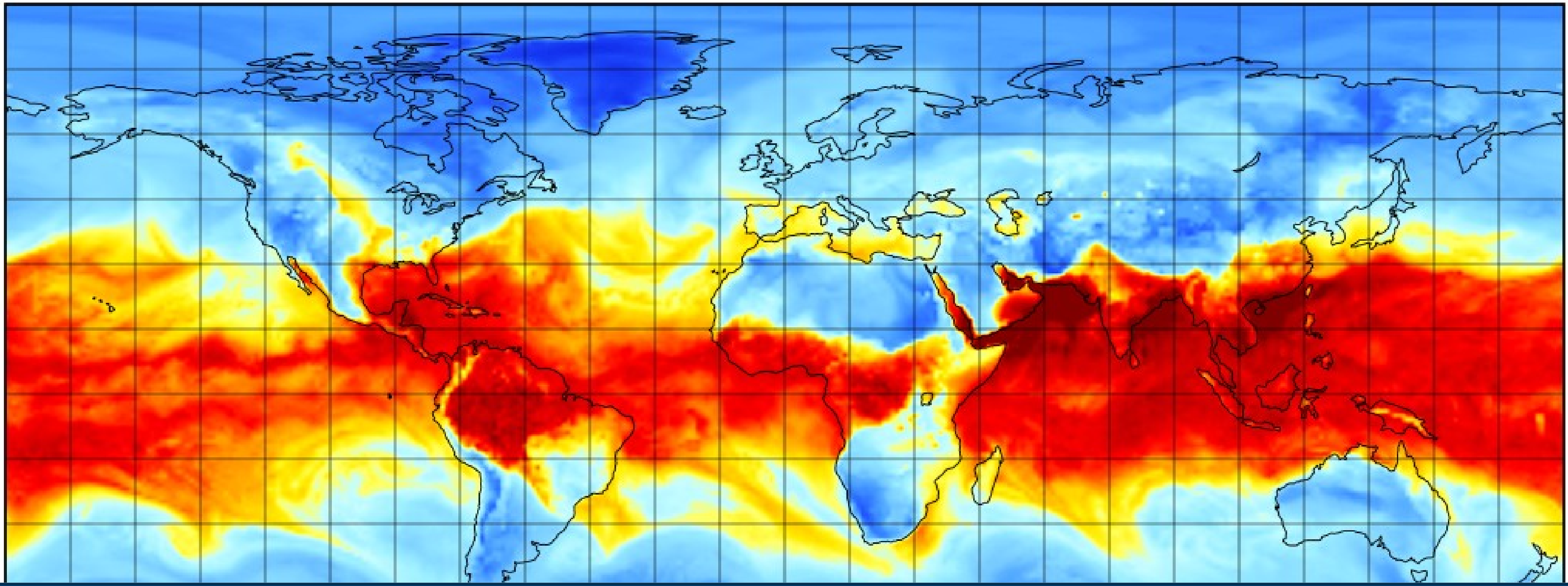

WATER IN THE ATMOSPHERE AND THE ROLE FOR CLIMATE

Part 6: Measurements of water in the atmosphere

WS 22/23 I CHRISTIAN ROLF

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TOPICS

1. Introduction into units and definitions
2. Water vapor and the relevance for the atmosphere
3. Cloud formation (water and ice clouds)
4. Water cycle
5. Water and climate feedback
6. Measurements of water in the atmosphere

SUBTOPICS

6. Measurements of water in the atmosphere

- **In-situ measurements**
  - Hair Hygrometers
  - Sling Psychrometer
  - Radiosonde
  - Dew / Frostpoint Mirror
  - Lyman-Alpha Hygrometer
  - Tunable diode laser Absorption spectroscopy (TDLAS)
  - Chemical ionization mass spectrometry
  - In-situ Aircraft Measurements

- **Remote sensing**
  - Satellite/Viewing Configurations
  - Passive Sounding (IR, MW)
  - Active Sounding (Lidar, GPS)
  - Remote sensing from satellites

MEASUREMENTS OF WATER

Measurements in the atmosphere can be distributed into two different kinds:

In-situ
Local measurement (on-site)

From:
- Aircraft / Drohnes
- Balloon / Rocket
- Ground observation
- Laboratory

Technique:
- Radiosonde
- Dew/ Frostpoint Mirror
- Lyman-α Hygrometer
- TDL Absorption Spectrometer
- Massspectrometer

Remote Sensing
Instrument far away from measuring site
(global observation possible)

From:
- Ground
- Satellite
- Aircraft / Balloon

Technique:
- **Active** Emitter + Receiver (Lidar, Radar, GPS)
- **Passive** Reveiver only (Wavelength dependent Emission, Absorption Spectroscopy)

SUBTOPICS

6. Measurements of water in the atmosphere

- **In-situ measurements**
  - **Hair Hygrometers**
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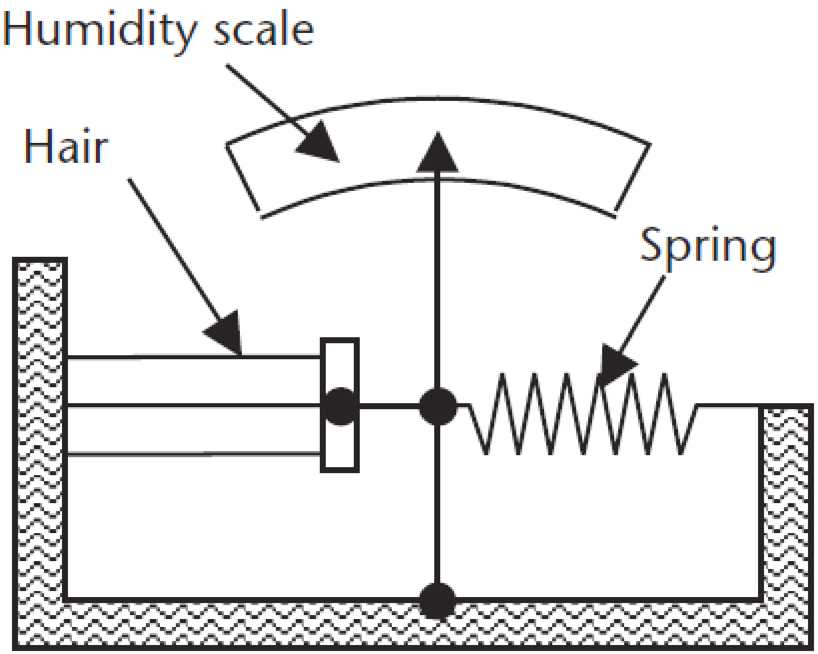
HAIR HYGROMETERS

The expansion or contraction of the hair (or other material) arrangement moves the arm and the pointer to a suitable position on the calibrated scale and, therefore, indicates the humidity present in the air / atmosphere.



Sensors and Actuators A: Physical, 2015

Application of Hair hygrometer:

- Temperature range of 0°C to 75°C.
- Relative humidity range from 30 to 95%.
- Limitations of the hydrometer are material dependent
- Slow response time
- Change in the calibration on long term

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SUBTOPICS

6. Measurements of water in the atmosphere

- **In-situ measurements**
  - Hair Hygrometers
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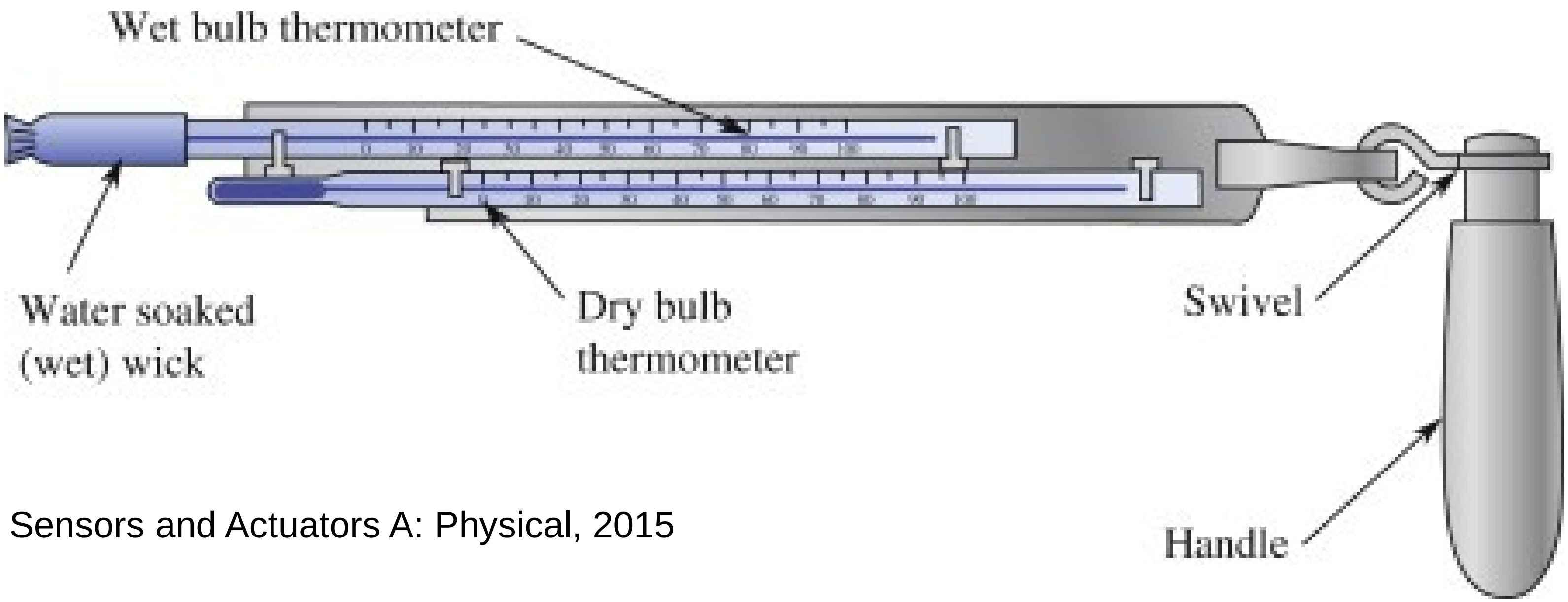
SLING PSYCHROMETER



Sensors and Actuators A: Physical, 2015

- The **easiest way** to measure humidity. A pair of thermometers one of which has a wetted cotton wick attached to the bulb. The **two thermometers** measure the **wet and dry bulb temperature**.
- Swinging the psychrometer causes air to circulate about the bulbs. When air is unsaturated, evaporation occurs from the wet bulb which cools the bulb.
- Once evaporation occurs, the wet bulb temperature stabilizes allowing for comparison with the dry bulb temperature. Charts gauge the amount of atmospheric humidity.

