Spectropolarimetric Measurements of Scattered Sunlight in the Huggins Bands

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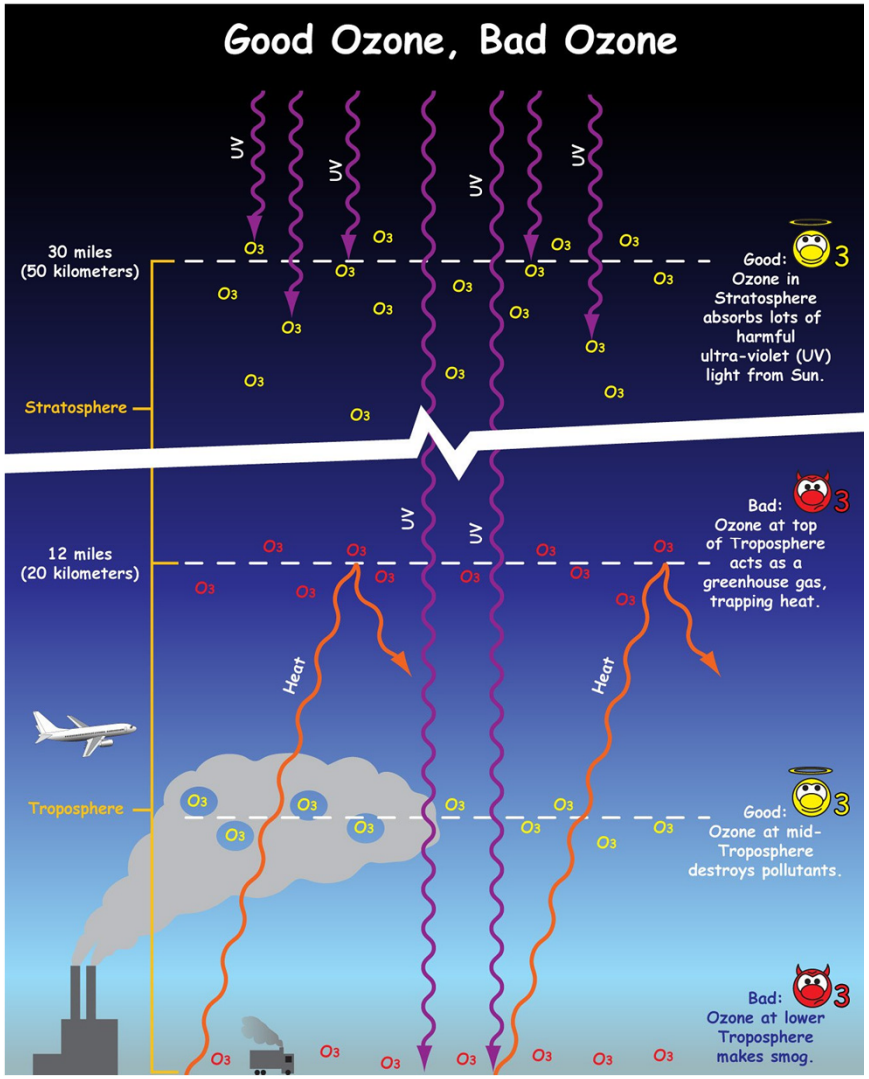
Atmospheric Ozone



Stratospheric O_3 - good O_3

- Absorbs the solar UV radiation
- Protects life in the Earth

O_3 in the upper troposphere - bad O_3

- Greenhouse gas trapping heat

O_3 in the middle troposphere - good O_3

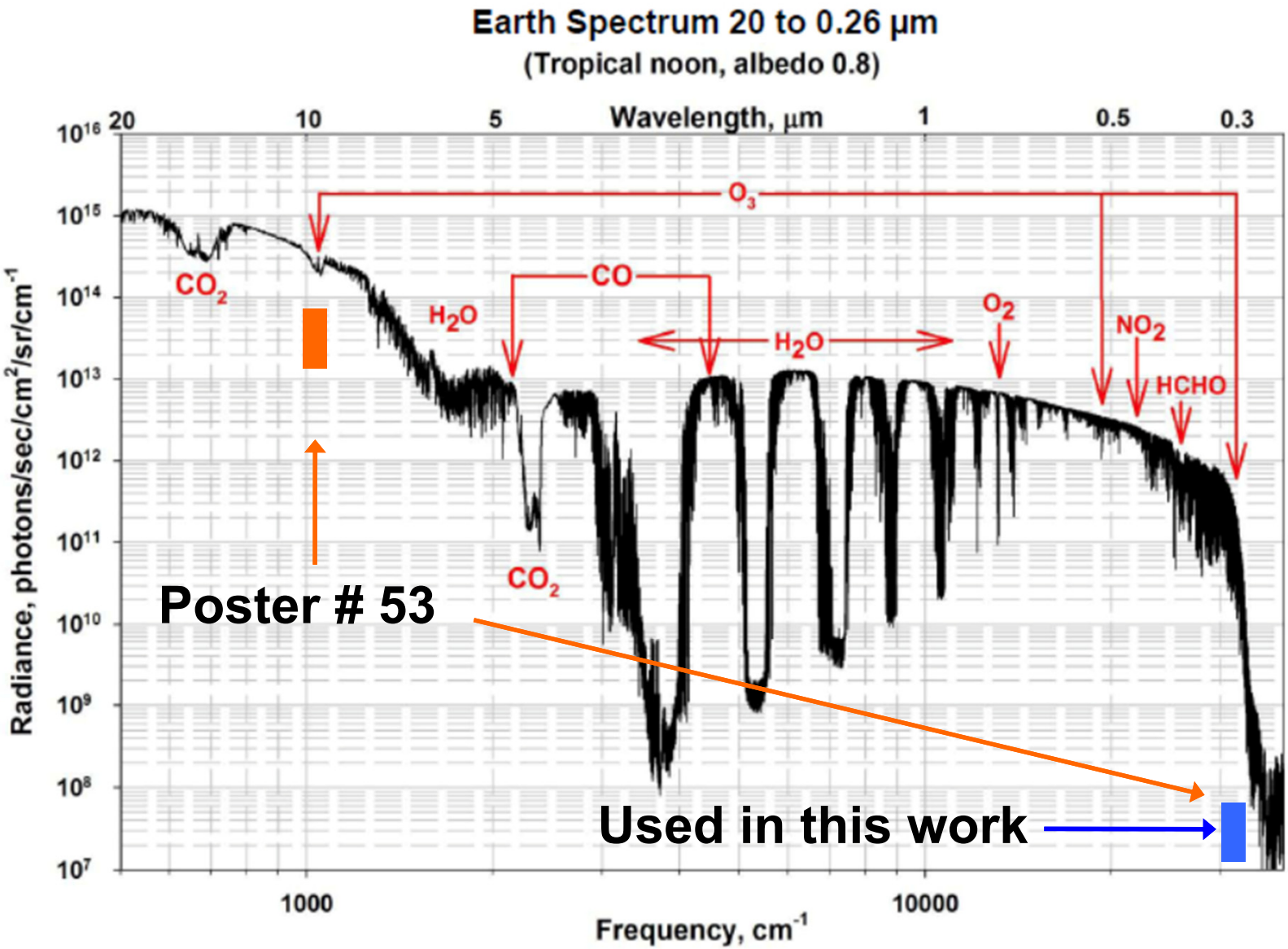
- Destroys pollutants

O_3 near surface - bad O_3

- is harmful to human health and plant life

Figure Courtesy: http://spaceplace.jpl.nasa.gov/en/kids/tes/gases/

Spectral Regions Used in O_3 Measurements



Observations of Tropospheric Ozone Vertical Distributions Using Remote Sensing Techniques

