Tropospheric water vapor observation from space through a new measurement concept: the SATCROSS Project

L. Facheris[*a], F. Cuccoli [*], F. Argenti[*a], A. Mazzinghi[*], U. Cortesi[*c], G. Macelloni[*b], M. Gai[*b], S. del Bianco[*b], A. Feta[*a], F. Montomoli[*b], A. Ortolani[+], A. Antonini[+], S. Melani[+], L. Rovai[+], A. Gregorio[o], F. Dogo[o], L. Severin[o], T. Scopa[#]

[*] **CNIT** (National Inter-University Consortium for Telecommunications), Italy

[*a] CNIT Research Unit c/o Dept. of Information Engineering, Univ. of Florence, Italy

[*b] CNIT Research Unit c/o Institute of Applied Physics (IFAC)-CNR, Florence, Italy

[+] **LaMMA** Lab. for Meteorology and Atmospheric Monitoring, Florence, Italy

[o] **PICOSATS s.r.l.**, Trieste, Italy

[#] **ASI** - Italian Space Agency, Rome, Italy

ESA ATMOS Conference 22-26 November 2021

consorzio nazionale interuniversitario per le telecomunicazioni

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The SATCROSS Project

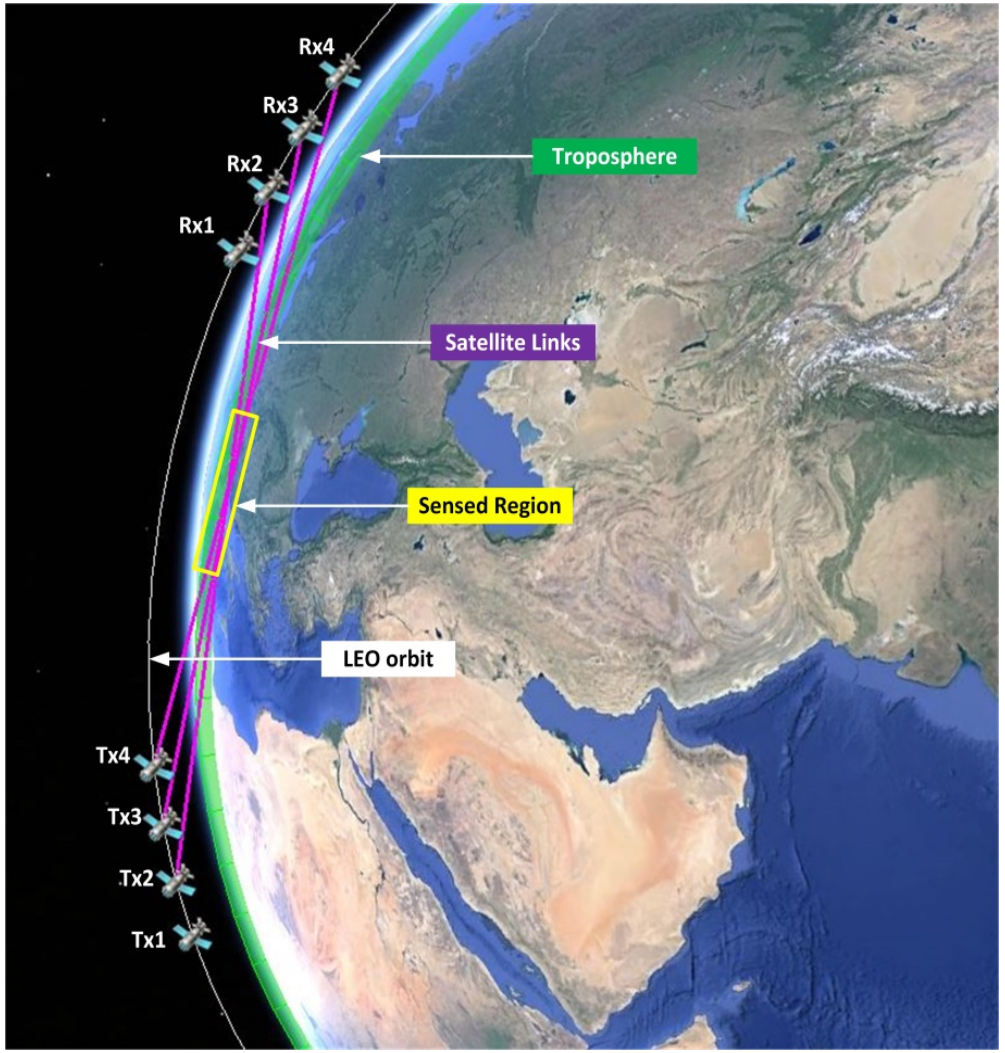
Co-rotating Satellites for estimating tropospheric water vapor

March 2020 - March 2022

OUTLINE:

- Project scope, proposed mission concept and motivations
- The NDSA (Normalized Differential Spectral Attenuation approach) for IWV measurements
- Application of NDSA to a constellation of co-rotating satellites
- Project topics

MISSION CONCEPT AND OBJECTIVE



SATCROSS scope: to carry out a **pre-feasibility study of a space mission for the observation of tropospheric water vapor**, based on:

- active differential measurement technique (***NDSA: Normalized Differential Spectral Attenuation***)
- A train of co-rotating LEO satellites.
- **Frequency bands: Ku/K**

Objective : estimating 2-D WV fields over vertical tropospheric sections ***on a continuous time basis***.

