Photon path distribution spectrometer

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Radiative transfer in the atmosphere:

$$\hat{\Omega} \bullet \nabla I = -\Sigma I + \int_{4\pi} d\hat{\Omega}' P(r, \hat{\Omega}' \rightarrow \hat{\Omega}) I(r, \hat{\Omega}') + \hat{S}(r, \hat{\Omega})$$

In GCM models
1D RT + cloud overlap

$$\mu \frac{dI}{dz} = -\beta I + \omega \int_{4\pi} d\Omega' p(z, \Omega' \rightarrow \Omega) I(z, \Omega') + s(z, \Omega)$$

Gas and particle
Absorption and scattering
&
Cloud overlap

Challenges:

- **Accurate measurements of atmospheric constituents**
  - **Reducing the ambiguity introduced by 3D structures of the scattering layers (clouds and aerosols)**
  - **Enhancing the vertical resolution of retrieved aerosol and cloud optical properties**
  - **Accurately detecting water vapor over and between clouds.**
  - **Better detection of thin layers of clouds and aerosols especially over surfaces with high albedo or clouds**

- **Developing and validating cloud overlap schemes and Broadband Heating Rate Profiles (BBHRP)**

Radiative transfer in the atmosphere:

$$\hat{\Omega}\bullet\nabla I = -\Sigma I + \int_{4\pi} d\hat{\Omega}' P(r,\hat{\Omega}' \rightarrow \hat{\Omega}) I(r,\hat{\Omega}') + \hat{S}(r,\hat{\Omega})$$

In GCM models
1D RT + cloud overlap

Alternative?

$$\mu\frac{dI}{dz} = -\beta I + \omega\int_{4\pi} d\Omega' p(z,\Omega' \rightarrow \Omega) I(z,\Omega') + s(z,\Omega)$$

The equivalence theorem:
Photon pathlength distribution

Gas and particle
Absorption and scattering
&
Cloud overlap

Radiative Transfer and Photon Pathlength Distribution

Equivalence Theorem: [Irvine, 1964]

$$I_\nu(\mu,\phi;\mu_0,\phi_0) = I_0(\mu,\phi;\mu_0,\phi_0)\int_0^\infty p(l,\mu,\phi;\mu_0,\phi_0)e^{-\kappa_\nu l}dl$$

Where ***p(l)*** **is photon path length distribution with path length** ***l***

K_ν is gaseous absorption coefficient

$I_0(\mu,\phi;\mu_0,\phi_0) \Rightarrow$ **cloud optical properties**

$p(l,\mu,\phi;\mu_0,\phi_0) \Rightarrow$ **cloud geometry**

$\Rightarrow$ **Radiation field**

- **Mean path length to ensues the radiation closure at the surface and TOA**
- **Higher moments to ensure the accuracy of heating profiles**

Radiative Transfer and Photon Pathlength Distribution

Equivalence Theorem: [Irvine, 1964]

$$I_\nu(\mu,\phi;\mu_0,\phi_0) = I_0(\mu,\phi;\mu_0,\phi_0)\int_0^\infty p(l,\mu,\phi;\mu_0,\phi_0)e^{-\kappa_\nu l}dl$$

Where ***p(l)*** **is photon path length distribution with path length** ***l***

K_ν is gaseous absorption coefficient

Taking inverse Laplace transform:

$$p(l,\mu,\phi;\mu_0,\phi_0) = L^{-1}\left(\frac{I_\nu(k_\nu,\mu,\phi;\mu_0,\phi_0)}{I_0(\mu,\phi;\mu_0,\phi_0)}\right) = L^{-1}R(k_\nu,\mu,\phi;\mu_0,\phi_0)$$

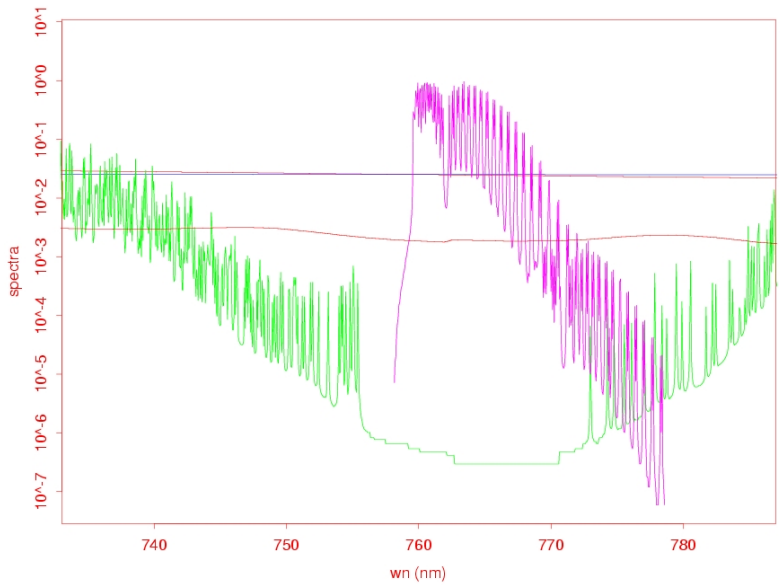
Radiation measurements of $I_0(\mu,\phi;\mu_0,\phi_0)$ **and** $R(k_\nu,\mu,\phi;\mu_0,\phi_0)$

provide a complete set for understanding RT in the atmosphere

Photon Pathlength Distribution and Oxygen A-band

Oxygen A-band: 759 -770 nm

- Vertical profile of Oxygen is well known (uniform mixture)
- No other absorbers interfere within Oxygen A-band
- A number of absorption lines cover a suitable dynamic range
- The lines are regular and “looser” to be resolved by an instrument
- 760nm is the central wavelength to represent SW



In the lower atmosphere, the line shape of Oxygen A-band

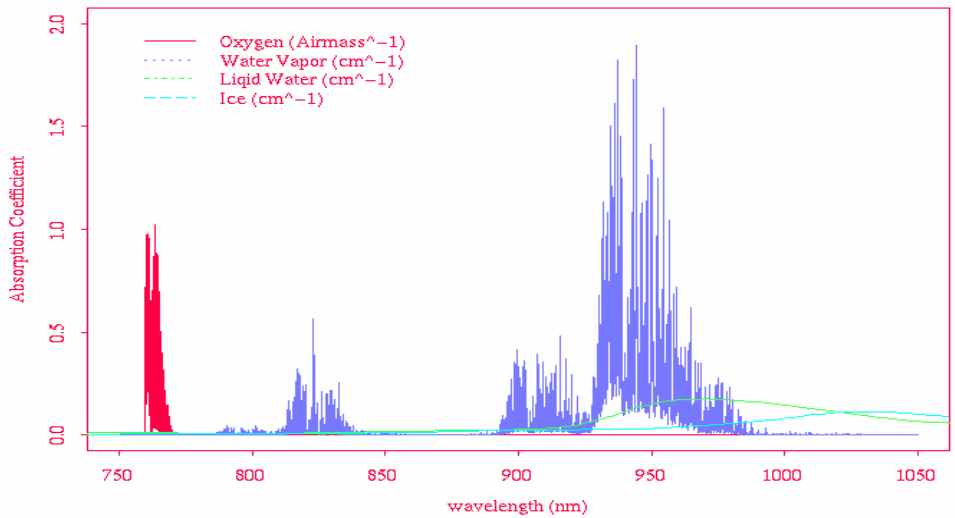
$$k_i = \frac{S_i}{\pi} \frac{\alpha_i}{(\upsilon - \upsilon_i)^2 + \alpha_i^2}$$

$$\alpha_i = \alpha_i^0 \frac{p}{p_0} \left(\frac{T_0}{T}\right)^{1/2}$$

$$S_i = S(T_0) \frac{T_0}{T} \exp[1.439 E'' (\tfrac{1}{T_0} - \tfrac{1}{T})]$$

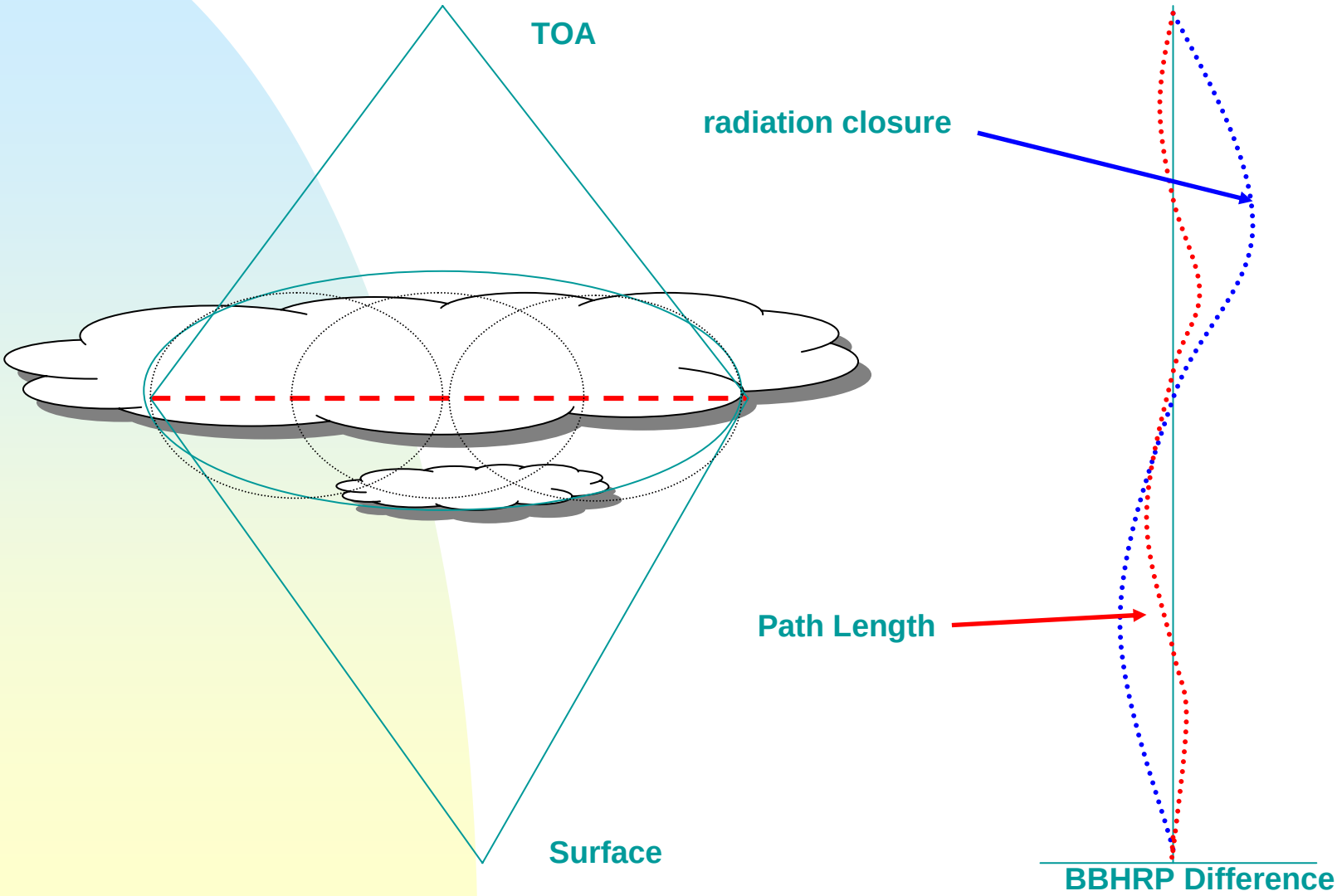
Photon Path length Distribution and water absorption band

