HiRadProp - High-frequency modeling and prediction of tropospheric radiopropagation parameters from ground-based multi-channel radiometric measurements between Ka and W band

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HiRadProp-E

Extension of high-frequency modeling and prediction of tropospheric radiopropagation parameters from ground-based radiometric measurements between Ka and W band to sun-beacon calibration and validation

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HiRadProp-E Final Report

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Abstract—Sun-tracking microwave radiometry is a ground-based technique where the Sun is used as a beacon source. The atmospheric antenna noise temperature is measured by alternately pointing toward-the-Sun and off-the-Sun according to a beam switching strategy. By properly developing an ad hoc processing algorithm, we can estimate the atmospheric path attenuation in all-weather conditions. A theoretical framework is proposed to describe the Sun-tracking radiometric measurements and to evaluate the overall error budget. Two different techniques, based respectively on elevation-scanning Langley method and on surface meteorological data method, are proposed and compared to estimate the clear-air reference. Application to available Sun-tracking radiometric measurements at Ka, V and W band in Rome (NY, USA) is shown and discussed together with the test of new physically-based prediction models for all-weather path attenuation estimation at Ka, V and W band from multi-channel microwave radiometric data. Results show an appealing potential of this overall approach in order to overcome the difficulties to perform satellite-to-Earth radiopropagation experiments in the unexplored millimeter-wave and submillimeter-wave frequency region.

Index Terms—Ground-based microwave radiometry, Sun tracking, all-weather path attenuation, clouds and precipitation, microwave and millimeter-wave frequencies.

I. INTRODUCTION

Atmospheric path attenuation is one of the most important limiting factors for the development of Earth-Satellite communications at Ka band and beyond [1], [2]. At these frequencies not only the impact of rain is significantly affecting the channel performances, but also the contribution of atmospheric gases and non-precipitating clouds can be non negligible [3], [4]. Radiopropagation beacon campaigns at Ka band and above are essential to experimentally characterize the medium behavior at these frequency bands from both a physical and a statistical point of view (e.g., [5]-[7]). However, these campaigns are conditioned by the limited number of dedicated space missions or by the opportunistic satellite constraints. An alternative way to approach the estimate and the monitoring of path attenuation is to resort to ground-based remote sensing techniques such as weather radar and microwave radiometers (MWR) (e.g., [8],[9]). The first are typically operated at frequencies less than 10 GHz so that a frequency scaling approach is needed for millimeter-wave estimates [10]. The latter are designed up 183 GHz, but they may be inadequate in presence of intense atmospheric scattering [11].

The estimation of atmospheric path attenuation from ground-based microwave radiometers (MWRs) may be affected by a significant underestimation during rain events, especially at frequencies higher than Ku band (e.g., [12],[13]). These errors are mostly due to the use of fixed empirical values or clear-air based estimates of the mean radiative temperature within path-attenuation retrieval algorithms [14], [15]. Model-based approaches have been proposed in the recent literature to overcome this problem by including multiple-scattering effects in the radiative transfer training schemes [16]. Indeed, microwave radiometric measurements of path attenuation during rainy and cloudy conditions can be accomplished in a quite accurate way by exploiting the detection of the solar beacon and a Sun-tracking (ST) operation mode [17]. This approach is quite well known in radioastronomy where it has been used for the estimation of the Sun brightness temperature at microwave and millimeter-wave frequencies (e.g., [18]-[20]). The application of ST in radiopropagation for estimating attenuation during rain was envisaged in early works [21]-[23].

The basic idea of Sun-tracking microwave radiometry (ST-MWR) consists in using the Sun as a source of radiation: the sky microwave emission is measured by alternately pointing toward-the-Sun and off-the-Sun, with and without the Sun contribution in the main lobe, according to a beam switching strategy [17],[23]. Observations toward-the-Sun and off-the-Sun fulfill two main goals: i) under clear-sky conditions they allow to compute the Sun brightness temperature at the different frequencies; ii) during rain events, they allowed to compute the path attenuation due to the rainfall. By properly choosing the switching time interval and taking into account the main lobe aperture, we can infer the atmospheric attenuation along the observed
path in all-weather condition through indirect evaluation of the difference between the two measurements [17].

The ST-MWR technique is here thoroughly examined and applied to microwave radiometric measurements at Ka, V and W band [17],[24],[25]. The available dataset consists of measurements, collected in 2015, by a ground-based microwave radiometer with a tracking control *stepping motor* recently installed in Rome, NY, USA. This new radiometer has four channels with receivers at 23.8, 31.4, 72.5 and 82.5 GHz and is an adaptation of a previous system [26]. The exploitation of ST-MWR in this experiment is aimed at characterizing the millimeter-wave atmospheric channels from V to W band for Geosynchronous Earth-orbit (GEO) and Low Earth-orbit (LEO) satellite communications without resorting to *ad hoc* radiopropagation beacon experiments.

This article is organized as follows. In section II the theoretical foundations of ST-MWR will be reviewed and main assumptions clearly identified. Subsections II.A and II.B will discussed two different techniques to estimate the brightness temperature of the Sun disk, whereas in subsection II.C a sensitivity analysis framework is proposed to examine the predicted performances in terms of errors with respect to antenna pattern, beam filling and Sun brightness temperature uncertainties. Section III is devoted to the description of the available ST-MWR data and to the development of physically-based path-attenuation prediction models in all-weather conditions. In section IV the comparison of ST-MWR estimated atmospheric path attenuations with those obtained from physically-based parametric prediction models at Ka, V and W band is presented. Finally, in section V conclusions and future developments are discussed.

### II. Sun-tracking microwave radiometry

For ground-based observations, the out-of-the-Sun (*ooS*) sky brightness temperature $T_{B_{\text{ooS}}}$, impinging upon the microwave radiometer antenna along the zenith angle $\theta$ and azimuth $\phi$, is given by [27]:

$$T_{B_{\text{ooS}}}(\theta, \phi) = T_{\text{mr}}(\theta, \phi) \left[ 1 - e^{-\tau(\theta, \phi)} \right] + T_{\text{cos}} e^{-\tau(\theta, \phi)}$$

(1)

where $\tau$ is the atmospheric optical thickness or path attenuation (in Neper), $T_{\text{mr}}$ is the sky mean radiative temperature, and $T_{\text{cos}}$ is the brightness temperature of the cosmic background (equal to about 2.73 K). The frequency dependence of parameters is here neglected in favour of geometric considerations. The antenna noise temperature $T_{\text{AtwS}}$ along the antenna pointing angle $(\theta_0, \phi_0)$ is the convolution between the sky brightness temperature and the antenna directivity pattern $D(\theta, \phi)$ expressed by [27]:

$$T_{A_{\text{ooS}}}(\theta_0, \phi_0) = \frac{1}{4\pi} \int_{4\pi} T_{B_{\text{ooS}}}(\theta, \phi) D(\theta_0, \phi_0, \theta, \phi) d\Omega$$

(2)

When observing the Sun with an antenna solid angle $\Omega_{\text{ant}}$, the toward-the-sun (*twS*) antenna noise temperature $T_{\text{AtwS}}$ is due not only to the Sun brightness temperature, but also to the sky brightness temperature emitted by the observed portion within the antenna beamwidth so that:

$$T_{A_{\text{twS}}}(\theta_0, \phi_0) = \frac{1}{4\pi} \int_{\Omega_{\text{sun}}} T_{B_{\text{twS}}}(\theta, \phi) D(\theta_0, \phi_0, \theta, \phi) d\Omega + \frac{1}{4\pi} \int_{\Omega_{\text{sky}}} T_{B_{\text{ooS}}}(\theta, \phi) D(\theta_0, \phi_0, \theta, \phi) d\Omega$$

(3)

where $\Omega_{\text{sky}} = \Omega_{\text{ant}} - \Omega_{\text{sun}}$ is the solid angle subtended by the antenna half-power beam subtracted by the Sun-disk solid angle $\Omega_{\text{sun}}$. It holds that

$$\int_{\Omega_{\text{ant}}} D(\theta, \phi) / D_M d\Omega = 4\pi$$

(4)

where $D_M$ is maximum directivity.

