Estimation of High-Frequency Earth-Space Radio Wave Signals via Ground-Based Polarimetric Radar Observations

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ABSTRACT

Expanding human presence in space, and enabling the commercialization of this frontier, is part of the strategic goals for NASA's Human Exploration and Development of Space (HEDS) enterprise. Future near-Earth and planetary missions will support the use of high-frequency Earth-space communication systems. Additionally, increased commercial demand on low-frequency Earth-space links in the S- and C-band spectra have led to increased interest in the use of higher frequencies in regions like K_u and K_a-band. Attenuation of high-frequency signals, due to a precipitating medium, can be quite severe and can cause considerable disruptions in a communications link that traverses such a medium. Previously, ground radar measurements were made along the Earth-space path and compared to satellite beacon data that was transmitted to a ground station. In this paper, quantitative estimation of the attenuation along the propagation path is made via inter-comparisons of radar data taken from the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) and ground-based polarimetric radar observations. Theoretical relationships between the expected specific attenuation (k) of spaceborne measurements with ground-based measurements of reflectivity (Z_h) and differential propagation phase shift (K_{dp}) are developed for various hydrometeors that could be present along the propagation path, which are used to estimate the two-way path-integrated attenuation (PIA) on the PR return echo. Resolution volume matching and alignment of the radar systems is performed, and a direct comparison of PR return echo with ground radar attenuation estimates is made directly on a beam-by-beam basis. The technique is validated using data collected from the TExas and FLlorida UNderflights (TEFLUN-B) experiment and the TRMM Large Biosphere-Atmosphere experiment in Amazonia (LBA) campaign. Attenuation estimation derived from this method can be used for strategic planning of communication systems for future HEDS missions.

1. INTRODUCTION

Ground observations from a multi-parameter radar can be used to estimate the path-integrated-attenuation (PIA) on high-frequency space radar systems, which can be used to derive the attenuation characteristics on earth-space communication links. Measurements from ground-based polarimetric radars have been used to study the effects of a precipitating medium on radio wave propagation along earth-space paths using satellite-based beacon data. A few of these studies are discussed in [1]. It has been shown by [2] that attenuation on microwave signals in rain is nearly linearly proportional to differential phase shift (ϕ_{dp}). Relationships between spaceborne specific attenuation (k) with ground-based observations of specific differential phase (K_{dp}) and reflectivity factor (Z_h) are determined, which is presented as a method to estimate the two-way PIA along a space radar beam.

Inter-comparisons between ground radar and space radar measurements are, in principle, straightforward. However, consideration of numerous details are important to proper alignment of radar observations from two distinct platforms that have different viewing aspects, operating frequencies and resolution volume sizes [3].

Simultaneous measurements were collected between ground and space radars during the TExas and FLorida UNderflights (TEFLUN-B) field campaign on August 13, 1998 near Melbourne, FL and the Large Biosphere-Atmosphere experiment in Amazonia (LBA on February 25, 1999 near Ji-Parana, Brazil. Data was selected based on coincident observations between the two systems when significant meteorological echoes were present. For brevity, a comparison of the k-correction method, as a means for attenuation estimation of high-frequency spaceborne signals, is made only for the LBA case. Comparisons of this method with the current single frequency attenuation correction algorithm used by the TRMM Precipitation Radar (PR) is shown. Discussions to space-based communications systems is also presented.

2. THEORETICAL MODEL

Theoretical modeling was performed to determine the relationships between the specific attenuation (k) of a nearly vertical pointing K_u-band spaceborne radar system with measurements of the reflectivity factor (Z_h) and specific differential phase (K_{dp}) taken from a nearly horizontal pointing ground radar system. Theoretical modeling is used to determine the scattering properties for ten different hydrometeor types: drizzle (dr), rain (rn), low-density ice crystals (li), high-density ice crystals (hi), wet ice crystals (wi), dry graupel (dg), wet graupel (wg), small hail (hs), large hail (hl) and rain mixed with hail (rh). The hydrometeor size distribution (HSD) for each class type is assumed to be of the form [4,5]

