Passive Remote Sensing of Clouds from Airborne Platforms

- Why airborne measurements?
- My instrument: the Solar Spectral Flux Radiometer (SSFR)
- Some spectrometry/radiometry basics
- How can we infer cloud properties (thermodynamic phase, droplet size, optical depth, liquid water path) from solar (visible and near infrared) reflected radiation?
- Some examples of data and retrievals

Why Make Airborne Measurements?

- For climate studies, the high temporal and spatial variability of aerosols and clouds require near-continuous observations and regional/global coverage: *satellites and ground networks (AERONET)*
- Most airborne field campaigns last a few weeks at most. Flights are limited to a few hours per day: snapshots in space and time.

Why Make Airborne Measurements?

- Flight observations provide vertical profiles of radiative flux: where is radiative energy being deposited?
- Combined with *in situ* sampling of the chemical and microphysical properties of aerosols and clouds, focused intensive airborne observations provide closure tests.
- Airborne observations can be used to calibrate satellite sensors, to validate satellite retrieval algorithms (MODIS/MAS), and to test future spaceborne sensors.

NASA Ames Solar Spectral Flux Radiometer (SSFR)

- wavelength range: 300 nm to 1700 nm
- spectral resolution ~ 8-12 nm
- simultaneous zenith and nadir viewing

- hemispheric FOV
- Accuracy: ~ 3%; precision: 0.5%
- Missions: FIRE/SHEBA, DOE ARM UAV (1999, 2000, 2002), PRIDE, SAFARI-2000, ACE-Asia, CRYSTAL-FACE, DOE Aerosol IOP

Radiation

Definitions:

- radiance, or intensity: rate of transfer of electromagnetic energy per unit solid angle per unit area perpendicular to the direction of propagation

$$I = \frac{d^3E}{d\Omega \, dA_\perp \, dt}$$

Units: $Wm^{-2}\ sr^{-1}$

Radiation

Definitions:

- irradiance, or flux density: rate of transfer of electromagnetic energy per unit area

$$F = \frac{d^2E}{dAdt}$$

Units: Wm^{-2}

Radiation

- Definitions:
- relationship between radiance and irradiance:

$$I = \frac{dF}{\cos\psi d\Omega}$$

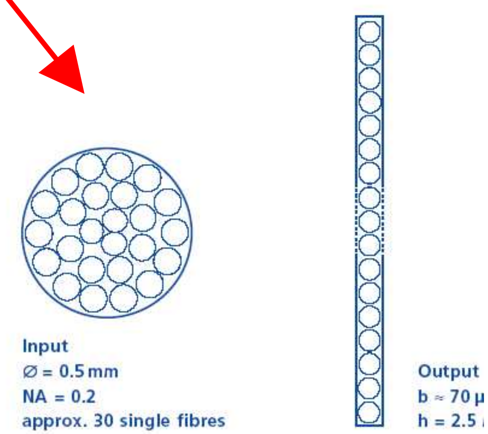
and

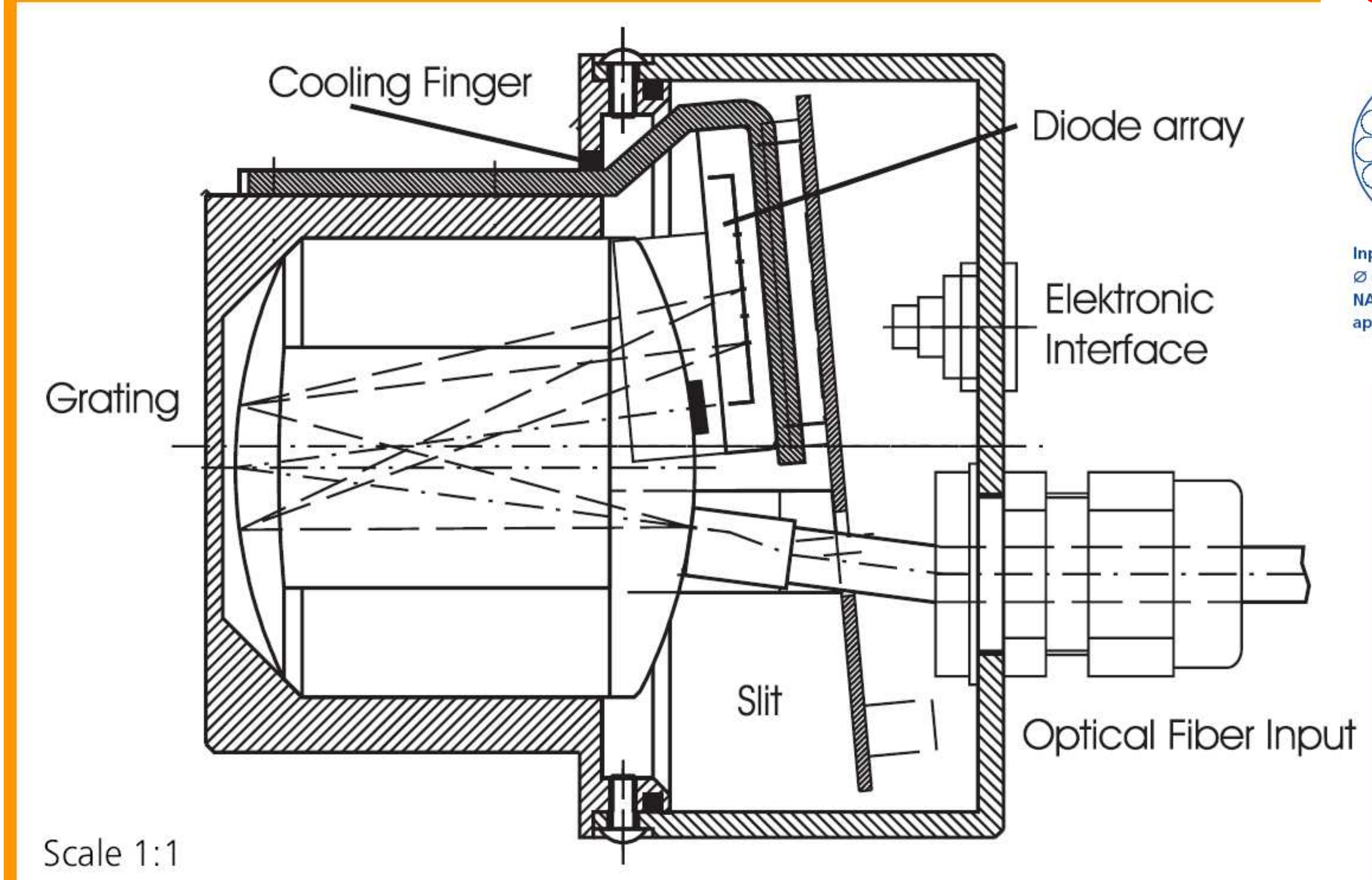
$$F = \int \cos\psi I d\Omega$$

where ψ is the angle between the pencil (beam) of radiation and the normal to the differential area, dA.

