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Water Vapor Retrieval to Support Space-borne Radar Systems: Results from Different Techniques

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Agenda

- Introduction and motivation
- Atmospheric effects on electromagnetic waves and impact on space-borne radar systems
- Experimental sites
- Experimental equipment and dataset
- Integrated water vapor from GNSS receivers
- Integrated water vapor from microwave radiometers
- Results and discussion
- Conclusions and future work

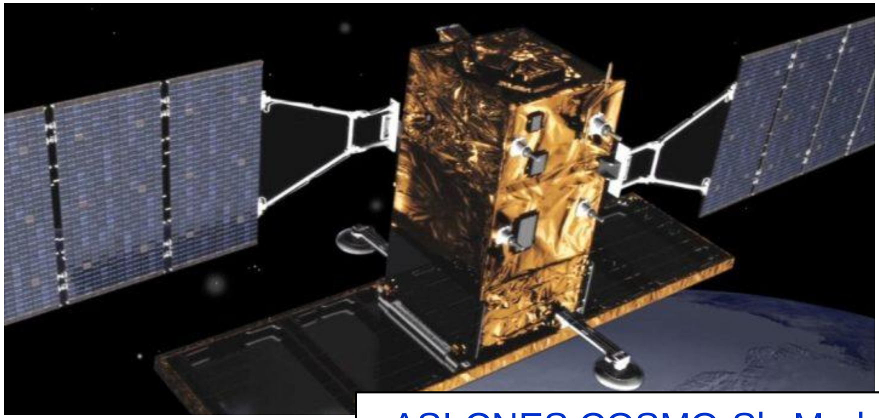
Background and motivation

Space-borne radar: Synthetic Aperture Radars

- Synthetic Aperture Radars (SAR)
- Continuous and all-weather conditions monitoring of the Earth surface
- Several Earth Observation LEO satellites carrying SARs
- Various carrier frequencies: from L band (≈ 1 GHz) to X band (≈ 9 GHz)

ESA Sentinel-1
C band (≈ 5 GHz)

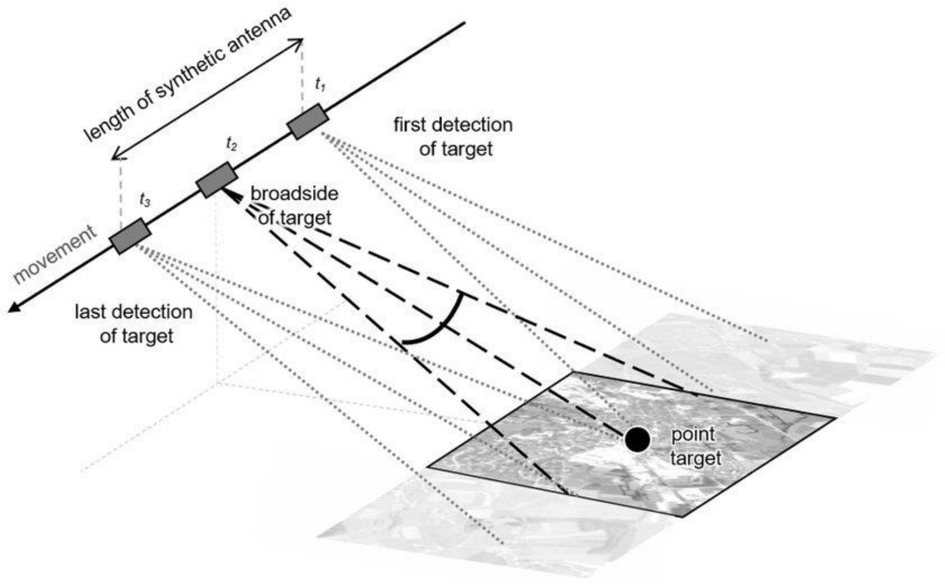
CONAE SAOCOM
L band (≈ 1 GHz)

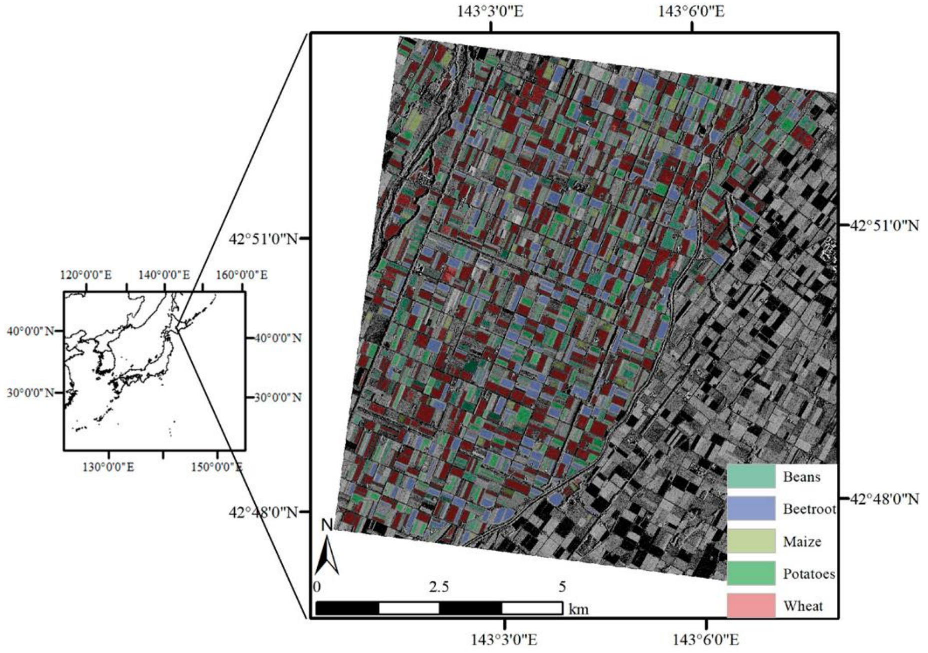


ASI-CNES COSMO-SkyMed
X band (≈ 9 GHz)

SAR products: intensity maps

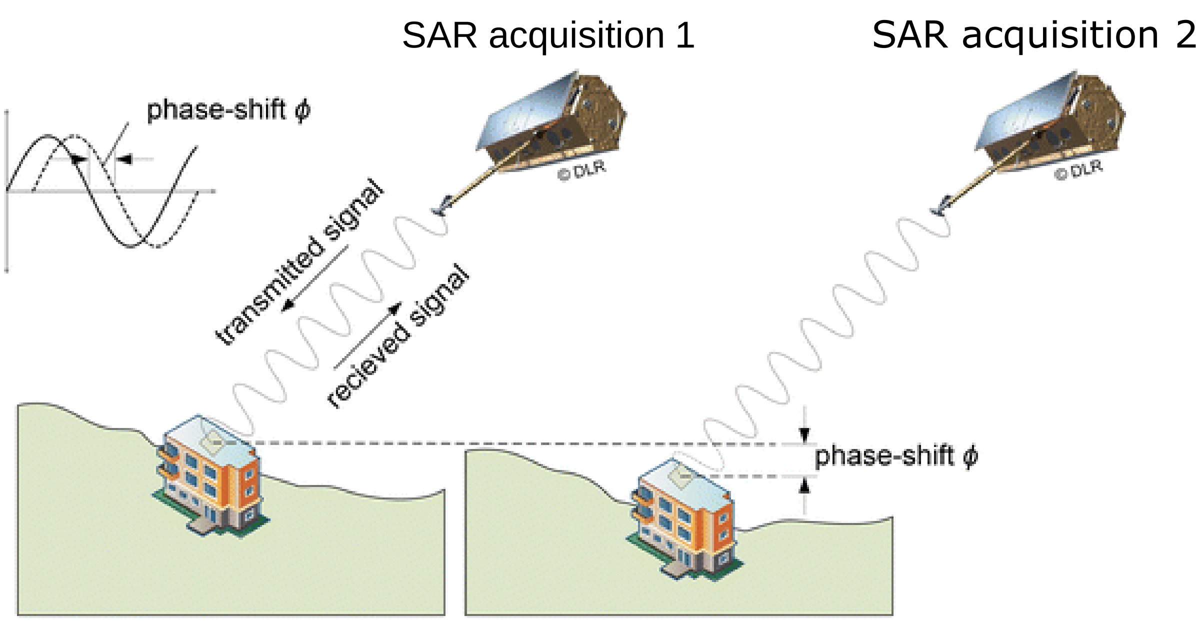
- Intensity maps (amplitude)
  - Goal → monitor the Earth surface: all-weather pictures and land classification
  - Method → multiple data acquisition over the same area during the same passage (focusing)
  - Key information needed → multiple amplitude measurements

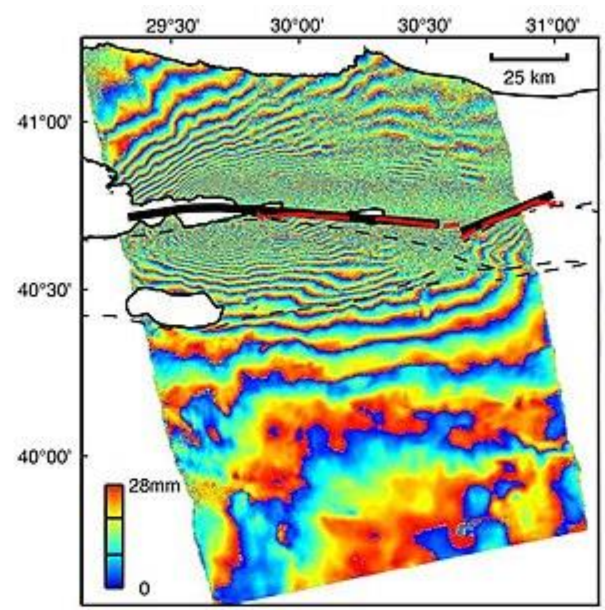




SAR products: interferometry

- Interferometric measurements (phase)
  - Goal → estimate displacement of the Earth surface (millimetric resolutions)
  - Method → multiple data acquisitions over the same area during different passages
  - Key information needed → differential phase measurements over highly reflective targets