- **Challenges**
  - Strong stratospheric signals of ozone in the spectra
  - Cloud contaminations in the line of sight
  - Unresolved spectra (in the sense of rotational lines) in the UV-VIS spectral regions
- **What can help to distinguish the tropospheric O_3 signals from those in the stratosphere?**
  - Infrared
    - Temperature broadening and pressure-broadening information in rotational lines
    - Thermal emissions in the troposphere
  - UV-VIS
    - Wavelength dependence of light penetration depth in the atmosphere
    - Temperature dependence of O_3 absorption cross sections
    - Polarization measurements
  - Viewing Geometry
    - Multi axis viewing
  - Combination of the above choices
    - UV + IR [Worden J., et al., GRL, 34, 2007; Fu D., et al., poster section #53]
    - UV + polarization + multi axis viewing – this work

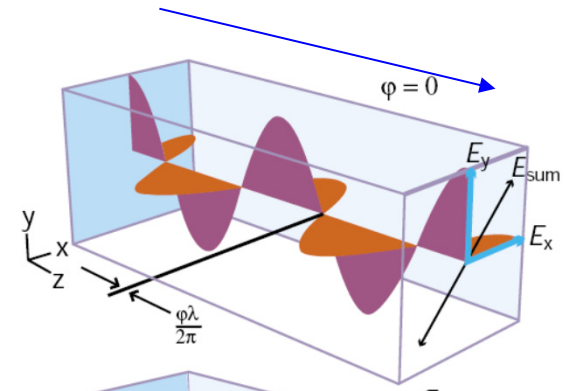
Polarization

- Light is a transverse wave.
- Polarized light can be represented as the sum of two orthogonal linear states.
- Polarization of light is a result of scattering due to
  - Molecules
  - Aerosols
  - Clouds
  - Surface
  - Instrument

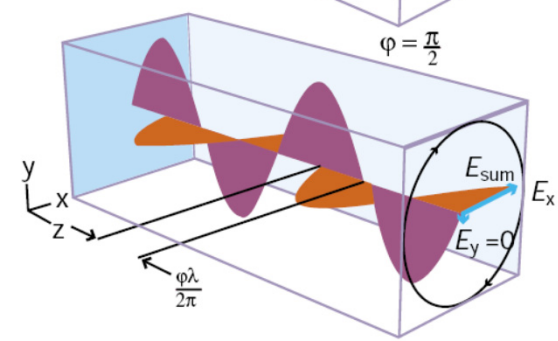
φ the relative phase between two waves

Propagation Direction

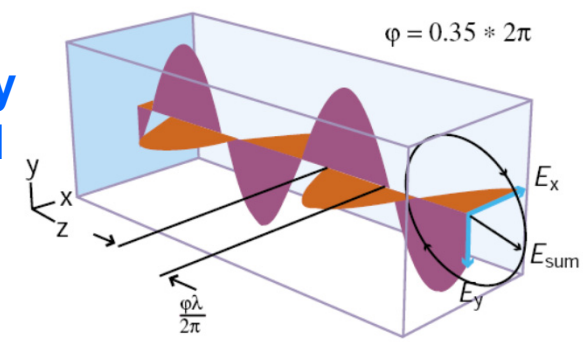
Linearly Polarized Light



Circularly Polarized Light



Elliptically Polarized Light



Stephen Guimond and David Elmore, Optical Design & Engineering Polarizing Views, DOI: 10.1117/2.5200405.0007, (2004)

Stokes Parameters and Degree of Linear Polarization

- Sir George Stokes, a English physicist, developed 4 parameters to characterize polarized light in 1852.
- Stokes parameters represent intensity, linear and circular polarization.

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} \text{total incident irradiance} \\ \text{horizontal or vertical polarization} \\ \pm 45^{\circ} \text{ polarization} \\ \text{circular polarization} \end{bmatrix}$$

Traditional technique only uses I component

Our technique includes Q and U together with I

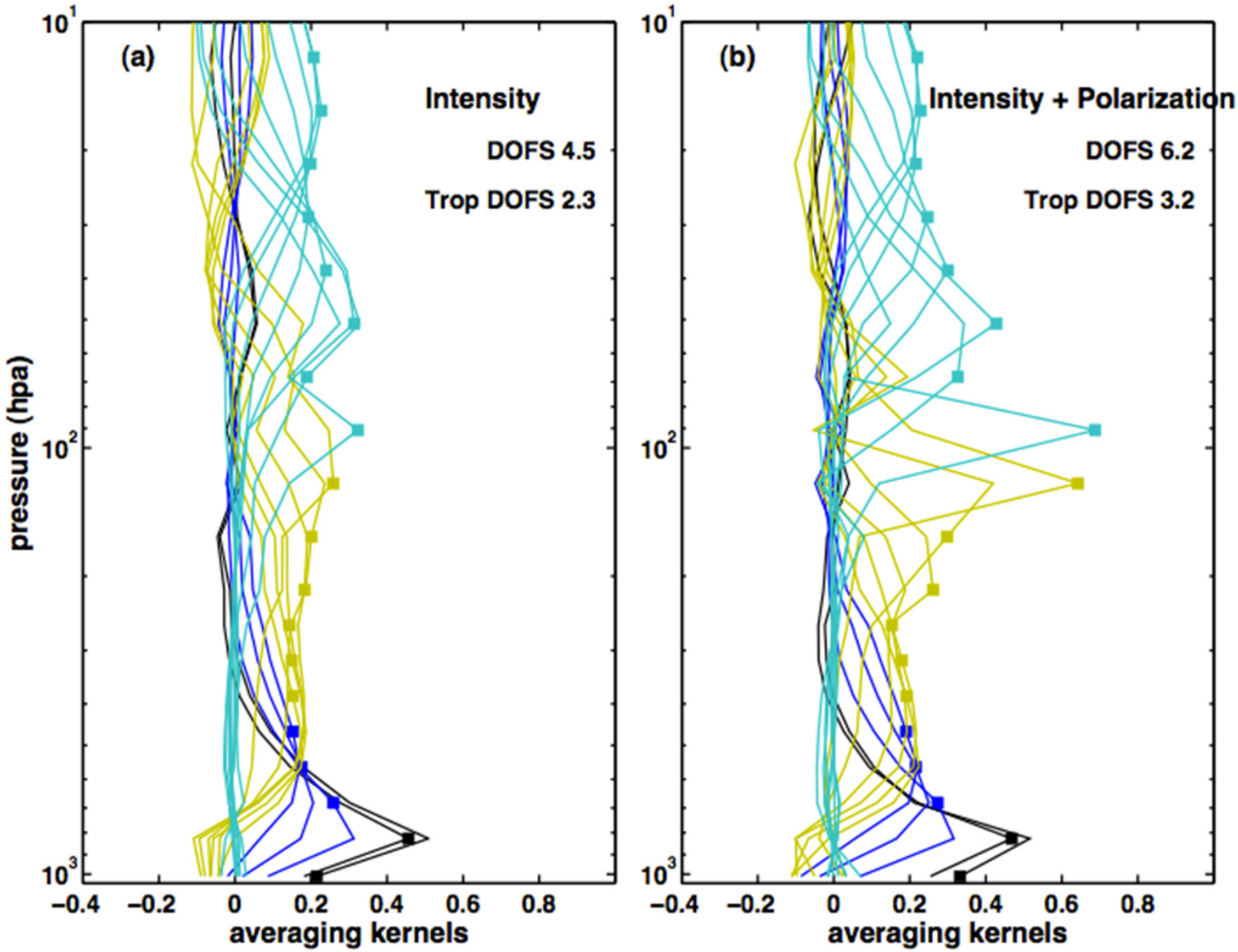
- The degrees of linear polarization (*DOLP*) can be calculated using the following equation