MOTIVATIONS FOR THE SATCROSS PROJECT

Tropospheric WV measurements are provided by:

- Radiosondes (in situ measurements)
- GNSS-based Radio Occultation techniques
- Infrared radiometers, spectrometers and spectroradiometers

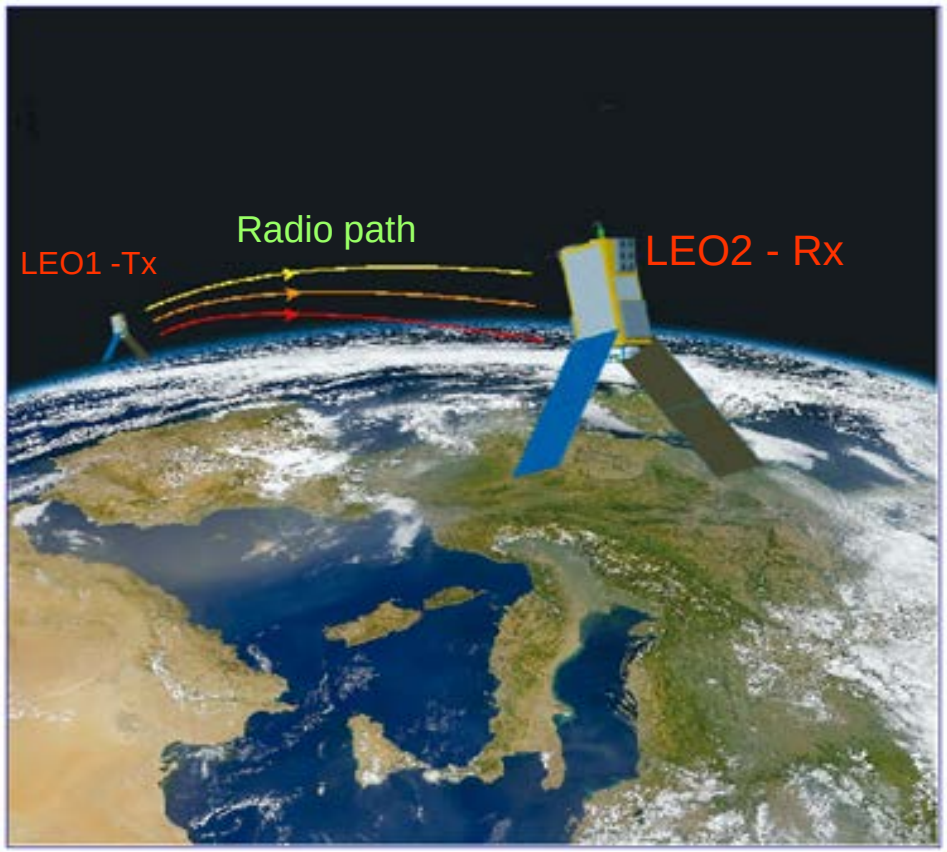
Limitations:

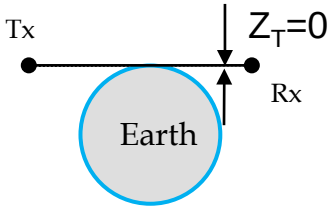
1) Uncertainties on the WV concentration estimates in the low troposphere, where the maximum amount of WV is present
2) Costs, accuracy, time and space sampling rates

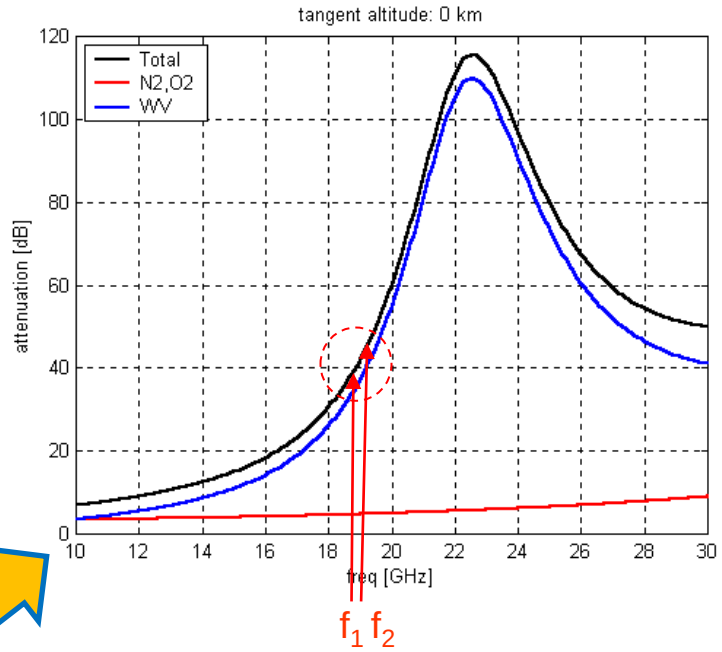
Factors hampering the ability to get WV concentration measurements on a continuous space-time basis and on a global scale in the low troposphere