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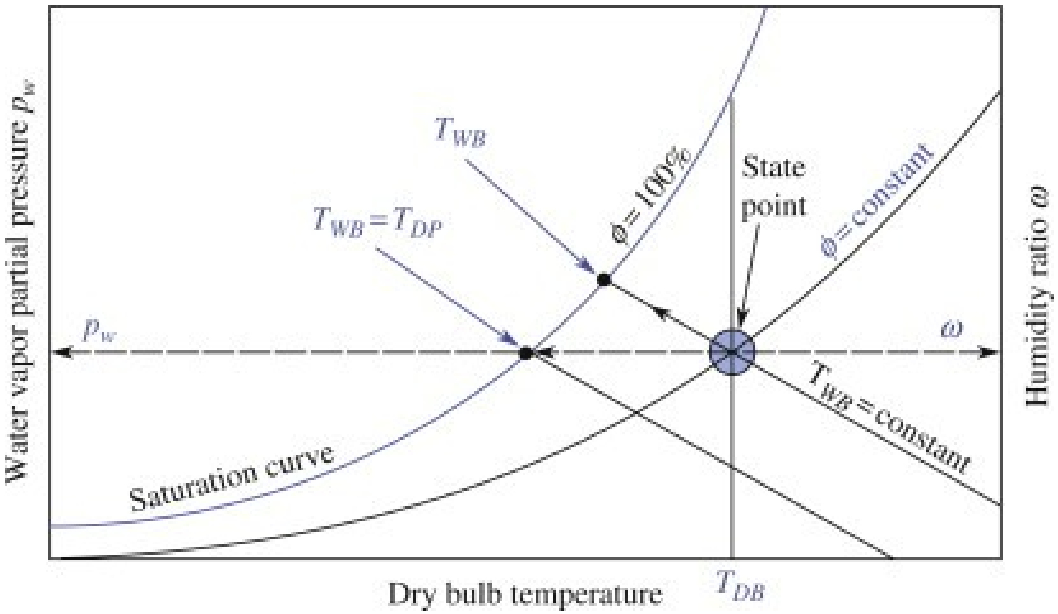
SLING PSYCHROMETER



Partial pressure of water vapor:

$$e_{a,w}=e_{s,w}(T_{WB})-\gamma P(T_{DB}-T_{WB})$$

Psychrometric constant:

$$\gamma=\frac{c_P}{l_v}=4.66\cdot10^{-4}C^{-1}$$

Application of Sling Psychrometer

- Relative humidity range of 0 to 100 % RH
- Wet bulb temperature range between 0°C to 180°C
- Slow response time
- Not usable for continuous recording purposes (drying of the wick, change of moisture in small rooms)

SUBTOPICS

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RADIOSONDE

Vaisala, 2021

Radiosonde: Vaisala RS-41 SGP

Temperature, pressure, humidity, GPS

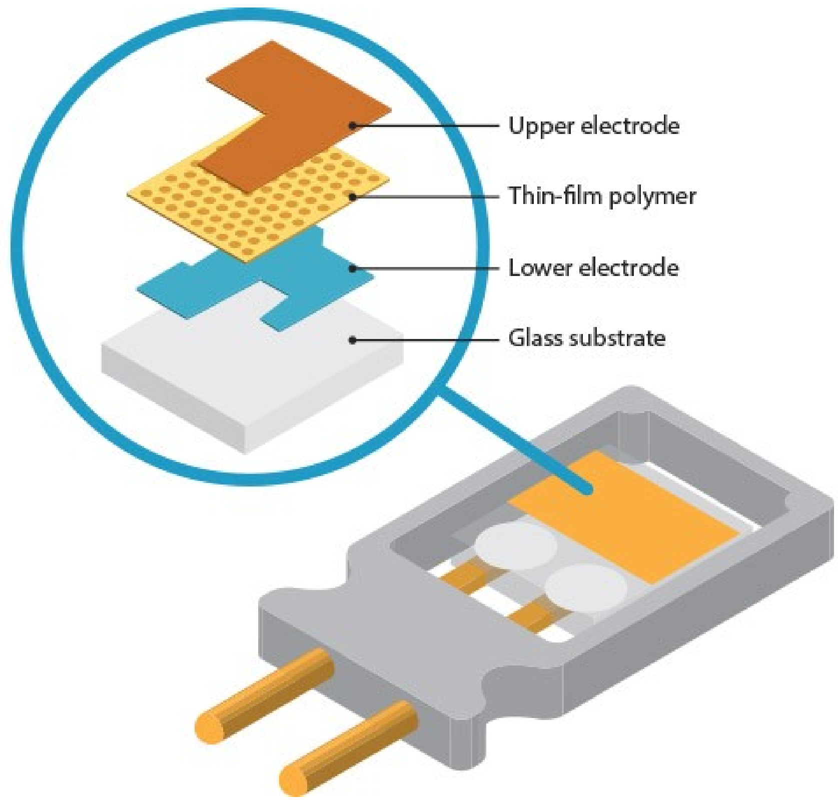
Transmitting Frequency: 400.15 – 405.99 MHz

Weight: 260g

HUMIDITY OBS. WITH A RADIOSONDE

Measurement of relative humidity

- **Thin-film polymer** either absorbs or releases water vapor as the relative humidity of the ambient air rises or falls.
- The dielectric properties of the polymer film depend on the amount of absorbed water.
- If RH around the sensor changes, the dielectric properties of the polymer film change (**capacitance change**)
- Electronics measure the capacitance of the sensor and convert it into a **relative humidity**.



Vaisala, 2021

SUBTOPICS

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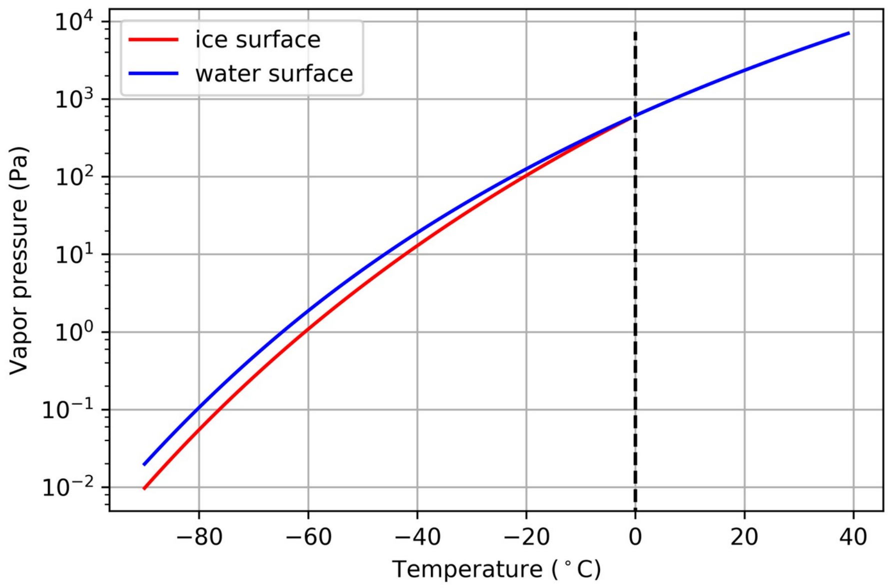
DEW / FROSTPOINT MIRROR

Measurement of Dew / Frostpoint

- **Indirect measurement** technique: Temperature instead of water vapor
- Dew/Frost layer condenses on a cooled mirror
- In case of a constant dew/frost layer:

  Dew/frost condensation exactly equals the rate of the dew/frost layer's evaporation

$$T_{mirror} = T_{Dew/Frost}$$



MBW

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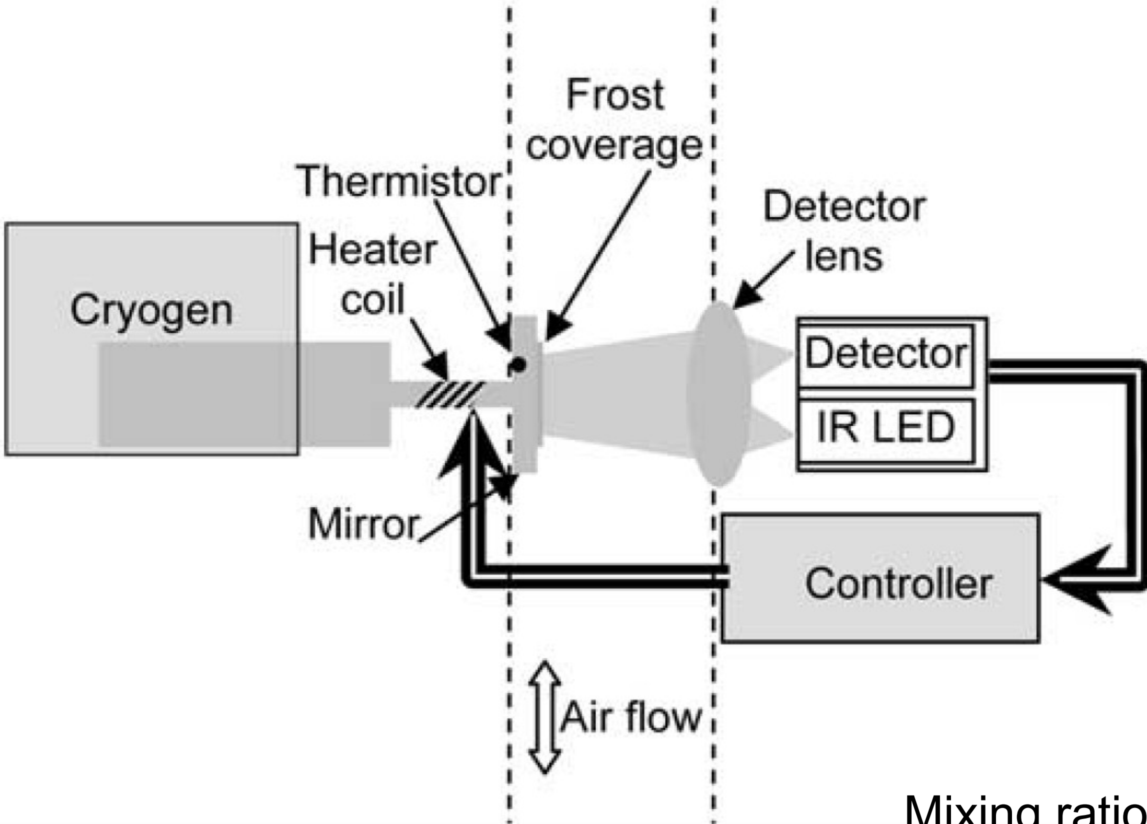
CRYOGENIC FROSTPOINT HYGROMETER (CFH)



Source: Vömel et al., JGR, 2007

Source: EnSci

Mixing ratios: >25000 ppmv to <0.8 ppmv
Uncertainty: ~ 3.5 % (surface)
~ 9% (tropopause)
~ 11% (28 km)