$$DOLP = \frac{\sqrt{Q^2 + U^2}}{I}$$

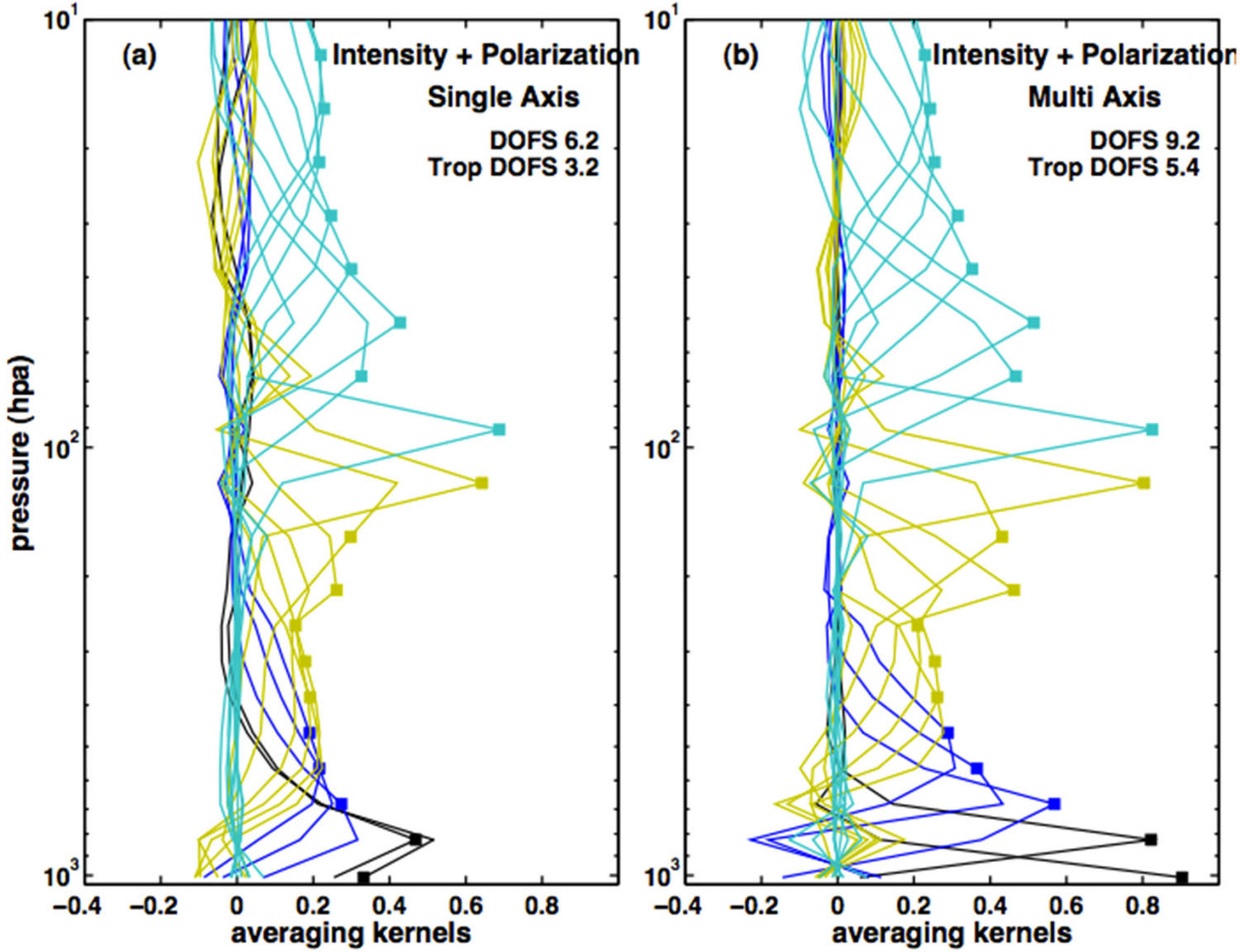
Sensitivity Study

- Set up forward model
  - Uses the linearized vector radiative transfer model VLIDORT [Spurr, 2006] for the numerical computation of the Stokes vector and Jacobian matrix in a multiply-scattering multilayer medium
  - Uses TES observed temperature and TES a priori O_3 volume mixing ratio profile on May 2009 over Houston to construct model atmosphere
- Use optimal estimation formalism to estimate the performances of O_3 measurements
  - Compute averaging kernel matrix A and degrees of freedom
  - Run retrievals using $[O_3]_{ret} = [O_3]_a + \mathbf{A}\,([O_3]_{true} - [O_3]_a)$
  - Evaluate the uncertainties

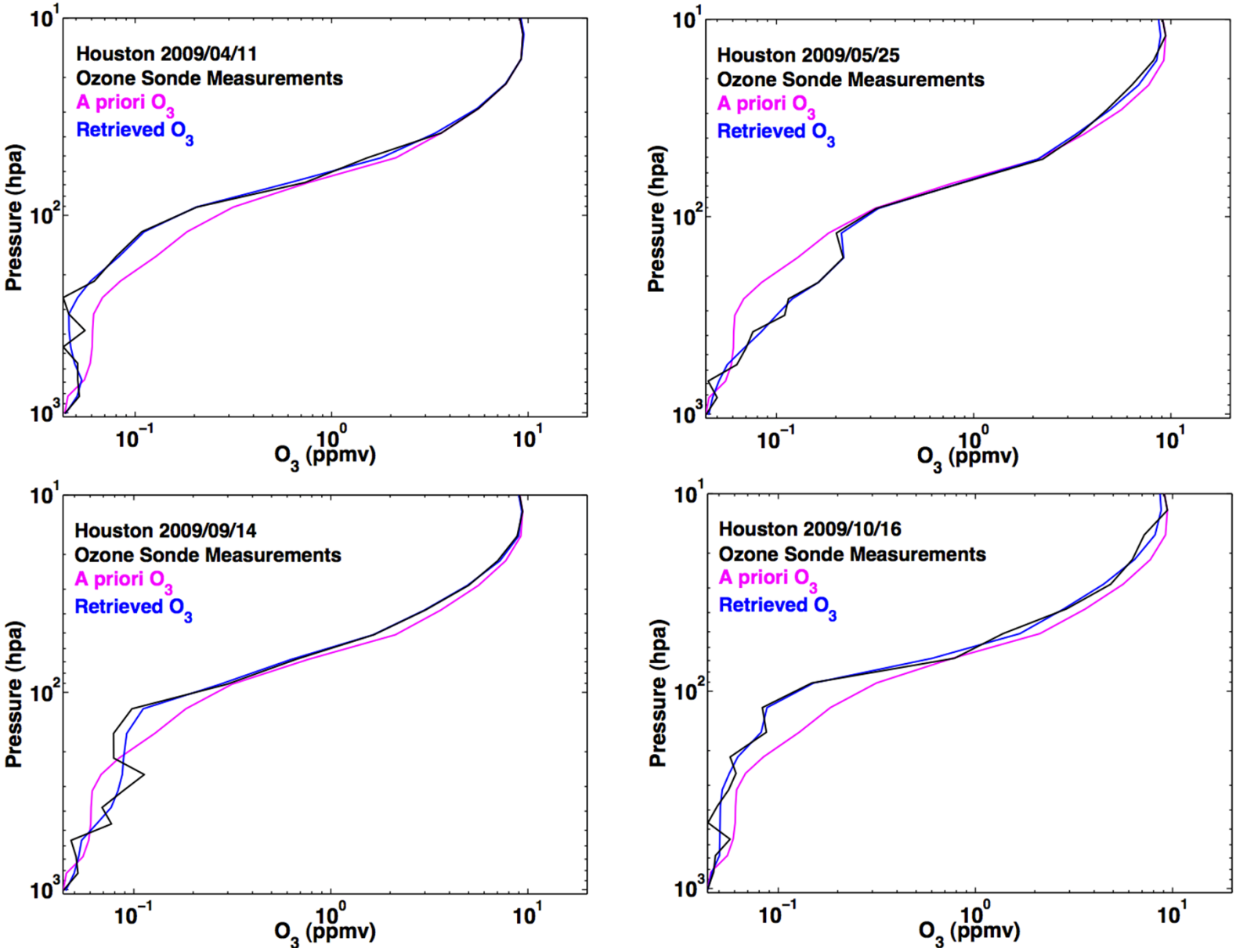
Vertical Sensitivity and Resolution of O_3 Observations: Intensity vs. Intensity + Polarization



