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Exploiting High-frequency bands by radio METeorological modeling and Sun-tracking microwave radiometry for satellite Communications and site diversity optimization

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Final Report for EOARD Grant FA9550-16-1-0446

“HIMETCOM-E EXPLOITING HIGH-FREQUENCY BANDS BY RADIOMETEOROLOGICAL MODELING AND SUN-TRACKING MICROWAVE RADIOMETRY FOR SATELLITE COMMUNICATIONS – EXTENSION OF APPLIED RESEARCH ACTIVITIES”

Date 03/29/2021

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Abstract: *The EOARD HiMetCom-E proposal is a yearly extension (2019-20) of the EOARD HiMetCom project (2016-18) aiming at the prediction of the ground to satellite path attenuation at Ka, Q, V and W bands at regional scale and for a time horizon within a day with hourly sampling. To achieve the aforementioned goal, HiMetCom foresees the use of Radiative Transfer Models (RTMs) able to translate input atmospheric scenarios into expected atmospheric self-emitted radiation and energy losses (absorption and scattering) along specific paths of interest. Such atmospheric scenarios are usually described by semi-punctual radio-soundings for clear air atmospheric conditions and by microwave-based retrievals for cloudy conditions. In rain conditions, crude approximations are usually considered into retrieval schemes. In general, approximations are aimed at characterizing the vertical structure of the clouds according to some atmospheric bulk profiles. The HiMetCom-E approach is aimed at extending 3D weather forecast model (WFM) outputs coupled with RTM to describe the state of the atmosphere and the related radio-propagation parameters at regional scales within the target area of Rome, NY USA at 43.2° North, 75.4° West for a further period with respect to the HiMetCom project. The use of meteorological model, directly coupled with RTMs, allows forecasting the radio-propagation parameters consistently with the forecasted atmosphere. This would open the opportunity for real-time prediction of the radio-propagation parameters for a specific target area thus suggesting a temporal updating of the predicted statistic of path attenuation. Thanks to the new installations at the Rome, NY supersite, the HiMetCom modeling suite can be in future further validated by properly exploiting available in-situ and remote-sensing data, such as micro rain-radar and millimeter-wave cloud radar.*

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Introduction:

Since from the beginning of the wireless telecommunications history, the exploration of new frequency regions has been always aimed to find allocation for a plenty of new services (e.g.: radio navigation, radio astronomy, remote sensing, telecommunication to cite some examples). In particular, high frequencies are very interesting in the telecommunication sector compared to the traditional lower bands for two main reasons: i) they can exploit larger bandwidths and ii) they allow smaller antenna sizes for a fixed gain or higher gain for a given antenna size. Because of the Shannon–Hartley theorem, larger bandwidth is directly proportional to higher data transfer rates which is a particular attractive feature for those applications and telecommunications protocols that require high data transfer rates (e.g. video, deep space, internet of things data streaming, etc...). Additionally, a larger bandwidth enables capabilities like wideband spread-spectrum techniques that allow to better reduce for impairments caused, for example, by multipath, clutter and radio frequency interferences. On the other hand, smaller antenna sizes for a fixed gain, fostered using higher frequencies, is an appealing characteristic for space born applications due to size constraints.

For the reasons previously exposed, accompanied by the fact that the today's spectrum use is crowded, and it does not permit to allocate additional services, an interest to improve spectrum usage gained

attention from the research community as well as private companies. A particular focus is in the exploitation of extreme high frequency bands or millimeter wave bands (wavelength and frequency in the range from 1 mm to 10 mm and from 30 GHz to 300 GHz, respectively) to meet global radio communication needs. At millimeter wave frequencies, wavelengths shrink by an order of magnitude (if compared to centimetre microwave frequencies) and became comparable with hydrometeors sizes. This implies that scattering and absorption effects along the propagation path will cause greater attenuation, thus elevating the importance of accurate propagation models. The latter aim at predicting, in statistical terms, the level of the signal to noise ratio expected at the receiver station for a given path thus aiding Earth-to-Earth or a satellite-to-Earth link budget design as well as to deliver a better quality to remote sensing data. By resorting to the Friis transmission equation in presence of path attenuation, the signal to noise ratio can be described in terms of atmospheric optical thickness (A) undergone by the transmitted signal during its travel and the brightness temperature (T_b) that accounts for the self-emission of the atmosphere delivered to the receiving antenna in the form of thermal noise. Thus, A and T_b become key quantities in designing a propagation model especially at the underexplored millimeter wave bands.

Experiment:

The closest radiosounding site to Rome, NY, is located at Albany County Airport, NY, USA (World Meteorological Organization station Identifier code: 72518, Weather Bureau Army Navy Identifier code: 14735; lat/lon 42.69/-73.83). Radiosounding data belonging to the period 2007-2016 have been collected for this study to compare and validate the outputs of the NWP models.

Sun-tracking microwave radiometer data at K, Ka, V and W band in Rome, NY

The ground-based Sun-Tracking Microwave Radiometer (ST-MWR) is a Radiometer Physics GmbH-Liquid Water Path (RPG-LWP-U72+82) water-vapor and cloud-liquid microwave radiometer with four channels at 23.8, 31.4, 72.5 and 82.5 GHz. **Error. L'origine riferimento non è stata trovata..** It is provided with an azimuth positioner allowing a scan step of 0.15° in elevation and 0.1° in azimuth. The Sun-tracking operation mode allows tracking the Sun motion along the ecliptic (Fig. 1). It considers a constant elevation angle (θ in Fig. 1) between two relatively close T_b measurements, which are taken only varying the azimuth angle by first pointing the antenna toward the Sun source (φ_1 in Fig. 1) and then measuring the atmospheric contribution without the Sun (φ_2 in Fig. 1). **Error. L'origine riferimento non è stata trovata..** A value at elevation θ is retrieved exploiting the difference between the brightness temperature toward the Sun and one without the Sun. This operation mode allows removing possible brightness temperature biases when atmospheric optical thickness is estimated. The integration time of each measurement is set to 1 second and the azimuth positioner switches every 6 seconds in order to perform the integration with fixed antenna position. The worst-case root-mean-square noise of 0.15 K is to be expected for a scene temperature of 300 K, assuming the overall bandwidth of 230 MHz and 1 second integration time. Therefore, 1-second integration time is enough for our purposes. One could theoretically integrate for up to 5-6 seconds (elevation and azimuth angles are constant for about 6 seconds), however it is not recommended since the Sun's position could vary within the mentioned interval. The processing and quality-control procedures applied to the radiometer data are described in **Error. L'origine riferimento non è stata trovata..**

The available dataset consists of measurements collected by the ST-MW radiometer from May 2015 to December 2016 in Rome, NY, USA (43.2°N, 75.4°W) at elevation angles varying between 20° and 70° (with some missing data days due to maintenance and calibration operations on the radiometer).

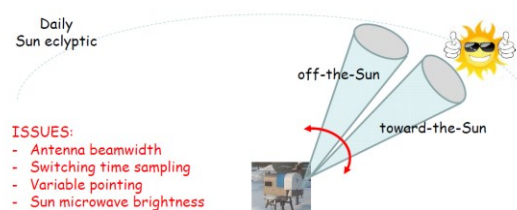


Fig. 1 ST-MWR operation: the radiometer tracks the Sun during its motion considering a constant elevation angle θ between two close measurements taken varying the azimuth from toward-the-Sun φ_1 to off-the-Sun φ_2 .

Microwave radiometric profilers in Rome, NY

The second source of radiometric measurements is available for the whole year 2016 in Rome, NY (43.2°N, 75.4°W) from RPG humidity and temperature profiler microwave radiometer (PRO-MWR) with 7 channels from 22.24 GHz to 31.4 GHz and 7 channels from 51 GHz to 58 GHz. **Errore. L'origine riferimento non è stata trovata., Errore. L'origine riferimento non è stata trovata..** PRO-MWR provides T_B measurements that are always taken at zenith, even though the radiometer is provided with an azimuth positioner allowing a scan step of 0.15° in elevation and 0.1° in azimuth. Time resolution and integration time are set to 1 second. In this project we only use the frequency channels overlapping with the ones of the ST-MWR that are: 23.8, 26.25 and 31.4 GHz.

Radiative transfer modeling at microwave frequencies

This section is devoted to the description of the radiative transfers models used to simulate T_B and A : 3D-RTM and 1D-RTM. Since the 3D-RTM is driven by weather forecasts, in the first paragraph of this section we describe the numerical weather prediction models considered in this project.

Weather Research and Forecasting (WRF) numerical model for Rome, NY area

Several numerical weather prediction models are designed to simulate mesoscale atmospheric circulation. In this project we have considered the Fifth-Generation Penn State University/National Center for Atmospheric Research Mesoscale Model (MM5), and the Weather Research and Forecasting (WRF) system, developed by the National Oceanic and Atmospheric Administration and by the National Center for Environmental Prediction, are used.

MM5 is a nonhydrostatic, terrain-following sigma-coordinate model, designed to simulate or predict mesoscale and regional-scale atmospheric circulation. It includes:

- a multiple-nest capability;
- nonhydrostatic dynamics, which allows the model to be used at a few-kilometer scale;
- multitasking capability on shared and distributed-memory machines;
- a four-dimensional data-assimilation capability;
- more physical options.

WRF model system is designed to be a flexible atmospheric simulation system, efficient on available parallel computing platforms. It represents:

- the state-of-the-art model that has good conservation characteristics (e.g., conservation of mass);
- an easy to modify model, that could well parallelize on many processors;
- plug-compatible physics to support improvements in model physics;
- designed for grid spacing of 1-10 km.

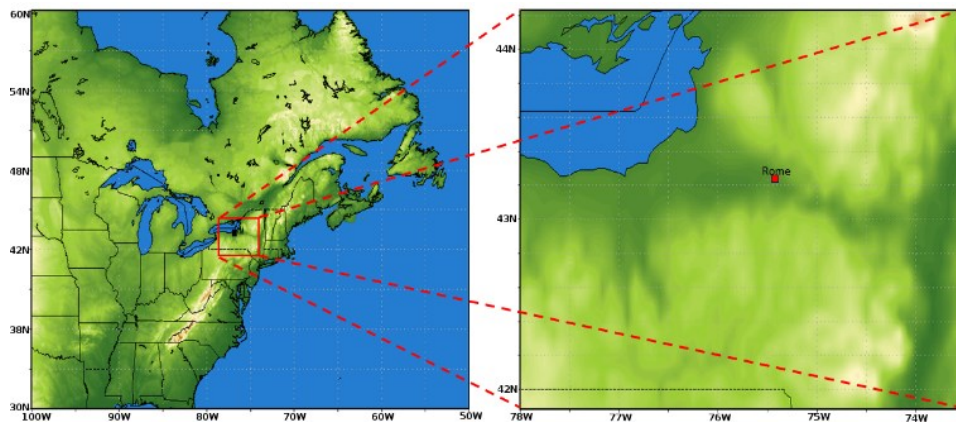


Fig. 2 Two nested domains of the NWP models centered on the target area of Rome, NY: (a) domain 1 at 18 km (and 9 km) resolution; (b): domain 2 at 6 km (and 3 km) resolution.

We have initialized both regional models (MM5 and WRF) with data from the global-scale model of the European Center for Medium-range Weather-forecast performing two-way nested domains simulations centered on Rome, NY (Fig. 2). We have compared the performances of the models for different resolutions of the initialization data.

After a climatological analysis of the target area of Rome, NY, we have defined the setup for the physical parameterizations for the considered models. The MM5 setup considers Reisner II for microphysics, Grell for cumulus, Rapid Radiative Transfer Model for radiations and Medium Range Forecast for planetary boundary layer. WRF setup includes Thompson for microphysics, Grell-Freitas for cumulus, Rapid Radiative Transfer Model for radiations and Mellor-Yamada-Janjic for planetary boundary layer.

Results and Discussion:

In this project, we have focused on the following frequencies: 23.80 (K band), 31.40 (Ka band), 72.50 (V band) and 82.50 GHz (W band), corresponding to wavelengths from 12.6 to 3.6 mm, where radiometric measurements were available. Channels at 23.8 and 31.4 GHz are used to estimate integrated water vapor and liquid water in atmospheric remote sensing. While K and Ka band are adopted in recent satellite missions, the potential advantages of using V and W band are under investigation. In this sense, the atmospheric channel characterization at such frequencies assumes a great importance and is the aim of this project to provide a valid reference to evaluation of propagation models and measurements in both atmospheric remote sensing and satellite communications fields. We characterize A and TB using both data derived by direct measurements and data simulated by radiative transfer models. As concerning the measurements, we have considered two ground-based microwave radiometers: a Sun tracking and a humidity and temperature profiler radiometer (ST-MWR and PRO-MWR, respectively).

As concerning the radiative transfer models, we have adopted a one-dimensional (1D) stochastic model, based on the sky-noise Eddington method (hereafter termed as 1D-RTM) and the pseudo three-dimensional (3D) radiative transfer module within the Goddard Satellite Data Simulator Unit suite, fed by numerical weather predictions (NWP) performed by the weather research and forecasting system (hereafter termed as 3D-RTM). We have also exploited data from weather radar netprojects and radiosounding observations to validate the NWP model. Both measurements and simulations analyzed in this project are co-located in space and time and they are performed in the area of Rome, NY, USA, within the Air Force Research Laboratory facility for a period of roughly one year between 2015 and 2016. With respect to previous projects on the same subject, the original aspect highlighted in this study is in the use of unconventional tools like ST-MWR and 3D-RTM. The former is a radiometer that uses the Sun as reference of stable radiance source with a special antenna pointing system which is able to continuously perform observations toward-the-Sun and out-of-Sun while tracking the Sun path [8]. So doing, ST-MWR is able to simultaneously derive both TB and A, with a single receiver, in all-weather conditions and along different slant directions, thus allowing the statistical characterization of the propagation channel for several elevation angles (see the Appendix for details on ST-MWR data processing and error budget). The shortage of high-frequency observations makes the statistical characterization of the channel one of the most primary interests of the scientific community, especially at millimeter waves. On the other hand, investigate the reliability of 3D-RTM model simulations of TB and A is an important task because it could open the way to the possibility of performing deterministic forecasts of the atmospheric channel.

In this project we also have introduced the main challenges in millimeter-wave satellite radiopropagation as well as characterized the atmospheric optical thickness and brightness temperature at centimeter and millimeter waves using both data derived by direct measurements and data simulated by 1D and 3D radiative transfer models being the latter driven by numerical weather predictions. After validating the numerical weather prediction model through comparisons with weather radar data and radiosounding observations, we have compared the 1D and 3D radiative transfer models with two different ground-based radiometric measurements: a Sun-tracking and a profiler microwave radiometer. The novelty of the Sun-tracking radiometer is that such instrument allows the simultaneous estimation of both atmospheric optical thickness and brightness temperature in all weather conditions and at continuously varying elevation angles. The comparisons between simulations and measurements provide satisfactory results that assess the reliability of the 3D-RTM

model with some biases, in terms of TB, that should be investigated. In particular, 3D-RTM turns out to be able to well replicate the TB - A correlations at all the frequencies. Moreover, statistics of atmospheric optical thickness obtained from 3D-RTM simulations are in excellent agreement with the one derived from ST-MWR. Errors between the two datasets become larger for increasing values of A, where saturation effects related to the ST-MWR operation mode occur. Such good results may pave the way to a successful use of weather forecast models combined with physically based radiative transfer models. On the other hand, although the simpler 1D-RTM satisfactorily reproduces the TB correlations among the different frequency-channels, it fails in reproducing statistics of the atmospheric optical thickness. This is probably due to a missing tuning of the 1D-RTM to select the clouds classes that better fits with the climatological trend of the geographical area of Rome, NY, for the considered period. The performed comparisons also highlight some possible calibration biases in the Sun-tracking radiometer that must be fixed. Finally, measurements from the Sun-tracking radiometer allows a statistical characterization of the radiometeorological variables in function of the elevation angle. In this sense, we have developed a preliminary model to retrieve the probability of atmospheric optical thickness, conditioned to a given elevation angle, in continental climate areas. Future projects will be devoted to identifying and fix biases and calibration errors emerged from the comparison between radiative transfer models and radiometric measurements, to refine the statistical model derived for the atmospheric optical thickness and to extend it also to the brightness temperature.

We have also verified the Generalized Parametric Prediction (GPP) model through the comparison with 4 years of measurements available at 18.7, 39.6 and 49.5 GHz from the ITALSAT campaign in Spino d'Adda. By considering ITALSAT data, we have obtained a root mean square error (RE) ranging from 0.045 to 0.068. We have also accomplished a comparison with the ITU-R model showing that the proposed GPP model can provide a lower RE up to about 20 K and 30 K depending on the considered frequency. Finally, a sensitivity analysis of the potential errors, induced on the mean radiative temperature by errors of atmospheric attenuation and brightness temperature, has been considered.

List of Publications and Significant Collaborations that resulted from your AOARD supported project:

a) papers published in peer-reviewed journals

1. Riva C., L. Luini, M. D'Amico, R. Nebuloni, A. Marziani, F. Consalvi, and F.S. Marzano, "The Alphasat Aldo Paraboni propagation experiment: Measurement campaign at the Italian ground stations", *Int. J. of Satellite Communications and Netprojecting*, vol. 37 (5), pp. 423-436, **2019**.
2. Biscarini M., L. Milani, M. Montopoli, K. De Sanctis, S. Di Fabio, K.M. Magde, G.A. Brost, and F.S. Marzano, "Exploiting Tropospheric Measurements From Sun-Tracking Radiometer for Radiopropagation Models at Centimeter and Millimeter Wave", *IEEE J. of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 12, n. 6, pp. 1697-1708, 2019.
3. Cimini D., J. Hocking, F. De Angelis, A. Cersosimo, F. Di Paola, D. Gallucci, S. Gentile, E. Gerdali, S. Larosa, S. Nilo, F. Romano, E. Ricciardelli, E. Ripepi, M. Viggiano, L. Luini, C. Riva, F.S. Marzano, P. Martinet, Y.Y. Song, M.H. Ahn, and P.W. Rosenkranz, "RTTOV-gb v1. 0—updates on sensors, absorption models, uncertainty, and availability", *Geoscientific Model Development*, vol. 12, n. 5, pp. 1833-1845, 2019.
4. Biscarini M. and F. S. Marzano, "Generalized Parametric Prediction Model of the Mean Radiative Temperature for Microwave Slant Paths in All-Weather Condition", *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 2, pp. 1031-1043, Feb. 2020.

b) papers published in peer-reviewed conference proceedings,

- A. Biscarini M., Milani L., Marzano F.S., Montopoli M., De Sanctis K., Magde K.M., and Brost G. A., "Statistical characterization of slant-path atmospheric channels exploiting microwave Sun-tracking radiometer", Proc. of EuCAP2019, Krakov (PL), 8-12 April 2019.
- B. Marziani, A.M., F. Consalvi, G. Fusco, F. S. Marzano, C. Riva, A. Martellucci, "AlphaSat dual-frequency receiving station in Rome, Italy: upgrade of the Ka-band front-end and case study analysis", Proc. of EuCAP2019, Krakov (PL), 8-12 April 2019.
- C. Milani L., Biscarini M., Montopoli M., De Sanctis K., Magde K.M., Brost G. A., and Marzano F.S., "Validating weather-forecast-driven propagation models at millimeter waves using multisource ground-based radiometric data", Proc. of EuCAP2019, Krakov (PL), 8-12 April 2019.
- D. Marziani, A.M., F. Consalvi, G. Fusco, A. Parodi, L. Pulvirenti, M. Lagasio, F. S. Marzano, N. Pierdicca, M. Biscarini, "Microwave Tropospheric Scintillation and Excess Attenuation Prediction for Satellite to Earth links using 3D High-Resolution Meteorological Forecast Models: Data Validation and Case Study", Proc. of PIERS2019, Rome (IT), 17-21 June 2019.

- E. Milani L., Biscarini M., Marzano F.S., "Cloud attenuation stochastic characterisation from ground-based microwave radiometric data at Ka-band", Proc. of PIERS2019, Rome (IT), 17-21 June 2019.
- F. Luini L., C. Riva, A. Panzeri, A. Rocha, S. Mota, F.S. Marzano, A. Marziani, M. Biscarini, F. Consalvi., V. Schena and A. Martellucci, "The MEKaP Project: Measuring Tropospheric Impairments at Ka Band with MEO Satellites," 2020 14th European Conference on Antennas and Propagation (EuCAP), Copenhagen, Denmark, 2020, pp. 1-5, doi: 10.23919/EuCAP48036.2020.9135489.

- c) papers published in non-peer-reviewed journals and conference proceedings,
- d) conference presentations without papers,
- e) manuscripts submitted but not yet published

- f) provide a list any interactions with industry or with Air Force Research Laboratory scientists or significant collaborations that resulted from this project.

Continuous interactions and joint publications with Dr. G.A. Brost and his group, AFRL, Rome, New York, USA

Attachments: Publications a), b), c) and d) listed above if possible.

DD882: As a separate document, please complete and sign the inventions disclosure form.

Important Note: *If the project has been adequately described in refereed publications, submit an abstract as described above and refer the reader to your above List of Publications for details. If a full report needs to be written, then submission of a final report that is very similar to a full length journal article will be sufficient in most cases. This document may be as long or as short as needed to give a fair account of the project performed during the period of performance. There will be variations depending on the scope of the project. As such, there is no length or formatting constraints for the final report. Keep in mind the amount of funding you received relative to the amount of effort you put into the report. For example, do not submit a \$300k report for \$50k worth of funding; likewise, do not submit a \$50k report for \$300k worth of funding. Include as many charts and figures as required to explain the project.*



HIMETCOM-E

EXPLOITING HIGH-FREQUENCY BANDS BY RADIOMETEOROLOGICAL MODELING AND SUN-TRACKING MICROWAVE RADIOMETRY FOR SATELLITE COMMUNICATIONS – EXTENSION OF APPLIED RESEARCH ACTIVITIES

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Final report

Period: September 1, 2019 –December 31, 2020

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Main peer-reviewed journal papers on ST-MWR derived from the HiMetCom project:

1. IEEE TAP, 2016: Sun-Tracking Microwave Radiometry: All-Weather Estimation of Atmospheric Path Attenuation at Ka-, V-, and W-Band.
2. IEEE JSTARS, 2017: Retrieval of Sun Brightness Temperature and Precipitating Cloud Extinction Using Ground-Based Sun-Tracking Microwave Radiometry.
3. IEEE JSTARS, 2019: Exploiting Tropospheric Measurements From Sun-Tracking Radiometer for Radiopropagation Models at Centimeter and Millimeter Wave.
4. IEEE TAP, 2020: Generalized Parametric Prediction Model of the Mean Radiative Temperature for Microwave Slant Paths in All-Weather Condition.



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List of acronyms

CB	Cosmic background
ECMWF	European Center for Medium-range Weather Forecast
EDR	Experiment Design Review
ERR	Experiment Readiness Review
FR	Final Review
GEO	Geostationary Orbit
GCOS	Global Climate Observing System
GRUAN	GCOS Upper Air Reference Network
ILWC	Integrated Liquid Water Content
IWVC	Integrated Water Vapor Content
LEO	Low-Earth-Orbit
MDR	Model Development Review
MWR	Microwave Radiometer
NWP	Numerical Weather Prediction
RF	Radio Frequency
SNEM	Sky Noise Eddington Model
ST	Sun tracking
WMO	World Meteorological Organization

1 Introduction

Since from the beginning of the wireless telecommunications history, the exploration of new frequency regions has been always aimed to find allocation for a plenty of new services (e.g.: radio navigation, radio astronomy, remote sensing, telecommunication to cite some examples). In particular, high frequencies are very interesting in the telecommunication sector compared to the traditional lower bands for two main reasons [1]: *i*) they can exploit larger bandwidths and *ii*) they allow smaller antenna sizes for a fixed gain or higher gain for a given antenna size. Because of the Shannon–Hartley theorem [2], larger bandwidth is directly proportional to higher data transfer rates which is a particular attractive feature for those applications and telecommunications protocols that require high data transfer rates (e.g. video, deep space, internet of things data streaming, etc...). Additionally, a larger bandwidth enables capabilities like wideband spread-spectrum techniques [3] that allow to better reduce for impairments caused, for example, by multipath, clutter and radio frequency interferences. On the other hand, smaller antenna sizes for a fixed gain, fostered using higher frequencies, is an appealing characteristic for space born applications due to size constraints.

For the reasons previously exposed, accompanied by the fact that the today's spectrum use is crowded, and it does not permit to allocate additional services, an interest to improve spectrum usage gained attention from the research community as well as private companies. A particular focus is in the exploitation of extreme high frequency bands or millimeter wave bands (wavelength and frequency in the range from 1 mm to 10 mm and from 30 GHz to 300 GHz, respectively) to meet global radio communication needs [4]. At millimeter wave frequencies, wavelengths shrink by an order of magnitude (if compared to centimetre microwave frequencies) and became comparable with hydrometeors sizes. This implies that scattering and absorption effects along the propagation path will cause greater attenuation, thus elevating the importance of accurate propagation models. The latter aim at predicting, in statistical terms, the level of the signal to noise ratio expected at the receiver station for a given path [5] thus aiding Earth-to-Earth or a satellite-to-Earth link budget design as well as to deliver a better quality to remote sensing data. By resorting to the

Friis transmission equation in presence of path attenuation [6], the signal to noise ratio can be described in terms of atmospheric optical thickness (A) undergone by the transmitted signal during its travel and the brightness temperature (T_B) that accounts for the self-emission of the atmosphere delivered to the receiving antenna in the form of thermal noise [5]. Thus, A and T_B become key quantities in designing a propagation model especially at the underexplored millimeter wave bands.

In this work, we focus on the following frequencies: 23.80 (K band), 31.40 (Ka band), 72.50 (V band) and 82.50 GHz (W band), corresponding to wavelengths from 12.6 to 3.6 mm, where radiometric measurements were available. Channels at 23.8 and 31.4 GHz are used to estimate integrated water vapor and liquid water in atmospheric remote sensing. While K and Ka band are actually adopted in recent satellite missions [5], the potential advantages of using V and W band are under investigation [4]. In this sense, the atmospheric channel characterization at such frequencies assumes a great importance and is the aim of this work in order to provide a valid reference to evaluation of propagation models and measurements in both atmospheric remote sensing and satellite communications fields. We characterize A and T_B using both data derived by direct measurements and data simulated by radiative transfer models. As concerning the measurements, we have considered two ground based microwave radiometers: a Sun tracking [7], [8] and a humidity and temperature profiler radiometer [9] (ST-MWR and PRO-MWR, respectively).

