united nations educational, scientific and cultural organization

international atomic energy agency

the
abdus salam
international centre for theoretical physics

SMR/1328/2 bis

School on the Physics of Equatorial Atmosphere

(24 September - 5 October 2001)

Appendix to

Observational Techniques

R. A. Vincent
(University of Adelaide)

strada costiera, 11 - 34014 trieste italy - tel. +39 040 2240111 fax +39 040 224163 - sci_info@ictp.trieste.it - www.ictp.trieste.it

Observational Techniques

International School on the

Physics of the Equatorial Atmosphere and Ionosphere

ICTP Trieste

September 2001

R. A. Vincent

Adelaide University

Techniques

- In-situ
  - Balloon-borne radiosondes
  - Rockets
- Ground-based
  - Radar
  - Lidar
- Satellite

Radiosondes

- Radiosondes are the primary means by which information on the thermal and dynamical state of the atmosphere up to heights near 30 km is obtained.
- Weather agencies usually make observations twice a day at 0000 UTC and 1200 UTC.
- The radiosonde is a balloon-borne package that makes observations of temperature, humidity, and pressure. The information is telemetered regularly to a ground receiving station using an onboard radio transmitter. The sonde, which is approximately the size of a shoe-box, is suspended some distance below the balloon to reduce the effects of the wake as the balloon ascends. Winds can also be measured if the position of the radiosonde can be tracked in some way.

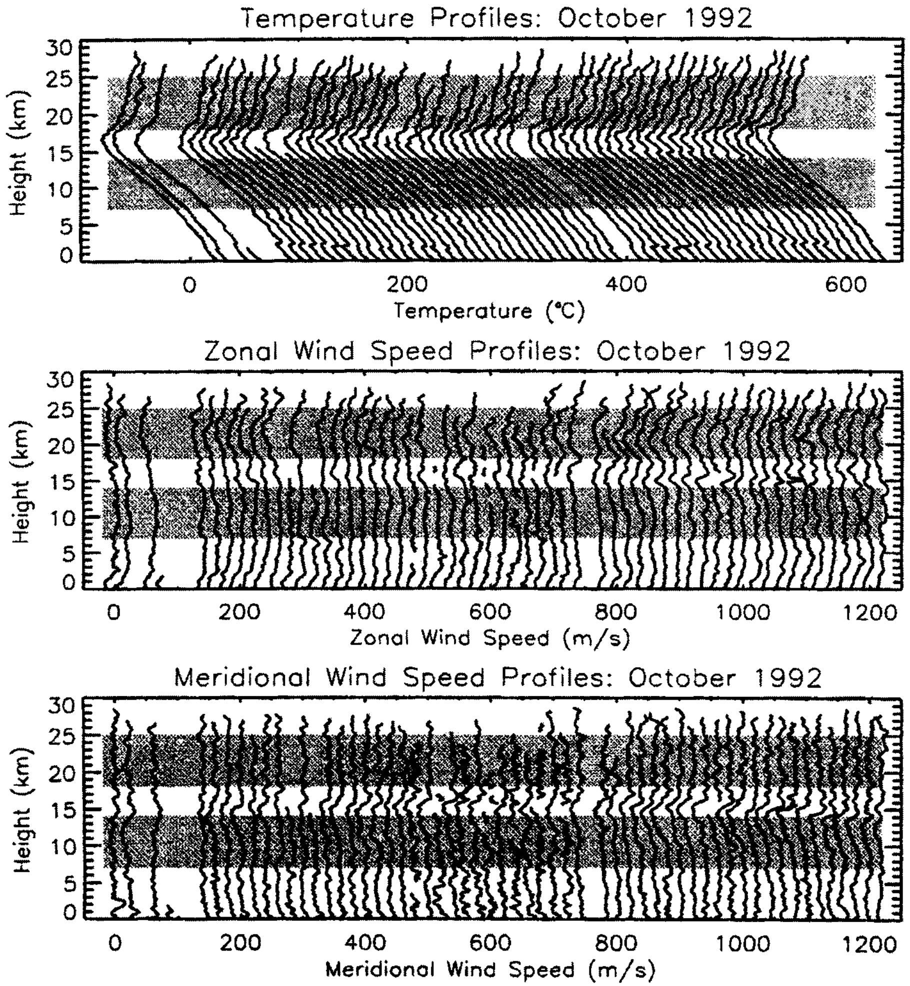
Example: Vaisala RS-80 radiosonde package

Temperature sensor external to package

- Package hangs well below balloon to avoid wake effects
- Measures T, T_d (humidity), and p
- Winds measured either by radar tracking or by measurements of position by GPS or LORAN navigation signals

Releasing balloons requires careful technique!

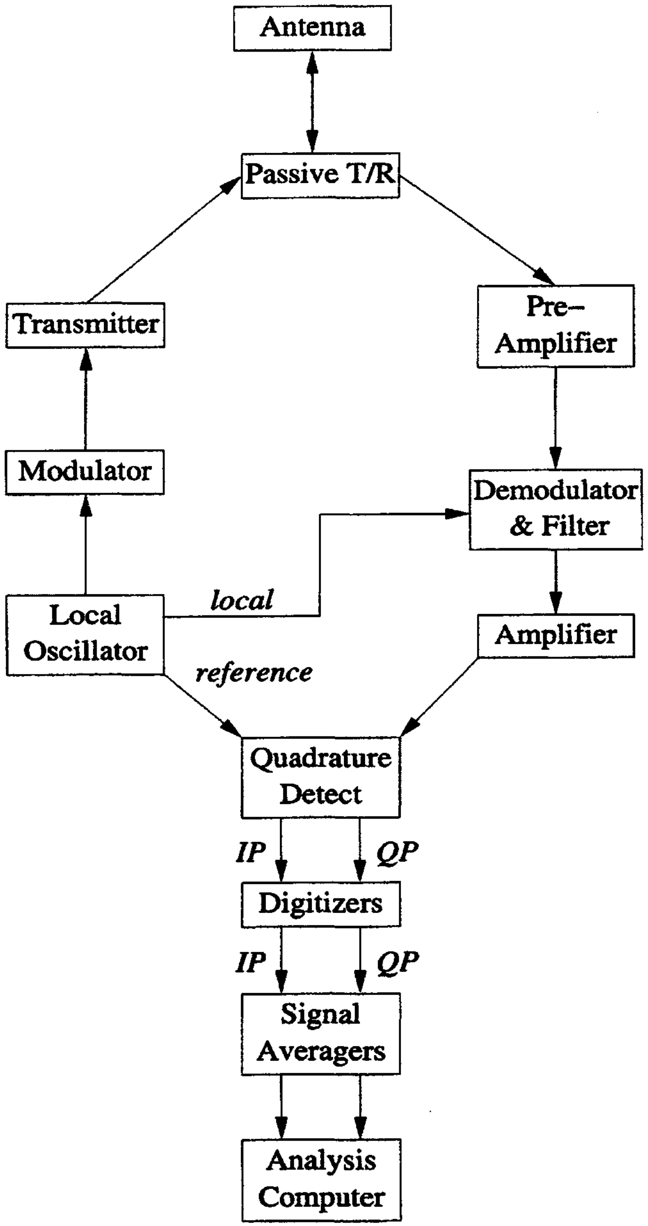
Radiosondes: Example



- **Routine soundings from Cocos Islands (12°S, 97°E)**
- **High and cold tropopause at 17 km**
- **Some balloons fail to penetrate the tropopause due to icing**
- **Important resource for studies of equatorially-trapped waves (Kelvin, Rossby-gravity) and gravity waves**

Atmospheric Radars

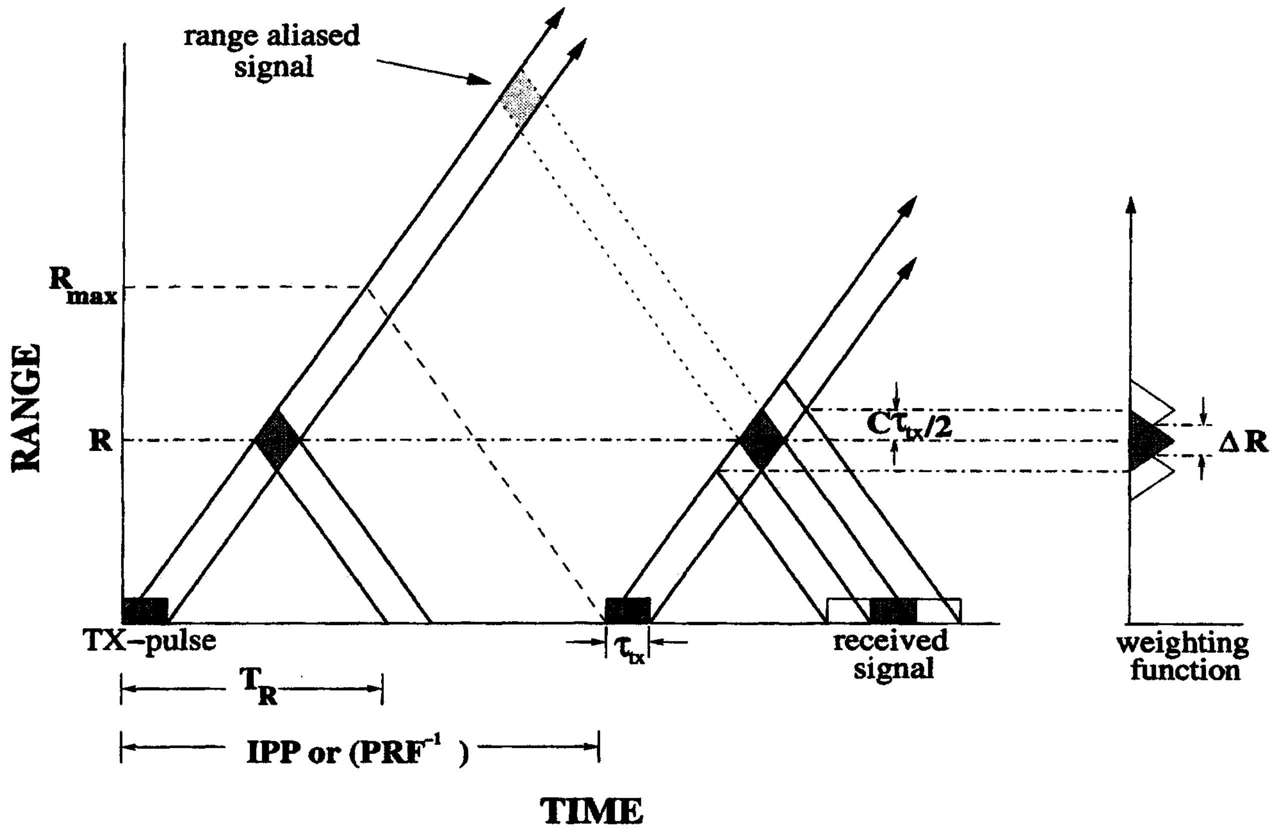
- Medium frequency (MF) partial reflection radars
  - Frequency ~2-3 MHz
  - Winds ~65-100 km (day)
  - Winds ~80-100 km (night)
- Meteor radars
  - Frequency ~30-50 MHz
  - Winds ~80 – 105 km
- Mesosphere-Stratosphere-Troposphere (MST) radars
  - Frequency ~50 MHz (VHF)
  - Winds ~2-20 km
  - Winds ~60-80 km (day)
- Incoherent Scatter radars (ISR)
  - Frequency 430 MHz (UHF)
    - Arecibo is only ISR at tropical latitudes