The *twS* sky brightness temperature is given by

The ST-MWR technique is here thoroughly examined and applied to microwave radiometric measurements at Ka, V and W band [17],[24],[25]. The available dataset consists of measurements, collected in 2015, by a ground-based microwave radiometer with a tracking control *stepping motor* recently installed in Rome, NY, USA. This new radiometer has four channels with receivers at 23.8, 31.4, 72.5 and 82.5 GHz and is an adaptation of a previous system [26]. The exploitation of ST-MWR in this experiment is aimed at characterizing the millimeter-wave atmospheric channels from V to W band for Geosynchronous Earth-orbit (GEO) and Low Earth-orbit (LEO) satellite communications without resorting to *ad hoc* radiopropagation beacon experiments.
\[ T_{B_{\text{TS}}} (\theta, \varphi) = T_{B_{\text{Sun}}} e^{-\tau(\theta, \varphi)} + T_{\text{mr}} (\theta, \varphi) [1 - e^{-\tau(\theta, \varphi)}] + T_{\cos} e^{-\tau(\theta, \varphi)} \]  

(5)

where \( T_{B_{\text{Sun}}} \) is the Sun brightness temperature. If we can approximately consider the brightness temperatures constant within the beam, then (for simplicity, we neglect here the angle dependence) eq. (3) can be rewritten as

\[ T_{A_{\text{TWS}}} = T_{B_{\text{TS}}} \frac{1}{4\pi} \int_{\Omega_{\text{sun}}} D(\theta, \varphi) d\Omega + T_{B_{\text{OOOS}}} \frac{1}{4\pi} \int_{\Omega_{\text{sky}}} D(\theta, \varphi) d\Omega = T_{B_{\text{TS}}} \Omega_{\text{sun}} + T_{B_{\text{OOOS}}} \Omega_{\text{sky}}' \]

(6)

where the prime symbol indicates the antenna pattern integration effect. If \( \Omega_{\text{sky}}' = \Omega_{\text{ant}} - \Omega_{\text{sun}} \), substituting the brightness temperature expressions and dividing by \( \Omega_{\text{ant}} \), we get:

\[ T_{A_{\text{TWS}}} \approx f_{\Omega} [T_{B_{\text{Sun}}} e^{-\tau} + T_{\text{mr}} (1 - e^{-\tau}) + T_{\cos} e^{-\tau}] + (1 - f_{\Omega}) [T_{\text{mr}} (1 - e^{-\tau}) + T_{\cos} e^{-\tau}] \]

(7)

being the beam-filling factor \( f_{\Omega} \) the ratio between the directivity-weighted Sun solid angle and the antenna beamwidth solid angle (see also (6)):

\[ f_{\Omega} = \frac{\Omega_{\text{sun}}'}{\Omega_{\text{ant}}} = \frac{\Omega_{\text{ant}} - \Omega_{\text{sky}}'}{\Omega_{\text{ant}}} \]

(8)

By reintroducing the angle dependence, the previous equation for the \( T_{\text{TS}} \) mode can be further rewritten as:

\[ T_{A_{\text{TWS}}} (\theta, \varphi_0) \equiv f_{\Omega} T_{B_{\text{Sun}}} e^{-\tau(\theta_0, \varphi_0)} + T_{\text{mr}} (\theta_0, \varphi_0) [1 - e^{-\tau(\theta_0, \varphi_0)}] + T_{\cos} e^{-\tau(\theta_0, \varphi_0)} \]

(9)

Analogously, for the \( T_{\text{OS}} \) mode, under the same assumptions, it holds

\[ T_{A_{\text{OS}}} (\theta_0, \varphi_1) = T_{B_{\text{OS}}} (\theta_0, \varphi_1) \equiv T_{\text{mr}} (\theta_0, \varphi_1) [1 - e^{-\tau(\theta_0, \varphi_1)}] + T_{\cos} e^{-\tau(\theta_0, \varphi_1)} \]

(10)

The different azimuth angles \( \varphi_0 \) and \( \varphi_1 \) are due to the ST operational mode. At each elevation \( \theta_0 \), the azimuth angle is switched from \( T_{\text{TS}} \) \( \varphi_1 \) to \( T_{\text{OS}} \varphi_0 \).

A. Estimation of atmospheric path attenuation

Assuming that the switching between \( T_{\text{OS}} \) and \( T_{\text{TS}} \) observation modes is fast enough and the elevation angle \( \theta_0 \) is kept constant (so that atmospheric attenuation does not change), the Sun-tracking antenna noise temperature difference for each pointing angle can be expressed by:

\[ \Delta T_A (\theta_0, \varphi_0, \varphi_1) = T_{A_{\text{TWS}}} (\theta_0, \varphi_0) - T_{A_{\text{OS}}} (\theta_0, \varphi_1) \]

(11a)

Note that the beam-filling factor \( f_{\Omega} \) can be dependent from the pointing angle itself. Substituting (9) and (10) into (11a) and assuming the mean radiative temperature and optical thickness do not change between the two observation modes (that is, \( T_{\text{mr}} (\theta_0, \varphi_0) \equiv T_{\text{mr}} (\theta_0, \varphi_1) \) and \( \tau (\theta_0, \varphi_0) \equiv \tau (\theta_0, \varphi_1) \)), we get:

\[ \Delta T_A (\theta_0, \varphi_0, \varphi_1) \equiv f_{\Omega} (\theta_0, \varphi_0) T_{B_{\text{Sun}}} e^{-\tau(\theta_0, \varphi_0)} = T_{B_{\text{Sun}}}' e^{-\tau(\theta_0, \varphi_0)} \]

(11b)
From (11b), we can estimate the atmospheric optical thickness \( \tau \) (in Np) in all-weather condition by means of:

\[
\hat{\tau}(\theta_0, \varphi_0) = \ln \left[ \frac{T_{\text{sun}}^*(\theta_0, \varphi_0)}{\Delta T_A(\theta_0, \varphi_0)} \right] \tag{12a}
\]

and in terms of path attenuation \( A \) (in dB)

\[
\hat{A}(\theta_0, \varphi_0) = 4.343 \hat{\tau}(\theta_0, \varphi_0) = 4.343 \ln \left[ \frac{T_{\text{sun}}^*(\theta_0, \varphi_0)}{\Delta T_A(\theta_0, \varphi_0)} \right] \tag{12b}
\]

where \( T_{\text{sun}}^* \) is the brightness temperature of the Sun weighted by the filling factor \( f_\Omega \).

Previous expression shows that path attenuation can be estimated once \( f_\Omega \) and weighted Sun brightness temperature \( T_{\text{sun}}^* \) are known. The first one can be derived from the antenna pattern and the pointing angle knowledge (with a given resolution and accuracy), whereas the second one must be estimated from the available measurements. Note that the dependence of the beam-filling factor \( f_\Omega \) on the pointing angle can be neglected if the radiometric system is properly designed and set up; an evaluation of the residual errors will be shown in section II.C.

