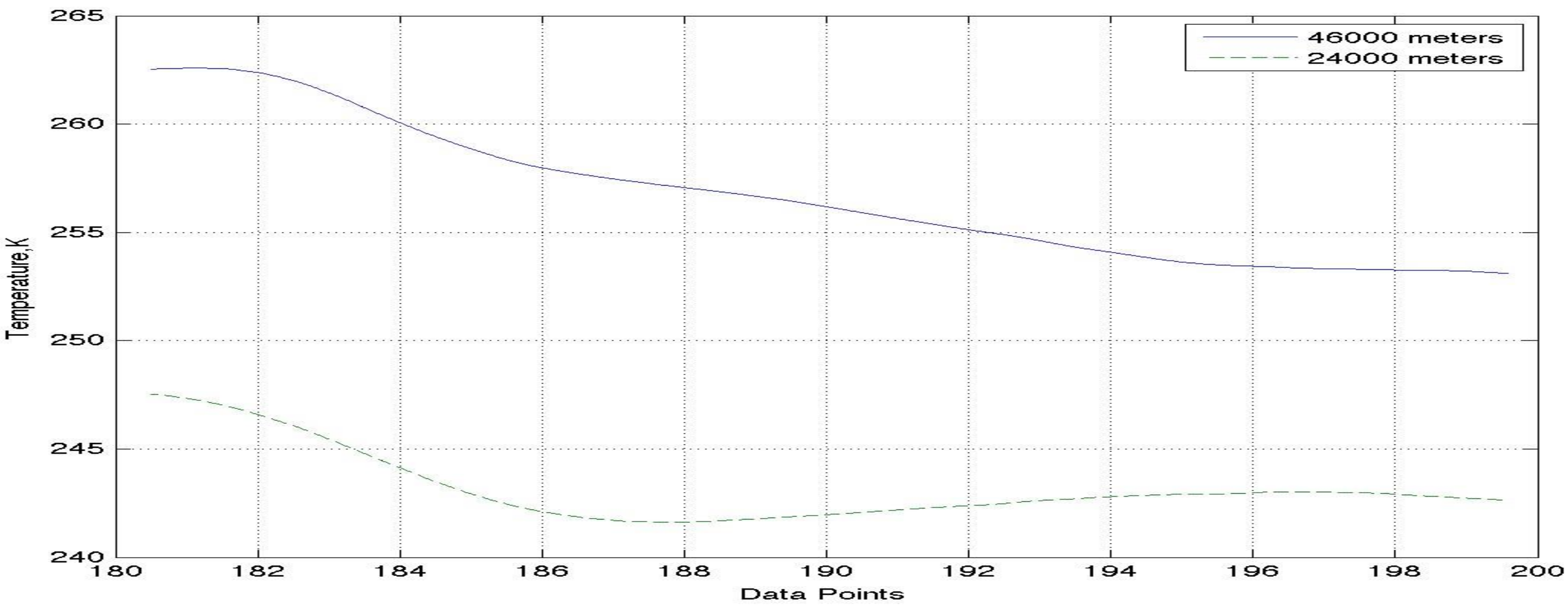
- Significantly enhanced atmospheric data coverage
  - Allows for mapping of atmosphere along intended trajectory
- Greater mission flexibility
- Capability to support several different CONOPS
- Improved measurement opportunity by beginning measurement above boundary layer and majority of cloud cover
- Ability to provide additional data such as the characterization of aerosol conditions that could cause ablation or other issues to a flight vehicle