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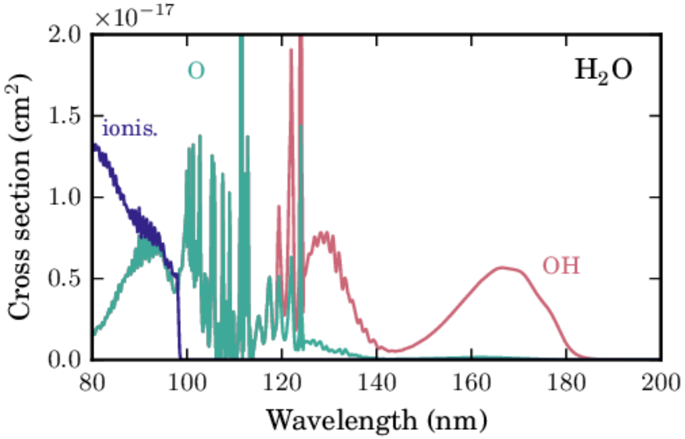
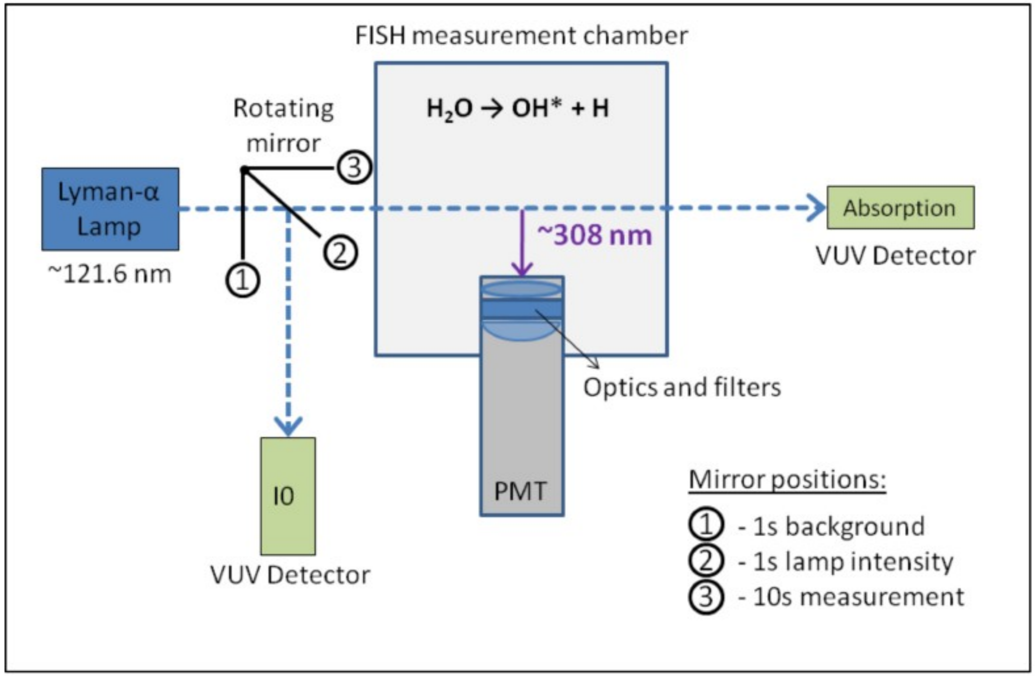
LYMAN-ALPHA HYGROMETER



Principle: Lyman-α photofragment fluorescence

$$H_2O + h\nu_{121.6nm} \rightarrow OH^* + H$$
$$OH^* \rightarrow OH + h\nu_{308nm}$$



Zöger et al., 1999; Meyer et al. 2015

Typical measurement range:

- 1-1000 ppmv @ 10-500 hPa
- Suited for **low concentrations**
- Calibration required
- Stable in operation
- Fast operation possible
  - ➔ suited for operation aboard aircraft

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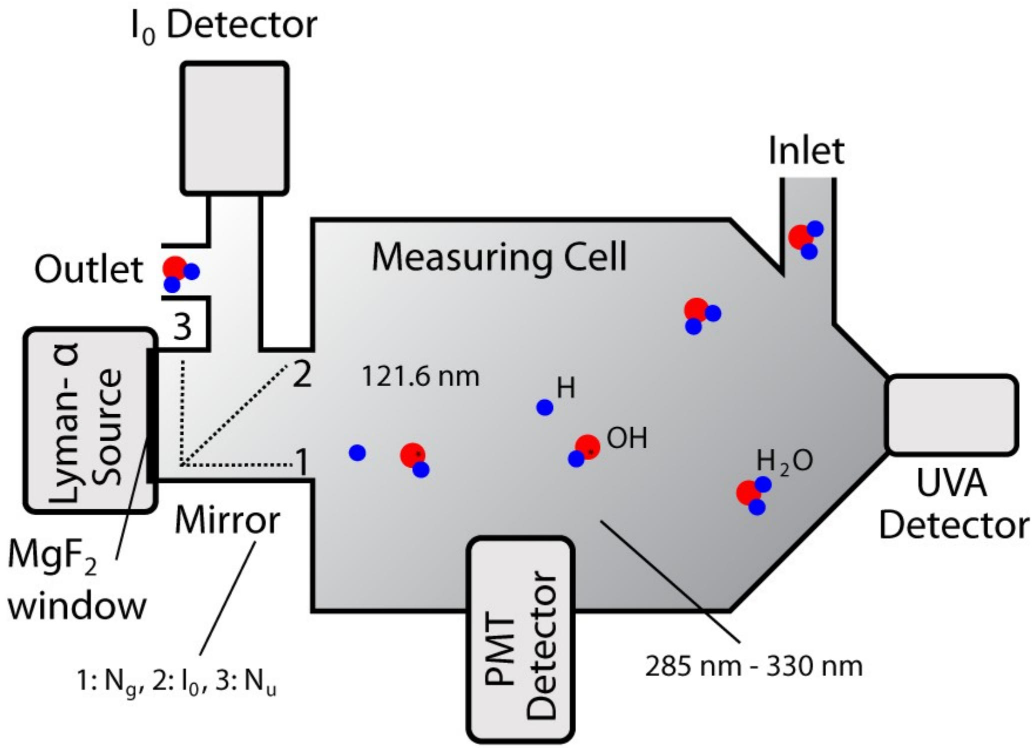
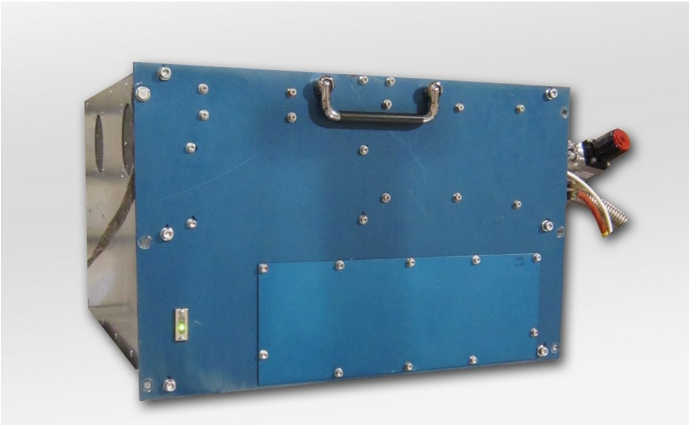
FAST IN-SITU STRATOSPHERIC HYGROMETER (FISH)





- Lyman-α source: flow lamp with RF field (Ar + 1% H2)
- FISH formula to derive WVMR with calibration factors (c_k, f_u)

$$r = \frac{c_k \cdot N_g - f_u \cdot N_u}{I_0 \cdot k_f}$$

N_g: fluorescence signal
N_u: background
I_0: lamp intensity

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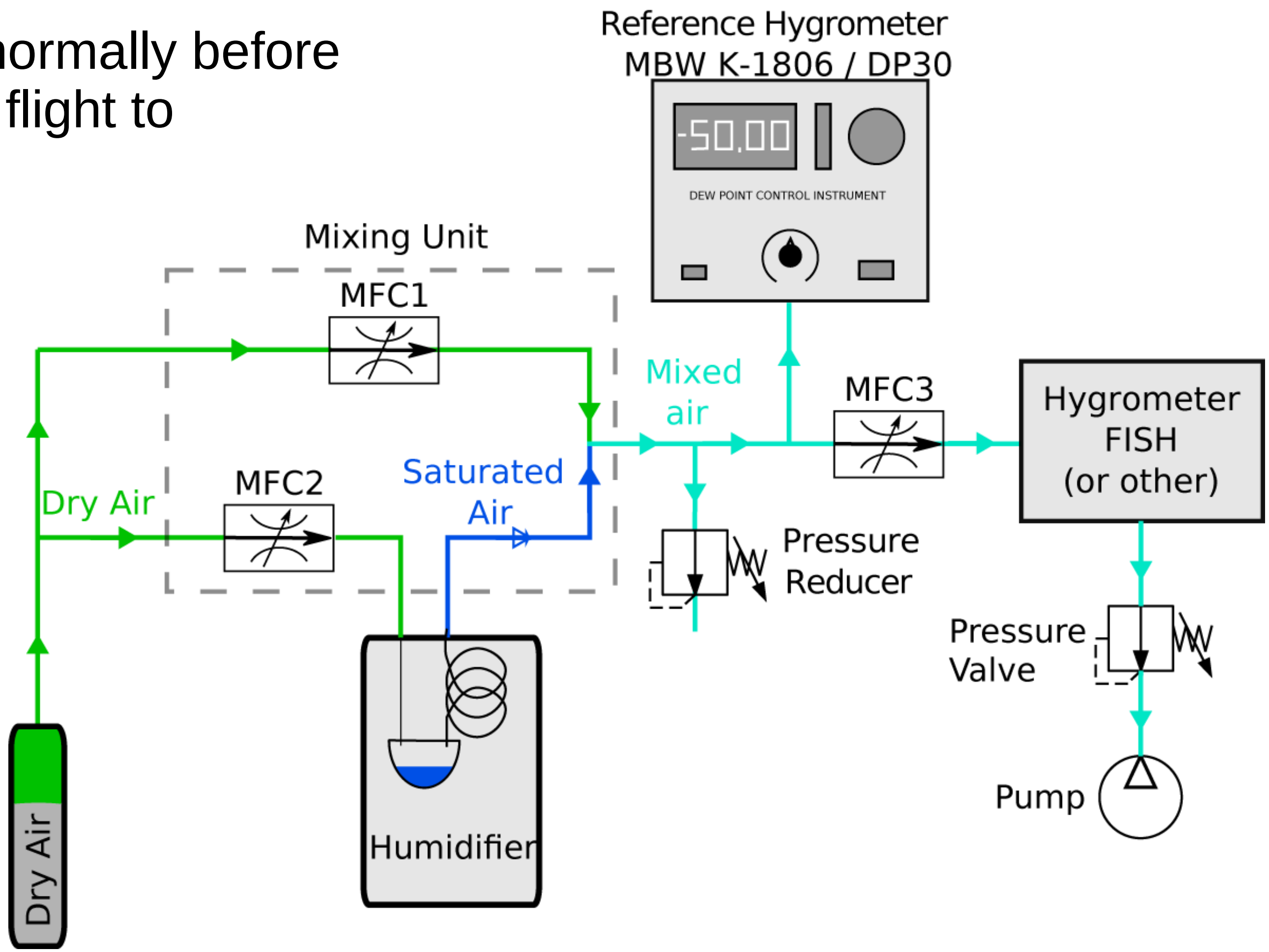
CALIBRATION OF FAST AIRCRAFT HYGROMETER

Calibration performed normally before and after each research flight to ensure high data quality.