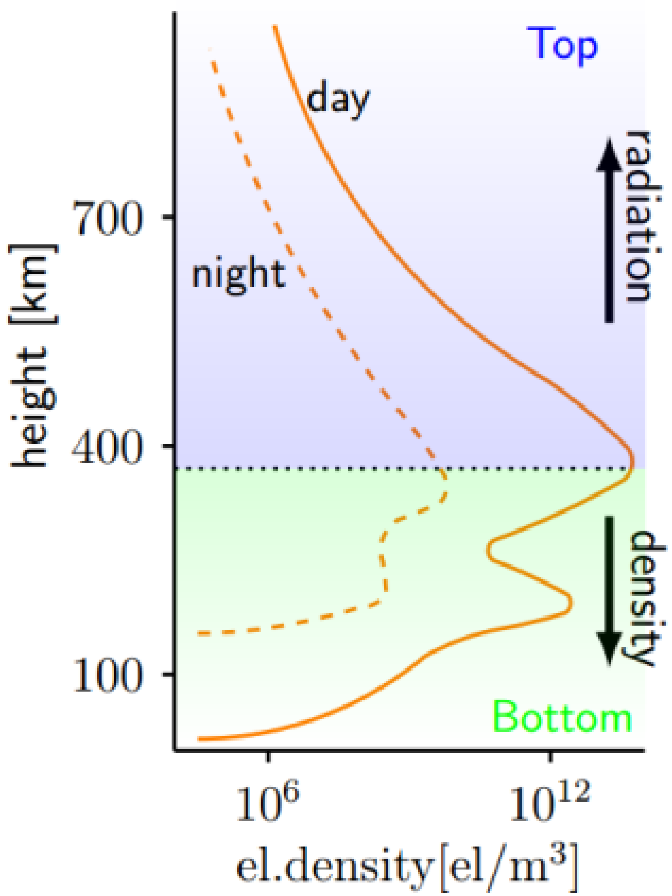


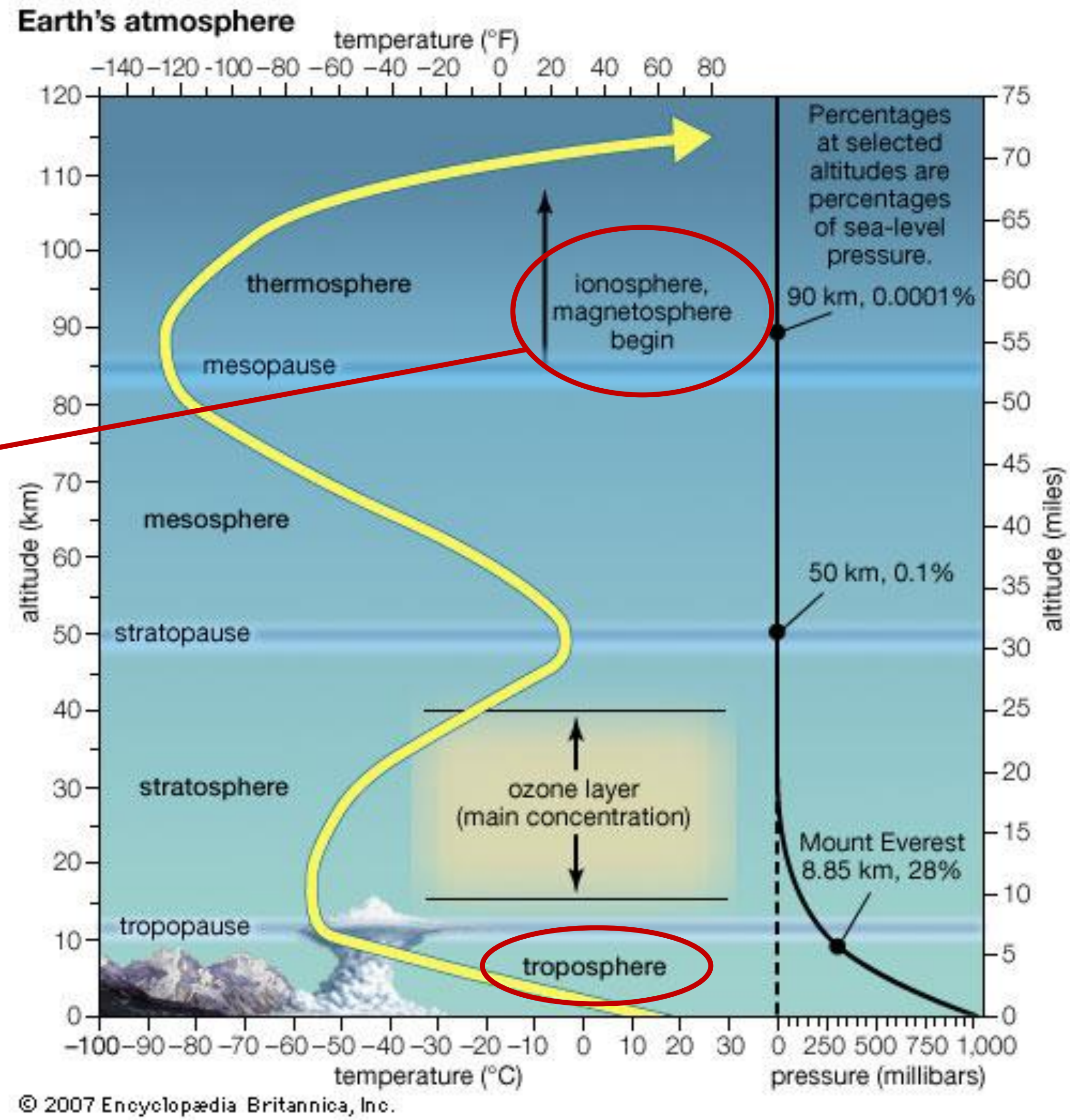
What about the impact of the atmosphere?

How does the atmosphere impair space-borne radar measurements?

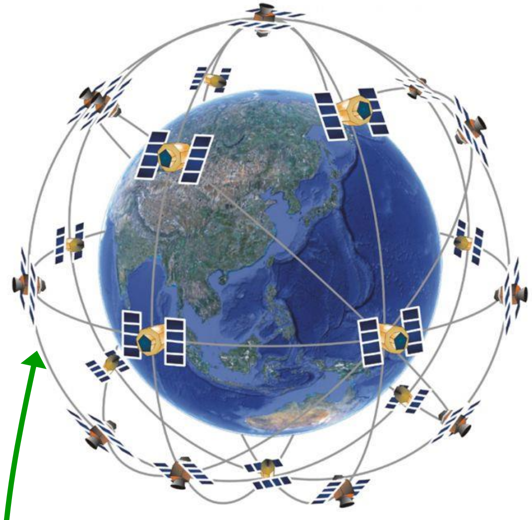
What are the key effects to be considered?