Potential Follow-On

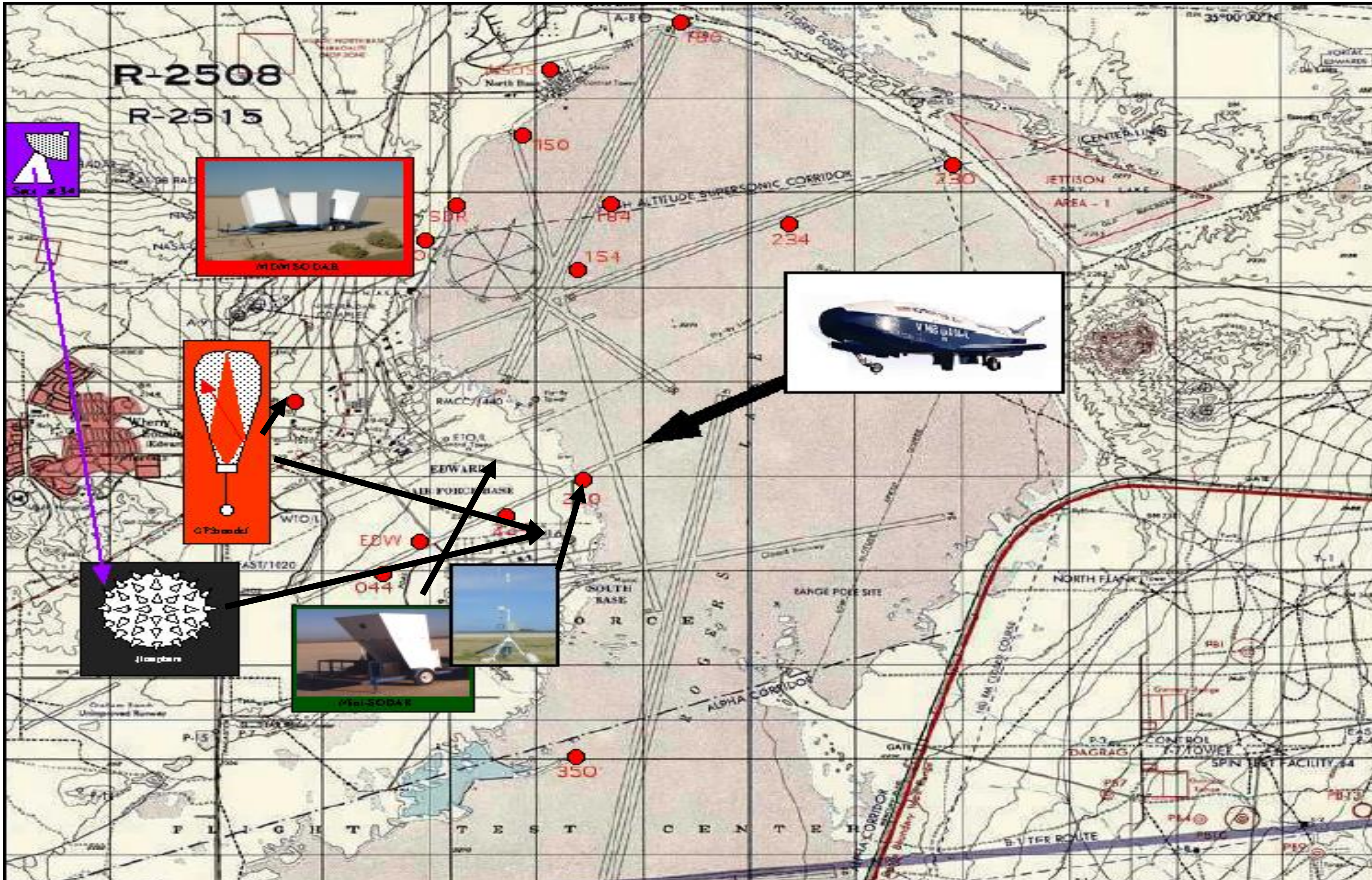


Trajectory Simulation





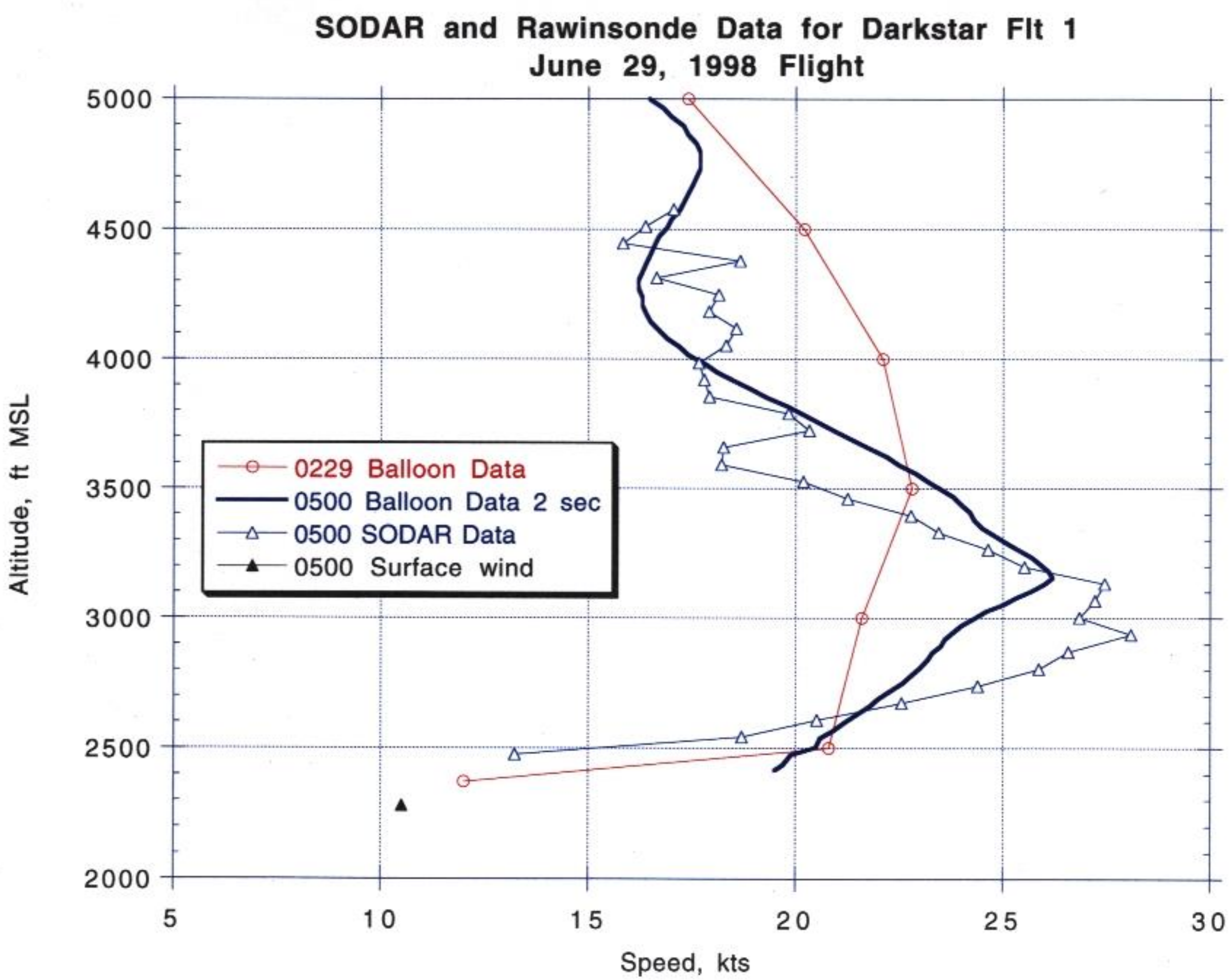
WX Sensor Deployment



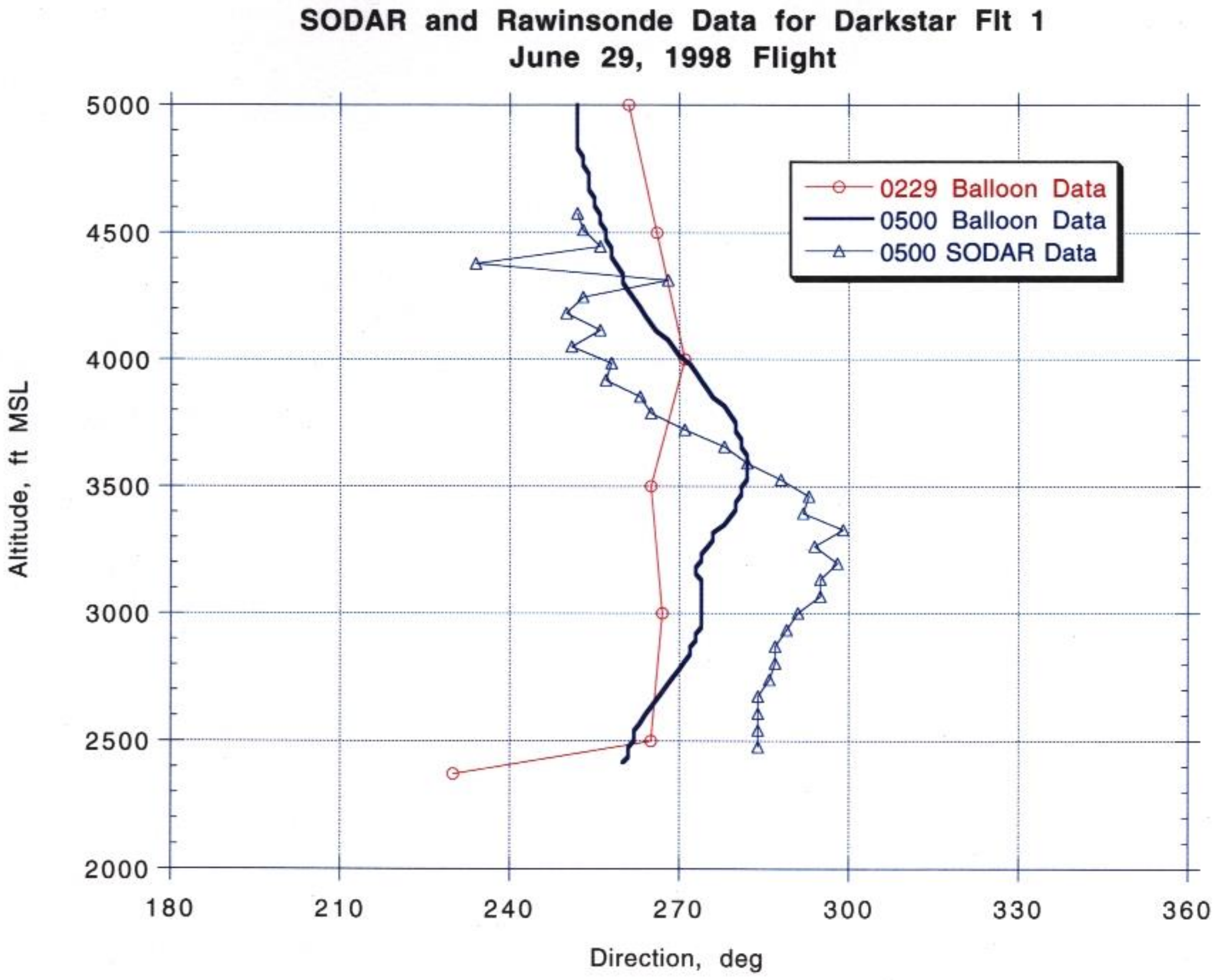
Model 2000 Doppler SODAR

- Operates at 1600-2300 (2000) Hz
- Wind Profiles
  - 60 meters AGL min
  - 740 meters AGL max
  - 20 meter intervals
- Sample Rate
  - 1 cycle per 15 sec
- Averaging times
  - 5-15 minutes