The optical components are:

- imaging grating
- fibre cross-section converter as the optical input
- diode array as the opto-electronic output

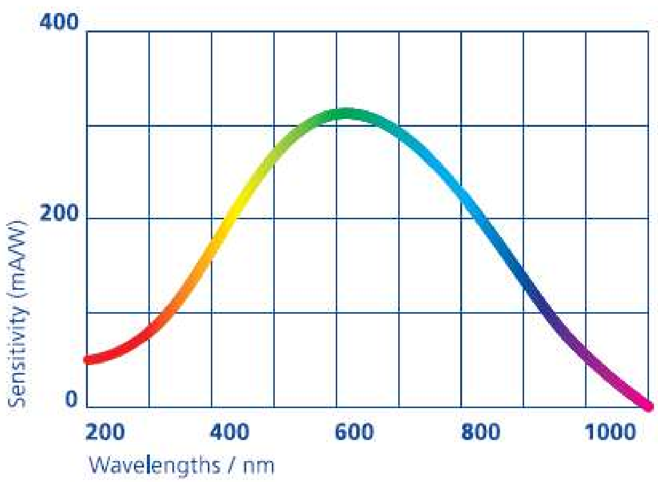


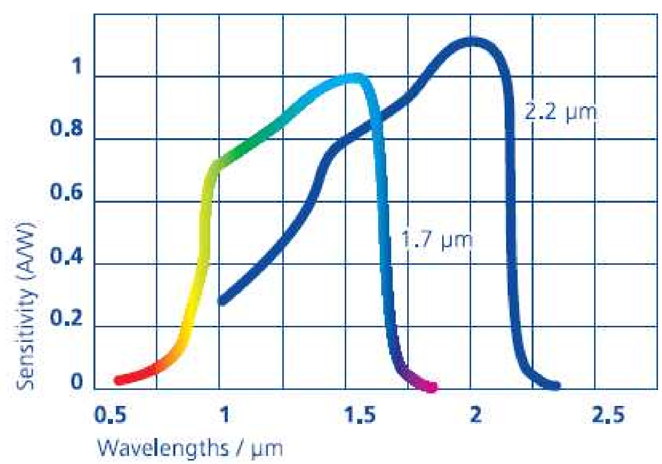


Zeiss MMS NIR

Spectral Range:
Si and InGaAs sensitivity

Spectral sensitivity of the diode array S3904-256Q, number of pixels: 256, area: 25 x 2500 µm², pitch: 25 µm