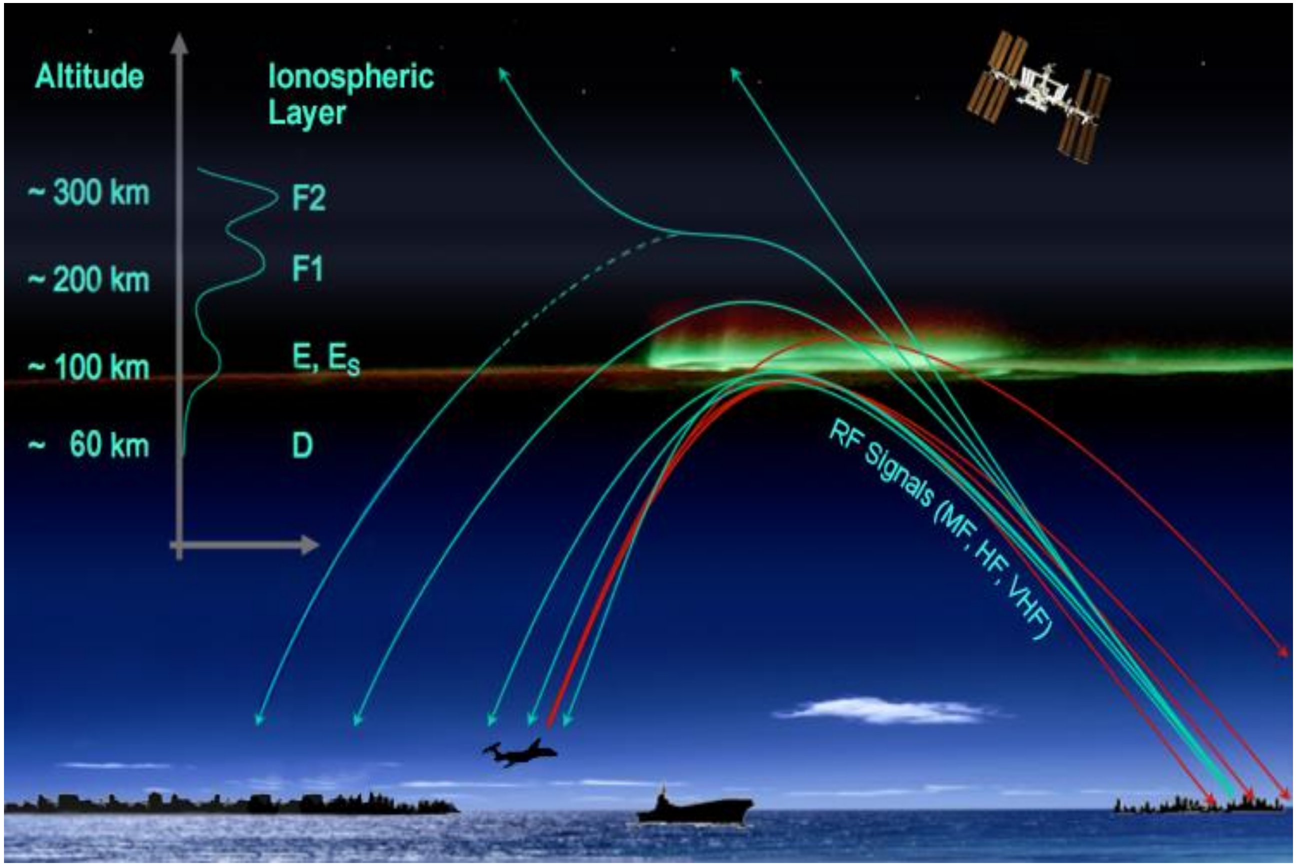
Atmospheric propagation





Impact of the ionosphere

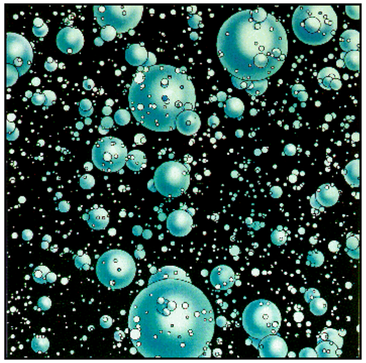




Effects of the ionosphere (1-10 GHz range):

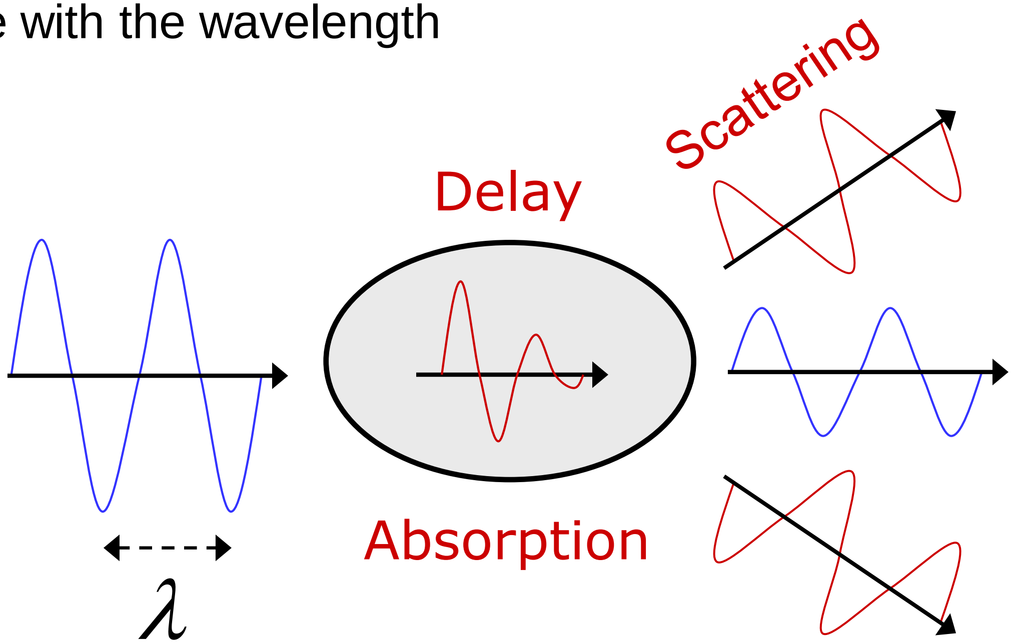
- Refraction: low
- Attenuation: low
- Faraday rotation: low
- Group delay: high, but the ionosphere is dispersive so the group delay can be estimated and removed using signals with a non-negligible bandwidth

Impact of the troposphere



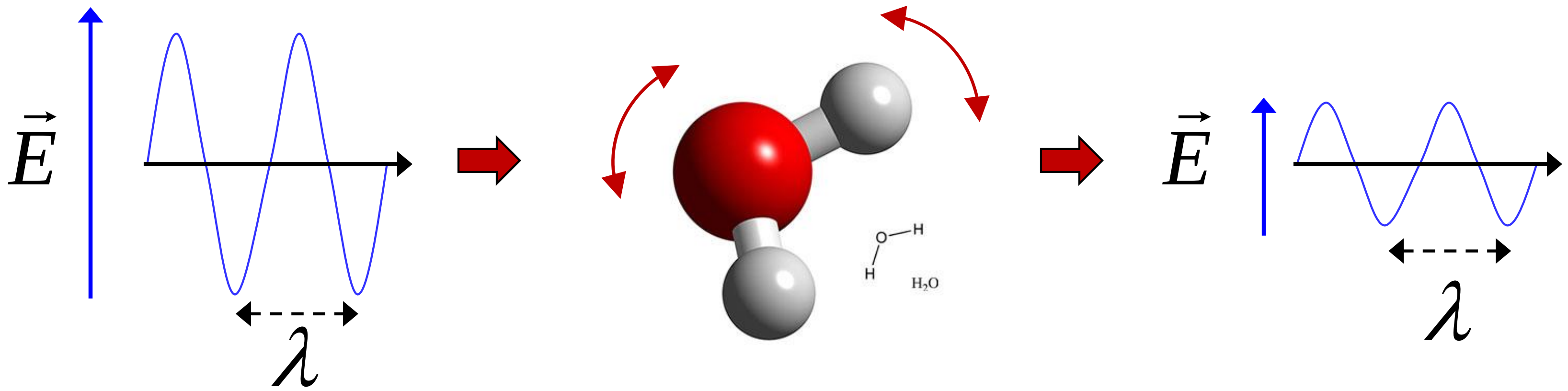
Effects caused by ice and water particles:

- Signal attenuation consisting of both scattering and absorption due to the ice and water particles; also group delay is introduced
- Strong effects for frequencies above approximately 10 GHz (rain) and 50 GHz (clouds) → dimensions of particles (e.g. few mm for rain and few μm) become comparable with the wavelength
- Different phenomena (e.g. rain and clouds) due to different size, concentration and physical state of the particles
- Clouds → below 10 GHz basically transparent to the wave
- Rain → below 10 GHz lower effects and low probability of occurrence (e.g. 5%-10% in temperate climates)



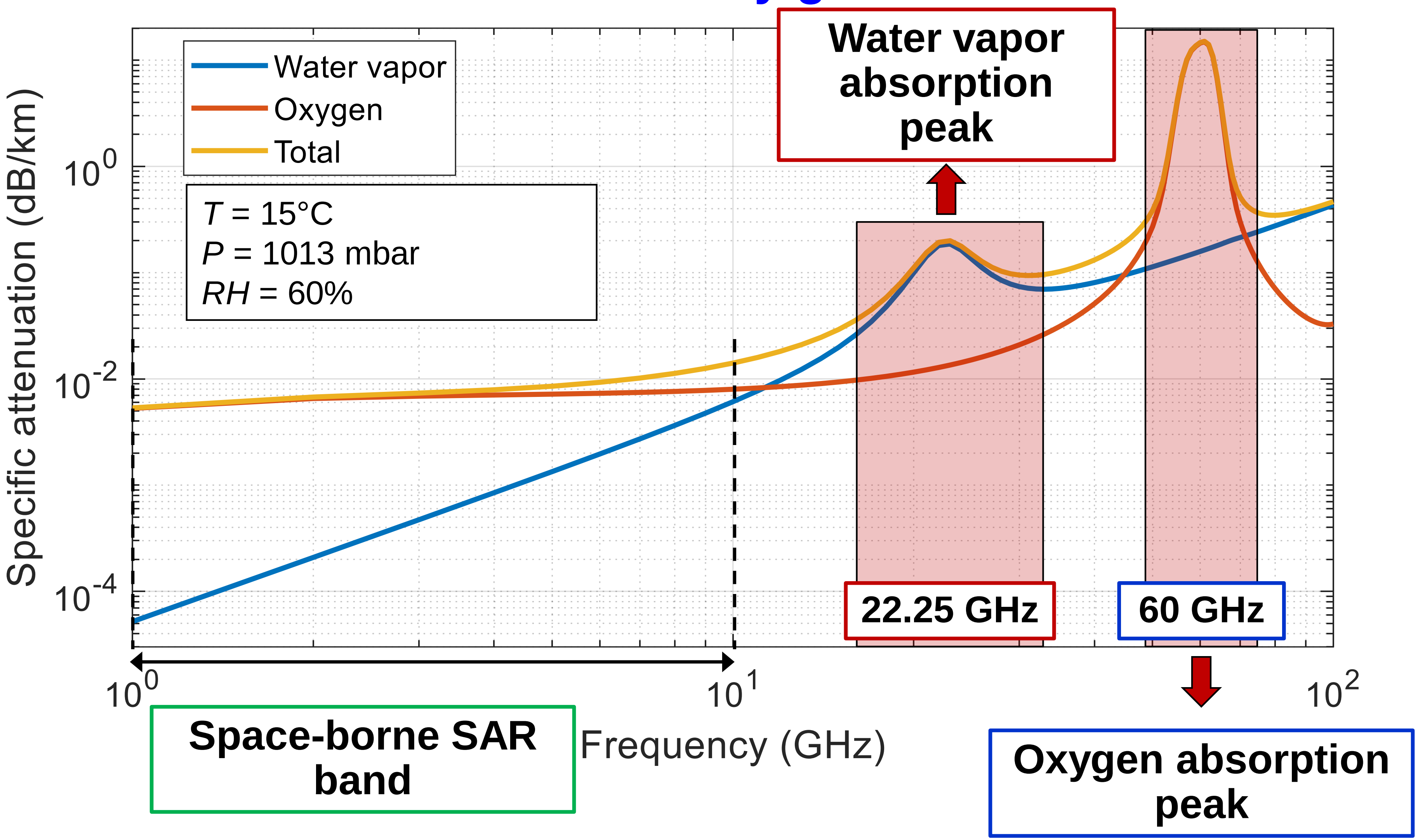
Effects caused by atmospheric gases (1–100 GHz)

