A hypothesis of 3D rainfall tomography using satellite signals

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Abstract: The attenuation of microwave signals due to rainfall, known as rain attenuation, can be used to measure rain. Similar to using X-ray to carry out human-body CT scans, the microwave signals of low earth and/or medium earth orbit satellites are proposed for carrying out 3D (Three Dimensional) rainfall tomography in this paper. The proposed method will not only complement the three major rain measurement methods in use today (i.e. rain gauge, weather radar, and weather satellite) but also potentially achieve 3D rainfall measurements with precision and coverage unachievable before. Along with the deployment of low earth orbit satellite constellations (e.g. the OneWeb constellation) for global broadband Internet services, small satellite receivers of the size of a pizza box may be used to achieve 3D rainfall tomography anywhere on the Earth, thereby paving the way for many practical applications and atmospheric research that are associated with rainfall.

Key words: satellite communications, computerized tomography, rain measurement

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1 Introduction

As a critical component of water cycle, rainfall is a key variable for fresh water availability, weather forecast, agriculture, natural disasters (e.g., floods and mudslides), and city drainage systems. Today three rainfall measurement methods are widely in use: rain gauge, weather radar, and weather satellite. Each of them has distinct rainfall measurement attributes in terms of deployment and operating cost, coverage, and measurement precision.

Currently there are over one thousand active LEO (Low Earth Orbit) and MEO (Medium Earth Orbit) satellites in orbit. More LEO/MEO satellites have been planned to be launched into the space in the near

future^{[1],1}. In particular, the OneWeb satellite constellation² of about 700 small LEO satellites are anticipated to be deployed in the near future to achieve global broadband Internet service.

To date all the communication links between satellites and ground stations use microwave signals, with more and more links employing *Ku* or *Ka* band signals. The path loss of microwave signal due to rainfall, known as rain attenuation, is a critical factor for the link design of satellite communications. On the other hand, from rain attenuation, we can obtain rainfall rate^[2-4]. In 2005, an Israeli research group employed rain attenuations of backhaul microwave links of a terrestrial cellular communication system recorded by a telecommunication operator to recon-

struct rainfall of Tel-Aviv and Haifa^[5]. More recently in 2011, a research group from the Netherlands used about 2 400 backhaul microwave links of an operator to reconstruct the national rainfall map of the Netherlands (about 35 500 km²)^[6].

Compared with rain gauges, weather radars and weather satellites, the use of backhaul microwave links of commercial cellular communication systems to measure rainfall does not require extra infrastructure investment, thereby incurring relatively low cost. For the operator of cellular communication systems, however, measuring and recording of the received signal levels (or the average received signal powers, from which rain attenuations are obtained^[7]) of the backhaul microwave links is for the purpose of network maintenance, not for rainfall measurement. As a result, neither the quantization precision nor the sampling frequency of the received signal levels is high enough^[7]. For example, the received signal levels for the above mentioned rainfall measurements in the Netherlands were the minimum and the maximum received powers over 15 min intervals with a precision of 1 dB, based on 10 Hz sampling of the received signals. As a comparison, a drizzle of 1mm per hour will only incur about 0.2 dB attenuation per kilometre^[8].

Instead of using the backhaul microwave links of cellular communication systems, we propose to employ the rain attenuations of the microwave communication links of LEO/MEO satellites to reconstruct rainfall. With multiple satellite ground receivers and/or multiple LEO/MEO satellites, similar to using X-ray to carry out human-body CT (Computerized Tomography) scans, it is possible to utilize the microwave signals of LEO/MEO satellites to achieve 3D rainfall tomography.

