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

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NASA Armstrong Flight Research Center , Edwards AFB, Edwards CA
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?
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.
Shaped Sonic Boom Demonstration Aircraft (SSBD)

Northrop–Grumman Corporation’s modified U.S. Navy F–5E Shaped Sonic Boom Demonstration (SSBD) aircraft.
X-29 in Flight from Above
Stratospheric Observatory for Infared Astronomy (SOFIA)
ERAST Helios
Phantom Eye Liquid H2
NASA’s IKHANA Predator B
Hypersonic Research  Mach 9.6 (7000mph)
Hypersonics


AHW 11/2011
Global Hawks
Global Hawk Flight Area for KQX Refueling

GH April 19, 2012 Flight, 00Z Forecast data for 18Z verification
Global Hawk “Poor Man’s Calibration”

GH April 19, 2012 Flight, 18Z verification

- Temperature, F
- Time, sec after Midnight

Legend:
- Model Temps
- GH OAT
- Latitude
Climatology

• Understanding the Atmosphere
  – Surface behavior
    • Seasonal vs time of day
      – Temperature
      – Winds
      – Precipitation
  – Upper Air profile
    • Seasonal
      – Temperature
      – Winds
      – Moisture
Tools of the Trade
High Altitude Lidar for Atmospheric Sensing (HALAS) Overview at NASA Armstrong
Testing Locations – NASA-Armstrong
UV LIDAR Technology Overview

1. Ultraviolet laser light is emitted and scatters off air molecules and aerosols.

2. Backscattered light is received with telescope and filtered to remove solar background.

3. Filtered backscatter is analyzed in comparison with laser reference using Fabry-Perot Interferometer and Raman channel.

4. Range-resolved, atmospheric parameters (wind speed/direction, temperature, density, water vapor, and mass fractions) are measured directly and simultaneously.

HALAS Overview
## Data Product Retrieval

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

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

![Graph showing the relationship between Doppler Shift and Signal Intensity](image)
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:
- \(\text{N}_2\): 2,331 cm\(^{-1}\)
- \(\text{O}_2\): 1,556 cm\(^{-1}\)
- \(\text{H}_2\text{O}\): 3,657 cm\(^{-1}\)

# Why HALAS vs Weather Balloons

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Balloon</th>
<th>HALAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement location</td>
<td>Dictated by the prevailing winds and ascent rate</td>
<td>Selectable</td>
</tr>
<tr>
<td>Timeliness of profile</td>
<td>Typically takes 1-2 hours to reach altitude and only provides single altitude per data point</td>
<td>Simultaneously provides full range profile in seconds to minutes (dependent on accuracy and range)</td>
</tr>
<tr>
<td>Data products</td>
<td>Winds, pressure, temperature and humidity (depends on radiosonde)</td>
<td>Winds, density, mass fraction (O₂, N₂ &amp; H₂O), temperature and humidity</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>Adequate uncertainty at low altitudes but suffer at high altitudes</td>
<td>Better uncertainty at higher altitudes. Comparable at lower elevations.</td>
</tr>
<tr>
<td>Environmental impact</td>
<td>Non-retrievable and not biodegradable</td>
<td>Only light is emitted from the system</td>
</tr>
<tr>
<td>Autonomous operation</td>
<td>Typically requires 1-2 people to launch and/or track a balloon</td>
<td>Can be made to run remotely with sufficient safety protocols</td>
</tr>
<tr>
<td>Operational coverage</td>
<td>Limited in number of profiles per day or night</td>
<td>Can run continuously 24/7</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>Dictated by hardware and ascent rate</td>
<td>Limited by detector update rate</td>
</tr>
<tr>
<td>Operational constraint</td>
<td>Land or sea-based. Can operate in adverse weather.</td>
<td>Land-and aircraft based (upon completion of Phase 3). Limited by heavy cloud cover from land.</td>
</tr>
</tbody>
</table>
Representative High Altitude Density

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

The 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

<table>
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<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date/time (UTC)</td>
<td></td>
</tr>
<tr>
<td>Azimuth/Elevation</td>
<td>(45,90,135,180,225)° /45°</td>
</tr>
<tr>
<td>Integration time</td>
<td>2 min/azimuth</td>
</tr>
<tr>
<td>Balloon launch (UTC)</td>
<td></td>
</tr>
<tr>
<td>Balloon distance; max altitude</td>
<td>170.6km; 32km (559,711ft; 104,987ft)</td>
</tr>
<tr>
<td>CCD gain</td>
<td>200</td>
</tr>
<tr>
<td>CCD shift rate</td>
<td>500ns</td>
</tr>
<tr>
<td>Laser power</td>
<td>11.5W</td>
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**Average is over 20 Azimuthal views (40 min total)**

Wind speed over altitude [m]

Wind direction over altitude [m]

Scan area: 27km

3D balloon track
Representative Density

Plot shows the relative difference between the balloon and the HALAS data, not uncertainty.
Representative Wind Speed/Direction

<table>
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<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date/time (UTC)</td>
<td>3/6/2015 (20:44)</td>
</tr>
<tr>
<td>Azimuth/Elevation</td>
<td>$(0, 90, 180, 270)^\circ / 65^\circ$</td>
</tr>
<tr>
<td>Integration time</td>
<td>6 min/azm</td>
</tr>
<tr>
<td>Balloon launch (UTC)</td>
<td>3/6/2015 21:00AF</td>
</tr>
<tr>
<td>Balloon distance / max altitude</td>
<td>37mi (estimate)/ 82,100ft</td>
</tr>
<tr>
<td>CCD gain</td>
<td>95</td>
</tr>
<tr>
<td>CCD shift rate</td>
<td>500ns</td>
</tr>
<tr>
<td>Laser power</td>
<td>11.2W</td>
</tr>
</tbody>
</table>

- 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 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

- 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

1. Outer window
2. Receive telescope
3. Laser head
4. Dome mounting plate
5. Raman channel
6. Interferometer
7. Laser electronics
8. Laser chiller
9. Processing electronics
10. Control electronics

Pressurized compartment
Fiber optic
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 and Rawinsonde Data for Darkstar Flt 1
June 29, 1998 Flight

Altitude, ft MSL

0229 Balloon Data
0500 Balloon Data 2 sec
0500 SODAR Data
0500 Surface wind

Speed, kts
SODAR/Rawinsonde Comparisons

SODAR and Rawinsonde Data for Darkstar Flt 1
June 29, 1998 Flight

- 0229 Balloon Data
- 0500 Balloon Data
- 0500 SODAR Data

Altitude, ft MSL

Direction, deg
SODAR Profile Trends

SODAR Data for Darkstar Flight
June 29, 1998 0600-0625

Altitude, ft AGL

Wind Speed, kts

Graph showing trends in wind speed and altitude for the specified flight period.
SODAR Profile Trends (cont.)

SODAR Data for Darkstar Flight
June 29, 1998 0625-0650

Altitude, ft AGL

Wind speed, kts

0 5 10 15 20 25

0 500 1000 1500 2000 2500
Morning Wind Profile
Afternoon Wind Profile
AM Facsimile Profile
Pathfinder Plus

Shear line
Convective plume
Convective plume

27 June, 1998 At PMRF4000
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
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


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 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

Temperature (K)

Altitude, m

SABER T
GEOS T

12Z Apr 22
Data Comparison
Lidar vs GEOS 5

Temperature (K)

Altitude, m

06Z Apr 21
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
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