Calibration bench consists of:

- Dry syn. air supply
- Humidifier
- Pressure regulator
- Reference Instrument (MBW DP30 / MBW 373 LX)

Meyer et al., 2015

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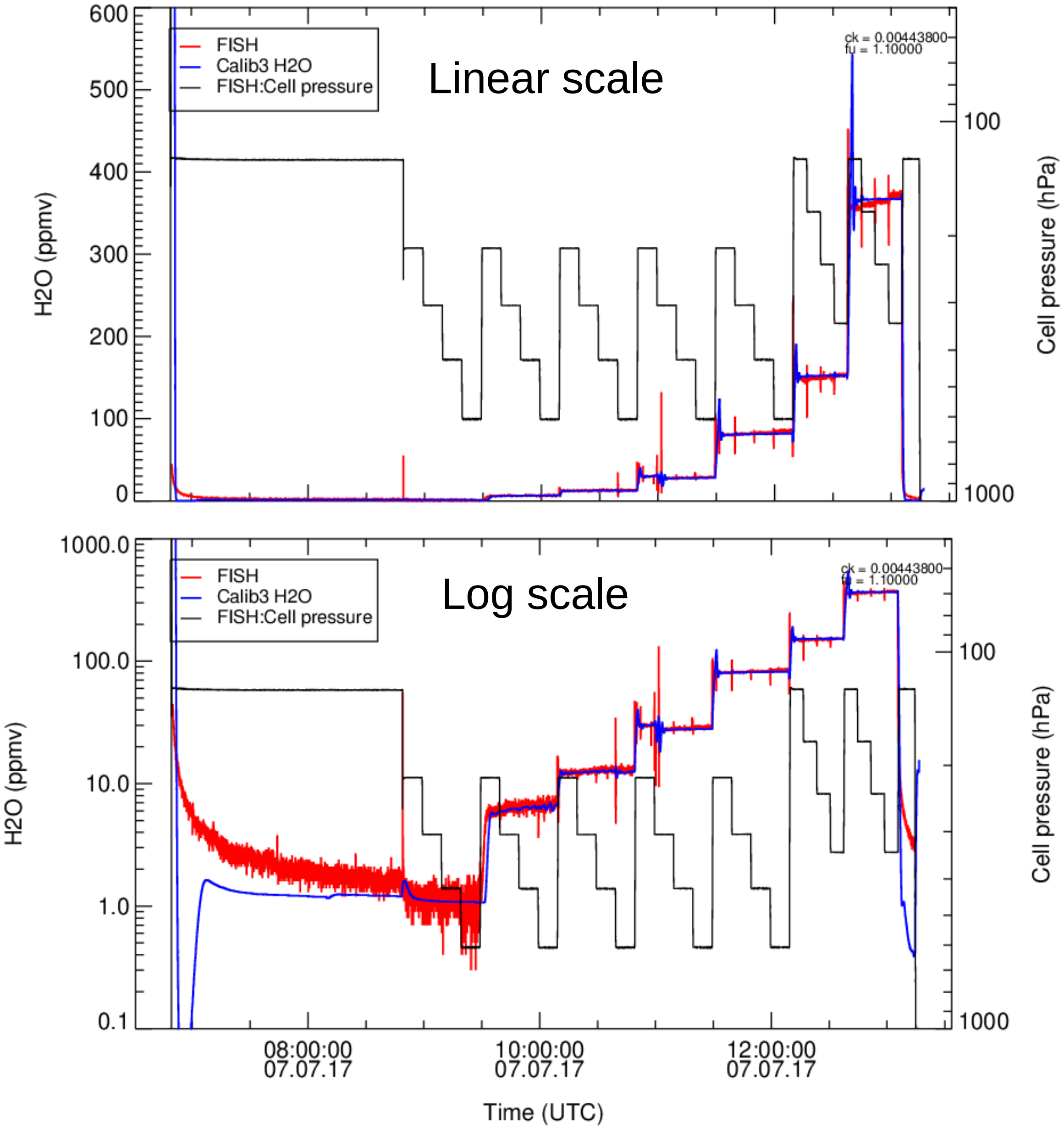
CALIBRATION OF FAST AIRCRAFT HYGROMETER



Calibration performed typically performed at **different humidity and pressure levels**, which are expected during an aircraft flight.

Pressure levels also help to identify possible leaks of the instrument.

SUBTOPICS

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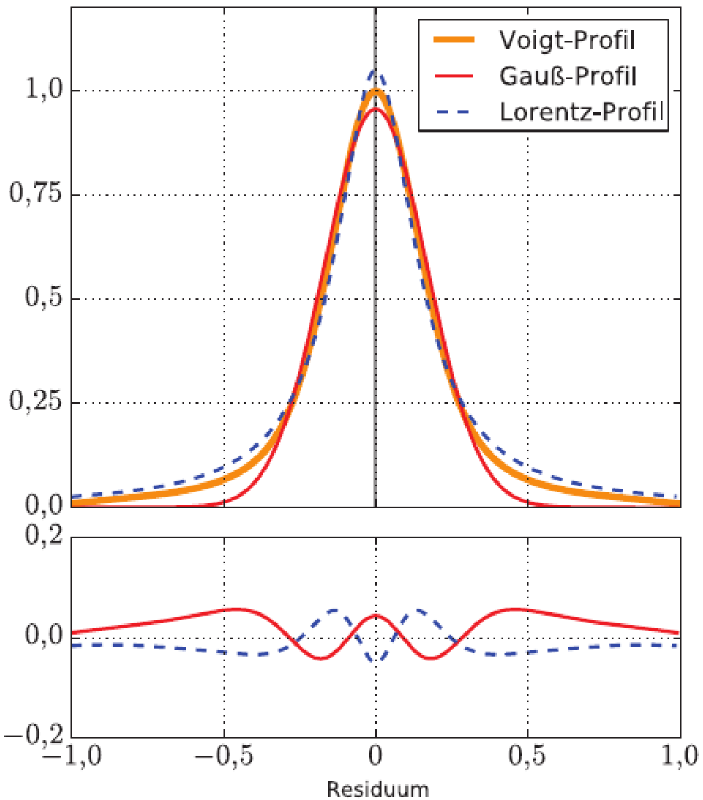
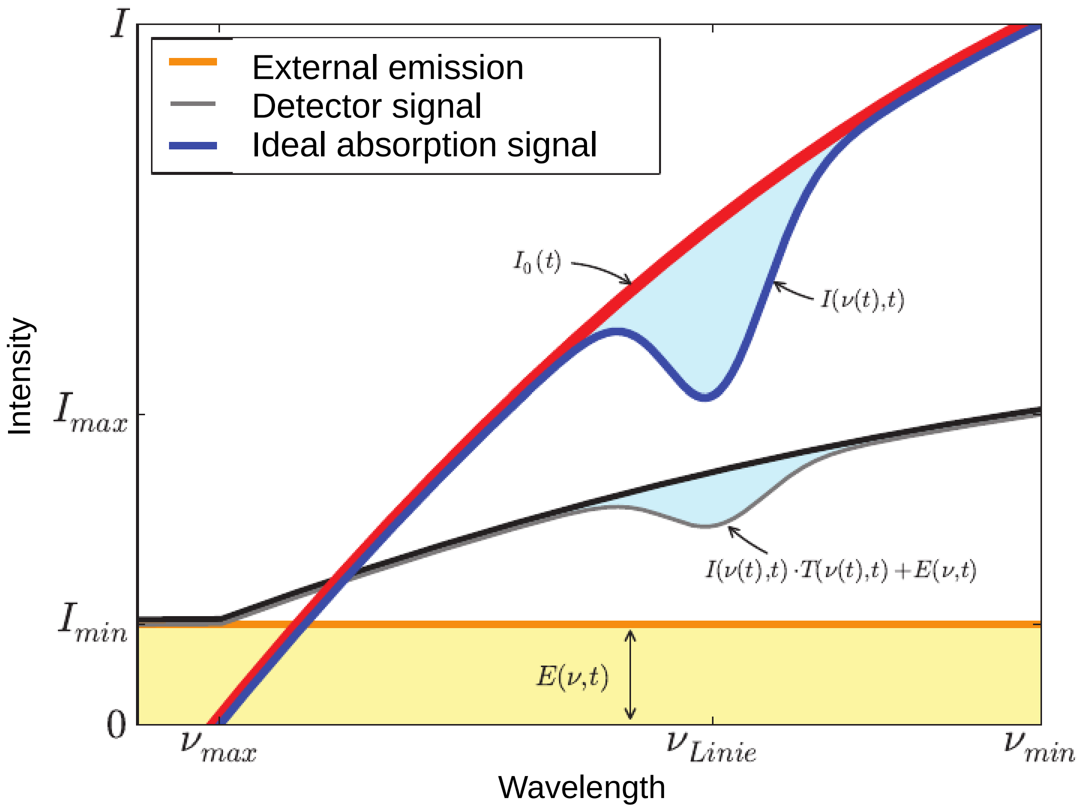
TUNABLE DIODE LASER ABSORPTION SPECTROSCOPY (TDLAS)





Measurement of absorption along the entire **water vapor absorption line** (Voigt-Profile) with tunable diode laser

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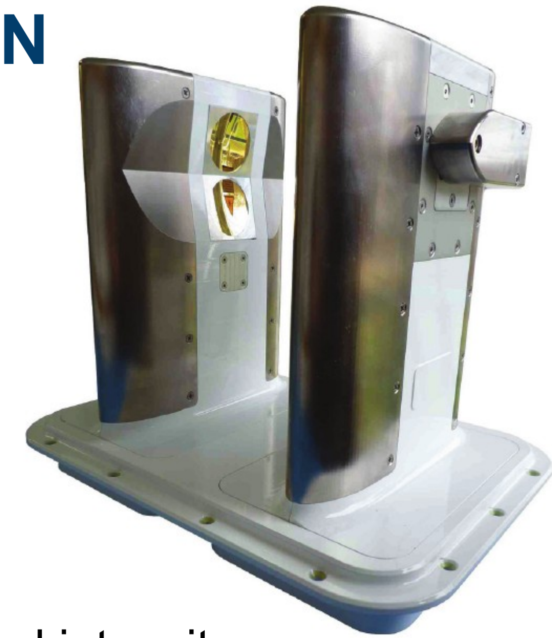
TUNABLE DIODE LASER ABSORPTION SPECTROSCOPY (TDLAS)



Measured Intensity (Lambert-Beer):

$$I(\nu(t),t) = I_0(t) \cdot T(\nu(t),t)\, e^{-S(T)\cdot\phi(\nu-\nu_0)\cdot N\cdot L} + E(\nu,t)$$

Solving for N and integration over υ:

$$N = -\frac{1}{S(T)\cdot L}\int_{-\infty}^{\infty} \ln \frac{I(\nu(t),t) - E(\nu,t)}{I_0(t)\cdot T(\nu(t),t)} d\nu$$

Concentration with ideal gas law:

$$c = -\frac{k_B \cdot T}{S(T)\cdot p \cdot L}\int_{-\infty}^{\infty} \ln \frac{I(\nu(t),t) - E(\nu,t)}{I_0(t)\cdot T(\nu(t),t)} d\nu$$

With:
I: Measured intensity
I_0: Laser emission intensity
S(T): integrated line strength
Φ: normed area of line profile,
N: number of absorbing water molecul
L: length of obsorption path
E: external emissions/ background