Radar Fundamentals

- Master oscillator
- High-power transmitter
- Antenna(s)
- Low-noise receiver
- Amplifier
- Complex (amplitude and phase) receivers
- Digitisers, signal averagers
- Digital storage and analysis
- Pulse operation

Pulsed Radar Operation



- **Range determined by time-of-flight of pulse, $R=cT_R/2$**
- **Range resolution, $\Delta R = c\ \tau_{Tx}/2$**

Radar Scattering

- Echoes come from vertical gradients in refractive index of air, n
- For frequencies > 30 MHz:

$$n = 1 + 0.373\frac{e}{T^2} + 77.6 \cdot 10^{-6}\frac{p}{T} - 40.3\frac{N_e}{f^2}$$

- Require fluctuations in
  - Humidity, e
  - Temperature, T
  - Electron density, N_e
- Scale of of fluctuations or irregularities ~λ/2
  - ~3 m at 50 MHz and ~75 m at 2 MHz

Radar Scattering

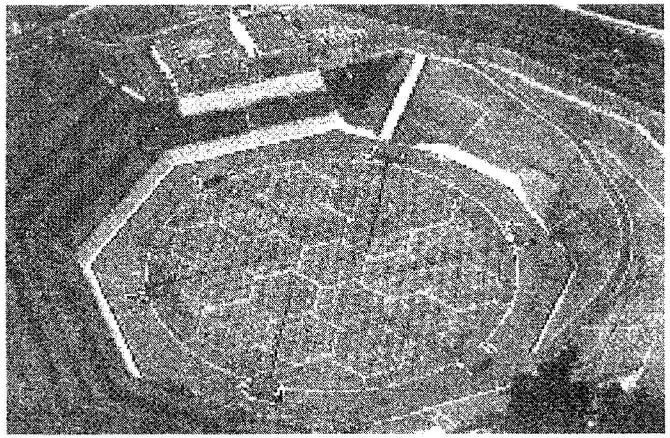
- **Nature of irregularities not well known**
  - **Isotropic turbulence** → $$P_r = \frac{\pi P A \alpha \Delta R}{64 R^2}\eta \quad \text{(Volume scatter)}$$
  - **Sharp steps ("Fresnel irregularities")** → $$P_r = \frac{P A^2 \alpha}{4\lambda^2 R^2}|\rho|^2 \quad \text{(Fresnel reflection)}$$

- **Strength of scatter depends on strength of turbulence,** η
- *PA* **is a "figure of merit" for a radar**
  - *P* **is average transmitted power**
  - *A* **is antenna area**

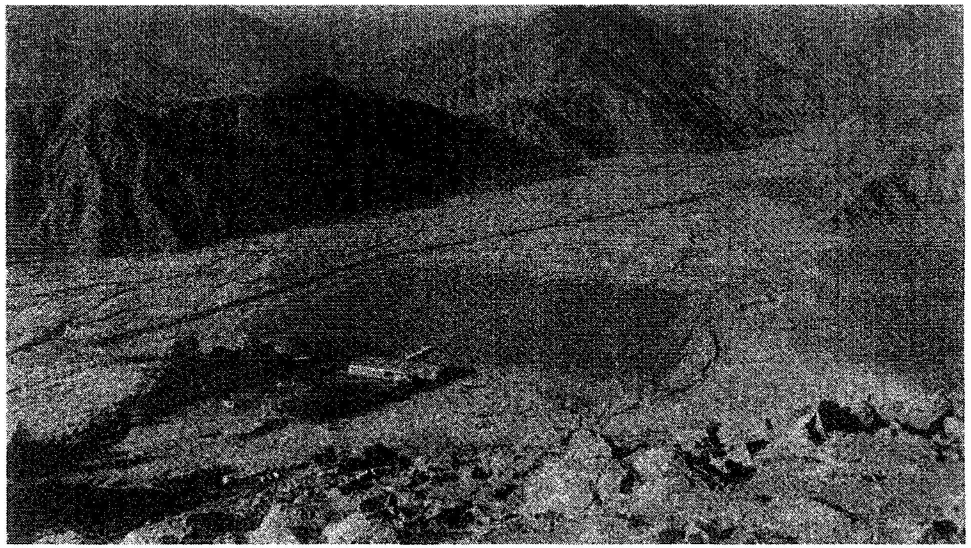
MST Radars

Equatorial Atmospheric Radar (EAR)
Sumatra, Indonesia (0°)

Versatile systems for studying atmospheric dynamics with excellent time and height resolution

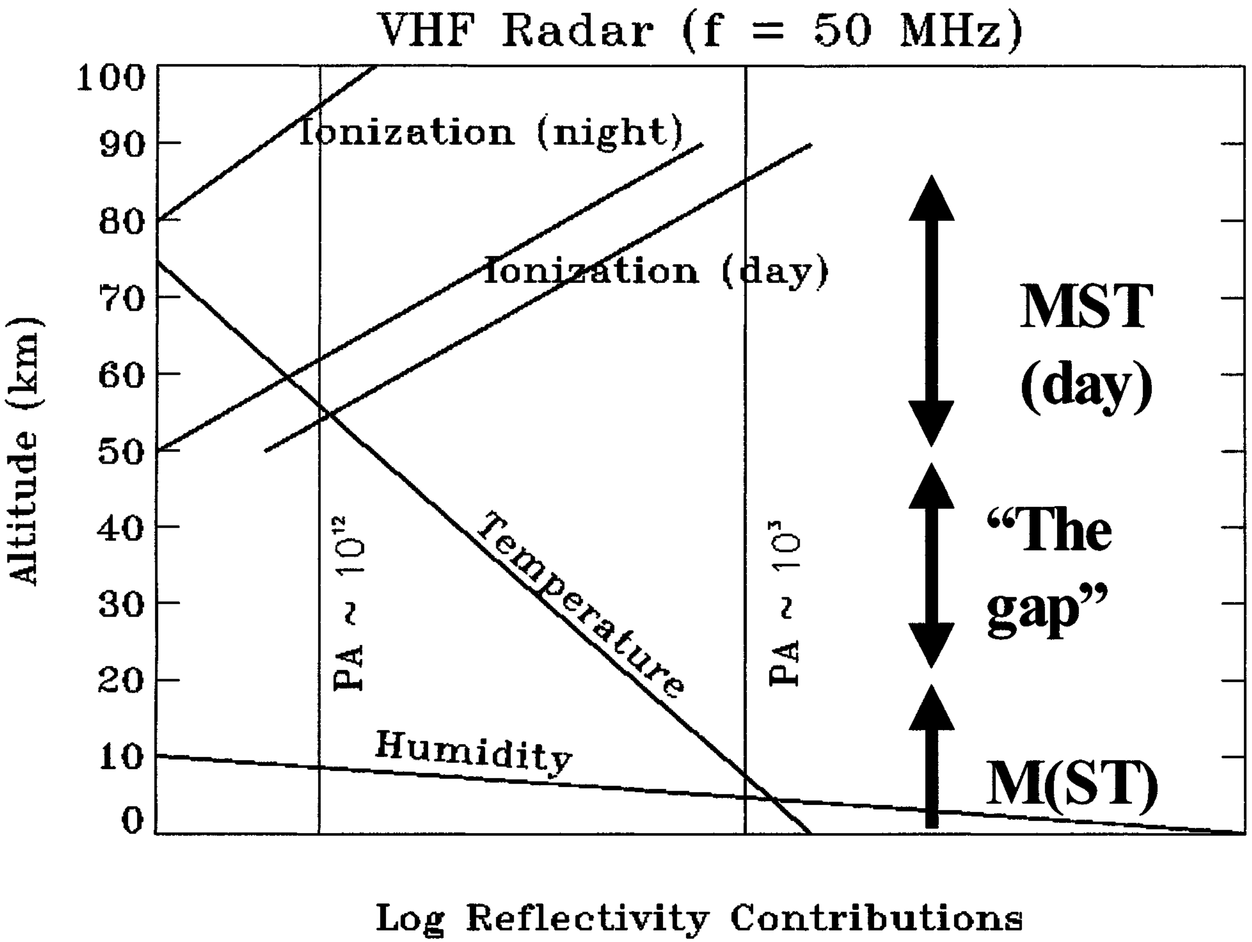


MU radar, Kyoto, Japan (35°N)