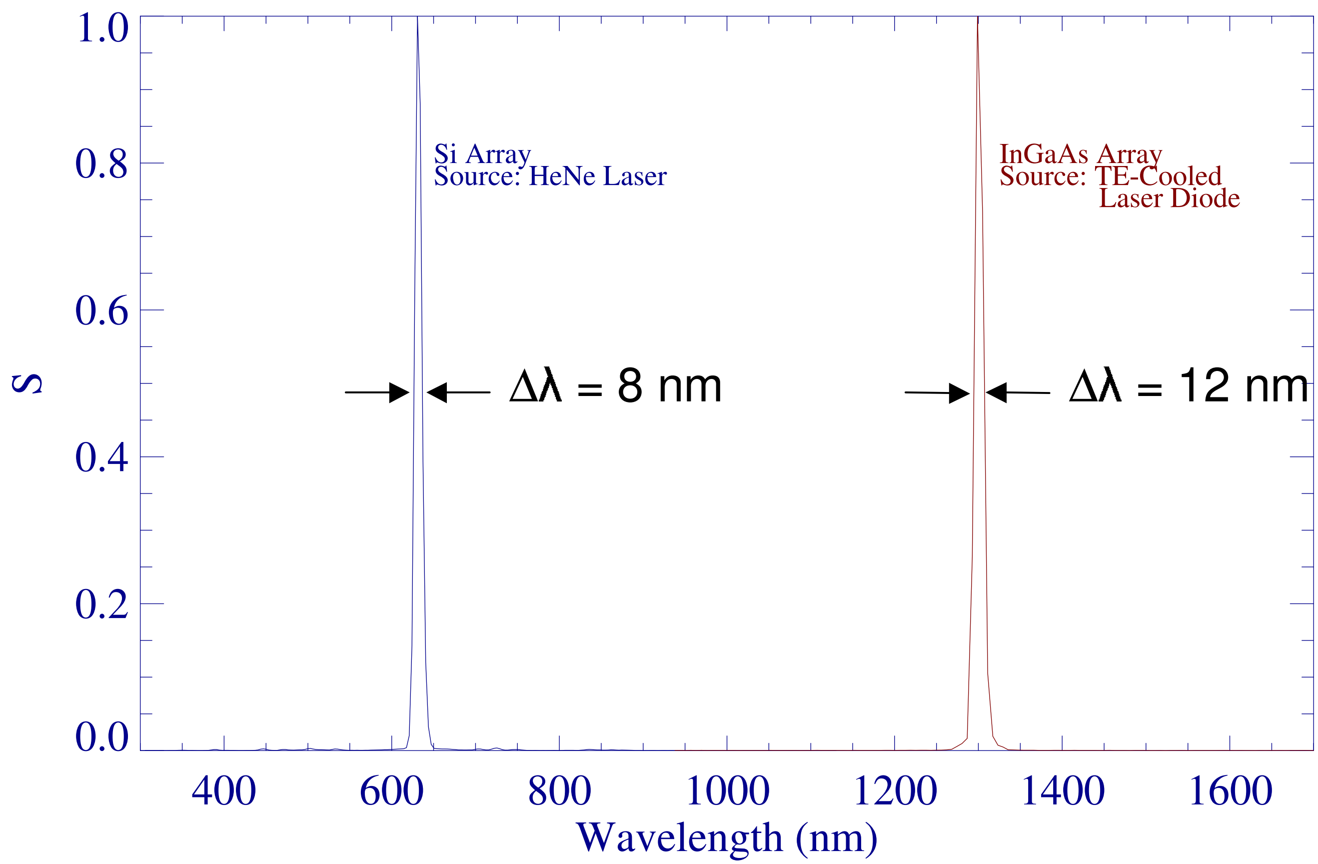


Spectral sensitivity of standard-InGaAs (1.7 µm) and extended-InGaAs (2.2 µm)

Resolution

- The resolution R is a measure of the minimum distance (in wavelength or frequency) needed to separate two spectral lines.
- One definition for resolution: full-width-at-half-maximum (FWHM) measured for a single monochromatic spectral line.