All quantities can be directly measured

→ **No reference calibration necessary**

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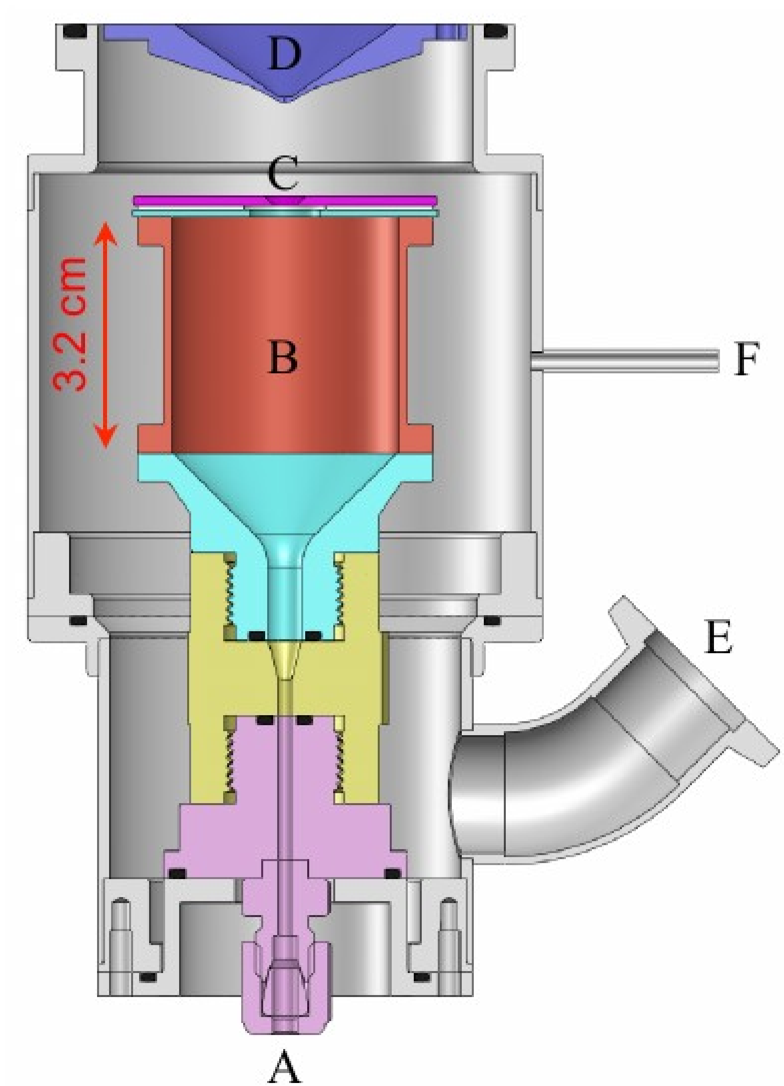
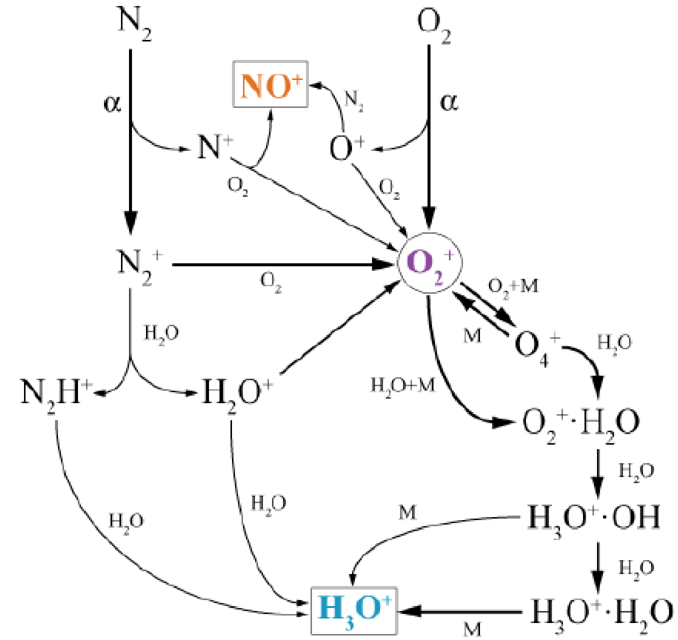
CHEMICAL IONIZATION MASS SPECTROMETRY





(A) Capillary inlet
(B) Chamber
with ^{241}Am foil
(C) Exit lens, extraction of positive ions
(−50 V relative to the chamber).
(D) Entrance nose cone of the mass spectrometer
(E) Pump
(F) Pressure monitoring

Thornberry et al, 2013

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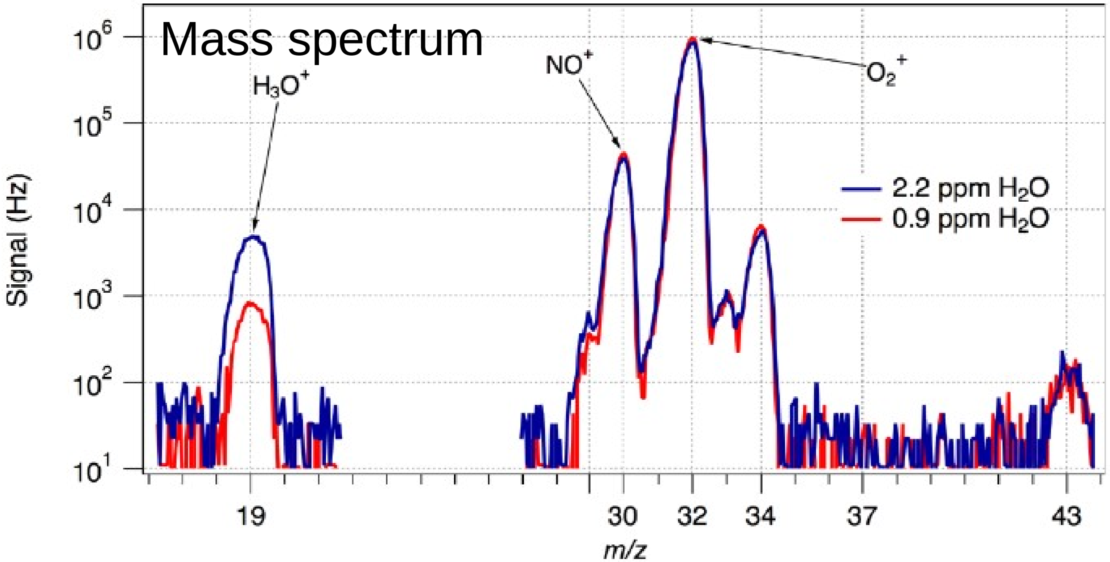
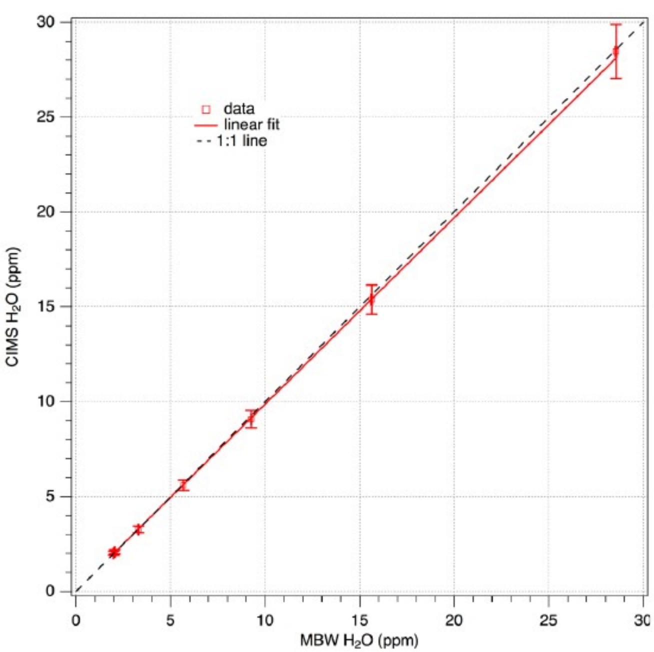
CHEMICAL IONIZATION MASS SPECTROMETRY



Calibration against frost point mirror



Typical measurement range:

- 1-100 ppmv @ 10-200 hPa
- Suited for low concentrations
- Calibration required
- Stable in operation
- Complex instrument
- Fast operation possible

→ **suited for operation aboard aircraft in the stratosphere**

Thornberry et al, 2013

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SUBTOPICS

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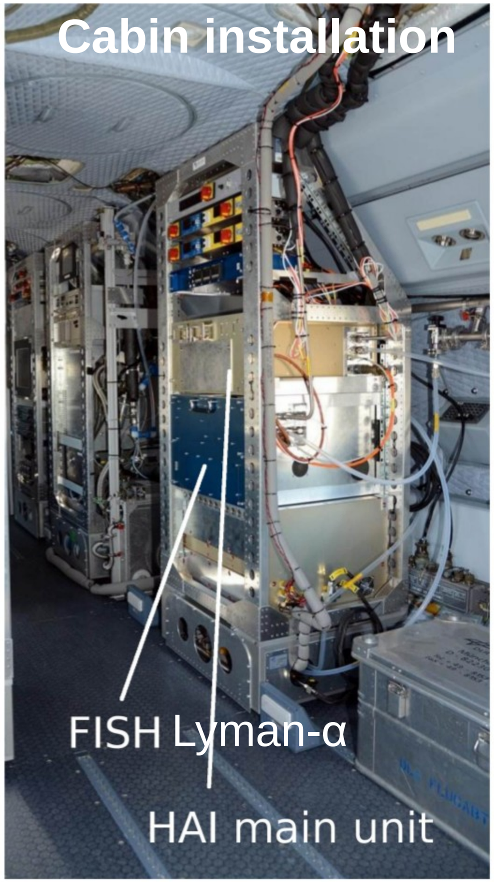
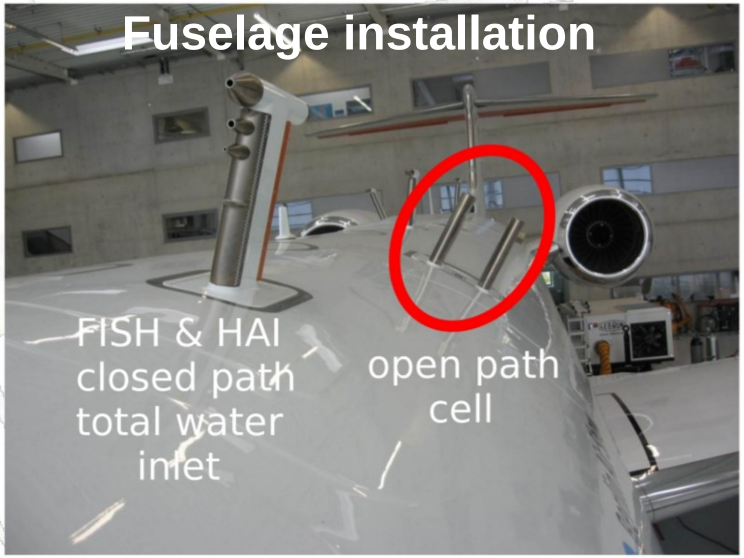
IN-SITU AIRCRAFT MEASUREMENTS ABOARD HALO AIRCRAFT

Measurement of:

- Water vapor with backward inlet
- Total water with forward inlet (cloud particles + vapor)
- Liquid/Ice water content with two hygrometers