- Gaseous components affecting E.M. propagation in this frequency range → oxygen and water vapor
- Absorption and delay → due to the oscillation of oxygen (magnetic dipole) and water vapor (electric dipole) molecules induced by E.M. waves



- Significant effects specifically around some key frequencies → resonance
- Effects dependent on temperature, pressure and relative humidity
- Both always present in the atmosphere

Attenuation by gases

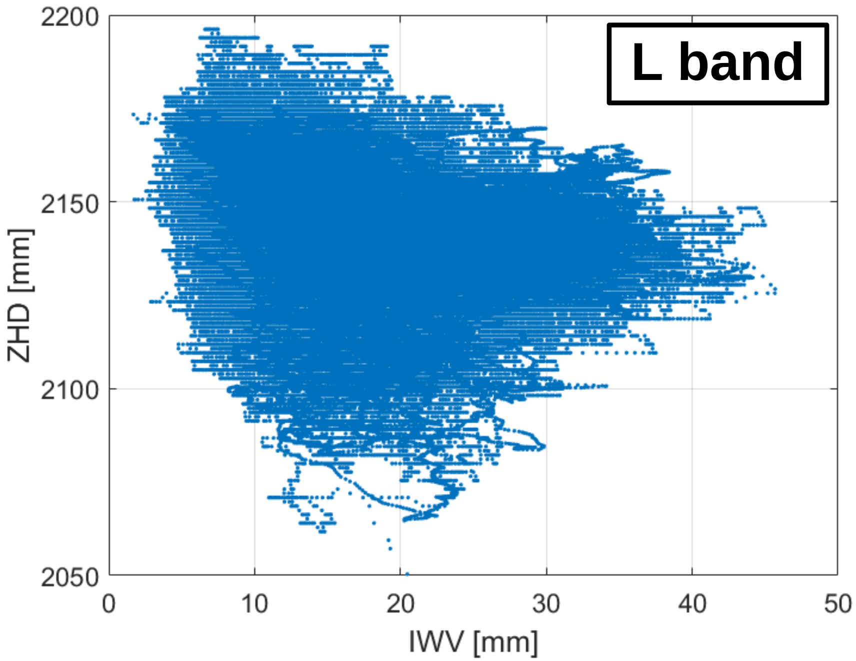


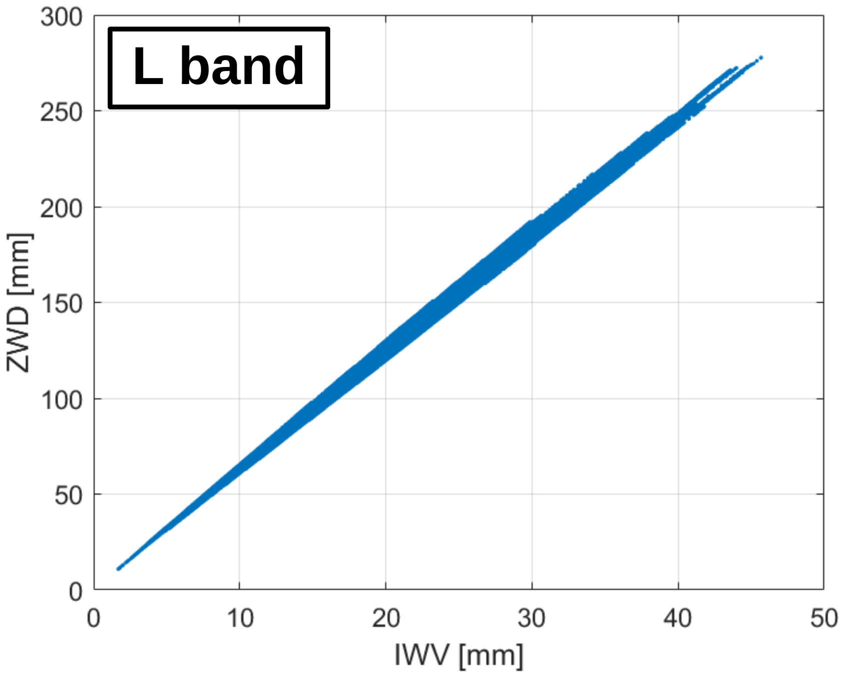
Group delay by gases

$$ZTD = ZHD + ZWD$$

Zenith Hydrostatic Delay (OX)

Zenith Wet Delay (IWV)





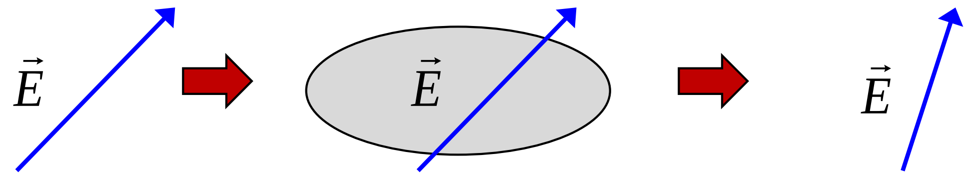
- It depends mainly on *P*
- Quite limited variability in space and time
- It can be estimated and removed accurately

- It depends mainly on IWV
- Quite high variability in space and time
- More difficult to estimate

Tropospheric and SARs

Depolarization

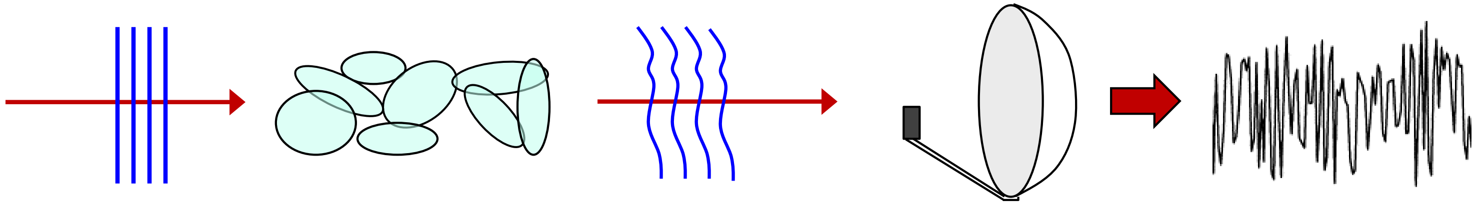
- Change in the wave polarization due to the non spherical shapes of ice/water particles



- Frequency used in SAR missions → low depolarization effects due to the particle size with respect to the wavelegth

Scintillations

- Very fast fluctuation of the received signal due to turbulence in the atmosphere (humidity variations, clouds, winds, rain drops …) → distortion of the wave front



- Effectively mitigated by using large antennas (like in SAR missions)

Tropospheric and SARs

To sum up on the atmospheric effects on SARs

- Ionosphere → effects either negligible (e.g. attenuation) or can be removed precisely (e.g. delay)
- Troposphere
  - Ice/water particles
    - limited effects for current SAR missions and anyway difficult to compensate for
    - low probability of occurrence
  - Gases (attenuation) → very low for frequencies used in SAR missions
  - Gases (group delay)
    - Hydrostatic part (mainly oxygen) → lower variability and quite easy estimation
    - Wet part (water vapor) → higher variability and more difficult to estimate