Slit Function and Resolution

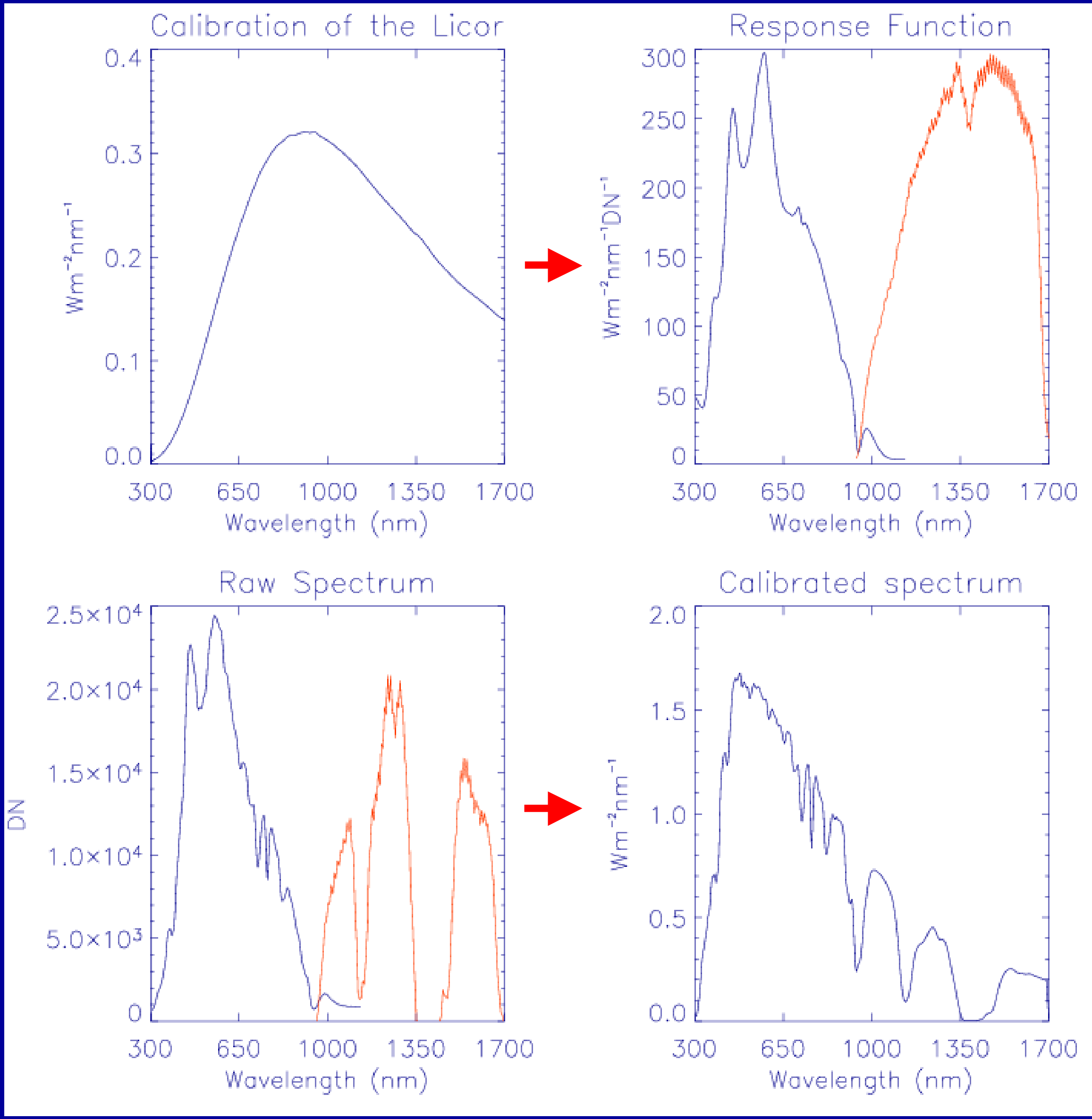


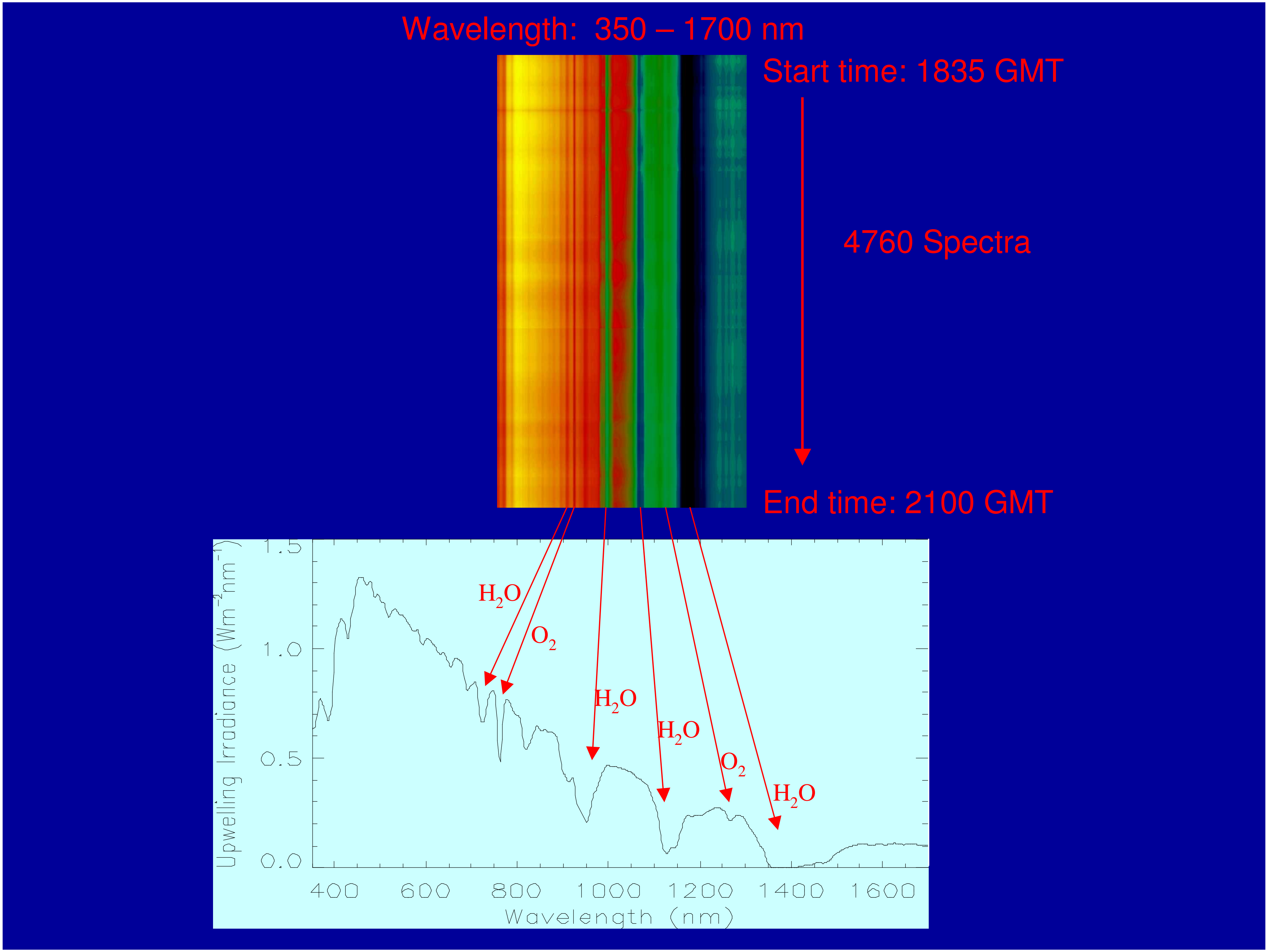
The measured signal is a convolution of the input waveform with the spectrometer slit function. We use the same instrument slit function in radiative transfer calculations to compare with measured spectra.

Stray Light

- Stray light is all spurious radiation transmitted by a spectrometer. Stray radiation sources include re-diffracted light, secondary sources, higher order diffraction, ghosts, scatters and imperfection in gratings.
- stray light is quantified by measuring a laser source and taking the ratio at out-of-band wavelengths to that at the peak.

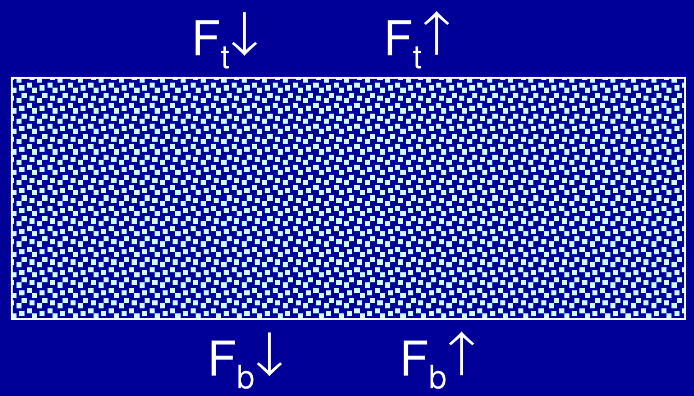
SSFR Calibration




Wavelength: 350 – 1700 nm
Start time: 1835 GMT
4760 Spectra
End time: 2100 GMT
H2O
O2
H2O
H2O
O2
H2O
Upwelling Irradiance (Wm-2nm-1)
1.5
1.0
0.5
0.0
400
600
800
1000
1200
1400
1600
Wavelength (nm)

Albedo, Net Flux, and Absorption

- Downwelliing Irradiance: $F\downarrow$
- Upwelliing Irradiance: $F\uparrow$
- Net Flux: $F\downarrow - F\uparrow$
- Albedo: $F\uparrow / F\downarrow$
- Flux Divergence (absorption):
  $(F\downarrow - F\uparrow)_{top} - (F\downarrow - F\uparrow)_{bottom}$
- Fractional absorption:
  $(F\downarrow - F\uparrow)_{top} - (F\downarrow - F\uparrow)_{bottom} / F\downarrow_{top}$



Cloud Remote Sensing

- How can droplet size be inferred?
  - Clouds scattering changes very little with angle, unlike scattering from a single droplet
- Geometric optics approximation, weak absoprtion ($r/\lambda \gg 1$ and $rk_a \ll 1$):

$$1 - \varpi_o \propto rk_a$$

- Multiple Scattering, fractional absorption:

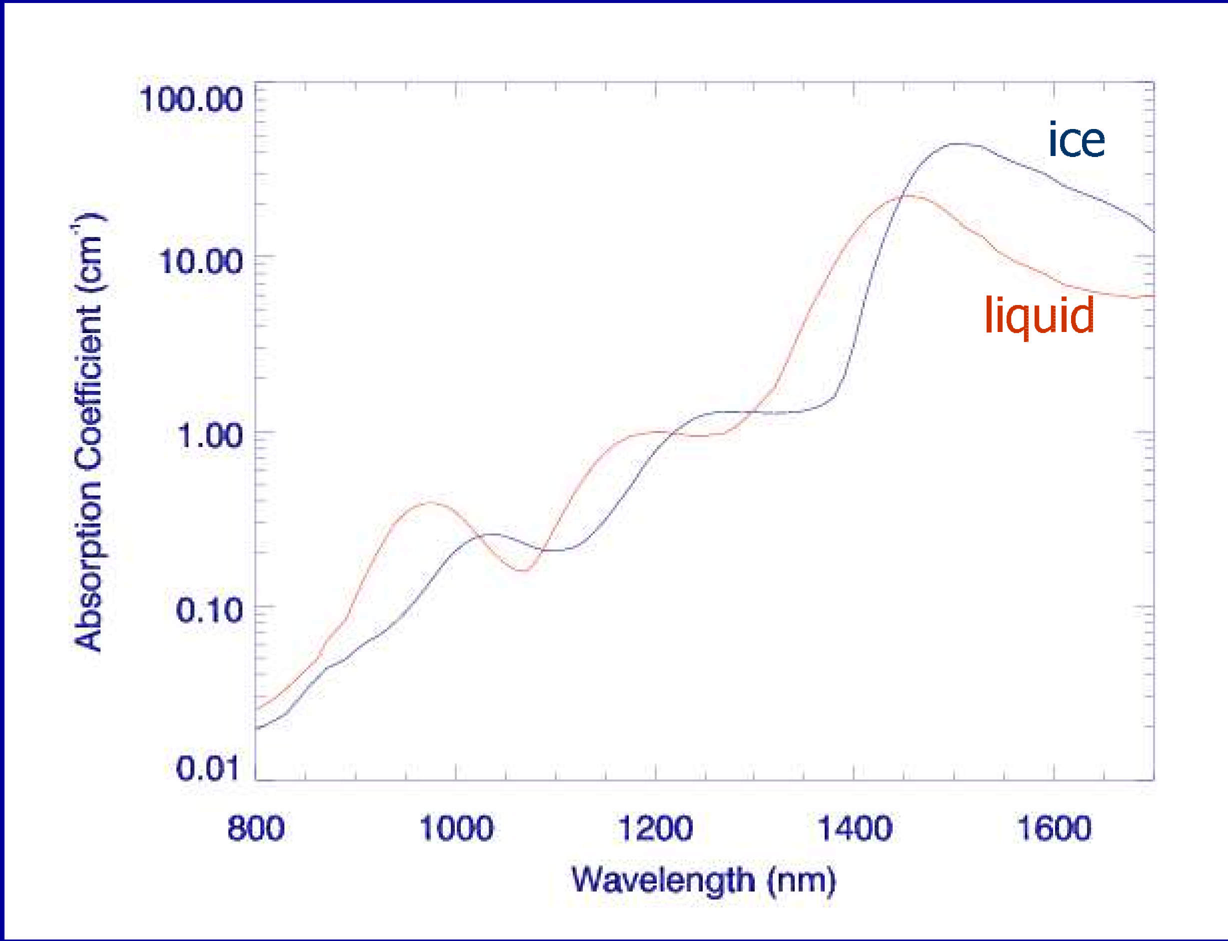
$$\alpha \propto \sqrt{1 - \varpi_o}$$

r: droplet radius

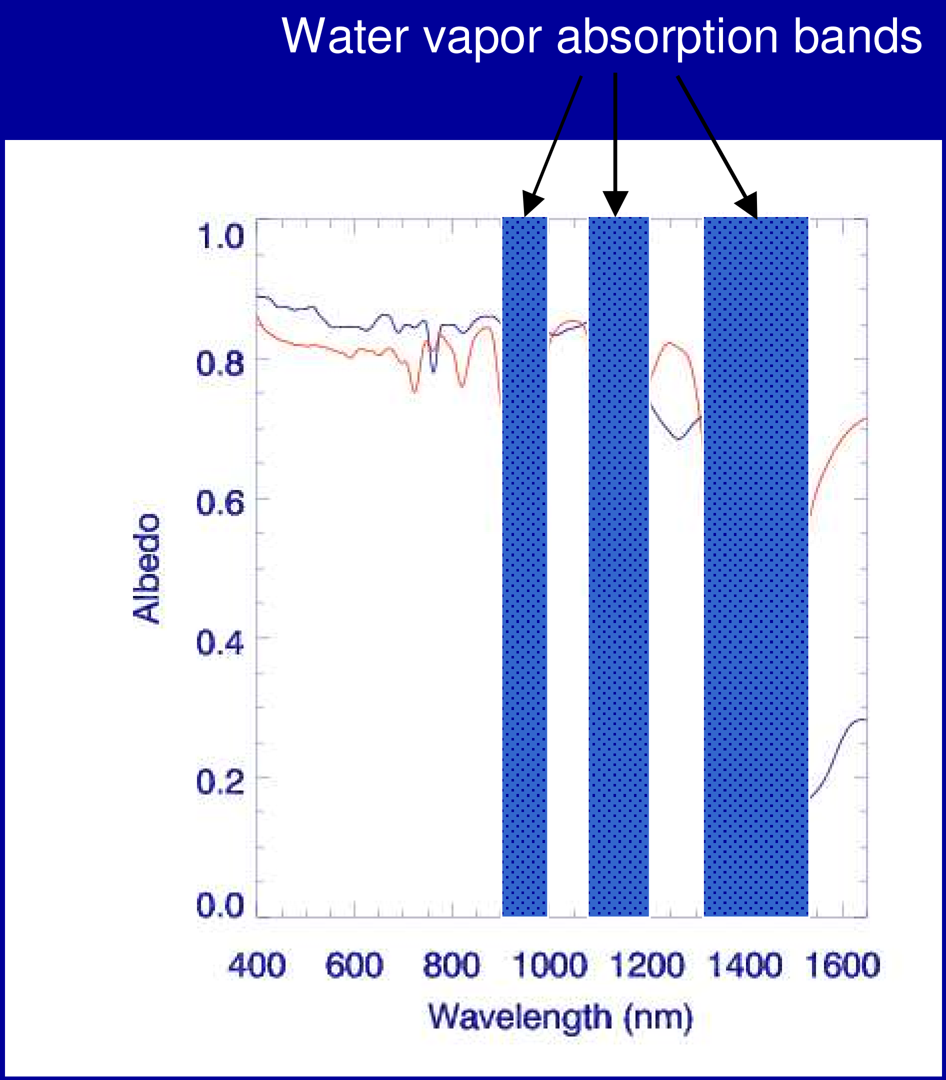
ka: absorption coeff.