Changes in radiative heating associated with changes in vertical cloud structure related to water vapor affect all aspects of the energy and hydrological cycles;

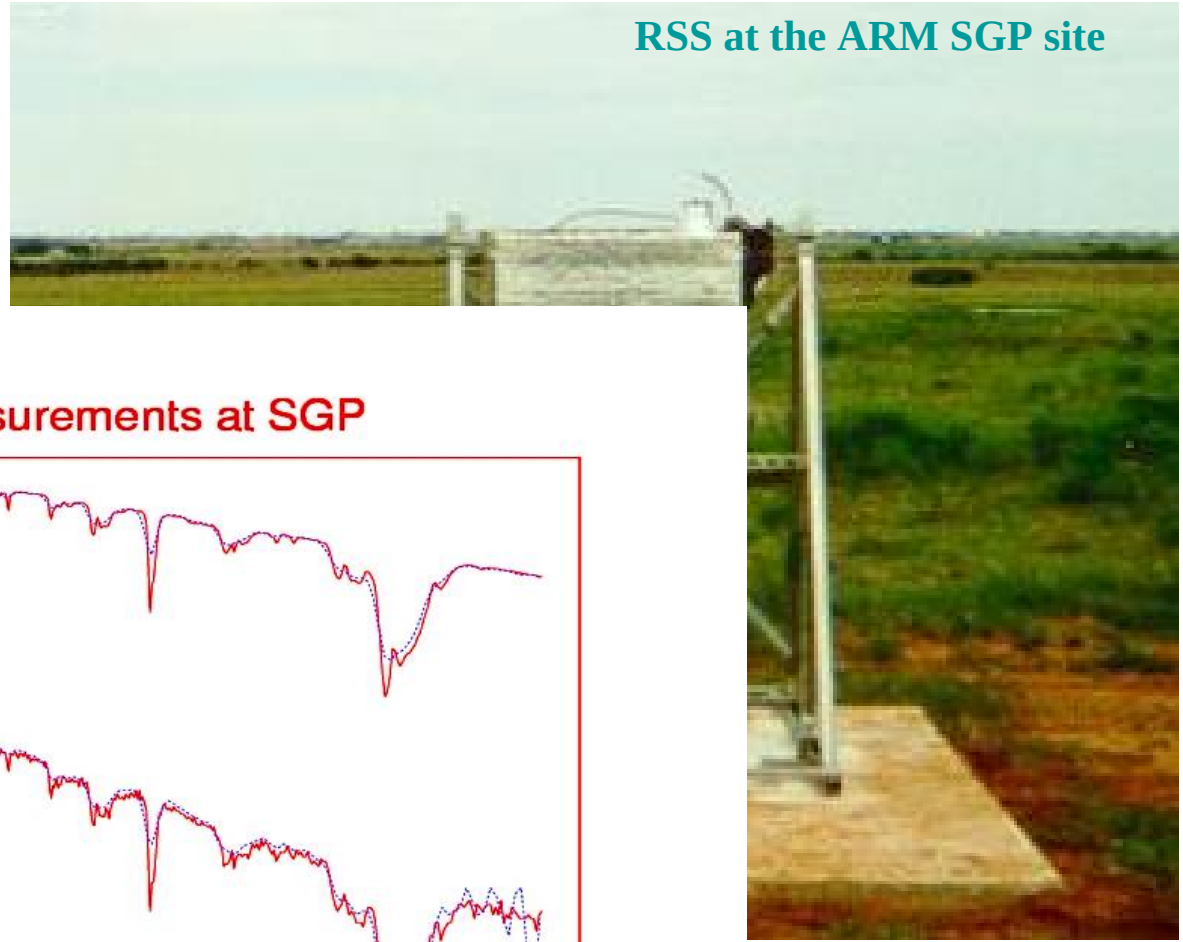


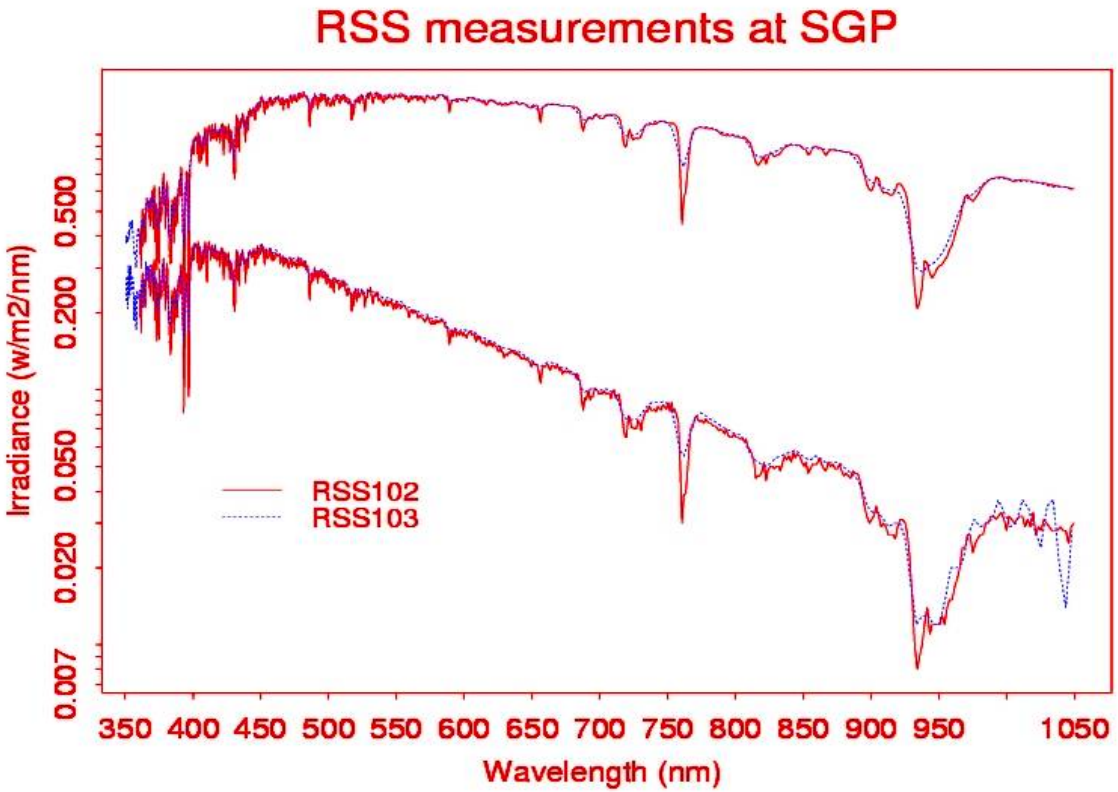
To use known absorption properties of a well mixed gas (oxygen) as a vehicle to understand radiative transfer in a multiple scattering medium, and then to exploit the scattering of the atmosphere and surface to deduce the properties of absorbing species (water).

Validate Broadband Heating Rate Profiles (BBHRP)

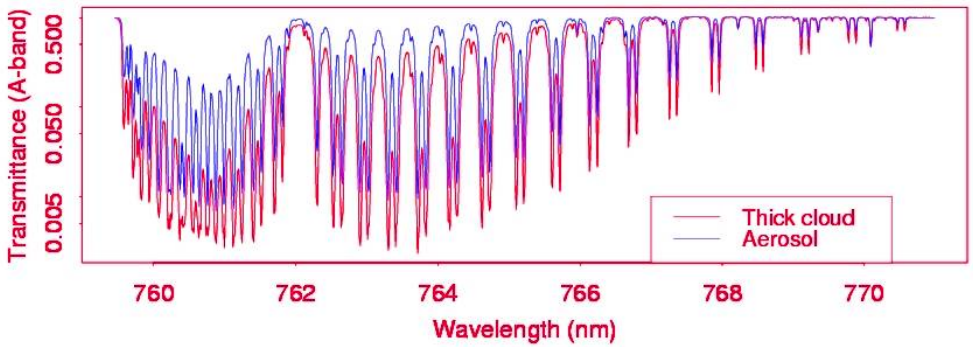


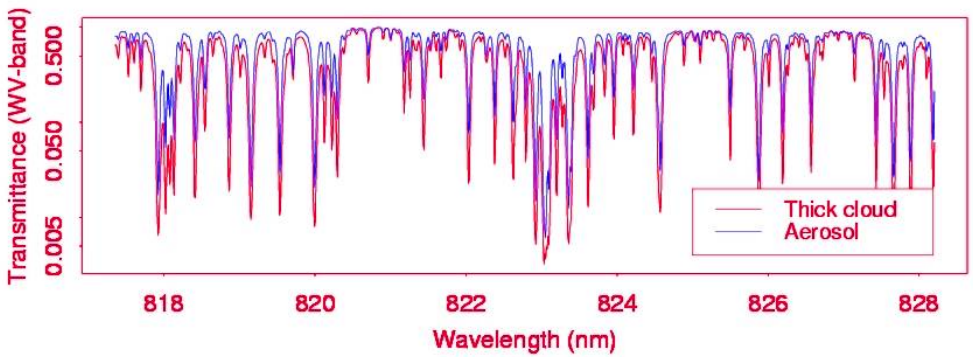
RSS at the ARM SGP site





High resolution A-band and Water vapor band Spectrometer (HAWS)