Compared with alternative methods, employing satellite signals to measure rainfall has distinct advantages. First, compared with using commercial terrestrial cellular communication systems^[5-8], which can only achieve 2D (Two-Dimensional) rainfall reconstruction with low precision microwave signal levels

available, 3D tomographic reconstruction of rainfall can be achieved with enhanced signal precision through the use of customized subsystems at satellite ground stations. Second, weather radars and weather satellites employ reflection and/or emission of microwave/visible light/infrared light signals, thereby the measurement precision for the interior of rainfall is quite low; the use of a tomographic approach, by contrast, will achieve high reconstruction precision for the interior of rainfall, since the signal attenuation employed in a tomographic approach is incurred by the interior and the exterior of an object in the same way. Third, compared with rain gauges that are scattered on the Earth, utilizing satellite signals can achieve rainfall measurements that are continuous in space. As a result, it is possible that the proposed 3D rainfall tomography using satellite signals can provide 3D measurements with precision and coverage unachievable to date.

We note that the idea of using signals emitted from artificial satellites to estimate some parameters of the Earth and the atmosphere is not new. For example, as water vapour in the air has an impact on the propagation delay of L band microwave signals, maps of atmospheric water vapor have been made using satellite signals of GOS (Global Positioning Systems)^[9-11], using GPS satellite signals, sea states and the soil moisture can also be monitored with GNSSR (Global Navigation Satellite Systems Reflectometry) technology^[12-14].

However, 3D rainfall tomography using satellite signals is still a hypothesis—to date no one else has done this. Only rainfall measurements using signals of geostationary satellites have been reported^[15,16]. With geostationary satellites, it is impossible to achieve 3D reconstruction of rainfall as only one projection (or one point) of the rain attenuation can be measured by one geostationary satellite and ground receiver pair. In this paper, we will report some preliminary rainfall measurement results using LEO satellites. Although they are still 2D, we believe that achieving 3D rainfall tomography is not far away.

3D reconstruction of rainfall could have a significant impact on atmospheric research and practical applications^[17-19]. In this regard, the GPM (Global Precipitation Measurement) mission, an international network of satellites that provides the global observations of rains and snows^[20], has recently been initiated by NASA and JAXA (Japan Aerospace Exploration Agency). The core observatory satellite of GPM, launched recently in 2014, has the capability of 3D imaging of rainfall. Fig.1 shows such a 3D image. However, since GPM is a global satellite precipitation measurement system, its focus is to help quantify the variability of global and regional water cycle processes^[20]. As will be shown in this paper, 3D rainfall tomography using satellite signals is most appropriate for measuring mesoscale or microscale rainfall systems.

Figure 1 A 3D rainfall map near the centre of the developing tropical cyclone Tropical Cyclone 05S (Bohale) on Dec. 9, 2015, produced by GPM. Credits: NASA/JAXA/SSAI/Hal Pierce, courtesy of NASA

The paper is organized as follows. The similarity to and differences with X-ray CT scans of the proposed 3D rainfall tomography are introduced in Section 2, along with possible solutions to two key problems. Preliminary research results are given in Section 3. In Section 4, some discussions are presented. Section 5 concludes the paper.

2 3D rainfall tomography using satellite signals

2.1 Coverage of the system

As shown in Fig.2, let us consider a system with multiple ground receivers and multiple LEO/MEO satellites. The diameter of the coverage of one ground receiver is given by

$$D = \frac{2h}{\tan \theta} ,$$

where h is the height of the rainfall and θ is the elevation angle of the satellite. Typically, the cloud height is 2 km to 4 km. The minimum elevation angle of the satellite can be less than 5° . Take $h=4$ km and $\theta=5^\circ$ as an example, the diameter of the coverage of one satellite ground receiver is then given by

$$D = \frac{2 \times 4}{\tan 5^\circ} \approx 91 \text{ km} .$$

Figure 2 Relationship between diameter of coverage, height of rainfall and satellite elevation angle for the proposed 3D rainfall tomography system with satellite signals

Mesoscale meteorology is the study of atmospheric phenomena with typical spatial scales between 10 km and 1 000 km, and microscale meteorology is the study of short-lived atmospheric phenomena smaller than mesoscale. As a result, the proposed system is most suitable for the measurement of rainfall at the mesoscale or microscale.