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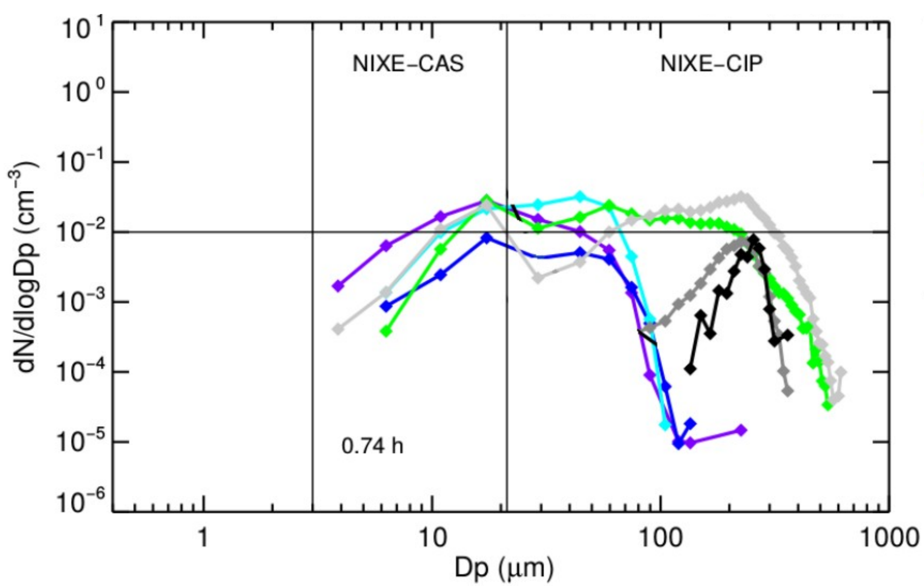
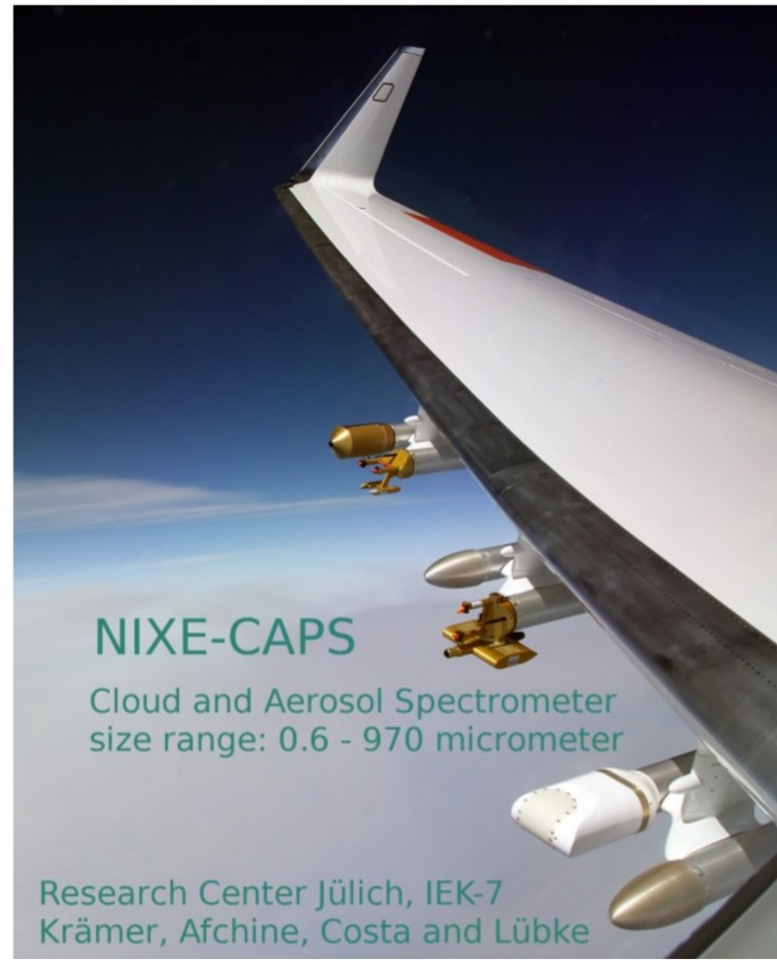
CIRRUS CLOUD PROPERTIES

NIXE-CAPS: Cloud and Aerosol spectrometer

Number of particles in certain size bins

- particle size distribution → N(Dp)
- Shape, habit of ice crystals





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MEASUREMENTS OF WATER

In-situ
Local measurement (on-site)

From:
- Aircraft / Drohnes
- Balloon / Rocket
- Ground observation
- Laboratory

Technique:
- Radiosonde
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- Lyman-α Hygrometer
- TDL Absorption Spectrometer
- Massspectrometer

Remote Sensing
Instrument far away from measuring site
(global observation possible)

From:
- Ground
- Satellite
- Aircraft / Balloon

Technique:
- **Active** Emitter + Receiver
  (e.g. Lidar, Radar, GPS)
- **Passive** Reveiver only
  (Wavelength dependent Emission, Absorption Spectroscopy)

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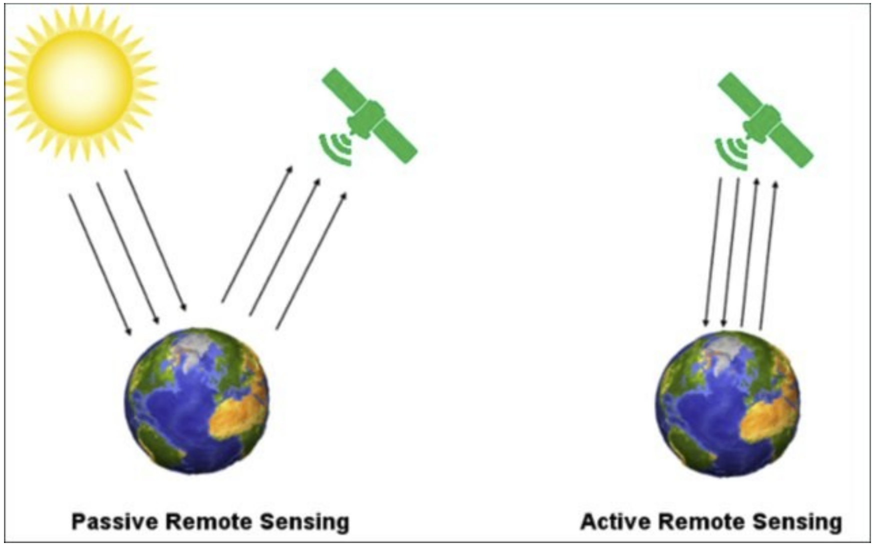
REMOTE SENSING MEASUREMENTS

Passive technologies:
sense LW radiation emitted by atmosphere, SW reflected by atmosphere.

- **imaging** (optically thin -> information on Earth surface)
- **sounding** (optically thick -> information on atmosphere)

Active technologies:
emit radiation & measure how much scattered/reflected back

- **Lidar/Radar**: Measure the properties of backscattered light
- **GPS**: measure phase delay of signal as it is refracted in atmosphere



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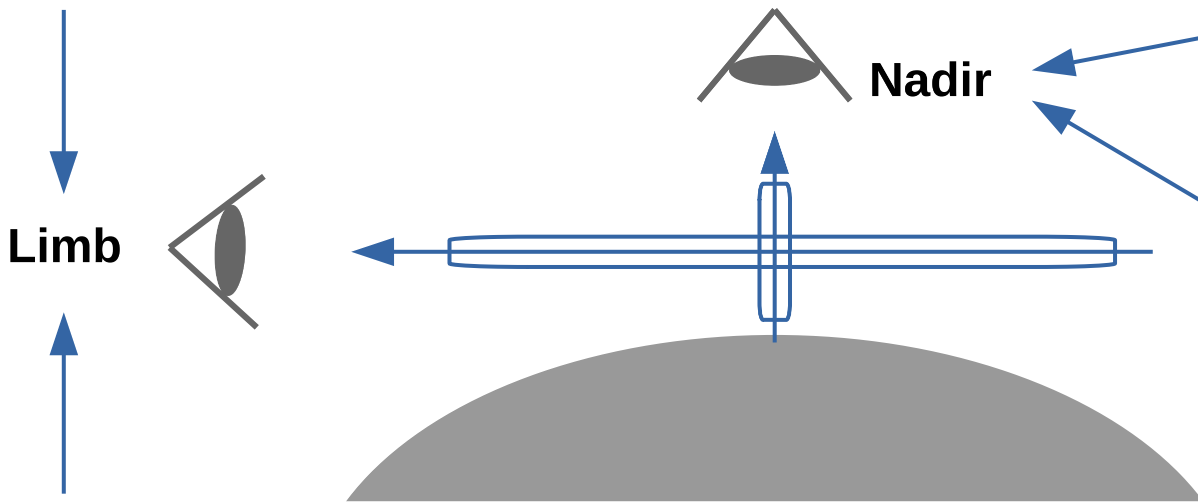
SATELLITE/VIEWING CONFIGURATIONS

Relatively **poor horizontal** resolution
Relatively **good vertical** resolution

Relatively **good horizontal** resolution
Relatively **poor vertical** resolution



Met agencies use these data mainly for tropospheric measurements

Research groups use these data mainly
Suited for upper troposheric / stratospheric / mesospheric measurements

SUBTOPICS

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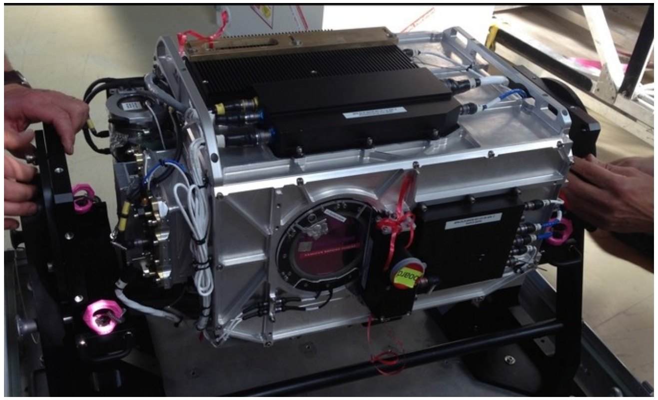
PASSIVE SOUNDING (IR, MW)

Passive soundings measurements are **indirect measurements**: The quantity we are interested in is obtained from the measurements by a complicated relationship (**inverse problem** or retrieval problem).