As concerning the radiative transfer models, we have adopted a one-dimensional (1D) stochastic model, based on the sky-noise Eddington method (hereafter termed as 1D-RTM) [10] and the pseudo three-dimensional (3D) radiative transfer module within the Goddard Satellite Data Simulator Unit suite [11], fed by numerical weather predictions (NWP) performed by the weather research and forecasting system [12] (hereafter termed as 3D-RTM). We have also exploited data from weather radar networks and radiosounding observations to validate the NWP model. Both measurements and simulations analyzed in this work are co-located in space and time and they are performed in the area of Rome, NY, USA, within the Air Force Research Laboratory facility for a period of roughly one year between 2015 and 2016. With respect to previous works on the same subject, the original aspect highlighted in this study is in the use of unconventional tools like ST-MWR and 3D-RTM. The former is a radiometer that uses the Sun as reference of stable radiance source with a special antenna pointing system which is able to continuously perform observations toward-the-Sun and out-of-Sun while tracking the Sun path [8]. So doing, ST-MWR is able to simultaneously derive both T_B and A , with a single receiver, in all-weather conditions and along different slant directions, thus allowing the statistical characterization of the propagation channel for several elevation angles (see the Appendix for details on ST-MWR data processing and error budget). The shortage of high-frequency observations makes the statistical characterization of the channel one of the most primary interests of the scientific community, especially at millimeter waves. On the other hand, investigate the reliability of 3D-RTM model simulations of T_B and A is an important task because it could open the way to the possibility of performing deterministic forecasts of the atmospheric channel.

This work is organised into six sections plus a technical note in an Appendix. After an overall overview of satellite radiopropagation models at microwave and millimeter models in Section 2, available measurements and simulations are described in Section **Errore. L'origine riferimento non è stata trovata.** Comparisons among the various sources of A and T_B are shown in Section **Errore. L'origine riferimento non è stata trovata.** Section 5 shows the assessment of the generalized parametric prediction (GPP) model. Finally, discussion and conclusions are drawn in Section 5.

2 Satellite propagation models at microwave and millimeter wave

In the development of Satellite Communication (SatCom) systems there is a continuous trend to use

higher frequencies, driven by the need for larger bandwidths and by the technology development of RF components. Current High Throughput Satellites (HTS) systems operate at Ka band and presumably their next implementation will use Q- and V- bands. The use of W band appears to be the next natural evolution of current or planned SatCom systems. However, the W band is characterized by a larger dynamics of atmospheric propagation effects, because of higher atmospheric losses (due to rain, liquid water clouds and atmospheric gases) with respect to lower frequencies [Riva et al., 2014].

Current propagation models and ITU-R recommendations are based on past experimental campaigns at Ku, Ka and Q/V bands. The application of existing models to predictions in the W band is thus affected by additional uncertainty, which cannot be estimated using actual data, posing a severe limitation on the planning of new systems operating at W band. It is therefore clear that the planning of W band for space systems would require experimental data, but so far, no W band measurement campaign has been performed to characterize the W-band satellite atmospheric radio channel [Biscarini et al., 2017].

This scientific objective can be pursued by means of different types of propagation campaigns. Ideally, one type would be based on the use of beacon signal transmitted from a satellite, but there are no W-band beacons currently embarked on any satellite. Alternatively, the characterization of the atmospheric radio channel can be pursued using ground based MWR, by means of retrieval algorithms based on the inversion of the measured sky noise emission. Two modes of MWR operations are envisaged, the “Cosmic background” (CB) mode, optimal for situations in which scattering can be neglected (e.g. non-raining conditions), and the “Sun tracking” (ST) mode, which can be used to derive attenuation in all weather conditions [Marzano et al., 2016; Mattioli et al., 2017]. The radiometric observations should be supported by ancillary equipment for the most complete characterization of atmospheric propagation and physical conditions (e.g. satellite beacon receivers, terrestrial W band radio links, and other meteorological in-situ and remote sensing instruments).

Thus, the objective of the ST-MWR activity is to design and execute a 2-year W-band propagation campaign based on the use of ground MWR (in both CB and ST modes) to derive the statistical local distributions of propagation and radio-climatological parameters. Specific objectives of the W band radiometric campaign are:

- measure the total atmospheric attenuation in clear air and cloudy conditions at radiometric frequencies and elevation angles typical of satellite links;
- use concurrent ST and CB modes to calibrate and validate algorithms for the estimation of total attenuation in presence of precipitation from CB measurements, and estimate the excess attenuation due to precipitation;
- generate the distribution of total atmospheric attenuation and sky brightness temperature at W band describing all the weather conditions (i.e. clear-air, cloudy and rainy), including monthly and diurnal statistics;
- characterize fade slope and fade duration of atmospheric attenuation along the slant path to a non-GEO orbit;
- test propagation prediction models for the measured frequencies against the observed distributions;
- validate and possibly improve the accuracy of Numerical Atmospheric Simulators (NAS) by comparing simulations with observations collected in the W band radiometric campaign;
- estimate the uncertainty of improved propagation prediction models for the (non-measured) operational frequencies by analysis of the uncertainty of measured channels in the same band;
- define the operational and data analysis procedures for radiometric measurements for non-GSO satellite systems, with particular regard to Earth Observation (EO) and Space Exploration (SE) missions;
- report derived experimental distributions and other main results to radio-regulatory bodies (i.e. ITU-R) for adoption as recommendations and new reference for experimental tables.

Several models are available to predict the impact of atmospheric constituents on electromagnetic waves propagation. Generally, propagation models can be grouped into:

1. statistical models, which aim at reproducing first-order statistics (e.g. atmospheric refraction and attenuation due to gases, clouds and rain) and/or second-order statistics (fade duration, fade slope and time/site diversity) of atmospheric impairments;
2. channel models, which aim at reproducing the temporal (or spatial and temporal) evolution of atmospheric impairments.

2.1 Statistical models for satellite radiopropagation

Radio propagation modelling combines information from electromagnetic theory, atmospheric physics and meteorology to predict propagation parameters from the knowledge of physical processes and meteorological (input) parameters.

The most rigorous approach aims at modelling the interaction between the atmosphere and electromagnetic waves (e.g. [Liebe, 1981]). These models, referred to as ‘**physical models**’, provide an accurate description of the processes, but require full characterization of the atmosphere composition and time-consuming calculations.

As the full knowledge of the atmospheric composition is hardly available for common applications, ‘**simplified models**’, physically based but using surface and/or equivalent meteorological parameters, are frequently used. Some of these models are calibrated and tested using ‘fully-physical’ models fed with meteorological data; others are empirically adjusted in order to make the model agree to the available radio propagation measurements (e.g. Section 2.2.1 in [ITU-R P.618-13, 2017]).

In the W band, the main effects on the radio wave propagation are due to tropospheric constituents. The objective of this Section is to present the state-of-the-art review of tropospheric propagation statistical prediction models. A specific sub-section will be devoted to the peculiar issue of the variable elevation angle. The interaction of radio waves with tropospheric constituents involves several processes:

- absorption and dispersion by atmospheric gases;
- absorption and scattering from hydrometeors;
- scintillation from atmospheric turbulence (not considered in this activity since scintillation cannot be measured by MWR).

In the following a brief review is offered concerning the state of the art in modelling the impairments induced by the various atmospheric constituents.

2.1.1 Effects of gas attenuation

Water vapor and oxygen are the gaseous components of the atmosphere. They are relevant to the propagation of electromagnetic waves, along a slant path and in the frequency range up to 300 GHz [Rothman et al., 1983], [Kyle, 1991], [Brussaard and Watson, 1995].

Oxygen is a paramagnetic molecule characterized by resonance peaks located in the frequency band from 50 to 70 GHz, at 118.7 GHz and by other lines centered at frequencies higher than 300 GHz. Water vapor is a polar molecule with resonance peaks located at 22.23 and 183 GHz, and at several other lines in the millimeter wave and infrared spectral regions. Several phenomena, such as the pressure and the Doppler line broadening effects, affect the molecular natural line widths. Therefore, the line shapes of these molecules result to be complex functions of the meteorological parameters such as pressure, temperature and water vapor density. Oxygen concentration, that is weakly dependent on the inverse of temperature, is almost constant during the day and during the year and slightly varies over the globe. On the contrary, the amount of water vapor is highly variable being a function of temperature and of atmospheric conditions and its main effect is measured in a broadened band around the H₂O absorption line at 22.2 GHz. The attenuation due to water vapor exhibits noticeable daily, seasonal and geographical variations.

The **most rigorous procedure** to estimate gas attenuation consists in calculating the gaseous specific attenuation for each point along the path, for example by using the Liebe’s ‘Microwave Propagation Model’, MPM93 [Liebe, 1981, 1985, 1989], [Liebe et al., 1993] or other physical models such as

[Rosenkranz, 1998]. Then it is necessary to integrate the specific attenuation along the path [Barbaliscia et al., 1995]. However, this procedure requires vertical profiles of temperature, humidity and pressure, which are seldom available [Salonen et al., 1990].

Table 2.1: Gas attenuation statistical prediction models

Model	Input data			Validity range
	Geometrical	Radiowave	Climatic	
ITU-R P.676-11 Annex 2 oxygen attenuation	Elevation	Frequency	Pressure Temperature	$1 \text{ GHz} \leq f \leq 350 \text{ GHz}$ altitude $\leq 10 \text{ km}$ $5^\circ \leq E_{\text{sat}} \leq 90^\circ$
Salonen oxygen attenuation	Elevation	Frequency	Pressure Temperature at t_0 and $t_0-12\text{h}$	$1 \text{ GHz} \leq f \leq 350 \text{ GHz}$ altitude $\leq 5 \text{ km}$ $5^\circ \leq E_{\text{sat}} \leq 90^\circ$
ITU-R P.676-11 Annex 2, water vapor attenuation	Elevation	Frequency	Pressure Temperature Water vapor density	$1 \text{ GHz} \leq f \leq 350 \text{ GHz}$ altitude $\leq 10 \text{ km}$ $5^\circ \leq E_{\text{sat}} \leq 90^\circ$
ITU-R P.676-11 Annex 2, water vapor attenuation	Elevation	Frequency	Pressure Temperature Total water vapor content	$1 \text{ GHz} \leq f \leq 350 \text{ GHz}$ altitude $\leq 10 \text{ km}$ $5^\circ \leq E_{\text{sat}} \leq 90^\circ$
ITU-R P.676-11 Annex 1 oxygen and water vapor attenuation	Elevation	Frequency	Pressure Humidity Temperature profile	$1 \text{ GHz} \leq f \leq 350 \text{ GHz}$ $0^\circ \leq E_{\text{sat}} \leq 90^\circ$

In addition to these physical models, which rely on the complete knowledge of the vertical profiles of the atmospheric parameters, other models have been developed [ITU-R P.676-11, 2016]. Such models are generally characterized by a simplified formulation and are based on **surface or integrated meteorological parameters**, much more readily available with respect to the vertical profiles. Those simplified methods are valid only in specific frequency intervals, such as the spectral transmission windows of the atmosphere, and are based on a-priori assumptions of the vertical profiles of the meteorological parameters (standard or typical atmospheres).

The **gaseous attenuation at the zenith** can be calculated, according to [ITU-R P.676-11, 2016], by multiplying the approximated gaseous specific attenuation at ground level, which is a function of ground water vapor density, temperature and pressure, by its effective height, which depends only on frequency and pressure. Otherwise the quasi-physical model in [Salonen et al., 1994] for oxygen attenuation performs a complete calculation of the oxygen specific attenuation at reference conditions and then uses a formula for calculating the effective height from surface meteorological values. As for water vapor, Section 2.3 of [ITU-R P.676-11 2016]) relates the zenith attenuation to the integrated water vapor amount in reference conditions at 20.6 GHz, and then defines a frequency-scaling factor. The zenith attenuation can then be scaled in elevation for all methods by the cosecant law [ITU-R P.676-11, 2016]. Table 1 summarizes the main characteristics of the most accredited gas attenuation statistical prediction models, in terms of input and output parameters, as well as validity range.

The **climatic input parameters** of the models (the surface air temperature, the water vapor density and the total water vapor content), are now available in global maps from ITU-R (on a yearly or monthly basis) (see e.g. [ITU-R P.836-6, 2017] for water vapor).

As for the band of interest for this study (70-90 GHz), the considered **gaseous prediction models** do not present any evident limitation even if the accuracy is lower in the 50-70 GHz band (outside the range of this study), due to the presence of the oxygen absorption lines. The accuracy of the ITU-R gas (zenith) attenuation prediction models [ITU-R P.676-11, 2016], has been assessed in [Capsoni et al., 2011] up to 85 GHz against the Liebe MPM93 physical models applied to a worldwide radiosoundings database [ITU-R P.835-6, 2017]. Even if the validation database was not completely independent (being calculated through the Liebe model which is also used in the statistical models), the results have shown stable performance in the 10-90 GHz band.

As for **elevation angle**, the models assume a stratified atmosphere which, as for oxygen and water vapor distribution, is reasonable, being the correlation distance usually much larger than the path length crossing the gaseous atmosphere (with an elevation angle greater than 5 degrees).

In conclusion, the ITU-R model for the prediction of oxygen and water vapor attenuation (Annex 2 of [ITU—R P.676-11, 2016]) is suggested to be used and tested in this study. It is proposed to compare the predicted gaseous attenuation statistics for fixed elevation angle to the measured statistics conditioned to the same elevation angle (in the range between 10° and 90°).

2.1.2 Effects of cloud attenuation

Clouds consist of suspended water droplets of size much smaller than the wavelength for frequencies up to V band. Hence the Rayleigh approximation of the Mie scattering theory can be used to calculate clouds attenuation that, below 300 GHz, depends only on the liquid water content and on the droplets' temperature. **Specific attenuation of clouds** can be calculated by using the method presented in [Slobin, 1982] or [Liebe, 1989], and integrated along the path if a classification of clouds or if profiles of Liquid Water Content (LWC) are given. If not, another physical model developed by [Salonen et al., 1990] allows clouds attenuation to be calculated from the introduction of Pressure, Temperature and Humidity (PTH) profiles (without LWC information). This is possible thanks to a procedure relying on the definition of a critical humidity value, above which a cloud is supposed to be present on the link.

Clouds attenuation is highly variable, depending on the presence or not of clouds along the link and on their liquid water content. In ITU-R model [ITU-R P.840-7, 2017], the dependence of clouds specific attenuation on droplets temperature is considered by defining the liquid water content reduced to 0°C, that, integrated as a function of height, results in the reduced total liquid water content measured in (kg/m² or mm). Global statistics of this parameter are provided through global maps [ITU-R P.840-7, 2017].

Cloud attenuation is then obtained as a function of the reduced liquid water content, the frequency, the elevation angle and the dielectric constant of the water. The comparisons against cloud attenuation distributions measured via a dual-channel radiometer have shown quite good agreement in different climates [Salonen et al., 1994]. Moreover, the probability of clouds occurrence is in close agreement with the observations presented in [Warren et al., 1986].

Several models have been proposed in the past to calculate the **CCDF of cloud attenuation** by [Konefal et al., 2000], [Dissanayake et al., 1997] and [Wrench et al., 1999]. The Konefal model [Konefal et al., 2000] is a variation of the Salonen model [Salonen and Uppala, 1991] (recommended in [ITU-R P.840-7, 2017]) in order to calculate monthly cloud attenuation. The DAH model [Dissanayake et al., 1997] calculates, instead, the cloud attenuation distribution due to four types of clouds using their average properties (vertical and horizontal extent, and water content) and their coverage percentage, that can be obtained, for example, by the database in [Hahn et al., 1996]. Finally, the Wrench model [Wrench et al., 1999] relies on the definition of 4 classes of clouds (stratocumulus, cumulus, nimbostratus and cumulonimbus), defined by their physical extent, liquid water content and percentage of occurrence.

Table 2.2 summarizes the key characteristics of the main cloud attenuation statistical prediction

models, in terms of input and output parameters, as well as validity range.

In the ITU-R models [ITU-R P.840-7, 2017] there is no frequency limitation in the band of interest of this study (70-90 GHz) as for specific attenuation due to liquid water. Nevertheless, the available global map of climatic input parameter of the model [ITU-R P.840-7, 2017], the total liquid water content reduced to 0°C, has been calculated for the 10-60 GHz frequency band and its possible use above 60 GHz should be verified. The accuracy of the ITU-R cloud (zenith) attenuation prediction models [ITU-R P.840-7, 2017] has been already assessed in [Capsoni et al., 2011] up to 85 GHz against the Liebe MPM93 physical models applied to a worldwide radiosoundings database; even if the validation database was not completely independent (being calculated through the Liebe model which is also used in the statistical models), the results have shown an rms error increasing with frequency (but always below 25%) in the 10-90 GHz band.

Table 2.2: Clouds attenuation statistical prediction models

Model	Input data			Validity range
	Geometrical	Radiowave	Climatic	
ITU-R P.840-7	Elevation	Frequency	TLWC reduced to 0°C	$1 \text{ GHz} \leq f \leq 200 \text{ GHz}$
Dissanayake-Allnutt-Haidara	Elevation	Frequency	Vertical extent Horizontal extent WV density	$1 \text{ GHz} \leq f \leq 50 \text{ GHz}$
Konefal	Elevation	Frequency	TLWC Mean humidity -20°C isotherm	$1 \text{ GHz} \leq f \leq 50 \text{ GHz}$
Wrench	Elevation	Frequency	Physical extent Temperature TLWC	Not tested

In conclusion, the ITU-R cloud attenuation prediction model [ITU-R P.840-7, 2017] is suggested to be used in this study after assessing its performance for high frequency (above 50 GHz). Like for gaseous attenuation, the predicted statistics at a fixed elevation angle can be compared to the measured statistics conditioned to the same elevation angle (in the range between 10° and 90°).

2.1.3 Effects of rain and hydrometeor attenuation

Attenuation due to hydrometeors is the main drawback to the propagation at frequencies above 10 GHz because the particle dimensions become comparable with the wavelength of the incident wave.

The **hydrometeors** that have an impact on propagation are rain, hail and snow (dry or wet). Hail and dry snow have a very limited effect because the dielectric constant of the particles is much closer to the one of air rather than to the one of water, while, for the opposite reason, wet snow can give significant attenuation. Attenuation due to rain is the most relevant propagation effect for the design of satellite telecommunication systems. All available methods of rain attenuation prediction attempt to relate the CDF of attenuation along a slant path to the CCDF of ground rainfall intensity. To this purpose a set of assumptions are however necessary; among them, those with stronger impact are:

- the relationship between specific attenuation and rainfall intensity;
- the horizontal and vertical profile of rainfall intensity.

The several methods available today in the literature [Martellucci, 2002] substantially differ from one to another mainly for the different hypotheses made about these assumptions. These issues become more and more important with the increase in the frequency, owing to the magnifying effect of these parameters on all the phenomena related to rain.

i) *Relationship between specific attenuation and rainfall intensity.*

The computation of the specific rain attenuation is usually performed by integrating numerically the equation:

$$\int_0^L S(0) N(D; R) \lambda^2 dL \quad (\text{dB/km}) \quad (2.1)$$

where subscripts H , V mean horizontal and vertical polarization respectively. $S(0)$ is the forward scattering coefficient, while $N(D; R)$ is the Drop Size Distribution (DSD); finally, λ is the wavelength. Analogously, the rain intensity value is obtainable through the following equation

$$\int_0^L R dL \quad (\text{mm/h}) \quad (2.2)$$

which needs in input the drop terminal velocity $v(D)$, for which there are some different proposals (e.g. [Brussaard and Watson, 1995]). The results for different rain intensity can be fitted with high accuracy to the power law equation:

$$K R^\alpha \quad (\text{dB/km}) \quad (2.3)$$

The values of K and α are given in [ITU-R P.838-3, 2005] as a function of the elevation angle, the frequency (between 1 and 1000 GHz) and the polarization.

Similar computations have been carried out within [Riva et al., 2006], with particular emphasis on the impact of the DSD on the computation of specific attenuation at different frequencies. In particular, Gamma distributions with different shape parameters m have been considered.

For this study we propose either to refer to the ITU-R model [ITU-R P.838-3, 2005] or to specific rain attenuation models tuned to the experimental sites by exploiting disdrometer-based measurements.

ii) *Rain attenuation prediction models*

The prediction of **rain attenuation CCDF** starting from the **rainfall intensity CCDF** has been the subject of a large effort carried out by many researchers in the last three decades. Several methods have been developed and their performance evaluated using statistics from propagation experiments at frequencies up to 50 GHz. The difference between the performances of the various methods is often negligible and their errors are in the order of the year-to-year variability of precipitation (around 20-30%). Australian [Flavin, 1996], Bryant [Bryant et al., 2001], Excell [Capsoni et al., 1987], ITU-R Rec. P.618-9 [ITU-R P.618-13, 2017], and Matricciani [Matricciani, 2008] are methods that appear to be among best according to testing activities [Riva, 2002] [Riva et al., 2006].

Table 3 summarizes the fundamental characteristics of the main rain attenuation statistical prediction models, in terms of input and output parameters. Except when mentioned, the time percentage validity range of the models is for percentages lower than 1 %. The frequency range extends from 1 to 50 GHz.

The above-mentioned models, especially the physically based ones, can be probably applied up to 90 GHz without significant performance degradation even if the accuracy assessment was not possible due to lack of measured data above 50 GHz. One of the main purposes of this activity is to test rain attenuation prediction models in the W band. All these statistical models, typically developed only for the GEO configuration, will be tested against the data to be collected during the experimental campaign at variable elevation angle. The rain attenuation model included in recommendation P.618-13 is of semi-empirical

nature and its applicability range is limited to 50 GHz.

Table 3: Rain attenuation statistical prediction models

Model	Input data			Validity range
	Geometrical	Radiowave	Climatic	
ITU-R P.618-13	Altitude, Latitude, Elevation	Frequency k, α	R_{001} 0 °C isotherm height	$p \leq 10 \%$
Bryant	Latitude, Elevation	k, α	$R(p)$ 0 °C isotherm height	/
Excell	Altitude, Latitude, Elevation	k, α	$R(p)$ rain height	/
SC Excell	Altitude, Latitude, Elevation	k, α	$R(p)$ monthly rain height	/
Flavin	Altitude, Latitude, Elevation	Frequency k, α	$R(p)$ 0 °C isotherm height	$5^\circ \leq E_{sat} \leq 90^\circ$
SST Matricciani	Altitude, Latitude, Elevation	Frequency Polarisation	$R(p)$ 0 °C isotherm height	/

For this reason, in addition to this ITU-R P.618-13 model, **other methodologies** with an increased physical basis will be considered in the tests. This is the case, for example, of SC-Excell [Capsoni et al., 2009], MultiExcell [Luini and Capsoni, 2011], and the SST [Matricciani, 1996], all of which aim at predicting rain attenuation starting from concepts linked to the formation and the evolution of precipitation events.

2.1.4 Effects of second order signal statistics

The **temporal dynamic of the propagation channel** is an important piece of information for the design of satellite links operating at centimetric and millimeter wavelengths, because it directly influences some aspects of adaptive satellite system design and fade mitigation technique (FMT) optimisation. The dynamic aspects of rain attenuation are (see Figure 1.1.1.2-1):

- the fade slope that represents the rate of change of rain attenuation in dB/s;
- the fade/interfade duration that corresponds to the time window during which a fixed threshold is exceeded by rain attenuation.

In the frame of this contract, **fade slope** is of specific interest since in the average time interval of fade slope calculation, the elevation angle can be assumed constant. This is not necessarily true for fade duration, especially for low attenuation thresholds. During the measurements campaign these aspects will be evaluated and possible comparison with ITU-R model [ITU-R P.1623-1, 2005] shall be carried out both for fade slope and fade duration.

Concerning fade duration and fade slope, the few models available in the literature and recommended by ITU-R [ITU-R P.1623-1, 2005] are valid only for GEO-satellite links. Adaptation of these models to

non-GEO orbit is not straightforward, as well as the theoretical development of new models.

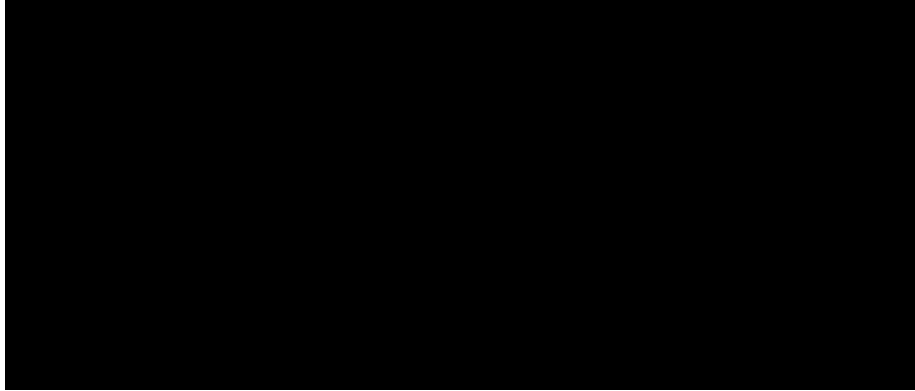


Figure 2.1: Features characterizing the dynamics of fade events

- **Fade duration**

Fade duration represents the time during which a given attenuation level is exceeded. Various fade duration distributions have been proposed to model the fade duration. Short fade durations are mainly due to scintillation and multiple scattering while long fade durations are caused by rain cells. So, it seems difficult to represent the fade duration statistics by a single distribution. From [Paraboni and Riva, 1994], it appears that the statistical distributions for both short and long fades are independent of the site, but depend on the attenuation threshold considered, the frequency and the link elevation angle.

Fade duration can be described by two different types of CCDF [Paraboni and Riva, 1994]:

- $P(d > D | a > A)$ or $P_n(D)$, the probability of occurrence of fades of duration d longer than D (s), given that the attenuation a is greater than A (dB);
- $F(d > D | a > A)$ or $P_t(D)$, the cumulative exceedance probability, or, equivalently, the total fraction (between 0 and 1) of fade time due to fades of duration d longer than D (s), given that the attenuation a is greater than A (dB).