Impact on the analysis of the water cycle and on the forecasting chain

The NDSA (Normalized Differential Spectral Attenuation) approach





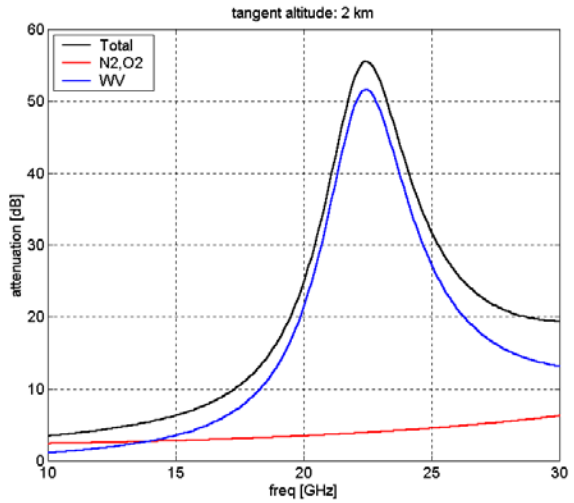


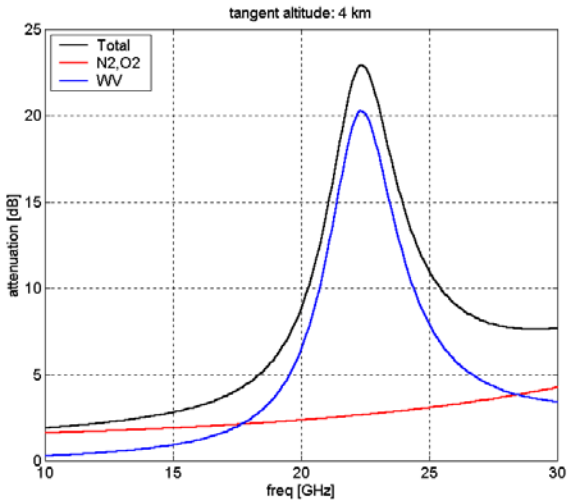
- Spherical symmetry extension of the MLS (Mid Latitude Summer) profiles
- MPM93 (Liebe)

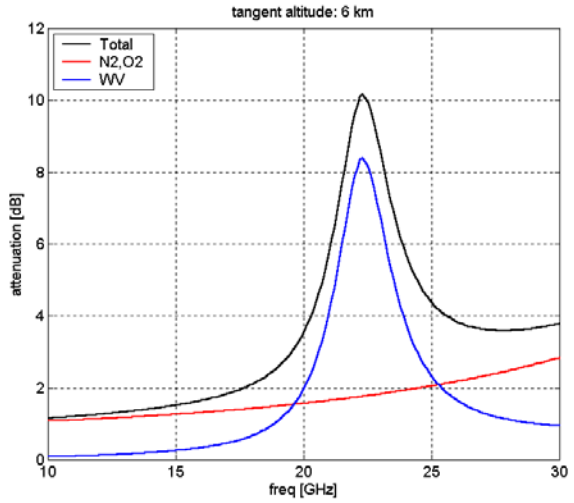
$$A(f) = P_{tx}(f) / P_{rx}(f)$$

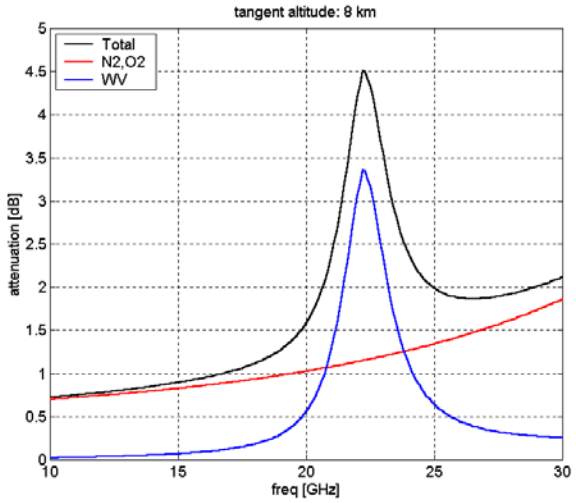
WV drives the spectral attenuation pattern

The NDSA approach – spectral attenuation patterns vs. z_T









The NDSA approach – the Spectral Sensitivity

Normalized derivative of the spectral attenuation

$$S(f) = \frac{1}{A(f)} \frac{d}{df} [A(f)]$$

Approximate version of S(f)