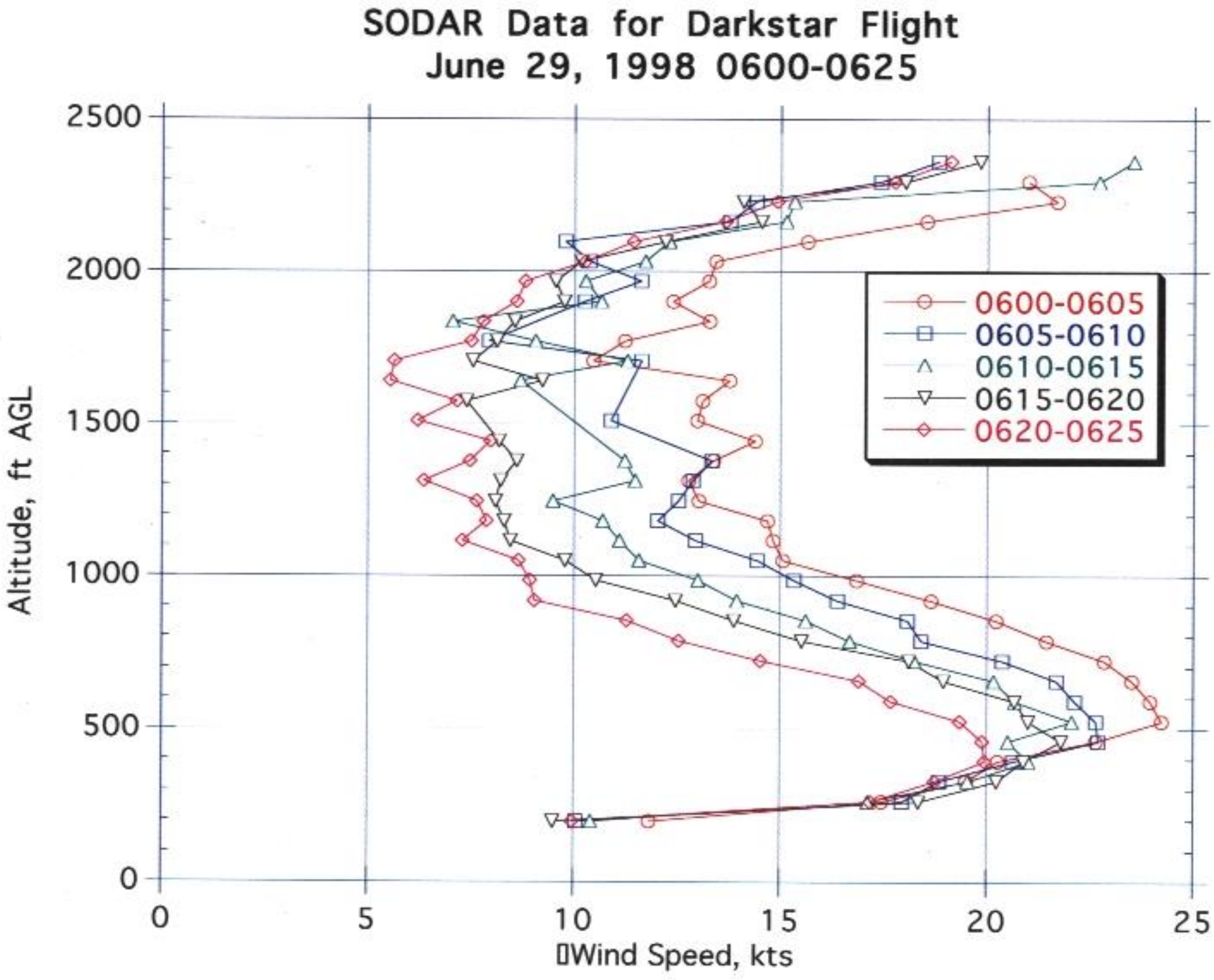
SODAR/Rawinsonde Comparisons



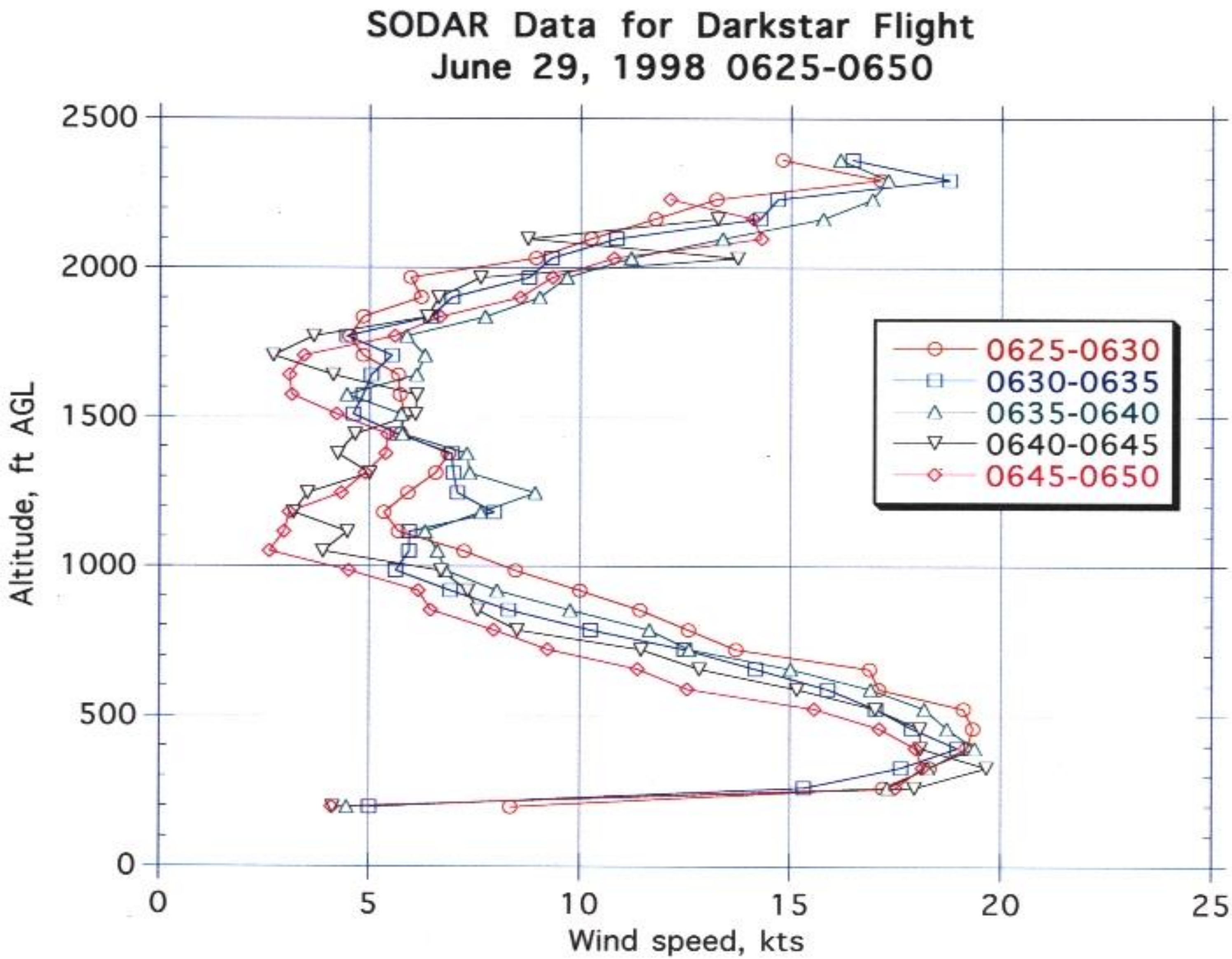
SODAR/Rawinsonde Comparisons



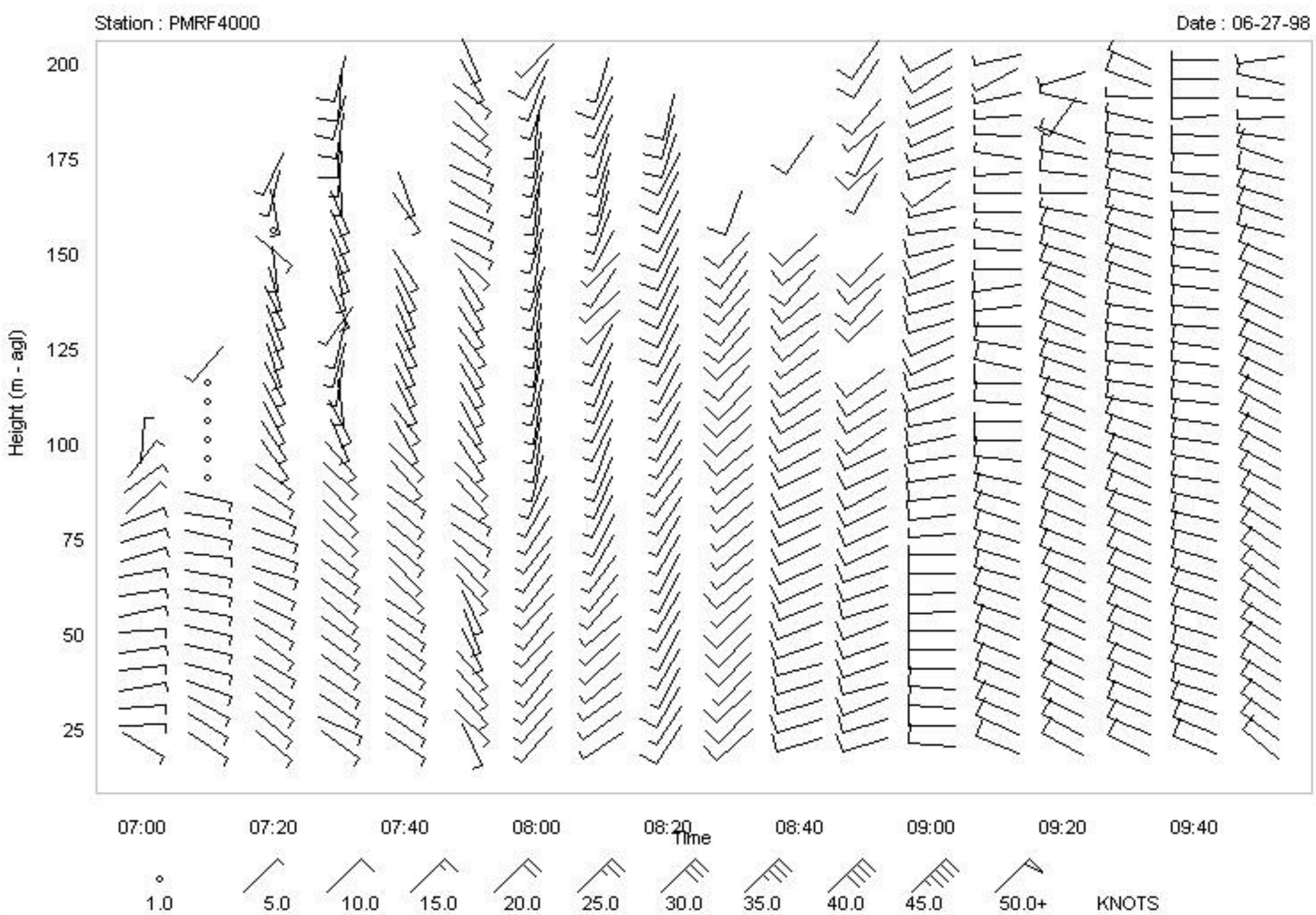
SODAR Profile Trends



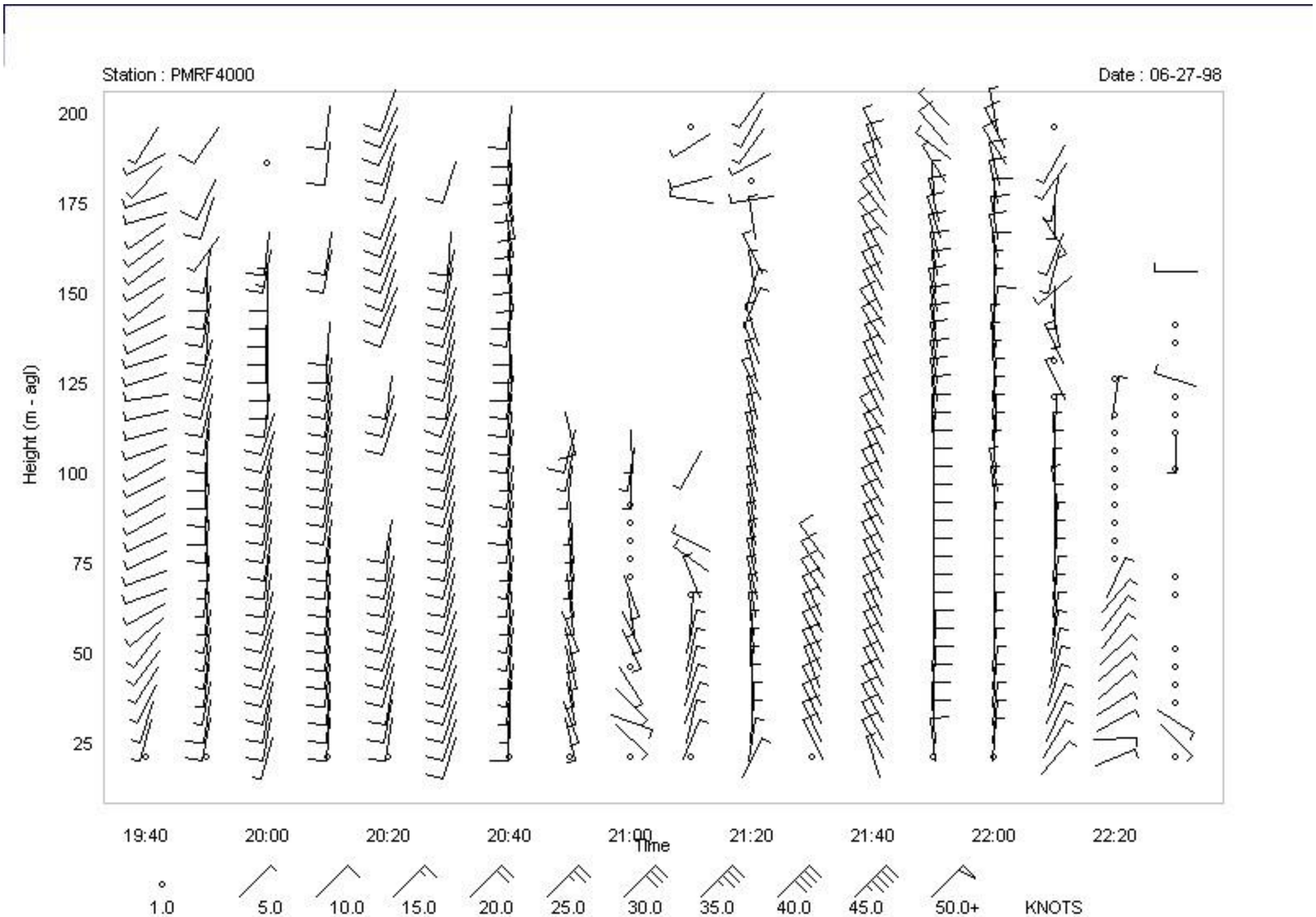
SODAR Profile Trends (cont.)



Morning Wind Profile

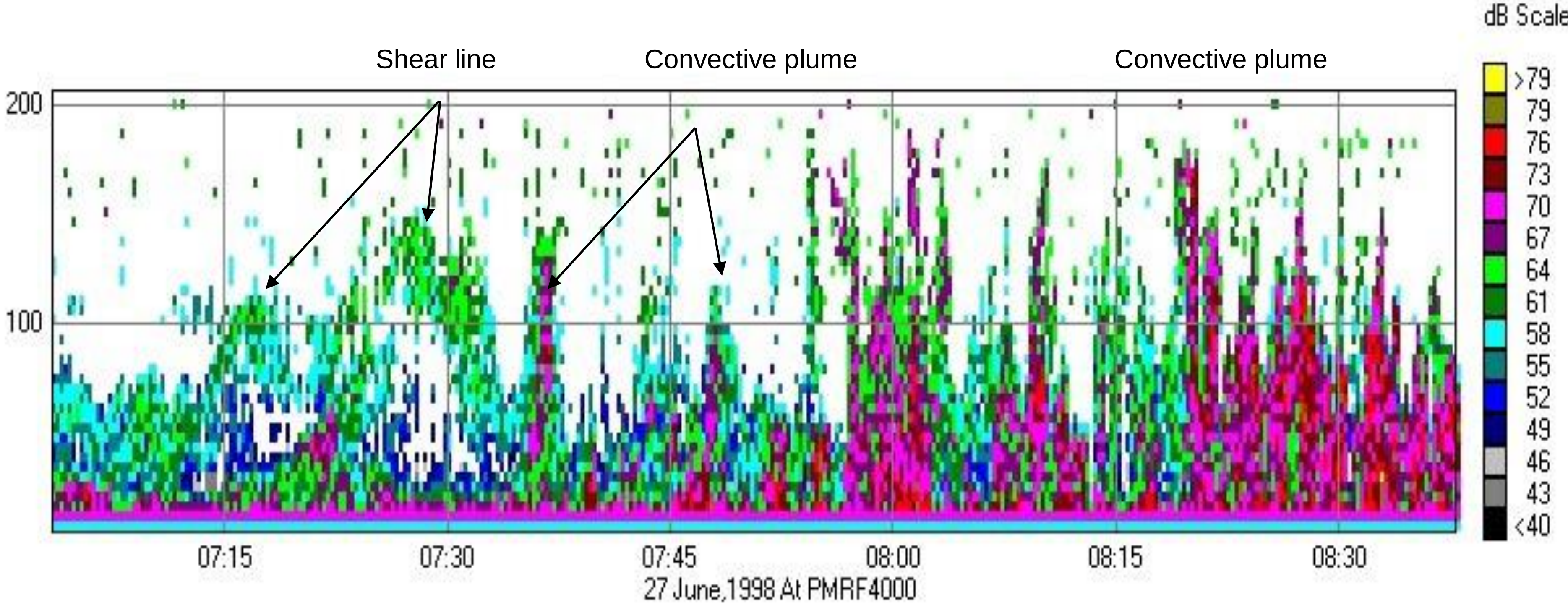


Afternoon Wind Profile



AM Facsimile Profile

Pathfinder Plus



Model 4000 (miniSODAR)