Delay (phase shift) → strong effects on SAR interferometry

Need of experimental activities to investigate accurate methods to retrieve IWV

Experimental equipment

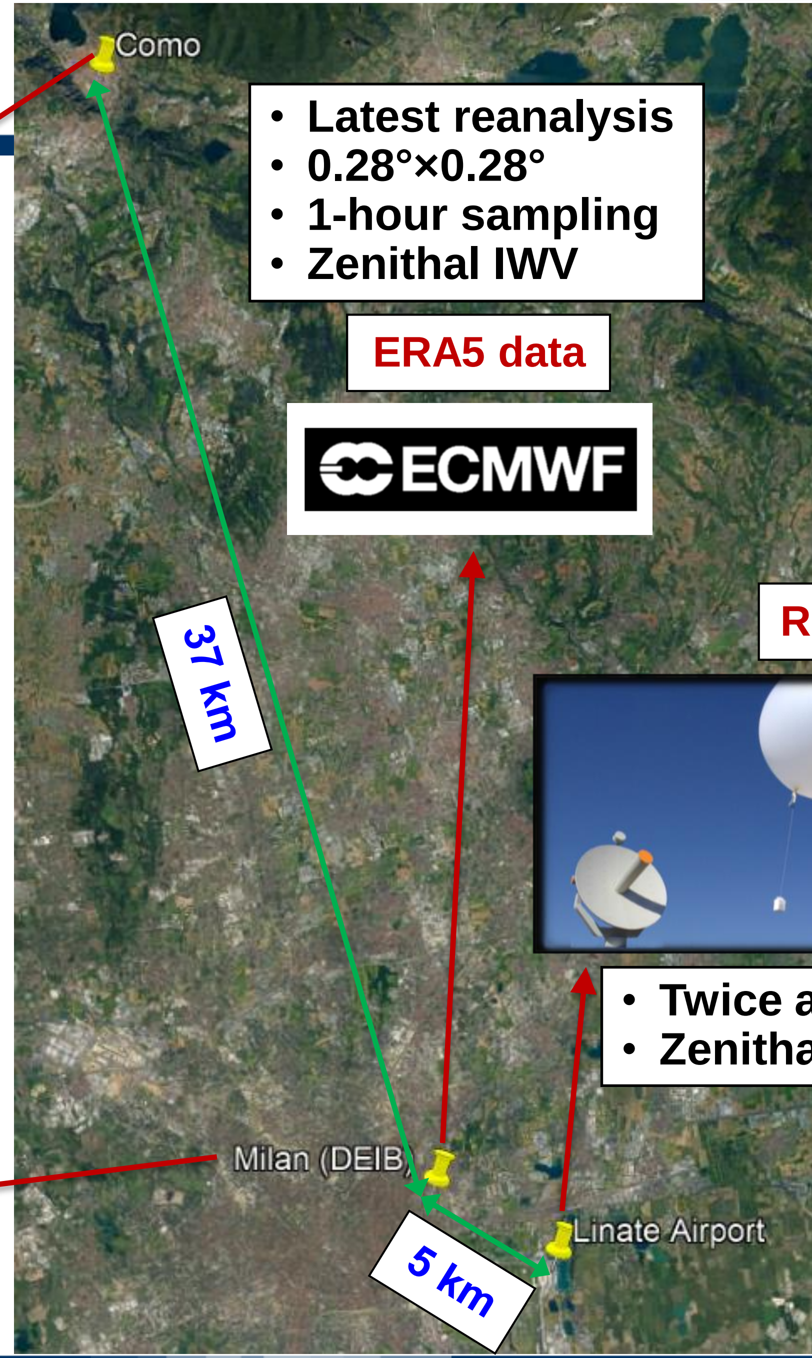
Milan site

EPN station

- GNSS receiver
- 1-hour sampling
- Zenithal IWV

- 4 channels
- 1-sec sampling
- IWV along the Alphasat path (35.6°)

Radiometer



- Latest reanalysis
- 0.28°×0.28°
- 1-hour sampling
- Zenithal IWV

ERA5 data

RAOBS

- Twice a day
- Zenithal IWV

Louvain-la-Neuve site

IGS station (BRUX)

- **GNSS receiver**
- **5-min sampling**
- **Zenithal IWV**

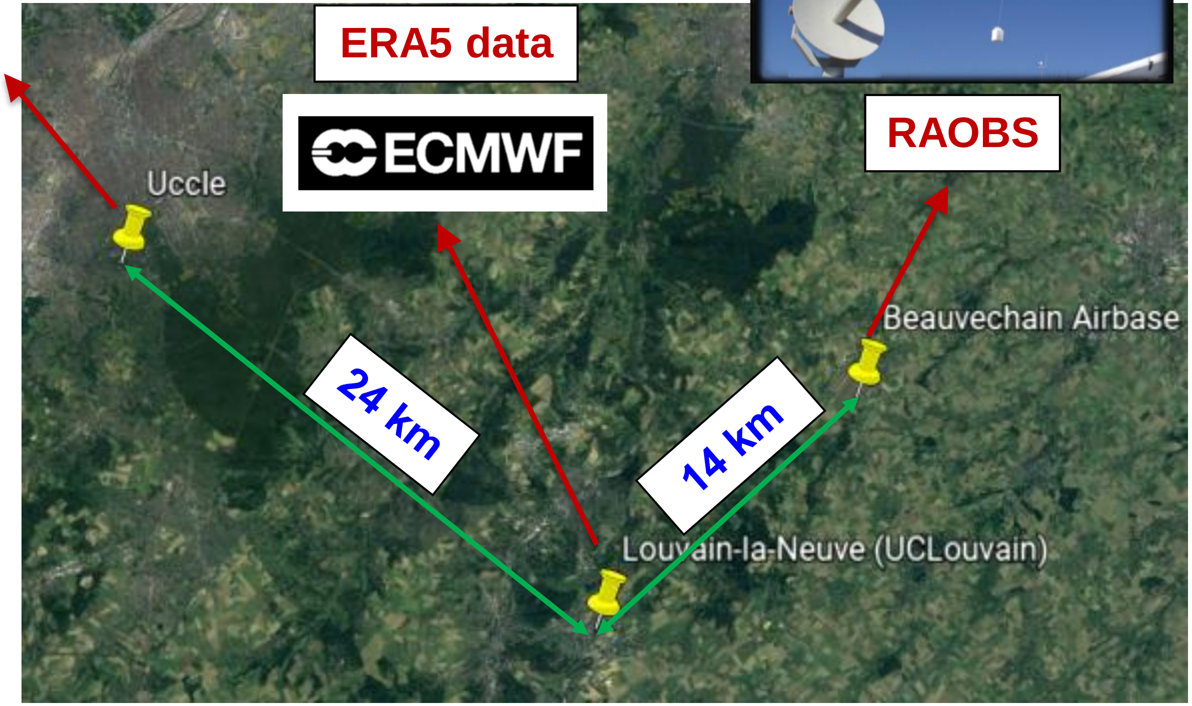
- **Latest reanalysis**
- **0.28°×0.28°**
- **1-hour sampling**
- **Zenithal IWV**

- **Mostly once a day**
- **Zenithal IWV**

RAOBS

ERA5 data

ECMWF



GNSS receivers

- GNSS receivers (known position) → estimation of the total signal delay (group velocity)
- Total delay = ionospheric delay + tropospheric delay

✓ Dependent on the total electron content (TEC) and on the frequency

✓ It can be precisely removed by using a two-frequency receiver

$$ZTD = ZWD + ZHD$$

Zenith Total Delay: from the GNSS receiver

Zenith Wet Delay: it contains the information on the IWV

Zenith Hydrostatic Delay: it depends on pressure, latitude and site altitude

Zenith Hydrostatic Delay

Zenith Hydrostatic Delay is calculated as:

$$ZHD = \frac{2.2768 P_0}{1 - 0.00266\cos(2\lambda) - 0.00028 H}$$

Como site latitude (°)

Como site altitude (km)

- ✓ Ground pressure not available in Como (P_0^{CO}), but values collected in Milan (P_0^{MI})
- ✓ Difference in height between the sites (ΔH = 155 m) → pressure from Milan to be scaled to Como. Similar altitudes between Uccle and Louvain-la-Neuve
- ✓ To this aim, use of the annual global reference standard atmosphere from ITU-R [1]:

$$P(h') = 1013.25\left[\frac{288.15}{288.15 - 6.5h'}\right]^{-34.1632/6.5}$$ and $$h' = \frac{6356.766h}{6356.766 + h}$$ ➡ $$\boxed{P_0^{CO} = 0.9797\, P_0^{MI}}$$

[1] *ITU-R, "Reference Standard Atmospheres," ITU-R Recommendation P. 835-6, 2017*

Zenith Wet Delay and IWV

- Zenith Hydrostatic Delay is removed from *ZTD*

$$ZWD = ZTD - ZHD$$

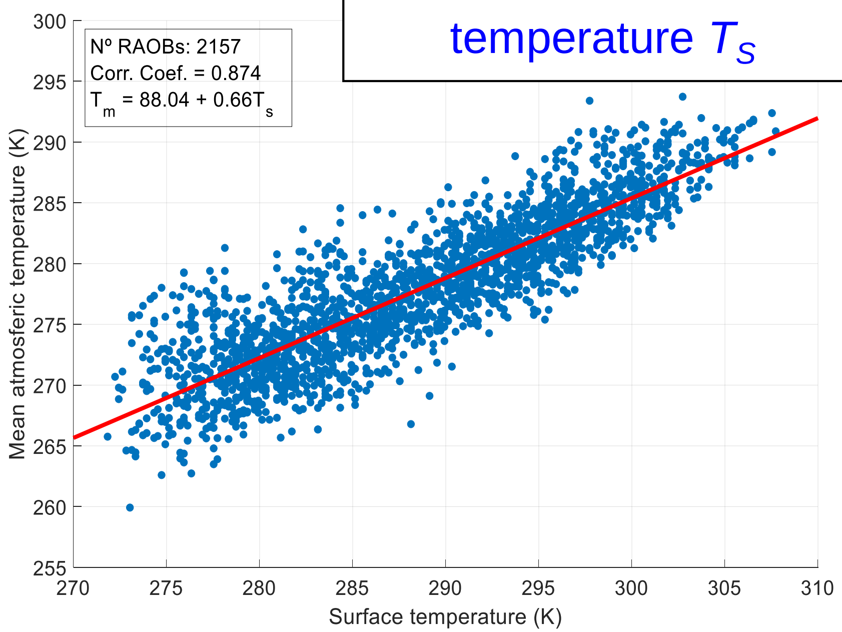
- IWV obtained from well-established procedure:

$$\boxed{IWV = \frac{ZWD}{c}}$$

$$c = 10^{-6}\left(k_2' + \frac{k_3}{T_m}\right)R_w \cdot \rho_L$$

$$k_2' = k_2 - k_1 \cdot \varepsilon$$
$$k_1 = 77.689 \quad \mathrm{K \cdot hPa^{-1}}$$
$$k_2 = 71.295 \quad \mathrm{K \cdot hPa^{-1}}$$
$$\varepsilon = 0.622$$
$$k_3 = 3.754 \times 10^5 \quad \mathrm{K^2 \cdot hPa^{-1}}$$
$$R_w = 461.51 \ \mathrm{J \cdot kg^{-1}} \cdot K^{-1}$$
$$\rho_L = 1000 \quad \mathrm{kg} \cdot m^{-3}$$