$$\hat{S}(f_o) = \frac{A(f_2) - A(f_1)}{\Delta f \, A(f_2)}$$

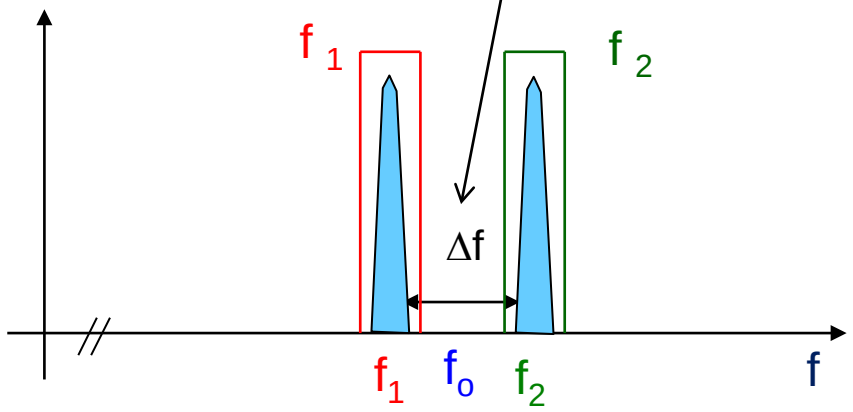
Spectral Sensitivity at f_o

$$\hat{S}(f_o) = \frac{P_1 - P_2}{\Delta f \, P_1}$$

$$f_1 = f_o - \Delta f / 2$$

$$f_2 = f_o + \Delta f / 2$$

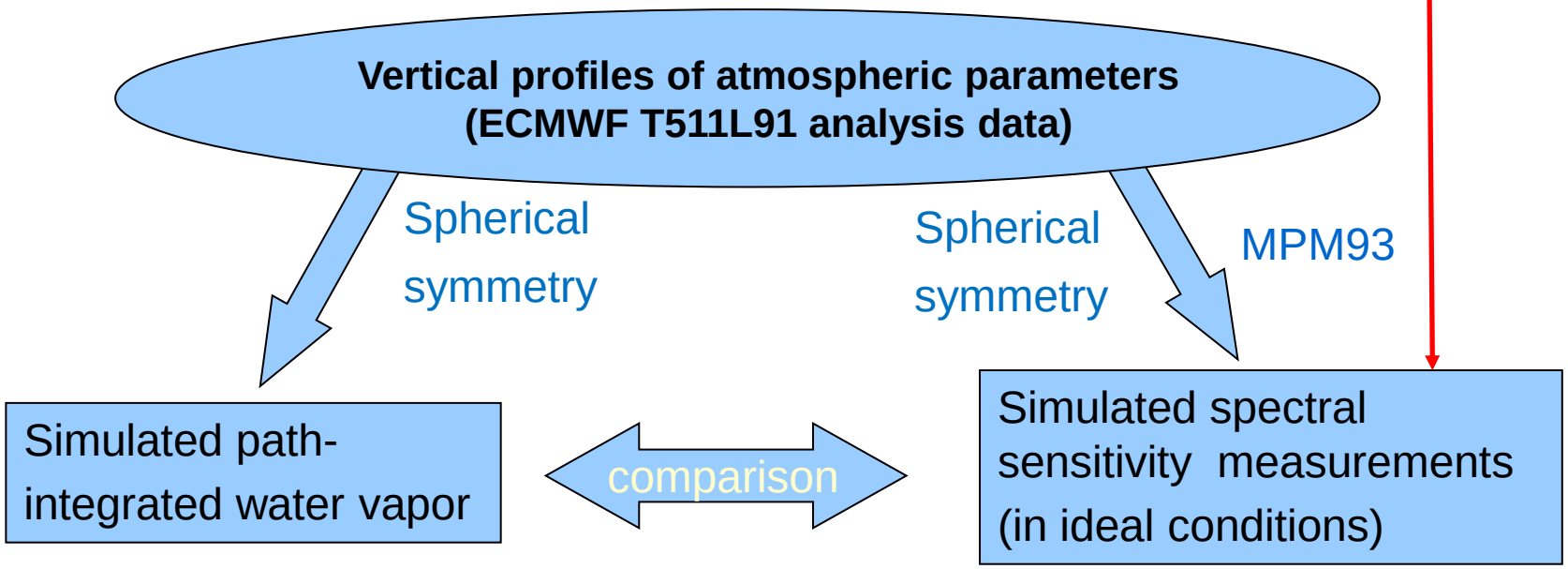
Δf: spectral separation



Spectral Sensitivity and Integrated Water Vapor (IWV)

In ideal measurement conditions (namely, no disturbance at the receiver nor propagation impairments), *S* measured at different frequencies f_o is tightly correlated to the IWV along LEO-LEO tropospheric propagation paths.

The frequencies considered are: 17 GHz | 19 GHz | 21 GHz



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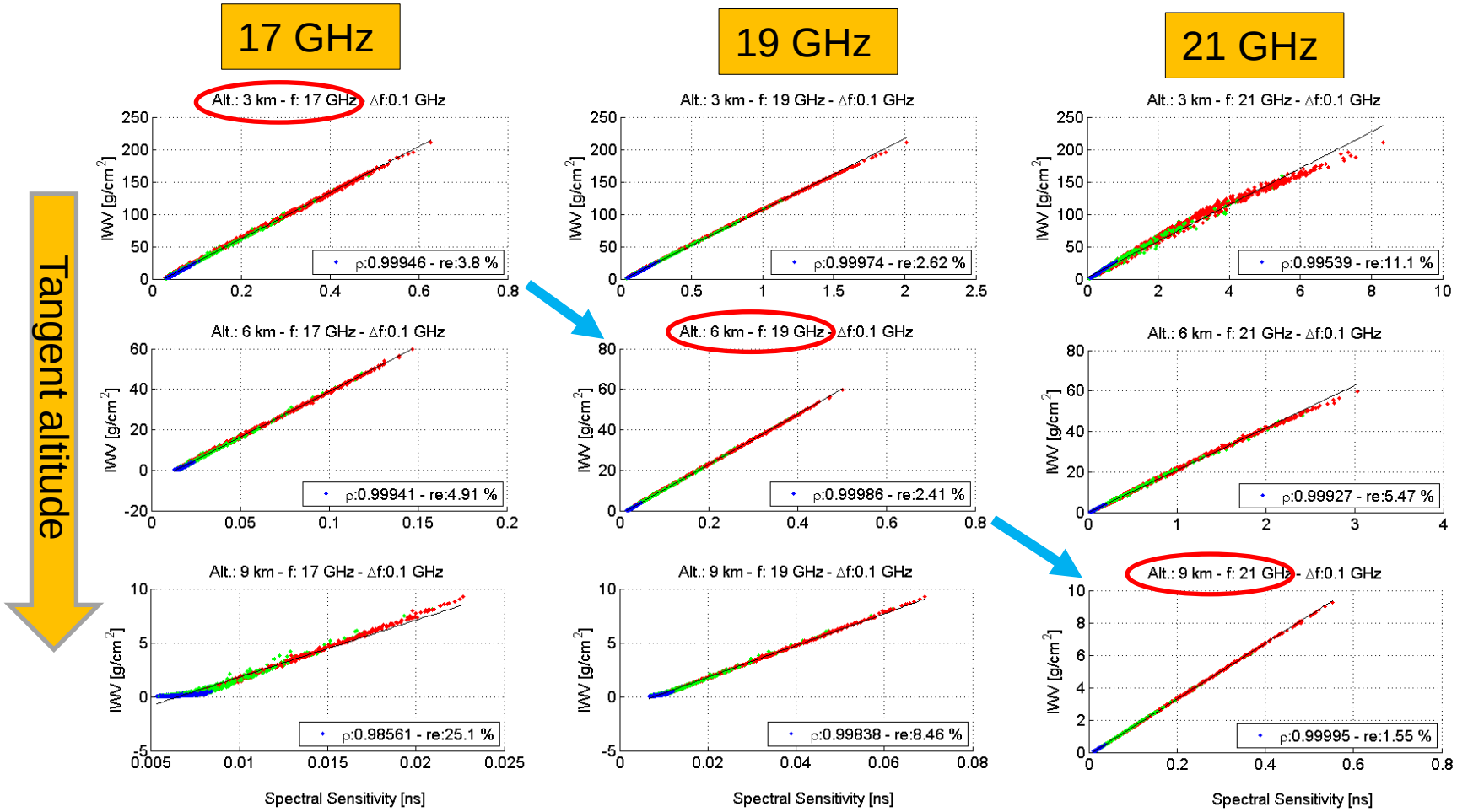
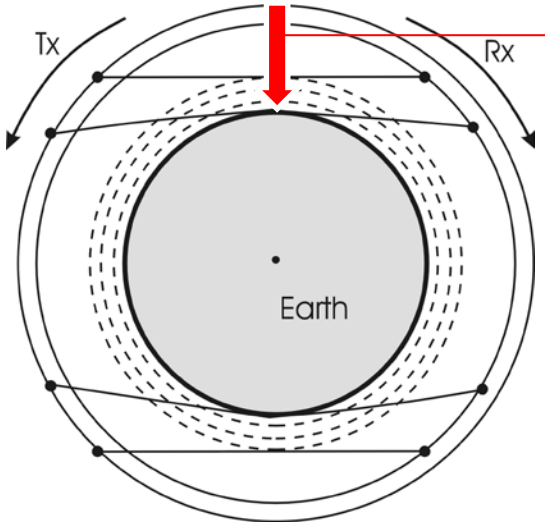