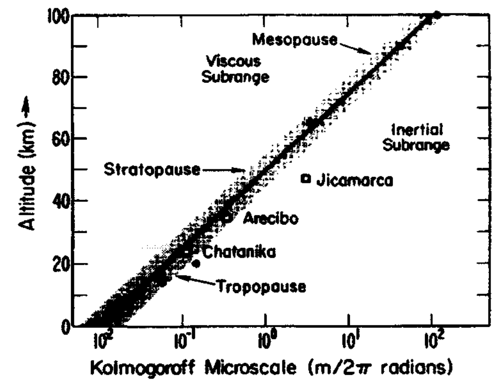


Jicamarca Observatory, Peru (12°S)

Performance of MST Radars

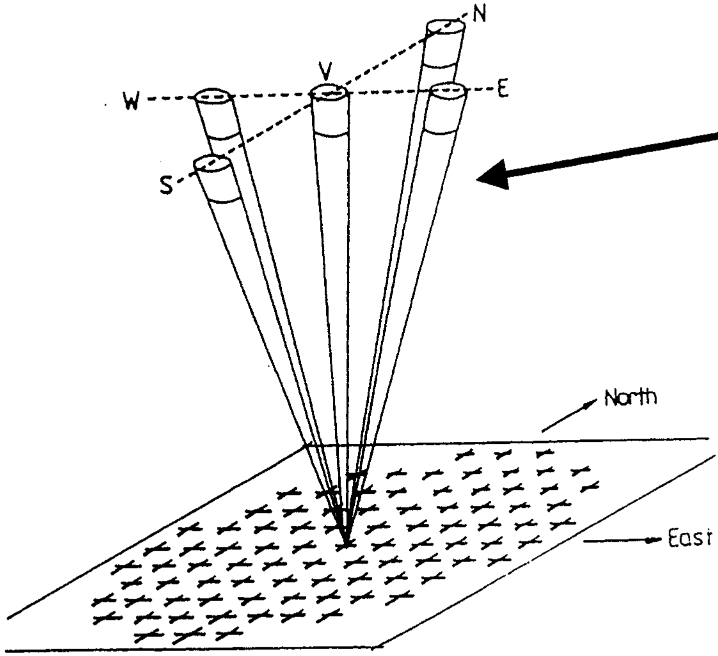


- For good height coverage need:
  - Large PA product
  - Strong turbulence
- Mesospheric scattering intermittent in time and space

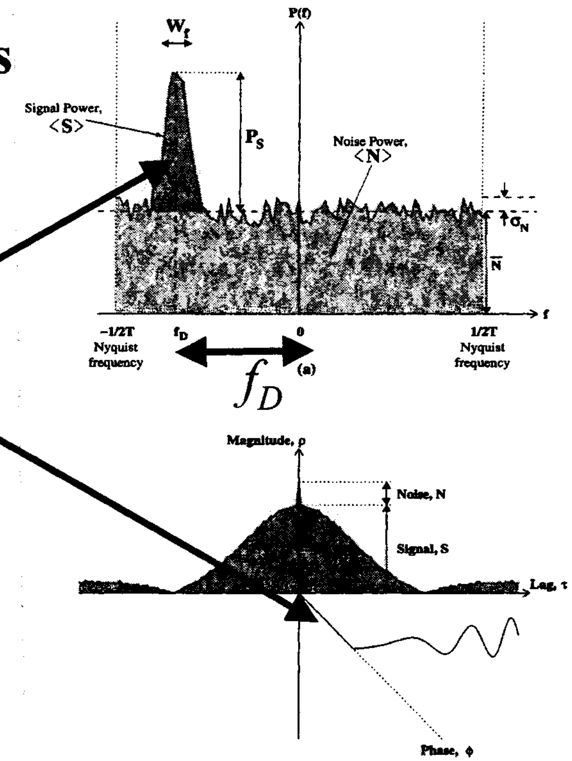


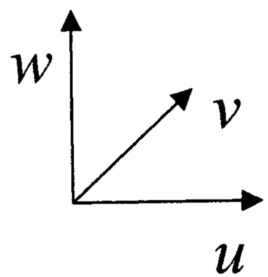
Intense turbulence required to generate mesospheric irregularities

Doppler Winds



- Phase antennas to point beams in different directions
- Measure Doppler shift of returned echoes to measure radial velocity, v_r
- Spectral widths provide information about strength of turbulence





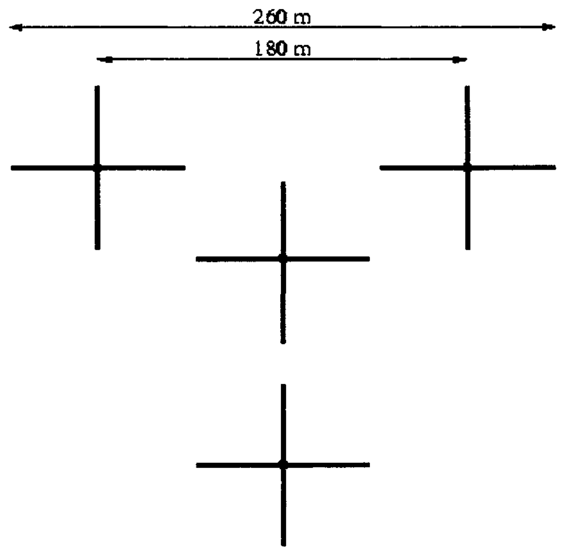
$$v_r = -\frac{\lambda}{2} f_D$$

$$v_r = u \sin\phi \sin\theta + v \cos\phi \sin\theta + w \cos\theta$$

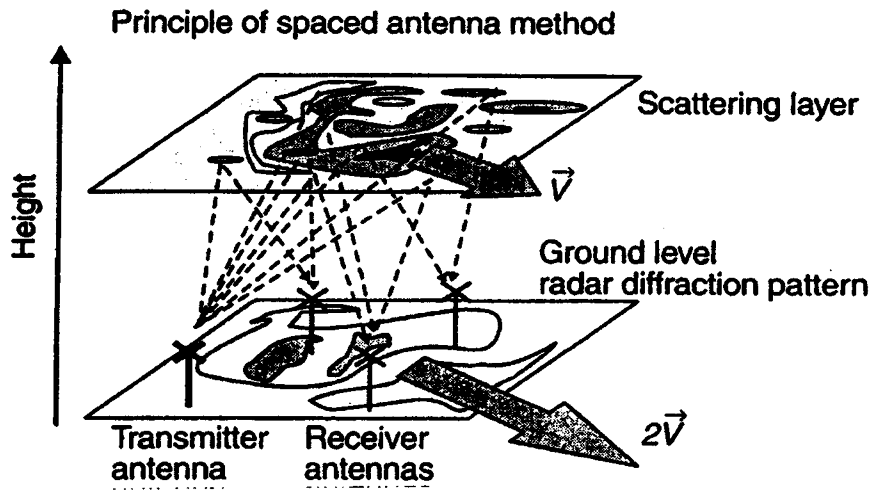
where $U = (u, v, w)$

MF Radars I

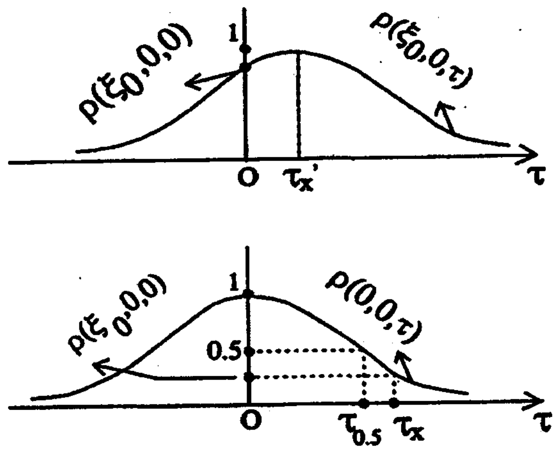
- **Strengths**
  - Moderate to good range and time resolution
    - range ~ 2 - 4 km
    - time ~ 2 - 5 min
  - Good height coverage
    - 60 - 100 km (day)
    - 80 - 100 km (night)
  - Low power, inexpensive to set up and run
  - Reliable continuous operation
- Use spaced-antenna technique to determine wind velocity
  - Measure motion of diffraction pattern across ground by sampling at 3 spaced antennas
- Measurement of turbulence motions



