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Statistical Study of Cloud Attenuation on Ka-band Satellite Signal in Tropical Region

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***Abstract*—A 2-year statistical study of cloud induced attenuation on Ka-band satellite communication link in the tropical region is presented. Different from other publications, experimental results from an 18.9 GHz beacon receiver is analyzed for cloud attenuation. Several new cloud detection methods are proposed in order to achieve accurate cloud attenuation estimation. These results are compared to the ITU-R model for the same frequency and elevation angle. The complementary cumulative distribution function (CCDF) of 2-year cloud attenuation shows that at time exceedance of 0.01%, cloud attenuation in the Ka-band can reach up to 4 dB. It is found that the ITU-R model underestimate the cloud attenuation in the tropical region.**

***Index Terms*—Cloud attenuation, satellite beacon signal, radio propagation.**

I. Introduction

WITH the rapid growth in satellite communication services, high frequency bands such as Ka and Q/V bands are becoming more attractive to satellite system operators [1-2]. The atmosphere such as rainfall, cloud and various gases has strong impact on the Space-to-Earth satellite communication links. Among these phenomena, precipitation is commonly known to cause the most severe impairment. As the operating frequency increases (Ka-band and above), cloud attenuation becomes significant and can no longer be neglected. This situation is much worse for the tropical region (e.g., Singapore [3]) due to the higher occurrence of cumulus and cumulonimbus clouds, which occupy large columnar volume with heavy liquid water content.

In a tropical country such as Singapore, the effects of rain on satellite links has been extensively studied using the beacon signal recorded at ground station [4]. As a continuous work [3, 5], cloud attenuation on the Ka-band WINDS (Wideband InterNetworking engineering test and Demonstration Satellite) propagation link is further discussed and analyzed in this paper.

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Two-year statistical results of cloud attenuation derived from the beacon signal will be presented, together with the ITU-R model [6] for reference.

II. Database Description

The beacon signal from the WINDS geostationary satellite has been continuously recorded at the ground station located at Nanyang Technological University (NTU), Singapore, with the operating frequency of 18.9 GHz at left-hand circular-polarization. The WINDS satellite is located at 143°E, and has an elevation angle of 44.5˚. In this study, two consecutive years (2014 and 2015) beacon signal data are used to perform a statistical cloud induced attenuation study on a Ka-band satellite link in the tropical region.

In order to understand cloud and rain events, data collected from a dual polarized weather Radar at Changi airport (1.35ºN, 103.97ºE) and a weather station at NTU (1.34ºN, 103.68ºE) are processed. The weather Radar operates in the S-band at a frequency of 2.71 GHz. It performs a full volume scan every 5 minute with a maximum range of 120 km at 8 elevation angles (1˚, 1.5˚, 3˚, 5˚, 7.5˚, 10˚, 20˚, and 40˚). The Davis Vantage weather station at NTU site measures the rainfall rate by using a tipping-bucket rain gauge with a resolution of 0.2 mm/tip. A whole sky imager at NTU site is also used to provide a visualization of the sky condition.

Radiosonde data over the same period of time collected at 48698 WSSS Singapore site [7] is used to perform cloud detection and validation [8]. The radiosonde is launched twice (00:00 UTC and 10:00 UTC) per day.

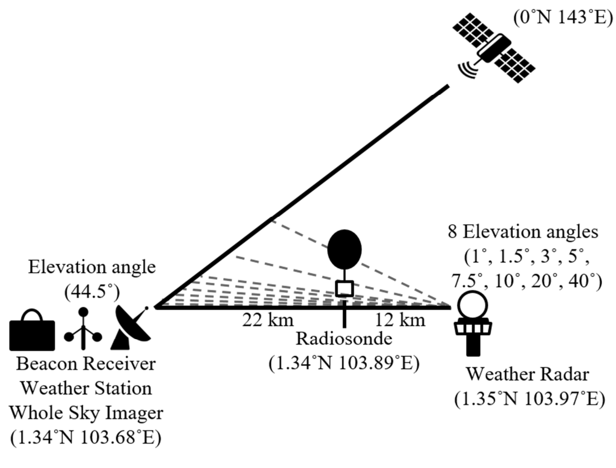

Fig. 1. The triangulation structure among WINDS satellite, beacon receiver, weather station, whole sky imager, radiosonde and weather Radar.

III. Data Processing and Cloud Detection

A. Data Processing

The triangulation structure between the WINDS satellite, beacon receiver, weather station, whole sky imager, radiosonde and weather Radar is shown in Fig. 1. The weather station and the whole sky imager are collocated with the beacon receiver at NTU site, while the weather Radar is at a distance of 34 km west of NTU site. For WINDS beacon signal processing, the rapid fluctuation due to tropospheric scintillation is removed using a 6th-order Butterworth filter at a cutoff frequency of 20 mHz [3]. Since the amplifier gain of the Low-Noise-Block (LNB) down convertor varies with temperature, the sliding window technique is applied to reduce its effect.