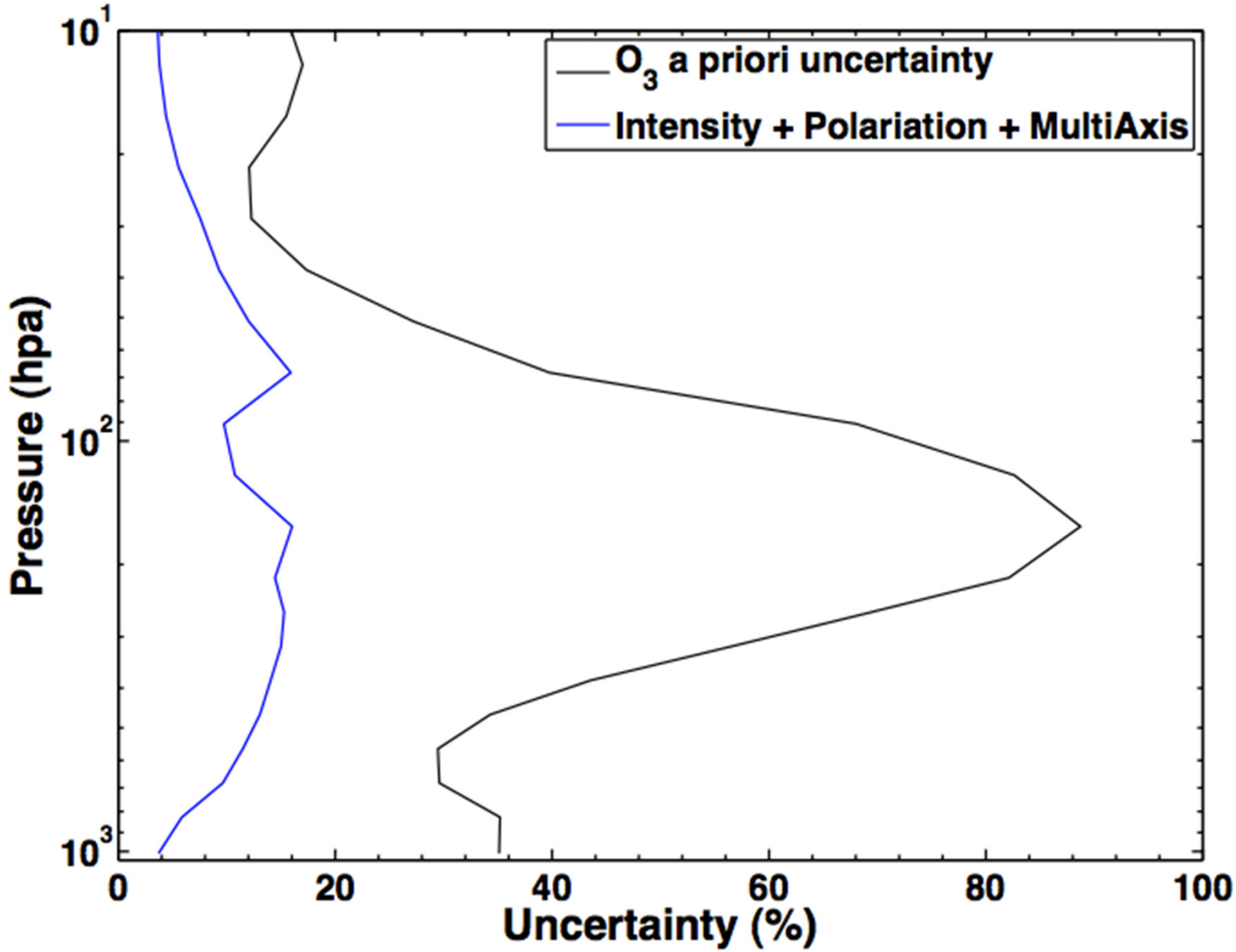
Vertical Sensitivity and Resolution of O_3 Polarization Measurements: Single Axis vs. Multi Axis



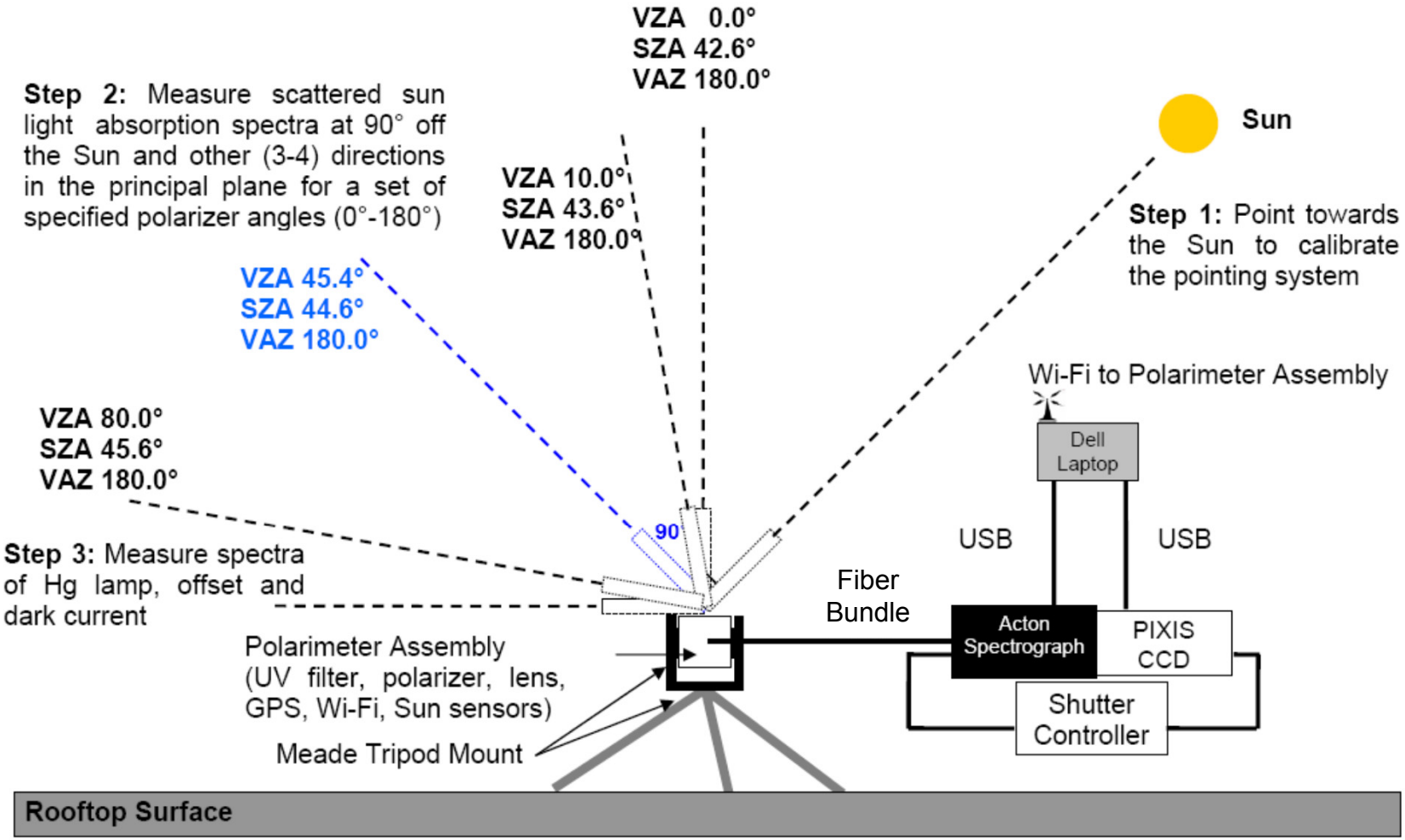
Ozone Profiles over Houston, Texas



Uncertainty of O_3 measurements Using Polarization Measurements with Multi Axis Viewing



JPL Spectropolarimeter



The JPL spectropolarimeter views the scattered sunlight through a linear polarizer with transmission axis at the polarizer angle θ to the normal of the principal plane. As the polarizer is being rotated, a set of spectra were measured.