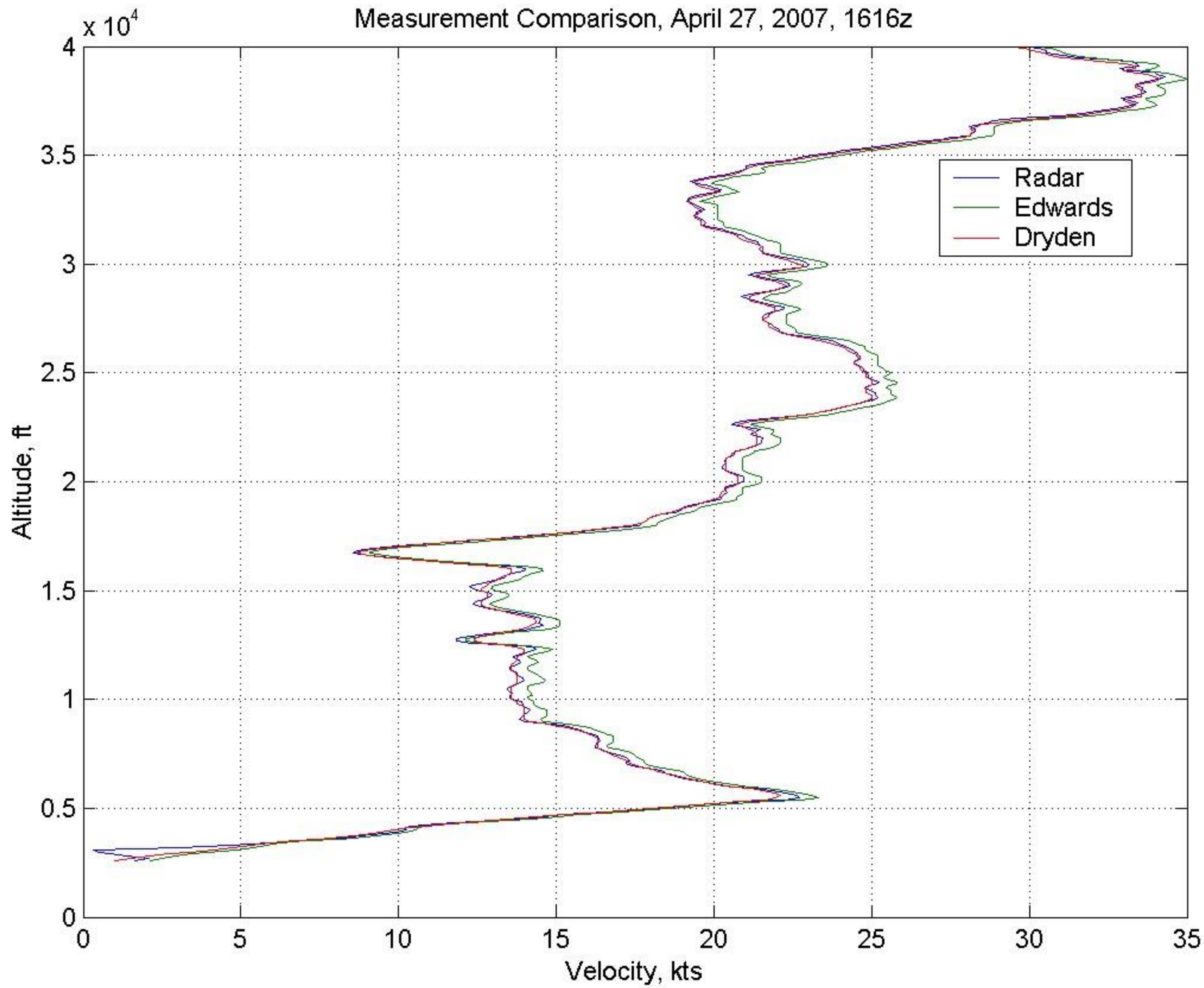
- Operates at 4500 Hz
- Wind profiles
  - 15 meter AGL min
  - 200 meter AGL max
  - 5 meter intervals
- Sample Rate
  - 1 cycle per 4 sec
- Averaging times
  - 1-5 minute

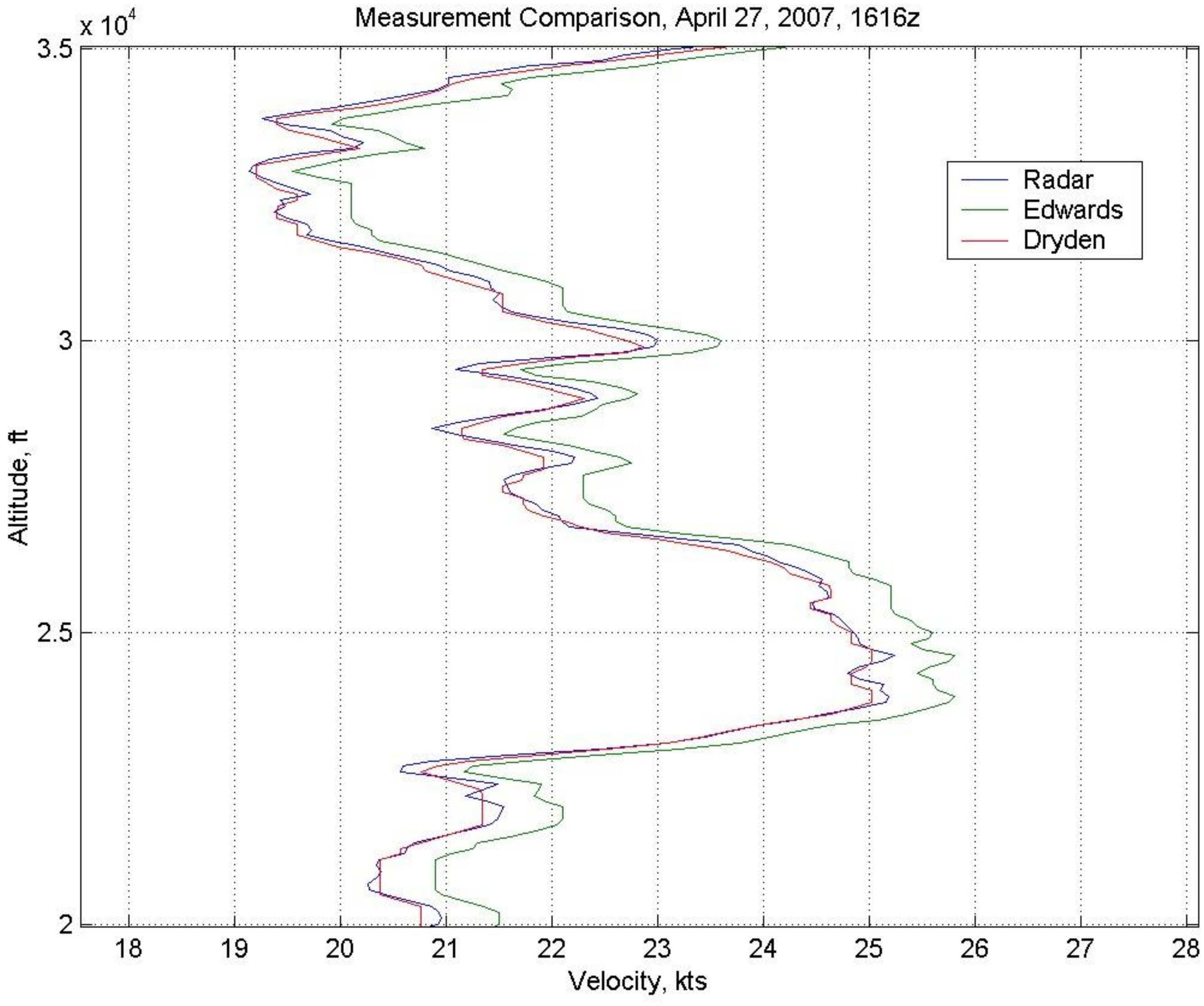
Radiosonde Balloon: Upper Atmosphere measurements

- Measure winds and altitude (GPS), temperature, humidity and Pressure
- Calculate density, pressure altitude, dewpoint and liquid water content
- Derive stability and turbulence potential