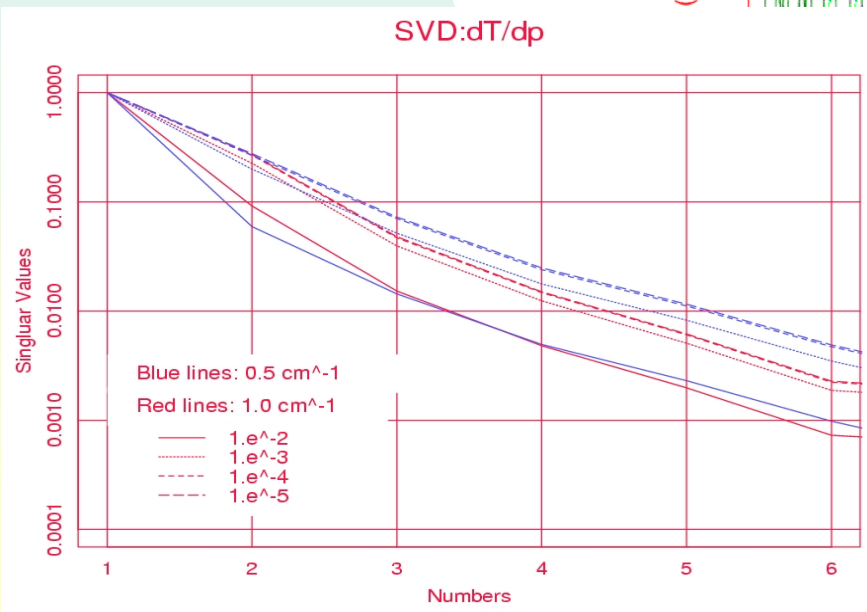


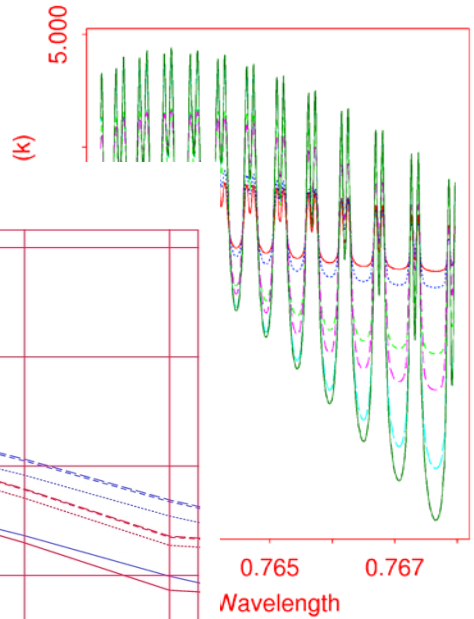


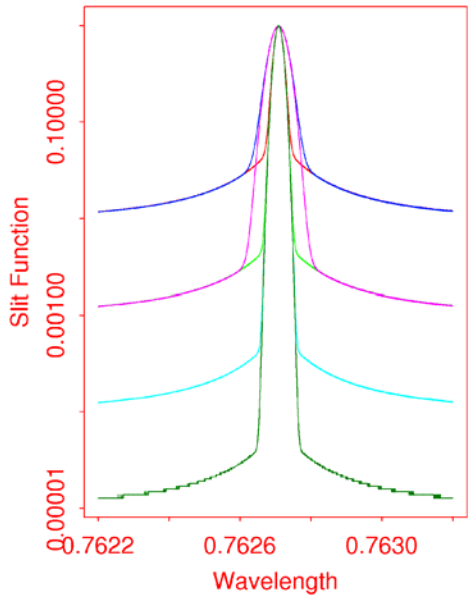
Information content and instrument specifications

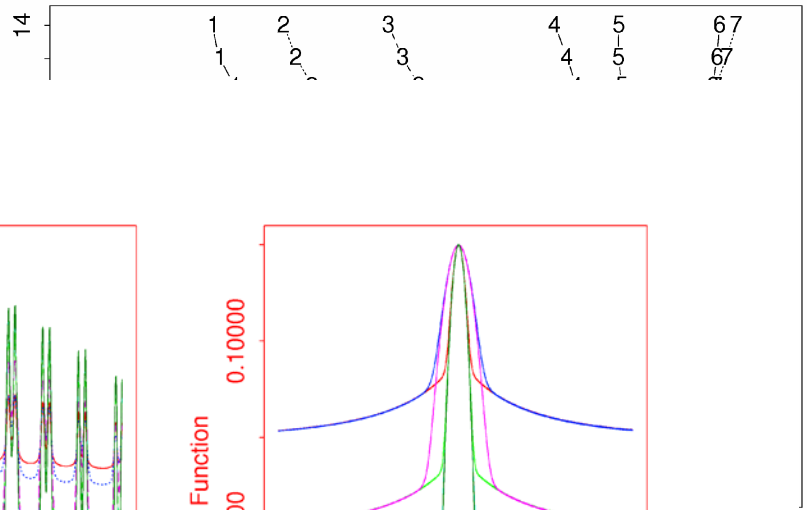
Instrument characteristics:

- **Resolution**
- **Signal to noise ratio**
- **Out of band rejection**
- **Stability**
- **Nonlinearity**
- **Calibration**



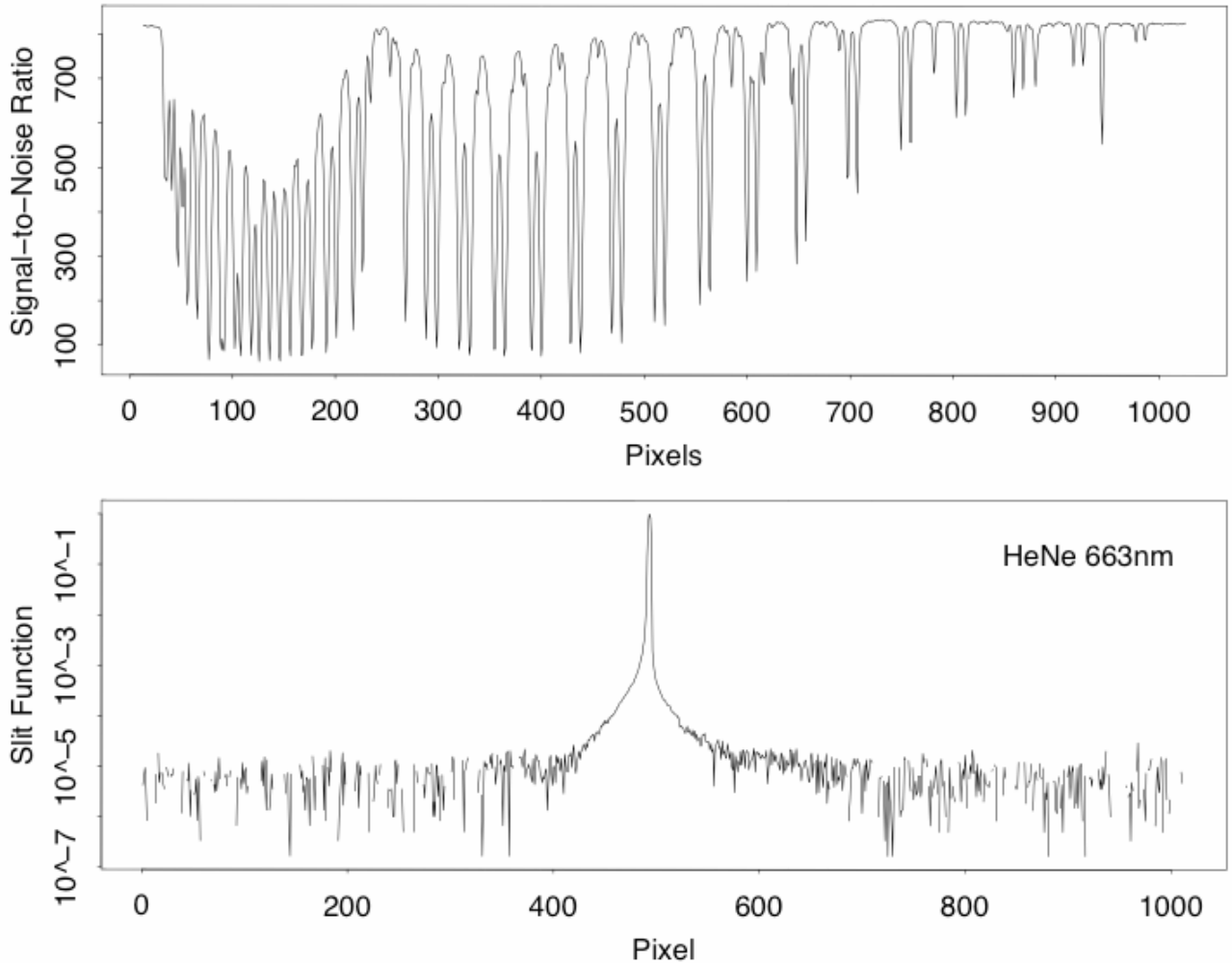






Min and Harrison, JAS, [2004]