ϖo: single scatt. albedo

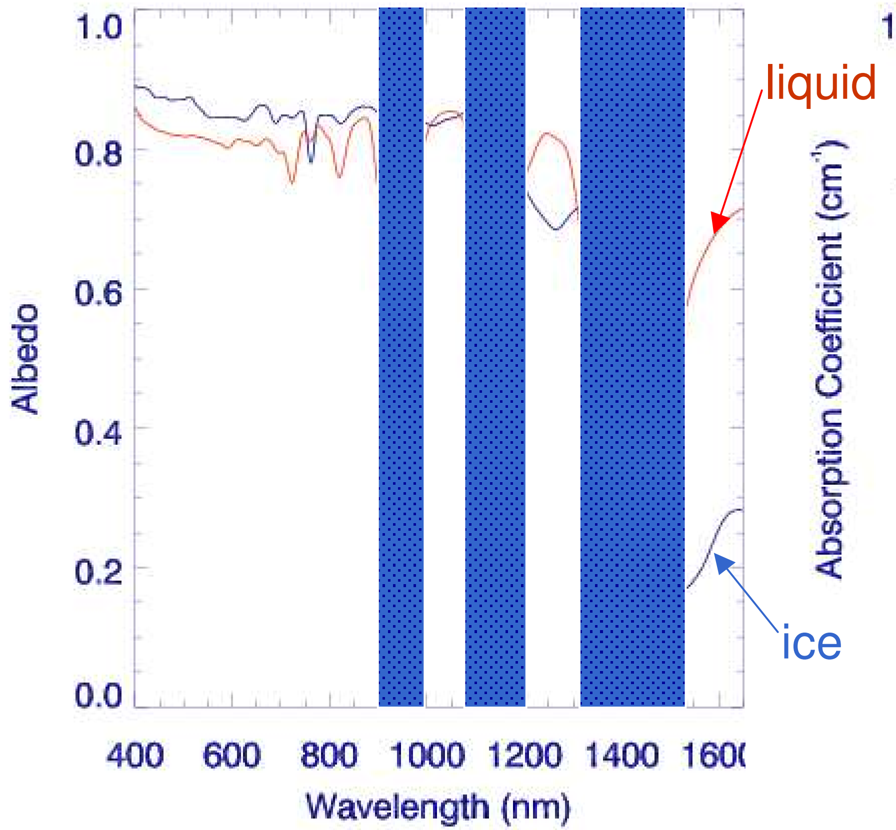
Absorption Coefficient of Condensed Water