- Linear IWV-S relations, with coefficients varying with tangent altitude.
- The normalized differential approach reduces the impact of tropospheric scintillation and scattering effects

NDSA: ESA studies and related publications

Case of counter-rotating LEO satellites



Immersion of the radio link

"Alternative Measurements Techniques for LEO-LEO Radio Occultation (**AlMeTLEO**)," ESA-ESTEC contract No. 17831/03/NL/FF Final report (end: 2004)

"**ACTLIMB**: Study of the performance envelope of active limb sounding of planetary atmospheres," ESA contract 21507/08/NL/HE (end: 2010)

ANISAP: "Analysis of Normalised Differential Spectral Attenuation (NDSA) technique for Inter-Satellite Atmospheric Profiling" ESTEC CONTRACT No. 4000104831 (end: Dec 2013)

Cuccoli, F. and L. Facheris, L., "'Estimate of the tropospherical water vapour through microwave attenuation measurements in atmosphere,"' IEEE Transactions on Geoscience and Remote Sensing 40, pagg. 735-741 (2002)

Facheris, L. and F. Cuccoli: "Normalized Differential Spectral Attenuation (NDSA): a novel approach to estimate atmospheric water vapor along a LEO-LEO satellite link in the Ku/K bands", IEEE Transactions on Geoscience and Remote Sensing, Vol. 44, pagg. 1493-1503 (2006)

Martini, E., A. Freni, L. Facheris and F. Cuccoli: "The impact of tropospheric scintillation in the Ku/K bands on the communications between two LEO satellites in a radio occultation geometry", IEEE Transactions on Geoscience and Remote Sensing, Vol. 44, pagg.2063-2071 (2006)

Facheris, L., F. Cuccoli, and F. Argenti, "Normalized differential spectral attenuation (NDSA) measurements between two LEO satellites: performance analysis in the Ku/K bands," IEEE Transactions on Geoscience and Remote Sensing 46, pagg. 2345-2356 (2008)

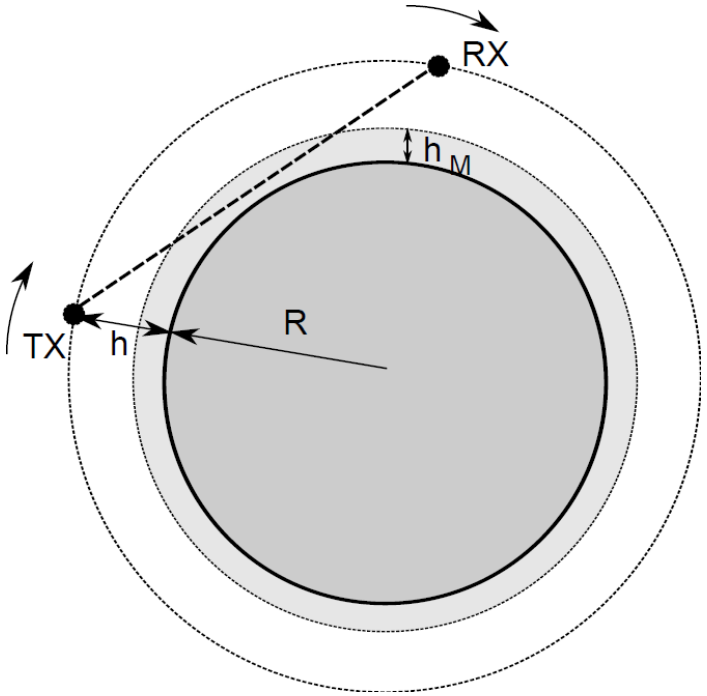
Martini, E., A. Freni, F. Cuccoli and L. Facheris : "Derivation of clear air parameters from high resolution radiosonde data", J. Atmospheric and Oceanic Technology, Vol. 32, pagg. 277-293 (2017)