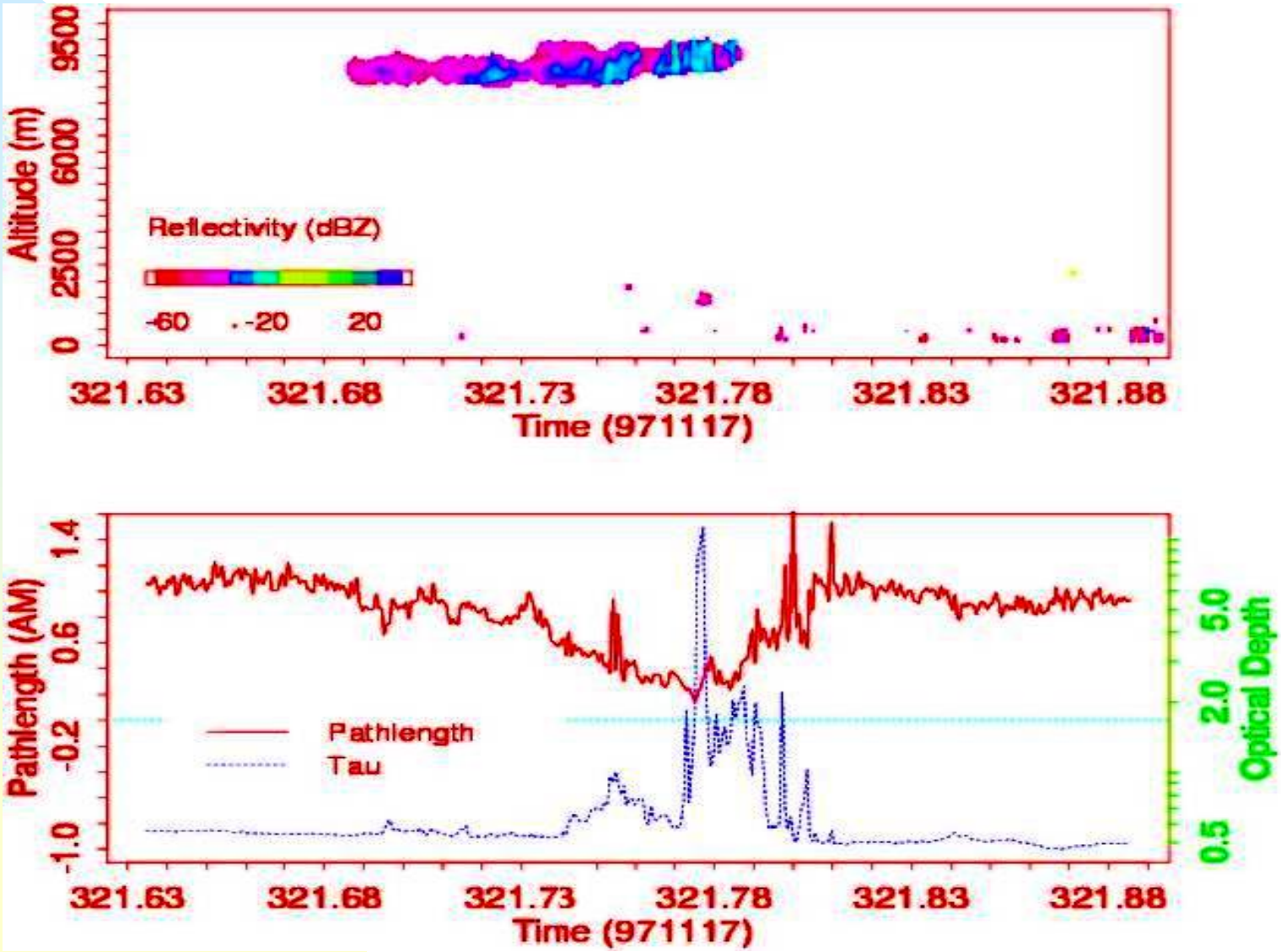
Slit Function and signal-to-noise ratio of HAWS



Min et al., JGR, [2004]

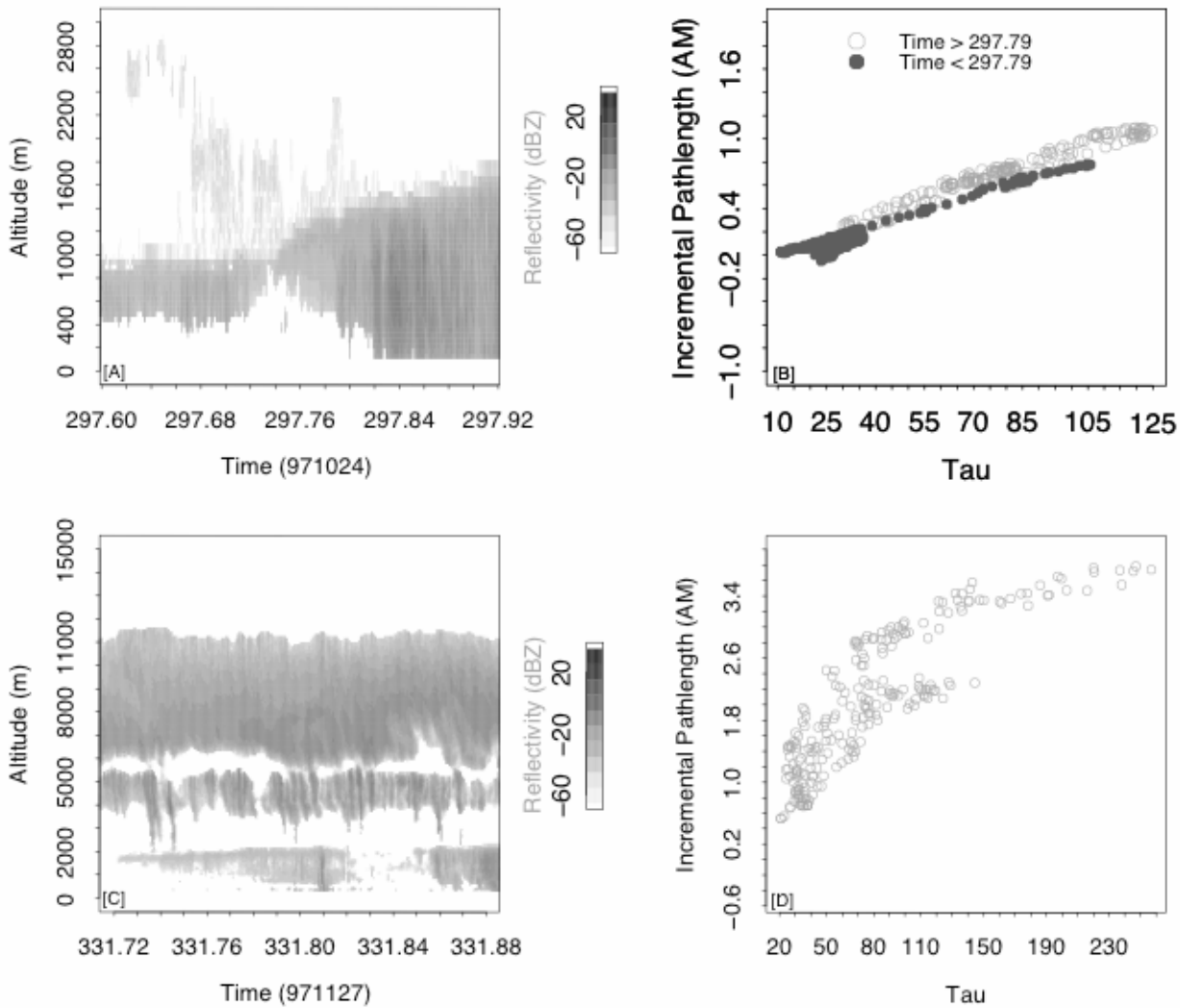
Retrievals of photon path length information from $R\ (k_{\nu,}\mu,\phi;\mu_0,\phi_0)$

Thin cirrus cloud and aerosol case [Min et al. 2001]



Retrievals of photon path length information from $R\ (k_{\nu}, \mu, \phi; \mu_0, \phi_0)$

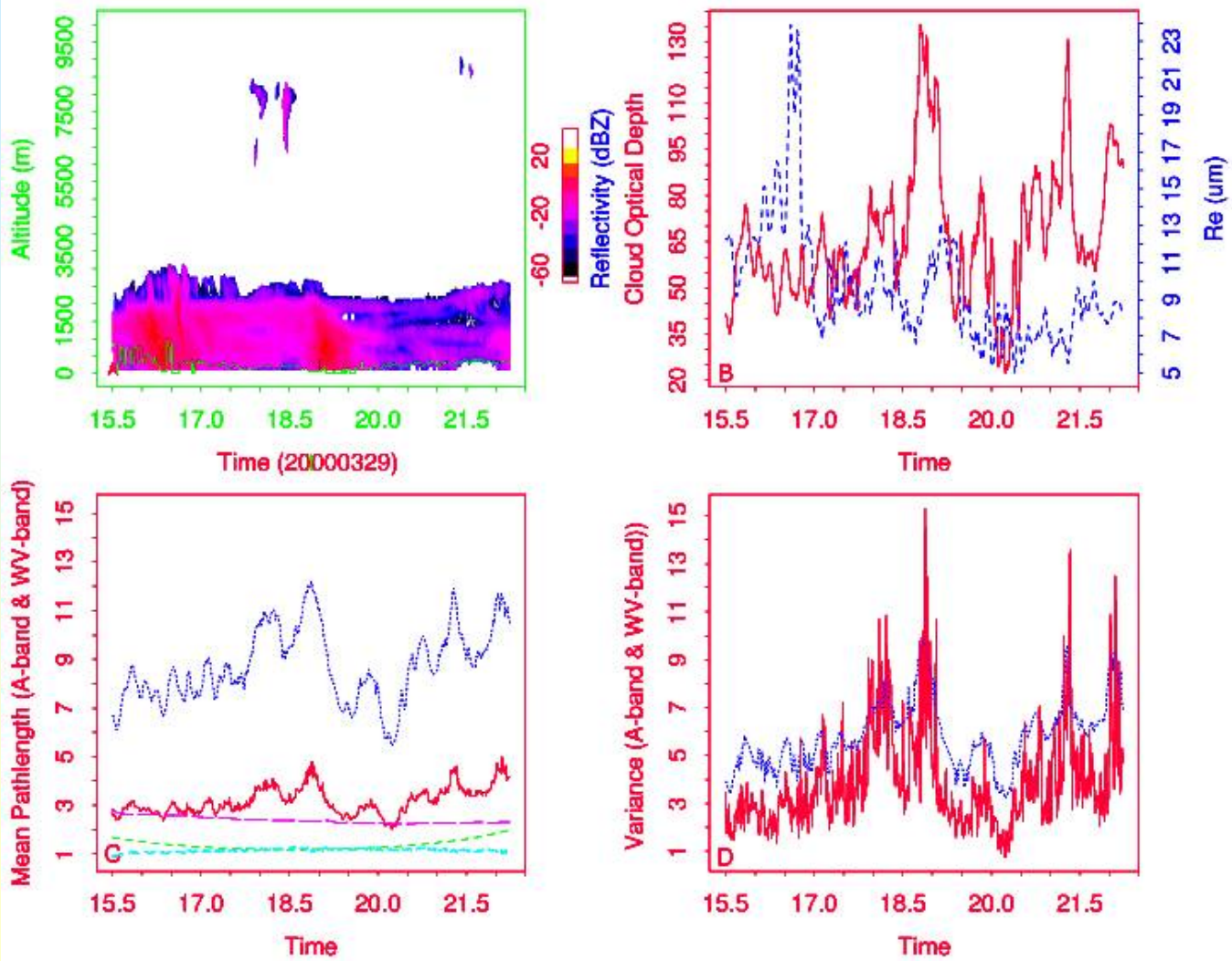
Single and multi-layer clouds [Min et al. 2001]