Average temperature of the atmosphere T_m calculated from RAOBS profiles and linked to the surface temperature T_S



Microwave radiometer

- The atmospheric attenuation $A_{RAD}(f_i,\theta)$ at the radiometric frequency f_i and elevation angle θ is obtained from the brightness temperature $T_B(f_i,\theta)$ (assumption of no scattering in the atmosphere → absence of rain) as follows:

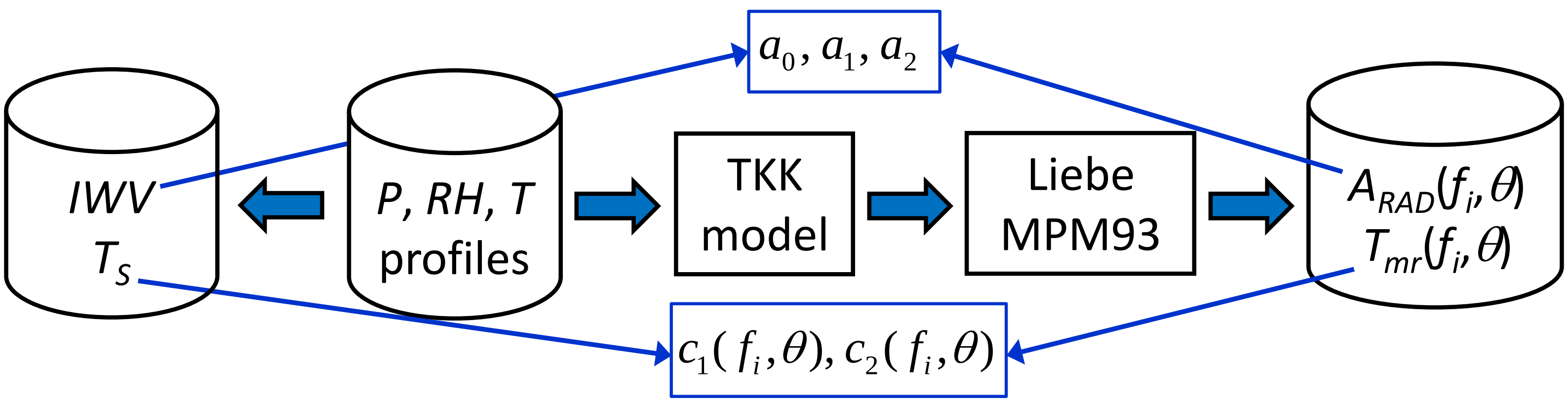
$$A_{RAD}(f_i,\theta) = 10\log_{10}\left(\frac{T_{mr}(f_i,\theta) - T_C}{T_{mr}(f_i,\theta) - T_B(f_i,\theta)}\right)$$

T_C → Cosmic background temperature (2.73 K)

T_S → Surface temperature

$$T_{mr}(f_i,\theta) = c_1(f_i,\theta)T_S + c_2(f_i,\theta)$$

- Estimated IWV → $\mathrm{IWV}(\theta) = a_0 + a_1 A_{RAD}(f_1,\theta) + a_2 A_{RAD}(f_2,\theta)$ → $\mathrm{IWV} = \mathrm{IWV}(\theta)\sin(\theta)$



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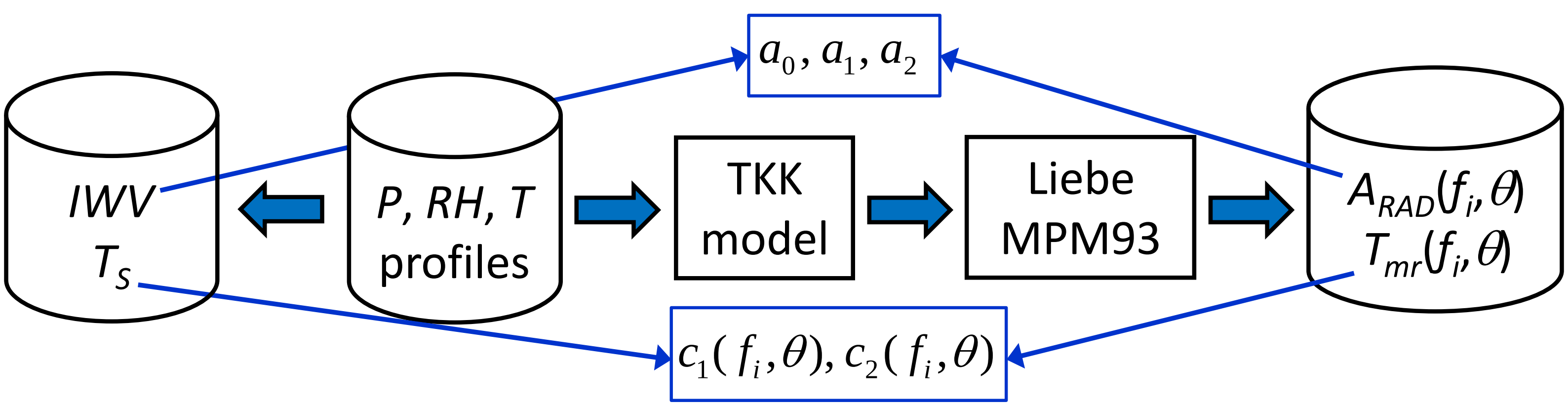
$$A_{RAD}(f_i,\theta) = 10\log_{10}\left(\frac{T_{mr}(\ldots}{T_{mr}(f_i,\theta \ldots}\right.$$

$$T_{mr}(f_i,\theta) = c_1(f_i,\theta)T_S + c_2(\ldots$$

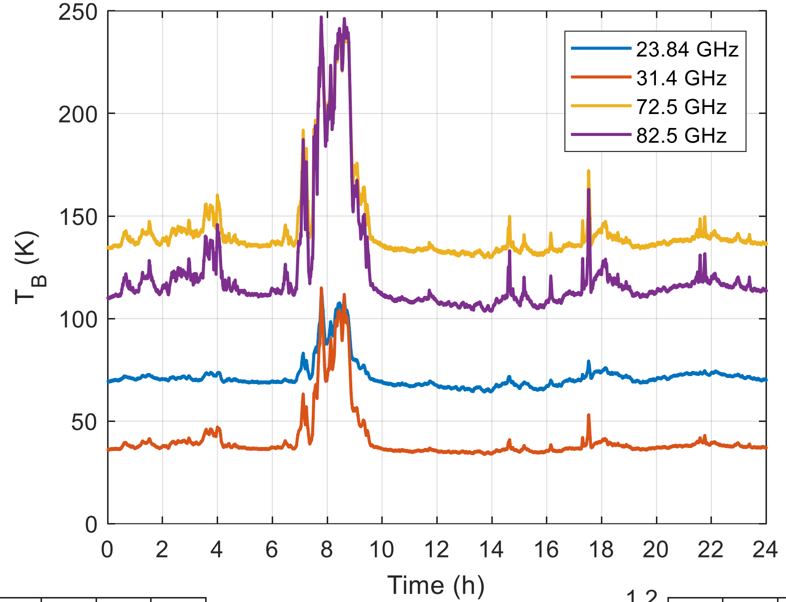
f_1 = 23.8 GHz
f_2 = 31.4 GHz
θ = 35.6°

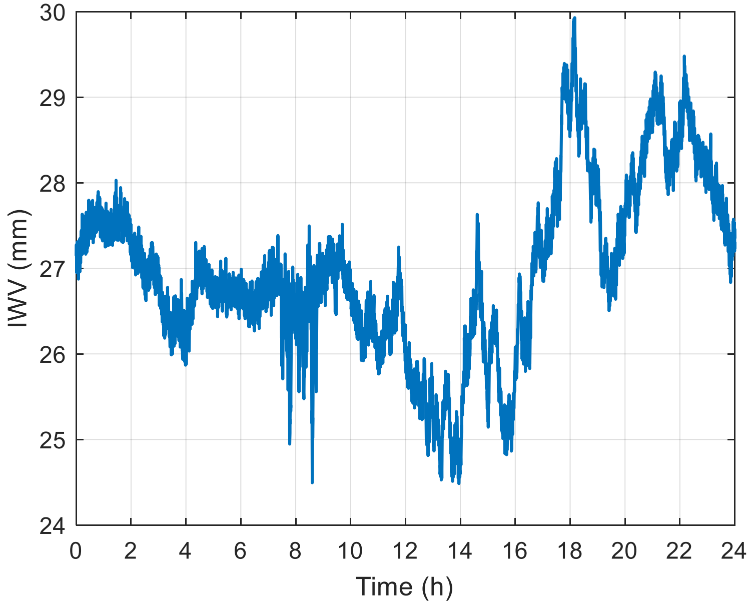
→ Cosmic background temperature (2.73 K)
→ Surface temperature