L. Facheris, F. Cuccoli: "Global ECMWF analysis data for estimating the water vapor content between two LEO satellites through NDSA measurements", IEEE Transactions on Geoscience and Remote Sensing, Vol. 56, pagg. 1546-1554, (2018)

SATCROSS: the NDSA approach applied to the CO-RO geometry

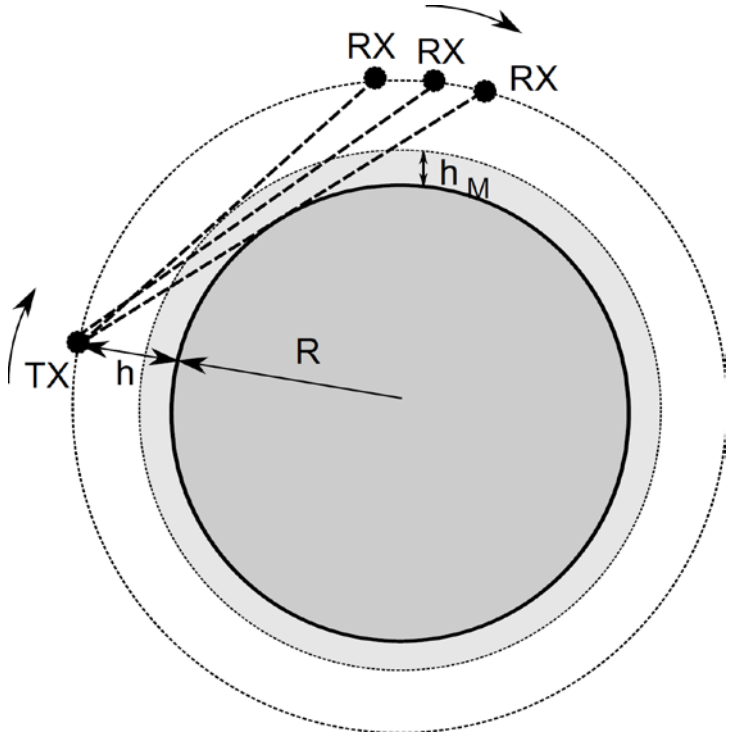
A. Lapini, F. Cuccoli, F. Argenti, L. Facheris; “The Normalized Differential Spectral Sensitivity Approach applied to the retrieval of tropospheric water vapor fields using a constellation of corotating LEO satellites” IEEE Transactions on Geoscience and Remote Sensing, pagg. 135-152, Vol. 54, 1 (2016)

- The microwave link scans an annular region in the orbital plane of the two LEO satellites
- A time series of IWV measurements is obtained through the NDSA approach, carrying information about the WV content in the scanned region
- Objective: retrieving the WV concentration field from the time series of IWV measurements.
- Solution: tomographic inversion based on a least squares approach or on the inversion of the so called “exterior Radon transform“



SATCROSS: the NDSA approach applied to the CO-RO geometry

- A «denser» and potentially more effective scan of the annular region is obtained utilizing more than two LEO satellites .
- The optimal NDSA frequency is considered for each link, depending on its tangent altitude
- Circular orbits and a spherical Earth are assumed in the analysis.
- The positions of the RX satellites are defined based on the lowest and highest tangent altitudes of the set of links.

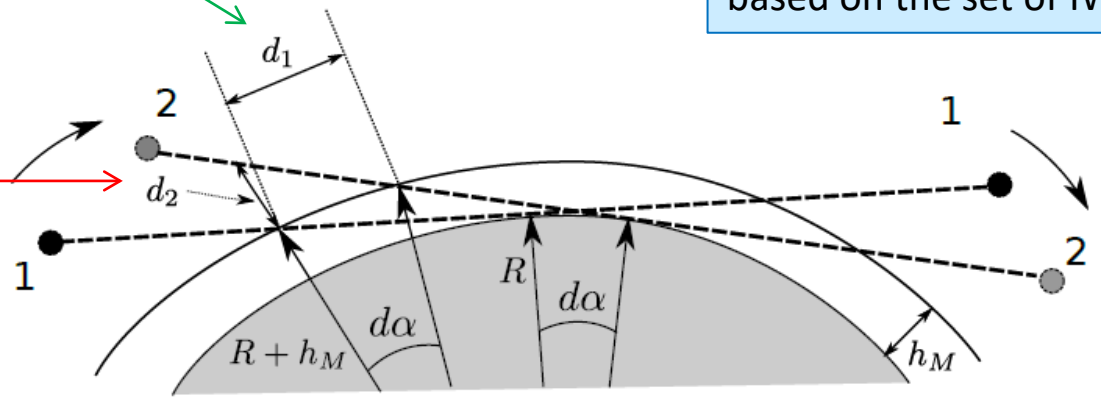


M Tx and N Rx → MxN IWV measurements every T_s seconds

IWV sampling rate

- The NDSA integration time T_s influences the spatial sampling rate of IWV and the SNR: higher integration time → higher SNR → smaller number of IWV measurements referring to a given scanned area.
  - $d\alpha$: angle traveled by the satellites in T_s
  - d_1 : "link displacement" at the maximum altitude h_M of the scanned annular area
  - d_2 : altitude variation of the link