2.2 Similarity to X-ray CT scans

The rainfall rate can be obtained using the following

well-established empirical relationship between rain attenuation and rainfall rate^[21].

$$A = aR^b,$$

where A is the rain attenuation in dB/km, a and b are two coefficients dependent on frequency and polarization of the microwave signal, and raindrop size distribution, and R is the rainfall rate in mm/h.

In Fig.2, along with the movement of an LEO/MEO satellite around the Earth, the line segment that connects the satellite antenna and the ground receiver antenna forms a plane. With multiple satellites and multiple ground receivers, multiple intersected planes are then formed, enabling 3D rainfall tomography using rain attenuations. To obtain the distribution of rain attenuations in a 3D space, in the following, we will show that the 3D tomographic reconstruction of rain attenuations has a similar mathematical model to the X-ray tomographic reconstruction of an object.

The rain attenuation in a 3D space of interest can be represented by a function $a(\mathbf{x})$, where $\mathbf{x}$ is a vector that denotes the three coordinates in the 3D space. The total rain attenuation along a line segment $\mathbf{x}_0 + t\boldsymbol{\omega}$, $t \in [\alpha, \beta]$, where $\mathbf{x}_0$ is a point on the line segment and $\boldsymbol{\omega}$ is the direction of the line segment, is then the line integral of $a(\mathbf{x})$,

$$A_t = \int_{\alpha}^{\beta} a(\mathbf{x}_0 + t\boldsymbol{\omega}) dt. \quad (1)$$

The total rain attenuation can also be obtained from the received signal power at the satellite ground station using the following measurement model.

$$A_t = P_T - P_R - A_0 - C, \quad (2)$$

where P_T is the transmitted power from the satellite, P_R is the received signal power at the ground station, A_0 is the distance dependent attenuation of the microwave signal due to factors other than rainfall, and C is an unknown constant that represents factors such as the gain of RF chains and antennas. It can be seen that the model described by Eq.(1) and Eq.(2) is similar to that in computerized tomography with non-diffracting sources (e.g., X-ray)^[22,23].

2.3 Differences with X-ray CT scans

Although the basic model given by Eq.(1) and Eq.(2) is similar to that in X-ray CT scans, there are two key differences (or problems) in tomographic reconstruction of rainfall:

Problem One—Unlike X-ray CT scans, where the geometry of the X-ray transmitters and receivers is a design parameter, we need to use satellites with orbits that are not purposely designed for rainfall measurements. Therefore, the projection-slice theorem^[22] that underpins X-ray CT scans cannot be satisfied for 3D rainfall tomography. At any specific time in a day, due to the limited number of satellites overhead, it is insufficient to only use the satellite data to reconstruct the rainfall of a 3D space.

Problem Two—In the measurement model of Eq.(2), while P_R is available at the satellite ground station and A_0 can be calculated based on the satellite's orbit (available at the satellite ground station, also available to the public from the European Space Agency³), $P_T - C$ is unknown. This is different from X-ray CT scans—the measurement of the ratio of monochromatic X-ray photons that enter an object to those that leave can be obtained, which gives the X-ray attenuation^[22].

Due to the above, the X-ray CT reconstruction algorithms such as the algebraic reconstruction algorithms^[22] and the ordered subsets Expectation Maximization based projection algorithms^[24] cannot be directly applied to the tomographic reconstruction of rainfall.

2.4 Proposed solutions

To solve the first problem, we propose to divide the 3D space of interest into multiple blocks. Each block is assumed to have an unknown but constant rainfall rate, which is associated with a rain attenuation variable. From Eq.(1), it can be seen that the total rain attenuation A_t is a linear function of those variables. At any specific time, as the number of satellites overhead is

3 <http://www.calsky.com/cs.cgi?obs=74710082991896>.

limited, the number of unknown variables can be larger than the number of received signal power measurements at the satellite ground station. The following two approaches can then be employed to tackle this issue.