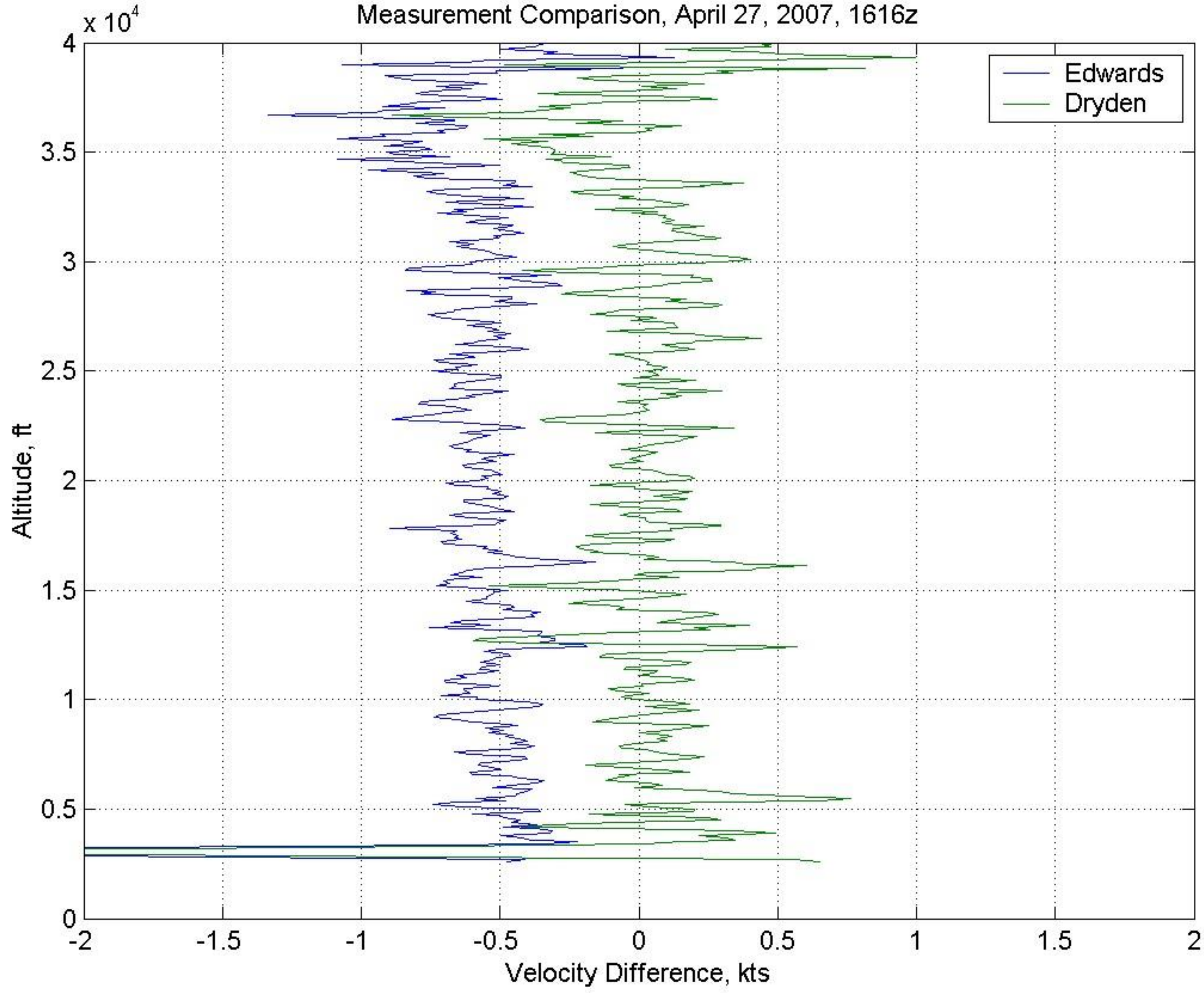
High Resolution Balloon

Jimsphere for high resolution winds tracked by radar + Radio sonde package for thermodynamic data

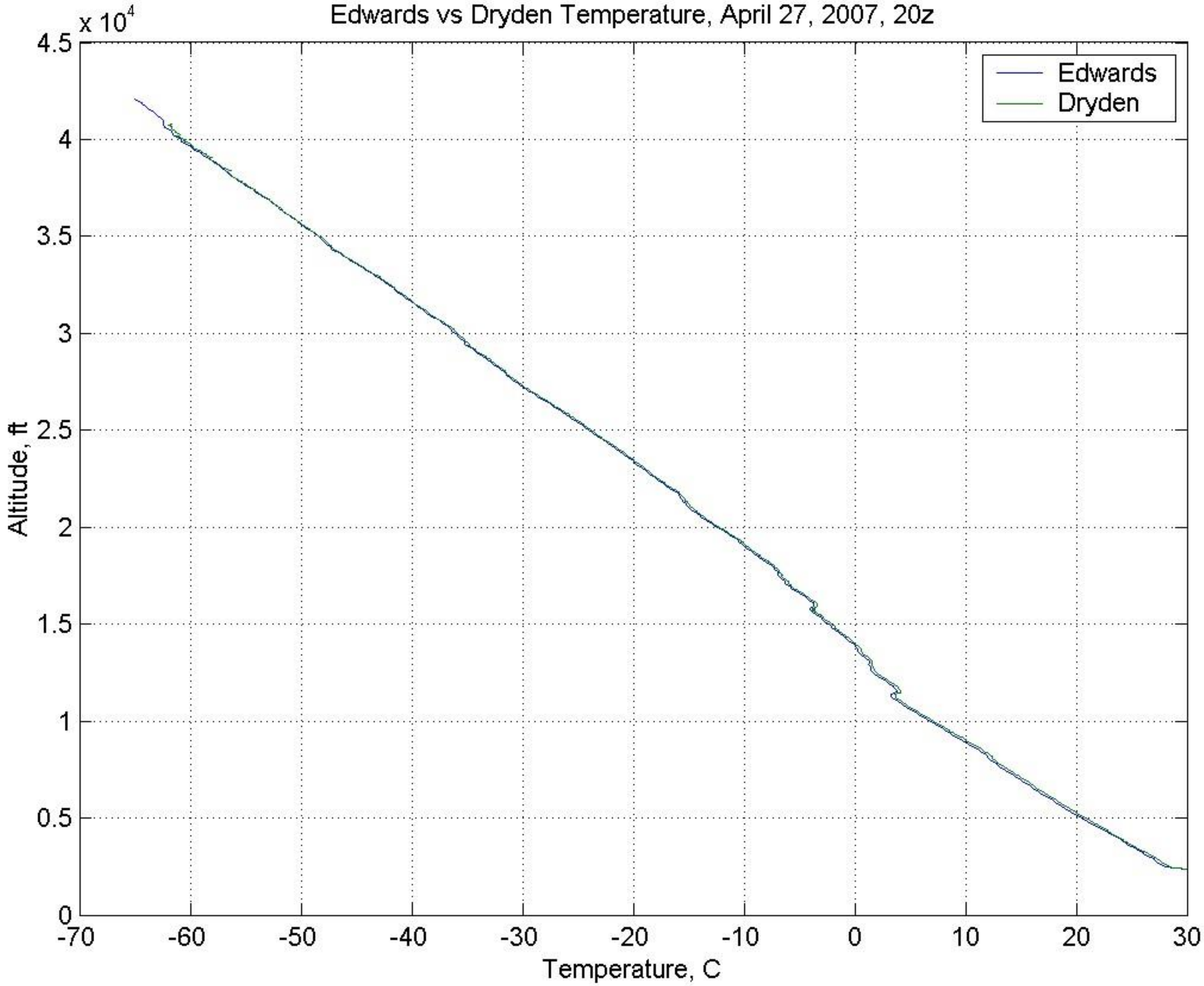

Measurement Comparison, April 27, 2007, 1616z
x 10^4
4
3.5
3
2.5
2
1.5
1
0.5
0
Altitude, ft
0
5
10
15
20
25
30
35
Velocity, kts
Radar
Edwards
Dryden



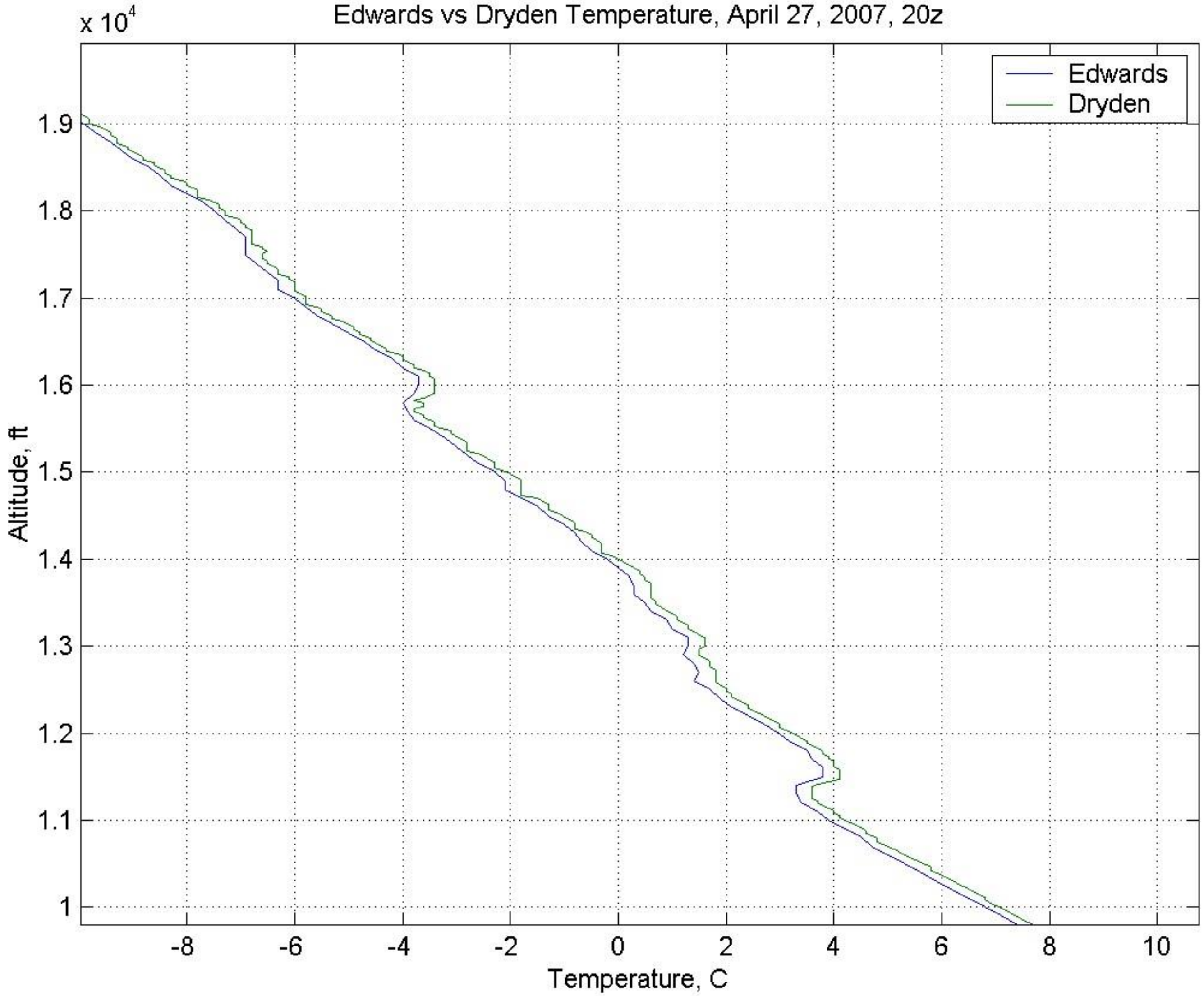
Measurement Comparison, April 27, 2007, 1616z
x 10^4
3.5
3
2.5
2
Altitude, ft
18
19
20
21
22
23
24
25
26
27
28
Velocity, kts
Radar
Edwards
Dryden