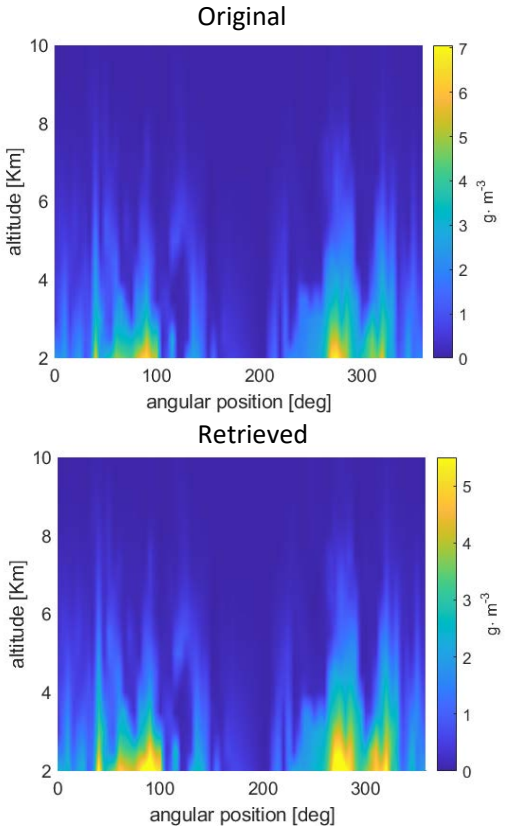
d_1 and d_2 have an impact on the spatial resolution with which the WV field is retrieved based on the set of IWV measurements



SATCROSS Research Topics and Activities

1. Development and performance evaluation of tomographic algorithms for retrieving 2D WV fields

- Generation of synthetic atmospheric reference scenarios on both a global and local scale
- Development of an end-to-end NDSA signal simulator including a propagation model and a signal impairments model. It accounts for the constellation geometry and the appropriate frequency channels
- Performance analysis of two tomographic algorithms (least squares-based and Radon transform-based) in both ideal and realistic disturbance conditions

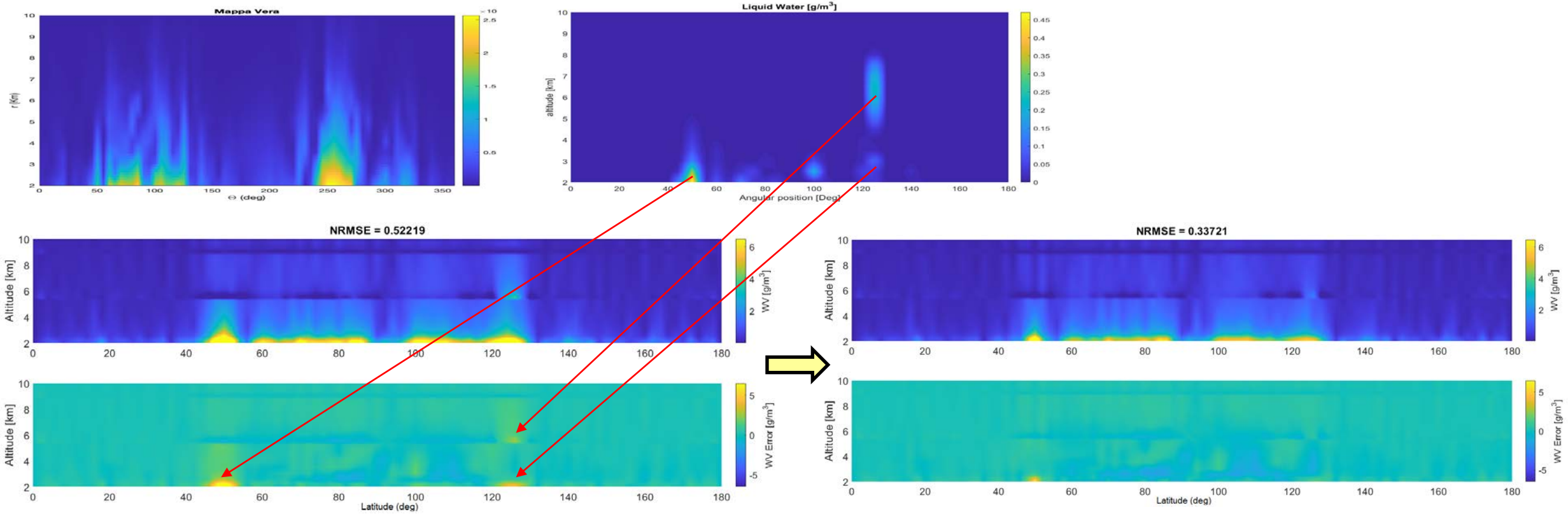


Poster Presentation: Inversion Methods for Tropospheric Water Vapor Retrieval by means of a Constellation of LEO Satellites: the SATCROSS Contribution.

SATCROSS Research Topics and Activities

2. Detection of Liquid Water and correction of IWV estimates

The presence of Liquid Water (LW) along the path causes an overestimate of IWV. LW can be detected and the overestimate corrected using an additional channel at 32 GHz.



Poster Presentation: Estimation Of The Tropospheric Liquid Water Content Between Two Corotating LEO Satellites Through Power Ratio Measurements.

SATCROSS Research Topics and Activities

3. Analysis of the potential impact of the retrieved WV fields on meteorological forecasts

Generation of an Observing System Simulation Experiment (OSSE) for evaluating the relevance of assimilating NDSA products

Poster Presentation: Evaluating the Impact of NDSA-based WV Measurements from MW Satellite Signals on Meteorological Forecasts.