The current ITU-R model [ITU-R P.1623-1, 2005] is the updated version of the model reported in [Paraboni and Riva, 1994]. The model has two segments, a power-law function for short fades and a log-normal distribution function for long fades. The input parameters necessary to run the model are the attenuation threshold A (dB), the frequency (between 10 and 50 GHz) and the elevation angle (between 5° and 60°). The total outage time corresponding to a given attenuation threshold is also necessary. To obtain this parameter, conventional rain attenuation prediction method such as [ITU-R Rec. P.618-13, 2017] can be used.

- **Fade slope**

Fade slope distributions of the slowly varying components (due to rain) are important for the design of Fade Mitigation Techniques and for the design of control loops. To obtain this component, it is necessary to filter out the rapid variations from the measured data. Fade slope depends on the attenuation level and the rain rate [Buné et al., 1988], [Matricciani, 1981]. This implies that the fade slope will depend on the drop size distribution and therefore on the type of rain (convective or stratiform rain) [Van de Kamp, 2003]. Another parameter of influence is the horizontal wind velocity perpendicular to the path which determines the speed at which the horizontal rain profile passes across the propagation path.

Various **models of fade slope** have been proposed:

- in [Nelson and Stutzman, 1996] a model for predicting the probability density function (PDF) of fade slope, based on Olympus measurements in Blacksburg, Virginia, at 12, 20 and 30 GHz, is presented;

- in [Timothy et al., 2000] a model for the CCDF of the absolute fade slope, based on measured statistics from 11 GHz INTELSAT beacon data measured in Singapore, is presented;
- an improvement of the ITU-R fade slope model was suggested in [Franklin et al., 2005] based on Ku-band measurements taken at four locations in Fukuoka, Kyushu Island, Japan.

These models are, however, empirical models and are not applicable in a different climate nor for different elevation angle or frequency. The Van de Kamp model [Van de Kamp, 2003] was adapted by ITU for predicting the fade slope statistics of rain attenuation [ITU-R P. 1623-1, 2005]. Based on measurement results of various sites, [Salonen and Heikkinen, 2003] proposed an adjustment of the parameter s in the van de Kamp-model. Gremont and Ndzi [Gremont and Ndzi, 2000] developed a model based on Maseng Bakken, assuming that rain is log-normally distributed and that the conditional PDF of the fade slope depends on attenuation and time lag but not on frequency. In [Riva et al, 2006], a comparative analysis between models, based on the Spino d'Adda database, has shown that the one-parameter linear model of the variation of $\sigma_{\zeta}(A)$ is enough.

In the frame of this **ST-MWR project**, fade slope is considered of specific interest since in the average time interval of fade slope calculation, the elevation angle can be assumed constant. This is not necessarily true for fade duration, especially for low attenuation thresholds. Moreover, for both fade duration and fade slope, the part of the predicted statistical distribution due to only attenuation (slow components) and not scintillation (fast components) can be tested in the frame of the ST-MWR activity, since the MWR cannot measure scintillation. During the measurements campaign these aspects will be evaluated and possible comparison with ITU-R model [ITU-R P.1623-1, 2005] shall be carried out both for fade slope and fade duration.

2.1.5 Impact of variable antenna elevation angle

The use of a link with a **variable elevation angle** is one of the most important peculiarities of this study. Since the receiving antenna of the earth station must point to a non-geostationary EO satellite, the slant path elevation angle is continuously changing during the contact time. The common approach for the link budget calculation, in this case, is to divide the elevation angle range in a certain number of intervals, and to calculate the time percentage of the contact time for which a given elevation angle occurs in each interval. To maintain homogeneous this probability among the various intervals, the intervals should be larger for low elevation angles (when the apparent velocity of the satellite is lower) and narrower for high elevation angle (when the apparent velocity is higher). By choosing properly the elevation angle intervals we can hence assume that the elevation angle is varying slowly in each interval and can be assumed equal to its center class value. This latter value can be used to calculate the 'static' distribution of attenuation (CCDF of total attenuation) conditioned to the elevation angle in each interval, by using the conventional statistical prediction models (gas, cloud, rain and scintillation prediction models).

These **conditioned CCDFs** can then be added (in probability and at the same attenuation level) to calculate the unconditional attenuation CCDF after weighting their probability axis with the probability that the elevation angle is in the corresponding interval. In particular, the following step algorithm can be adopted to take into account for the variable elevation angle of the link:

- calculate the probability, w_i , that the link elevation angle is in the interval i (we could choose for example 20 intervals whose edges are: 5, 6, 7, 8, 9, 10, 12, 14, 16, 18, 20, 25, 30, 35, 40, 45, 50, 55, 60, 70, 90 degrees);
- by using conventional statistical attenuation prediction models, calculate the probability $P_i(A_j)$ of exceeding the total attenuation (gas, cloud, rain and scintillation) threshold A_j on the link with elevation angle equal to the center value of the interval i (e.g. 5.5 degree, for the interval between 5 and 6 degrees);
- calculate, for the considered ground station, the probability, $P(A_j)$ of exceeding the total attenuation threshold A_j , by summing, over all the N elevation angle intervals, the probabilities $P_i(A_j)$ multiplied by w_i :



The same algorithm can be used to combine the distribution of site diversity gain as a function of probability for the different elevation angles.

2.2 Channel models for satellite radiopropagation

Concerning **channel models**, at least two types appear to be appropriate for non-GEO satellites: a) **time-series synthesizers**, able to consider both the variation of the tropospheric impairments due to the change in the troposphere itself and in the link elevation; b) **full space-time channel models**, relying on the knowledge of tropospheric variables (e.g. rain, clouds, temperature, etc.), achieved using stochastic or deterministic approaches, and on the simulation of their interaction with the link. A review of time series synthesizer models is available through the framework of the European Network of Excellence SatNEx [Castanet et al., 2009]. Among the full space-time channel models are stochastic, fractal, and cellular models. In this category fall the models developed at PoliMI, either cellular [Luini and Capsoni, 2011; Luini and Capsoni, 2016] or mixed stochastic-cellular [Luini, 2017]. More recently, meteorologically based methods have been proposed, e.g. the one developed at SUR [Biscarini et al, 2016; Biscarini et al, 2017], which exploit the full high-resolution atmospheric description achieved by NWP models.

Two types of channel models, appropriate for the ST-MWR activity, can be considered:

1. time series synthesizers where not only the propagation channel dynamics but also the elevation dynamics due to the link variation need to be considered;
2. full space-time channel models in order to consider on the one hand the dynamics of the channel, especially within precipitating systems, and on the other hand the spatial variations of the channel.

2.2.1 Attenuation time series synthesis

Propagation time series is a critical issue for the optimization of adaptive systems at high frequency bands such as Ka or Q/V band in temperate areas or even at Ku-band for tropical and equatorial areas. In the last 10 years, several approaches to synthesize time series of propagation impairments and in particular of total attenuation and of tropospheric scintillation have been implemented.

A comprehensive review of rain attenuation time series synthesizers has been carried out in the framework of the European action COST 280 [Fiebig et al., 2003], of the ESA study ESTEC 16865/03/NL/EC [Lemorton et al., 2004] and in the framework of the European Network of Excellence SatNEx [Castanet et al., 2008].

The ITU-R suggests a set of channel models within the Recommendation P.1853-1 for “Tropospheric attenuation time series synthesis”. The ITU-R models deal with:

- Rain attenuation time series synthesis method;
- Scintillation time series synthesis method (not of interest in ST-MWR);
- Integrated cloud liquid water content time series synthesis method;
- Integrated water vapor content time series synthesis method;
- Total attenuation and scintillation time series synthesis method for Earth-space paths.

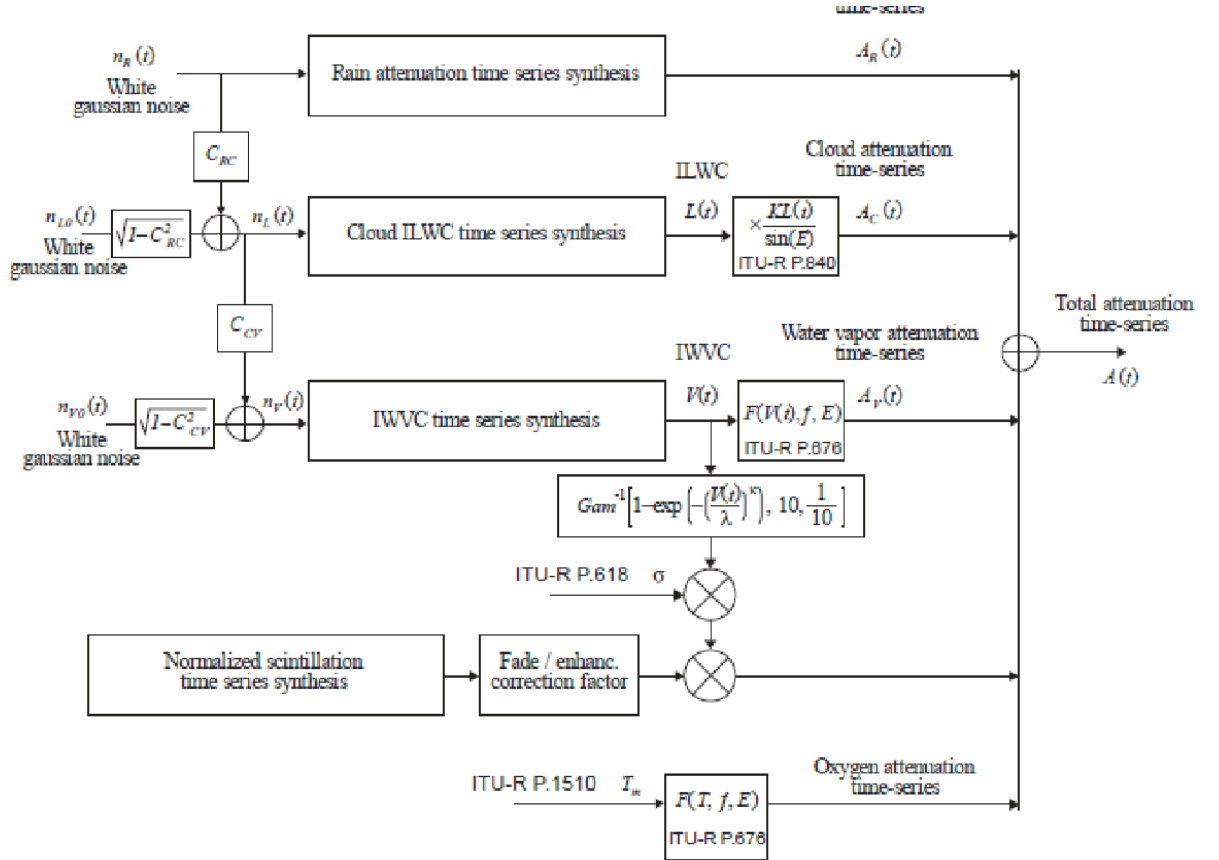


Fig. 2.3 Block diagram of ITU-R P1853-1 total attenuation time-series synthesizer.

Fig. 2.3 summarizes the block diagram of total attenuation, whereas Fig. 2.4 focuses on the blocks for rain attenuation. Note that for Earth-space paths, the time-series synthesis method in P.1853-1 is valid for frequencies between 4 GHz and 55 GHz, and elevation angles between 5° and 90°. For some circumstances (e.g. low frequencies, moderate to high elevations, temperate areas), the total attenuation may be approximated by the rain attenuation with sufficient accuracy. The time series synthesis method generates a time series that reproduces the spectral characteristics, fade slope and fade duration statistics of total attenuation events. Inter-fade duration statistics are also reproduced but only within individual attenuation events. Recent updates are also available in [ITU-R, 2019].

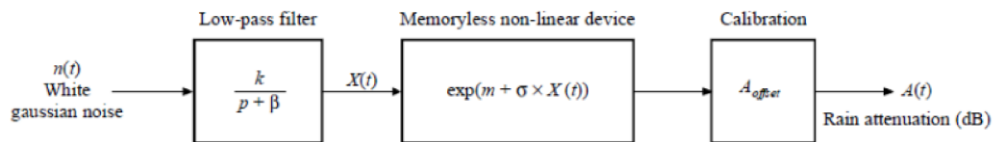


Fig. 2.4 Block diagram of ITU-R P1853-1 rain attenuation time-series synthesizer.

i) Markov and semi-Markov models

The DLR channel model is based on a hidden Markov chain approach [Fiebig, 2002]. It can be run in either a discrete-valued (limited number of attenuation states) or a continuous-valued version. This channel model requires as inputs sets of mean values and standard deviations allowing the description of the transition probabilities of the Markov chain. These sets can be derived from experimental time series.

The generator described in [Shin et al., 1999] consists of a four-state semi Markov chain considering: a beginning state (decreasing received power), an ending state (increasing received power), a

fading state (constant received power between beginning and ending states) and an inter-fade state (intermediate full time). Using rain attenuation measurements in Taejon (Korea) from Koreasat 2 12.25 GHz beacon signal, ETRI (Electronics and Telecommunications Research Institute, Daejeon, Rep. Korea) found empirical uniform distributions for the state duration.

The ONERA N-states Markov chain time series synthesizer [Castanet et al, 2003] aims at modeling rain attenuation with two states (rain and no rain) and at filling rain periods with a N-state Markov chain. The main interest of this model is to rely only on available statistical prediction models (first and second order statistics with ITU-R prediction models) in order to fill the transition matrices.

The Gremont's model [Gremont and Tawfik, 2003] has been developed on similar principles. It considers both the long-term statistics and the temporal variations of the rain attenuation phenomenon.

The BUTE N-state Markov chain model [Heder and Bito, 2006] is also similar to the ONERA N-state Markov model; its parameters are derived from the fade slope statistics. The model parameters were determined from one-year measured attenuation data measured on a terrestrial microwave link operating at 38 GHz.

ii) Maseng-Bakken models

A stochastic model of rain attenuation relying on the first order Markov theory has been proposed by Maseng and Bakken in the eighties [Maseng and Bakken, 1981]. This concept has been applied to generate time-series of rain attenuation for satellite communications systems operating at Ku-band and above [Gremont and Filip, 2004] [Lemorton et al, 2007] [Cheffena, 2008]. The ONERA-CNES attenuation time series synthesizer (Enhanced Maseng-Bakken model) relies on this theoretical stochastic rain attenuation model. Two versions of the model have been developed to generate either long-term time series [Lacoste et al., 2005] or rain attenuation events on-demand (from the input of maximum attenuation and total duration) [Carrie et al., 2009] at any sampling rate, that maintain the spectral properties of the propagation channel and the long-term distribution of rain attenuation.

iii) Experimental Measurements Based model

The Experimental Measurements Based model [Bertorelli et al., 2008] is based on a large set of experimental rain attenuation time series collected in the framework of the ITALSAT propagation experiment. The principle of the time series synthesizer consists in extracting rain attenuation events and in scaling them in frequency, polarization, elevation, rain height, to consider the conditions existing in different locations worldwide.

iv) Synthetic Storm Technique

Starting from the rain rate time series of rain storm collected at a site with a rain gauge (a robust and economic device), the Synthetic Storm Technique can generate rain attenuation time series at any frequency, polarization, slant path above about 20° and at any site, thanks to a model of the vertical structure of rain modeled with two layers of precipitation of different thickness [Matricciani, 1996].

A synthetic storm is obtained by converting a rain rate time series, recorded at a point by a rain gauge and averaged over 1 minute (or less, as experimented with the ITALSAT database collected at Spino d'Adda), to an attenuation time series, by using an estimate of the storm translation speed v to transform time to distance, through a convolution integral.

The vertical structure of rain is modeled with two layers of precipitation of different depths. Starting from ground, there is rain (hydrometeors in the form of raindrops, water temperature of 20°C, layer A) followed by a melting layer (layer B), i.e., melting hydrometeors at 0°C. The vertical rain-rate R (mm/h) in the lower layer is assumed to be uniform and given by the rain rate time series (measured at ground). The vertical precipitation rate in the melting layer, termed “apparent rain-rate”, is supposed to be uniform and given by XXXXXXXXXX (mm/h).

The height of the precipitation (rain and melting layer) above sea level is assumed to be the ITU-R 0°C isotherm height above sea level and the depth of the melting layer is 0.4 km. Rain attenuation, A (dB), is calculated as a line integral of the specific rain attenuation (dB/km), according to the values of rain-rate found in the rain-rate space series obtained with the synthetic storm technique.

v) Time series synthesizer of Arapoglou

The approach proposed in [Arapoglou, 2011] [Kourogiorgas, 2012] consists in an extension of the Maseng and Bakken related models of rain attenuation which have been intensively validated for GEO satellite links. The proposed extension of the models aims at considering the statistical distribution of LEO satellite elevation angles. More precisely, the long-term distribution of rain attenuation is assumed to be log-normal conditioned to elevation angle. Then, considering the distribution of the elevation angles and a sector segmentation of the elevation domain, a new rain attenuation distribution is numerically computed for each angular sector. The obtained distributions constitute the basis for a new log-normal fit and then for the synthesis of time series for each angular sector. As recognized by the author, the overall concept is considered as a first analytical approach and has not been tested with experimental data. However, one can already note that the dynamic parameter used in the model is constant regardless of the angular sector (as it is the case for the model in ITU-R P.1853 for GEO satellite links) and does not consider the rate of change of the elevation angle within an angular sector. So, it is expected that this method is adequate for MEO satellites for which the velocity is not too large but that the model will probably not be accurate enough for LEO satellites. Furthermore, there is no statement about the transition between angular sectors.

vi) Model of Liu and Michelson

Liu and Michelson propose a method to synthesize rain attenuation time series [Liu and Michelson, 2010]. The rain cells are simulated using the Excell model. The fade slope being determined by rain intensity variations in a range of 100 m; the spatial distribution of the rain cells is assumed not to play a significant role in the fade slope distribution. This hypothesis is of course a direct consequence of the exponential model of the rain intensity in the rain cells. The model uses the CCDF of rain rate as given by ITU-R P.837 model. The parameters of the Excell model are then calculated and the number of rain cells belonging to a given peak rain interval is evaluated. The rain cells are then randomly distributed throughout the rain field. The free space losses, gases, cloud and rain attenuation are calculated. In the absence of LEO data, the model has been checked against data measured with a GEO satellite for which the slope is due to the movement of the rain field due to wind.

vii) Total attenuation time series synthesizers

In the framework of the ESA contract 20887/NL/LvH "Verification of Propagation Impairment Mitigation Techniques", ONERA developed complementary modules allowing time series of total attenuation and tropospheric scintillation to be synthesised. Indeed, for frequencies higher than 20 GHz, the effects of the other contributions of the atmospheric attenuation (such as attenuation due to oxygen, water vapor, clouds and scintillation) necessarily have to be considered because no more negligible. Consequently, a global channel model of total impairment is required. The developed methodology to synthesize total attenuation time series for satellite communication systems at Ka and Q/V bands has been proposed and adopted by ITU-R in [ITU-R P.1853-1, 2012; ITU-R, 2019]. The generation of the clear air effects is based on the synthesis of atmospheric parameters time series such as Integrated Water Vapor Content (IWVC) and Integrated Liquid Water Content (ILWC), which are then converted into attenuation. The macroscopic step by step procedure is as follows:

1. Rain attenuation is generated using the model in [Lacoste et al., 2005];
2. Integrated liquid water content (ILWC) is generated through a mixed lognormal model, cloud attenuation is then deduced from ILWC using [ITU-R P.840-7, 2017];

3. Integrated water vapor content (IWVC) is modelled thanks to a Weibull distribution; it is then converted into attenuation according to [ITU-R P.676-11, 2016];
4. A constant value of the oxygen attenuation is computed from [ITU-R P.676-11, 2017] and [ITU-R P.1510-1, 2017];
5. The envelope of the short-term scintillation time series is controlled by the IWVC transformed so as to reproduce the long-term scintillation statistics predicted by [ITU-R P.618-13, 2017].
6. The total attenuation is obtained by summing the 5 above attenuation components. In doing this, the cloud attenuation is interpolated when both the rain attenuation is strictly positive and the ILWC content exceeds the 1 mm threshold.

Concerning the ILWC and IWVC components, the basic assumptions are quite similar to the ones used in the Maseng and Bakken related models. The two main hypotheses concerning the processes are the following:

1. The individual processes long-term distributions follow given statistical laws (mixed log-normal for ILWC and Weibull for IWVC), characterized by a set of parameters.
2. The individual processes can be transformed into stationary Gaussian processes using nonlinear transformations.

More recently, a more flexible attenuation time series synthesizer has been proposed in [Montopoli et al., 2008] and [Boulanger et al, 2013]. The latter is based on a mixed lognormal model of the rain attenuation distribution; the model is unchanged for the other attenuation components. The new approach brings significant improvement with respect to first order statistics for frequencies higher than 20 GHz without degrading neither the second order statistics (whatever the frequency band), nor the first order statistics for lower frequency bands.

2.2.2 Space-time channel simulation

In the recent years, several methods have been proposed to generate time correlated attenuation fields or space-correlated attenuation time series for propagation studies. Dynamic cellular models can be used but other kinds of models exist, which can be classified as statistical models (mainly from the hydrology domain), fractal models and stochastic models. In statistical models, the rainfall process is modeled as a combination of multiple random processes, each one governing a specific feature of the rain field (e.g. occurrence and duration of storms); fractal models exploit the scaling property of rain field; finally, stochastic models consider a rain field as a realization of a given random process.

i) Joint Rain Attenuation ITALSAT based model

The Joint Rain Attenuation model is derived by the framework proposed in [Paraboni and Bertorelli, 2005] and is based on a large set of experimentally derived rain attenuation data; it aims to describe concurrent rain attenuation conditions at different stations, preserving the actual spatial and temporal variability of the rain process, both in terms of rain occurrence and rain attenuation.

The framework proposed in [Paraboni and Bertorelli, 2005] has been consolidated and refined by addressing two new issues. Firstly, instead of considering only the joint rainy time among the stations, correlated time series which include periods of no rain are to be obtained. Secondly, a new approach was developed to achieve accuracy in reproducing the mutual correlation of rain attenuation among the stations.

The Joint Rain Attenuation model [Nebuloni et al, 2014] is based on 7 years of experimental rain attenuation time series collected at 18.7, 39.6 and 49.5 GHz in Spino d'Adda in the framework of the ITALSAT propagation experiment. This database of experimental rain attenuation time series is large enough to reproduce the main features of the phenomenon. The model output consists of measured time series of rain/no rain times for each station of interest and for a specific time duration (1 year or more); the series suitably adapted to resemble the joint attenuation conditions over multiple sites. The allocation of real measured data to generate correlated time series has the attractive advantage that all the features of the rain phenomenon are already included in the measured data (i.e. event dynamics and fades).

In order to extract and properly scale the time series of attenuation measurements, the model needs the following inputs: the geographical information of the stations (latitude, longitude, height above sea level), the satellite link parameters (frequency, polarization, elevation angle), the probability of rain and the rain rate exceeded CCDF [ITU-R P.837-7, 2017] and the spatial rain correlation, both in terms of rain probability and attenuation probability [Paraboni and Barbaliscia, 2002], [ITU-R P.618-13, 2017]. A reference model (e.g., SC-ExCell) [Capsoni et al, 2009] is used to obtain the attenuation probability distribution from the rain rate distribution.

The model consists of two independent mathematical processes, which represent the rain attenuation correlation and are required to assign the proper data series to the stations. The generated time series consist of basic periods of fixed duration (usually 30 min or 1 hour, different duration can be easily introduced) filled with rain/no rain samples according to the following processes.

1. The first conditioning process assigns rain/no rain time over the stations of interest, correlating the rainy times according to the spatial distribution described in [Paraboni and Barbaliscia, 2002], [ITU-R P.618-13, 2017]. This process randomly generates a binary sequence for each station, corresponding to rain/no rain times, reproducing the desired spatial correlation of rain events occurrence. The resulting rain probability over 1 year sequence duration is the target probability of rain for each station, derived from [ITU-R P.837-7, 2017]. The random binary sequences are obtained by a non-linear transformation of continuous Gaussian random processes according to a set of station specific rain thresholds. The accuracy in reproducing the spatial correlation of rain events has been the subject of a proper analytical investigation.
2. For each basic period and only for stations in rainy conditions, the second conditioned process is responsible for the extraction of properly correlated time series of fixed duration from the database of measurements. Two main issues have been addressed: on one hand the extracted series for the desired simulation duration must reproduce the long-term attenuation statistic of each single station, on the other hand attenuation values of the series selected for the rainy stations must show the correct spatial correlation. These two results have been obtained by a new specific algorithm. The main hypothesis at the core of this process is the log-normal distribution of the long-term rain attenuation statistic. This hypothesis allows to represent the single station rain attenuation distribution by a proper sampling of the Gaussian statistic, equivalent to a selection of a limited number of time series, according to the mean and variance of the log-normal distribution. Moreover, the correlation of rain attenuation during concurrent periods of rain is achieved by selecting time series whose average attenuation values over the basic period duration show the desired mutual correlation in accordance to [Paraboni et al. 2002, ITU-R P.618-10]. In this way, the original data are preserved except from a frequency scaling to match the link requirements. The independence of the two mathematical processes 1 and 2 was already discussed in [Paraboni and Barbaliscia, 2002].

ii) Fractal rain fields

The fractal nature of rain has been highlighted by [Lovejoy and Mandelbrot, 1985]. They searched for self-similarity in rain fields, because self-similarity can be found in the physical equations of turbulence which is the physical cause of rain. This self-similarity implies a power law spectral density for the rain fields. The exponent of the spectral density is the fractal dimension of the field. Efficient algorithms exist to generate fractal rain fields [Callaghan, 2006]. The inputs needed for such kind of modeling are the fractal dimension that may vary according to the type of rain event. The distribution of rain rates is also needed to rescale the value of the field. Other types of fractal models such as random cascade (a rain rate at a fine scale is the result of the product of the rain rate at coarser scale and a white noise) have a strong formal background but have limited practical implementation.

iii) Generation of stochastic rain fields

In order to generate a rain field using a stationary Gaussian random field, the distribution of the rain

rate and its correlation function need to be known. To synthesize a rain field, a Gaussian correlated random field is first generated and the values of the Gaussian field are transformed into values drawn from the rain rate distribution. This transformation changes the correlation of the field, but a link can be made between the correlation of the underlying Gaussian field and the correlation of the rain rate. This methodology is very efficient computationally speaking and the temporal dimension can easily be added.