B. Estimation of Sun brightness temperature

As mentioned, in order to estimate atmospheric path attenuation \( A \), the weighted Sun brightness temperature \( T_{\text{sun}}^* \) 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 \( T_{\text{sun}}^* \) 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.

(i) The Langley technique starts from (11) which can be rewritten in clear air as (e.g.,[18], [28]):

\[
\ln[\Delta T_A(\theta_0)] = \ln[f_\Omega T_{\text{sun}}] + \tau_{clr}(\theta_0) = \ln[T_{\text{sun}}^*] + \tau_{zclr}(\theta_0) \sec(\theta_0) \tag{13}
\]

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

\[
\tau_{clr}(\theta_0) = \tau_{zclr}(\theta_0) \sec(\theta_0) = \tau_{zclr}(\theta_0, \varphi_0) m(\theta_0) \tag{14}
\]

In (14) \( m(\theta_0) \) 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:

\[
\ln[\Delta T_A(\theta_0)] = a + b m(\theta_0) \tag{15}
\]

we can estimate \( T_{\text{sun}}^* \), using (11b), from the intercept of the previous line:

\[
\begin{cases}
T_{\text{sun}}^*(\theta_0) = \exp(a) \\
\hat{\tau}_{zclr}(\theta_0) = -b
\end{cases} \tag{16}
\]
Once $T_{BS\text{sun}}^*$ is estimated during clear-sky, it is then possible to retrieve the atmospheric path attenuation $A(\theta_0, \varphi_0)$ via (12) in all weather conditions.

(ii) The meteorological technique is based on the radiometer equation in clear air, which can be written from (1) as [27]:

$$T_{\text{Actr}}(\theta_0) = T_{B\text{ctr}}(\theta_0) = T_{m\text{rcitr}}\left[1 - e^{-\tau_{m\text{rcitr}}(\theta_0)/\sin(\theta_0)}\right] + T_{\cos}e^{-\tau_{m\text{rcitr}}(\theta_0)/\sin(\theta_0)}$$

(17)

By using radiosounding profile measurements of meteorological variables, we can simulate $T_{\text{Actr}}$ and $T_{m\text{rcitr}}$. Indeed, there are modeling evidences that the mean radiating temperature $T_{m\text{rcitr}}$ can be estimated directly from surface meteorological measurements in clear air (e.g., [29], [30]):

$$T_{m\text{rcitr}} = a_0 + a_1 T_s + a_2 p_s + a_3 \text{RH}_s$$

(18)

where $a_i$ are the regression coefficients. This means that in a horizontally-stratified clear air we can obtain the zenith atmospheric optical thickness $\tau_{m\text{rcitr}}(\theta_0)$:

$$\hat{\tau}_{m\text{rcitr}}(\theta_0) = \sin(\theta_0)\ln\left[\frac{T_{m\text{rcitr}} - T_{\cos}}{T_{m\text{rcitr}} - T_{\text{Actr}}(\theta_0)}\right]$$

(19)

From (13), using the Sun-tracking measurements, we can estimate the weighted Sun brightness temperature:

$$\ln[\Delta T_A(\theta_0)] = \ln[f_A T_{BS\text{sun}}] + \hat{\tau}_{m\text{rcitr}}(\theta_0) = \ln[T_{BS\text{sun}}^*] + \hat{\tau}_{m\text{rcitr}}(\theta_0)/\sin(\theta_0)$$

(20)

that is

$$\left\{\begin{array}{l}
\ln[T_{BS\text{sun}}^*] = \ln[\Delta T_A(\theta_0)] - \hat{\tau}_{m\text{rcitr}}(\theta_0)/\sin(\theta_0) \\
T_{BS\text{sun}} = \frac{T_{BS\text{sun}}^*}{f_A(\theta_0)}
\end{array}\right.$$ 

(21)

Note that, with respect to the Langley technique, the meteorological technique provides a time series of $T_{BS\text{sun}}^*$ on a clear-air daily basis. The retrieval of the atmospheric path attenuation $A(\theta_0, \varphi_0)$ via (12) is then performed by taking the mean value of $T_{BS\text{sun}}^*$ time series.

C. 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.

Path attenuation is directly affected by antenna noise temperature difference uncertainties. The path attenuation error $\delta \tau$ or $\delta A$ (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:

$$\delta A = 4.343 \delta \tau = -4.343 \frac{\delta \Delta T_A}{\Delta T_A}$$

(22a)

Fig. 1a shows the previous equation of $\delta A$ for $\Delta T_A$ values expected in clear-sky situations between Ka and W band (see also sect. III). As $\Delta T_A$ is typically much smaller at K band with respect to V band, lower frequencies are more affected by uncertainties in $\Delta T_A$ (due to calibration errors, antenna mispointing during
Sun tracking and atmospheric variability) with respect to higher frequencies. For an uncertainty in $\Delta T_A$ 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. 1b shows the same analysis, but for $\Delta T_A$ values expected in rainy situations. Due to the strong attenuation of Sun emission by rain layers, $\Delta T_A$ differences are expected to be much smaller than those in clear sky. For heavy rain $\Delta T_A$ tends to zero in principle. Although the sensitivity increases for lower $\Delta T_A$ 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.

As noted from (12b), since $\Delta T_A$ values may be negligible for heavy rain (when the Sun disk contribution is completely attenuated by the atmosphere), this suggests an upper limit of the attainable attenuation during rain. For $\Delta T_A$ values of 0.5 K and 1 K at K and V-, W-band, the maximum attainable attenuation with the ST method is about 25 to 28 dB, respectively. The sensitivity of $\delta A$ with respect to uncertainties $\delta T_{BSun}$ in the estimate of $T_{BSun}$ is given by

$$\delta A = 4.343 \delta T = \frac{4.343}{T_{BSun}} \delta T_{BSun}$$

(22b)

Fig. 1c shows $\delta A$ for a set of $T_{BSun}^*$ values which are those expected at K and V band (see sect. III). Alike Fig. 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. 1c.

Note that, when using the antenna noise temperature difference, we have assumed the same elevation both of-the-Sun and toward-the-Sun observations. If this is not the case, a further error should be considered. This means that, assuming the out-of-the-Sun observation in (10) is performed at an elevation angle $\theta_1$, the antenna noise temperature difference in (11) should be replaced by:

$$\Delta T_A(\theta_0, \phi_0, \theta_1, \phi_1) = T_{AWS}(\theta_0, \phi_0) - T_{Aos}(\theta_1, \phi_1)$$

(23)

By substituting the expressions (9) and (10) into (23) 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 $\delta m$ between the two observations:

$$
\delta T_{BSun}^* = (T_{cos} - T_{mr}) \tau_{zcir} \delta m
$$

Fig. 1d shows the previous equation for a set of $\tau_z$ 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 $\tau_{zcir}$ values give higher errors).

III. Available data and model-based prediction

This section, organized in 2 subsections, is devoted to the description of the available ST-MWR data and to the development of physically-based prediction models at Ka, V and W band to be tested by using ST-MWR measurements.

A. Experimental setup and MWR data processing

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 [26]. The antenna is shaped to reduce sidelobes (-30dB 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 processing and quality-control procedures applied to the AFRL-MWR data are described in the following paragraphs.

I) Clear-air data discrimination.