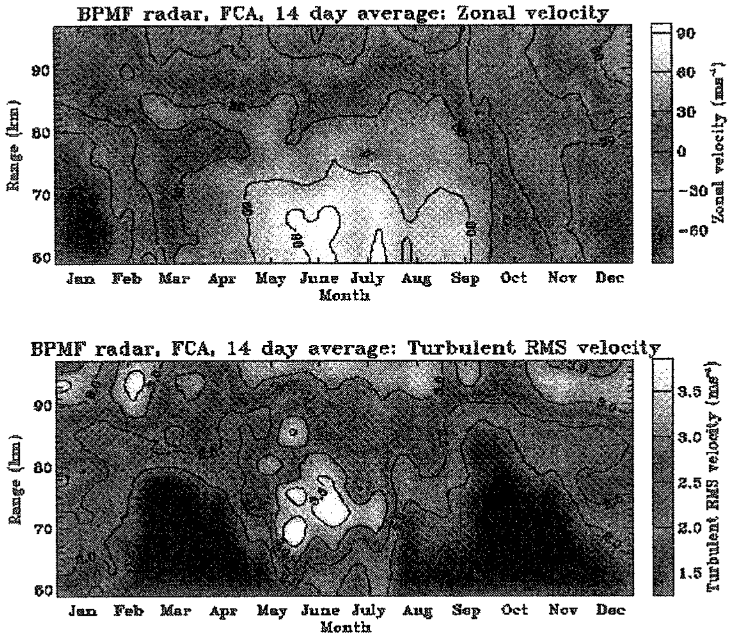
Typical antenna layout



(After Hocking, 1997)



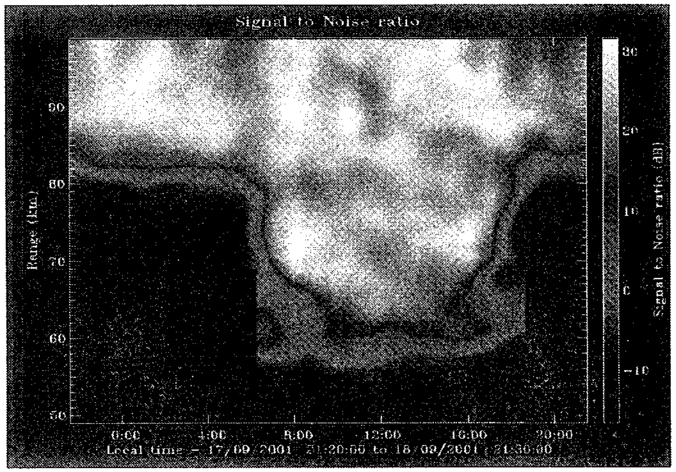
Correlation analysis (After Briggs, 1984)



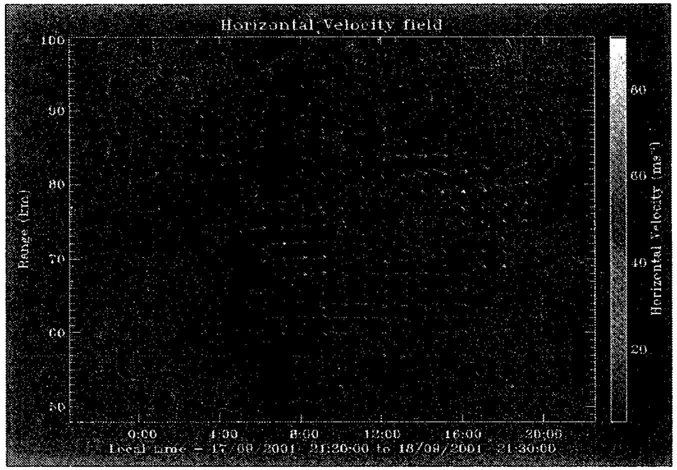
MF radar observations, Adelaide, 1999

Limitations

- Small antennas, wide beams. This means that height resolution can degrade if angular scatter is wide (> 10 deg)
- Total reflection occurs near 100 km at MF. This represents an upper limit to the technique during daytime
- Group retardation near midday causes incorrect heights to be measured above about 95 km

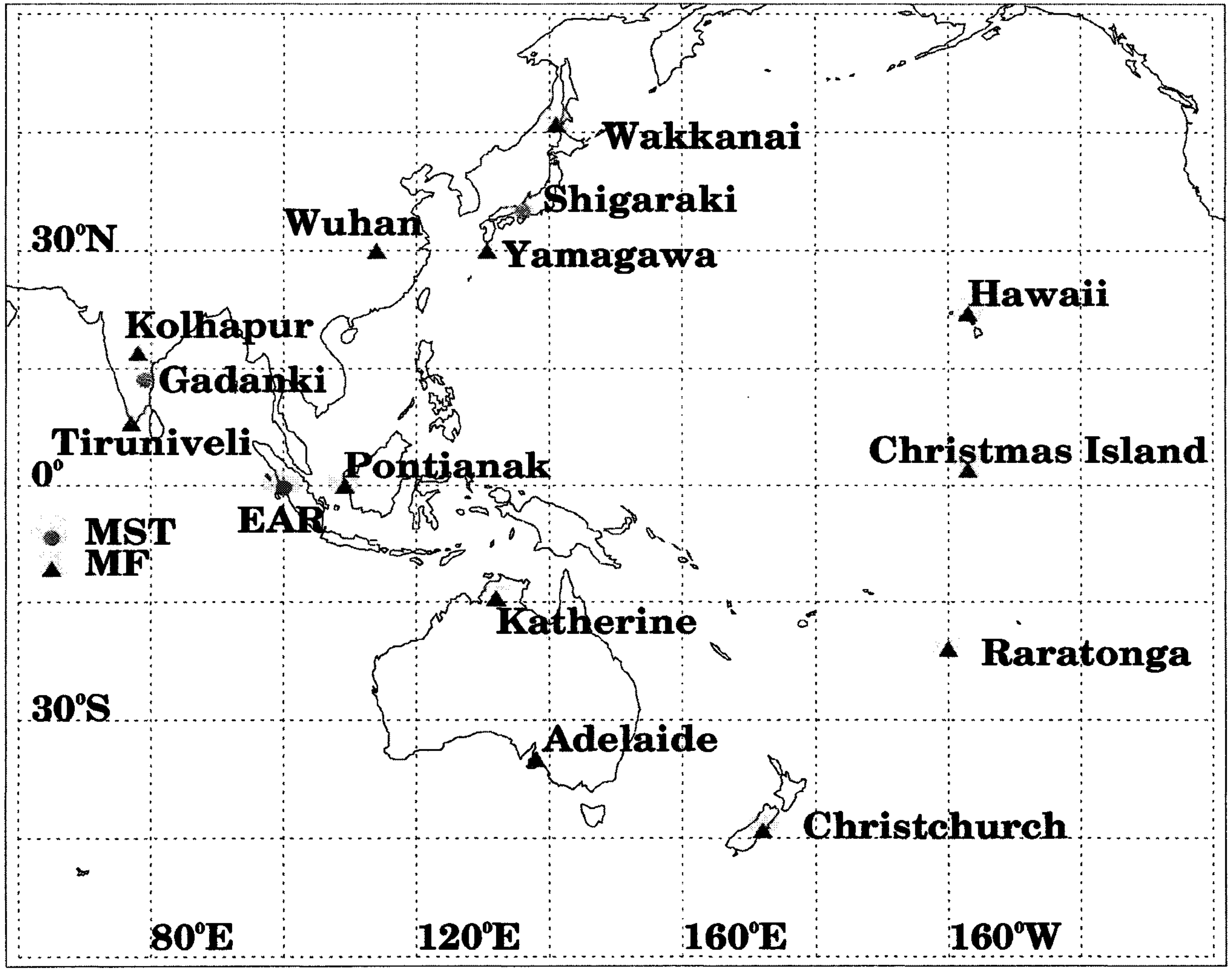


SNR 18/9/2001



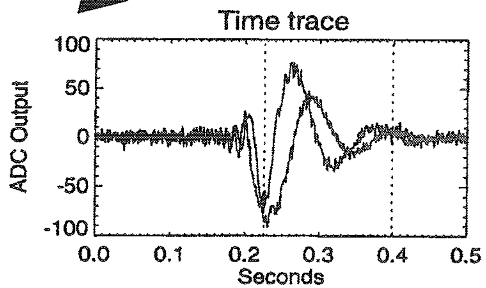
Winds 18/9/2001

Asia/Pacific Radar Network

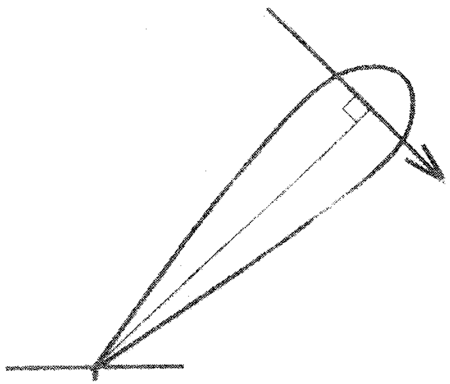


Meteor Techniques I

- Frequency ~30-50 MHz
- Reflections from randomly occurring meteor trails
- Two techniques:
  - broad-beam method with interferometer to locate meteor
  - Narrow-beam radar (often ST radar)
- Line-of-sight velocities measured from Doppler shift of trail