In [Gremont and Filip 2004], the authors use the same methodology as described above, but replace the rain rate directly with attenuation values and use a different kind of correlation function.

Jeannin [Jeannin et al, 2008] and [Jeannin et al, 2012] proposed to rely on a Numerical Weather Product (ERA 40 ECMWF database) to generate realistic stochastic rain fields at a continental scale over long period of time. The inputs needed are the correlation function of the Gaussian random field and the CCDF of rain rate. A framework to derive space-time correlation functions from weather radar datasets has been proposed in [Jeannin et al, 2012]. Parameterization on various climatic areas (Europe, US, Western Africa) have been derived for rain rate fields. The conversion of the rain rate fields into rain attenuation fields is achieved through the integration of the specific attenuation along the path of the link below the rain height. A stochastic interpolation procedure described in [Carrie et al., 2010] is used in order to obtain time series with a sampling rate of 1 Hz. Long term simulations using the model have been shown to reproduce various statistical features of the rain attenuation fields in space as well as in time.

The model has been extended [Jeannin et al., 2011] to generate simultaneously of all attenuation components, that is cloud, water vapor and cloud attenuation, as well as tropospheric scintillation. The spatial parameterization of the cloud water content fields being has been derived from MODIS data in [Jeannin et al, 2010], and confirmed by NWP simulations in [Jeannin et al, 2012]. Those NWP simulations over France have also been used to derive space time correlation of water vapor fields.

2.3 Radiopropagation modeling improvement at millimeter wave

Possible area of improvements at W band can be evaluated. We can anticipate some directions:

1. Cloud slant path attenuation at W band can be significant and data will surely provide new inputs for the improvement of statistical and channel models. Cloud liquid attenuation can be derived from W-band radiometric measurements and this dataset will be precious to verify the extension of the attenuation statistical and channel models to the W band.
2. Sky noise temperature model and the associated mean radiative temperature should be revisited at W band since both cloudy and rainy are poorly documented. Mean radiative temperature at W band can be estimated from W-band radiometric measurements in clear and cloudy conditions; the extension to rainy conditions can be investigated.
3. Angle variability is a challenge in non-geostationary measurements. The approach to deal with the attenuation CCDF conditioned to the elevation angle has to be investigated and possibly parametrized from W-band Sun-tracking MWR data.
4. Rain attenuation time series synthesizer have been developed and tested at Ka band, but not beyond 70 GHz. This means that the spectral filter parameterization should be updated and refined at W band. The possibility to extend the approach to cloud attenuation time series synthesizer could be investigated.

3 Data from the AFRL supersite and radiative transfer modeling

The following sections provide a complete overview of all the input data and actual measurements adopted in this paper to train, tune and validate the proposed weather forecast and radiative transfer models. Details on the ST-MWR data processing and error budget are provided in the Appendix.

The closest radiosounding site to Rome, NY, is located at Albany County Airport, NY, USA (World

Meteorological Organization station Identifier code: 72518, Weather Bureau Army Navy Identifier code: 14735; lat/lon 42.69/-73.83). Radiosounding data belonging to the period 2007-2016 have been collected for this study to compare and validate the outputs of the NWP models.

3.1 Sun-tracking microwave radiometer data at K, Ka, V and W band in Rome, NY

The ground-based Sun-Tracking Microwave Radiometer (ST-MWR) is a Radiometer Physics GmbH-Liquid Water Path (RPG-LWP-U72+82) water-vapor and cloud-liquid microwave radiometer with four channels at 23.8, 31.4, 72.5 and 82.5 GHz [13]. It is provided with an azimuth positioner allowing a scan step of 0.15° in elevation and 0.1° in azimuth. The Sun-tracking operation mode allows tracking the Sun motion along the ecliptic (Fig. 3.1). It considers a constant elevation angle (θ in Fig. 3.1) between two relatively close T_B measurements, which are taken only varying the azimuth angle by first pointing the antenna toward the Sun source (φ_1 in Fig. 3.1) and then measuring the atmospheric contribution without the Sun (φ_2 in Fig. 3.1) [8]. A value at elevation θ is retrieved exploiting the difference between the brightness temperature toward the Sun and one without the Sun. This operation mode allows removing possible brightness temperature biases when atmospheric optical thickness is estimated. The integration time of each measurement is set to 1 second and the azimuth positioner switches every 6 seconds in order to perform the integration with fixed antenna position. The worst-case root-mean-square noise of 0.15 K is to be expected for a scene temperature of 300 K, assuming the overall bandwidth of 230 MHz and 1 second integration time. Therefore, 1-second integration time is enough for our purposes. One could theoretically integrate for up to 5-6 seconds (elevation and azimuth angles are constant for about 6 seconds), however it is not recommended since the Sun's position could vary within the mentioned interval. The processing and quality-control procedures applied to the radiometer data are described in [8].

The available dataset consists of measurements collected by the ST-MW radiometer from May 2015 to December 2016 in Rome, NY, USA (43.2°N , 75.4°W) at elevation angles varying between 20° and 70° (with some missing data days due to maintenance and calibration operations on the radiometer).

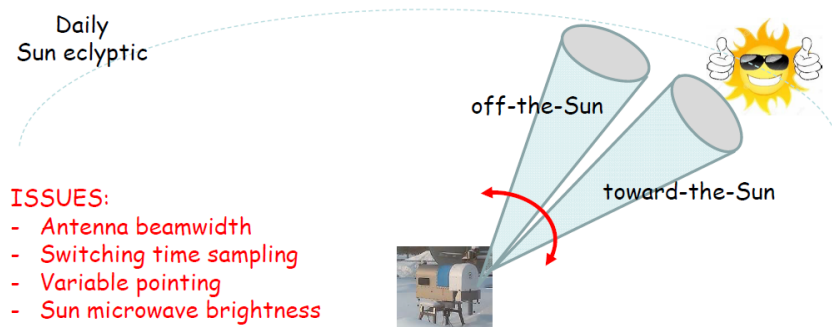


Fig. 3.1 ST-MWR operation: the radiometer tracks the Sun during its motion considering a constant elevation angle θ between two close measurements taken varying the azimuth from toward-the-Sun φ_1 to off-the-Sun φ_2 .

3.2 Microwave radiometric profilers in Rome, NY

The second source of radiometric measurements is available for the whole year 2016 in Rome, NY (43.2°N , 75.4°W) from RPG humidity and temperature profiler microwave radiometer (PRO-MWR) with 7 channels from 22.24 GHz to 31.4 GHz and 7 channels from 51 GHz to 58 GHz [13], [14]. PRO-MWR provides T_B measurements that are always taken at zenith, even though the radiometer is provided with an azimuth positioner allowing a scan step of 0.15° in elevation and 0.1° in azimuth. Time resolution and

integration time are set to 1 second. In this work we only use the frequency channels overlapping with the ones of the ST-MWR that are: 23.8, 26.25 and 31.4 GHz.

3.3 Radiative transfer modeling at microwave frequencies

This section is devoted to the description of the radiative transfers models used to simulate T_B and A : 3D-RTM and 1D-RTM. Since the 3D-RTM is driven by weather forecasts, in the first paragraph of this section we describe the numerical weather prediction models considered in this work.

3.3.1 Weather Research and Forecasting (WRF) numerical model for Rome, NY area

Several numerical weather prediction models are designed to simulate mesoscale atmospheric circulation. In this work we have considered the Fifth-Generation Penn State University/National Center for Atmospheric Research Mesoscale Model (MM5) [18], and the Weather Research and Forecasting (WRF) system [19], developed by the National Oceanic and Atmospheric Administration and by the National Center for Environmental Prediction, are used.

MM5 is a nonhydrostatic, terrain-following sigma-coordinate model, designed to simulate or predict mesoscale and regional-scale atmospheric circulation. It includes:

- a multiple-nest capability;
- nonhydrostatic dynamics, which allows the model to be used at a few-kilometer scale;
- multitasking capability on shared and distributed-memory machines;
- a four-dimensional data-assimilation capability;
- more physical options.

WRF model system is designed to be a flexible atmospheric simulation system, efficient on available parallel computing platforms. It represents:

- the state-of-the-art model that has good conservation characteristics (e.g., conservation of mass);
- an easy to modify model, that could well parallelize on many processors;
- plug-compatible physics to support improvements in model physics;
- designed for grid spacing of 1-10 km.

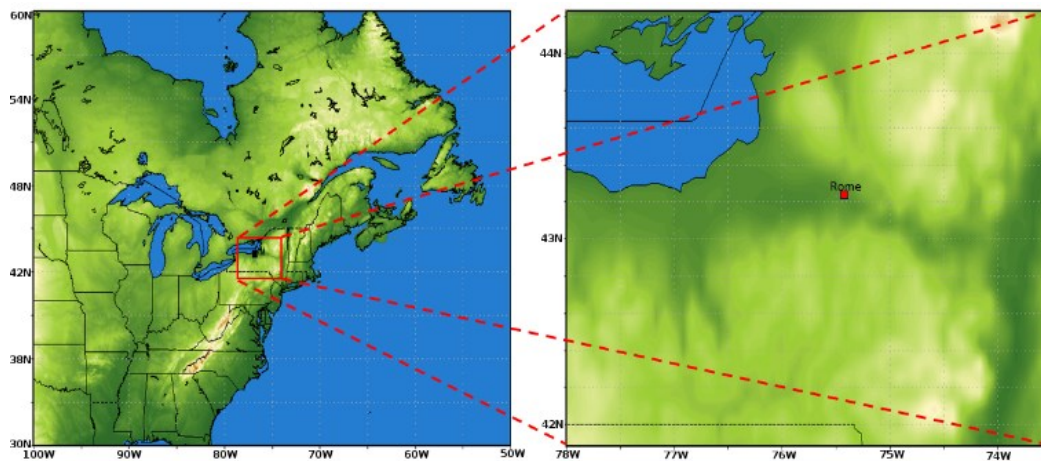


Fig. 3.2 Two nested domains of the NWP models centered on the target area of Rome, NY: (a) domain 1 at 18 km (and 9 km) resolution; (b): domain 2 at 6 km (and 3 km) resolution.

We have initialized both regional models (MM5 and WRF) with data from the global-scale model of the

European Center for Medium-range Weather-forecast performing two-way nested domains simulations centered on Rome, NY (Fig. 3.2). We have compared the performances of the models for different resolutions of the initialization data.

After a climatological analysis of the target area of Rome, NY, we have defined the setup for the physical parameterizations for the considered models. The MM5 setup considers Reisner II for microphysics [20], Grell for cumulus [18], Rapid Radiative Transfer Model for radiations [21] and Medium Range Forecast for planetary boundary layer [22]. WRF setup includes Thompson for microphysics [23], Grell-Freitas for cumulus [24], Rapid Radiative Transfer Model for radiations and Mellor-Yamada-Janjic for planetary boundary layer [25].

3.3.2 1-D and 3-D numerical radiative transfer physically based models

As previously stated, in this work we consider two radiative transfer models, both focused on the area of Rome, NY, where ST-MWR measurements are available.

The first is a pseudo three-dimensional radiative transfer model (3D-RTM) included in the Goddard Satellite Data Simulator Unit suite [11]. The 3D-RTM is based on the two-stream model with Eddington's Second Approximation using bulk single-scattering properties along selected slant paths [26]. These slant-paths mimic rigorous 3D microwave radiative transfer approach by using a 1D radiative transfer model and for this reason it is referred as "pseudo" 3D-RTM. It takes into account the gas absorption (i.e. nitrogen, cloud water, oxygen and water vapor) and the single-particle single-scattering due to five hydrometeors species (cloud, rain, ice, snow, graupel). Consequently, values of downwelling T_B and A are produced at several frequencies and elevation angles for a period going from 1 August 2015 to 31 July 2016 (according to ST-MWR availability). Input scenarios in terms of spatial and temporal hydrometeor and background gases distributions are derived by WRF simulation forecasts at the temporal sampling of one hour. Single-particle single-scattering properties are computed at each WRF grid point and subsequently integrated over the explicit particle size distribution for the various species (e.g. rain, ice, snow, graupel etc.) to represent bulk single scattering properties. Lorenz-Mie method is used to calculate single scattering properties in rain regimes whereas for ice and snow, discrete dipole approximation or T-matrix calculations are selected. Polarization is not taken into account in our simulations. Effective refractive indices needed to calculate single scattering properties are obtained through the Maxwell-Garnett method that accounts for bin-by-bin particle effective density (riming fraction) and melting fraction. The absorption coefficients for water vapor, oxygen, nitrogen and cloud water are calculated using formulas from [27], [28], [29] and [30], respectively. Fig. 3.3 shows the statistics of A for the target period obtained from the 3D-RTM at the zenith view.

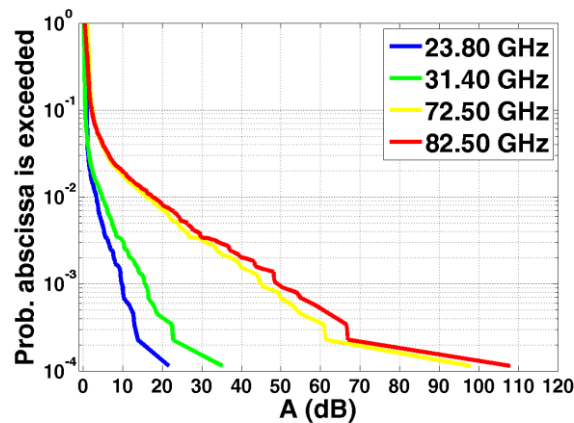


Fig. 3.3 Complementary cumulative distribution function of A computed from 3D-RTM simulations from

1 August 2015 to 31 July 2016 for the frequencies of interest.

The second model that we consider is a sky noise Eddington model that was developed and described in [10]. It is a 1Dimensional radiative transfer model (1D-RTM) that gives an Eddington-based analytical approximation of the solution of the radiative transfer equation [31]. The input of 1D-RTM is a synthetic clouds dataset for the random generation of seasonal-dependent and time-decorrelated radiometeorological variables at the desired frequencies and elevation angles, with statistics driven by radiosounding profiles in clear sky [10] available from the World Meteorological Organization. The simulated variables are relative to ten clouds classes (including the clear air): cumulonimbus, cumulonimbus with incus, cumulus, cumulus congestus, altocumulus, altostratus, nimbostratus, stratus, cirrus and clear air. Each cloud class has 500 realizations per each season (winter, spring, summer, autumn) for a total of 20000 realizations per each considered frequency and elevation angle.

Both 3D-RTM and 1D-RTM simulations are obtained at several elevation angles (i.e., 10°, 20°, 30° 36°, 40°, 50°, 54°, 60°, 70°, 80, 90°) for the frequencies at 23.8, 31.4, 72.5 and 82.5 GHz where ST-MWR measurements are available.

3.3.3 Meteorological verification of WRF numerical model

We have performed quantitative analysis using some statistical parameters: bias (Bias), standard deviation (STD) and correlation coefficient (Corr) calculated on the vertical profiles of humidity and temperature between simulations and observations according to the following definitions:

$$Bias = \langle x_{sim} - x_{obs} \rangle \quad (3.1)$$

$$STD = \sqrt{\langle [(x_{sim} - x_{obs}) - \langle (x_{sim} - x_{obs}) \rangle]^2 \rangle} \quad (3.2)$$

$$Corr = \frac{\sigma_{(x_{sim}x_{obs})}}{\sigma_{x_{sim}}\sigma_{x_{obs}}} \quad (3.3)$$

where x represents the considered variable (humidity or temperature) and the subscripts sim and obs stand for simulations and observations, respectively. In this case, simulations are from Numerical Weather Predictions and observations are from radio soundings or weather radar measurements.

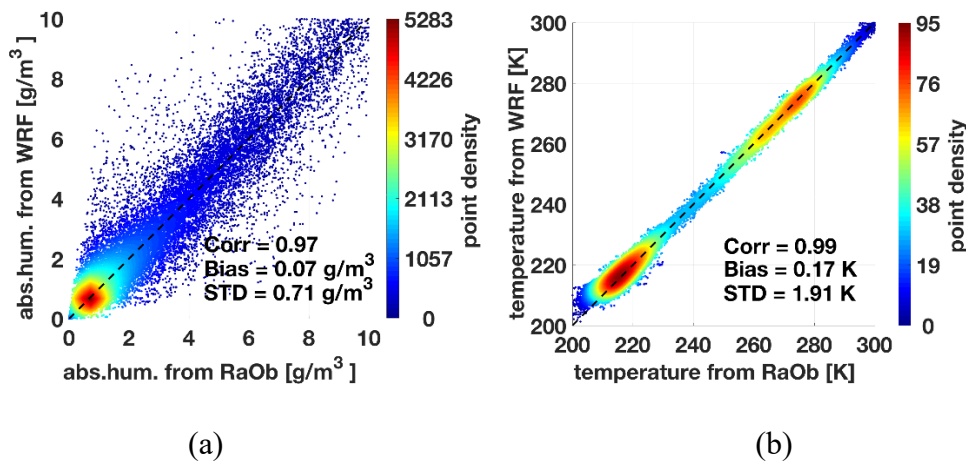


Fig. 4 Numerical weather predictions validation with radiosounding data: (a) absolute humidity, (b) temperature.

First, we have explored the sensitivity of MM5 and WRF to different initialization data and we have found that the best configuration is represented by WRF model initialized with data from the European Center for Medium-range Weather-forecast at 0.125° resolution.

Then, we have validated the WRF best configuration performing a long run in the analysis period using two domains, at 12 km and 4 km horizontal spatial resolution, one hour of temporal resolution and daily forecast. The run was from 1 August 2015 to 31 July 2016 (according to ST-MWR availability) on a volume with a base of 4x4 km² and height ranging from surface to ~ 10-12 km centered on Albany, NY, where radiosounding data were available for the validation. Fig. 4 a and b report the scatter plot of absolute humidity and temperature, respectively, with respective values of bias, correlations and standard deviation.

To quantify the capability of WRF setup to reproduce radio soundings at every altitude, the Index of Agreement (IA) has been adopted [32]. IA is a standardized measure of the degree of model prediction error that varies between 0 and 1. An agreement index score of 0 suggests little or rather no agreement between weather forecast simulations and radiosounding data, while an agreement score of 1 suggests complete match. An IA less than 0.5 might suggest a diversity (between forecast and observation).

$$IA = 1 - \frac{\langle (x_{nwp} - x_{raobs})^2 \rangle}{\langle (|x_{nwp} - \langle x_{raobs} \rangle| + |x_{raobs} - \langle x_{raobs} \rangle|)^2 \rangle} \quad (3.4)$$

where x stands for absolute humidity or temperature and the subscripts ‘*raobs*’ and ‘*nwp*’ indicate that the vertical profile of the variable x is from the radio soundings or from the numerical weather prediction model, respectively. The results are reported in Fig. 3.5. Humidity content profile (red curve in Fig. 3.5 obtained from the dataset in Fig. 4a) shows an IA ranging between ~1 (around surface) and ~0.8 (around 12 km). The IA of temperature profiles (blue curve in Fig. 3.5 obtained from the dataset in Fig. 4b) ranges between ~1 (around surface) and ~0.9 (around 12 km).

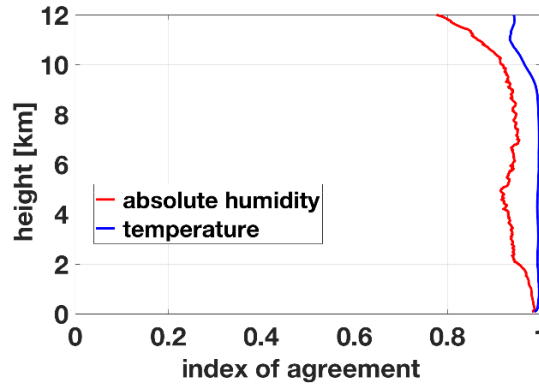


Fig. 3.5 Vertical profile of Index of Agreement between WRF and radiosounding data for absolute humidity and temperature profiles.

We have accomplished a further comparison using hourly surface precipitation, which can mainly affect the atmospheric optical thickness A , to evaluate the NWP performances close to the surface level. We have compared the output of the NWP model with measurements available from a radar-gauge mosaic on an area of 4 km x 4 km centered on Albany site (Fig. 3.6). The distribution of points density shows a correlation coefficient of 0.44, a bias of -0.09 mm and a standard deviation of 0.93 mm. The evaluation scores for the precipitation are sensibly worse than those obtained for temperature and humidity previously discussed but, given the large spatial and temporal variability of precipitation, they can be considered satisfactory.

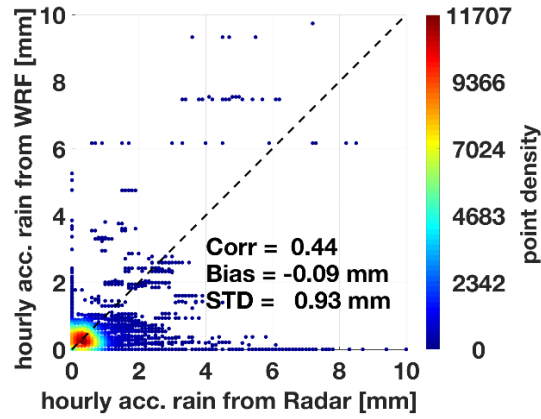


Fig. 3.6 Comparison between WRF and Radar Data in terms of rain accumulated in 1 hour on a domain centered on Albany site.

3.3.4 Verification of radiative transfer models using AFRL data

In this section we show several validation comparisons of both 1D-RTM and 3D-RTM with available radiometric measurements (ST-MWR and PRO-MWR).

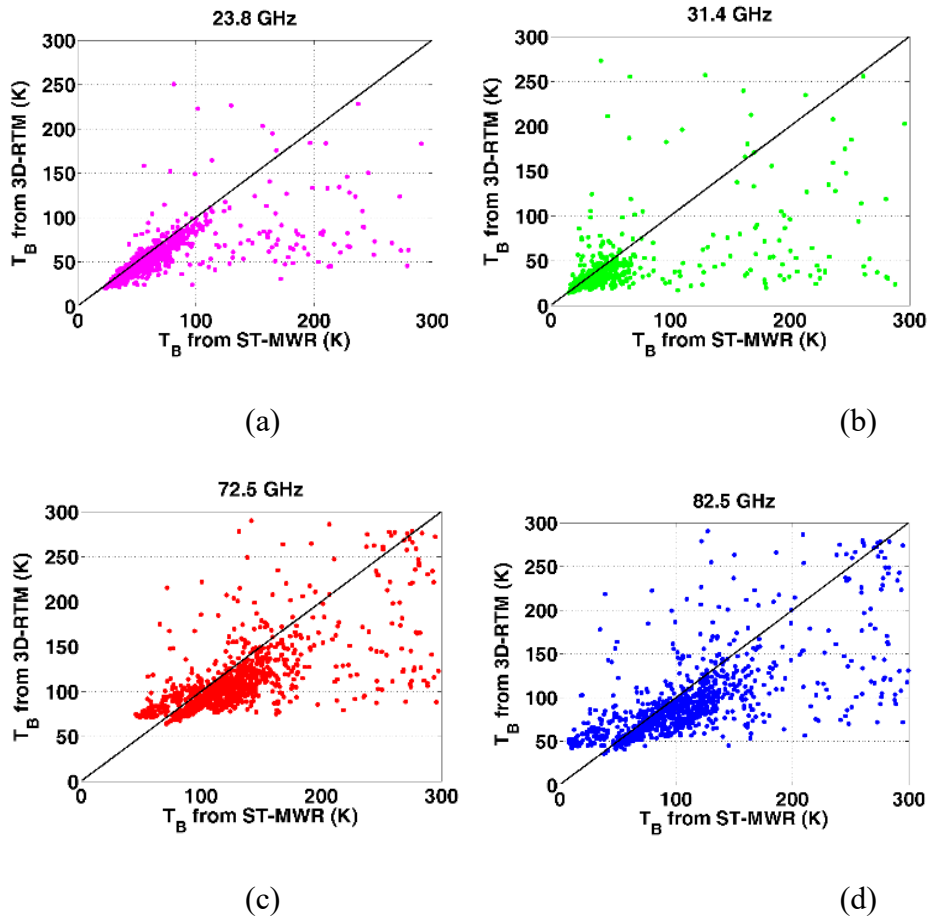


Fig. 3.7 T_B scatterplot for the period from 1 August 2015 to 31 July 2016: 3D-RTM vs ST-MWR after time-matching at all elevation angles interested by the ST-MWR measurements.

Fig. 3.7 shows T_B scatterplots comparing data from 3D-RTM simulations with ST-MWR measurements available from 1 August 2015 to 31 July 2016 for the four radiometric channel frequencies. Due to the Sun-tracking operation mode, ST-MWR acquires measurements at continuously varying elevation angles (from about 20° to about 70°). The comparisons in Fig. 3.7 are done considering all the points within the elevation-angle range covered by ST-MWR measurements performing a time-matching between the two datasets. Because of the different time sampling between 3D-RTM and ST-MWR (1 hour vs few seconds, respectively) we have averaged ST-MWR measurements over 1 minute around each nominal hour of 3D-RTM simulations. We have done the same plots of Fig. 3.7 in terms of A (not shown for brevity) and listed the error scores in Table for both T_B and A . Error scores between radiometric measurements and radiative transfer model are presented in terms of correlation, bias, standard deviation and root mean square error.

Both Fig. 3.6 and Table show a general agreement between model and measurements although, from Fig. 3.7 we note a larger point dispersion at high T_B values, i.e. where rainy events likely occur. In addition, from Table 3.1 we observe an underestimation bias of 3D-RTM in terms of T_B of the order of 11 K to 18 K depending on the frequency. Such biases could be ascribed to several factors: inaccuracies in the 3D-RTM routines of the radiative transfer, errors introduced by the slant path interpolation implemented within 3D-RTM [11] or to possible calibration biases of the ST-MWR [8]. We have also accomplished the same comparison of Fig. 3.7 but at a fixed elevation angle of 36° (which is one of the most frequent value during the Sun-tracking antenna motion). Results in terms of error scores were promising: correlations always larger than 0.74 and 0.68 for T_B and A , respectively, and biases ranging from 6 K to 11 K and from 0.13 dB to 0.49 dB.