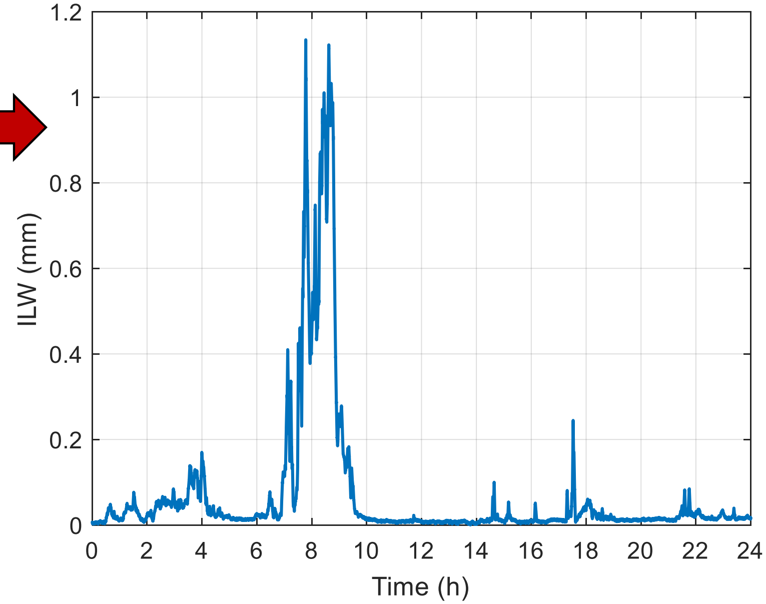
- Estimated IWV → $\mathrm{IWV}(\theta) = a_0 + a_1 A_{RAD}(f_1,\theta) + a_2 A_{RAD}(f_2,\theta)$ → $\mathrm{IWV} = \mathrm{IWV}(\theta)\sin(\theta)$



Data processing for integrated water vapor retrieval

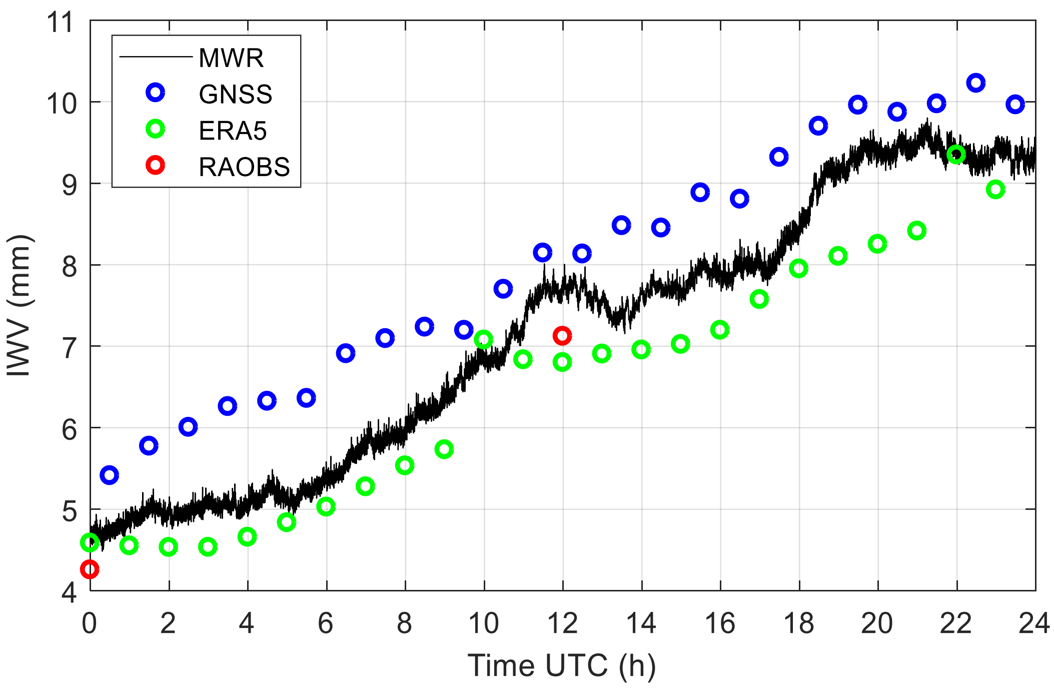






Results and discussion: Milan

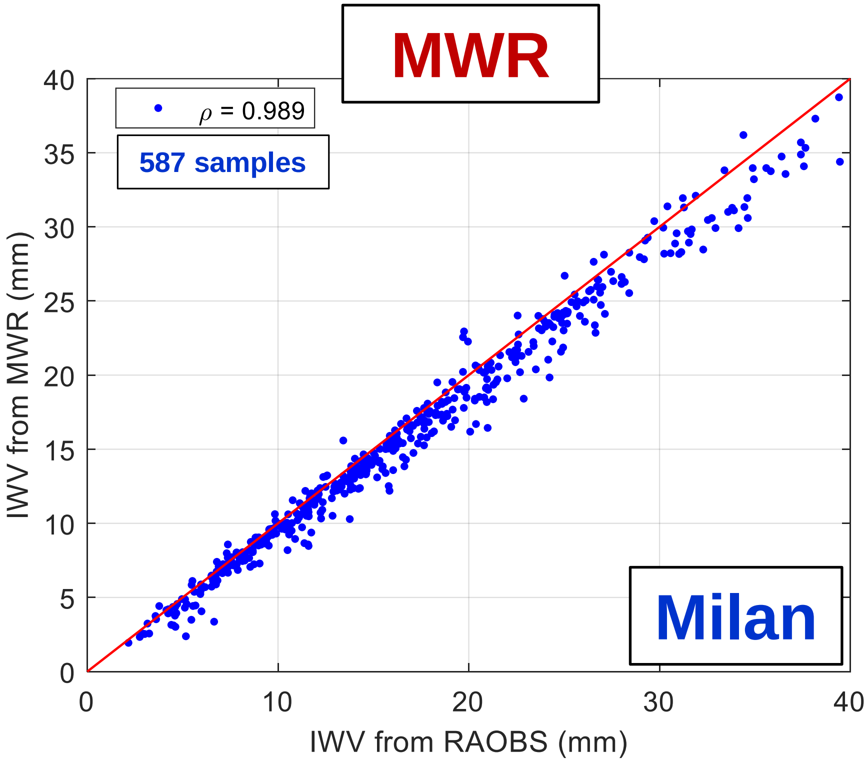
- Evaluation of the accuracy in retrieving IWV using MWRs, GNSS receivers and ERA5 data
- Reference data → RAOBS
- Database → the whole of 2017
- Sample comparison: Milan site, 7th of January 2017

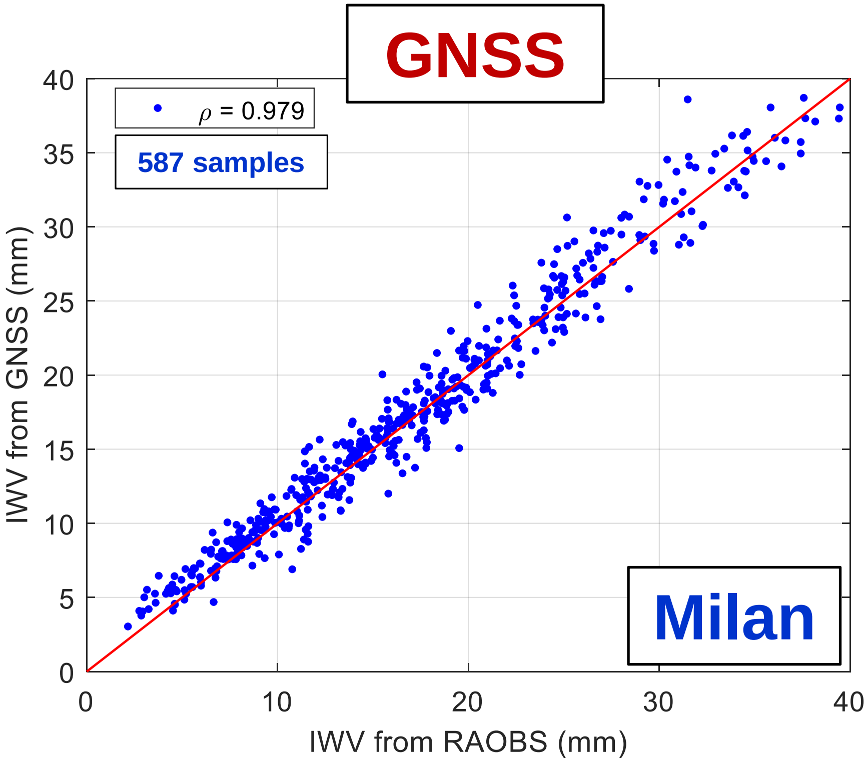


- All datasets indicate increase in the IWV
- Best agreement → MWR and ERA5
- GNSS receiver → linearly interpolated; slightly lower agreement (likely, distance between Como and Milan)