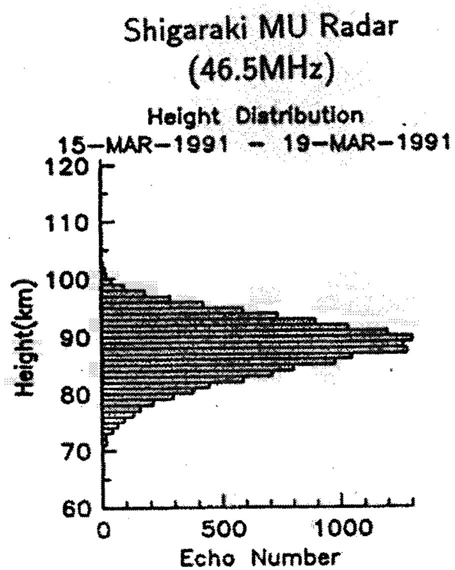


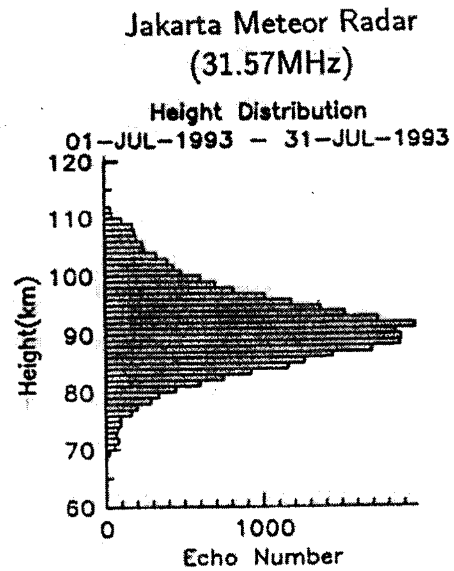
Transverse or specular meteor

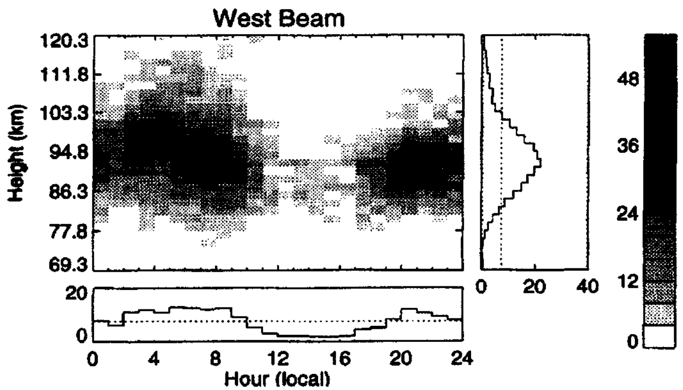


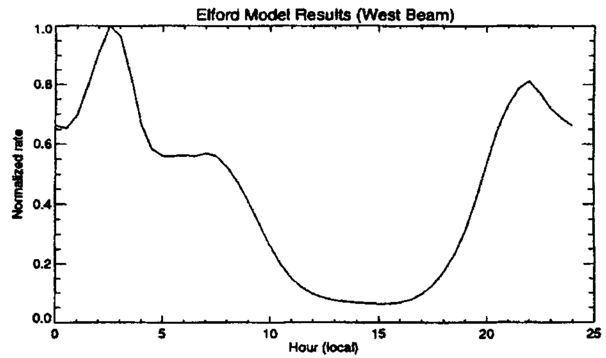
Meteors II

- **Strengths**
  - Reliable
  - 24-h observations
  - Continuous long-term observations for long period winds and tides
  - It is possible to infer T'/T from the diffusion of the trails
- **Limitations**
  - Large diurnal variation of echoes
  - Large spatial average
  - Height coverage 80 - 105 km
  - Low echo rates (~500 - 1000 day)



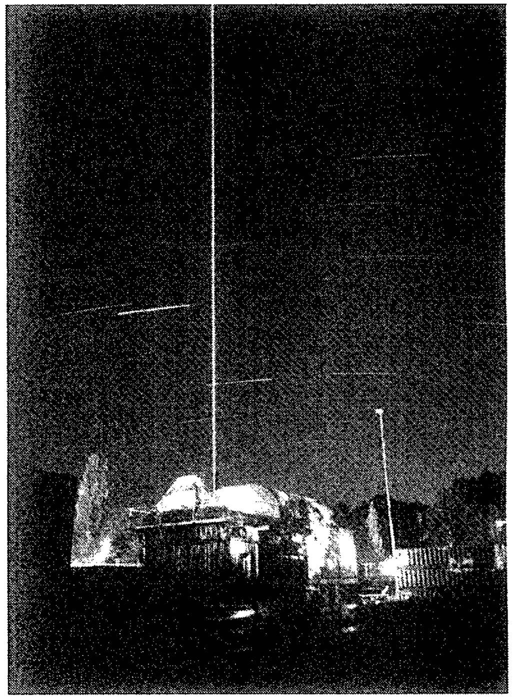






Lidar Techniques

- Rayleigh-scatter lidars are becoming a powerful tool for measuring density of neutral atmosphere
  - Vertical laser transmission
  - Telescope for reception
  - Narrow-band filter to remove unwanted light
  - Photon detection and counting
- Rayleigh scattering dominates above ~30 km, where aerosol (Mie) scattering is negligible



Number of photons received

Number of photons transmitted

Collecting area

Transmissivity of atmosphere

$$N(z) = \frac{N_o A \varepsilon \Im(0,z)}{4\pi z^2} n_o(z) \beta_R \Delta z$$

Pulse length

Number density of atmospheric molecules

Scattering cross-section

Lidar equation

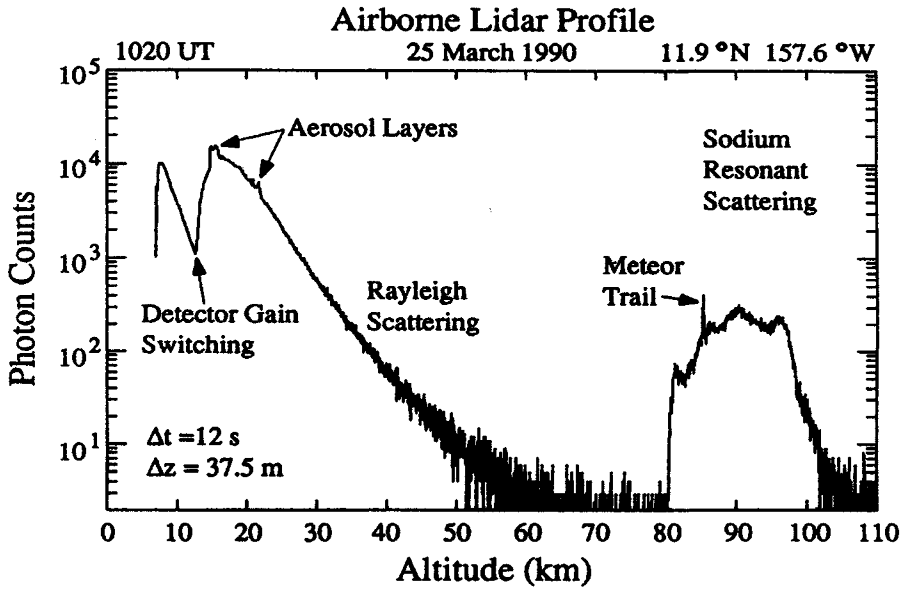
Lidar Density

- **Invert lidar equation to solve for neutral density**

$$\rho(z) = N(z)K\frac{z^2}{\Delta z}\Im^{-1} - n_n(z)$$

- **System constant, *K*, usually unknown**
- **Need to calibrate with independent estimate of ρ. Usually derived from nearby radiosonde observation**

Resonant scattering from sodium atoms is important technique for studying 80-105 km region

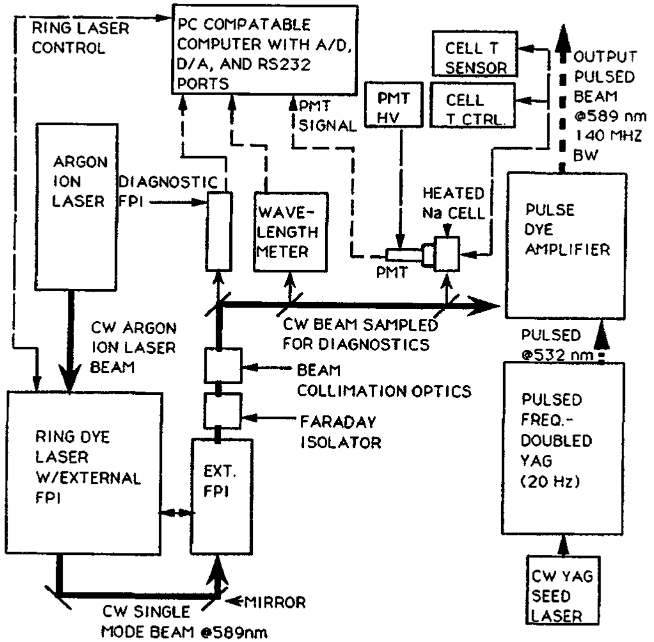


Na lidar observations

Lidar Temperatures

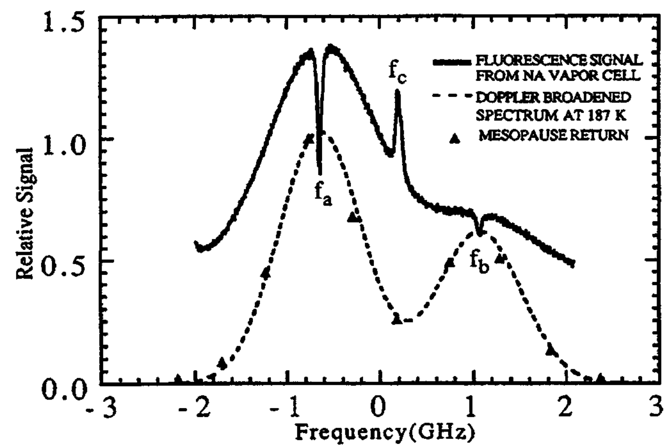
- **Convert density to temperature via eqn of state and hydrostatic relation**
- **Make an initial guess for T_1 at *top of atmosphere* and integrate down in height**