TABLE 3.1. T_B AND A ERROR SCORES FROM 1 AUGUST 2015 TO 31 JULY 2016: 3D-RTM VS ST-MWR AFTER TIME-MATCHING AT ALL ELEVATION ANGLES OBSERVED BY ST-MWR

	Freq. (GHz)	23.80	31.40	72.50	82.50
T_B	Corr.	0.65	0.56	0.68	0.70
	Bias (K)	-13.40	-10.83	-17.48	-14.03
	Std (K)	31.42	39.00	36.63	43.04
	RMSE (K)	34.14	40.46	40.57	45.25
A	Corr.	0.52	0.40	0.43	0.43
	Bias (dB)	-0.34	-0.34	-0.58	-0.46
	Std (dB)	1.12	1.73	3.30	3.62
	RMSE (dB)	1.17	1.76	3.35	3.65

To partially check the origin of the biases listed in Table I, we have compared 3D-RTM simulations with PRO-MWR in the period of interest (1 August 2015 - 31 July 2016) after a time-matching between the two sources of information. Fig. 3.8 and 3.2 show the results of the comparison in two cases of all-weather and clear-sky conditions. The clear-sky identification is accomplished using the sky status indicator [33]. However, it should be noted that with respect to the previous comparison between 3D-RTM and ST-MWR, where data were compared along the direction of 36° elevation angle, in the case of 3D-RTM vs PRO-MWR, the comparisons are at 90° since PRO-MWR is a zenithal-pointing radiometer.

From 3.2 we note that the bias in terms of T_B sensibly reduces with respect to those listed in Table and this lead to conclude that most of the bias in the 3D-RTM vs ST-MWR comparisons could be ascribed to ST-MWR calibration issues. Inaccuracies in the 3D-RTM routines of the radiative transfer still play a role, especially in clear-sky, as highlighted by the overestimation of T_B of 3D-RTM with respect to PRO-MWR (look at the lower left tail in Fig. 3.8 panels *b, d, f*). The impact of 3D-RTM overestimation of T_B in clear-sky is larger at 31.4 GHz than at 23.84 GHz (see biases in Table in clear-sky).

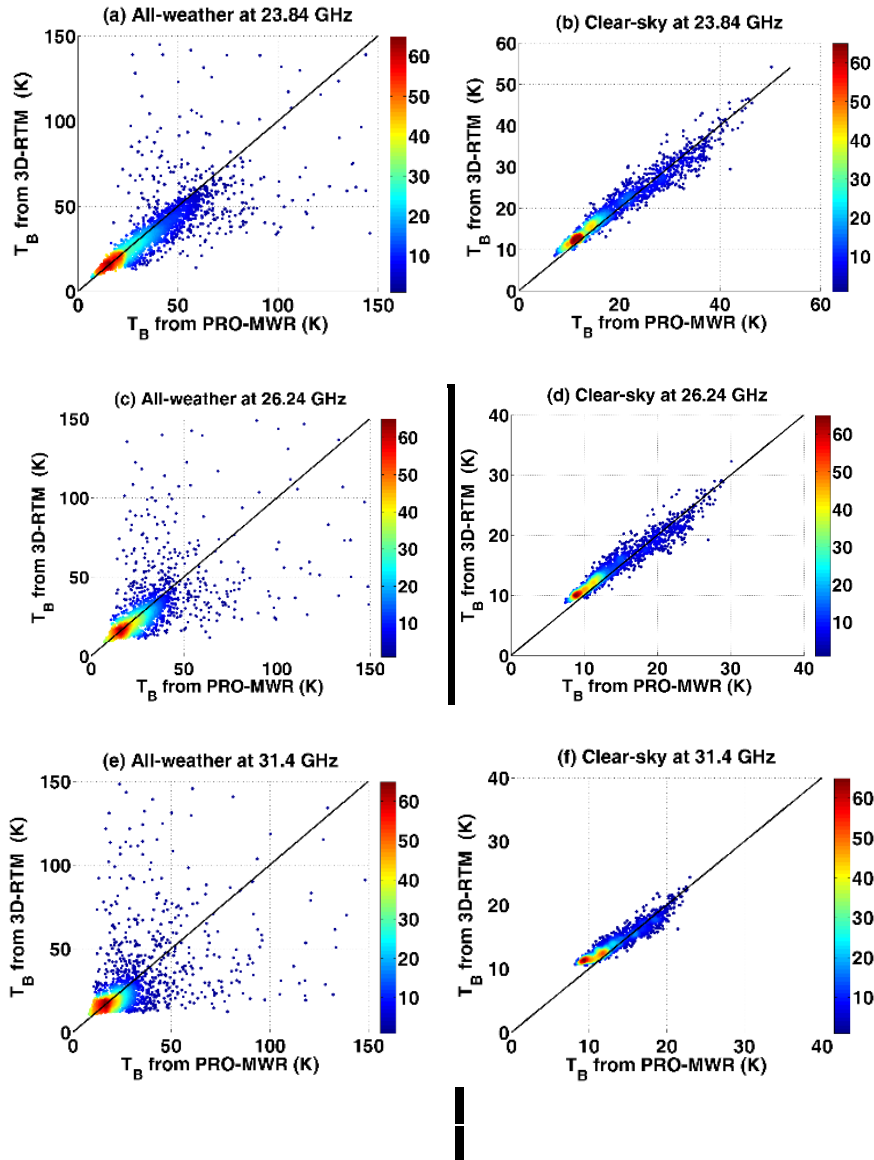


Fig. 3.8 T_B scatter density plot for the period from 1 August 2015 to 31 July 2016: 3D-RTM vs PRO-MWR after time-matching at zenith view.

TABLE 3.2. T_B ERROR SCORES FROM 1 AUGUST 2015 TO 31 JULY 2016: 3D-RTM vs PRO-MWR AFTER TIME-MATCHING AT ZENITH VIEW (SEE FIG. 3.8)

Freq. (GHz)		23.84	26.24	31.4
<i>All-weather</i>	Corr.	0.70	0.56	0.52
	Bias (K)	-1.48	-0.15	0.07
	Std (K)	17.44	20.02	23.63
	RMSE (K)	17.50	20.02	23.62
<i>Clear-sky</i>	Corr.	0.97	0.97	0.95
	Bias (K)	0.60	0.51	0.74
	Std (K)	2.06	1.32	1.17
	RMSE (K)	2.14	1.42	1.38

This behavior suggests that the water vapor representation in 3D-RTM is not able to accurately reproduce

PRO-MWR observations. In all weather conditions (i.e. clear-sky+ cloud-sky and precipitation, Fig. 3.8, panels *a*, *c*, *e*), the overestimation previously noted in 3D-RTM simulations in clear-sky is masked by the variability of cloud and precipitation events.

Fig. 3.9 shows the correlation between brightness temperatures at the four channel frequencies comparing 1D-RTM, 3D-RTM and ST-MWR. These scatterplots are often exploited for data-quality check and for calibrating and validating both measurements and models. Indeed, anomalies in the channel correlation can help to find if a channel is unreliable (e.g., due to calibration errors) or a simulation is inaccurate (e.g., due to radiative model under or over estimation). Due to the variation of the elevation-angle of the ST-MWR measurements and in order to have a robust comparison, in Fig. 3.9 we have considered all the elevation angles within the range of the ST-MWR data (20°-70°). The figure highlights as the 3D-RTM is able to well reproduce the overall statistical trend of ST-MWR measurements. Moreover, the two radiative transfer models (3D-RTM and 1D-RTM) are in quite excellent agreement. From Fig. 3.9 we note a considerable T_B underestimation of the 3D-RTM in the right flank region of the “banana” shape shown in panels *a* and *b*. Interestingly both 1D-RTM and 3D-RTM models fails in reproducing lower T_B values in the 82.5 vs 23.8 GHz plane.

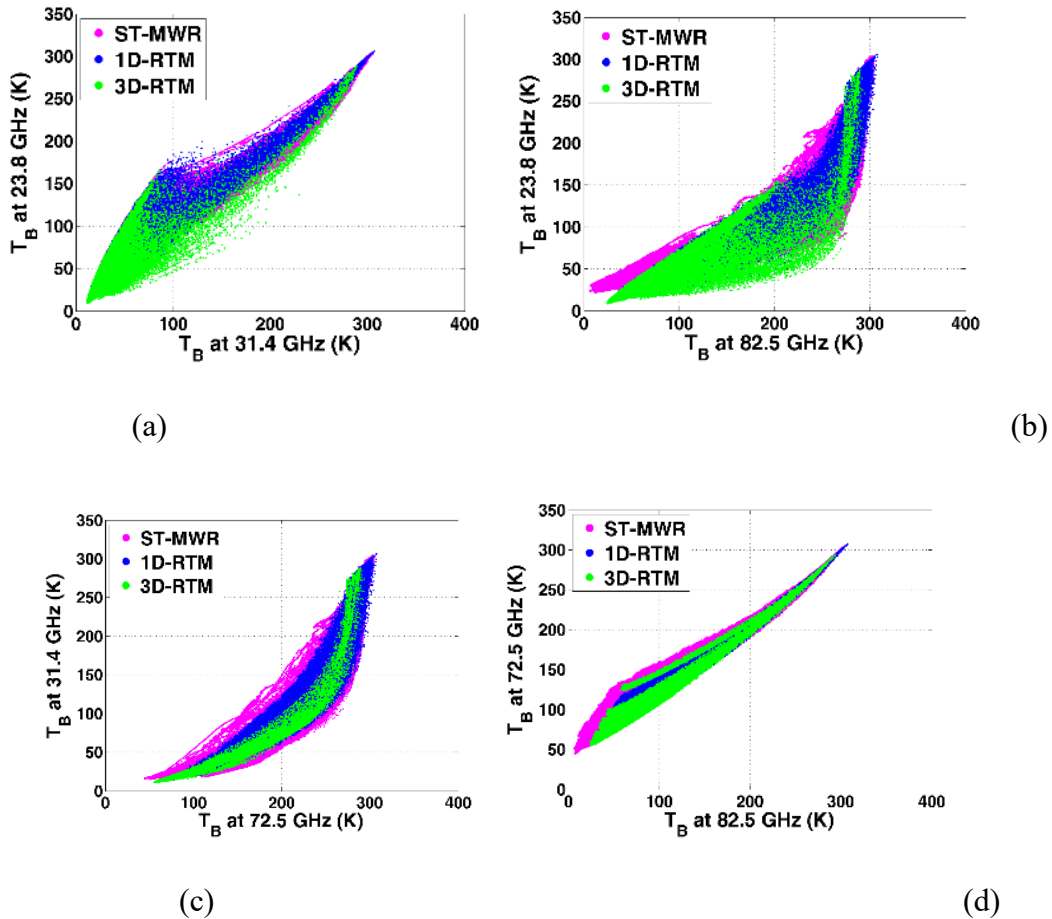


Fig. 3.9 $T_B - T_B$ channel correlation of ST-MWR, 1D-RTM and 3D-RTM at the ST-MWR frequency channels. All the elevation angles are included.

Similar considerations can be done looking at the $T_B - A$ correlation scatterplots reported in Fig. 3.10 with ST-MWR, 1D-RTM and 3D-RTM data. Fig. 3.10 also highlight the saturation occurring at high values of A measured by ST-MWR. This behavior is expected because in heavy rain condition (i.e., for high values

of A), the atmosphere appears as a screen from the radiometer point of view and obstructs the sight of the Sun preventing the Sun-tracking operation.

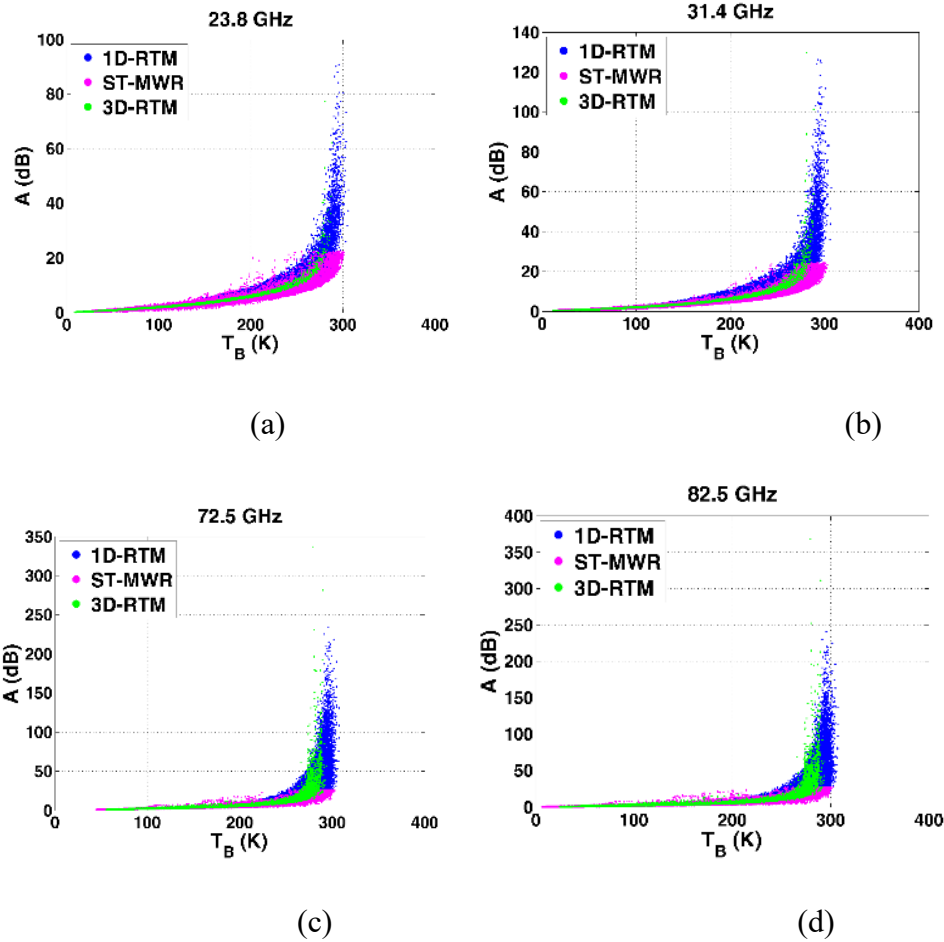


Fig. 3.10 $T_B - A$ correlation of ST-MWR, 1D-RTM and 3D-RTM at the four ST-MWR frequency channels. All the elevation angles are included.

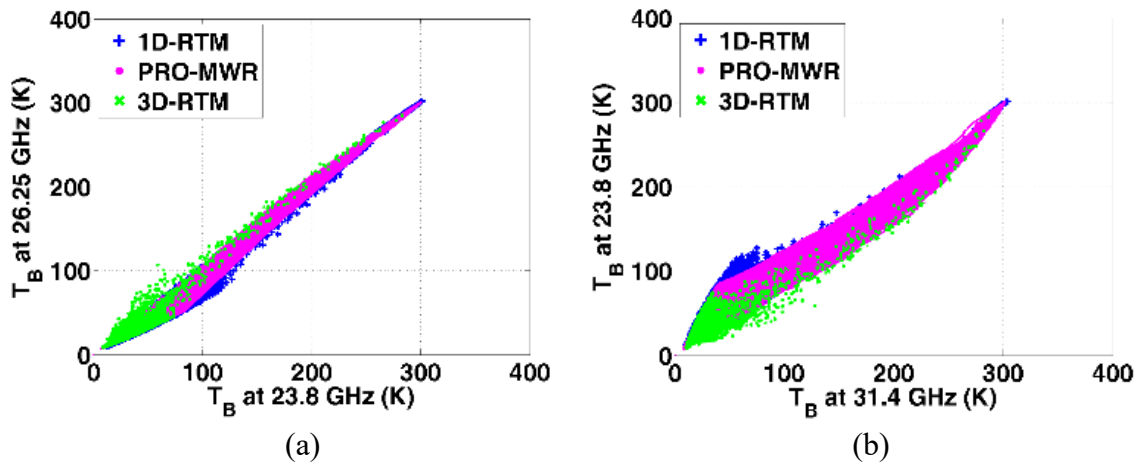


Fig. 3.11 $T_B - T_B$ channel correlation of PRO-MWR, 1D-RTM and 3D-RTM at the PRO-MWR frequency channels, zenith view.

Fig. 3.11 reproduces the same quantities as in Fig. 3.9 except that in this case ST-MWR is replaced by

PRO-MWR and the plots are realized at zenith view. We note a general agreement among the three datasets except for the region $T_B < 150$ K where 3D-RTM is not totally superimposed to 1D-RTM and PRO-MWR.

4 Assessing the mean radiative temperature prediction at microwave frequencies

The disadvantage of current approaches to the estimation of satellite path attenuation is that they require the knowledge of the optical parameters (extinction coefficients k_e , albedo w and asymmetry factor g of the scattering phase function) that are not always available, known or predictable [54]. The theoretical expressions show that, once known the atmospheric attenuation $A(\theta, f)$, the brightness temperature can be derived through the knowledge of the *normalized* $T_{mr}(\theta, f)$:

$$\frac{T_{mr}(\theta, f)}{T_s} = \frac{e_a(\theta, f) - (T_c/T_s)e^{-\frac{A(\theta, f)}{4.343}}}{\left(1 - e^{-\frac{A(\theta, f)}{4.343}}\right)} \quad (4.1)$$

Moreover, (4.1) suggests that $T_B(z=0, \theta, f)$, and then $e_a(\theta, f)$, might be expressed as a rational function by properly expanding in series the atmospheric transmittance $t(H, f)$ and the optical parameters as a function of $A(\theta, f)$.

In this work we propose a *generalized parametric prediction* (GPP) model to derive the $T_{mr}(\theta, f)$, normalized to the surface temperature T_s (K), as a ratio of 2 truncated polynomial series as a function of $A(\theta, f)$. We can then approximate (4.1) as:

$$\left. \frac{T_{mr}(\theta, f)}{T_s} \right|_{HS} \cong \frac{c_0(\theta, f) - c_1(\theta, f)A(\theta, f) + c_2(\theta, f)A^2(\theta, f)}{c_3(\theta, f) - c_4(\theta, f)A(\theta, f) + c_5(\theta, f)A^2(\theta, f)} \quad (4.2)$$

where the function $c_k(\theta, f)$ (with $k=0$ to 5) depend on both frequency and elevation angle according to the following polynomial equation:

$$\log_{10}[c_k(\theta, f)] = \sum_{i=0}^N \sum_{j=0}^M p_{ij}^{(k)} f^i (\sin \theta)^j \quad (4.3)$$

with $N=4$ and $M=4$ within the proposed GPP model. The acronym HS in (4.2) stands for “horizontally stratified” since the regression coefficients $p_{ij}^{(k)}$ (with $i, j=0$ to 4) in (8) can be derived within the transmission windows from 5 to 95 GHz and for elevation angles from 5° to 90° , exploiting numerical simulations from the plane-parallel RTE models [48], as it will be clarified in this section.

One of the main drawbacks of the plane-parallel RTE models is the assumption of a horizontally stratified atmosphere. This issue translates into a beam-filling effect that implies a non-uniformity of the atmospheric medium within the antenna beamwidth. We expect the beam-filling effect to be less significant for: i) an optically thin atmosphere where path attenuation is relatively low as in the case of microwave links at Ku band and below in clear, cloudy and moderate rainy conditions; ii) an optically thick atmosphere where path attenuation is relatively large as in the case of high-frequency links above Ku band and intense precipitating clouds since the atmosphere can be assimilated to a black-body close to the receiving antenna. In all other cases, the beam-filling effect should be taken into account.

To tackle this issue, we can introduce a non-uniform *beam-filling factor* f_{bf} . At a first-order approximation, the latter allows modeling the T_{mr}/T_s ratio through a weighted linear combination of clear-air (CA) brightness temperature and the horizontally-stratified (HS) all-weather brightness temperature,

derived from (T5). The GPP model, including the beam-filling effect, has the following expression in terms of the *normalized* $T_{mr}(\theta, f)$:

$$\frac{T_{mr}(\theta, f)}{T_s} = \frac{[1 - f_{bf}(\theta, f)] \left. \frac{T_B(z=0, \theta, f) - T_c e^{-\frac{A(\theta, f)}{4.343}}}{T_s} \right|_{HS} + f_{bf}(\theta, f) \left. \frac{T_B(z=0, \theta, f) - T_c e^{-\frac{A(\theta, f)}{4.343}}}{T_s} \right|_{CA}}{1 - e^{-\frac{[1 - f_{bf}(\theta, f)] A(f, \theta) + f_{bf}(\theta, f) A_0(\theta, f)}{4.343}}} \quad (4.4)$$

where $A_0(\theta, f)$ is clear-air path attenuation (note that the subscript θ indicates the clear-air condition) and the terms in (9) are given by:

$$\begin{cases} \left. \frac{T_B(z=0, \theta, f) - T_c e^{-\frac{A(\theta, f)}{4.343}}}{T_s} \right|_{HS} = \left. \frac{T_{mr}(\theta, f)}{T_s} \right|_{HS} \left(1 - e^{-\frac{A(f, \theta)}{4.343}} \right) \\ \left. \frac{T_B(z=0, \theta, f) - T_c e^{-\frac{A(\theta, f)}{4.343}}}{T_s} \right|_{CA} = \left. \frac{T_{mr}(\theta, f)}{T_s} \right|_{CA} \left(1 - e^{-A_0(f, \theta)/4.343} \right) \end{cases} \quad (4.5)$$

and it holds for clear-air conditions:

$$\begin{cases} \left. \frac{T_{mr}(\theta, f)}{T_s} \right|_{CA} \cong \frac{c_0(\theta, f) - c_1(\theta, f) A_0(\theta, f) + c_2(\theta, f) A_0^2(\theta, f)}{c_3(\theta, f) - c_4(\theta, f) A_0(\theta, f) + c_5(\theta, f) A_0^2(\theta, f)} \\ A_0(\theta, f) = (a_1 e^{a_2 f} + a_3 e^{a_4 f}) / \sin \theta \end{cases} \quad (4.6)$$

In (4.6) the ratio $T_{mr}/T_s|_{CA}$ is nothing else that the ratio $T_{mr}/T_s|_{HS}$ in (4.2) for $A(\theta, f) = A_0(\theta, f)$, whereas for clear-air path attenuation we have adopted a cosecant angular law and a frequency-scaling parametric relationship with a_l ($l=1$ to 4) the proper regression coefficients. The latter can be derived from plane-parallel RTE numerical simulations over the target frequency span in the transmission frequency bands, as it will be shown later in this section.

Note that from (4.4) to (4.6) the beam-filling factor is applied to T_{mr}/T_s in *HS* condition and its counterpart in *CA* as well as to the path attenuation A . The rationale is that both T_{mr} , i.e. T_B , and A are integrated quantities which suffer for the horizontal inhomogeneity of the atmosphere.

The beam-filling factor f_{bf} in (4.4) is the most difficult parametrization in the GPP model. Its expected behavior should impact the intermediate values of path attenuation, leaving the low and high tails of the mean radiative temperature curve less influenced by the values of f_{bf} . On the other hand, the latter should scale with frequency since the optically thickness of the scattering atmosphere changes. The proposed function is the following:

$$f_{bf}(\theta, f) = f_{sigm}(f) e^{-[A(\theta, f)/4.343]^\alpha} \quad (4.7)$$

where f_{sigm} is the frequency-dependent sigmoid function and α is its shape parameter given by:

$$\begin{cases} f_{sigm}(f) = \frac{1}{1+e^{-(f-f_0)}} \\ \alpha = \frac{f_{ref}}{f} \end{cases} \quad (4.8)$$

with f_{ref} is the transition reference frequency and f_0 the clear-air effective frequency within the GPP model. The factor f_{ref} is a parameter that allows introducing a more complex frequency-dependence in the beam-filling factor expression. Its value has been set by minimizing the error budget in the best fitting algorithm. The beam-filling factor discriminates between the use of T_{mr}/T_s in clear-sky or rainy atmosphere. Between these two extremes there are conditions, mainly due to cumulus clouds, where a 1D horizontally-stratified radiative transfer model is not anymore adequate. In case of intense rainfall, due to cumulonimbus for instance, the atmosphere is behaving like a scattering black body so that the atmospheric structure is less important. In particular, the beam-filling factor in (4.7) is such that it affects the horizontally-stratified model formula in (7T) with a trend that exponentially decreases with path attenuation. In addition, the sigmoid function f_{sigm} makes the f_{bf} contribution negligible for frequencies lower than f_0 and rapidly increasing for frequencies approaching f_0 . For $f > f_0$ we have $f_{sigm} \rightarrow 1$, whereas for $f < f_0$ we have $f_{sigm} \rightarrow 0$. Note that f_{bf} ranges between 0 and 1: if $f_{bf} \rightarrow 0$, then $T_{mr}/T_s \rightarrow T_{mr}/T_s|_{HS}$ and viceversa, if $f_{bf} \rightarrow 1$, then $T_{mr}/T_s \rightarrow T_{mr}/T_s|_{CA}$.

Summarizing, the GPP model in (4.4) should be able to provide the all-weather radiative mean temperature T_{mr} once known the frequency f and elevation angle θ of the considered satellite-to-Earth link as well the surface temperature T_s . This makes the GPP model relatively simple and suitable for radiopropagation purposes, once the coefficients $p_{ij}^{(k)}$ in (8) and a_l in (4.6) are known within the selected frequency and angle range. This parameterization will be the objective of the next 2 sections.

4.1 ITALSAT dataset and radiometric frequency scaling

Colocated beacon (signal) and radiometric (noise) measurements are not always available since the same antenna typically measures the received carrier power, but not the related antenna noise temperature. Very often separate microwave ground-based radiometers are associated to the beacon receiving station to calibrate its clear-air signal level [49]. This section is devoted to the assessment of the GPP model by exploiting 3-year measurements available from the ITALSAT campaign in Spino d'Adda [49].