For selecting clear-sky days in order to estimate $T_{BSun}^*$ with both Langley and Meteorological techniques, we have implemented an atmospheric index, a scalar quantity named Status Sky Indicator (SSI), purely based on the available radiometric measurements and successfully applied in several MWR campaigns [30][31]. SSI is defined as:

$$
SSI = \frac{T_B(31.4 \text{ GHz}) - c}{T_B(23.8 \text{ GHz})}
$$

where $c$ is a parameter dependent on air mass $m$. If SSI is minor than a given threshold $SSI_{th}$, a clear air condition is assumed. In this work and for the Rome, NY, site, we have set $c = -0.13 \cdot m^2 + 6.3 \cdot m + 2.1$ and the $SSI_{th} = -0.00012 \cdot m^2 + 0.0066 \cdot m + 0.31$.

SSI parameterization has been set up by performing radiative transfer simulations at several elevation angles applied to a long-term available radiosonde observation (RaOb) dataset. The closest RaOb site to Rome, NY, is located at Albany County Airport, NY, USA (WMO station ID code 72518, WBAN ID code 14735). RaOb data belonging to the period 1994-2012 have been collected for this study. Downwelling brightness temperatures have been generated using a plane parallel radiative transfer scheme with an updated version of for gas absorption and cloud model [32]-[34].
2) Filtering toward-the-Sun observations in clear air in the estimation of \( T'_{BSun} \)

In order to estimate \( T'_{BSun} \) with the Langley technique (see sect. IV.A), the data processing has been designed to select the maximum \( T_{A_{twS}} \) for each elevation angle. The AFRL-MWR operational mode maintains a constant elevation for a finite time so that the Sun can move inside the antenna beam during that period. As noted from Fig. 1a, small pointing errors of the Sun position can lead to errors in \( \Delta T_A \) of several kelvins with a large impact on attenuation estimates, especially at K band. The maximum value of \( T_{A_{twS}} \) ensures to identify the best matching observation where the Sun disk is centred with respect to the antenna beamwidth.

Finally, a binning average with respect to air mass \( m \) has been performed considering steps of 0.2. In this way, an equal distribution of samples in terms of air mass is achieved and the results of the linear regression in (15) are not influenced by the different distribution of samples with airmass.

3) Antenna noise temperature self-consistency check

For estimating path attenuation, ST-MWR approach needs valid antenna noise temperature differences \( \Delta T_A \) between \( twS \) and \( ooS \) modes to work properly. These differences may reach zero or even negative during intense rain events, which limits the application of this technique, as detailed in Section II.C.

Only differences, greater than the MWR brightness temperature absolute accuracy, have been taken into account. The latter have been set to 0.5 K at 23-31 GHz and 1 K at 72-82 GHz in agreement with the manufacturer specifications.

![Fig. 2. Time series of ST-MWR measurements in terms of ooS (lower couple of curves) and twS (upper couple of curves) antenna noise temperatures for two case studies referring to a clear air (8 May 2015, blue dots for ooS and red dots for twS) and cloudy day (28 May 2015, green dots for ooS and grey dots for twS) and for the AFRL-MWR available frequencies a) 23.8 GHz; b) 31.4 GHz; c) 72.5 GHz; d) 82.5 GHz.](image)

ST-MWR measurements are interesting to analyze with respect to their temporal trend. As an example here discussed, Fig. 2 shows the time series of ST-MWR measurements in terms of \( ooS \) (lower curves) and \( twS \) (upper curves) antenna noise temperatures for two case studies referring to a clear air (8 May 2015) and cloudy day (28 May 2015) and for the four AFRL-MWR available frequencies (Fig. 2a-d). Fig. 3 shows the same as in Fig. 2, but for two different case studies referring to a moderate rain (11 May 2015) and intense rain event (30 June 2015).

As noted in Fig. 2a-b, the behavior of the \( ooS \) and \( twS \) antenna temperatures at 23.8 and 31.4 GHz in clear sky is similar with respect to the elevation, being higher values observed at low elevation (at the beginning of
the daily Sun-tracking) and reaching minimum values at the solar noon (at the maximum tracking elevation). Conversely, at 72.5 and 82.5 GHz, the behavior of $T_{aoS}$ and $T_{twS}$ time series is the opposite, with $twS$ time series reaching their maximum values at the solar noon (Fig. 2c and Fig. 2d). Such behavior is explained by recalling (9) and (10) and the different impact of $T_{sun}$ at Ka and V, W band (see Fig. 1c). At Ka band the atmospheric contribution with airmass still dominates over the one due to the Sun, whereas a V and W band it is the reverse. In presence of clouds, the antenna noise difference between the two measurement modes $ooS$ and $twS$ decreases when the optical thickness increases (i.e., for each frequency, lower curves tend to to be closer to the upper curves in Fig. 2). This is especially evident in the rainy event where the difference goes to zero as atmospheric extinction significantly increases during rainfall (see Fig. 1b for average $\Delta T_a$ values during rainy conditions). As expected, this behavior is more dominant at V and W band than at Ka band.

Fig. 3. Time series of ST-MWR measurements as in Fig. 2, but for two case studies referring to a moderate rain (11 May 2015, blue dots for $ooS$ and red dots for $twS$) and intense rain event (30 June 2015, green dots for $ooS$ and grey dots for $twS$) for the four AFRL-MWR available frequencies a)-d).

B. Physically-based prediction models of path attenuation

The ST-MWR technique can offer a very interesting framework to validate parametric prediction models at frequency bands above Ka band where satellite-to-Earth beacon measurements are rare. In previous works physically-based prediction models (PPM) have been proposed for estimating specific atmospheric parameters (i.e. attenuation $A$, $T_{mr}$ and $TB$) as a function of selected input parameters depending on both the frequency and the elevation angle [9], [16]. These models have been based on the non-linear regression fit of numerical simulations, derived from the sky-noise Edington radiative-transfer model (SNEM) in an absorbing and scattering medium such as gaseous, cloudy and rainy atmosphere [14], [32].

The PPM approach is based on the exploitation of RaOb datasets, collected in a location close to the site of interest and used to statistically characterize the local meteorology in terms of temperature, pressure and humidity average and standard-deviation profiles [24]. The latter statistics is then imposed in the Monte Carlo pseudo-random generation of vertical cloud structures where average profiles and cross-correlation among hydrometeor concentration are imposed [14]. The considered hydrometeor categories are cloud droplets, raindrops, graupel particles, ice crystals and snow aggregates, whereas 9 classes of cloud structures (including nimbostrati and cumulonimbi) are included [16].

The PPM general approach has been adapted for Rome (NY, USA) using our available radiosonde dataset from the site of Albany, NY, USA, about 70 km far away. By extracting the meteorological statistics, SNEM simulations have been performed at 23.8, 31.4, 72.5 and 82.5 GHz and for 8 elevation angles between 20°
and 90° in order to compute both brightness temperature and path attenuation.

Fig. 4 (a-d) shows the scatterplot of $T_{Boos}$ versus corresponding path attenuation $A$ at zenith (elevation angle of 90°) for each considered frequency in all weather condition (all cloud classes plus clear air condition). Fig. 5 (a-d) shows the same as in Fig. 4, but for an elevation angle of 36°. Previous scatterplots suggest that a PPM can be developed to estimate path attenuation $A$ from measured antenna noise temperature (in our case $T_{Boos}$). Two parametric non-linear models are here proposed to estimate path attenuation at 23.8, 31.4, 72.5 and 82.5 GHz using a multifrequency or a dual-frequency MWR.