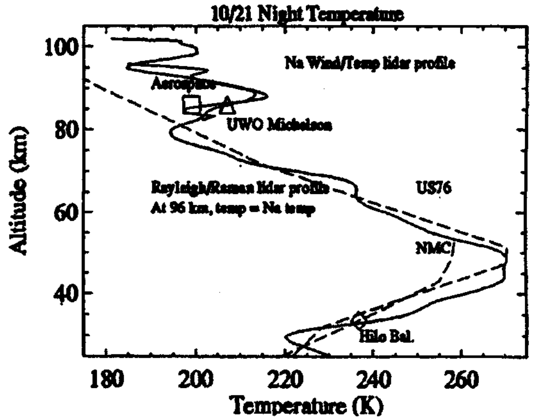
$$T(z) = \frac{\rho_1 T_1 + \frac{Mg}{R}\int_{z_1}^{z} \rho\, dz}{\rho(z)}$$

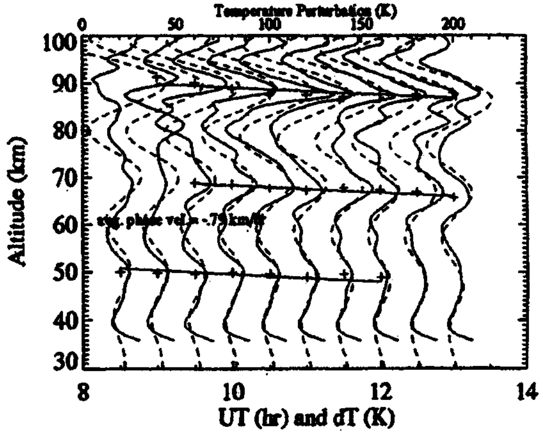


Na temperature lidar

(She et al, 1990)



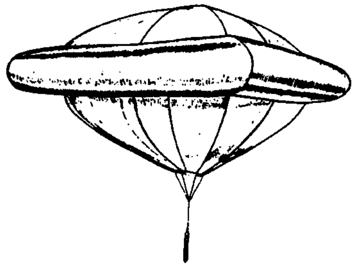




Examples from Hawaii during ALOHA-93

Rocket Techniques

- Important early source of information on tropical middle atmosphere from Meteorological Rocket Network (MRN)
- Dropsondes are instrumented package similar to radiosonde that are carried to 60-80 km by small rocket and released
  - Fall is stabilised and slowed with aid of parachute
  - Temperature and pressure information telemetered to ground
  - Radar tracking gives winds
- Falling Spheres are spheres inflated to ~1m diameter and released at heights > 100 km.
- Accelerations tracked by high-precision radars
- Atmospheric density derived from acceleration and known drag coefficients
- Temperatures derived from densities as for Rayleigh lidars
- Winds derived from horizontal accelerations



US Datasonde

Advantages:

Reliable

Accurate

Limitations:

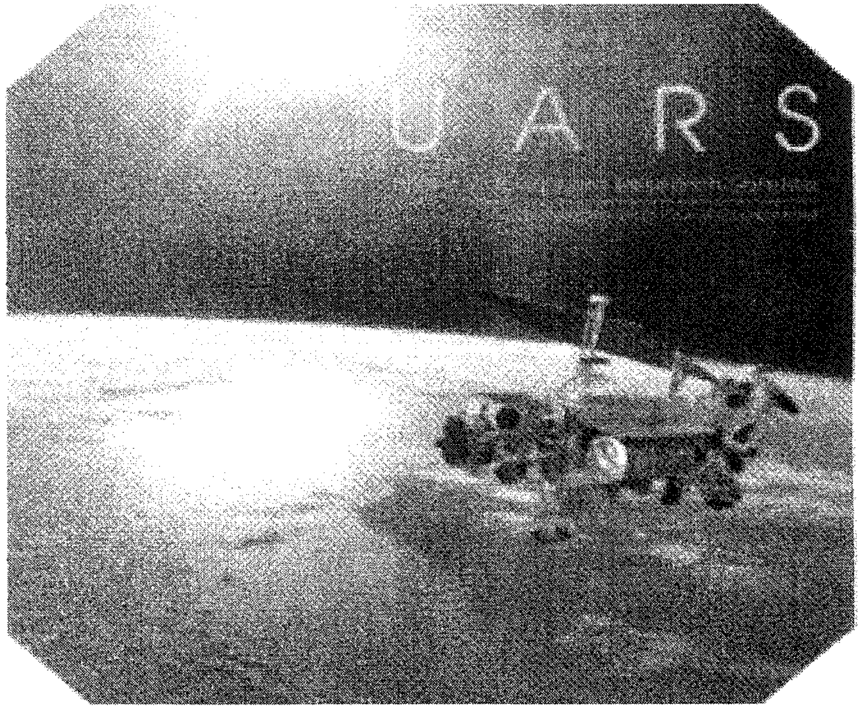
Expensive

Infrequent

(campaign basis)

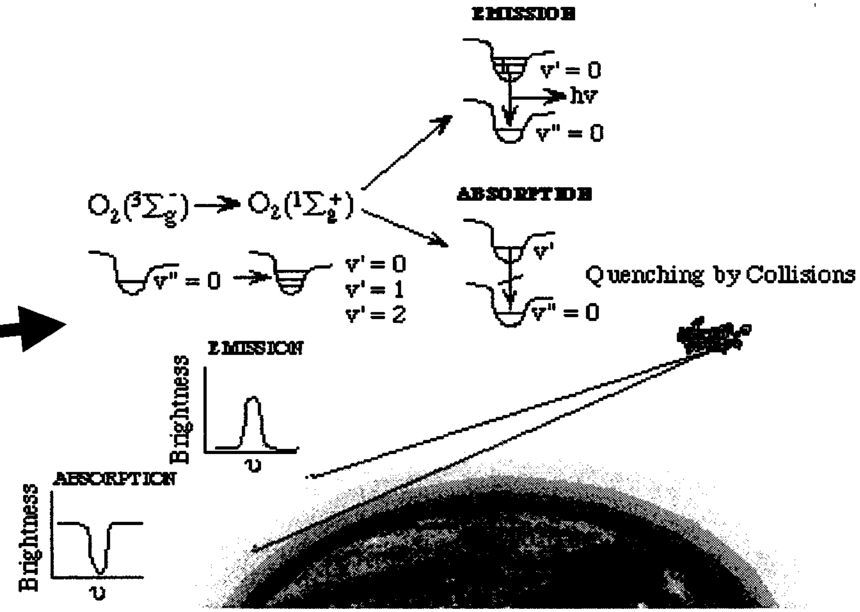
Satellite Techniques

- The satellite was launched in 1991 by the Space Shuttle Discovery.
- 35 feet long, 15 feet in diameter, weighs 13,000 pounds, and carries 10 instruments.
- Orbits at an altitude of 375 miles with an orbital inclination of 57 degrees
- UARS measures:
  - ozone and chemical compounds
  - Winds and temperatures in the stratosphere as well as the mesosphere
  - energy input from the Sun.

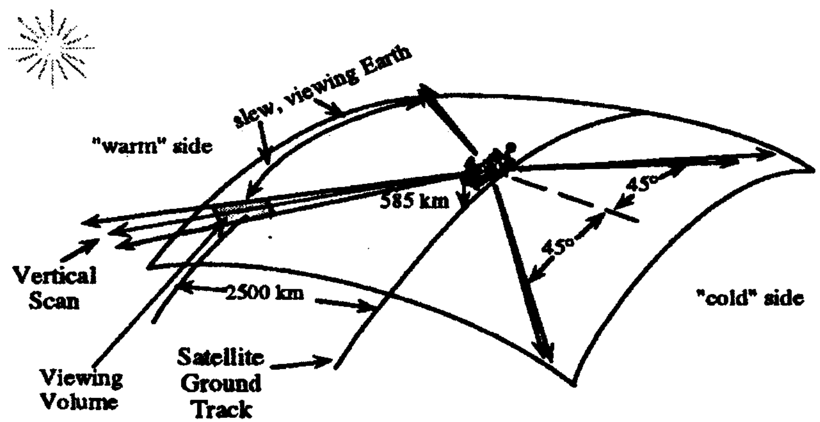


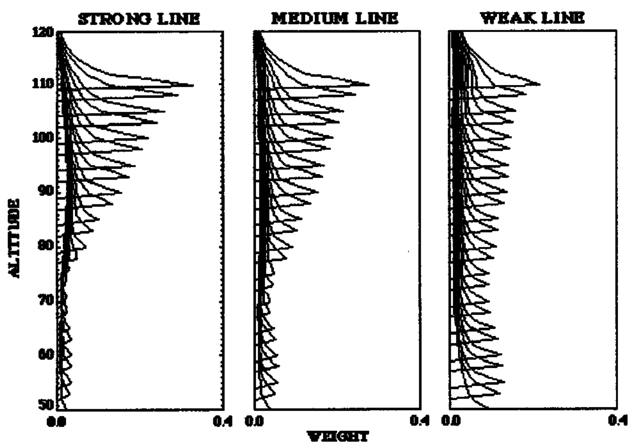
HRDI

- Limb-viewing Fabry-Perot instrument
- Measures Doppler shift of airglow emission and absorption lines
- Two views of same volume at 90° to UARS gives velocity
- Vertical resolution ~2-3 km
- ~60-120 km (MLT mode)
- ~10-40 km (stratospheric mode)