Measurement Configurations

- **Date with Measurements:**
  - May 20th, Jul 8th, Aug. 3rd, 5th, 7th, 10th, and Oct. 16th, 2009
  - June 27th, 2011
- **Spectral Range:** 280 – 345 nm
- **Resolving Power:** 875 – 1078 (FWHM of Hg line 0.32nm)
- **Exposure Time:** 1 second/scan
- **Co-addition:** 10 scans
- **Signal to Noise Ratio:** ~1000:1,
- **Polarizer Angles θ:**

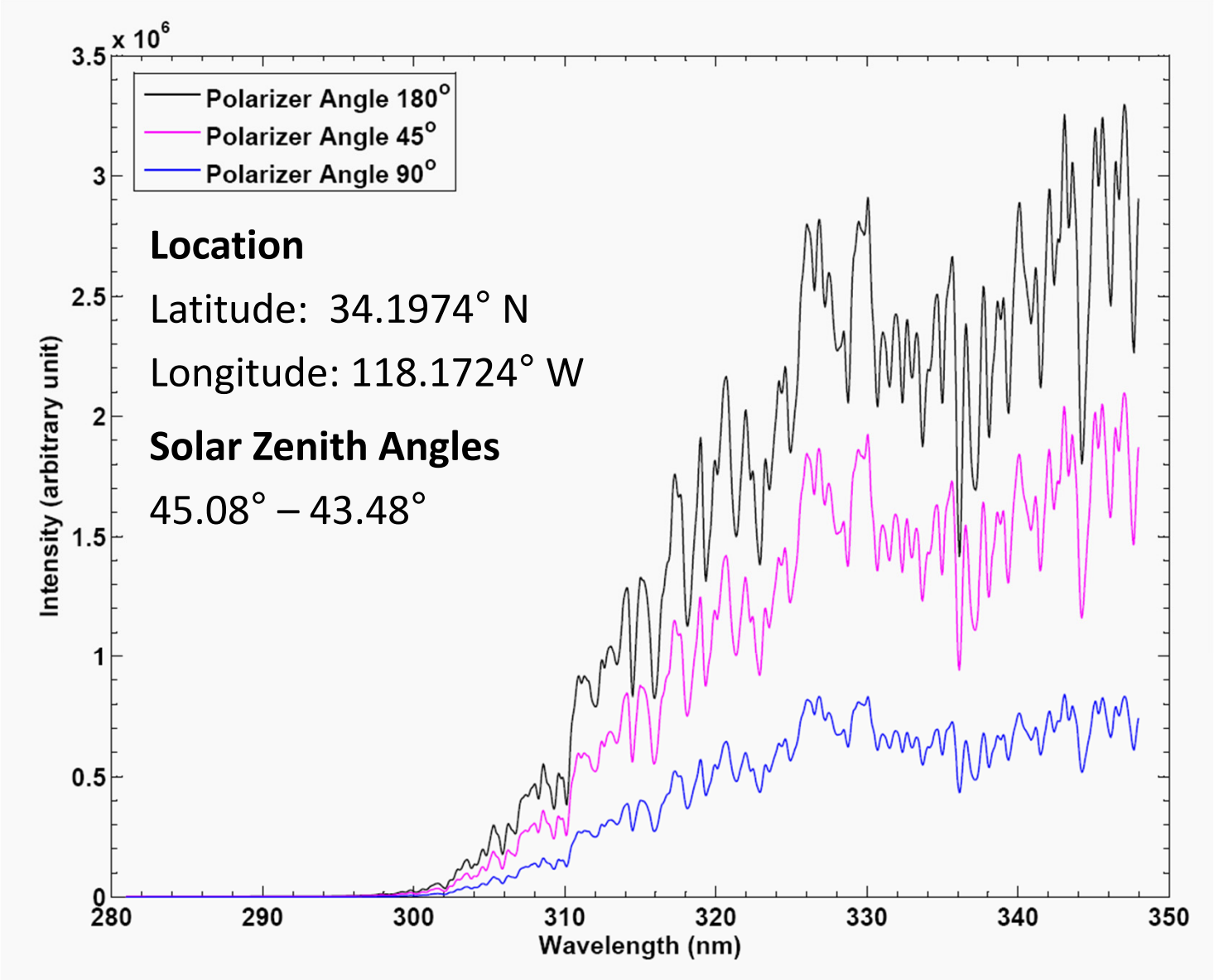
a.) May 20th – Aug. 10th 2009

358°, 359°, 359.5°, 0°, 0.5°, 1°, 2°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, 88°, 89°, 89.5°, 90° ,90.5°, 91°, 92°.