The first PPM model is a multi-frequency approach and it is based on a polynomial regression ($Pol$) on SNEM dataset [24], [25]. The proposed multifrequency PPM-$Pol$ form is given by:

$$A_{Pol}(f) = m \cdot \sum_{i=1}^{4} a_i T_{Boos}(f_i) + b_i T_{Boos}^2(f_i)$$

where $f_i = 23.8, 31.4, 72.5, 82.5$ GHz and $f$ is one of 4 available frequencies $f_i$, whereas the coefficients are all function of the air mass $m$. Table A1 in the Appendix provides their expressions and numerical values.

**Fig. 4.** Scatterplot of $T_{Boos}$ versus corresponding path attenuation $A$ at zenith (elevation angle of 90°) in all weather conditions for each considered frequency a) 23.8 GHz; b) 31.4 GHz; c) 72.5 GHz; d) 82.5 GHz.

**Fig. 5.** The same as in Fig. 4, but for an elevation angle of 36°.

The second model ($PolDEx$) is an extended version of PPM-$Pol$ approach, reinforced with a double exponential single-frequency term, able to achieve better results in heavier rainy cases. The polynomial and
the exponential terms are weighted by the SSI index and tuned through the parameter $h$. The PPM-PolDEx is able, substantially, to balance heavy weather conditions by the double exponential expression with the good results of PPM-Pol in cloudy and moderately rainy conditions. The multifrequency PPM-PolDEx expression is expressed by:

$$A_{\text{PolDEx}}(f) = m\{\left(1 - SSI + h\right)A_{\text{Pol}}(f) + (SSI - h)A_{\text{DE}}(f)\}$$

being the single-frequency double-exponential form given by

$$A_{\text{DE}}(f) = \left[c_1 \cdot e^{c_2 T_{\text{Boos}}(f)} + d_1 \cdot e^{d_2 T_{\text{Boos}}(f)}\right]$$

where, as in (28), the coefficients $a_i$ and $b_i$ have the same expressions reported in Table A1. The coefficients $h, c_1, c_2, d_1$ and $d_2$ are all function of the air mass $m$. Table A2 in the Appendix provides their expressions and numerical values.

To highlight the advantages of our all-weather models, we can also show the comparison with the conventional technique using the clear-air approximation of the mean radiative temperature $T_{mr}$ at the frequency $f$ of interest:

$$A_{\text{ctr}}(f) = 4.343 \ln\left[\frac{T_{mr\text{ctr}}(f) - T_{\text{cox}}}{T_{mr\text{ctr}}(f) - T_{\text{AOSctr}}(\theta_0)}\right]$$

where $T_{mr\text{ctr}}$ is the clear-air mean radiative temperature estimated by (18). We can expect a significant error when trying to apply (28), instead of (26) or (27), in cloudy and, more importantly, rainy conditions. Note that the difference $T_{mr\text{ctr}}(f) - T_{\text{AOSctr}}(\theta_0)$ is less than zero, the estimator in (28) is not applicable. As mentioned, we have conservatively set this applicability limit not to zero, but to 0.5 K for 23 and 31 GHz to 1 K for 72.5 and 82.5 GHz.

In order to evaluate the accuracy of Pol and PolDEx PPM prediction models, we can evaluate the error of the regressive parametric estimates with respect to corresponding SNEM simulations. Table A3 in the Appendix shows the intercomparison between Pol and PolDEx models in terms of root-mean-square-error (RMSE) and average error (AvE), where the error is defined as the difference between the considered model and the simulation. We can clearly note from Table III how the PolDEx parametric model shows better results at all frequencies and for all elevation angles. RMSE and AvE values increase with the decrease of the elevation angle, and this behavior is expected as optical thickness (and path attenuation) increases with the decrease of the elevation angle thus meaning that the percentage error is still comparable at any angle.

In order to stress the latter consideration, an index of agreement (IA) has been also considered to better evaluate the percentage accuracy [35]. IA is a standardized measure of the degree of model prediction error and it varies between 0 and 1. An agreement index score of 0 suggests no agreement between the PPM model and the SNEM dataset, while an agreement score of 1 suggests complete match between the model and the dataset. IA is defined as [35]:

$$IA = 1 - \frac{(x_{\text{PPM}} - x_{\text{SNEM}})^2}{(|x_{\text{PPM}} - x_{\text{SNEM}}| + |x_{\text{SNEM}} - x_{\text{SNEM}}|)^2}$$

where $x_{\text{PPM}}$ and $x_{\text{SNEM}}$ are the PPM estimate and SNEM reference simulation. Considering the PolDEx model at zenith (elevation angle of 90°) in Table III, we can note as IA is equal to about 0.99 at 23.8 GHz and about 0.84 at 82.5 GHz. The accuracy decreases with the decrease of elevation angle but the IA is always greater than 0.7, that is PPM-PolDEx is able to provide reliable results with respect to SNEM dataset.

Worldwide distribution of MWR with channels in V and W bands is still very limited. For this reason a further dual-frequency polynomial model has been developed in order to provide a stand-alone solution only using channels at Ka band, i.e. at 23.8 and 31.4 GHz (e.g., [6]). Indeed, in order to retrieve path attenuation estimate for a dual-channel MWR we might use the double-exponential DEx model in (27b)
since it is single-frequency and SSF exclusively depends on the brightness temperatures at 23.8 and 31.4 GHz. However, an extension to a dual-frequency frequency can improve the results. The dual-frequency PPM-Pol2 model is given by:

$$A_{Pol2}(f) = m \cdot \sum_{i=1}^{2} a_i T_{Boos}(f_i) + b_i T_{Boos}^2(f_i)$$ (30)

where $f_{i=1,2}=23.8,31.4$ GHz and the coefficients are all function of the air mass $m$. Table A4 in the Appendix provides their expressions and numerical values. Properly replacing $A_{Pol}(f)$ in (27) by $A_{Pol2}(f)$ given by (30), the PolDEx model can be used to retrieve path attenuation in all-weather conditions from the MWR measurements at 23.8 and 31.4 GHz only.

IV. Application to sun-tracking data

This section is devoted to the description of results obtained from ST-MWR in terms of path attenuation estimates at Ka, V and W band. This work has been performed according to the following steps: i) careful selection of clear-sky days with minimum atmospheric variability; ii) computation of $T_{Bsun}$ by means of both Langley and meteorological methods; iii) application of the Sun-tracking technique to estimate total atmospheric attenuation in all weather conditions with a focus on rainy cases; iv) application of PPM Pol and PolDEx prediction methods to estimate all-weather total attenuation from ooS observations; v) inter-comparison analysis of the retrieved attenuations from steps iii) and iv). Verification of PPM Pol and PolDEx prediction algorithms is also discussed together with an error budget analysis.

A. Results for Sun brightness temperature estimate

By using the antenna noise temperature difference versus air mass, Fig. 6 (a-d) shows the estimate of $T_{Bsun}$ using the Langley technique, as discussed in sect. II.B, for each frequency and two selected clear-air days (May 8 and May 21, 2015). The best-fitting line is also shown.

Data processing steps for clear-sky, as described in III.A, have been performed to obtain robust estimates of $T_{Bsun}$ in order to ensure as much as possible a constant daily optical thickness. For the Langley technique, this means to obtain a linear dependence with a relatively small deviation in (15), being $\tau_{zcir}$ the slope in the linear approximation.