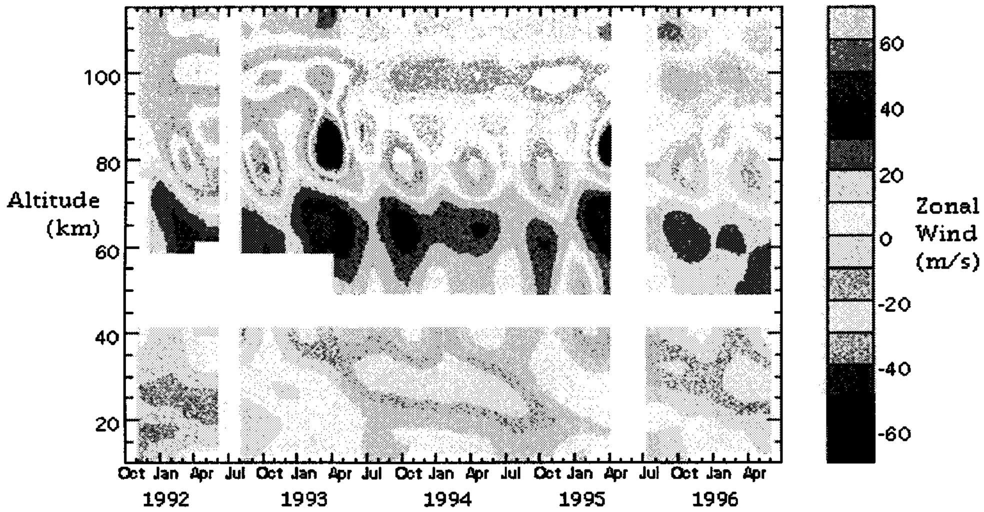


HRDI / UARS Measurement Schematic

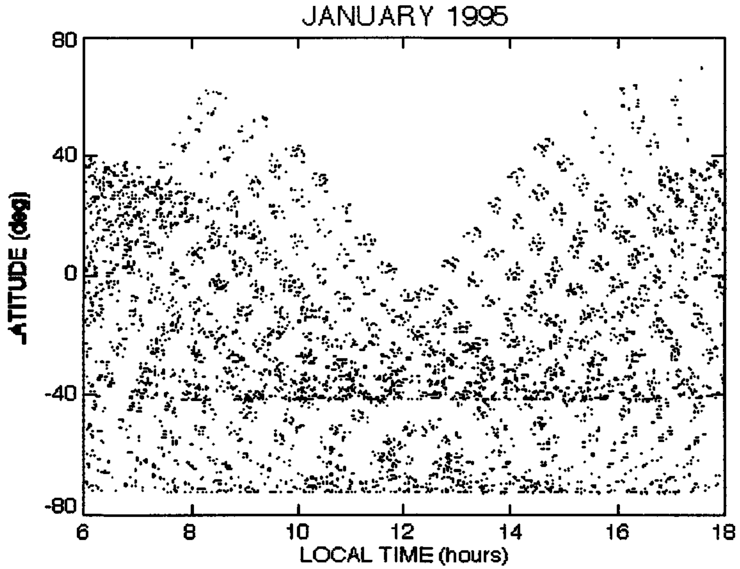




HRDI WINDS



Monthly-mean zonal winds

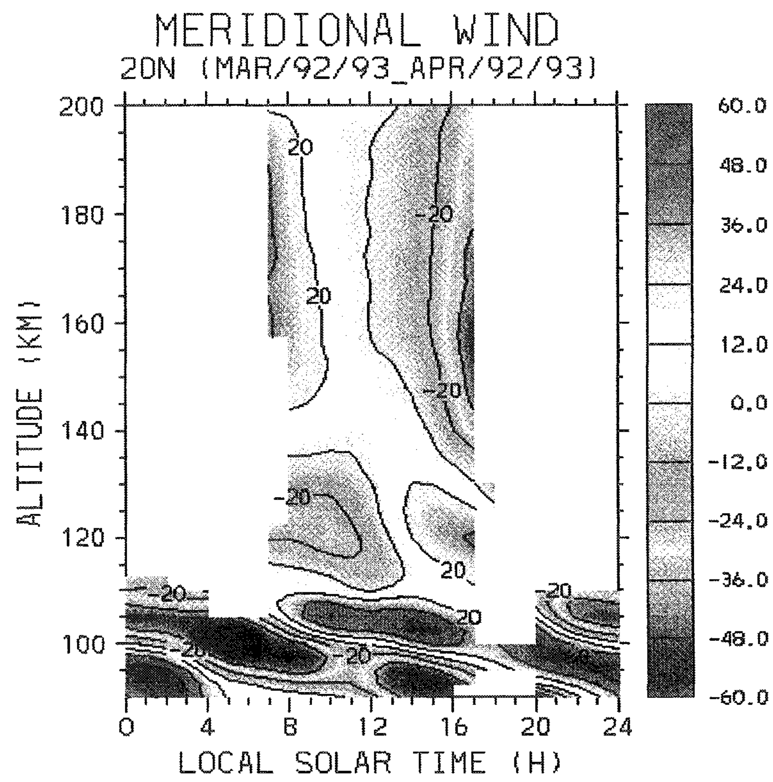


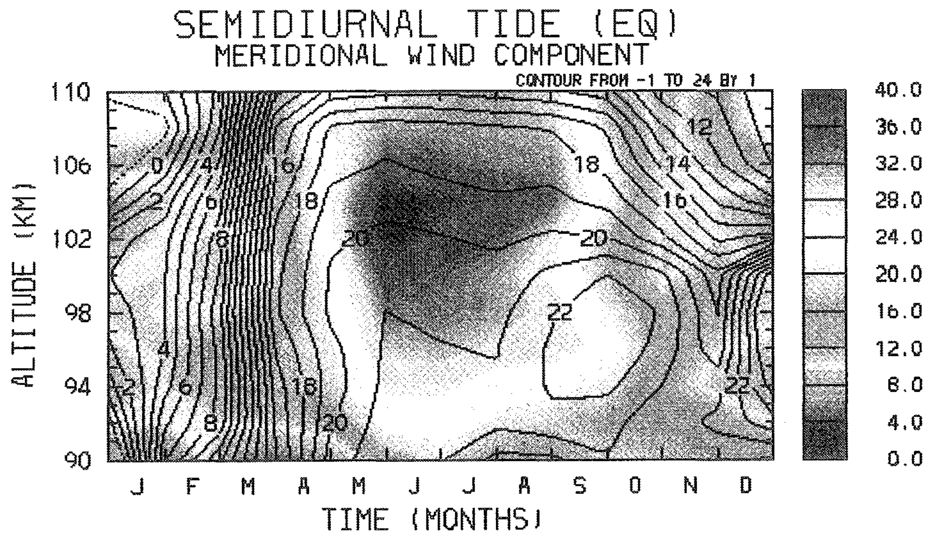
- **Strengths**
  - **Global coverage**
  - **Large height range**
  - **Good height resolution**
- **Weaknesses**
  - **Limb-viewing means horizontal resolution ~200 km**
  - **Slow precession of UARS limits latitudinal coverage**
  - **Limited local time coverage**

Local time coverage as a function of latitude for January 1995.

WINDII

- Uses Michelson interferometer to measure Doppler shifts of airglow emissions.
- Coverage from ~90 –200+ km
- Similar strengths and weaknesses to HRDI



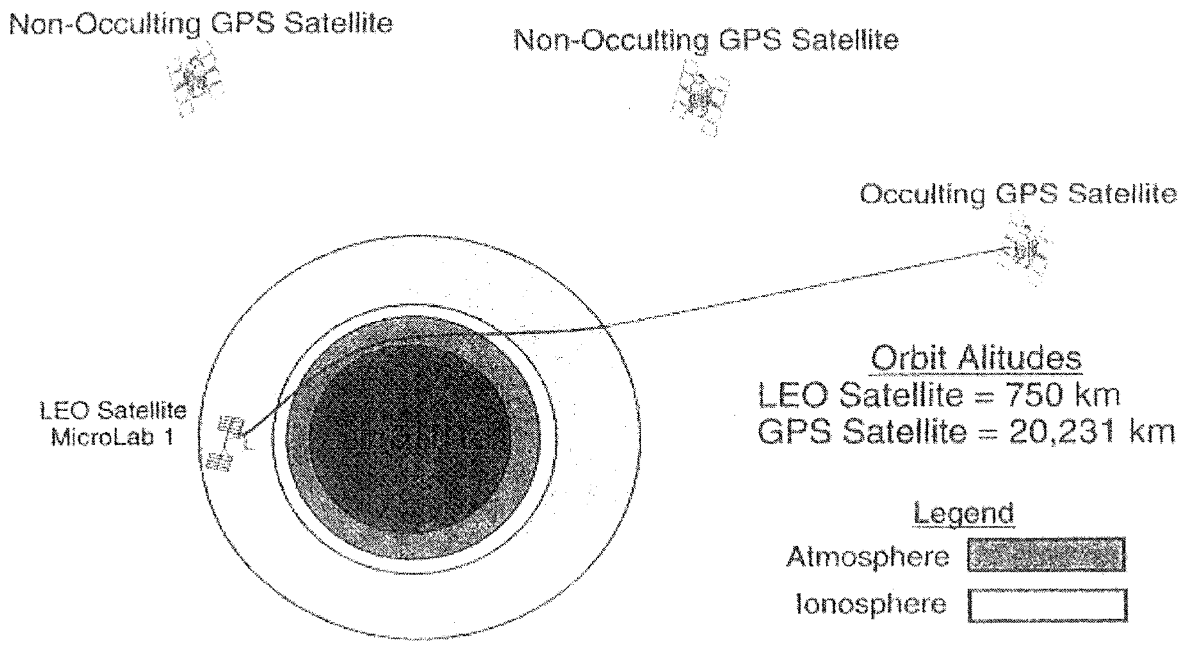


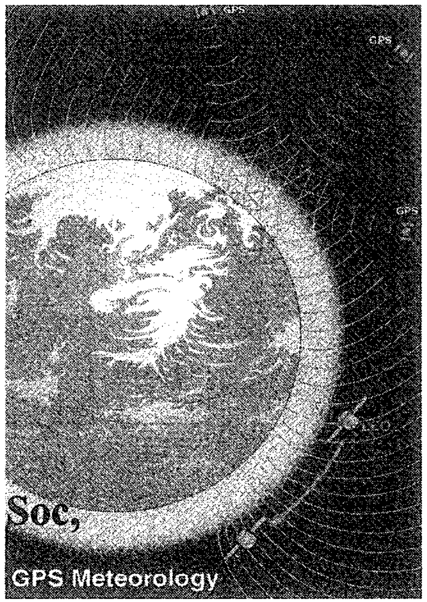
Examples of WINDII data

GPS Occultation Techniques

- Low-Earth orbit (LEO) satellite monitors 1.2 GHz L1, L2 transmissions from GPS satellites
- L1 (L2) = 1.6 (1.2) GHz
- Signals strongly refracted as GPS satellite is occulted by atmosphere and ionosphere