4. Mission analysis and payload

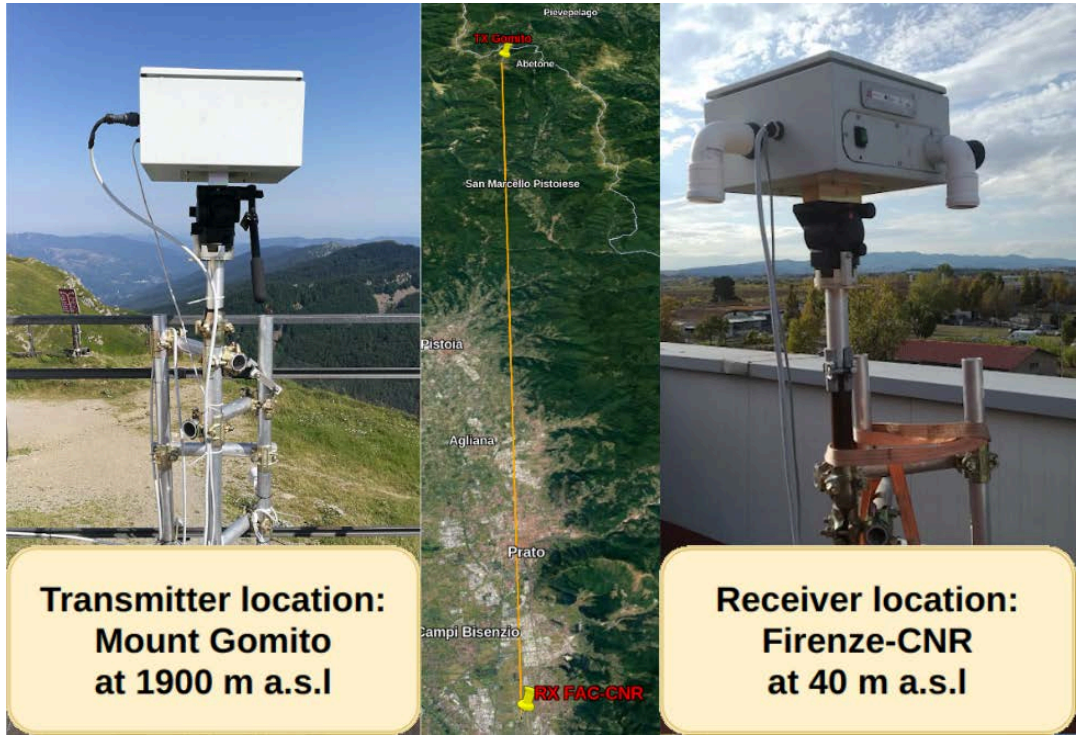
Definition of the payload (based on Cubesat technology), orbit analysis and mission requirements

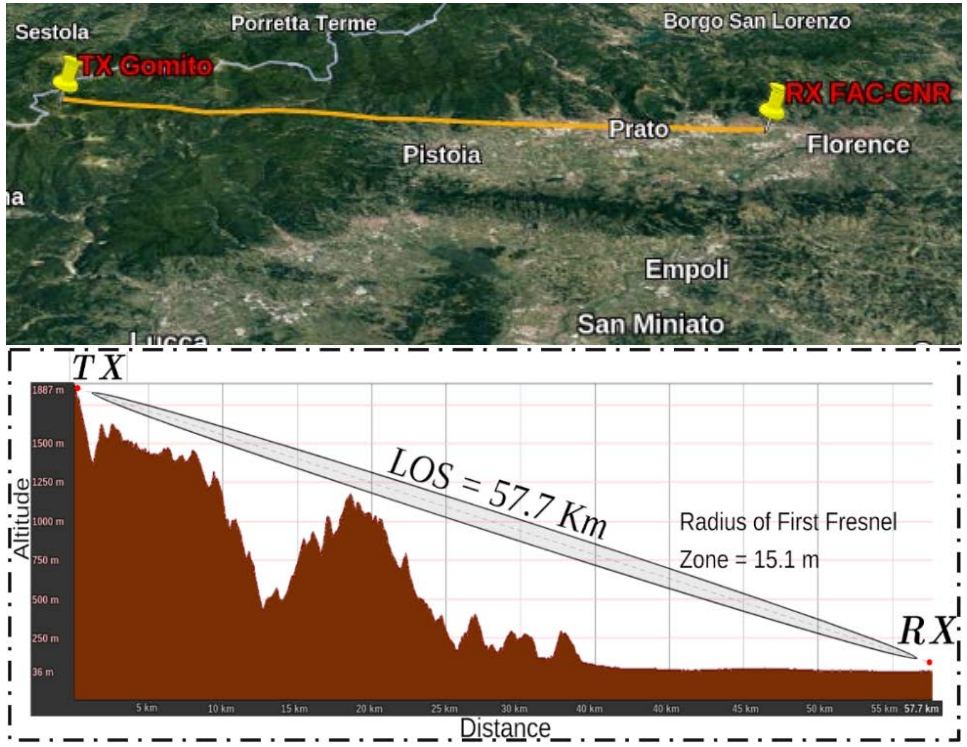
Poster Presentation: SATCROSS Project - Mission Analysis And Payload

SATCROSS Research Topics and Activities

5. Measurement campaign (ongoing)

Implementation of a measurement campaign with a NDSA demonstrator (19 GHz, Δf=400 MHz) based on a ground-to-ground link





Poster Presentation: The SATCROSS Measurement Campaign - Application of the NDSA technique to a Ground-to-Ground Radio Link.

Conclusion

The novelty of the SATCROSS project is related to:

- the NDSA technique, which is able to provide IWV estimates through active systems and power measurements (also incoherent)
- the use of tomographic inversion algorithms, which may theoretically provide WV fields on a continuous time basis and on a global scale
- the possibility to resort to Cubesat technology in order to get a satellite constellation with an effective number of links and relatively low cost