Data used to verify the proposed GPP model are relative to the ITALSAT campaign [49]. More specifically, we have exploited measurements collected at the receiving station of Spino d'Adda (Milan, Italy) during the years 1994, 1995, 1996 and 1999. The receiving station has an elevation angle of 37.8° and three beacon channels at 18.7, 39.6 and 49.5 GHz for the attenuation measurement. The receiving antenna, characterized by 3 sub-reflectors and a main dish with a diameter of 3.5 m, has a half-power beamwidth going from 0.26° at 18.7 GHz to 0.12° at 39.6 GHz and 0.10° at 49.5 GHz. Three co-located microwave radiometers performed brightness temperature measurements at 13.0, 23.8 and 31.6 GHz with half-power beamwidths of 3.5° , 1.8° and 1.9° , respectively. After a data-quality check, measurements relative to the 13-GHz channel were considered unreliable and not used. The ground-based ITALSAT station was also equipped by a set of meteorological instruments (thermometer, hygrometer, barometer and raingauge).

ITALSAT data, together with SNEM data, are shown in Fig. at 39.6 and 49.5 GHz (the 18.7 GHz channel is not shown for brevity). For a given attenuation value, SNEM data are largely distributed at higher values of brightness temperature, whereas ITALSAT data show a notable dispersion around lower brightness temperatures. This effect can be ascribed to the SNEM assumption of a homogenous atmosphere in the observing direction (without considering any antenna pattern and beam filling effect), as described in

previous sections and explained in [45].

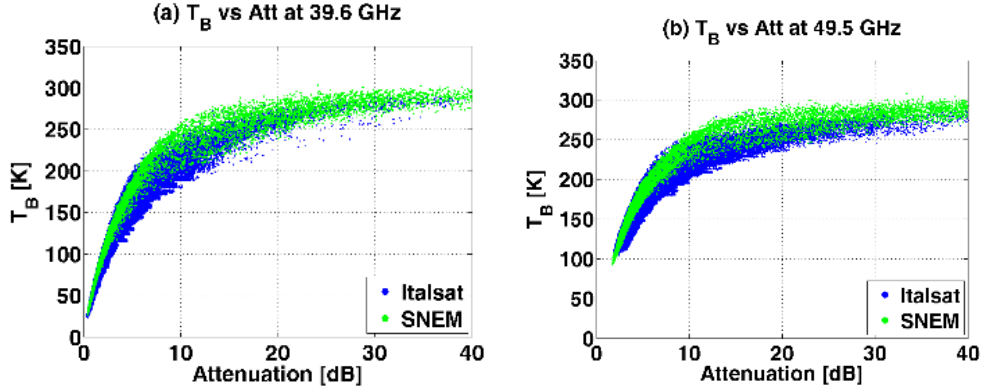


Fig. 4.1 ITALSAT data at 37.8° elevation. Brightness temperature channel correlation of T_B vs A at 39.6 GHz (a) and 49.5 GHz (b).

TABLE 4.1. COEFFICIENTS FOR THE DUAL CHANNEL REGRESSION IN (14)

Beacon frequency [GHz]	18.7	39.6	49.5
q_{00}	12.34	5.474	85.3
q_{10}	-0.03474	-0.1193	-0.1365
q_{01}	0.2099	1.521	1.404
q_{20}	0.002014	-0.001576	-0.001367
q_{11}	$8.209 \cdot 10^{-05}$	0.004136	0.005443
q_{02}	0.0003985	-0.00396	-0.005923

Note1: q_{ij} values not reported in this table are set to 0.

For a correct verification of the GPP model, we need attenuation and brightness temperature values at the same frequency and possibly with the same beamwidths. ITALSAT data do not satisfy this requirement and, for this reason, we have performed a radiometric frequency scaling. Beamwidth effects should be less influencing in presence of precipitation and, on the other, the beam-filling factor f_{bf} should smooth their impact. All-weather dual-channel estimation of brightness temperature at the considered beacon frequencies f_b is proposed from brightness temperature at the available radiometric frequencies f_r using the following parametric model:

$$T_B(\theta, f_b) = \sum_{i=0}^2 \sum_{j=0}^2 q_{ij} [T_B(\theta, f_{r1})]^i [T_B(\theta, f_{r2})]^j$$

where the beacon frequency f_b is the one the ITALSAT carries (i.e., 18.7, 39.6 or 49.5 GHz), whereas f_{r1} and f_{r2} are radiometric channel-frequencies of 23.8 and 31.6 GHz, respectively. The frequency-scaling regression coefficients q_{ij} at 37.8° elevation, computed using the SNEM database for Spino d'Adda site, are given in 4.1. Note that (14) is used to extrapolate T_B at frequencies out of the frequency interval $(f_{r1}; f_{r2})$, leading to possible inaccuracies in the brightness temperature estimation with respect to typical cases where extrapolated frequencies are within the available interval $(f_{r1} < f < f_{r2})$.

4.2 Generalized Parametric Prediction (GPP) model assessment

The GPP model has been trained by a multiple-site SNEM dataset. Indeed, for the assessment, it may be worth considering also the single-site version of GPP. The latter is obtained training the GPP model with SNEM data of a given site (specifically those of Spino d’Adda at the frequencies in the second transmission window).

4.2.1 GPP model validation using Italsat data

Fig. 2 shows the GPP model T_{mr}/T_s from (9) compared with the ITALSAT measurement at 2 ITALSAT beacon frequencies (the 18.7 GHz channel is not shown for brevity) and at an elevation angle of 37.8° . The site-specific GPP model in Spino d’Adda is also shown. A fairly good agreement between GPP model and binning-average of empirical T_{mr}/T_s from ITALSAT is noted. In particular, the GPP model appears to be very similar to the site-dependent GPP version in Spino d’Adda.

In order to quantify the agreement with respect to the average behavior, Table shows the root mean square error (R_E) of the difference between the GPP T_{mr}/T_s ratio and the empirical $T_{mr}/T_s|_{ITALSAT}$ from ITALSAT (i.e., blue points in Fig.):

$$R_E = \sqrt{\frac{1}{N} \sum_{i=1}^N \left(\left. \frac{T_{mr}}{T_s} \right|_i - \left. \frac{T_{mr}}{T_s} \right|_{ITALSAT_i} \right)^2}$$

where N is the total number of ITALSAT measurements. Note that R_E is always lower than 0.07, thus confirming that the choice of f_{ref} and f_0 (described in II.C.2) for modeling f_{bf} is appropriate. The larger R_E of 0.068 at 18.7 GHz is probably due to the tail of the 22 GHz absorption peak that causes a larger dispersion at this frequency. The best result in terms of R_E are at 39.6 GHz (see Fig. a) where the general and the site-specific models are almost superimposed with R_E of 0.045 and 0.046, respectively.

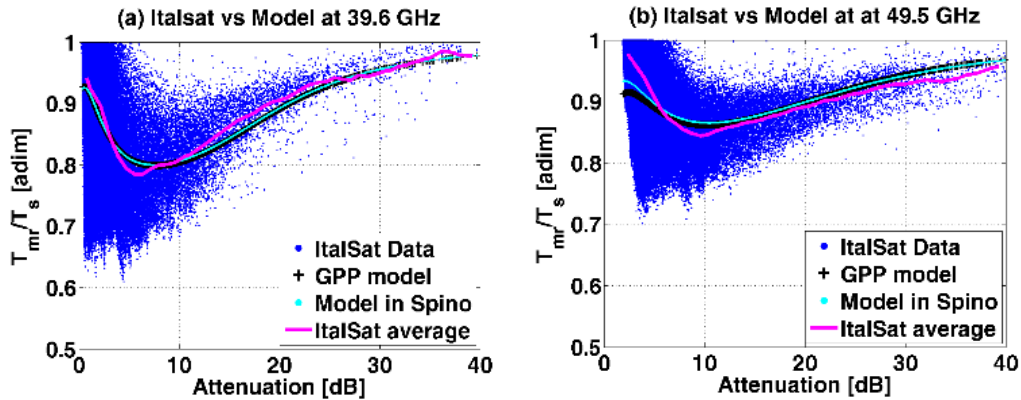


Fig. 4.2 GPP model verification with ITALSAT data in Spino d’Adda at elevation of 37.8° . T_{mr}/T_s vs A at 39.6 (a) and 49.5 (b) GHz. Blue points represent ITALSAT measurements, magenta line is the binning-average trend of ITALSAT measurements, black line is the GPP model, cyan line is the site-dependent GPP model in Spino d’Adda.

When applying (14) to ITALSAT data to retrieve brightness temperature at 49.5 GHz, we expect a larger error with respect to the retrieval at 39.6 GHz because of the larger distance from range of frequency used to estimate it (i.e., 23.8 and 31.6 GHz). This can explain the 0.062 R_E , which reduces to 0.049 when using the site-dependent GPP model at 49.5 GHz. Note that (see Fig. b) the highest error is for path attenuation

values lower than 5 dB (i.e., clear sky and moderate rainy conditions).

TABLE 4.2. ROOT MEAN SQUARE ERROR (R_E) OF THE GPP MODEL VS ITALSAT MEASURED ONE (SEE FIG.)

<i>Model</i>	R_E		
	18.7	39.6	49.5
<i>GPP model</i>	0.068	0.045	0.062
<i>Site-dependent GPP model</i>	-	0.046	0.049

4.2.2 GPP model sensitivity to surface temperature

The GPP model in (9) can be exploited to retrieve the mean radiative temperature from available measurements of path attenuation by multiplying the T_{mr}/T_s ratio for the surface temperature T_s . Although we have set the GPP model using “instantaneous” T_s values (i.e., in one-to-one correspondence with attenuation values), we can investigate what happens to R_E budget if T_s is not available and only average surface temperature values (e.g., yearly, seasonal, monthly or weekly) are available.

In this respect, Fig. shows the average seasonal trend of surface temperature in Spino d’Adda from both ITALSAT measurements and SNEM simulations. Seasons are defined as follows: December, January and February for winter; March, April and May for spring; June, July and August for summer; September, October and November for autumn. The step-like behavior of SNEM data is due to the different dataset used for seasonal simulations.

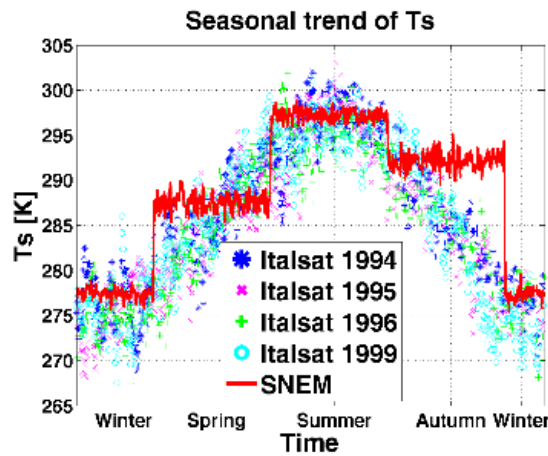


Fig.4.3 Average seasonal trend of surface temperature in Spino d’Adda from ITALSAT measurements and SNEM simulations.

The left panels of Fig.4.4 show the mean radiative temperature T_{mr} , directly derived from ITALSAT measurements (using (14) and inverting (5)), compared with T_{mr} retrieved multiplying the GPP model in (9) for instantaneous and yearly average T_s (derived from the meteorological station in Spino D’Adda). As a reference, the T_{mr} computed from the ITU-R recommendations [43], [44] considering instantaneous and yearly average T_s is shown, too. Even though the ITU-R model does not claim to be neither generalized nor physically-based, it is the most well-known reference in the radiopropagation field and the Fig. should be taken as a qualitative comparison.

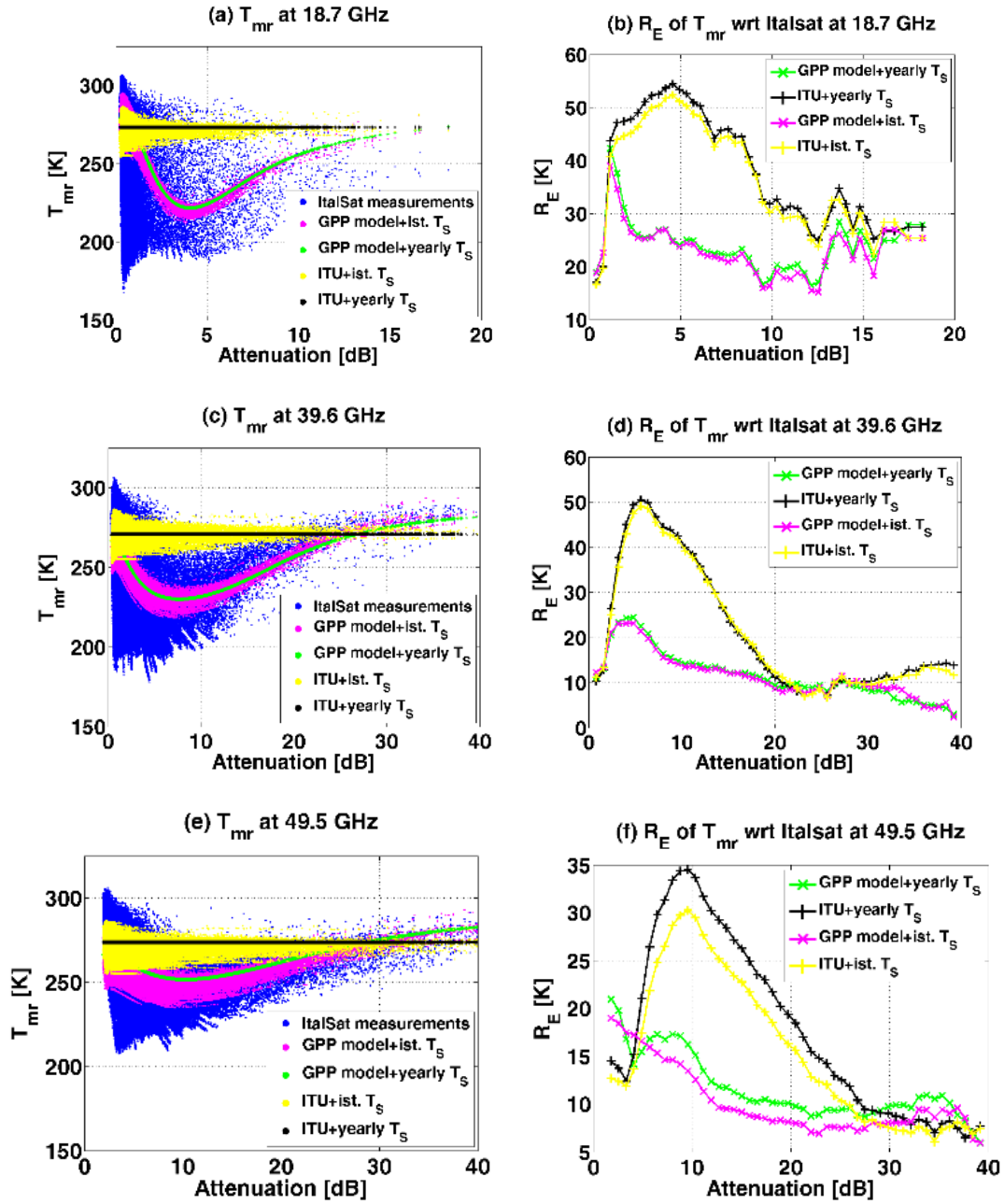


Fig. 4.4. Left panels, T_{mr} retrieved with: ITALSAT measurements (blue), generalized parametric model with instantaneous (magenta) and yearly average (green) T_S , ITU-R model [43], [44] with instantaneous (yellow), and yearly average (black) T_S . Right panels: binned R_E of the retrieved T_{mr} with respect to ITALSAT measurements.

The T_{mr} retrieved from the GPP model follows the ITALSAT measurements showing a decreasing trend up to a minimum (around 5 to 10 dB depending on frequency and elevation angle) and an increasing trend up to a saturation at high attenuation values. On the contrary, the T_{mr} derived from ITU-R does not grab such behavior because the model in [43], [44] is linearly dependent on the surface temperature and there is no dependence on the attenuation and elevation angle. This leads the ITU model to overestimate T_{mr} values at medium and high attenuation values. The binned root mean square error in the right panels of Fig. highlights the strength of the GPP model which exhibits a R_E lower than the one of the ITU-R model (green line generally lower than the black line). At 18.7 GHz the ITU-R model overestimates the T_{mr} values for

attenuation higher than 1.5 dB. At 39.6 GHz the ITU overestimates between 2.5 and 20 dB and underestimates above 30 dB. At 49.5 GHz the overestimation is between 4.5 and 25 dB and the error strongly decreases for attenuation values above 30 dB. For frequency approaching the 60 GHz absorption peak, the T_{mr} point distribution saturates toward its highest values (i.e. the minimum value of T_{mr}/T_S increases) thus reducing the data dispersion and the GPP model error. A similar trend is expected when the elevation angle decreases.

From the right panels of Fig. we have that the GPP model allows a reduction of the R_E up to about 30 K at 18.7 GHz (Fig.a) and 39.6 GHz (Fig.b) and about 20 K at 49.5 GHz (Fig.c) when compared to the ITU-R model. Note that, the ITU-R model in [43], [44] provides a T_{mr} model as a linear function of T_S for clear and cloudy weather and, in the absence of T_S measurements, suggests $T_{mr} = 275$ K in clear and rainy conditions. This means that the ITU-R model should be considered reliable only at very low and very high attenuation values (e.g., up to about 2-4 dB and above about 10, 20 and 25 dB at 18.7, 39.6 and 49.5 GHz, respectively).

Fig. shows that using average values of the surface temperature T_S causes a reduction in the variability of the retrieved T_{mr} . Indeed, the standard deviation of the GPP model points in Fig. (a), (c), (e) ranges between 7.6 K and 9.4 K (depending on the considered frequency) when the instantaneous T_S is adopted. This range decreases to 2.9-5.5 K when yearly average T_S is used. For ITU points, standard deviation is around 5.4–6.5 K when instantaneous T_S is considered and 0 K for yearly average T_S . ItalSat points exhibits a standard deviation between 13 K and 18.4 K. Anyway, thanks to its dependence on both attenuation and elevation angle, the GPP model (11) is able to follow the average trend of the expected T_{mr} also when average values of T_S are considered and the errors are mainly due to data dispersion (see blue dots in the left panels of Fig.). On the contrary, the errors of the ITU-R model are caused by a different trend of the actual T_{mr} with respect to the one estimated with the ITU-R model.

4.2.3 GPP error sensitivity analysis

This section presents a sensitivity analysis of the GPP T_{mr}/T_S ratio derived exploiting the radiative transfer equation that provides T_{mr} by inverting (5) and dividing for T_S , i.e.:

$$\frac{T_{mr}}{T_S} = \frac{T_B - T_C e^{-A/4.343}}{T_S(1 - e^{-A/4.343})}$$

where we have assumed a fixed frequency and elevation angle. The following analysis is important to investigate the (maximum) errors δ of the T_{mr}/T_S ratio due to variations of T_B and A . From the first-order error propagation theory, using (16) we get:

$$\delta\left(\frac{T_{mr}}{T_S}\right) = \frac{1}{T_S} \frac{(T_C - T_B)e^{-A/4.343}}{4.343(1 - e^{-A/4.343})^2} \delta A$$

$$\delta\left(\frac{T_{mr}}{T_S}\right) = \frac{1}{T_S} \frac{1}{1 - e^{-A/4.343}} \delta T_B$$

We have computed the errors in (17) and (18), with respect to A and T_B values, selecting 3 cloud classes from the SNEM dataset in order to cover different meteorological conditions [54]: i) stratus (St), low clouds with no ice content and a low rain-rate (<5 mm/h); ii) nimbostratus (Ns), medium-height cloud associated to stratiform rain events (with a rainrate typically lower than 20 mm/h); iii) cumulonimbus (Cb), vertical

structures up to 15 km associated to convective precipitation with rain-rates ranging from 10 to 100 mm/h.

TABLE 4.3

CENTROIDS OF A [dB] AND T_B [K] FOR THE SELECTED CLOUDS CLASSES, FREQUENCIES AND ELEVATION ANGLES

Freq. [GHz]	Elev.	St		Ns		Cb	
		A	T_B	A	T_B	A	T_B
18.68	90°	0.253	18.300	0.670	40.923	4.572	177.810
	45°	0.349	24.473	0.945	54.589	7.375	199.149
39.59	90°	0.545	35.212	2.062	100.927	11.308	227.500
	45°	0.742	47.430	2.780	126.585	13.043	240.165
82.5	90°	1.438	79.913	5.408	178.886	14.746	251.346
	45°	1.970	104.233	6.250	204.239	20.099	260.677

We have considered two elevation angles (90° and 45°) and three sample frequencies at 18.68, 39.59 and 82.5 GHz for the first, second and third transmission window, respectively. Table shows the centroids (i.e., A and T_B average values) at the selected frequencies and elevation angles and for the considered cloud classes (i.e., the centroids of the clouds classes). Fig. shows an example for the zenithal view at 18.68 and 39.59 GHz.

The errors in A and T_B values can be ascribed to the beam filling effects due to the different beamwidth of the beacon and the radiometer antenna. The errors in T_B values can be caused by the frequency scaling processes, as the one applied in (14) to the ITALSAT data to switch from radiometric channels to beacon frequencies. In this sense we have assumed variations ranging from -0.5 dB to 0.5 dB for δA and from -1 K to 1 K for δT_B with respect to the average values in Table .

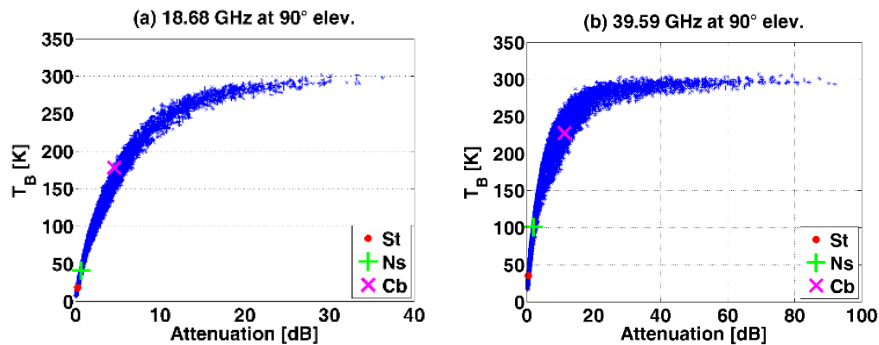


Fig. 4.5 Centroids of A and T_B from SNEM dataset for the selected clouds classes (Nb, St, Cb) at 90° elevation at 18.68 GHz (a) and 39.59 GHz (b).

Fig. shows the error sensitivity analysis, computed applying (17) and (18) under these assumptions. The largest values of $\delta(T_{mr}/T_s)$, corresponding to the errors obtained when δA and δT_B assume their maximum values in modulus, are listed in Table . Note that the errors decrease at low elevation angles and high frequencies because of the saturation effect of T_{mr}/T_s toward high values. Moreover, moving from stratiform (St) to convective (Cb) cloud classes, the errors become smaller. Indeed, stratiform clouds are characterized by low/medium attenuations corresponding to a large scatter of T_{mr}/T_s points. On the contrary, convective clouds are characterized by high attenuation values where the saturation of T_{mr}/T_s reduces the T_{mr}/T_s variations and the errors connected with δA and δT_B .

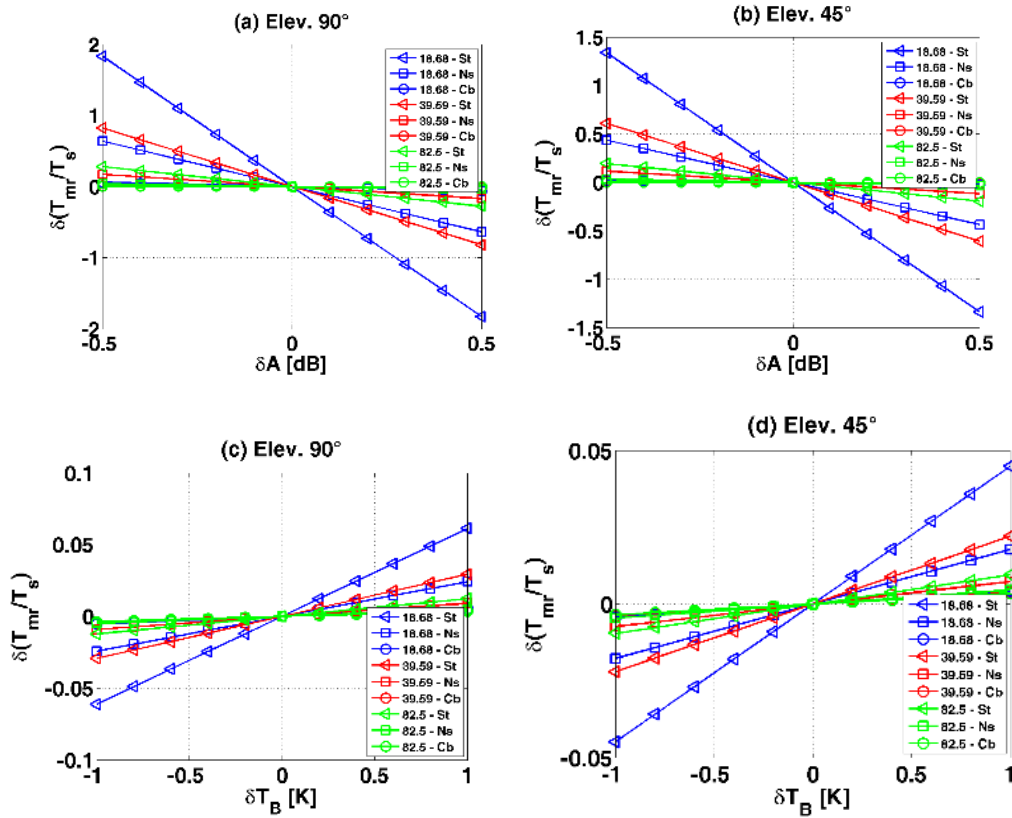


Fig. 4.6 $\delta(T_{mr}/T_s)$ errors obtained applying (21) (a-b) and (22) (c-d) at 90° (a-c) and 45° (b-d) to the centroids in Table .