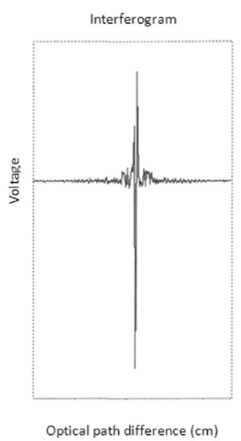
GLORIA

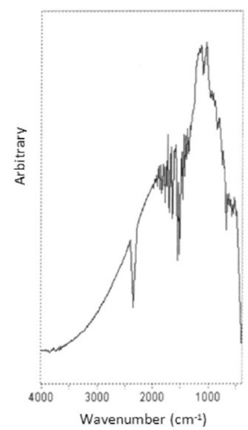
Transformation

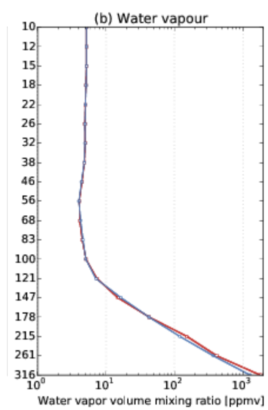
Spectrometer (e.g. FTIR) → Spectrum

Inverse Modelling / Radiative transfer calculation

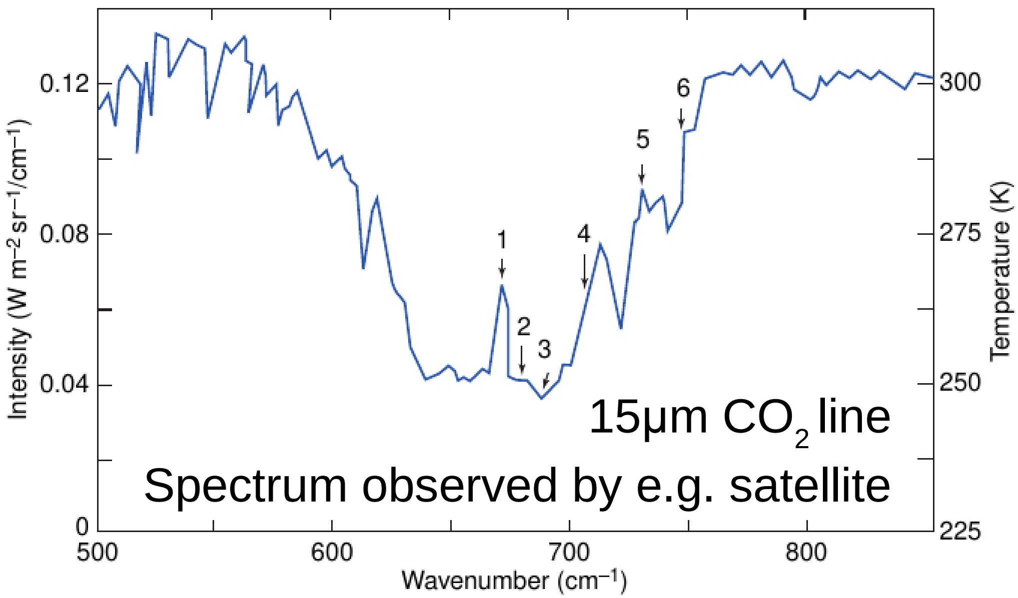
Spectrum → Water vapor profile





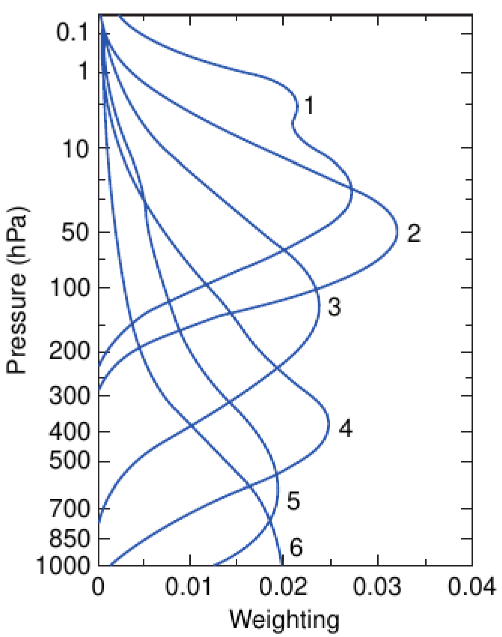


PASSIVE SOUNDING (IR, MW)

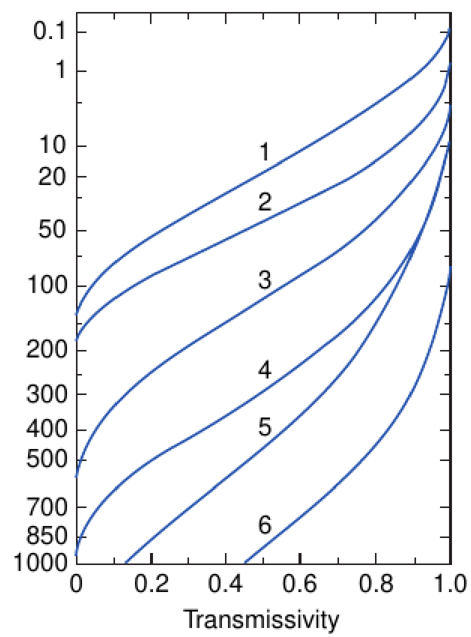


- Different trace gas absorption lines provide radiation from **different height regions** (weighting function)
- **Radiative transfer calculation** is necessary to retrieve water vapor profile

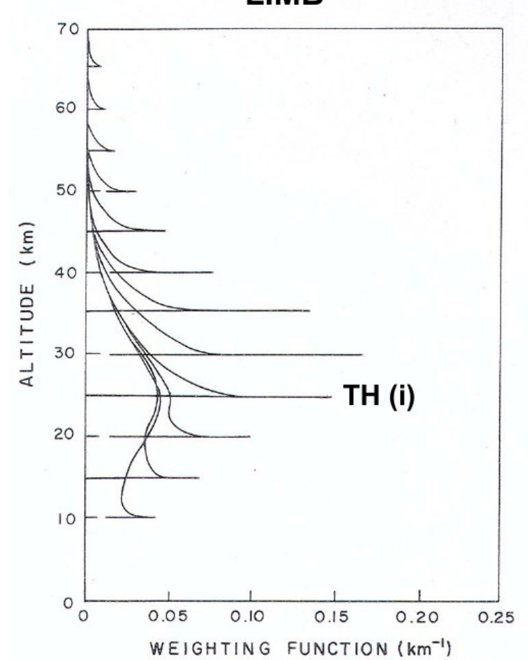
NADIR



NADIR



LIMB



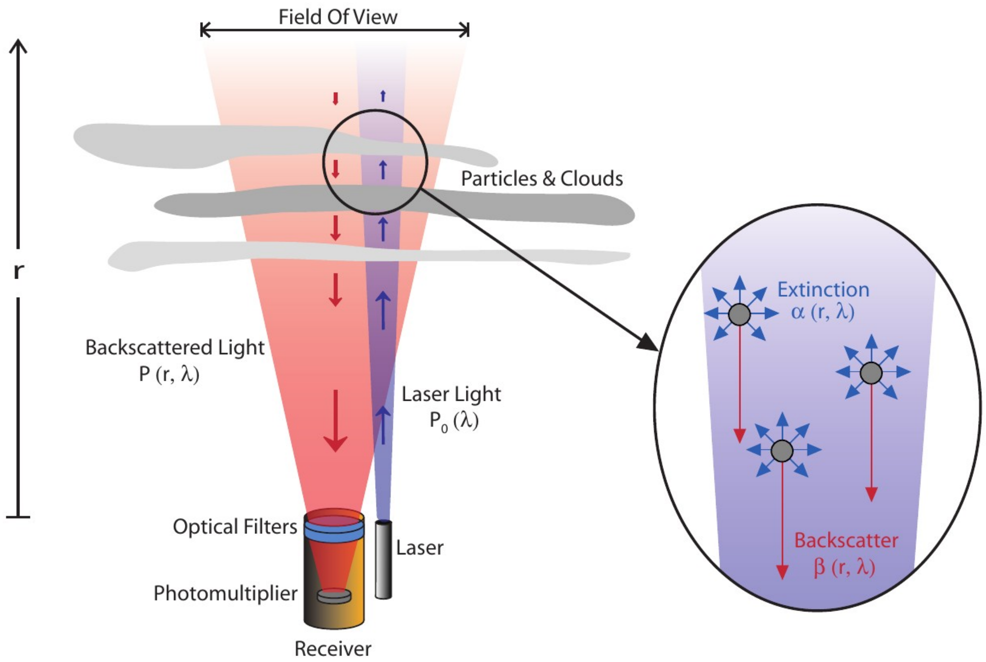
SUBTOPICS

6. Measurements of water in the atmosphere

- **In-situ measurements**
  - Hair Hygrometers
  - Sling Psychrometer
  - Radiosonde
  - Dew / Frostpoint Mirror
  - Lyman-Alpha Hygrometer
  - Tunable diode laser Absorption spectroscopy (TDLAS)
  - Chemical ionization mass spectrometry
  - In-situ Aircraft Measurements

- **Remote sensing**
  - Satellite/Viewing Configurations
  - Passive Sounding (IR, MW)
  - **Active Sounding (Lidar, GPS)**
  - Remote sensing from satellites

LIDAR MEASUREMENTS



Light detection and ranging (LIDAR)

- Profiles of cloud and aerosol optical properties
- High temporal & vertical resolution
- Low horizontal resolution

Differential absorption lidar (DIAL)

- Two laser wavelengths (λ_{on} @ absorption line, λ_{off} no absorption)
- Water vapor profiles can be determined with the ratio of the photon count rate

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COMPARISON OF CFH AND WATER VAPOR DIAL

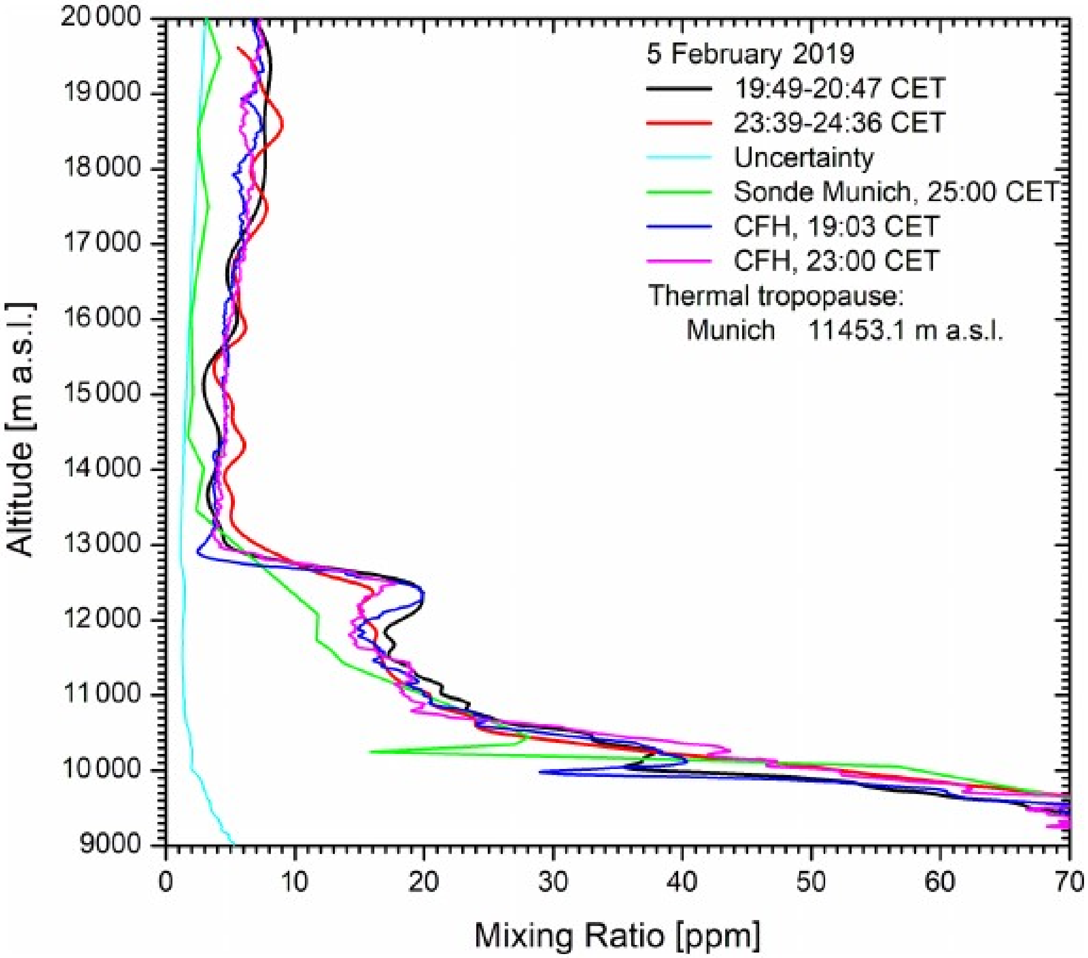

Figure 16. A close-up portion of Fig. 20: the agreement between the lidar and the CFH is satisfactory up to almost 20 km. Above this, the lidar values start wider excursions around the CFH mixing ratios.