- Optimization with the use of a measure of the rain attenuation variables—An optimization problem can be formulated by minimizing a proper norm (e.g. the Euclidean norm) of the variables with the constraints of the measurement Eq.(2). Then, optimization tools such as convex optimization^[25] may be employed to tackle the optimization problem. For rainfall phenomena with significant space variations (e.g., tornadic storms and downbursts), an objective function that biases towards the contrast of an image may be adopted for the optimization problem. The rain attenuation variables may have some sparse representations. Therefore, the methods available in compressed sensing^[26] can be used.
- Introduction of constraints to the rain attenuation variables explicitly—Correlations among the rainfall rates of different blocks, which are closely relevant to the types of rainfall and the orographic effects, lead to the constraints among the rain attenuation variables. The wind field map⁴ may also be employed to help establish such constraints. Some mathematical models such as the PGM (Probabilistic Graphical Models) or HMM (Hidden Markov Models) can be used to introduce constraints among the rain attenuation variables. Algorithms associated with PGM or HMM^[27] can then be employed to estimate the distribution of the rain attenuations in a 3D space.

To solve the second problem, the following methods may be employed.

- Satellites with spot beams (i.e. narrow beamwidth)—We can assume that $P_T - C$ is an unknown constant during one pass of the satellite. The unknown constant may then be treated as an extra

variable accommodated into the 3D tomographic reconstruction algorithms. Alternatively, as in rainfall reconstruction with backhaul networks of cellular communication systems, the rain period and the no-rain period may be determined first^[7]. The no-rain period can then be treated as a baseline accommodating the unknown constant. The rain attenuation can be obtained from the received signal power during the rain period taking out the received signal power during the no-rain period. In addition, rain gauges may be employed to calibrate the system, thereby eliminating the impact of the unknown constant.

- Satellite with large beamwidth—In this case, $P_T - C$ can be time-varying during one pass of the satellite, since the main beam of the satellite antenna does not always point to the ground station. In this scenario, stochastic models (e.g., the autoregressive model^[28]) may be employed to capture the time-varying characteristics. Probabilistic graphical models and their associated algorithms can then be used to estimate the time-varying $P_T - C$.

3 Preliminary results

Using the average received signal powers recorded by the Miyun satellite ground station of the Institute of Remote Sensing and Digital Earth (RADI), Chinese Academy of Sciences, we have carried out some preliminary work in rainfall tomography using X band satellite signals. The basic idea of the work is as follows. First, to introduce constraints among the rain attenuation variables, we use a set of basis functions to represent them. That is, each rain attenuation variable associated with a block in the 3D space of interest is a linear combination of the basis functions. To estimate the value of a rain attenuation variable, the problem then amounts to determine the weighting coefficients of the linear combination. Second, an ANN (Artificial

4 <http://earth.nullschool.net/>.

Neural Network) model^[29] is employed to learn the weighting coefficients of the linear combination. In addition, we assume that during one pass of the satellite, $P_T - C$ does not change, which is treated as a positive DC offset in the radial basis function of the neural network model^[29]. Third, to the 3D space of interest, we only consider a 2D horizontal plane, i.e. in the vertical column of the 3D space, the rainfall rate is assumed to be a constant from ground to the top of the rainfall.

Fig.3(b) shows an example of the reconstructed 2D rainfall maps using a commercial LEO satellite covering a rural area of about 10 000 km² near Miyun, Beijing, China. The corresponding rainfall map provided by the GSMaP_NRT (Global Rainfall Map in Near Real Time⁵) products covering the same area is shown in Fig.3(a). It can be seen that they have good agreement. In particular, the location of the center of the heavy rain is roughly the same. Note that the Earth map is also shown in Fig.3, which is covered by the rainfall map. We deliberately eliminate part of the rainfall map with a rainfall rate less than 5 mm/h to show part of the Earth map. Also note that the measurement time of the two maps was slightly different, as GSMaP_NRT only provides one hour average rainfall map, but the overhead time of the employed satellite was about eight minutes.