<table>
<thead>
<tr>
<th>$f$ [GHz]</th>
<th>$a_0$ [K]</th>
<th>$a_1$ [K/K]</th>
<th>$a_2$ [K/mbar]</th>
<th>$a_3$ [K/%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.8</td>
<td>-118.65</td>
<td>0.962</td>
<td>0.107</td>
<td>0.146</td>
</tr>
<tr>
<td>31.4</td>
<td>-125.65</td>
<td>0.99</td>
<td>0.102</td>
<td>0.162</td>
</tr>
<tr>
<td>72.5</td>
<td>-110.88</td>
<td>0.932</td>
<td>0.102</td>
<td>0.155</td>
</tr>
<tr>
<td>82.5</td>
<td>-134.49</td>
<td>1.03</td>
<td>0.099</td>
<td>0.170</td>
</tr>
</tbody>
</table>

By using the times series of antenna noise temperature difference, Fig. 7 (a-d) shows the estimate of $T_{Bsun}$ using the meteorological technique for each frequency and the two selected clear-air days. The average value of $T_{Bsun}^*$ is also highlighted as a constant line. The regression coefficients $a_0$, $a_1$, $a_2$ and $a_3$, used to estimate $T_{wcl}$ in (18), are reported in Table I for completeness.

In terms of Sun emission variation at the involved frequencies, we have assumed that the long-term component is small, also considering that the antenna beamwidth is much larger than the Sun arch. Indeed, we have not observed noticeable variations of the estimated Sun brightness temperature in our measurements, even though this should be proved on a longer dataset.
Fig. 6. Estimate of $T_{bsun}^*$ using the Langley technique, as discussed in sect. II.B, for each frequency and the 2 selected clear-air days.

Fig. 7. Estimate of $T_{bsun}^*$ using the meteorological technique for the two selected clear-sky days (May 8, blue dots; May 21 cyan dots) at each frequency a) 23.8 GHz; b) 31.4 GHz; c) 72.5 GHz; d) 82.5 GHz.

Table II shows the intercomparison between the Langley and meteorological technique estimates for $T_{bsun}^*$ together with the confidence intervals (in terms of standard deviation for the meteorological technique and the maximum deviation for the Langley technique). Note that Table I also provides the values of $\tau_{zcltr}$ and the maximum deviations $\sigma_{zcltr}$ (which is below 5% at all frequencies thus proving a good selection of clear-sky days). The uncertainty of $T_{bsun}^*$ estimates is comparable for both Langley and meteorological techniques, even though small differences are noted above Ka band.
B. Results for path attenuation estimate

The ST-MWR technique is intrinsically based on a variable antenna pointing in order to follow the Sun movement along its ecliptic. In order to make atmospheric path attenuation values intercomparable, we can show all results in terms of the zenith-equivalent path attenuation, obtained by multiplying each estimated path attenuation for the corresponding air mass.

As an example, Fig. 8 (a-d) shows the time series of zenith-equivalent attenuation estimates at 23.8, 31.4, 72.5 and 82.5 GHz respectively, for the cloudy case of Fig. 2. Predictions, based on models from PPM Pol in (26), PPM PolDEx in (27), and Clr in (28), are compared against ST-MWR attenuation retrievals. All parametric prediction models, as expected in this case, provide quite good results in agreement with ST-MWR time series.

Fig. 9 (a-d) shows a time series similar to Fig. 8, but for the intense rainy event of Fig. 3. Especially at 72.5 and 82.5 GHz, as expected, the application of the Clr model is not adequate to retrieve path attenuation during rain.

For an overall quantitative estimation of the PPM prediction approaches, Fig. 10 (a-d) shows the scatterplot of PolDEx and Clr model estimates for each frequency versus the corresponding ST-MWR A for all weather conditions and the all available dataset. Fig. 11 (4x4) shows the same comparison as in Fig. 10, but for Pol model. Table III quantifies the comparison in terms of RMSE and AvE, where the error is defined as the difference between prediction model under consideration and ST-MWR.

---

**TABLE II. INTERCOMPARISON OF LANGLEY AND METEOROLOGICAL ESTIMATES OF WEIGHTED SUN BRIGHTNESS TEMPERATURE**

<table>
<thead>
<tr>
<th>[GHz]</th>
<th>( T_{\text{zen}} ) [K]</th>
<th>( \sigma_{T_{\text{zen}}} ) [K]</th>
<th>( \tau_{\text{zen}} ) [Np]</th>
<th>( \sigma_{\tau_{\text{zen}}} ) [Np]</th>
<th>( T_{\text{zen}} ) [K]</th>
<th>( \sigma_{T_{\text{zen}}} ) [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.8</td>
<td>120.82</td>
<td>0.96</td>
<td>0.098</td>
<td>0.005</td>
<td>119.99</td>
<td>1.11</td>
</tr>
<tr>
<td>31.4</td>
<td>182.78</td>
<td>1.03</td>
<td>0.043</td>
<td>0.004</td>
<td>183.40</td>
<td>1.47</td>
</tr>
<tr>
<td>72.5</td>
<td>570.56</td>
<td>7.19</td>
<td>0.304</td>
<td>0.008</td>
<td>569.07</td>
<td>7.49</td>
</tr>
<tr>
<td>82.5</td>
<td>719.22</td>
<td>10.90</td>
<td>0.183</td>
<td>0.010</td>
<td>704.92</td>
<td>8.12</td>
</tr>
</tbody>
</table>

---

Fig. 8. Time series of zenith-equivalent path attenuation estimates on May 28, 2015 (cloudy case) at a) 23.8 GHz; b) 31.4 GHz; c) 72.5 GHz; and d) 82.5 GHz.
Fig. 9. Time series of zenith-equivalent path attenuation estimates on June 30, 2015 (rainy event) at a) 23.8 GHz; b) 31.4 GHz; c) 72.5 GHz; and d) 82.5 GHz.

Fig. 10. Scatterplot of ST-MWR path attenuation for each frequency versus path attenuation estimated from PolDEx and Clr models for all weather condition.
From Fig. 10 and 11 it is worth noting that the PPM Pol prediction tends to underestimate significantly path attenuation at Ka band, showing performances even worse than Clr prediction. On the other hand, the PolDEx approach shows a fairly good correlation with reference ST-MWR data for all frequencies, whereas the Clr model is much worse than the other models at V and W band. Note that the latter is not even applicable in rainy conditions and at higher frequencies when the atmosphere is opaque. Table III confirms these visual considerations stressing the very low bias of PolDEx estimates and its flexibility in dealing with both clear and rainy cases. Note that the scores of the Clr model are slightly optimistic as they computed for a reduced number of applicable points.

In (30), coupled with (27), we have introduced a dual-frequency approach to path estimation retrieval. Table IV, similarly to Table III, quantifies the results of this reduced-channel technique in terms of RMSE and AvE. Note how path attenuation retrieval errors from Pol2DEx model is still relatively small; nevertheless, higher accuracy is obtained using more than 2 Ka-band channels.