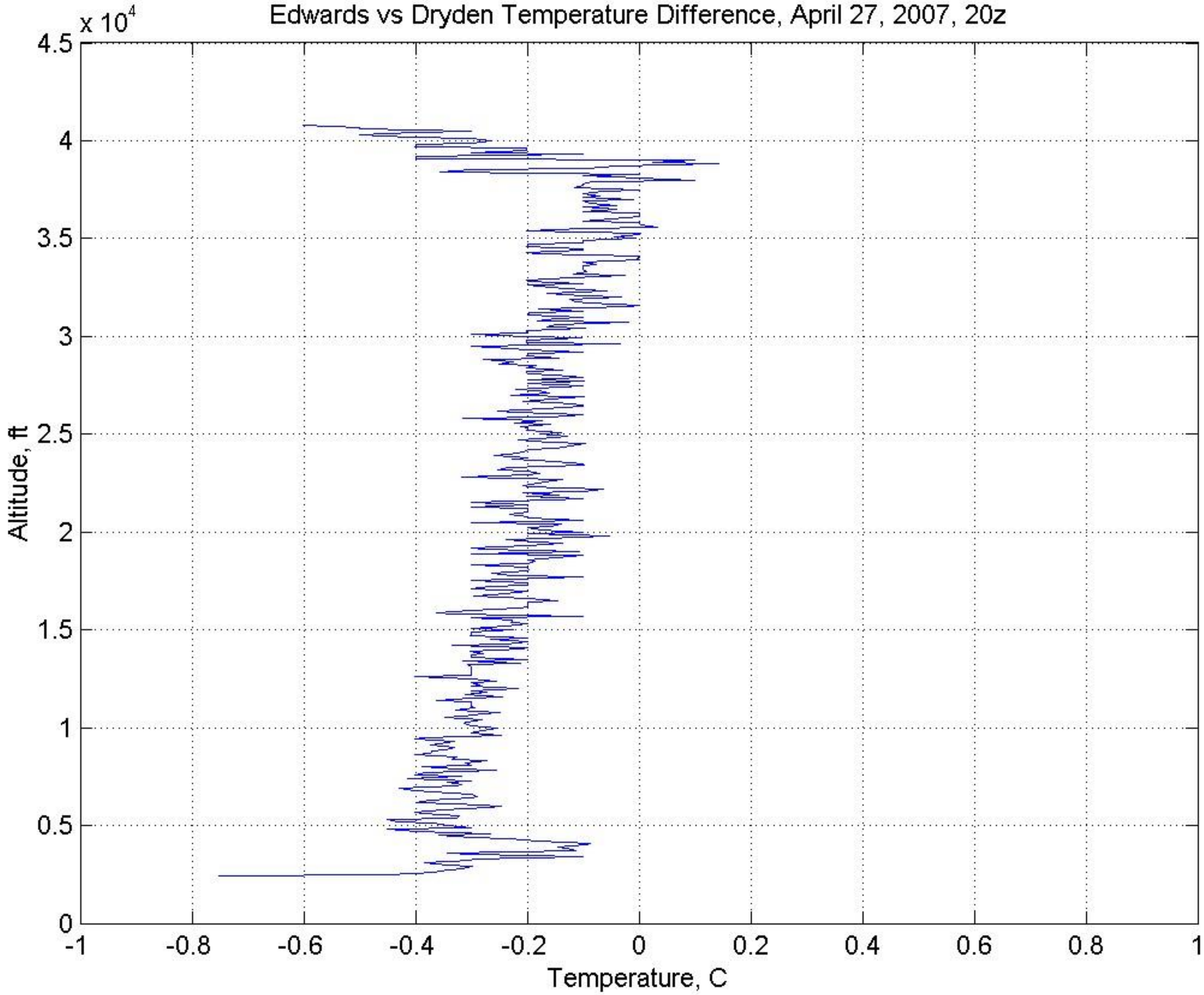
Measurement Comparison, April 27, 2007, 1616z
x 10^4
4
3.5
3
2.5
2
1.5
1
0.5
0
Altitude, ft
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Velocity Difference, kts
Edwards
Dryden

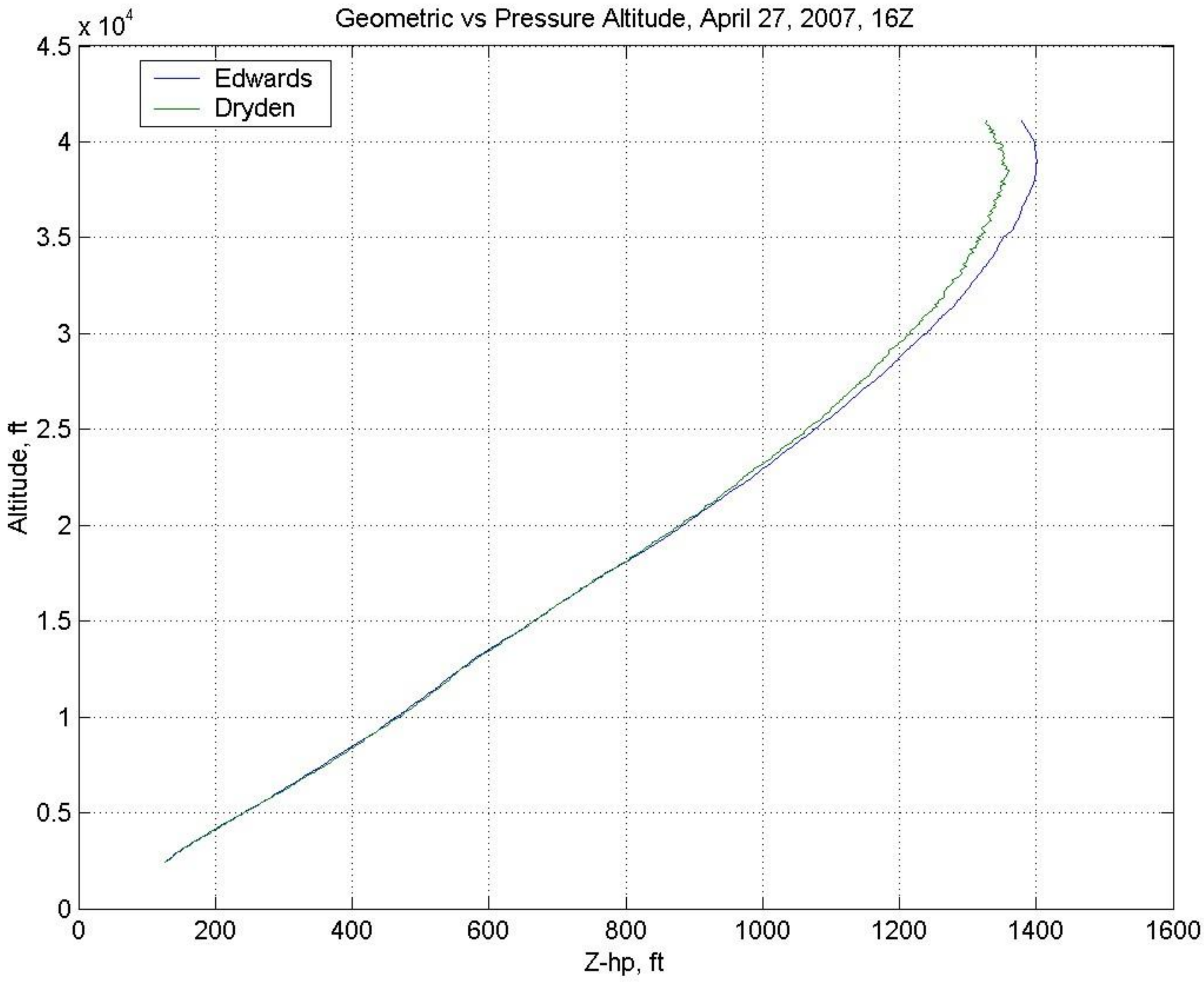


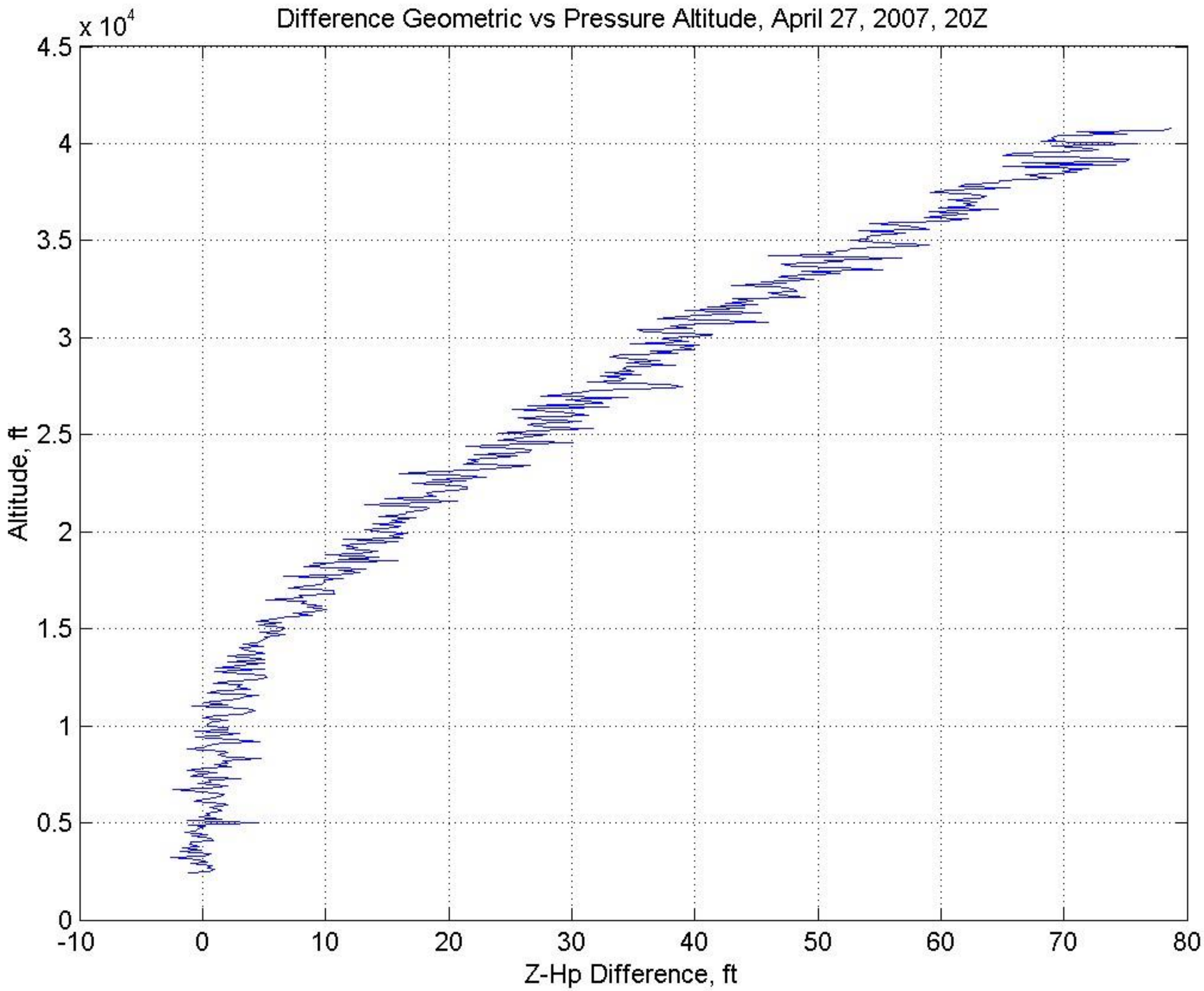
Edwards vs Dryden Temperature, April 27, 2007, 20z
x 10^4
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Altitude, ft
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
Temperature, C
Edwards
Dryden



Edwards vs Dryden Temperature, April 27, 2007, 20z
x 10^4
Edwards
Dryden
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
Altitude, ft
-8
-6
-4
-2
0
2
4
6
8
10
Temperature, C


Edwards vs Dryden Temperature Difference, April 27, 2007, 20z
x 10^4
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Altitude, ft
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Temperature, C


Geometric vs Pressure Altitude, April 27, 2007, 16Z
x 10^4
Edwards
Dryden
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Altitude, ft
0
200
400
600
800
1000
1200
1400
1600
Z-hp, ft