After the scintillation and temperature effects are removed, the total slant path attenuation on the beacon signal can then be estimated, this total attenuation may consist of rain attenuation, cloud attenuation and gaseous absorption. Typically, the attenuation by atmospheric gases does not vary much over a day. Surface relative humidity, temperature and pressure recorded (per minute) by the weather station is used in the ITU-R P. 676-10 model [9] to remove the effect of both dry air attenuation and water vapor attenuation.

B. Differentiate Cloud from Rain Attenuation

To differentiate the cloud events from the rain events, the weather station and the whole sky imager at NTU site can be used as references. Since the WINDS satellite link is a slant path with an elevation angle of 44.5°, weather Radar reflectivity data can also be used to provide information along the slant path as illustrated in Fig. 1. In order to detect and differentiate the clouds from the rain events, the technique reported in [10] is used. The dual-polarized weather Radar performs full volume scan with 8 elevation angles, and therefore the 8 non-uniforming distributed intersection points provide rainfall information along the slant satellite link. As concluded in [10], if the reflectivity is less than 20 dBZ, the event will be considered as cloud instead of rain.

In order to show this differentiating technique from [10], an example with both cloud and rain events are shown in Fig. 2. The top plot shows the maximum (out of 8) weather Radar reflectivity along the satellite slant path link over a day. The middle plot is the rainfall rate obtained from the weather station. The bottom plot is the attenuation (cloud and rain attenuation) suffered by the WINDS satellite beacon signal.

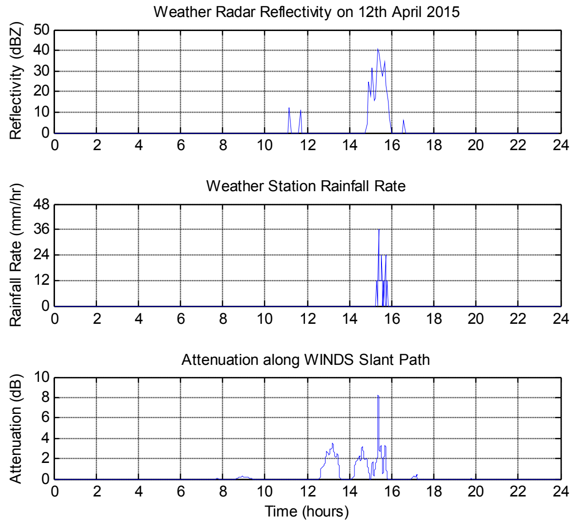

Fig. 2. The processed Ka-band beacon signal for WINDS slant path with Radar reflectivity and rainfall rate on 12th April 2015.

From Fig. 2, it can be observed that a rain event was recorded by the weather station at 15:12 at NTU site, the maximum rainfall rate reached was 36 mm/hr. At that instance, the Radar reflectivity along the path reached a maximum of 40 dBZ and the corresponding rain attenuation was 8 dB. However, before this rain event, the Radar reflectivity was larger than 20 dBZ at around 14:50; this is due to the rainfall happening along the satellite-to-ground station slant path, which can be observed using the Radar PPI (plan position indicator) as shown in Fig. 3. The solid black line from NTU site towards East shows the projected path of WINDS slant link, and at this moment the path suffers from rainfall at around -30 to -10 km in zonal distance. Therefore, by using the Radar reflectivity, rain events along the slant path can easily be detected. This allows for the differentiation between a rain event and a cloud event.

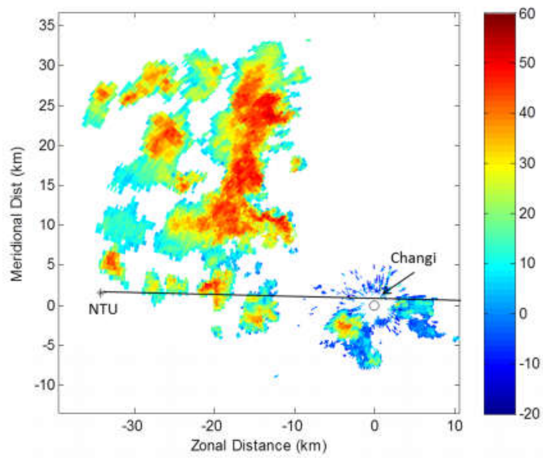

Fig. 3. The Radar reflectivity PPI map between NTU and Changi airport with WINDS slant path link at 14:50 on 12th April 2015.

Fig. 4. Cloud image taken by Whole Sky Imager at 13:14 on 12th April 2015 at NTU.

Next, a cloud attenuation event is analyzed based on observations from Fig. 2. Before the rain event, starting at around 12:30, there is no rainfall recorded by the weather station nor the weather Radar. Therefore, it can be deduced that the attenuation is mainly caused by multiple layers of clouds along the satellite slant path. A maximum cloud attenuation of 3.5 dB can be seen at 13:13 in Fig. 2. The existence of corresponding cloud image taken by the whole sky imager at NTU site also shows the dark thick clouds with heavy liquid water content at 13:14 as shown in Fig. 4.

All the above information and techniques described will be used to accurately determine attenuation caused by cloud from the received beacon signal strength.