**TABLE III. ESTIMATED ZENITH-EQUIVALENT ATTENUATION ERROR CONSIDERING THE ST-MWR AVAILABLE DATASET IN 2015 IN ROME, NY FOR POL AND AND POLDEX MODELS**

<table>
<thead>
<tr>
<th>$f$ [GHz]</th>
<th>Pol (AvE)</th>
<th>Pol (RMS)</th>
<th>PolDex (AvE)</th>
<th>PolDex (RMS)</th>
<th>Clr (AvE)</th>
<th>Clr (RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>dB</td>
<td>dB</td>
<td>dB</td>
<td>dB</td>
<td>dB</td>
<td>dB</td>
</tr>
<tr>
<td>23.8</td>
<td>0.0224</td>
<td>0.220</td>
<td>0.0866</td>
<td>0.126</td>
<td>0.0271</td>
<td>0.135</td>
</tr>
<tr>
<td>31.4</td>
<td>0.0068</td>
<td>0.352</td>
<td>0.147</td>
<td>0.128</td>
<td>0.0069</td>
<td>0.219</td>
</tr>
<tr>
<td>72.5</td>
<td>0.0212</td>
<td>0.323</td>
<td>0.379</td>
<td>0.383</td>
<td>0.0224</td>
<td>0.619</td>
</tr>
<tr>
<td>82.5</td>
<td>0.1258</td>
<td>0.428</td>
<td>0.1624</td>
<td>0.1624</td>
<td>0.219</td>
<td>0.616</td>
</tr>
</tbody>
</table>

**TABLE IV. SAME AS TABLE III, BUT FOR THE DUAL-FREQUENCY PREDICTION MODEL**

<table>
<thead>
<tr>
<th>$f$ [GHz]</th>
<th>Pol (AvE)</th>
<th>Pol (RMS)</th>
<th>PolDex (AvE)</th>
<th>PolDex (RMS)</th>
<th>Tmr (AvE)</th>
<th>Tmr (RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>dB</td>
<td>dB</td>
<td>dB</td>
<td>dB</td>
<td>dB</td>
<td>dB</td>
</tr>
<tr>
<td>23.8</td>
<td>0.0178</td>
<td>0.242</td>
<td>0.127</td>
<td>0.135</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>31.4</td>
<td>0.004</td>
<td>0.351</td>
<td>0.147</td>
<td>0.219</td>
<td>0.0069</td>
<td>0.0069</td>
</tr>
</tbody>
</table>

**Fig. 11. Scatterplot of ST-MWR path attenuation for each frequency versus path attenuation estimated from Pol. for all weather condition. Results of the Clr models are shown as a reference.
C. Error budget analysis

Sect. II.C has been devoted to the discussion of the theoretical error analysis of path attenuation estimates with respect to several error sources. By using previous results, obtained from the AFRL-MWR measurements, we can now evaluate in a more quantitative way the overall error budget. The latter is shown in Table V 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 various sources.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>23.8</td>
<td>4</td>
<td>-0.20</td>
<td>23.8</td>
<td>0.83</td>
<td>0.030</td>
</tr>
<tr>
<td>31.4</td>
<td>5</td>
<td>-0.13</td>
<td>31.4</td>
<td>0.62</td>
<td>0.015</td>
</tr>
<tr>
<td>72.5</td>
<td>12</td>
<td>-0.13</td>
<td>72.5</td>
<td>1.49</td>
<td>0.011</td>
</tr>
<tr>
<td>82.5</td>
<td>19</td>
<td>-0.14</td>
<td>82.5</td>
<td>14.3</td>
<td>0.085</td>
</tr>
</tbody>
</table>

Sensitivity $\delta A$ with respect to $\delta T_A$ is given by (22a); on the left side of Table V reports the attenuation uncertainties for typical $\delta T_A$ in clear air. The latter are derived from the variability of AFRL-MWR data during the ooS and twS switching. In this case $\delta A$ are less than 0.2 dB at all frequencies, slightly higher at Ka band. On the right side of Table V, a the sensitivity analysis of $\delta A$ is shown with respect to uncertainties $\delta T_{Bsun}$. The latter has been derived from the differences between Langley and meteorological estimates shown in Table V. 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.

V. Conclusion

Sun-tracking microwave radiometry has been introduced to estimate the atmospheric path attenuation in all-weather conditions at Ka, V and W band. A detailed theoretical framework has been proposed to describe the Sun-tracking microwave radiometric measurement modes and to evaluate the overall error budget with respect to several sources of uncertainties. This approach has clearly identified the critical assumptions behind the ST-MWR data processing such as the accurate knowledge of the antenna beamwidth, the uniformity of incident brightness temperature within the antenna beamwidth and the atmospheric stationarity within each ST system switch.

The weighted brightness temperature of the Sun $T_{Bsun}^*$ has been estimated by means of two different techniques, based on the elevation-scanning Langley method and the surface meteorological data method. These two techniques show comparable results, but the first one needs a careful selection of candidate clear-air days whereas the second one is depending on the external weather station data and daily variability of clear air extinction. The ST-MWR methodology has been applied to AFRL available radiometric measurements at Ka, V and W band in Rome (NY, USA) during 2015, in order to test two new physically-based prediction models for path attenuation estimation. The single-frequency double-exponential parametric model seems to outperform the multi-frequency polynomial model when compared to ST-MWR retrievals. The clear-air based approach to estimate path attenuation, as expected, is unsuitable to estimate path attenuation in heavy cloudy and rainy conditions and at higher millimeter-wave frequency.

These results show an appealing potential of ST-MWR technique, which can be exploited to overcome the overall costs and the logistic difficulty to accomplish satellite-to-Earth radiopropagation experiments in the unexplored millimeter-wave and submillimeter-wave frequency region. A further validation of the ST-MWR technique should foresee by enlarging the available dataset and by comparing with collocated measurements.
performed by a satellite beacon receiver, even though the telecommunication bandwidths are typically different from the available MWR ones. The deployment of several AFRL MWRs, where PPM are applied to estimate path attenuation after a verification through ST-MWR, might allow very promising site diversity experiments at V and W band.

APPENDIX. PARAMETRIC PREDICTION MODELS

This appendix provides the tables of the regression coefficients and modeling functions used to express the physically-based parametric models (PPMs), discussed in sect. III.B. Two vPPM versions are considered: i) multifrequency, assuming to have a disposal all 4 AFRL-MWR channels (sect. A); ii) dual-frequency, assuming to have only Ka band channels at 23.8 and 31.4 GHz (sect. B).

A. Multifrequency PPM model

Table A1 provides the regression coefficients expressions to apply Pol model in (26), whereas Table A2 the same but for the DEx model in (27b) for each considered frequency $f$ at 23.8, 31.4, 72.5 and 82.5 GHz. Table A3 provides the Pol and PolDEx model intercomparison in terms of error indexes.

<table>
<thead>
<tr>
<th>TABLE A1. PPM POLYNOMIAL MODEL COEFFICIENTS IN (26)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>23.8 GHz</td>
</tr>
<tr>
<td>31.4 GHz</td>
</tr>
<tr>
<td>72.5 GHz</td>
</tr>
<tr>
<td>82.5 GHz</td>
</tr>
</tbody>
</table>
### TABLE A3. PPM MODEL INTERCOMPARISON

<table>
<thead>
<tr>
<th>Elev</th>
<th>Pol</th>
<th>PolDex</th>
<th>23.8 GHz</th>
<th>31.4 GHz</th>
<th>72.5 GHz</th>
<th>82.5 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>RMSE</td>
<td>IA</td>
<td>RMSE</td>
<td>IA</td>
</tr>
<tr>
<td>90°</td>
<td>-0.213</td>
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<td>0.798</td>
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<td>0.511</td>
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<td>0.784</td>
<td>-0.042</td>
<td>0.558</td>
<td>0.988</td>
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<td>45°</td>
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<td>0.748</td>
<td>-0.072</td>
<td>0.838</td>
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<td>36°</td>
<td>-0.386</td>
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<td>3.569</td>
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<td>0.596</td>
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<td>0.596</td>
<td>-0.546</td>
<td>3.623</td>
<td>0.881</td>
</tr>
</tbody>
</table>

**Notes:**
- RMSE: Root Mean Square Error
- IA: Index of Agreement
- Elev: Elevation
- Pol: Polarization
- PolDex: POLarization DEXtraction
TABLE A4. DUAL-FREQUENCY POLYNOMIAL MODEL COEFFICIENTS IN (30).