Retrievals of photon path length information from $R\ (k_{\nu,}\mu,\phi;\mu_0,\phi_0)$

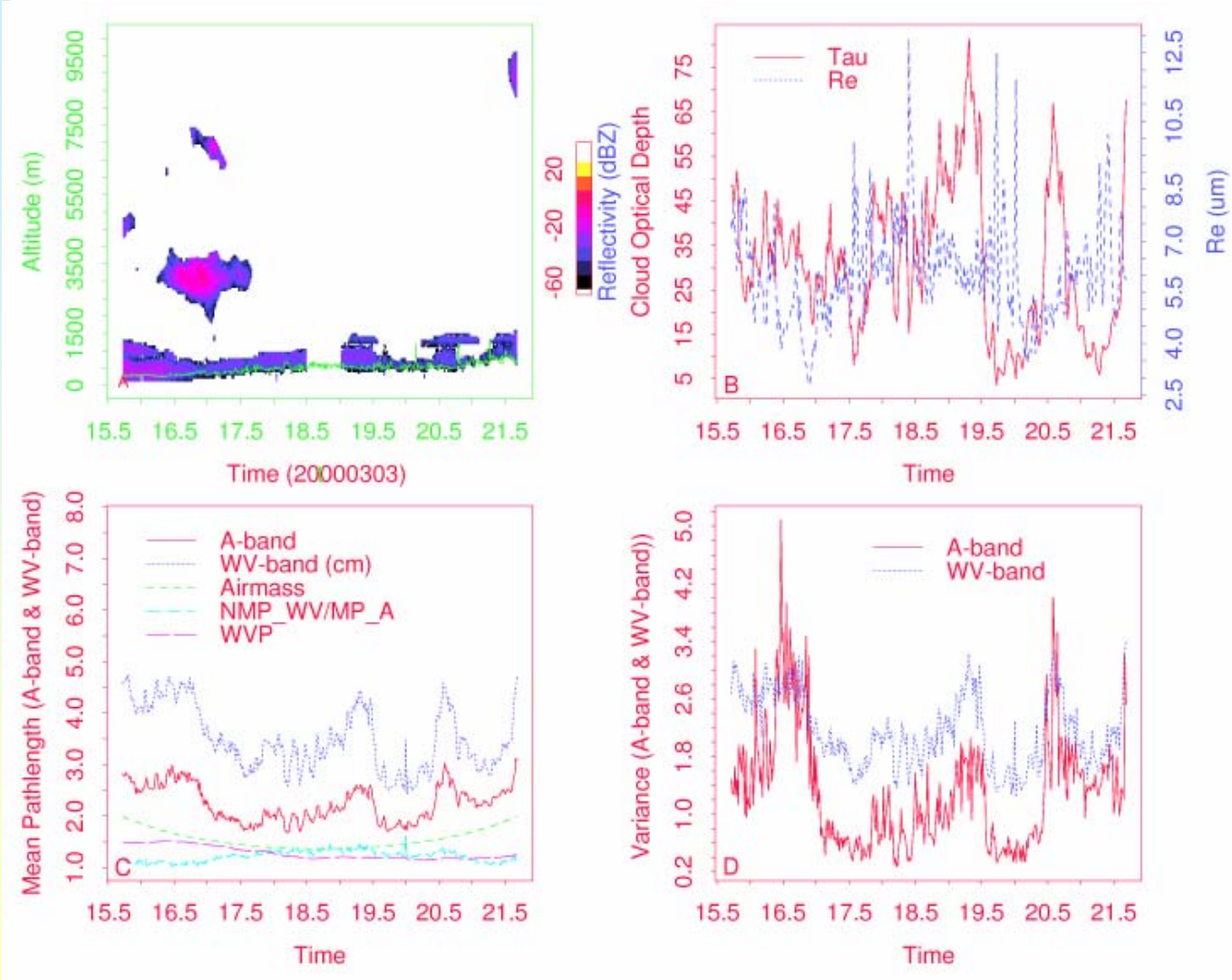
Detecting "missed" cloud by MMCR from mean and variance

[Min and Clothiaux, 2003]



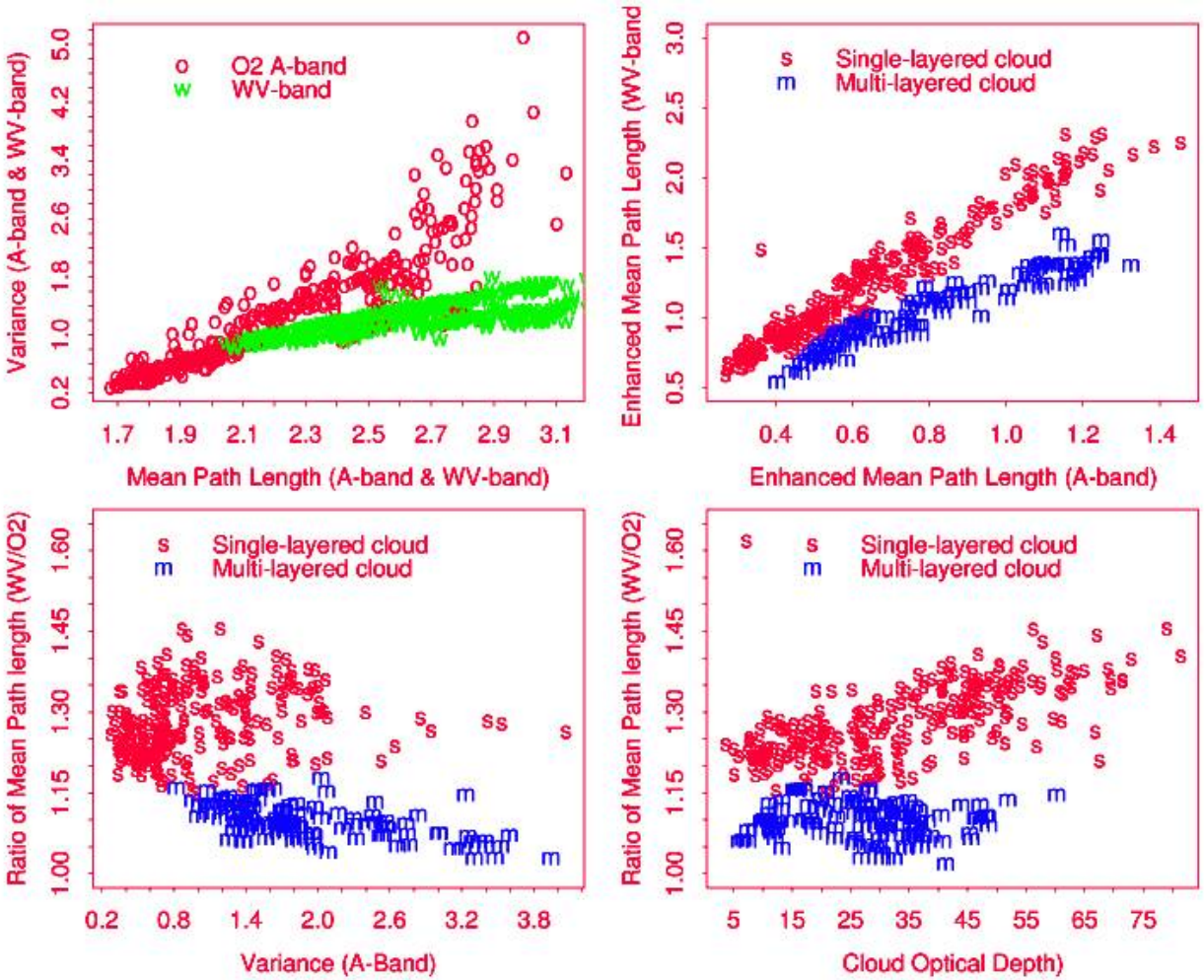
Retrievals of photon path length information from $R\ (k_{\nu}, \mu, \phi; \mu_0, \phi_0)$

Mean and variance of path length distribution [Min and clothiaux, 2003]