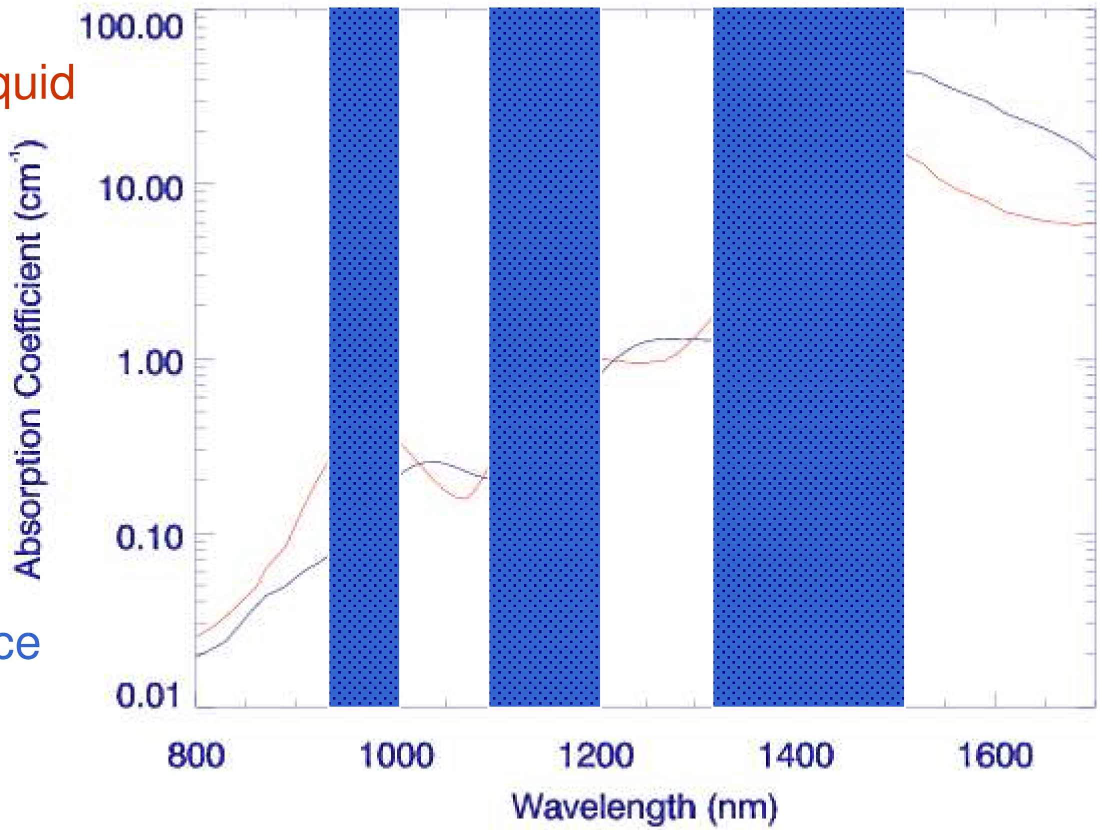


Measured Cloud Albedo

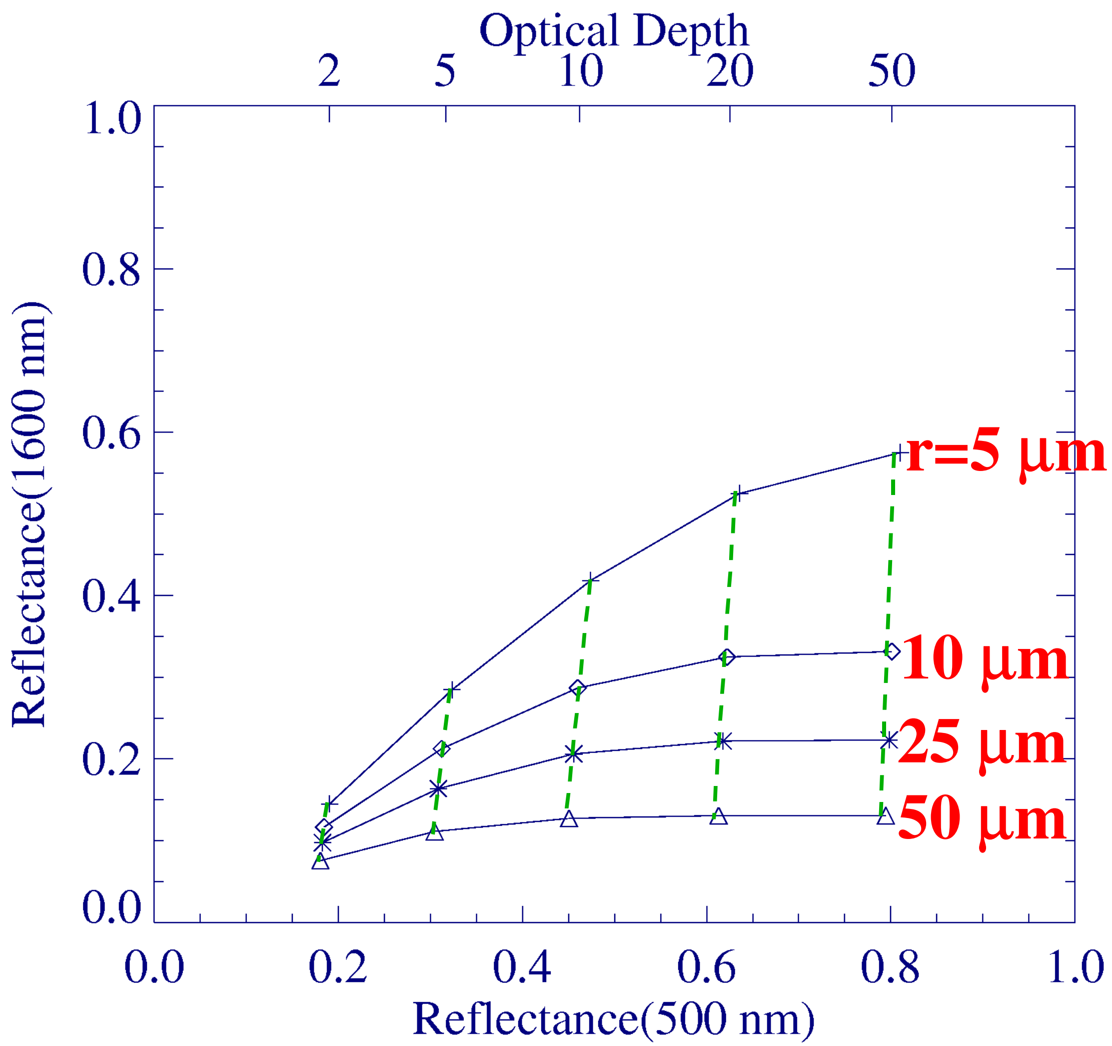


What is the cloud phase?





Cloud Reflectance



Retrieval of r_e and optical depth

- Find the best fit between measured and calculated spectra
- Use only a few bands in the window regions
- Minimize a chi-square statistic comprised of direct albedo differences (absolute) and differences of albedo ratios (relative).

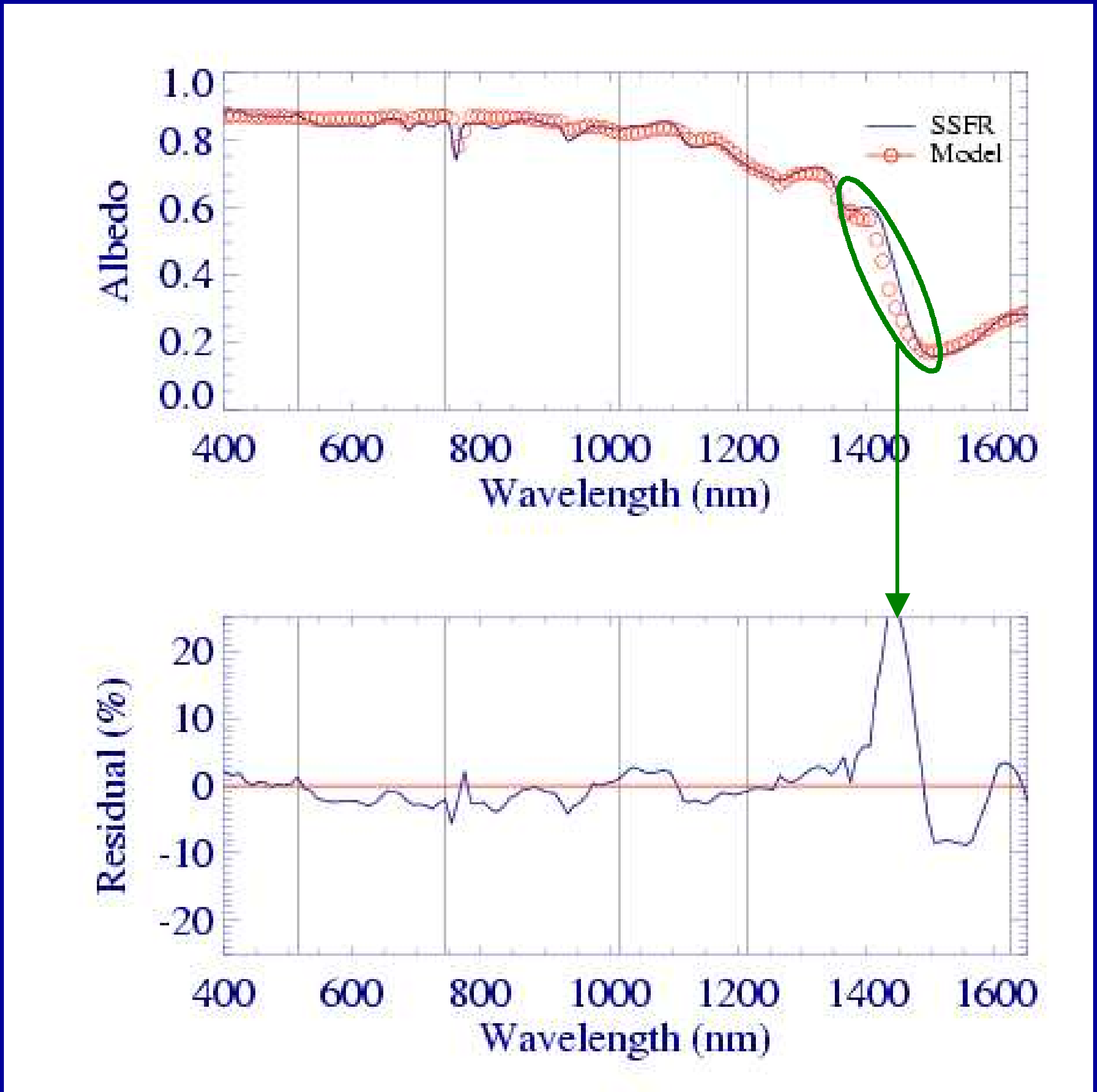
$$\chi^2 = \sum \{a_i[A_{i_{ssfr}} - A_{i_{mod}}]\}^2 + \{b_i[(A_i/A_{500nm})_{ssfr} - (A_i/A_{500nm})_{mod}\}^2$$