Difference Geometric vs Pressure Altitude, April 27, 2007, 20Z
x 10^4
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Altitude, ft
-10
0
10
20
30
40
50
60
70
80
Z-Hp Difference, ft

Results

2005 Comparison:

Velocity Difference due to offset in altitude		1-2 kts
Direction Difference	"	3-5 deg
Temperature Difference	"	1 Deg

2007 Comparison

Velocity Difference	0.2 -0.4 kts
Direction Difference	0.1 –0.3 deg
Temperature Difference	0.15 deg

Hypersonics

HTV-2 4/2010 & 8/2011

X-51 5/2010, 3/2011, 8/2012, 5/2013

AHW 11/2011

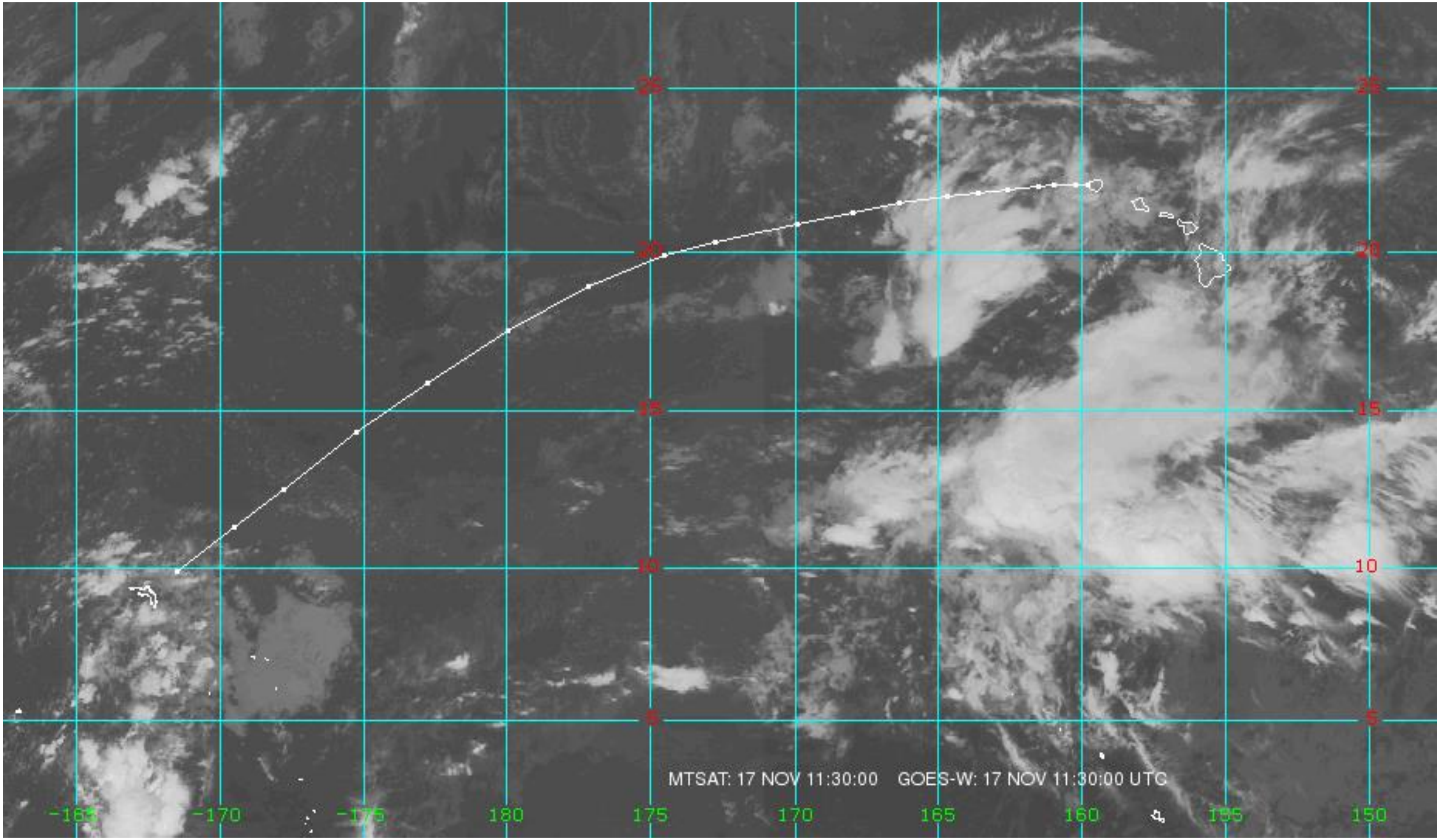
Background Issues

- High altitude (to 50 km) parameters: pressure, temperature, winds and density over 1000’s km.
- Very difficult to measure by conventional methods (Balloons).
- Range of sensors too extreme and no airdata probes on vehicles due to severe aerothermal heating during hypersonic speeds.
- GRAM standard deviations grow very large with altitude.

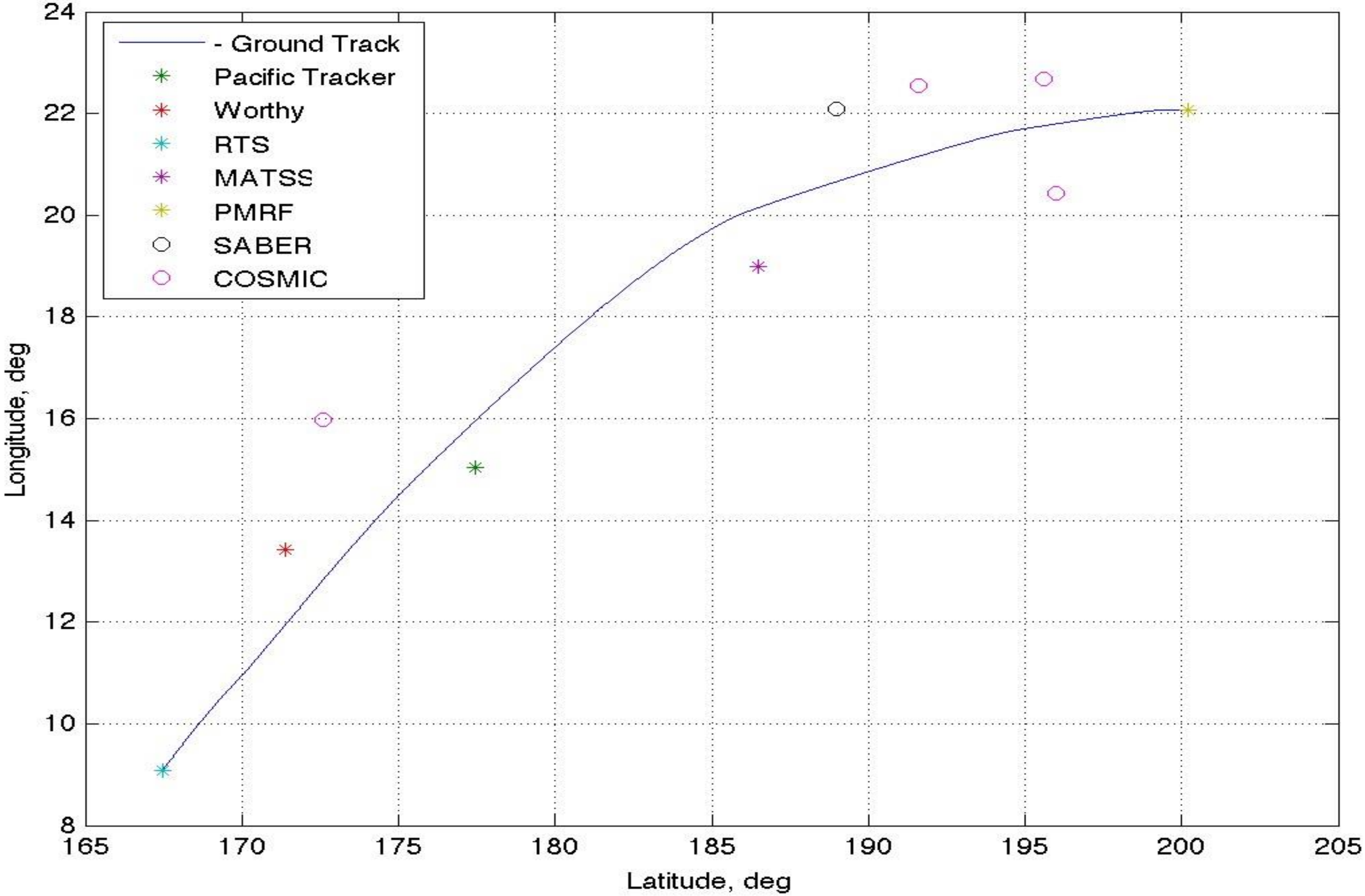
Challenges

- Obtaining data in a region of the atmosphere where data is very limited (ignorosphere).
- Formulate a Best Estimate Atmosphere (BEA) that meets uncertainty requirements.
- Identify data sources that are/were projected to become available and to determine how to integrate these data.
- Develop a data analysis tool to evaluate the data and produce a modeled atmosphere based on representative data.

AHW Flight Path Nov 17, 2011



AHW Measurement Locations



Example of Data Sources

- GEOS-5 data
  - 3d instantaneous fields (no averaging)
  - 0.25° lat by 0.33° long to 72 km (236Kft)
- NOGAPS –NAVY
  - Mandatory levels to .4 mb 52km (170 Kft)
  - 1° Lat x 1° Long
- Radiosondes (Locations along flight track to 40 km (130 Kft)
- Meteorological rocket data to 85km (280 Kft)
- SABER data
- COSMIC data
- Satellite imagery
- Global Reference Atmospheric Model (GRAM) - Earth v.2010
- No Mauna Loa LIDAR (down and clouds)
- HALAS Lidar
- ACLAIM lidar