IV. Results and Discussion

By applying the above mentioned cloud detection and differentiation methods, the cloud attenuation suffered by the WINDS beacon signal can be estimated. The yearly (Year 2014 and Year 2015) complementary cumulative distribution function (CCDF) for cloud induced attenuation is presented in Fig. 5 with the cloud attenuation calculated by using the ITU-R model [6] at the same frequency of 18.9 GHz with the same elevation angle of 44.5˚. It is noted that the statistics derived from beacon data include only the contribution of clouds in non-rainy conditions. Since the reduced liquid water content maps of recommendation ITU-R P.840-6 [6] were derived by applying the Salonen Uppala (SU) method [11] to ECMWF-derived vertical profiles, both the ITU-R model and the SU model are briefly introduced below;

1) The ITU model: As reported in [6, 12], the ITU-R model provides the overall yearly digital map of the global statistics of atmospheric liquid water content, the cloud attenuation from ITU-R model is reproduced in this study.

2) The SU model: Salonen and Uppala [11] proposed that cloud attenuation can be calculated by integrating the specific cloud attenuation Υ_c(dB/km) along the path,

$$\Upsilon_c = 0.819 f w / \varepsilon''(1+\eta^2) \ , \qquad (2)$$

where f is the frequency in GHz, w is the liquid water density in g/m^3, and $\eta = (2+\varepsilon')/\varepsilon''$. ε' and ε'' are the real and imaginary parts of the permittivity of water. However, since the cloud detection algorithm from the SU model was developed by using meteorological data collected from temperate region instead of tropical region, it is well-known that it underestimates the cloud attenuation in tropical region and therefore not used in comparison in Fig. 5.

As shown in Fig. 5, the yearly complementary cumulative distribution function of cloud attenuation estimated from WINDS beacon signal is compared with the ITU-R model. The majority of clouds in Singapore are either cumulus (76%) or cumulonimbus (22%). These cloud types result in larger cloud attenuation as compared to the cloud types observed in the temperate region. It should be noted that the ITU-R is a global model and might not serve well for specific regions. It is reported in [13] that severe weather conditions in the tropical region can result in much higher cloud attenuation at lower percentages of time exceedance (less than 0.1% of time). For higher percentage of time exceedance (greater than 1% of time), the beacon derived cloud attenuation appears to be less than that estimated by the ITU-R model. One reason is that the ITU-R model applies the SU model (its cloud detection algorithm) to NWP (Numerical Weather Prediction) vertical profiles to detect the cloud, and this may lead to a high percentage of cloud occurrence since the SU model was developed using the meteorological data collected in temperate region. Another reason is that, larger percentage of time exceedance includes a significant amount of cloud attenuation caused by thin layer of cloud. Since the thin cloud attenuation is very small for Ka-band satellite signal, it is difficult to extract it from the beacon signal [14] which also contains the scintillation effect. Attenuation due to thin layer of clouds is often smaller than scintillation effect and therefore cannot be estimated from the satellite beacon signal.

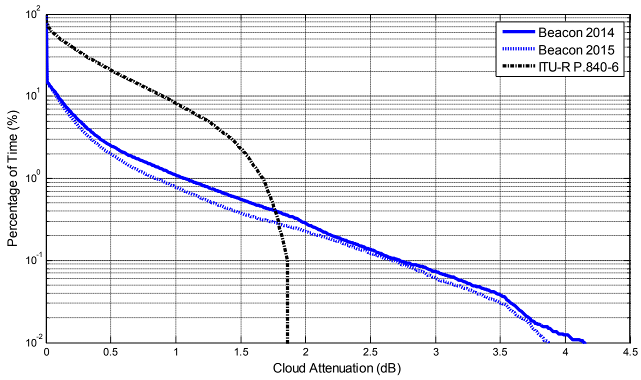

Fig. 5. Complementary cumulative distribution function of cloud attenuation estimated from WINDS satellite beacon signal for the year of 2014 and 2015.

From Fig. 5, it is also observed that at time exceedance of 0.01%, the cloud attenuation on the WINDS satellite is 4.2 dB for the year of 2014 and 3.9 dB for the year of 2015. In addition, the cloud attenuation of 2014 is larger than that in 2015 for same percentage of time exceedance. It is noted that in the year of 2014, the La Nina climate dominates and the weather of Singapore became cold and wet, thus the consistently higher attenuation for that year; while in the year of 2015, climate changed to the El Nino, Singapore suffered from warm and dry weather condition. Therefore, less heavy clouds and rainfall events are recorded in Singapore for the year of 2015 as compared to the year of 2014.

V. Conclusion

In this letter, two-year statistical results of cloud attenuation on a Ka-band satellite link have been reported, with correlation analysis of cloud existence using different techniques.

The yearly CCDF results indicate that at time exceedance of 0.01%, the cloud attenuation can reach up to 4.2 dB in the tropical region. It is also shown that the ITU-R model underestimate the cloud attenuation in the tropical region. Further study will be carried out to evaluate and model the cloud attenuation in the tropical region.

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