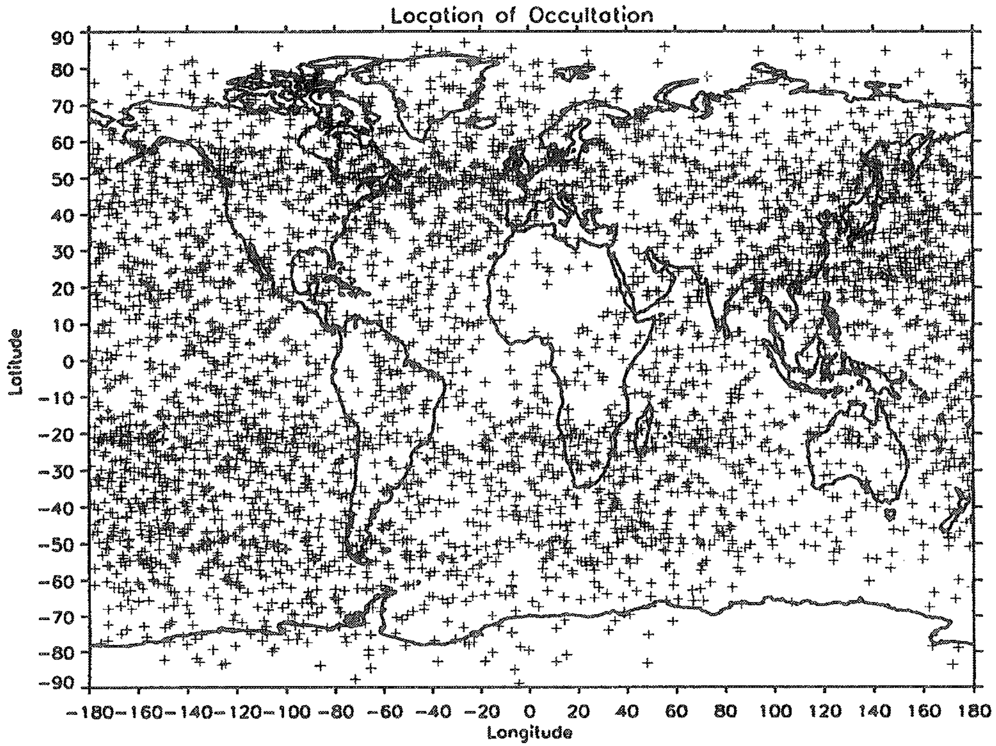
- Signal delays converted to $p(z)$ after removal of ionospheric (dispersive) refraction
- Temperature profiles derived using hydrostatic equation
- Humidity profiles if pressure known at surface





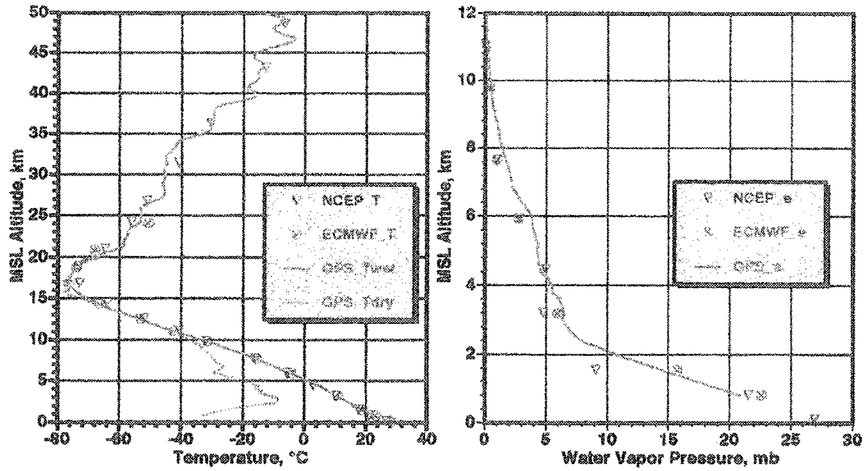
Bull. American Meteorological . Soc, Jan 1996

GPS II



GPS/MET Occultations Nov 96-Feb 97

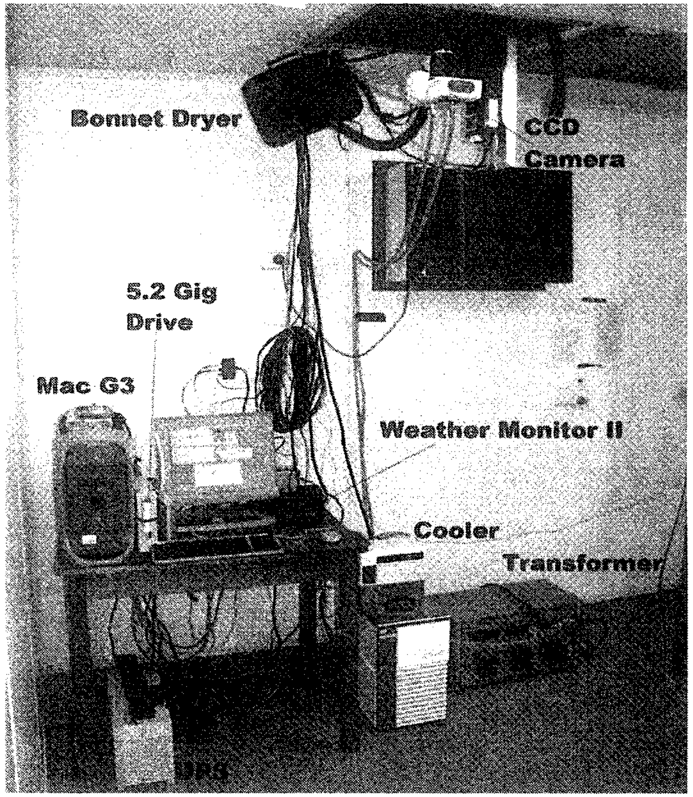
- Strengths
  - Global coverage
  - Use "inexpensive"LEO satellites
  - N_e, T, e profiles and climatologies
  - Moderate height resolution (~1-2 km)
- Weaknesses
  - ~300 km horizontal resolution



Validation

Airglow Imagers

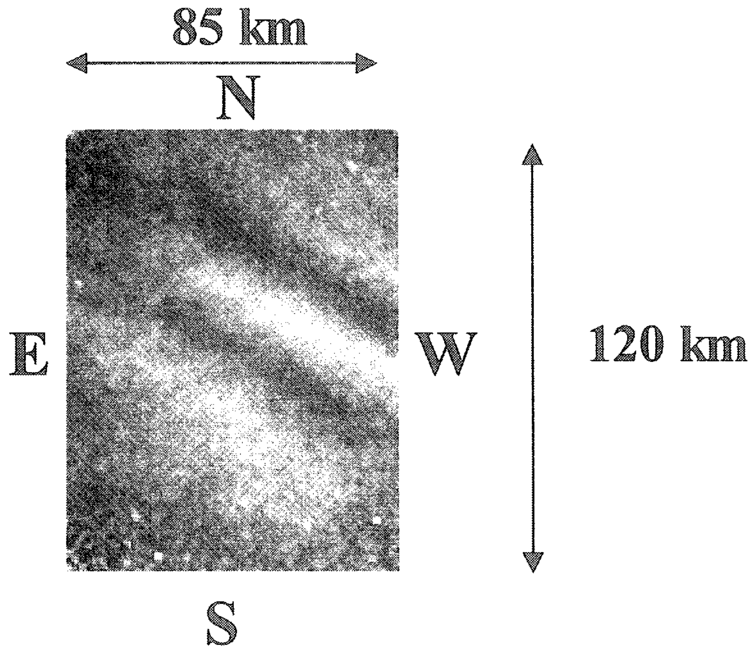
- Optical techniques to allow direct imaging of airglow layers
  - OH ~87 km
  - O_2 atmospheric ~93 km
  - $O(^1S)$ 557.7 nm ~97 km
- Emissions focussed on CCD detector through narrow-band filter
- Small-scale structure of atmosphere
- Temperatures measured by comparing line strengths in OH, O_2 bands



Aerospace Imager

Imager Observations

- Visualize gravity wave motions and instabilities
- Gravity wave horizontal scales



OH airglow 13 Feb 2000