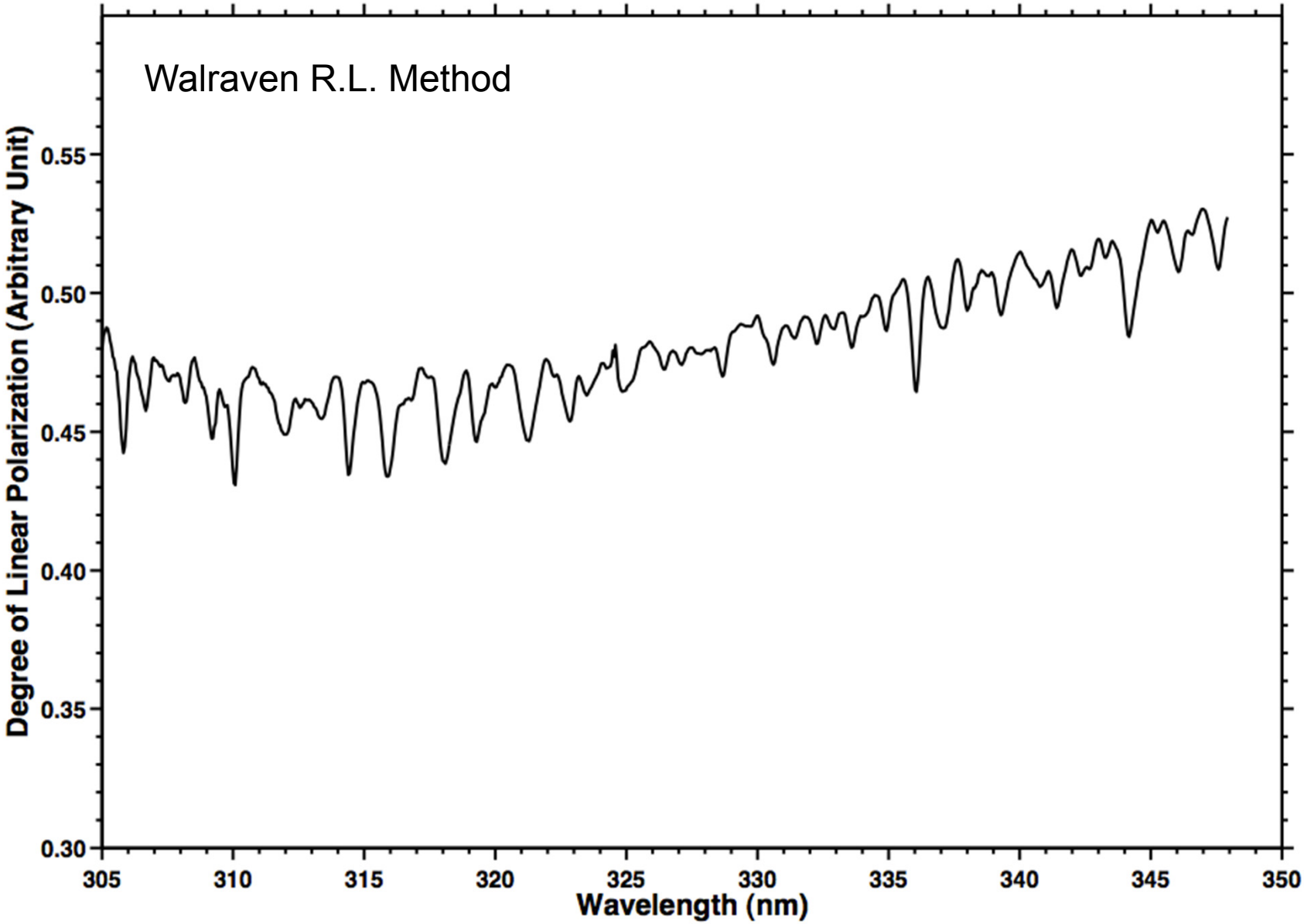
b.) since October 16th 2009

0° to 180° with an interval of 3°

Sample Spectra on October 16th, 2009

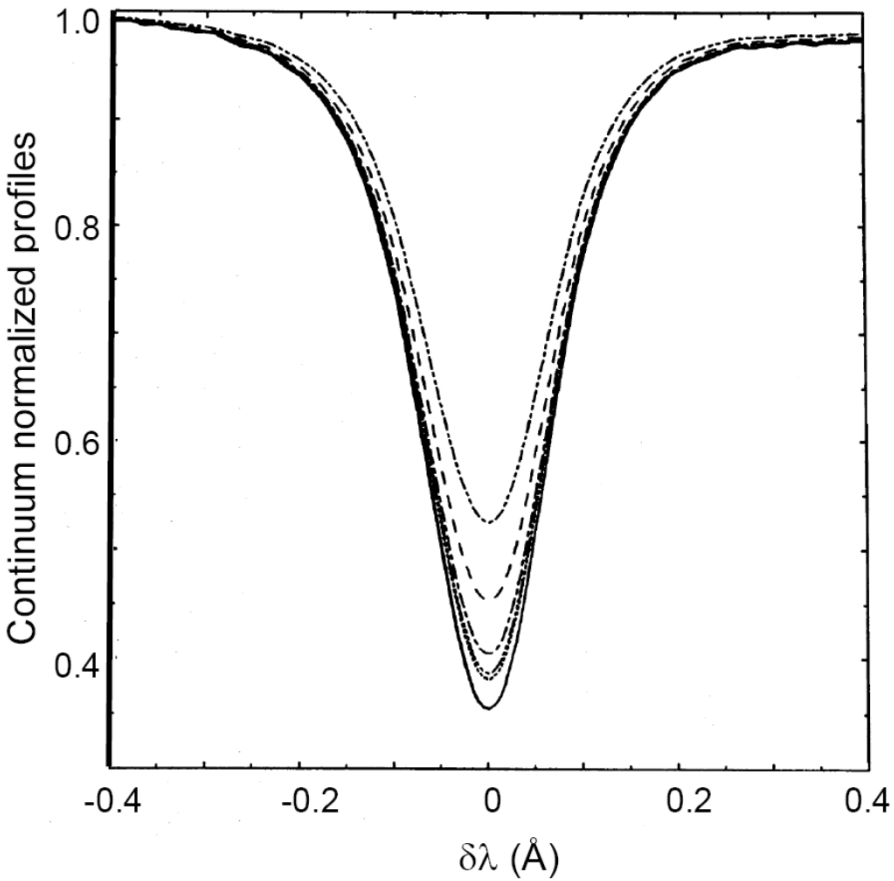


Walraven Method vs. Smith Approach



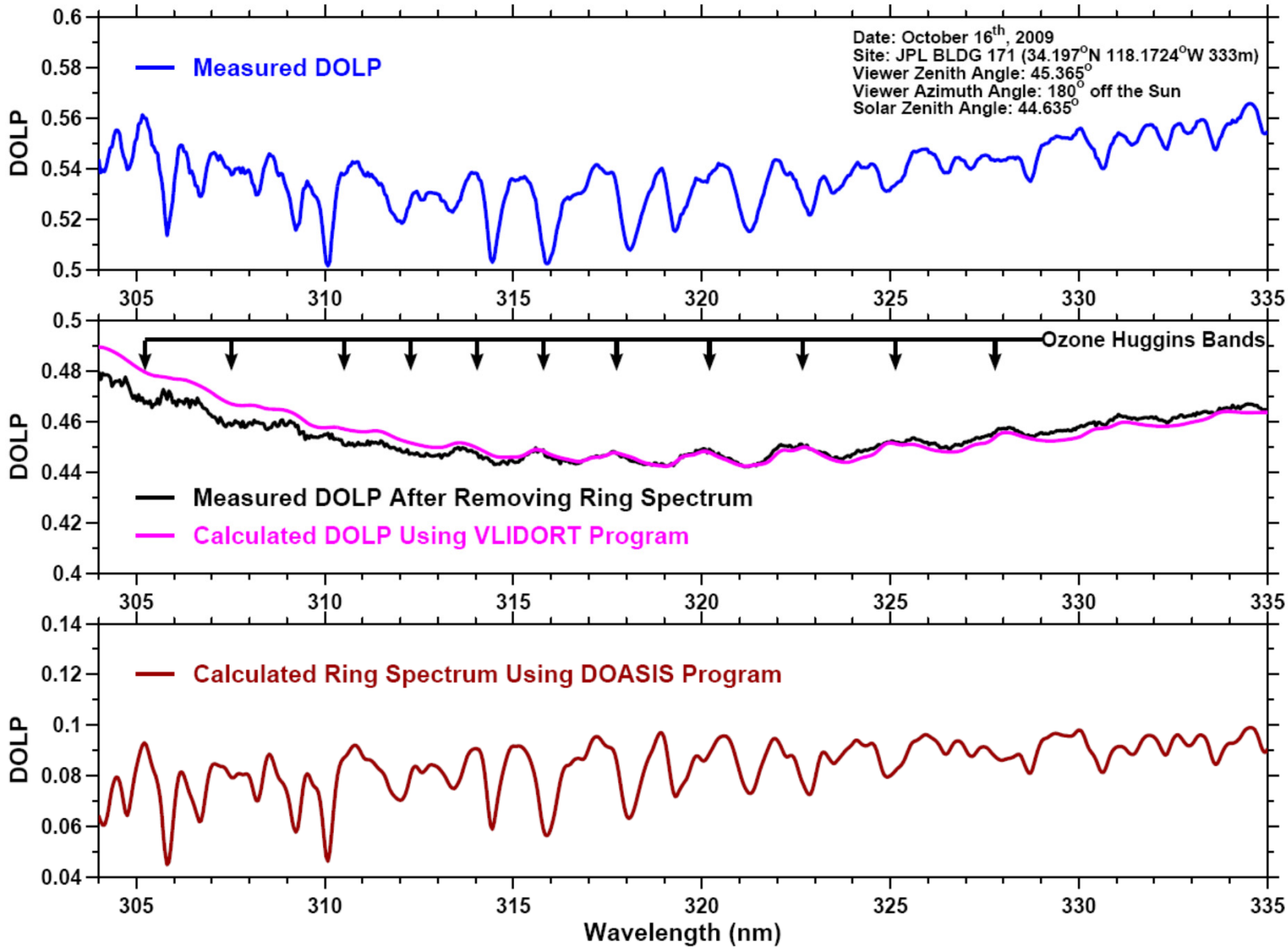
Ring Spectra

- Grainger and Ring [1962] discovered that the Fraunhofer lines seen in the scattered sunlight are relatively less deep (or more filled-in) than in the direct sunlight.