### 23.8 GHz

\[
\begin{align*}
\text{a} &= +1.26 - 9.27 \cdot 10^{-4} \cdot m + 1.78 \cdot 10^{-3} \cdot m^2 \\
\text{b} &= +6.85 \cdot 10^{-3} + 7.61 \cdot 10^{-3} \cdot m - 2.06 \cdot 10^{-3} \cdot m^2 \\
\text{c} &= +2.38 \cdot 10^{-3} + 2.92 \cdot 10^{-3} \cdot m - 2.70 \cdot 10^{-3} \cdot m^2 \\
\text{d} &= +1.17 \cdot 10^{-3} + 0.00 \cdot m - 1.42 \cdot 10^{-17} \cdot m^2 \\
\text{h} &= -2.01 \cdot 10^{-3} + 6.18 \cdot 10^{-1} \cdot m - 1.44 \cdot 10^{-4} \cdot m^2
\end{align*}
\]

### 31.4 GHz

\[
\begin{align*}
\text{a} &= +1.01 - 5.38 \cdot 10^{-4} \cdot m + 7.38 \cdot 10^{-2} \cdot m^2 \\
\text{b} &= +1.57 \cdot 10^{-2} - 4.56 \cdot 10^{-3} \cdot m + 1.83 \cdot 10^{-3} \cdot m^2 \\
\text{c} &= -9.36 \cdot 10^{-14} + 1.57 \cdot 10^{-13} \cdot m - 4.17 \cdot 10^{-14} \cdot m^2 \\
\text{d} &= +1.25 \cdot 10^{-1} - 1.12 \cdot 10^{-2} \cdot m + 3.14 \cdot 10^{-3} \cdot m^2 \\
\text{h} &= +5.34 \cdot 10^{-3} - 1.46 \cdot 10^{-1} \cdot m + 3.26 \cdot 10^{-2} \cdot m^2
\end{align*}
\]

### 72.5 GHz

\[
\begin{align*}
\text{a} &= +1.75 - 1.11 \cdot 10^{-3} \cdot m + 2.03 \cdot 10^{-5} \cdot m^2 \\
\text{b} &= +7.56 \cdot 10^{-2} + 2.46 \cdot 10^{-3} \cdot m - 4.31 \cdot 10^{-4} \cdot m^2 \\
\text{c} &= -1.85 \cdot 10^{-9} - 3.88 \cdot 10^{-10} \cdot m - 7.97 \cdot 10^{-11} \cdot m^2 \\
\text{d} &= +9.00 \cdot 10^{-2} - 1.30 \cdot 10^{-2} \cdot m - 9.49 \cdot 10^{-1} \cdot m^2 \\
\text{h} &= +1.42 - 1.09 \cdot m + 2.37 \cdot 10^{-1} \cdot m^2
\end{align*}
\]

B. Dual-frequency PPM

Table A4 provides the regression coefficients expressions to apply Pol2 model in (30).

### TABLE A4. DUAL-FREQUENCY POLYNOMIAL MODEL COEFFICIENTS

<table>
<thead>
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<th>Frequency</th>
<th>Coefficient Expression</th>
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<td>23.8 GHz</td>
<td>[ a_i = +2.02 \cdot 10^{-3} - 1.14 \cdot 10^{-4} \cdot m + 2.02 \cdot 10^{-3} \cdot m^2 ]</td>
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<td>[ b_i = +3.86 \cdot 10^{-3} - 2.02 \cdot 10^{-3} \cdot m + 3.09 \cdot 10^{-4} \cdot m^2 ]</td>
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<td>[ c_i = +9.62 \cdot 10^{-5} - 6.71 \cdot 10^{-5} \cdot m + 1.28 \cdot 10^{-3} \cdot m^2 ]</td>
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<td>[ d_i = +2.24 \cdot 10^{-5} - 1.22 \cdot 10^{-5} \cdot m - 3.65 \cdot 10^{-6} \cdot m^2 ]</td>
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<td>31.4 GHz</td>
<td>[ a_i = +4.19 \cdot 10^{-4} + 5.84 \cdot 10^{-3} \cdot m - 0.77 \cdot 10^{-4} \cdot m^2 ]</td>
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<td>[ b_i = +3.19 \cdot 10^{-3} - 2.02 \cdot 10^{-3} \cdot m + 3.23 \cdot 10^{-3} \cdot m^2 ]</td>
</tr>
<tr>
<td></td>
<td>[ c_i = +3.45 \cdot 10^{-5} + 4.32 \cdot 10^{-5} \cdot m + 8.55 \cdot 10^{-6} \cdot m^2 ]</td>
</tr>
<tr>
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<td>[ d_i = +7.25 \cdot 10^{-5} - 1.26 \cdot 10^{-5} \cdot m + 2.36 \cdot 10^{-6} \cdot m^2 ]</td>
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<tr>
<td>82.5 GHz</td>
<td>[ a_i = +1.69 \cdot 10^{-4} \cdot m + 6.77 \cdot 10^{-5} \cdot m^2 ]</td>
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<td>[ b_i = +3.19 \cdot 10^{-3} - 2.02 \cdot 10^{-3} \cdot m + 3.23 \cdot 10^{-3} \cdot m^2 ]</td>
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<tr>
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<td>[ c_i = +3.45 \cdot 10^{-5} + 4.32 \cdot 10^{-5} \cdot m + 8.55 \cdot 10^{-6} \cdot m^2 ]</td>
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<tr>
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<td>[ d_i = +7.25 \cdot 10^{-5} - 1.26 \cdot 10^{-5} \cdot m + 2.36 \cdot 10^{-6} \cdot m^2 ]</td>
</tr>
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The contribution of A.V. Bosisio (CNR, Italy) P. Ciotti (Univ. of L’Aquila) and P. Basili (Univ. of Perugia) for data analysis is acknowledged. The work of L. Milani was carried out within the Excellence program of the Sapienza University of Rome.

REFERENCES


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Grant/Contract Number
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FA8655-12-1-2019

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The full name of the principal investigator on the grant or contract.
Frank S. Marzano

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The AFOSR Program Manager currently assigned to the award
MILLER, KENT L DR

Reporting Period Start Date
04/01/2015

Reporting Period End Date
11/30/2015

Abstract
Sun-tracking microwave radiometry is a ground-based technique where the Sun is used as a beacon source. The atmospheric antenna noise temperature is measured by alternately pointing toward-the-Sun and off-the-Sun according to a beam switching strategy. By properly developing an ad hoc processing algorithm, we can estimate the atmospheric path attenuation in all-weather conditions. A theoretical framework is proposed to describe the Sun-tracking radiometric measurements and to evaluate the overall error budget. Two different techniques, based respectively on elevation-scanning Langley method and on surface meteorological data method, are proposed and compared to estimate the clear-air reference. Application to available Sun-tracking radiometric measurements at Ka, V and W band in Rome (NY, USA) is shown and discussed together with the test of new physically-based prediction models for all-weather path attenuation estimation at Ka, V and W band from multichannel microwave radiometric data. Results show an appealing potential of this overall approach in order to overcome the difficulties to perform satellite-to-Earth radiopropagation experiments in the unexplored millimeter-wave and submillimeter-wave frequency region

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Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

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Report Document

Report Document - Text Analysis

Appendix Documents

2. Thank You

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