Finally, we can note that the largest errors are coupled with δA variations more than with δT_B . This can be appreciated from Fig. noting that small variations of A corresponds to large variations of T_B . From 4.6b for A in the range $[0 - 5]$ dB, we have T_B values from 100 to 150 K. Thus, small δA (less than 1 dB) are enough to cause $\delta(T_{mr}/T_s)$ of the order of unity (note that T_{mr}/T_s theoretically ranges between 0 and 1), especially at small attenuation values where stratiform clouds are more probable. Moving towards high attenuation values (i.e., for convective clouds corresponding to Cb centroids in Fig.), the saturation of the T_B - A distribution in Fig. leads to $\delta(T_{mr}/T_s)$ errors more stable around small values (less than 0.06).

TABLE 4.4. $\delta(T_{mr}/T_s)$ VALUES RELATIVE TO FIG. FOR $\delta T_B = \pm 1$ K AND $\delta A = \mp 0.5$ dB

Freq. [GHz]	Elev.	St		Ns		Cb	
		δA	δT_B	δA	δT_B	δA	δT_B
18.68	90°	± 1.830	± 0.306	± 0.639	± 0.121	± 0.057	± 0.027
	45°	± 1.341	± 0.224	± 0.435	± 0.089	± 0.021	± 0.021
39.59	90°	± 0.822	± 0.147	± 0.170	± 0.046	± 0.008	± 0.019
	45°	± 0.609	± 0.110	± 0.116	± 0.037	± 0.005	± 0.018
82.5	90°	± 0.278	± 0.061	± 0.040	± 0.024	± 0.004	± 0.018
	45°	± 0.193	± 0.047	± 0.033	± 0.023	± 0.001	± 0.017

5 Conclusions

In this work we have introduced the main challenges in millimeter-wave satellite radiopropagation as well as characterized the atmospheric optical thickness and brightness temperature at centimeter and millimeter waves using both data derived by direct measurements and data simulated by 1D and 3D radiative transfer models being the latter driven by numerical weather predictions. After validating the numerical weather prediction model through comparisons with weather radar data and radiosounding observations, we have compared the 1D and 3D radiative transfer models with two different ground-based radiometric measurements: a Sun-tracking and a profiler microwave radiometer. The novelty of the Sun-tracking radiometer is that such instrument allows the simultaneous estimation of both atmospheric optical thickness and brightness temperature in all weather conditions and at continuously varying elevation angles. The comparisons between simulations and measurements provide satisfactory results that assess the reliability of the 3D-RTM model with some biases, in terms of T_B , that should be investigated. In particular, 3D-RTM turns out to be able to well replicate the $T_B - A$ correlations at all the frequencies. Moreover, statistics of atmospheric optical thickness obtained from 3D-RTM simulations are in excellent agreement with the one derived from ST-MWR. Errors between the two datasets become larger for increasing values of A , where saturation effects related to the ST-MWR operation mode occur. Such good results may pave the way to a successful use of weather forecast models combined with physically based radiative transfer models. On the other hand, although the simpler 1D-RTM satisfactorily reproduces the T_B correlations among the different frequency-channels, it fails in reproducing statistics of the atmospheric optical thickness. This is probably due to a missing tuning of the 1D-RTM to select the clouds classes that better fits with the climatological trend of the geographical area of Rome, NY, for the considered period. The performed comparisons also highlight some possible calibration biases in the Sun-tracking radiometer that must be fixed. Finally, measurements from the Sun-tracking radiometer allows a statistical characterization of the radiometeorological variables in function of the elevation angle. In this sense, we have developed a preliminary model to retrieve the probability of atmospheric optical thickness, conditioned to a given elevation angle, in continental climate areas. Future works will be devoted to identifying and fix biases and calibration errors emerged from the comparison between radiative transfer models and radiometric measurements, to refine the statistical model derived for the atmospheric optical thickness and to extend it also to the brightness temperature.

We have verified the GPP model through the comparison with 4 years of measurements available at 18.7, 39.6 and 49.5 GHz from the ITALSAT campaign in Spino d'Adda. By considering ITALSAT data, we have obtained a root mean square error (R_E) ranging from 0.045 to 0.068. We have also accomplished a comparison with the ITU-R model showing that the proposed GPP model can provide a lower R_E up to about 20 K and 30 K depending on the considered frequency. Finally, a sensitivity analysis of the potential errors, induced on the mean radiative temperature by errors of atmospheric attenuation and brightness temperature, has been considered.

As future works we aim at performing additional verifications of the GPP model in sites different from the considered training locations (to assess the site-independency of the model) and at frequencies in the third transmission window (where, currently, very few models and measurements are available). An extension of the clear-air component of the GPP model would be to introduce a weighted dependence not only on surface temperature T_s , but also on relative humidity as, for example, in [19]. This would complicate the GPP parametric modeling, but would also improve T_{mr} estimation in clear air as well established in literature.

APPENDIX. Note on Sun-tracking radiometric data processing

The design of the radiometric algorithms is related to the rationale of a field campaign for high-frequency radiopropagation channel development and assessment, based on a Sun-tracking microwave radiometer. Its basic ingredient is the exploitation of “Sun-tracking” (ST) and “cosmic-background” (CB) radiometric measurements to derive both sky-noise and atmospheric path attenuation.

A.1 Microwave radiometric observation modes

In the “**Sun-tracking**” (ST) mode, the instrument points and tracks the Sun measuring the spectrally-broad noise emission at the frequencies of interest by pointing alternatively toward-the-Sun (twS) and off-of-the-Sun (ooS) and recording the difference between the two power signals. Using this sky-noise difference and estimating the Sun emission, which is a complex task for a given frequency and antenna, the total atmospheric attenuation can be derived. In presence of precipitation along the path, the conventional excess (liquid, melted and ice water) path attenuation can be estimated as the difference between the attenuation during the event and at the start of the event. The main limitation is that the ST method is applicable to a fraction of the day cycle (night time is not useful) and a subset of possible elevation angles and meteorological conditions (due to the Sun ecliptic).

In the “**cosmic-background**” (CB) mode, the instrument points towards the sky avoiding radio emitters. The path total attenuation at the frequency of the radiometric channel is derived after inversion of the radiative transfer equation, using as a reference the cosmic background noise temperature (~ 2.7 K) and an estimation of the atmospheric mean radiating temperature. Path excess attenuation can be again estimated as the difference between the attenuation during the event and at the start of the event. The application of CB-mode radiometric inversion algorithms on the state of the atmosphere with respect to the conditions for radiowave propagation can be carried out in 2 scenarios:

- i) in **clear and cloudy conditions**, or more precisely in absence of atmospheric particle scattering (i.e. typically clear and cloudy sky at millimeter waves), the atmospheric mean radiating temperature can be estimated with relatively good accuracy using simulated scenarios with local surface data; therefore, atmospheric attenuation at measurement frequencies can be retrieved fairly precisely. Total attenuation at operational frequencies different from those received by the radiometer, can be estimated with good accuracy in the absence of precipitation, by using frequency-scaling algorithms based on regression analyses of simulated scenarios.
- ii) in **presence of precipitation**, the effect of particle scattering and reflections at the boundaries of the atmospheric media becomes important; the atmospheric mean radiating temperature is strongly affected by geometric and physical conditions making its estimation more complex and less accurate than in clear/cloudy conditions. Nevertheless, accurate modelling and simulation of the propagation conditions including scattering effects allow the retrieval of atmospheric attenuation at the radiometric frequencies with a fair accuracy.

Based on previous considerations, it is appealing the combination of “Sun-tracking” (ST) and “cosmic-background” (CB) modes in a radiometric campaign for radiopropagation channel characterization to perform the following steps:

1. Clear air and cloudy scenarios

- a. measure accurately the sky noise temperature at radiometric frequencies for calibration checks;
- b. estimate accurately the total atmospheric attenuation at radiometric frequencies and extend to operational frequencies through frequency scaling;

2. Precipitation scenarios

- a. In the ST mode use concurrent twS (towards-the-Sun) and ooS (off-of-the-Sun) radiometric measurements to calibrate and validate the algorithms for the estimation of total attenuation obtained in presence of precipitation, derived from CB radiometric multifrequency measurements, using an estimate of the atmospheric mean radiating temperature including hydrometeor scattering effects;
 - b. Use the validated algorithm of point 2.a to collect long-term (24/7) data of radiometric atmospheric attenuation in presence of precipitation exploiting the whole dataset (i.e., night measurements in CB mode and toward/off-the-Sun observations during the ST mode);
 - c. Estimate the excess attenuation during precipitation events, using data from point 2.b, and derive the corresponding distribution;
3. **Combine data** from point 1 and point 2 to generate a distribution of total atmospheric attenuation describing all the weather conditions of the location (i.e. clear-air, cloudy and rainy);
 4. **Test and improve** propagation prediction models for the measured frequencies using the cumulative distributions from point 3;
 5. **Estimate the error** of new propagation prediction models for the (not-measured) operational frequencies by analysis of the error of measured channels in the same band.

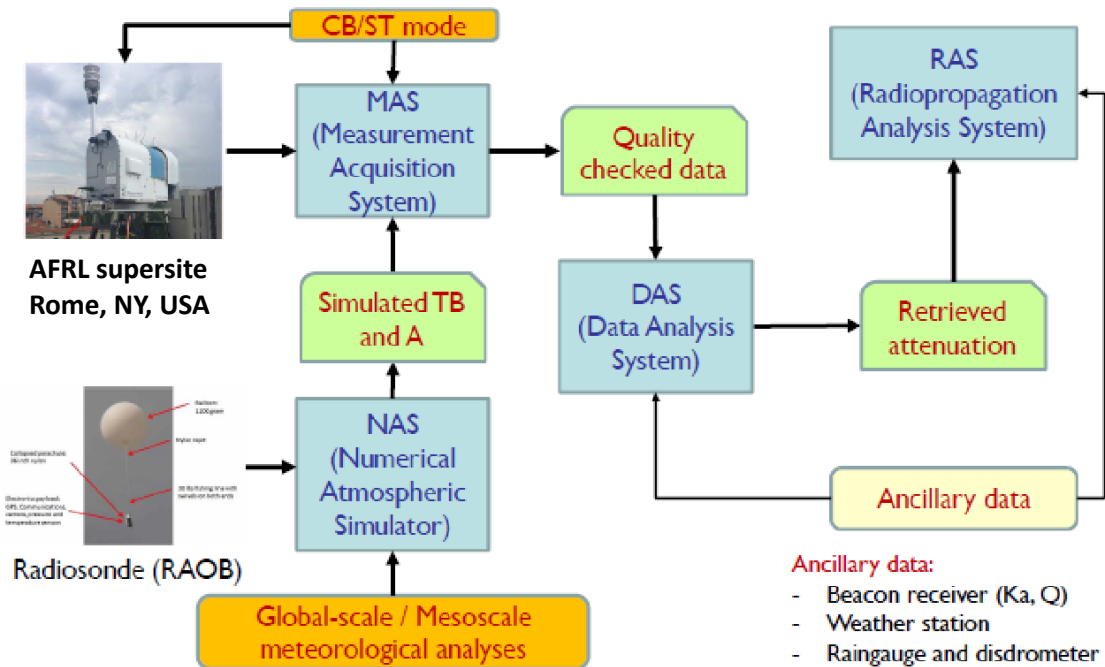


Fig. 1. System and data flow block diagram of ST-MWR campaign

The processing above will be supported by data acquired from a number of ancillary equipment. Among these, we highlight the availability of satellite beacon receivers, a terrestrial W band radio link, GPS receivers, rain gauges, ceilometer, surface meteorological sensors, and operational radiosondes at either or both the two experimental sites (Milano and Potenza). The ancillary data will be used to characterize the atmospheric physical and radiopropagation conditions during the field experiment. The general **data processing chain** is designed as follows (see Fig. 1).

A.2 Sun-tracking (ST) observation-mode theory and application

The ST-mode radiometric algorithmic steps are reviewed following [Marzano et al., 2015]. The CB-mode radiometric algorithms are well established and briefly summarized below.

Considering ground-based observations, the measured antenna noise temperature T_A along the radiometer antenna pointing angle (θ_0, φ_0) is the convolution between the received sky brightness temperature and the normalized antenna power radiation pattern $F_n(\theta_0, \varphi_0, \theta, \varphi)$ [Marzano et al., 2015]:

$$T_A(\theta_0, \varphi_0) = \frac{\int_{4\pi} T_B(\theta, \varphi) F_n(\theta_0, \varphi_0, \theta, \varphi) d\Omega}{\int_{4\pi} F_n(\theta_0, \varphi_0, \theta, \varphi) d\Omega} \quad (1)$$

with

$$\int_{4\pi} F_n(\theta_0, \varphi_0, \theta, \varphi) d\Omega = \Omega_{Pant} \quad (2)$$

where Ω_{Pant} is the antenna radiation-pattern solid angle. All the involved parameters are also dependent on frequency, which is neglected in the formulations in favor of geometric considerations.

When **pointing out-of-the-Sun (ooS)**, the sky brightness temperature T_{BooS} , impinging upon the antenna along the zenith angle ϑ and azimuth ϕ , can be written as

$$T_{BooS}(\theta, \varphi) = T_{mr}(\theta, \varphi)[1 - e^{-\tau(\theta, \varphi)}] + T_{cos}e^{-\tau(\theta, \varphi)} \quad (3)$$

where T_{mr} is the sky mean radiative temperature (that can be defined in all-weather conditions), τ is the atmospheric optical thickness (in Neper) and T_{cos} is the brightness temperature of the cosmic background (equal to about 2.73 K).

When **pointing at the Sun, the toward-the-sun (twS)** sky brightness temperature T_{BtwS} is given by the sum of two components, the Sun brightness temperature T_{BSun} , attenuated by the atmosphere, and the brightness temperature of the sky

$$T_{BtwS}(\theta, \varphi) = T_{BSun}e^{-\tau(\theta, \varphi)} + T_{mr}(\theta, \varphi)[1 - e^{-\tau(\theta, \varphi)}] + T_{cos}e^{-\tau(\theta, \varphi)} \quad (4)$$

According to (1), the computation of the antenna noise temperature T_{AtwS} , measured observing the Sun, implies that the T_{BtwS} is observed by the antenna within the solid angle Ω_{sun} subtended by the Sun. Therefore, it holds:

$$\begin{aligned} T_{AtwS}(\theta_0, \varphi_0) = & \frac{1}{\Omega_{Pant}} \int_{\Omega_{sun}} [T_{BSun}e^{-\tau(\theta, \varphi)} + T_{mr}(\theta, \varphi)(1 - e^{-\tau(\theta, \varphi)}) + \\ & T_{cos}e^{-\tau(\theta, \varphi)}] F_n(\theta_0, \varphi_0, \theta, \varphi) d\Omega + \frac{1}{\Omega_{Pant}} \int_{4\pi - \Omega_{sun}} (T_{mr}(\theta, \varphi)[1 - e^{-\tau(\theta, \varphi)}] + \\ & T_{cos}e^{-\tau(\theta, \varphi)}) F_n(\theta_0, \varphi_0, \theta, \varphi) d\Omega \end{aligned} \quad (5)$$

which can be rewritten as

$$T_{AtwS}(\theta_0, \varphi_0) = \frac{1}{\Omega_{Pant}} \int_{\Omega_{sun}} T_{BSun}e^{-\tau(\theta, \varphi)} F_n(\theta_0, \varphi_0, \theta, \varphi) d\Omega + \frac{1}{\Omega_{Pant}} \int_{4\pi} (T_{mr}(\theta, \varphi)[1 - e^{-\tau(\theta, \varphi)}] + T_{cos}e^{-\tau(\theta, \varphi)}) F_n(\theta_0, \varphi_0, \theta, \varphi) d\Omega \quad (6)$$

It is useful to introduce the beam-filling factor f_Ω as the ratio between the Sun radiation-pattern solid angle $\Omega_{P_{sun}}$ and the antenna beamwidth radiation-pattern solid angle $\Omega_{P_{ant}}$:

$$f_\Omega = \frac{\int_{\Omega_{sun}} F_n(\theta_0, \varphi_0, \theta, \varphi) d\Omega}{\Omega_{P_{ant}}} = \frac{\Omega_{P_{sun}}}{\Omega_{P_{ant}}} \quad (7)$$

If it is assumed that the Sun has a uniform brightness temperature within the beam (e.g., Ω_{sun} is much smaller than the antenna main beam half-power solid angle), then, using (7), we can approximate (6) as

$$T_{A_{twS}}(\theta_0, \varphi_0) \cong f_\Omega T_{B_{sun}} e^{-\tau(\theta_0, \varphi_0)} + T_{mr}(\theta_0, \varphi_0) [1 - e^{-\tau(\theta_0, \varphi_0)}] + T_{cos} e^{-\tau(\theta_0, \varphi_0)} \quad (8)$$

In ground-based radiometry, it is also commonly assumed that the atmospheric contribution is constant within the main beam and $T_{A_{ooS}}$ is approximated by the $T_{B_{ooS}}$ at (θ_0, φ_0) . Analogously, for the *ooS* mode, we can simplify

$$\begin{aligned} T_{A_{ooS}}(\theta_0, \varphi_1) &= \frac{1}{\Omega_{P_{ant}}} \int_{4\pi} (T_{mr}(\theta, \varphi) [1 - e^{-\tau(\theta, \varphi)}] + T_{cos} e^{-\tau(\theta, \varphi)}) F_n(\theta_0, \varphi_1, \theta, \varphi) d\Omega \cong \\ &\cong T_{mr}(\theta_0, \varphi_1) [1 - e^{-\tau(\theta_0, \varphi_1)}] + T_{cos} e^{-\tau(\theta_0, \varphi_1)} \end{aligned} \quad (9)$$

In the ST technique, the radiometer antenna is pointing alternatively on and off the Sun, and between these two measurements, the elevation angle θ_0 is kept constant, while the azimuth angle is switched from φ_0 (*twS*) to φ_1 (*ooS*). Then, after a few observations, the elevation angle is varied, in accordance with the Sun movement along its diurnal ecliptic.

The **ST antenna noise temperature difference** for each pointing angle can then be expressed by:

$$\Delta T_A(\theta_0, \varphi_0, \varphi_1) = T_{A_{twS}}(\theta_0, \varphi_0) - T_{A_{ooS}}(\theta_0, \varphi_1) \quad (10)$$

If the switching between *ooS* and *twS* observation modes is fast enough and the azimuth distance is chosen so that the Sun is just outside the field of view of the instrument, it can be assumed that the mean radiative temperature and optical thickness do not change between the two observation modes (i.e. $T_{mr}(\theta_0, \varphi_0) \cong T_{mr}(\theta_0, \varphi_1)$ and $\tau(\theta_0, \varphi_0) \cong \tau(\theta_0, \varphi_1)$). Substituting (8) and (9) into (10) we obtain:

$$\Delta T_A(\theta_0, \varphi_0) \cong f_\Omega(\theta_0, \varphi_0) T_{B_{sun}} e^{-\tau(\theta_0, \varphi_0)} \quad (11)$$

where the beam-filling factor f_Ω depends on the pointing angle. Previous equation gives the basis for estimating $T_{B_{sun}}$ and the atmosphere path attenuation, as described in Appendix A.1.

Starting from (11), provided that estimates of $T_{B_{sun}}^*$ are available for instance from ST measurements obtained during clear sky, the **ST-mode path attenuation** A_{ST} (in dB) in all weather conditions and in for an azimuthally isotropic atmosphere can be retrieved from the ΔT_A differences between *ooS* and *twS* measurements, according to

$$A_{ST}(\theta_0) \cong A_{ST}(\theta_0, \varphi_0) = 4.343 \tau(\theta_0, \varphi_0) = 4.343 \ln \ln \left[\frac{T_{BSun}^*(\theta_0, \varphi_0)}{\Delta T_A(\theta_0, \varphi_0)} \right] \quad (12)$$

In the presence of clouds or precipitation, as the atmospheric extinction significantly increases, the Sun signal is also increasingly attenuated, and therefore the antenna noise temperature difference between the two measurement modes *ooS* and *twS* decreases. For heavy precipitation, the contribution of the Sun is completely masked by the rain attenuation and the ΔT_A differences are only dependent on the radiometer noise and the atmosphere variability, providing an upper limit to the application of the technique for the retrieval of rain attenuation.

The **calibration of the ST-mode** through (12) is extensively discussed in the Appendix A. In order to estimate atmospheric path attenuation A , the weighted Sun brightness temperature T_{BSun}^* must be estimated. Two approaches can be foreseen: i) the Langley elevation-based self-consistent method; ii) the Tmr-based meteorologically-oriented method. Both methods assume the availability of radiometric measurements in clear air conditions where a plane-parallel horizontally stratified and azimuthally homogeneous troposphere can be assumed. In these homogeneous conditions we can hypothesize that T_{BSun}^* estimates are minimally affected by the atmospheric variability. This means that the “*secant law*” can be applied to describe the zenith angle dependence of antenna noise temperatures. A theoretical error budget is also presented in Appendix A.

Summarizing, the **following algorithmic steps** are foreseen for the processing of ST radiometric data:

1. Clear-air data discrimination
For selecting clear-sky days in order to estimate beam-affected Sun brightness temperature (T_{BSun}^*) with both Langley and Meteorological techniques, it can be implemented an atmospheric index, a scalar quantity named Status Sky Indicator (SSI).
2. Filtering toward-the-Sun observations in clear air in the estimation of beam-affected Sun brightness temperature (T_{BSun}^*) [Marzano et al., 2016]. In order to estimate the beam-affected Sun brightness temperature (T_{BSun}^*), the data processing is designed to select the maximum of toward-the-Sun sky noise temperature for each elevation angle.
3. Antenna noise temperature self-consistency check
For estimating path attenuation, the ST-MWR approach needs valid antenna noise temperature difference ΔT_A between toward-the-Sun (*twS*) and off-the-Sun (*ooS*) modes to work properly. Ad hoc thresholds are specified: the latter have been set to 0.5 K at 23-31 GHz and 1 K at 72-82 GHz in agreement with the MWR manufacturer specifications.
4. Impact of Radiometer Antenna Side Lobes
The approximation of an antenna Gaussian beam can be used for computing beam filling factor f_Ω to estimate Sun brightness temperature for internal checking (in principle, not needed for radiopropagation product generation).
5. Estimation of atmospheric path excess attenuation
Once that estimates of T_{BSun}^* are available, i.e. from ST measurements obtained during clear sky, the atmospheric excess path attenuation from ST-MWR (in dB) in all weather conditions can be retrieved from the ΔT_A differences between *ooS* and *twS* measurements, according to formula (12) above, corresponding to (22) in [Mattioli et al., 2017].

A.3 Cosmic-background (CB) observation-mode theory and application

The **CB mode is coincident with out-of-the-Sun (*ooS*) ST-mode**, indeed. As mentioned, when pointing

out-of-the-Sun (*ooS*), the sky brightness temperature T_{BooS} , impinging upon the antenna along the zenith angle ϑ and azimuth ϕ , can be written as

$$T_{BCB}(\theta, \varphi) = T_{BooS}(\theta, \varphi) = T_{mr}(\theta, \varphi)[1 - e^{-\tau(\theta, \varphi)}] + T_{cos}e^{-\tau(\theta, \varphi)} \quad (13)$$

Assuming that the atmospheric contribution is constant within the main beam, we can simply express the approximate antenna noise temperature as

$$\begin{aligned} T_{ACB}(\theta, \varphi) &= \frac{1}{\Omega_{Pant}} \int_{4\pi} (T_{mr}(\theta, \varphi)[1 - e^{-\tau(\theta, \varphi)}] + T_{cos}e^{-\tau(\theta, \varphi)}) F_n(\theta, \varphi, \theta, \varphi) d\Omega \cong \\ &\cong T_{mr}(\theta, \varphi)[1 - e^{-\tau(\theta, \varphi)}] + T_{cos}e^{-\tau(\theta, \varphi)} \end{aligned} \quad (14)$$

Thus, path attenuation in the CB mode in an azimuthally-isotropic atmosphere can be expressed as:

$$\hat{A}_{CB}(\theta) \cong \hat{A}_{CB}(\theta, \varphi) = 4.343 \tau(\theta, \varphi) = 4.343 \ln \left[\frac{\hat{T}_{mr}(\theta, \varphi) - T_{cos}}{\hat{T}_{mr}(\theta, \varphi) - T_{ACB}(\theta, \varphi)} \right] \quad (15)$$

In **clear and cloudy conditions**, radiosonde observation (RAOB) datasets can be used to generate corresponding mean radiating temperatures T_{mr} at the same frequencies and angles. Note that RAOB data need to be modified in order to include cloud water where relative humidity is higher than 90%-95% [Mattioli et al., 2013]. Monthly or yearly regression coefficients for each frequency and angle were computed to relate T_{mr} values to the surface temperature T_s , pressure p_s and relative humidity RH_s provided by the RAOB:

$$T_{mr}(\theta) \cong T_{mr}(\theta, \varphi) = a_0(\theta) + a_1(\theta)T_s + a_2(\theta)p_s + a_3(\theta)RH_s \quad (16)$$

where the regression coefficients a_i are dependent on the elevation angle θ_0 . The regression coefficients have been fitted with respect to air mass m to provide the final coefficients a_i . Those coefficients are applied to the concurrent surface measurements from the meteorological sensors that are part of the radiometer equipment.

In **precipitation conditions**, a model-based general approach can be adapted for the specific site using available radiosonde dataset and performing Sky-Noise Eddington Simulation (SNEM) simulations at 23.8, 31.4, 72.5 and 82.5 GHz and for 8 elevation angles between 20° and 90° in terms of both brightness temperature and atmospheric extinction. This procedure is described in [Mattioli et al., 2017]. The multifrequency *PolDEx* model, discussed in [Marzano et al., 2015], is based on a polynomial regression on SNEM dataset, reinforced with a double exponential single-frequency term, able to achieve better results in heavier rainy cases. The SSI index is used to discriminate precipitation conditions (see Appendix A). This multi-frequency weighted approach polynomial is able to balance the use of two different models depending on the weather conditions. The *PolDEx* **atmospheric path attenuation** estimates are given for an azimuthally isotropic atmosphere by:

$$\hat{A}_{CB}(\theta_0) \cong A_{CB}(\theta_0, \varphi_0) = m(\theta_0)\{(1 - SSI + h)A_{Pol}(\theta_0) + (SSI - h)A_{DEx}(\theta_0)\} \quad (17)$$

where

$$A_{Pol}(\theta_0; f_i) = \sum_{i=1}^4 a_i T_{ACB}(f_i) + b_i T_{ACB}^2(f_i) \quad (18)$$

$$A_{DEx}(\theta_0; f) = [c_1 e^{c_2 T_{ACB}(f)} + d_1 e^{d_2 T_{ACB}(f)}] \quad (19)$$

where $f_{i=1,2,3,4}=23.8,31.4,72.5,82.5$ GHz and f is one of 4 available frequencies f_i , whereas the coefficients are all function of the air mass m . Regression coefficients are provided in [Marzano et al., 2015].