- Figure from Kattawar *et al.* [1981]
- The bottom line is the incident Fraunhofer line. Proceeding upwards corresponding to increasing scattering angles: 24.5°, 40°, 60°, 79° and 90°.
- Available programs to simulate Ring effect:
  - Wagner T et al. [2009]
  - Spurr RJD, [2009]
  - Chance KV and Spurr RJD [1997]

DOLP at the Ozone Huggins Bands



Summary

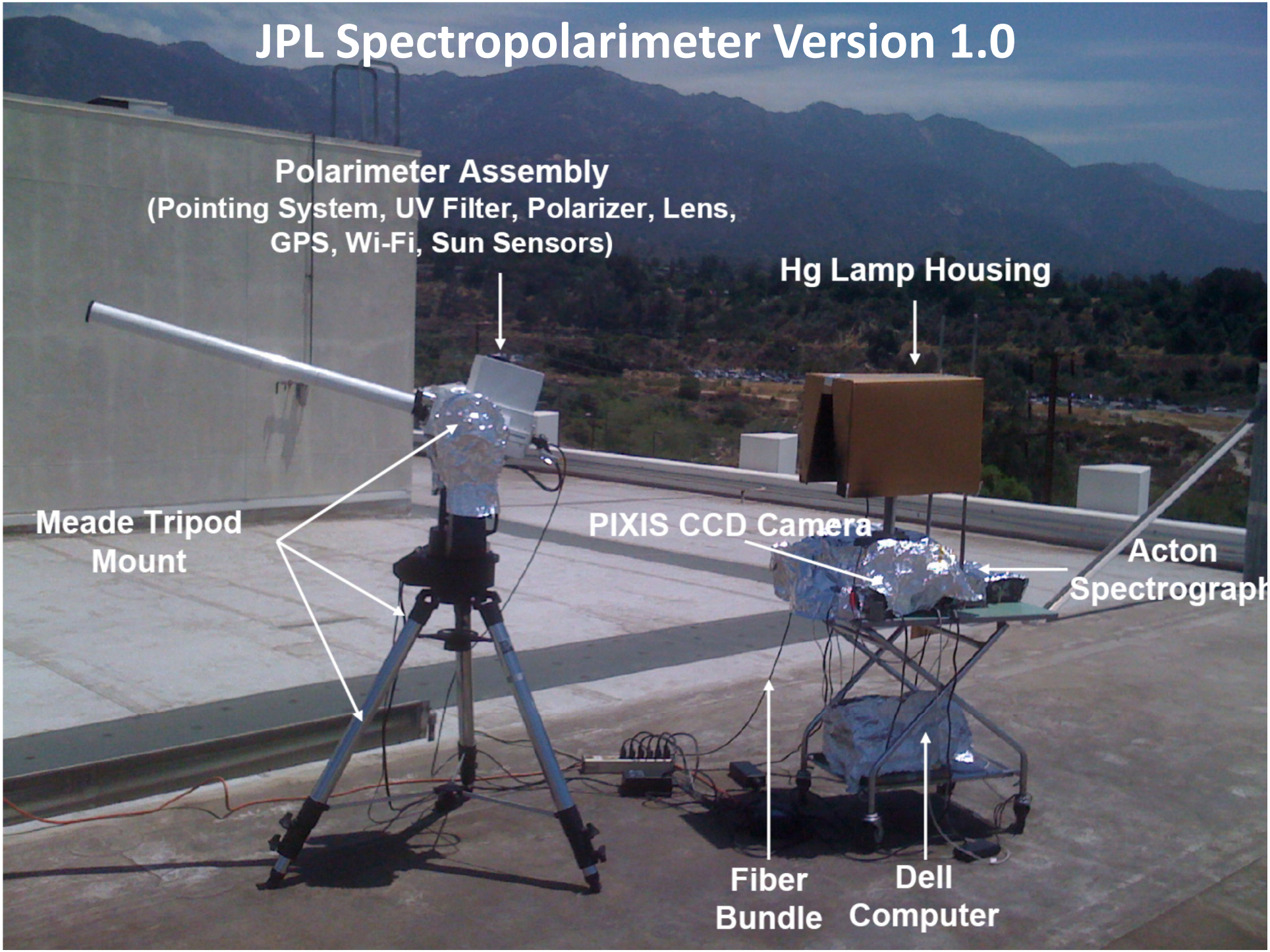
- The JPL spectropolarimeter has been built. First polarization measurement in the Huggins bands has been carried out for O_3 measurements.
- Sensitivity study show that multiple axis viewing provide high sensitivity of ozone concentration in both troposphere and stratosphere.
- A manuscript on this novel technique is being prepared for *Applied Optics*.
- To make retrieval programs to obtain the ozone volume mixing ratio profiles from the measured spectra.
- To attend the field measurement campaigns in the future and validate this novel technique.
- To make contributions on ozone measurements over Pasadena

Acknowledgements

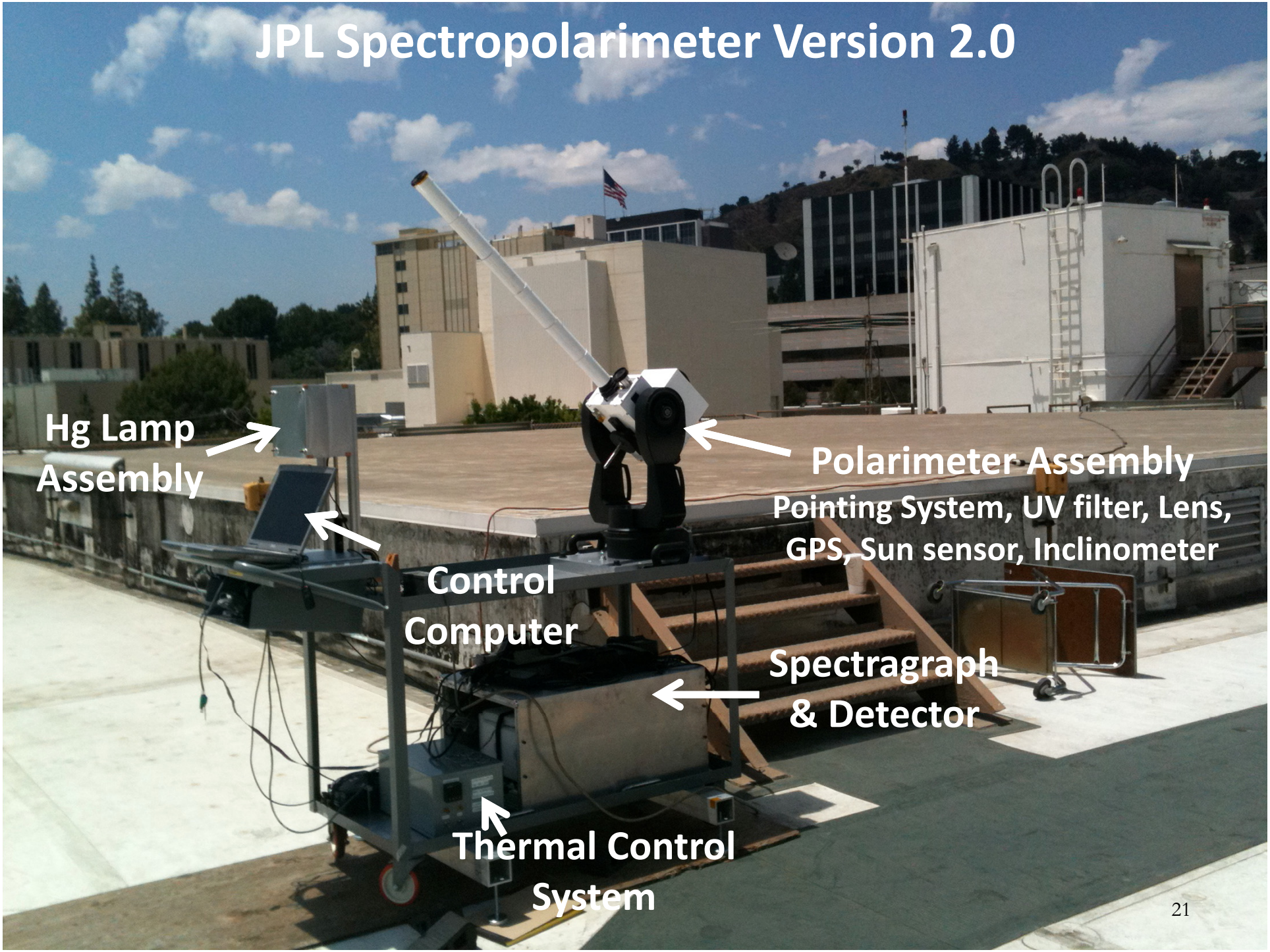
- Tropospheric Emission Spectrometry Group