AHW Data Sources

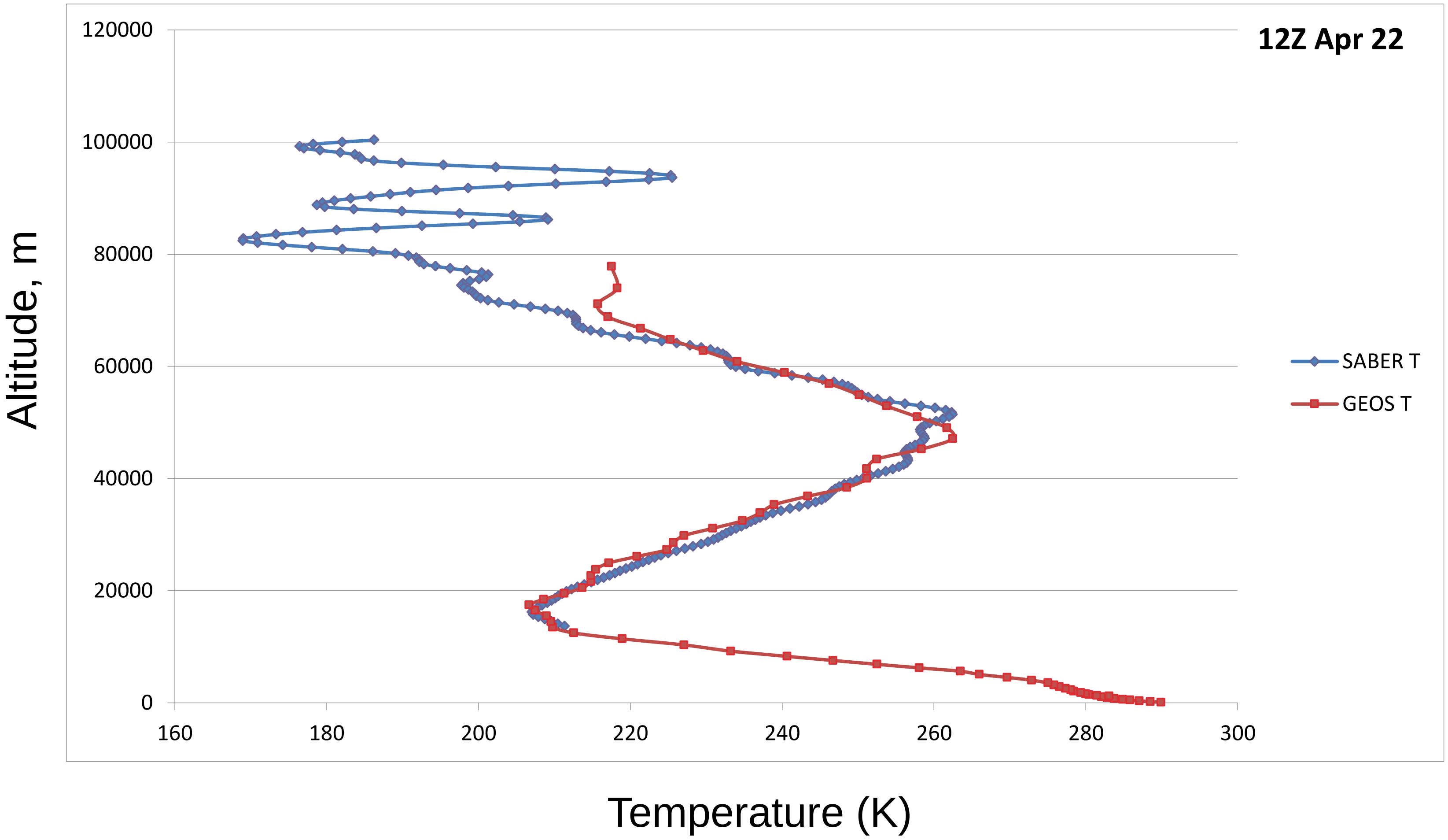
- Lower Atmosphere (SFC – 40km):
  - Radiosonde Balloons (6)
  - Models (2)

- Middle Atmosphere (30 – 80km)
  - Rocketsonde (2)
  - Satellites (2)
  - GRAM-2010
  - Models (2)

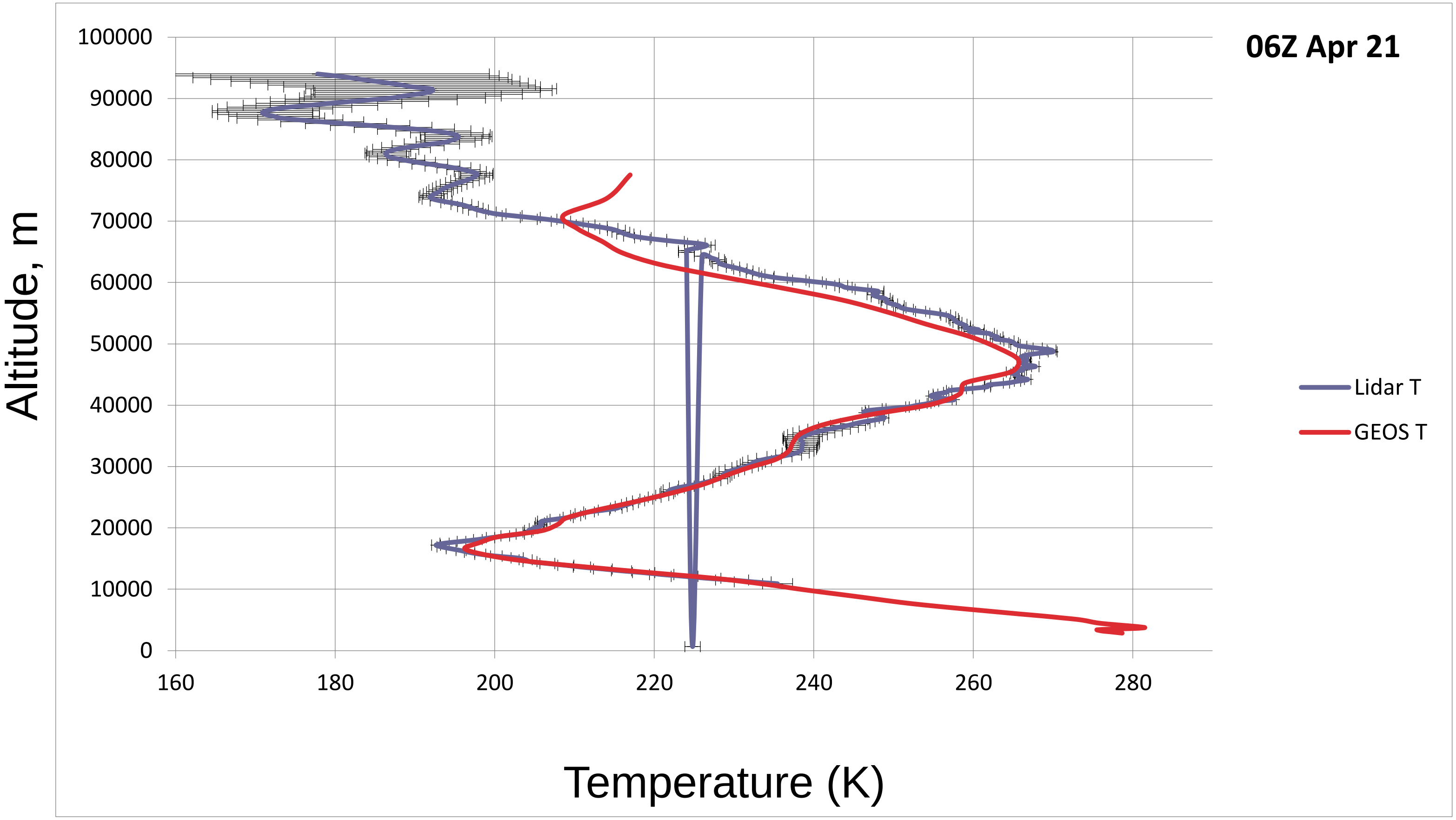
- Upper Atmosphere (70 – 120km)
  - GRAM-2010
  - Satellites (2)

- Blending technique for overlap regions

Data Comparison
SABER vs GEOS 5

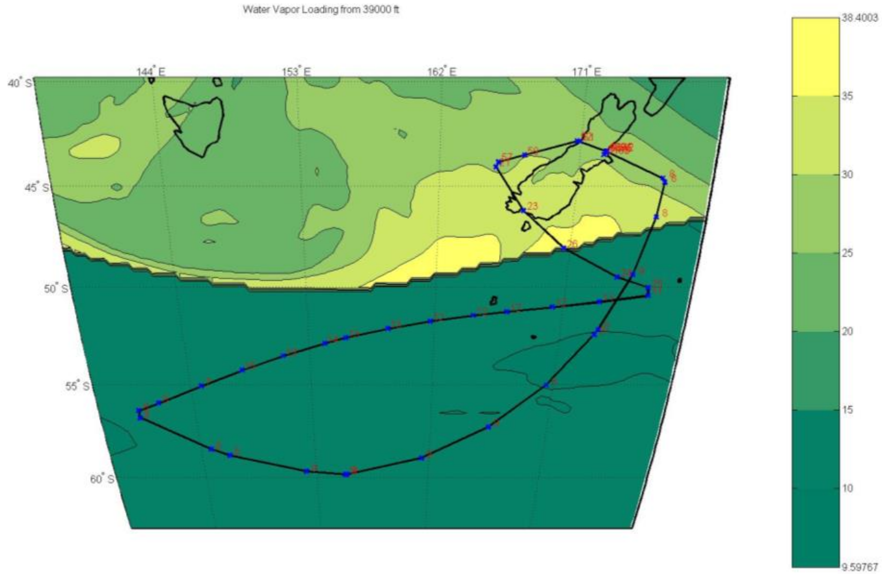


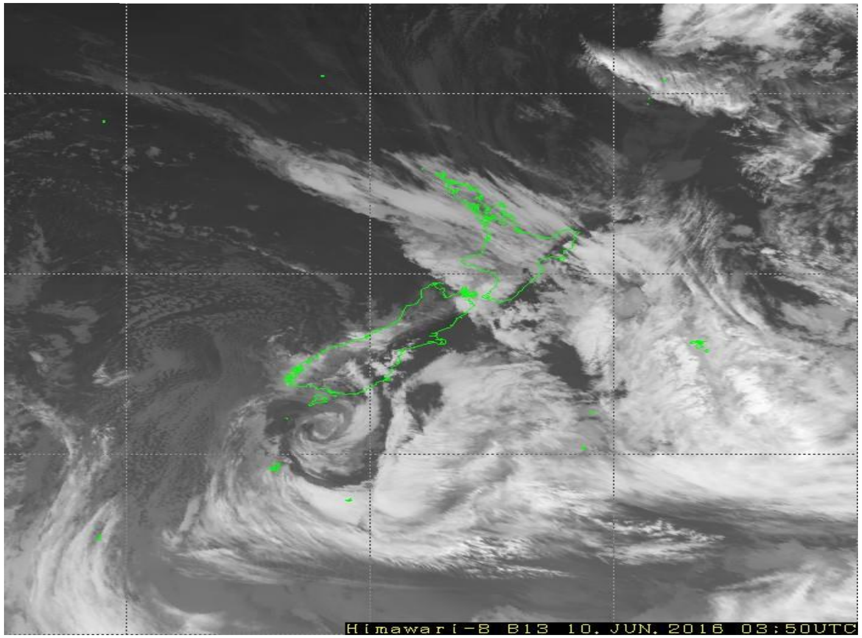
Data Comparison
Lidar vs GEOS 5



NASA Meteorology Group

- **Forecasts and courtesy briefings**
  - Winds, gusts, visibility, clouds, particulates, water vapor loading
- **Hazards**
  - Turbulence, icing, wind shear, T-storms, IFR conditions, mountain wave, lightning
- **Flight/project support**
  - Crew briefs, T-x briefings
  - Full-time in-flight weather monitoring
- **Best-Estimate-Atmosphere**
  - Trajectory analysis for atmospheric parameters
  - Airdata calibration
  - RVSM
- **Climatology**
  - Project planning studies
- **Real-time ground measurements**
  - Extensive weather station network
- **Mobile balloon launches**
  - Portable for project specific applications





Want more info:

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