weight most heavily at shortest (vis) wavelengths: optical depth

weight most heavily at longest (nir) wavelengths: effective radius

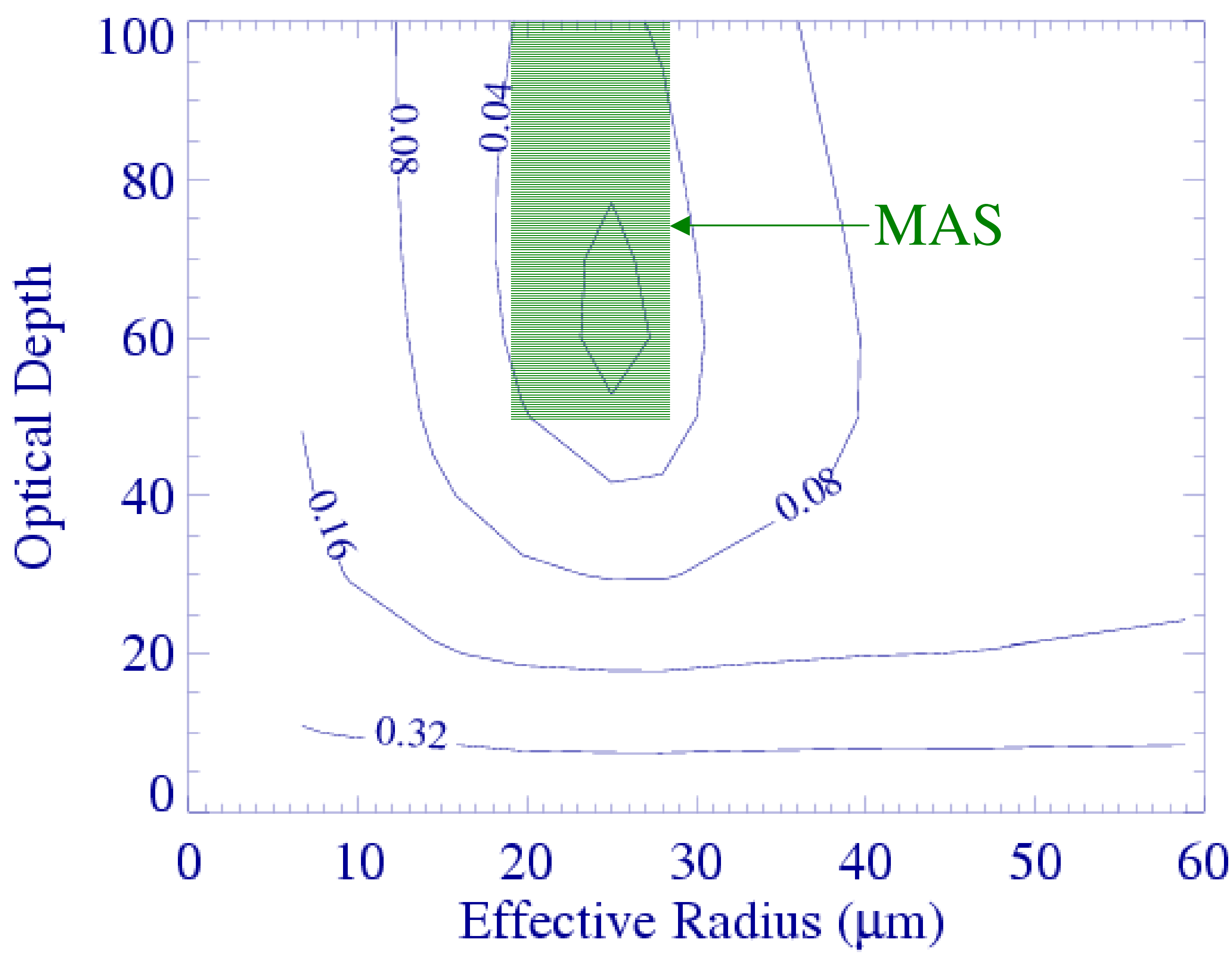
Thick Cirrus Cloud

ER2 SSFR/MODEL Comparison



Thick Cirrus Cloud

SSFR-MODEL Residuals



Stratus Cloud