Photo of Los Angeles Air Basin December 31st, 2009

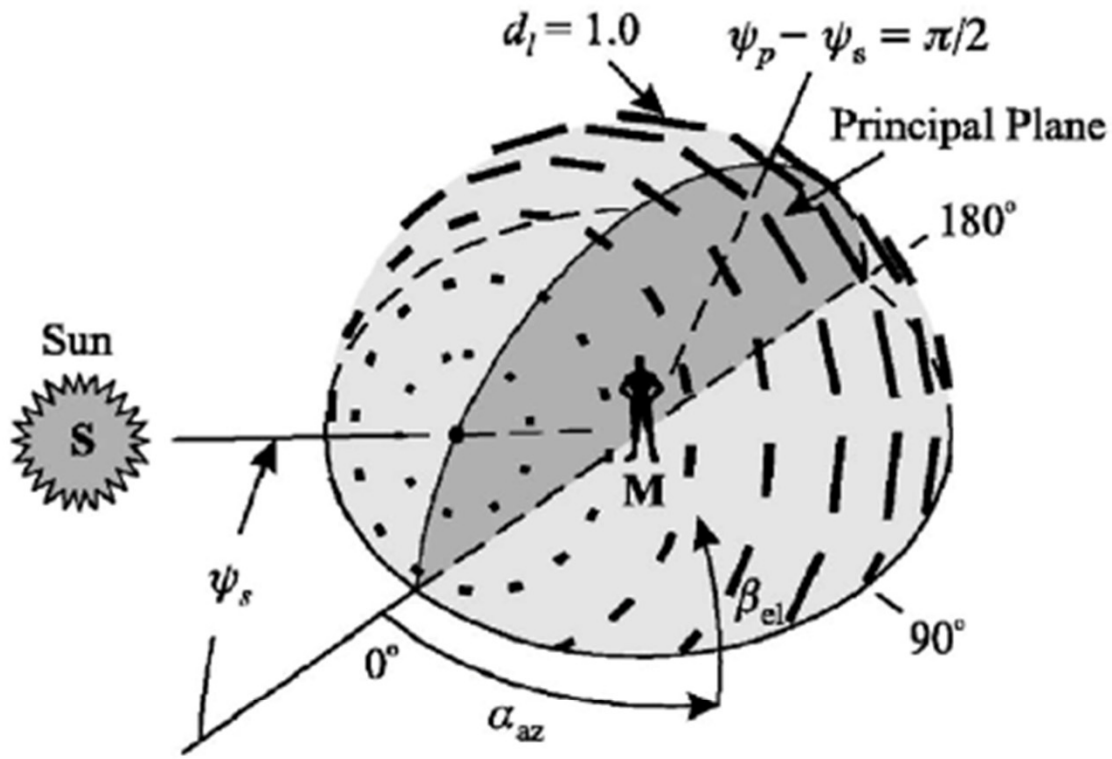
JPL Spectropolarimeter Version 1.0



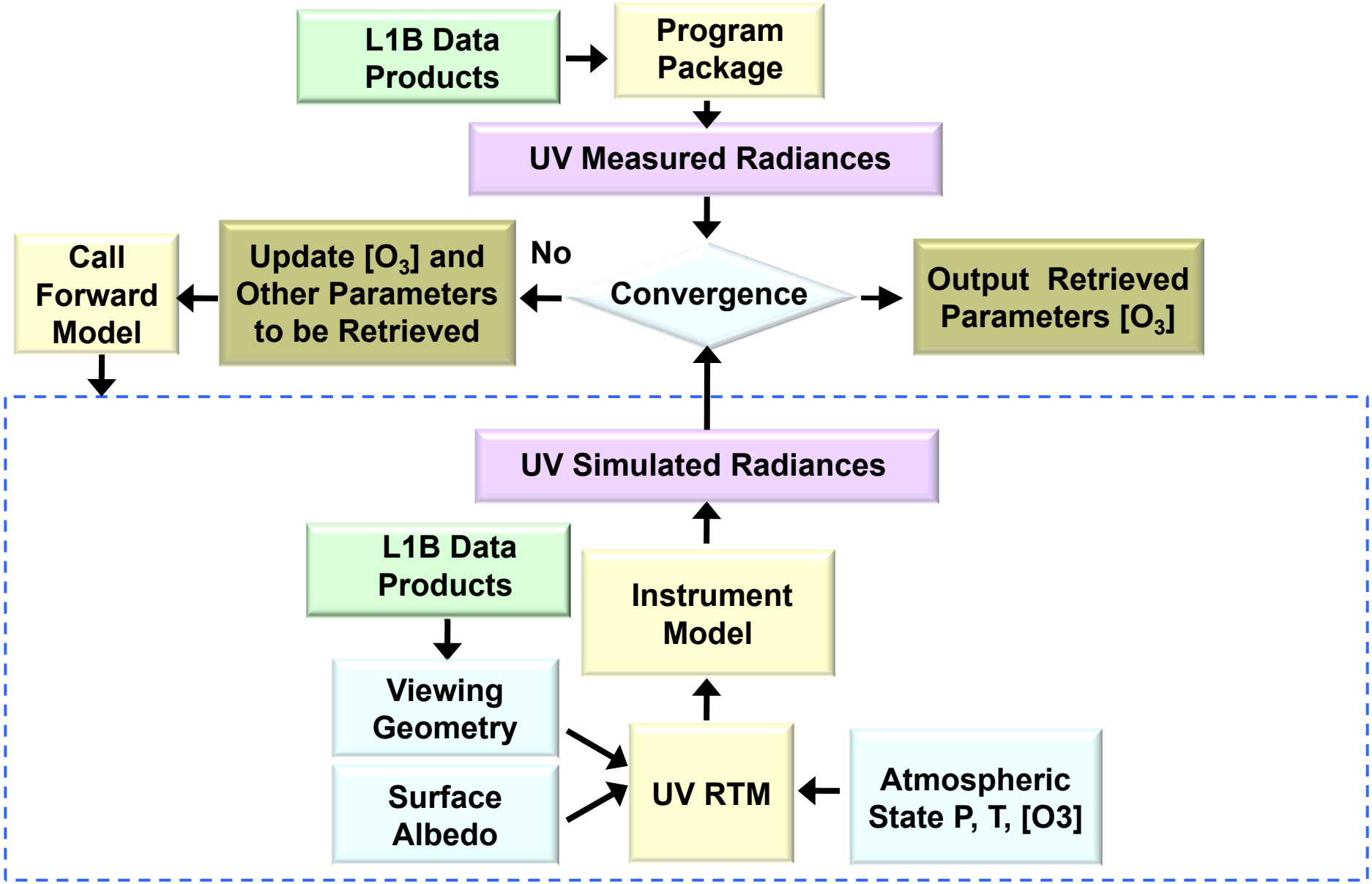
JPL Spectropolarimeter Version 2.0



Viewing Geometry



(a)

Fig. 7. Polarization diagram for the entire sky when ψ_s=35°. The length of the heavy line indicates the degree of linear polarization d_l; the line is parallel to the direction of the linearly polarized component of the electric field. Results are shown for two orientations: (a) mainly the solar half of the sky and (b) mainly the anti-solar half of the sky.

Retrievals: From Measured Spectra to O_3 Profiles