Klanner et al., 2021

Good agreement between both observation methods:

- **CFH** balloon *in-situ* observations (blue, pink)
- **water vapor DIAL** *remote sensing @* Zugspitze (black, red)

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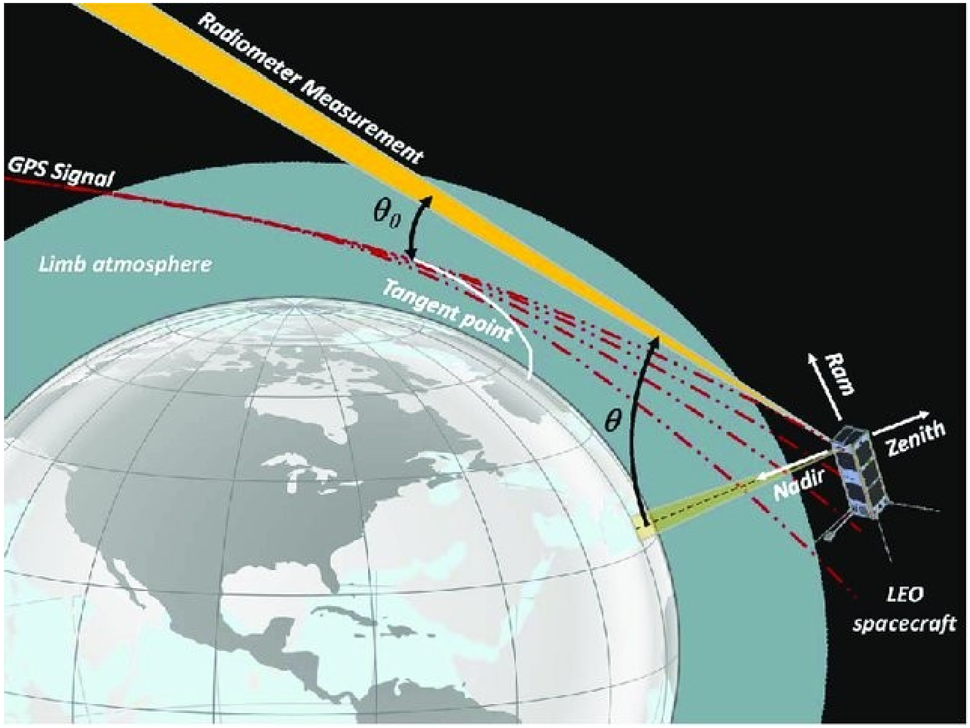
GLOBAL POSITIONING SYSTEM RADIO OCCULTATION (GPSRO)

- **Active remote** sensing technique
- **Refractive index** (n) / Refractivity (N) of the atmosphere depends on temperature, pressure and water vapor concentration

$$N = 10^6 (n-1) = \frac{c_1 P}{T} + \frac{c_2 e_w}{T}$$

- GPS Radio Occultation (Profile information)
- Ground-based GPS (Column integrated water vapour)
- RO provide useful humidity information in the troposphere



Backwell et al., 2014

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SUBTOPICS

6. Measurements of water in the atmosphere

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REMOTE SENSING FROM SATELLITES

Orbits for global observations:

1) **Geostationary** (fixed point over the equator): 60N-60S
   Only one orbit: 35,800 km; 1⁄4 Earth's surface

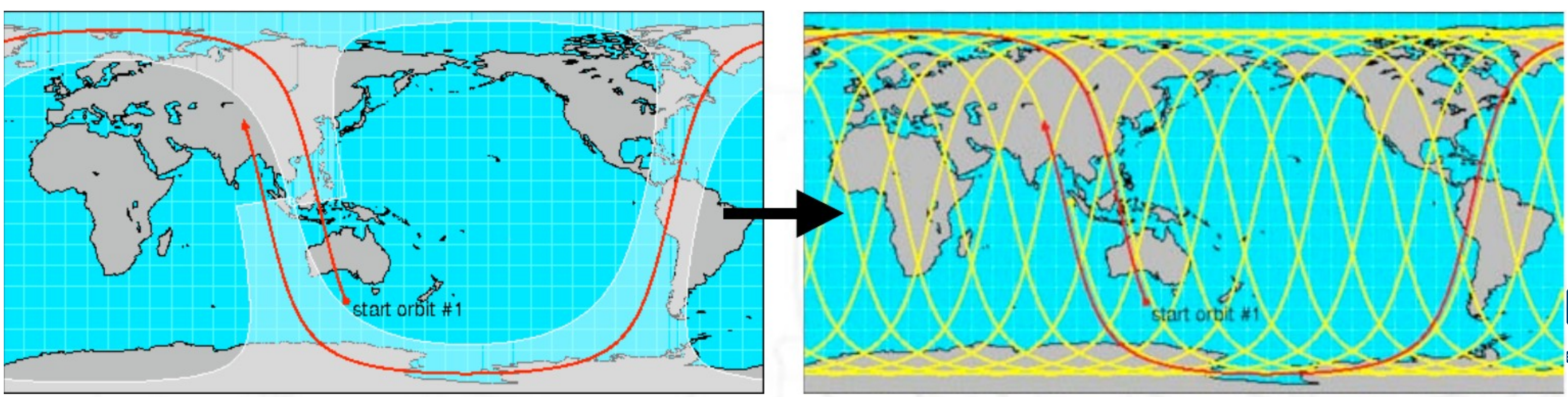
2) **Polar**: quasi-global (e.g. 600 km Hubble)

3) **Sun-synchronous** (fixed equator crossing time, e.g. NASA A-Train)

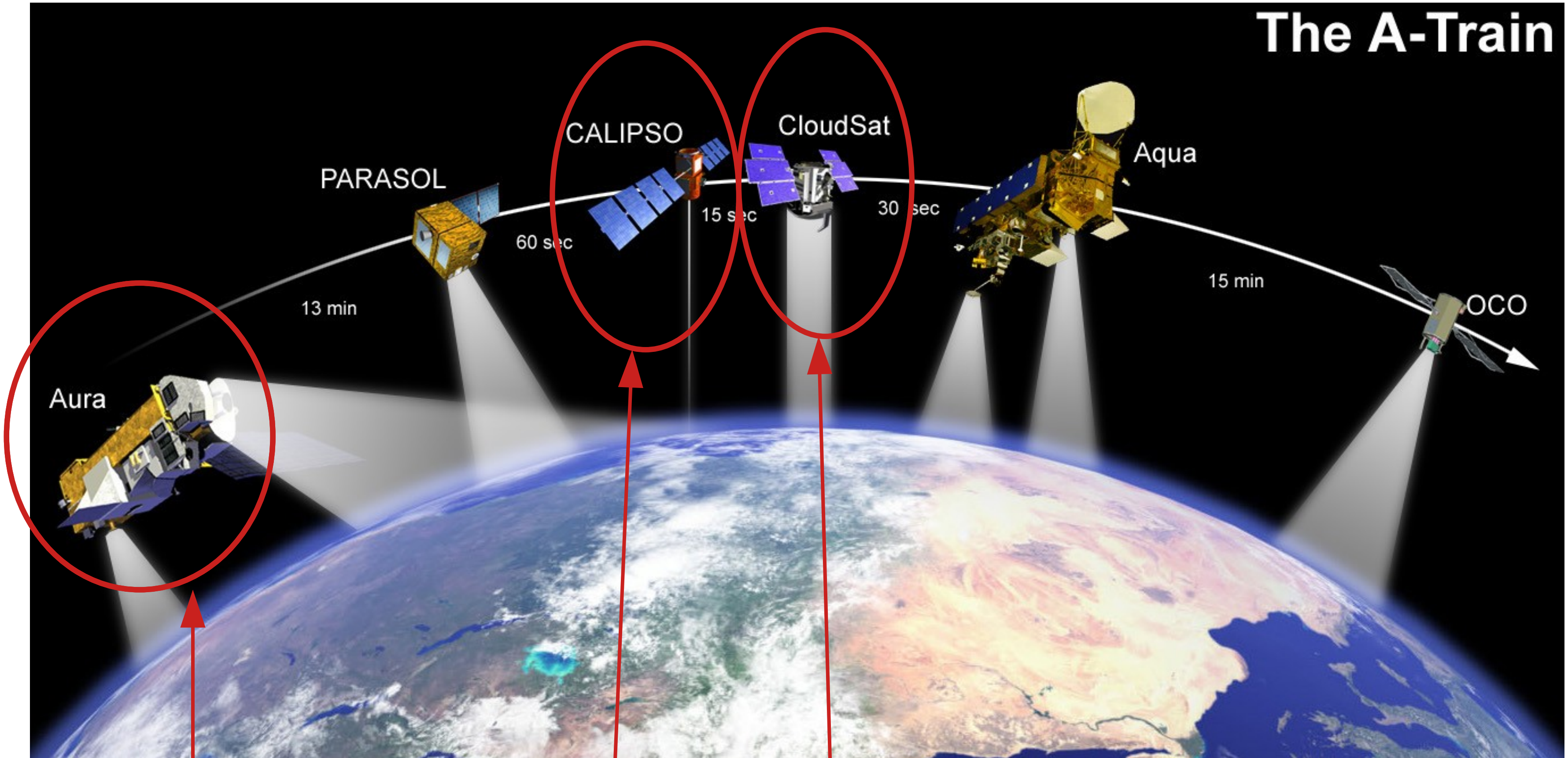
   - Instruments look away from the sun
     (no maneuver to prevent the sun damaging the instruments)
   - Cannot observe the diurnal cycle at a particular place
     (e.g. diurnal cycle of NO, NO2)

4) **Non sunsynchronous** (variable equator crossing time)

   - Can observe the diurnal cycle at a particular place
   - Have to do maneuver to prevent the sun damaging the instruments



SATELLITE EXAMPLES



NASA

Microwave limb sounder (MLS)
Water vapor profiles

CloudSat (Cloud Radar at 94 GHz)
Cloud particles (mainly Liquid and dense Ice clouds)

Cloud-Aerosol Lidar with Orthogonal Polarization
(Caliop) *Cloud particles (mainly Ice)*

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