$$N(D) = n_C\, f(D) \qquad \text{mm}^{-1}\,\text{m}^{-3} \qquad (1)$$

where N(D) is the number of particles (with diameter D in mm) per unit volume per unit size interval, n_c is the concentration, and f(D) is the gamma probability density function (pdf), given by

$$f(D) = \frac{\Lambda^{\mu+1}}{\Gamma(\mu+1)} e^{-\Lambda D} D^{\mu} \qquad (2)$$

where Λ and μ are parameters of the pdf, and Γ denotes the gamma function [6]. This can subsequently be written in a normalized form as

$$N(D) = N_W f(\mu)\left(\frac{D}{D_o}\right)^{\mu} \exp\left[-(3.67+\mu)\frac{D}{D_o}\right] \quad (3)$$

where D_o is the volume-weighted median drop diameter [7].

Particles are also assumed to be rotationally and equatorially symmetric with orientation canting angles. The parameters of the HSD model (N_w, D_o and μ) were varied according to the values available in the literature: drizzle as per [8]; rain as per [9]; low density ice crystal and wet ice crystal as [10]; high density ice crystal as per [11]; graupel, wet and dry as per [12]; and hail as per [13]. The rain-hail mixture was determined from simultaneous inputs of both rain and hail hydrometeors to the simulation. It is noted that with the exception of rain, all other HSD's have μ set equal to zero.

Scatter plots of S-band Z_h vs. K_u-band specific attenuation (k) were constructed for each hydrometeor, and a power-law relationship of the form $k = aZ_h^b$ was fit to the points. A summary of the coefficients (a and b) for each of the hydrometeors is shown in Table 1. For rain rate when $K_{dp} \geq 0.5$, a k-K_{dp} relationship was used. A linear fit to the scatter points of S-band K_{dp} measurements vs. K_u-band k yields a slope of 1.96 dB/deg from modeling.

Hydrometeor	a	b
drizzle (dr)	7.8502E-06	2.8496
rain (rn) (for K_{dp} < 0.5 deg/km)	3.2923E-09	5.1042
low density ice crystals (li)	1.1385E-06	4.4664
wet ice crystals (wi)	4.3007E-07	3.6489
dry graupel (dg)	4.8156E-18	9.4689
wet graupel (wg)	1.1786E-16	9.4216
small hail (hs)	5.5571E-20	11.2724
large hail (hl)	6.6175E-22	11.3342
rain & hail (rh)	3.6786E-15	8.4093

Table 1: Summary of power-law coefficients for each hydrometeor. ($k = aZ_h^b$)

3. GR AND SR MEASURMENT MATCHING

Inter-comparisons between ground and space radar (SR) data can be a challenging task. Differences in viewing aspects, operating frequencies and resolution volume size can produce errors in direct comparisons between the two systems. Geometric distortion introduced into the space radar retrieved image, due to the movement and attitude perturbations of the satellite itself, further complicate the problem of alignment and comparison [14].

In the alignment process between the two radar systems, potential first order errors are minimized by collecting ground and space data during simultaneous intervals not exceeding 2-3 minutes in time difference. Small areas (50 x 50 km) are typically defined around a region of interest to minimize non-linear distortion effects. Both sets of data are re-mapped to a satellite-centered Cartesian coordinate system using a non-spherical earth model (WGS-84 model); GR re-sampling uses a 4/3-earth model to compensate for beam refraction. The vertical and horizontal extents of both GR and SR beams at a given location are used to define a 3-dimensional volume that encloses both GR and SR resolution volumes, thus "matching" the two radar resolutions volumes in spatial extent [15]. Lastly, a polynomial distortion model technique is used to reduce relative geometric diifferences between GR and SR images [14]. The final result is a set of coincident GR and SR measurements that are aligned and matched in resolution.