Results and discussion

- More general results for the whole year (Milan)





- Higher correlation coefficient for MWR
- Samples in rainy conditions filtered: MWR inversions not reliable under electromagnetic scattering

- Comparison assessment using the absolute error on IWV:

$$\varepsilon(t) = \mathrm{IWV}_P(t) - \mathrm{IWV}_R(t)$$

Predicted:
MWR/GNSS/ERA5

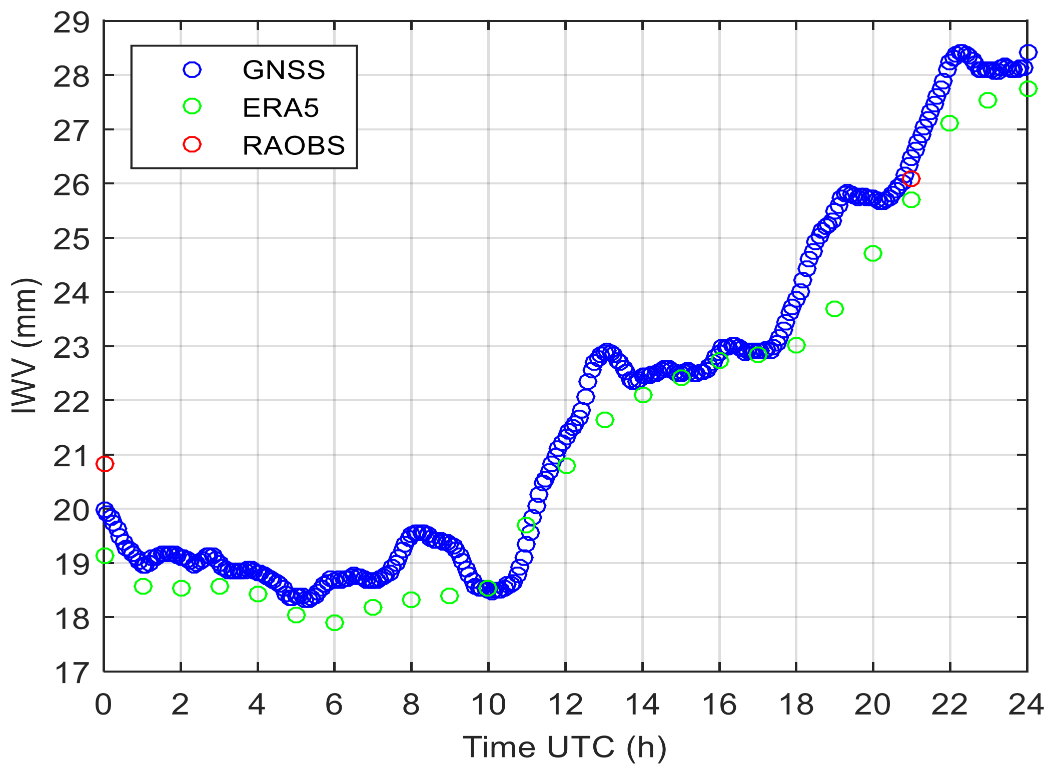
Reference: RAOBS

- Calculation of the mean (E) and root mean square (RMS) error

	MWR	ERA5	GNSS
E of IWV (mm)	-0.54	-0.99	0.27
RMS of IWV (mm)	1.34	1.72	1.76

Results and discussion: Louvain-la-Neuve

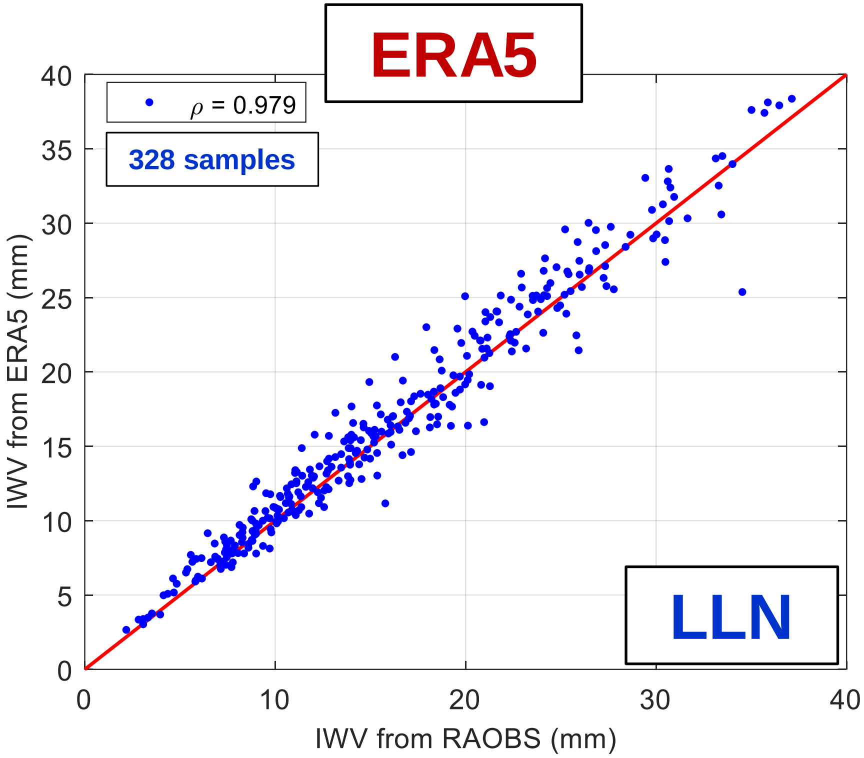
- Same evaluation
- Database → from 27/3/2017 to 24/3/2018
- Sample comparison: Louvain-la-Neuve site, 14th of June 2017

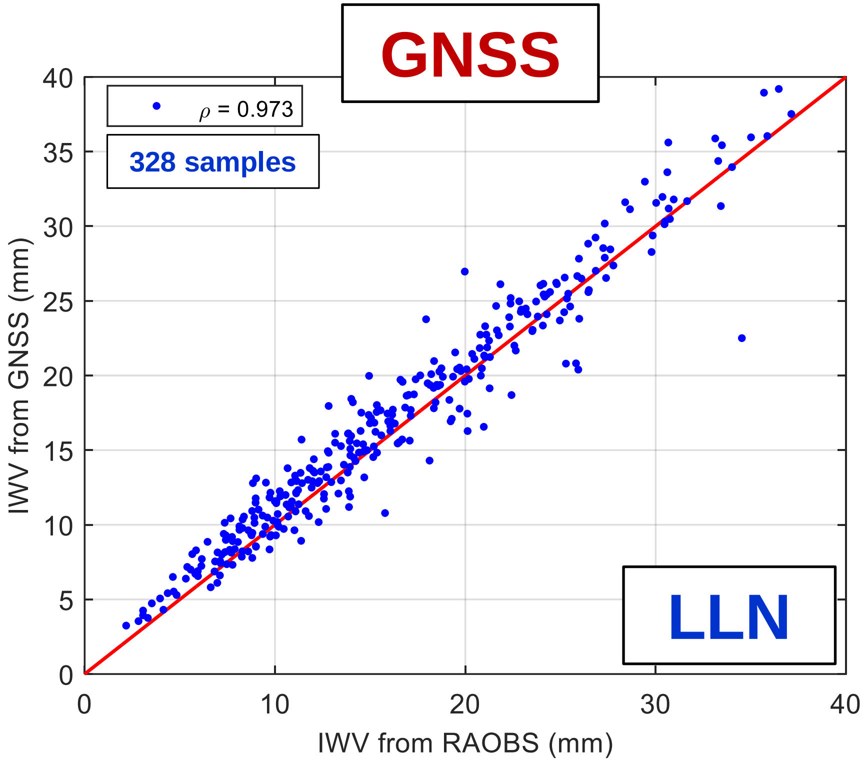


- No MWR available
- Higher temporal resolution of the GNSS-derived data
- All datasets showing an increase in IWV
- Good agreement of both datasets (within ±1-2 mm)

Results and discussion

- More general results for the whole year (Louvain-la-Neuve)





- Slightly higher correlation coefficient for ERA5 data

Error comparison for LLN:

	ERA5	GNSS
E of IWV (mm)	0.54	0.76
RMS of IWV (mm)	1.68	1.95

Results:

- ERA5 data → slight better accuracy (same level as ERA5 for Milan)
- GNSS receiver → slightly worse accuracy if compared to GNSS in Milan

Conclusions

- Comparison of different techniques to derive IWV (against RAOBS data) in two sites:
  - ✓ Microwave radiometer (MWR)
  - ✓ GNSS receiver
  - ✓ ERA5 data from ECMWF
- Key results:
  - ✓ Best accuracy → MWR
  - ✓ Comparable accuracy from GNSS receivers and using ERA5 data (latter slightly better)
- Final recommendations:
  - ✓ ERA5 data → no processing needed, readily available and usable with good spatial and temporal resolution (as for water vapor)
  - ✓ Choice on the source for IWV → also dependent on the time resolution: typically 1 second for MWR, 1 hour for GNSS and ERA5
- Future work:
  - ✓ comparison in other sites with very different climatic features (e.g. equatorial, tropical, cold, …)
  - ✓ Use of NWP data with higher spatial (e.g. 9 km×9 km from ECMWF forecast) and spatio-temporal (e.g. WRF outputs) resolutions

Thank you for your attention!