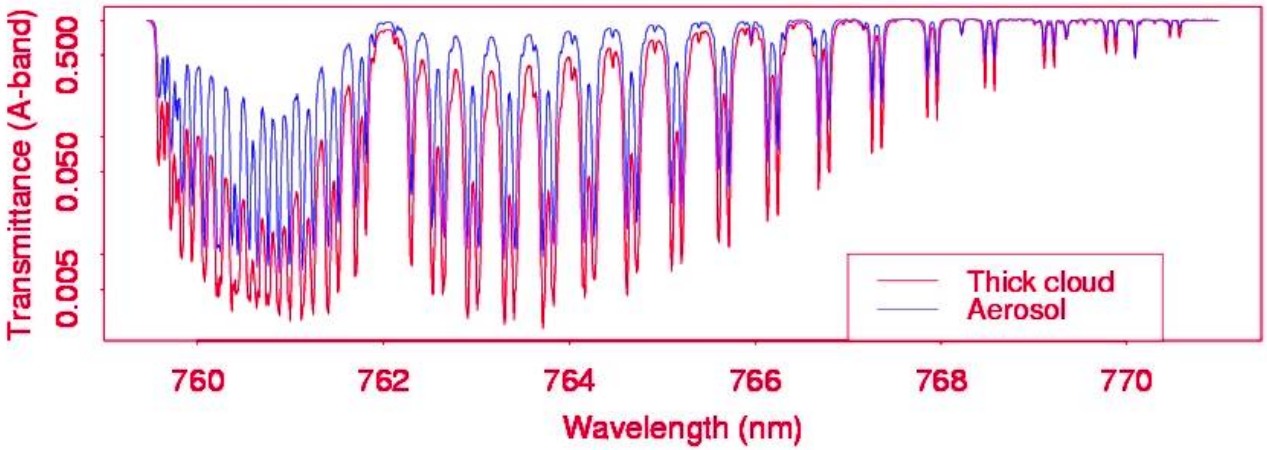


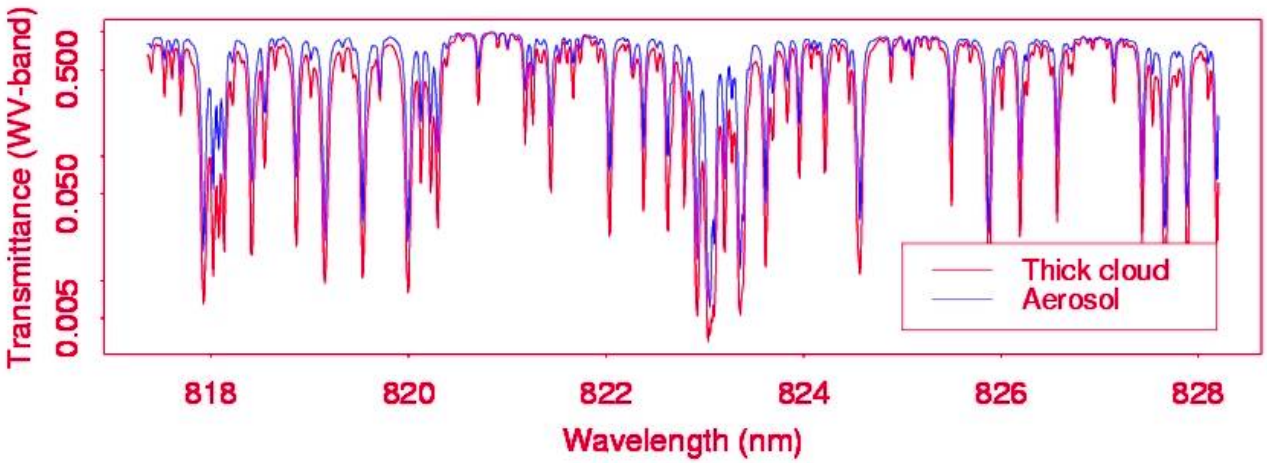
Retrievals of photon path length information from $R\ (k_{\nu}, \mu, \phi; \mu_0, \phi_0)$

Joint statistics of mean and variance of photon path length with cloud optical depth in O2 and H20 bands [Min and Clothiaux, 2003]



Measured A-band and water vapor band spectra on June 20, 2001

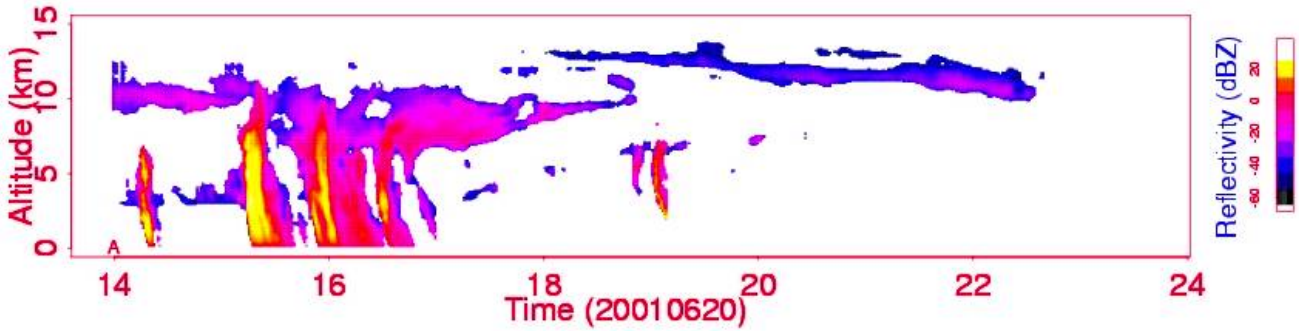


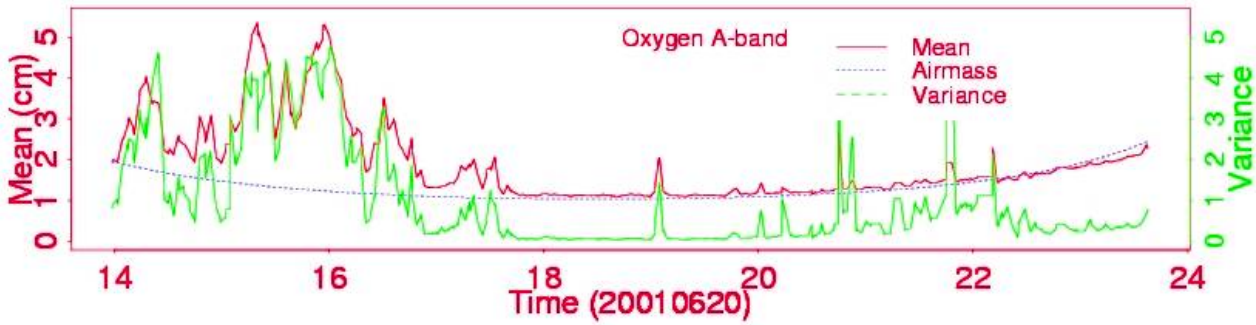


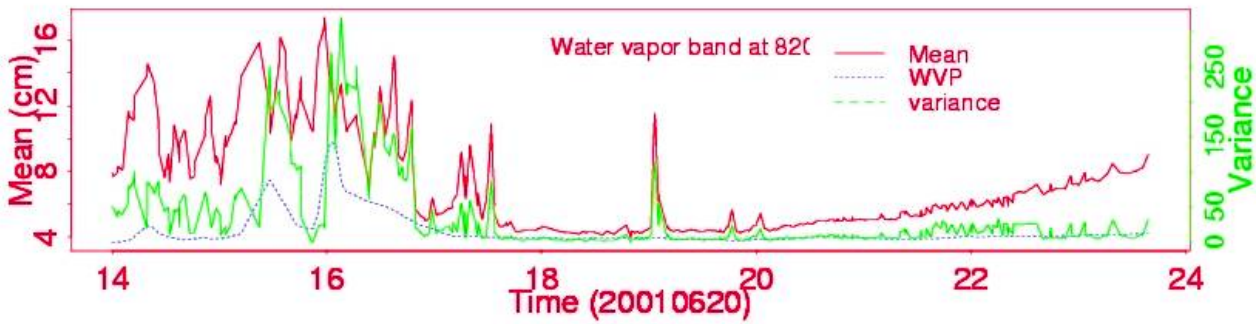
Retrievals of photon path length information from $R\ (k_{\nu,}\mu,\phi;\mu_0,\phi_0)$

moments of photon path length distribution from HAWS

[Min et al, 2004c]

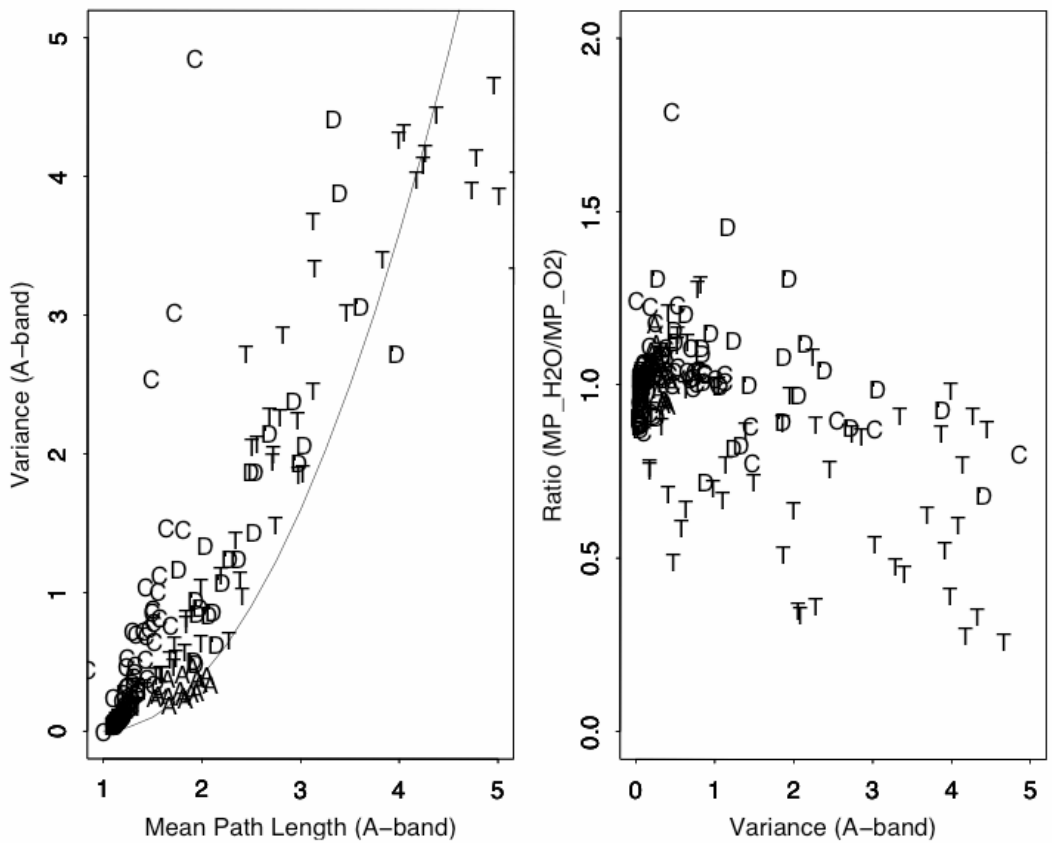






Retrievals of photon path length information from $R\ (k_{\nu}, \mu, \phi; \mu_0, \phi_0)$

moments of photon path length distribution from HAWS: Joint statistics and photon diffusion theory [Min et al, 2004c]