A.4 Path-attenuation retrieval error sources

In this section an error budget evaluation is provided to describe the expected errors when estimating the path attenuation using CB-MWR and ST-MWR mode measurements.

Errors can be distinguished into systematic (bias) and random (uncertain) ones. We may assume that systematic errors can be removed by adopting a suitable calibration technique, such as the tipping-elevation curve and the hot/cold load approach.

The latter may be due either to the instrumental characteristics or to the processing algorithms. For the ST mode we can use the algorithm in (12). For the CB mode we can use 2 different algorithms for estimating path attenuation: i) retrieval algorithm in (15)-(16) in clear and cloudy air; ii) the retrieval algorithm in (17)-(19) in rain conditions.

Sun-tracking microwave radiometric measurements and the slant path attenuation, based on ST-MWR data, can be affected by several error sources. An example of an operational ground-based ST-MWR is the one at disposal of Air Force Research Laboratory (AFRL) MWR. The AFRL-MWR has four channels with receivers at 23.8, 31.4, 72.5 and 82.5 GHz and is a modified version of the RPG LPW-U72-82 water-vapor and cloud-liquid microwave radiometer series in order to allow an automatic Sun-switching operation mode [Marzano et al., 2016]. The antenna is shaped to reduce sidelobes (-30 dB at K-band and -40 dB at V,W-band); and the antenna radiation pattern is considered approximately Gaussian with a half-power beamwidth decreasing with the frequency and equal to 3.74°, 2.97°, 1.47°, and 1.30°, respectively. Measurements have been collected at elevation angle between 20° and 70°, with a scan step of 0.1° in both elevation and azimuth, during clear sky days and during raining events.

The following **Table I** lists the possible instrumental and algorithmic error sources. In both cases we provide an estimate and a reference, if available.

Table I. Potential error sources of Sun-tracking MWR measurements and path attenuation estimation.

Sun-tracking MWR error source	Estimated value and reference	Intermediate variable affected
Radiometric accuracy absolute or RMS value (@ given integration time) for each channel <i>Note: channel central frequency may vary as a function MWR type</i>	For AFRL ST-MWR (absolute accuracy of the difference): - 0.7 K at K and Ka band - 1.4 K at V W band <i>Ref.: [Mattioli et al., 2017]</i>	$\delta \Delta T_A$
Radiometric accuracy absolute or RMS value (@ given integration time) for each channel	<i>Note: see above.</i>	$\Delta T_{A \min}$
Sun pointing error: elevation pointing accuracy (radiometer)	From AFRL ST-MWR: - 0.01° (10% of step motor)	$\delta \Delta T_A$



● azimuth pointing accuracy (radiometer) ● Sun tracking accuracy (angular data, RPG software) <i>Note: The Sun shall always fill the same portion of the antenna main beam.</i>	angle 0.1° - 0.01° (10% of step motor angle 0.1°) - Unknown	
Atmospheric homogeneity in azimuth (approximation) ● operational constraint ● the difference in azimuth between the two observations shall be the smallest possible, taking into account that the out-of-Sun observation should be far enough not to have the Sun into the antenna beamwidth ● it can be improved by doing two out-of-Sun observations: ○ fixing an elevation angle, we therefore perform three measurements (ooS – twS – ooS). The two ooS measurements refer to two different deltas in azimuth (one positive and one negative wrt the Sun azimuth) ○ the three measurements shall be performed within a limited amount of time (the faster, the better). This mainly depends on the radiometer (azimuth motors and software) as 1-second integration time is enough in terms of radiometric resolution. If the two ooS TBs are close enough, they are averaged. If their difference is larger than a given threshold, the measurements are discarded (or flagged.)	- to be verified - to be verified - - to be verified; new version of the AFRL-MWR RPG can allow this operational mode.	
Error sources depend on the adopted technique to estimate the T_{Bsun}^*: ● Langley technique ○ Same observations as before affecting $\delta\Delta T_A$ (only in clear air conditions) ○ Variations of the zenithal optical thickness τ_{zclr} during the day, estimated by linear regression fit – basic assumption of the technique is to estimate a zenithal optical thickness value, which characterizes the whole clear-air day. ○ Elevation angle readings as provided by the instrument [minor] ● Meteorological technique ○ Same observations as before affecting $\delta\Delta T_A$ (only in clear air conditions) ○ Estimation of the mean radiating temperature T_{mrclr} through surface meteorological measurements ○ Estimation of the zenithal optical thickness τ_{zclr} time series making use of the “classic” formulation (mean radiating temperature + ooS measurement)		$\hat{T}_{Bsun}^*$ <i>Note: if the same radiometer is used to estimate both Sun’s brightness temperature and atmospheric path attenuation, the filling factor does not play a role as the $\hat{T}_{Bsun}^*$ value is used in the computation.</i>

Elevation angle readings as provided by the instrument [minor]		
The computation of the filling factor f_Ω suffers from several error sources Antenna radiation pattern shall be known <i>Note: the antenna pattern is typically unknown.</i>	For AFRL ST-MWR: - Half-power beamwidth: 3.74°, 2.97°, 1.47°, and 1.30° at 23.8, 31.4, 72.5, and 82.5 GHz - Main beam efficiency η_{ML} of 0.969 at Ka band and 0.979 at V and W band Ref.: [Mattioli et al., 2017]	f_Ω needed to compute $\hat{T}_{Bsun}$
- Estimation of the solid angle Ω_{sun}, subtended by the Sun as seen by the radiometer antenna: - variations in Θ_{sun} (Sun's angular radius) as seen by the radiometer antenna - approximation to compute Ω_{sun}	For AFRL ST-MWR: - Assumed uniform disk Θ_{sun} of 0.533° arch (fixed) $\Omega_{sun} \cong \frac{\pi}{4} \Theta^2_{sun}$ Ref.: [Mattioli et al., 2017]	

The Appendix A.2 is devoted to the discussion of the theoretical error analysis of path attenuation estimates with respect to several error sources. By using results from the Rome (NY) campaign in 2015 (six months of data), obtained from the AFRL-MWR measurements [Marzano et al., 2015], we can evaluate in a more quantitative way the overall error budget using typical values of the free parameters. The error budget is shown in **Table II** which summarizes the expected errors in A and at 23.8, 31.4, 72.5 and 82.5 GHz with respect to the uncertainty of the main sources within ST-MWR data processing, that is the $\delta\Delta T_A$ and δT_{Bsun}^* .

Table II. Error evaluation for path-attenuation estimates from ST-MWR data with respect to typical errors in $\delta\Delta T_A$ and δT_{Bsun}^* .

δA with respect to $\delta\Delta T_A$			δA with respect to δT_{Bsun}^*		
f [GHz]	$\delta\Delta T_A$ [K]	δA [dB]	f [GHz]	δT_{Bsun}^* [K]	δA [dB]
23.8	4	-0.20	23.8	0.83	0.030
31.4	5	-0.13	31.4	0.62	0.015
72.5	12	-0.13	72.5	1.49	0.011
82.5	19	-0.14	82.5	14.3	0.085

Sensitivity δA with respect to $\delta\Delta T_A$ is given in Appendix A. The left side of Table I reports the attenuation uncertainties for typical $\delta\Delta T_A$ in clear air. The latter are derived from the variability of AFRL-MWR data during the *ooS* and *twS* switching. In this case δA are less than 0.2 dB at all frequencies, slightly higher at Ka band. On the right side of Table I, a the sensitivity analysis of δA is shown with respect to uncertainties δT_{Bsun}^* (the latter has been derived from the differences between Langley-based and meteorologically-based estimates). Errors in path attenuation retrievals are less than 0.1 dB at all frequencies. Finally, we have estimated the error in assuming the horizontal homogeneity in clear sky through the analysis of the *ooS* time series at the same elevation and different azimuths. Attenuation uncertainties are estimated to be 0.017, 0.007, 0.023, and 0.027 dB for an average azimuth distance of 5°. As such, the horizontal homogeneity assumption holds.

The ST-MW radiometry technique is able to estimate a valid atmospheric extinction, according to (12),

only if consistent antenna noise temperature differences are available. During intense rain events ΔT_A differences can reach zero or even negative, which limits the application of this technique. The maximum atmospheric extinction value A_{STmax} depends on both considered frequency and standard deviation $std(\Delta T_A)$ and it can be computed from (12). By considering a measurement deviation equal to the MW radiometric brightness temperature absolute accuracy (equal to 0.5 K at K-band and 1 K at W-band), we can evaluate the standard deviation (std) of the noise temperature difference from (10) according to:

$$std(\Delta T_A) = \sqrt{var(T_{AooS}) + var(T_{Atws})} \quad (20)$$

where “var” stands for the noise variance equal to the square of the absolute accuracy. By properly substituting $std(\Delta T_A)$ values (0.7 at K and Ka band and 1.4 at V and W band) in (12), the maximum atmospheric extinction values A_{STmax} are about 22 dB, 24 dB, 26 dB and 27 dB, at 23.8, 31.4, 72.5 and 82.5 GHz, respectively. **Table III** summarizes these results.

Table III. Assuming values $std(\Delta T_A)$ of 0.7 at K and Ka band and 1.4 at V and W band, the maximum atmospheric extinction values for each frequency band.

f [GHz]	A_{STmax} [dB]
23.8	22
31.4	24
72.5	26
82.5	27

The percentages of ΔT_A values lower than its standard deviation result less than 0.1% at K and Ka band and 0.6% at V and W band, taking into account the entire available dataset.

In Marzano et al. (2015) the available dataset consists of measurements collected by the ground-based Air Force Research Laboratory (AFRL) MWR during May 2015 (20 days) and June 2015 (26 days) in Rome, NY, USA (43.2°N, 75.4° W). The AFRL-MWR has four channels with receivers at 23.8, 31.4, 72.5 and 82.5 GHz and is a modified version of the RPG LPW-U72-82 water-vapor and cloud-liquid microwave radiometer series in order to allow an automatic Sun-switching operation mode. Using this dataset, the PolDex estimation algorithm errors in (17) can be evaluated by comparing its estimates with ST-derived path attenuation. **Table III** quantifies the comparison in terms of root mean square error (RMSE) and average error (AvE), where the error is defined as the difference between prediction model under consideration and ST-MWR measurements.

Table III. Estimated zenith-equivalent attenuation error considering the ST-MWR available measurement dataset in 2015 (six months) in Rome, NY for PolDex models. Results for all-weather and cloudy/rainy cases are shown.

	All-weather	All-weather	Cloudy/rainy	Cloudy/rainy
f [GHz]	AvE[dB]	RMSE[dB]	AvE[dB]	RMSE[dB]
23.8	0.0069	0.1721	0.0093	0.2014
31.4	-0.0500	0.2441	-0.0315	0.2820
72.5	0.0593	0.7061	0.0933	0.8421
82.5	0.0513	0.6242	0.0893	0.7425

A.5 Sun-tracking calibration and error budget

The track of the Sun along the ecliptic is based on input data (latitude, longitude, time) and it is performed in a Sun-switching operation mode, keeping the elevation angle θ_0 constant, and varying the azimuth angle from φ_0 (*twS*) to φ_1 (*ooS*) according to (10). The integration time of each measurement is set to 1 second and the azimuth positioner switches every 6 seconds in order to perform the integration with fixed antenna position. The processing and quality-control procedures applied to the radiometer data are described in the following.

As mentioned, in order to estimate atmospheric path attenuation A , the weighted Sun brightness temperature T_{Bsun}^* must be estimated. Two approaches can be foreseen: i) the Langley elevation-based self-consistent method; ii) the Tmr-based meteorologically-oriented method. Both methods assume the availability of radiometric measurements in clear air conditions where a plane-parallel horizontally stratified and azimuthally homogeneous troposphere can be assumed. In these homogeneous conditions we can hypothesize that T_{Bsun}^* estimates are minimally affected by the atmospheric variability. This means that the “secant law” can be applied to describe the zenith angle dependence of antenna noise temperatures.

1) Langley and meteorological ST-calibration technique

(i) The **Langley technique** starts from (11) which can be rewritten in clear air as:

$$\ln[\Delta T_A(\theta_0)] = \ln[f_\Omega T_{Bsun}] - \tau_{clr}(\theta_0) = \ln[T_{Bsun}^*] - \tau_{zclr}(\theta_0) \sec(\theta_0) \quad (A.1)$$

where, due to the previous assumptions, the azimuth dependence has been removed, and the following relation holds between the clear-air slant τ_{clr} and zenith τ_{zclr} optical thickness

$$\tau_{clr}(\theta_0) = \tau_{zclr}(\theta_0) \sec(\theta_0) = \tau_{zclr}(\theta_0, \varphi_0) m(\theta_0) \quad (A.2)$$

In (A.2) $m(\theta_0)$ stands for atmospheric air mass and is equal to $\sec(\theta_0)$. By plotting $\ln[\Delta T_A(\theta_0)]$ against air mass $m(\theta_0)$ for available Sun-tracking measurements in clear air and approximating the measurements through a linear best-fitting curve:

$$\ln[\Delta T_A(\theta_0)] = a + b m(\theta_0) \quad (A.3)$$

we can estimate T_{Bsun}^* , from the intercept of the previous line:

$$\{\hat{T}_{Bsun}^*(\theta_0) = \exp \exp(a) \quad \hat{\tau}_{zclr}(\theta_0) = -b \quad (A.4)$$

Once T_{Bsun}^* is estimated during clear-sky, it is then possible to retrieve the atmospheric path attenuation $A(\theta_0, \varphi_0)$ in all weather conditions.

(ii) The **meteorological technique** is based on the radiometer equation in clear air, which can be written from (1) as:

$$T_{Aclr}(\theta_0) \cong T_{Bclr}(\theta_0) = T_{mrclr} \left[1 - e^{-\tau_{zclr}(\theta_0)/\sin(\theta_0)} \right] + T_{cos} e^{-\tau_{zclr}(\theta_0)/\sin(\theta_0)} \quad (A.5)$$

By using radiosounding profile measurements of meteorological variables, we can simulate T_{Aclr} and T_{mrclr} . Indeed, there are modeling evidences that the mean radiating temperature T_{mrclr} can be estimated directly from surface meteorological measurements in clear air:

$$\hat{T}_{mrclr} = a_0 + a_1 T_s + a_2 p_s + a_3 RH_s \quad (\text{A.6})$$

where a_i are the regression coefficients and T_s , p_s , RH_s are the surface temperature, pressure and relative humidity, respectively. This means that in a horizontally-stratified clear air we can obtain the zenith atmospheric optical thickness $\tau_{zclr}(\theta_0)$:

$$\hat{\tau}_{zclr}(\theta_0) = \sin \theta_0 \ln \ln \left[\frac{\hat{T}_{mrclr} - T_{cos}}{\hat{T}_{mrclr} - T_{Aclr}(\theta_0)} \right] \quad (\text{A.7})$$

Using the Sun-tracking measurements, we can estimate the weighted Sun brightness temperature:

$$\ln[\Delta T_A(\theta_0)] = \ln[f_\Omega T_{Bsun}] + \hat{\tau}_{clr}(\theta_0) = \ln[T_{Bsun}^*] + \hat{\tau}_{zclr}(\theta_0)/\sin(\theta_0) \quad (\text{A.8})$$

that is

$$\{\ln \ln [\hat{T}_{Bsun}^*] = \ln \ln [\Delta T_A(\theta_0)] - \hat{\tau}_{zclr}(\theta_0)/\sin(\theta_0)\} \hat{T}_{Bsun} = \frac{\hat{T}_{Bsun}^*}{f_\Omega} \quad (\text{A.9})$$

Note that, with respect to the Langley technique, the meteorological technique provides a time series of $\hat{T}_{Bsun}^*$ on a clear-air daily basis. The retrieval of the atmospheric path attenuation $A(\theta_0, \varphi_0)$ is then performed by taking the mean value of $\hat{T}_{Bsun}^*$ time series.

2) Theoretical error sensitivity analysis

The sensitivity analysis of atmospheric path attenuation estimate to residual errors or uncertainties of ST-MWR measurements is fundamental to understand the expected accuracy of the technique. Several sources of uncertainty can be identified intrinsic in the different techniques (Langley vs meteorological). In order to perform this error budget analysis, we can use for simplicity the first-order error propagation theory by assuming a statistical independence among the error sources.

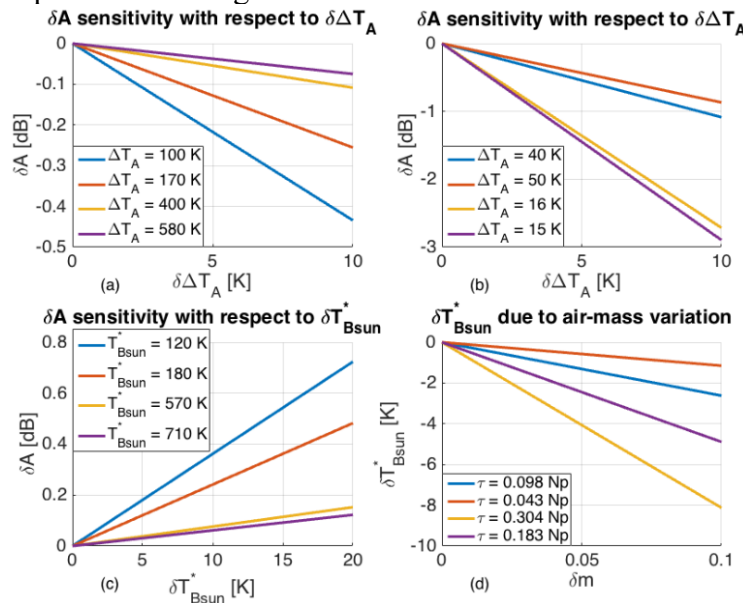


Fig. A.1. Sensitivity analysis of ST-MWR performances for typical values, which are those expected between Ka and W band. Blue line corresponds to 23.8 GHz, red line to 31.4 GHz, yellow line to 72.5

GHz and finally violet line to 82.5 GHz. More details in [Marzano et al., 2015].

Path attenuation is directly affected by antenna noise temperature difference uncertainties. The path attenuation error $\delta\tau$ or δA (in dB) with respect to the antenna noise difference uncertainty $\delta\Delta T_A$ is obtained from the governing equation in (12) of ST-MWR leading to:

$$\delta A = 4.343\delta\tau = -\frac{4.343}{\Delta T_A} \delta\Delta T_A \quad (\text{A.10a})$$

The sensitivity of δA with respect to uncertainties δT_{Bsun}^* in the estimate of T_{Bsun} is given by:

$$\delta A = 4.343\delta\tau = \frac{4.343}{T_{Bsun}^*} \delta T_{Bsun}^* \quad (\text{A.10b})$$

Fig. A.1a shows the previous equation of δA for ΔT_A values expected in clear sky between those at Ka and W band (see also sect. III.A). As ΔT_A is typically much smaller at Ka band with respect to V band, lower frequencies are more affected by uncertainties in ΔT_A (due to calibration errors, antenna mispointing during Sun tracking and atmospheric variability) with respect to higher frequencies. For an uncertainty in ΔT_A of 6 K, the error in path attenuation goes from -0.05 dB at 82.5 GHz up to -0.27 dB at 23.8 GHz.

Fig. A.1b shows the same analysis, but for ΔT_A values expected in rainy situations. Due to the strong attenuation of Sun emission by rain layers, ΔT_A differences are expected to be much smaller than those in clear sky. For heavy rain ΔT_A tends to zero in principle. Although the sensitivity increases for lower ΔT_A values, possible errors associated to antenna mispointing of the Sun position are less important. Nevertheless, the atmospheric variability, due to the different observation geometry, is somehow larger.

Fig. A.1c shows δA for a set of T_{Bsun}^* values which are those expected at K and V band (see sect. III). Alike Fig. A.1a, lower frequencies are associated to smaller T_{Bsun}^* values, and are more sensitive to errors in path attenuation. For an uncertainty of T_{Bsun}^* up to 10 K, the error in path attenuation goes from 0.06 up to 0.36 dB; for larger uncertainties, the error can reach 1 dB in Fig. A.1c.

Note that, when using the antenna noise temperature difference, we have assumed the same elevation for both off-the-Sun and toward-the-Sun observations. If this is not the case, a further error should be considered. This means that, assuming the off-of-the-Sun observation in (10) is performed at an elevation angle θ_1 , the antenna noise temperature difference in (11) should be replaced by:

$$\Delta T_A(\theta_0, \varphi_0, \theta_1, \varphi_1) = T_{Atws}(\theta_0, \varphi_0) - T_{Aos}(\theta_1, \varphi_1) \quad (\text{A.11})$$

By substituting and truncating to the first order the Taylor expansion of the atmospheric transmittance ratio, we can obtain the following T_{Bsun}^* uncertainty due to the air mass variation δm between the two observations:

$$\delta T_{Bsun}^* = (T_{cos} - T_{mr})\tau_{zclr} \delta m \quad (\text{A.12a})$$

Fig. A.1d shows the previous equation for a set of τ_z values, which are those expected in clear air between Ka and W band, and for a fixed mean radiative temperature ($T_{mr} = 270$ K). For an air-mass uncertainty of about 0.03, corresponding to 0.2 deg at 20 deg elevation, the error in estimating T_{Bsun}^* goes from -0.3 up to -2.5 K, depending on the value of the considered clear air optical thickness (higher τ_{zclr} values give higher errors).

Finally, since ΔT_A values may reach zero or even negative values for heavy rain (when the Sun disk contribution is completely attenuated by the atmosphere), there should be an upper limit of the attainable path attenuation during rain. The maximum path atmospheric attenuation value A_{max} depends on both

T_{Bsun}^* at the considered frequency and minimum detectable ΔT_{Amin} so that:

$$A_{max}(\theta_0, \varphi_0) = 4.343 \ln \left[\frac{T_{Bsun}^*(\theta_0, \varphi_0)}{\Delta T_{Amin}(\theta_0, \varphi_0)} \right] \quad (A12.b)$$

For typical ΔT_{Amin} values of about 0.5 K (1 K) and T_{Bsun}^* at Ka, V, and W band similar to those in Fig. A.1c, the maximum attainable attenuation with the ST-MWR method is about 24-26 dB (21-23 dB) at Ka band and about 31-32 dB (28-29 dB) at V-W band.

3) Clear-air data discrimination and antenna beamwidth estimate

Both Langley and meteorological techniques need measurements in clear-sky to estimate T_{Bsun} [Marzano et al., 2015; Mattioli et al., 2017]. The discrimination has been carried out through a scalar quantity, named Status Sky Indicator (*SSI*), purely based on the measured brightness temperatures. The method has been successfully applied in several applications with ground-based radiometers. *SSI* is defined as [Mattioli et al., 2017]:

$$SSI(\theta_0) = \frac{T_{AoS(31.4\text{ GHz})}(\theta_0) - c(\theta_0)}{T_{AoS(23.8\text{ GHz})}(\theta_0)} \quad (A.13a)$$

with

$$c(\theta_0) = -0.13 m^2 + 6.3 m + 2.1 \quad (A.13b)$$

where c is a parameter dependent on air mass $m = \sec(\theta_0)$. A clear air condition is assumed if *SSI* is less than a given threshold SSI_{th} given by

$$SSI_{th}(\theta_0) = -0.00012 m^2 + 0.0066 m + 0.31 \quad (A.14)$$

A clear-sky day is assumed if the number of measurements for which the *SSI* value is below the threshold is larger than the 98% of available samples (neglecting the non-clear-air samples in the T_{Bsun} estimation).

The maximum $T_{A_{twS}}$ values were held on for each elevation angle to compute T_{Bsun} with both Langley and Meteorological technique. MWR sun-tracking mode maintains a constant elevation for a certain time and the Sun does not remain stationary during that period. The best matching observation corresponds to the maximum value, where the Sun disk is centered with respect to the antenna beamwidth. Only for the Langley technique, a binning average with respect to air mass (steps of 0.1) was performed to achieve an equal distribution of samples with airmass and not to influence the linear regression in (13).

The ST-MWR antenna is typically a feedhorn/parabola system shaped to reduce the sidelobes to less than -30 dB at K-band and less than -40 dB at V and W band. The antenna radiation pattern results approximately Gaussian, following the approximation given in [Mattioli et al., 2017]. In order to evaluate the filling factor, both the Sun disk angle θ_{sun} and the half-power beamwidth θ_{3dB} values must be retrieved. Higher accuracy is needed in knowing θ_{ML} exact values with respect to the instrument (LPW-U72-82) technical specifications provided by the manufacturer (RPG), i.e. 3.7°, 3.3°, 1.3° and 1.3°, at 23.8, 31.4, 72.5 and 82.5 GHz, respectively.

The radiation pattern can be measured by scanning the radiometer across the Sun, i.e. letting the Sun drift across the radiometer path. From the known ephemeris, it has been possible to determine the relative

angular position of the sun assuming a uniform disk θ_{sun} of 0.533° arch. Finally, the measured brightness temperatures can be fit to a Gaussian profile convolved with the sun to obtain θ_{ML} measurements for each frequency. For the MWR used by [Mattioli et al., 2017], the full-width half-power beamwidth values are equal to 3.74° , 2.97° , 1.47° , and 1.30° at 23.8, 31.4, 72.5 and 82.5 GHz, respectively with a main beam efficiency η_{ML} of 0.969 at Ka band and 0.979 at V and W band. In [Mattioli et al., 2017], a detailed theoretical sensitivity analysis and error budget has been reported, with particular emphasis on side lobe contributions.

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