4. EARTH-SPACE LINK ATTENUATION ESTIMATE

After resolution cell matching and alignment, ground radar observations of K_{dp}, made by the NCAR S-POL radar, were taken along the TRMM PR beam from data collected during the TRMM-LBA field campaign. The hydrometeor type was determined along the beam path via a Fuzzy-logic technique using ground-based polarimetric observations [16]. In practice, the hydrometeor constituents found within the matched resolution volume along the PR beam may not be homogeneous. The specific attenuation within the matched volume is, hence, determined by a weighted-average of the relationships for each hydrometeor present in the volume taken from GR observations. The PIA is determined from

$$\mathrm{PIA}(s) = \int_{r=0}^{s} \bar{k}(r)\,dr \quad (4)$$

where s is the beam slant range starting from the cloud top at r = 0, and $\bar{k}(r)$ is the *mean-weighted specific* attenuation within the matched resolution volume. The PR reflectivity corrected for attenuation is given by:

$$Z_m(\mathrm{PR}; k\text{-corrected}) = Z_m(\mathrm{PR}) + \mathrm{PIA}. \quad (5)$$

The k-corrected PR reflectivity, the measured GR reflectivity, Z_m(GR), measured PR reflectivity, Z_m(PR), and PR attenuation corrected reflectivity from the current PR attenuation correction algorithm, Z_c(PR), as well as ground radar polarimetric measurements of linear depolarization ratio (LDR), cross-correlation coefficient (ρ_{co}), specific differential phase (K_{dp}) and differential reflectivity (Z_{dr}), along the PR beam are shown in Figure 1 for the TRMM-LBA case study. In this figure, attenuation is seen to be nearly 10 dB on PR reflectivity measurements, relative to GR measurements. PR attenuation corrected reflectivity closely follows the Z_m(GR) vertical profile as well as the k-corrected reflectivity (shown as a solid line).

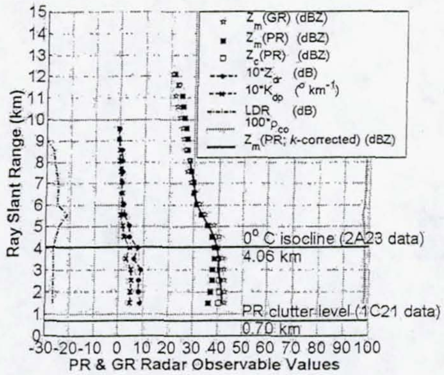

Figure 1: PR measurements, GR polarimetric measurements, and *k*-corrected PR reflectivity along PR beam for TRMM-LBA data on February 25, 1999.

5. SPACE COMMUNICATIONS APPLICATIONS

Attenuation estimates of the precipitating medium can be used to adjust optimum power levels on earth-space communications links. Open loop estimation of signal degradation can be performed via a network of ground-based polarimetric radars. Such a network can also be used in site-diversity schemes for commercial spot-beam satellite systems, such as those used in the cellular mobile industry. Maps of specific attenuation estimates derived from the proposed method can be used near ground sites to determine link quality due to precipitation signal degradation. Scheduled links can be dynamically routed based on the attenuation maps. Atmospheric attenuation impact on pre-flight checkout of Space Shuttle Orbiter (SSO) K_u-band links from the NASA/JSC ESTL (Electronic Systems Test Laboratory) facilities can be determined *a priori*. Quality assessment can also be made on direct data link distribution from low earth orbit (LEO) satellites supporting other NASA enterprises such as high data rate meteorological science missions in the Earth Science Enterprise (ESE).

6. SUMMARY

Attenuation effects on high-frequency earth-space communication systems can be significant. A method for quantitatively determining the attenuation of space-based signals, using individual space radar beams, and ground-based polarimetric observations has been presented. A theoretical model was developed to determined the relationship between high-frequency spaceborne specific attenuation with ground-based Z_h and K_{dp} observations for ten different hydrometeor types. The PIA was then calculated along the beam. The method was validated from data collected during the TEFLUN-B and TRMM-LBA field campaigns. It was found that, under certain circumstances, the proposed method for attenuation correction performed better than the current correction algorithm being used by the TRMM PR data products, and that attenuation could be as high as 15 dB.

7. ACKNOWLEDGEMENTS

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