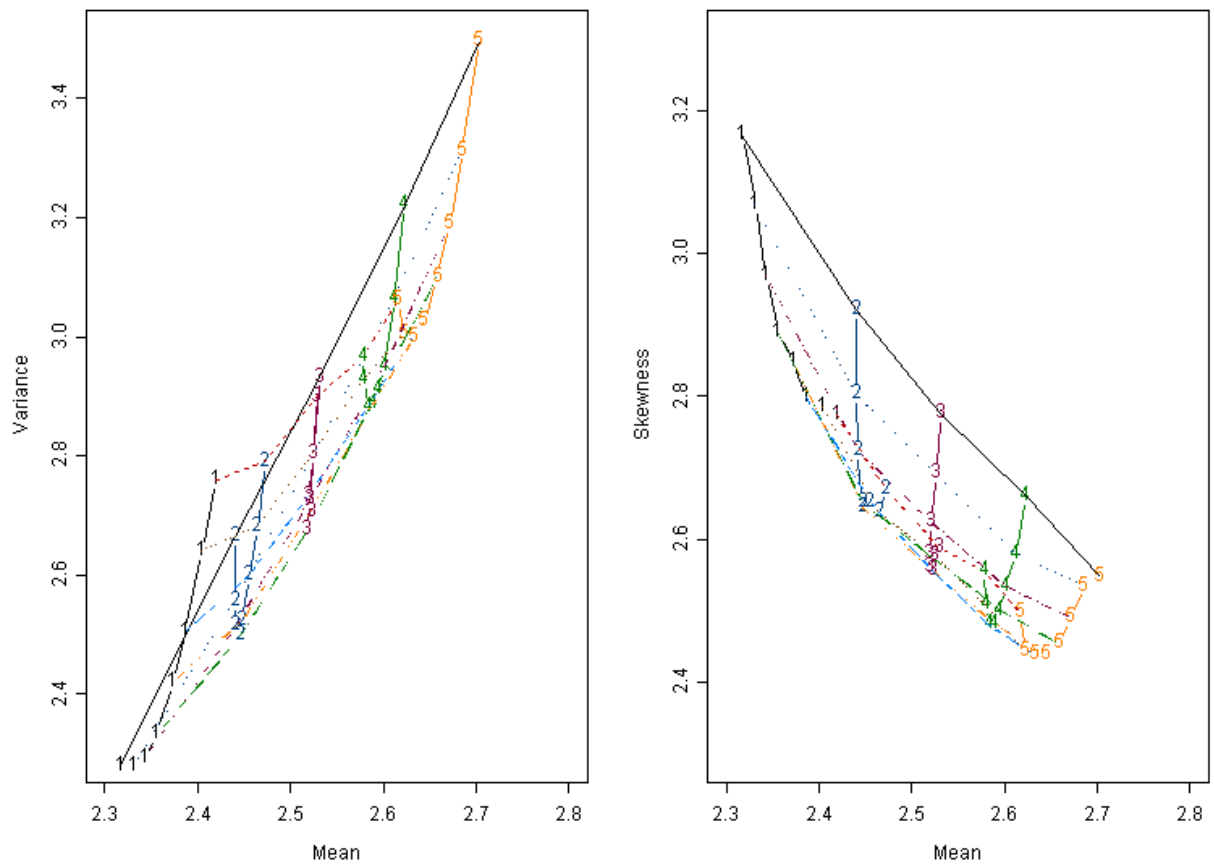


photon diffusion theory [Davis and Marshak, 2002]

$$Variance = \frac{2}{5}(Mean - 1)^2$$

Retrievals of photon path length information from $R\ (k_{\nu,}\mu,\phi;\mu_0,\phi_0)$

moments of photon path length distributions for different cloud layering relation



Photon Path Length Distribution Spectrometer

Issues:

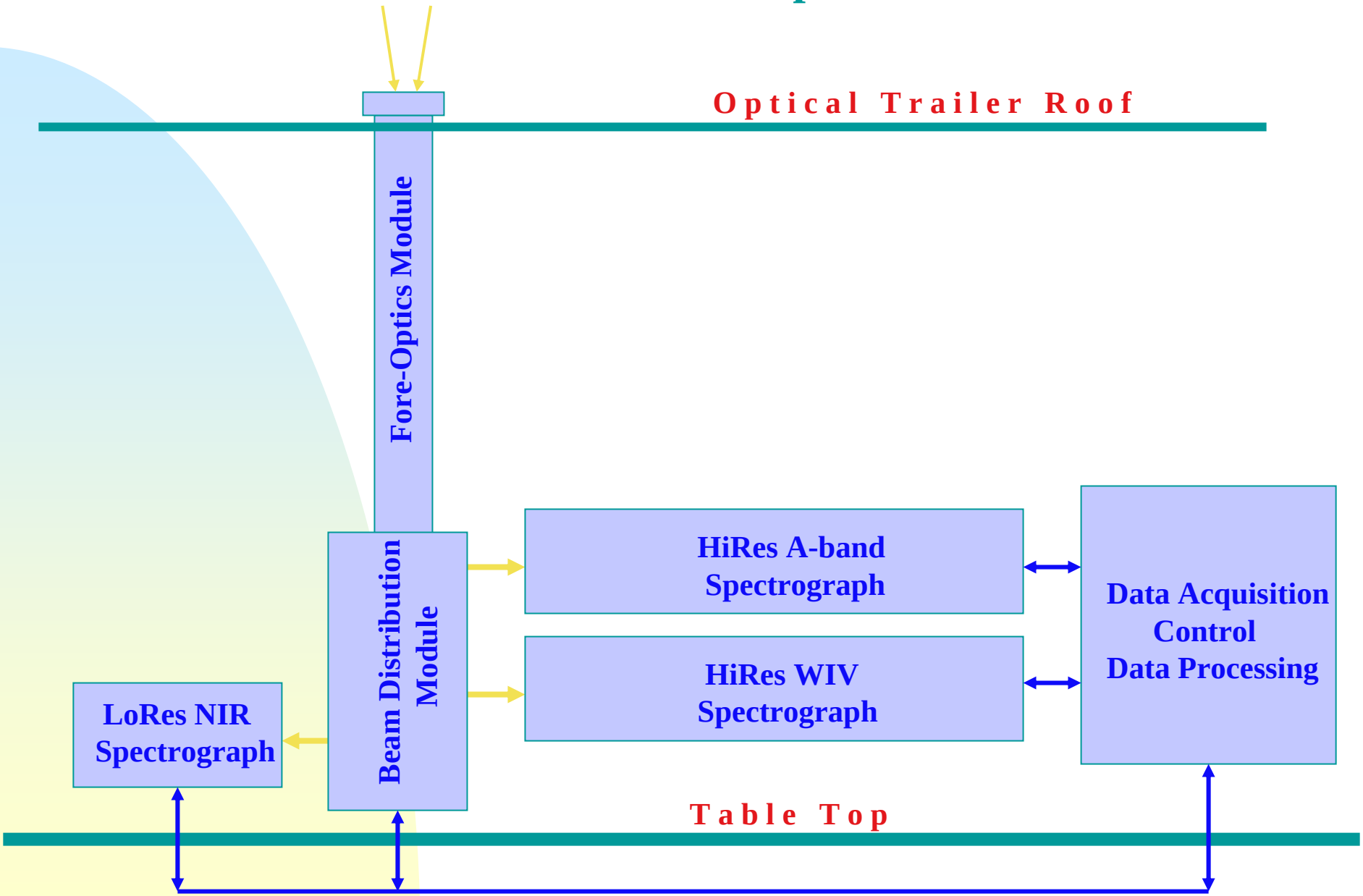
- **Understanding information content and instrument specifications**
  - **Resolution; Signal to noise ratio; Out of band rejection; Stability; Nonlinearity; and Calibration**
- **Secondary physics for instrumentation**
- **Cost-efficiency**
  - **Instrument (parts and development); measurement operation; and data analysis**

Current Status:

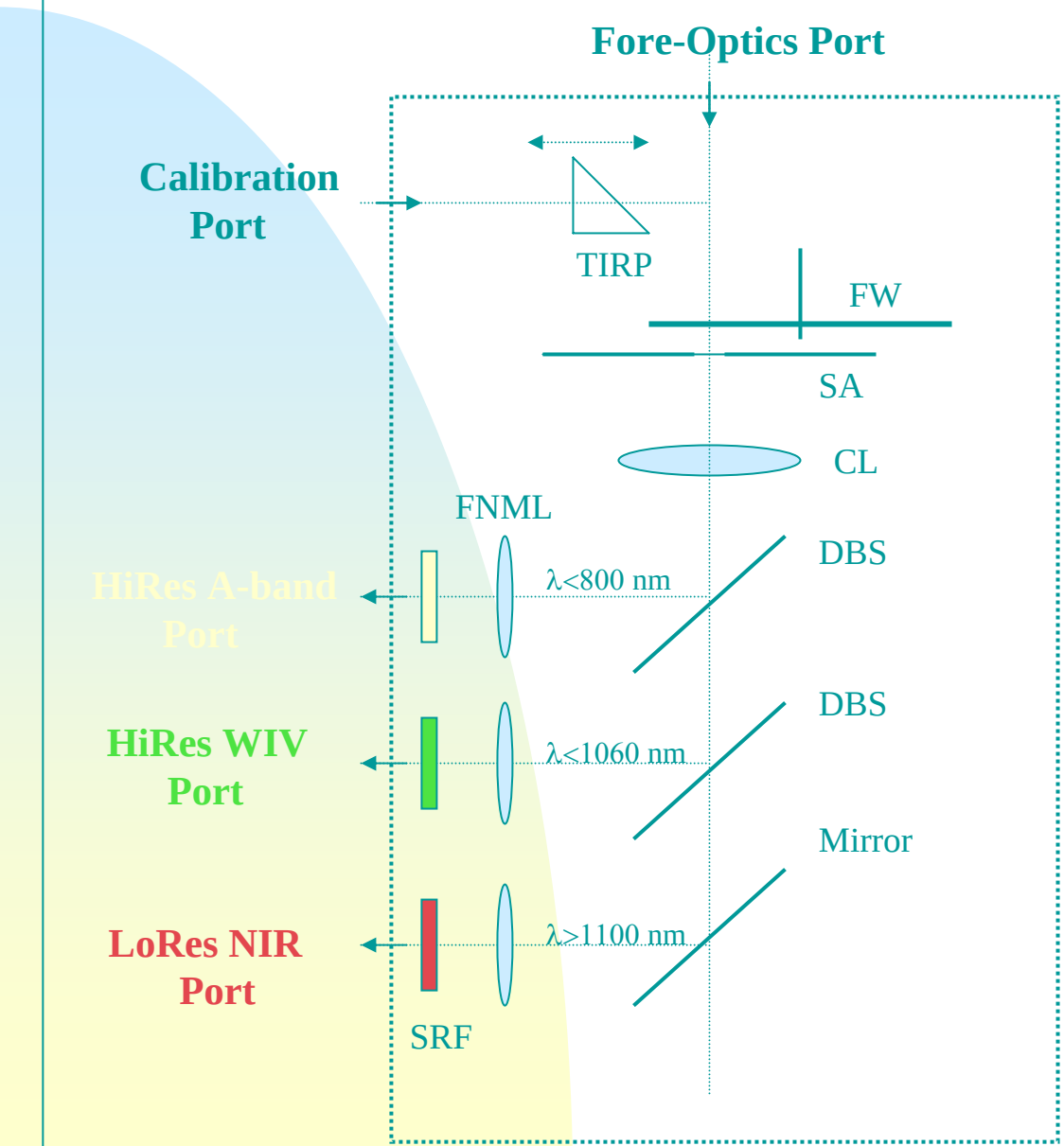
- **A working prototype that meets various specifications**
- **Retrieval algorithms are developed**

>>>A cost-efficient system (instrument/algorithm) can be developed in a timely manner

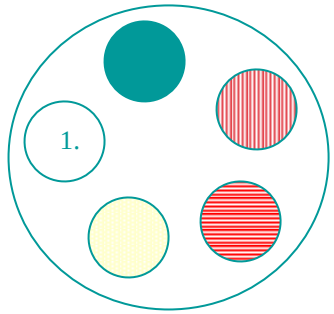
A-Band & Water-Ice-Vapor Instrument



Beam Distributor Module (BDM)



Filter wheel



1. Open
2. Shut
3. S-Polarization
4. P-Polarization
5. Attenuator

TIRP - total internal reflection prism

FW - filter wheel

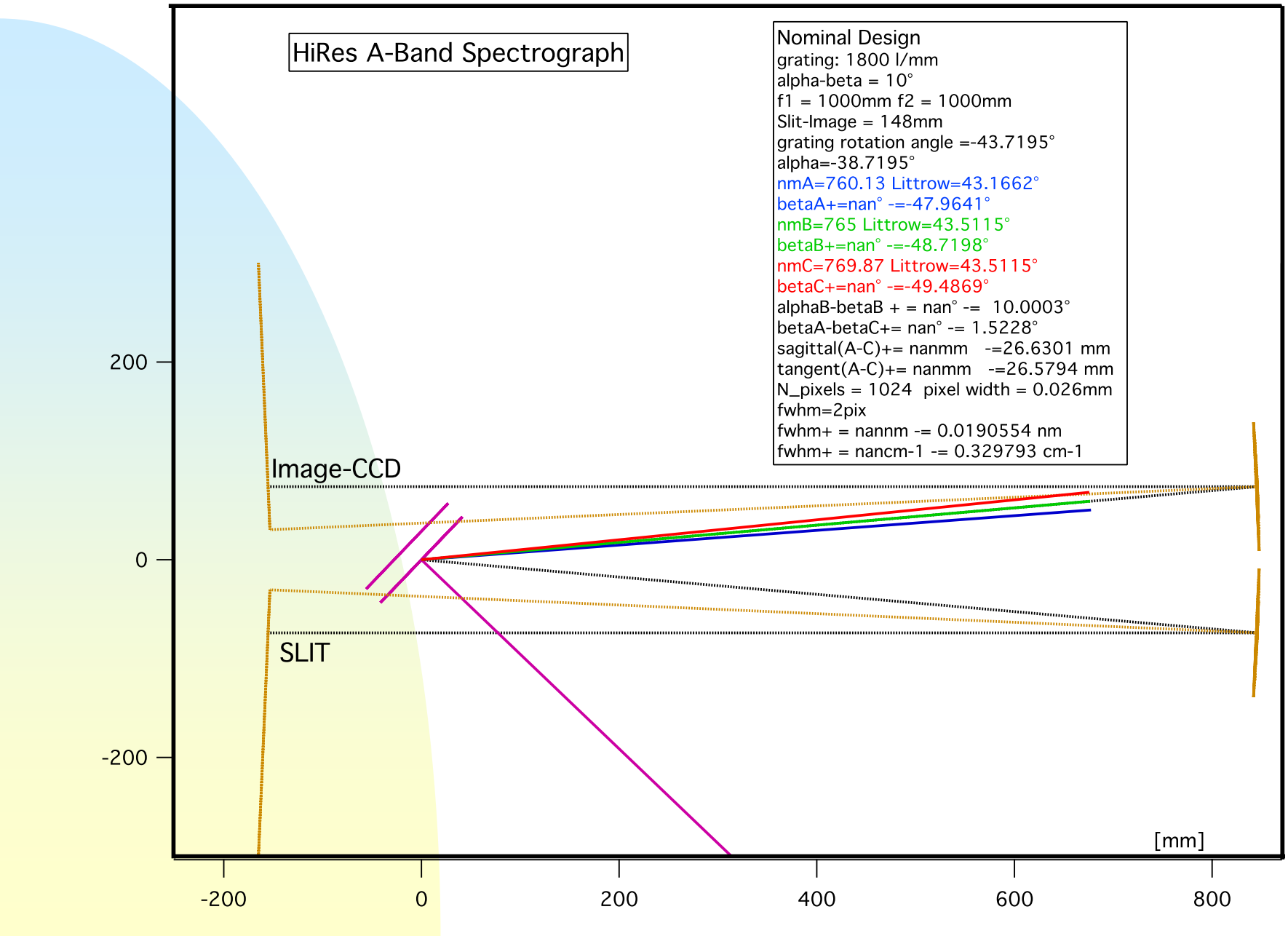
SA - secondary aperture

CL - collimating lens

DBS - dichroic beam splitter

FNML - f# matching lenses

SRF - spectral range filters


HiRes A-Band Spectrograph
Nominal Design
grating: 1800 l/mm
alpha-beta = 10°
f1 = 1000mm f2 = 1000mm
Slit-Image = 148mm
grating rotation angle =-43.7195°
alpha=-38.7195°
nmA=760.13 Littrow=43.1662°
betaA+=nan° -=-47.9641°
nmB=765 Littrow=43.5115°
betaB+=nan° -=-48.7198°
nmC=769.87 Littrow=43.5115°
betaC+=nan° -=-49.4869°
alphaB-betaB + = nan° -= 10.0003°
betaA-betaC+= nan° -= 1.5228°
sagittal(A-C)+= nanmm -=26.6301 mm
tangent(A-C)+= nanmm -=26.5794 mm
N_pixels = 1024 pixel width = 0.026mm
fwhm=2pix
fwhm+ = nannm -= 0.0190554 nm
fwhm+ = nancm-1 -= 0.329793 cm-1
Image-CCD
SLIT
200
0
-200
[mm]
-200
0
200
400
600
800

Retrievals of cloud and aerosol optical properties from $I_0(\mu,\phi;\mu_0,\phi_0)$

- **Direct beam measurements of RSS and MFRSR: optical depths of thin clouds (0~7) and aerosols [Min et al., JGR, 2004a]**
- **Diffuse measurements of RSS and MFRSR: cloud optical depth (from 5 and up) and effective radius [Min and Harrison, GRL, 1996; Min et al., JGR, 2003b]**
- **Simultaneously retrieving cloud optical depth and effective radius for optically thin clouds from forward scattering lobe of direct beam [Min and Duan, 2005]**

Retrievals of photon path length information from $R\ (k_{\nu,}\mu,\phi;\mu_0,\phi_0)$

- **Mean path length from the first generation of RSS [Min and Harrsion, GRL, 1999; Min et al., JGR, 2001]**
- **Mean and variance of phton path length distribution from oxygen A-band and water vapor band [Min and Clothiaux, JGR, 2003; Min et al, JGR, 2004b].**