Figure 3 The rain map courtesy of GSMaP_NRT (one hour average rainfall rate UTC 13:00-14:00, Aug. 5, 2015); The 2D tomographic reconstruction of rainfall by us (note that the red line is the ground track of the LEO satellite that was used in this work. The satellite overhead time was UTC 13:39:58-13:48:04, Aug. 5, 2015). In both (a) and (b), the Miyun station is located at the centre

4 Discussions

4.1 3D rainfall benchmark

To produce a 3D rainfall map itself is not a difficult task. For example, the ANN based method of the previous Section can be used to produce it. But without a proper benchmark, such a map does not tell anything meaningful. Except for those produced by the GPM, however, there are few 3D rainfall maps available for comparison. To solve the problem, synthetic data should be employed. In particular, the ARPS (Advanced Regional Prediction System)⁶, which is a 3D, non-hydrostatic modelling system that can simulate atmospheric phenomena ranging from regional scale down to microscale and is free for public use, may be employed to create them.

4 <http://sharaku.eorc.jaxa.jp/GSMaP/>.

5 <http://www.caps.ou.edu/ARPS/arpdown.html>.

4.2 Enhanced 3D tomography of rainfall using power spectral density and polarization

To increase the data rate, the microwave signals employed by satellite communications are often broadband. As a result, besides the average signal power, the power spectral density is available at a satellite ground station. On the other hand, rain attenuations depend on the frequencies of microwave signals, which can be exploited to improve the performance of rainfall measurement. For example, it has been shown that the difference in the attenuations experienced by a pair of frequencies, if well chosen, can be insensitive to unknown parameters such as raindrop size distribution^[30-32]. Rain attenuations at multiple different frequencies can be obtained from the power spectral density of a broadband microwave signal; therefore they can be exploited to improve the performance of rainfall reconstruction.

The polarization of the satellite signals is often used in satellite communications too. As a result, the depolarization effects to the microwave signals due to raindrop canting angles, ice crystals, and the melting layer can be observed at a satellite ground station^[33-35].

Since both power spectral density and polarization of LEO/MEO satellite signals are impacted by rainfall, both may be exploited to enhance the proposed 3D rainfall tomography. In particular, it may be possible to analyse the dynamics of the precipitation microphysics (e.g., raindrop size distribution, attributes of melting layer and ice crystal layer^[37,38]) using the power spectral density and polarization of the satellite signals. In addition, it is also possible to use power spectral density and polarization of satellite signals to measure atmospheric phenomena other than rainfall, such as sleet^[39], water vapour^[40], and sand dusts^[41,42], as they all have an impact on the propagation of microwave signals.

4.3 Potential applications of 3D tomography of rainfall

Through 3D rainfall tomography, real-time observation of the 3D dynamics of microscale or mesoscale meteorological phenomena, e.g. tornados and thunderstorms, may be achieved. As a result, it can help improve our understanding of many rainfall relevant phenomena including extreme weather, floods, landslides, and the spread of water-borne diseases, potentially paving the way for many new applications such as weather modification (e.g., by telling the right time and the right place in the atmosphere to put some proper materials to enhance rainfall) and accurate hydrological modelling.

By taking rainfall as an agent in the atmosphere, rainfall tomography using satellite signals may also provide a means of observing the dynamics of the atmosphere, thereby potentially paving the way for new findings in atmospheric sciences. For example, although there are research projects on tornados (e.g., the VORTEX projects⁷), there remain many mysteries; some microscale/mesoscale meteorological phenomena such as downbursts and microbursts can incur severe damages. How to predict them and mitigate their impact? 3D rainfall tomography with satellite signals may help to find the truths/solutions.

3D rainfall tomography is a new tool with a capability of retrieving 3D rainfall data that are difficult to be obtained with alternative technologies. As a complement to other available global data, the new data may be used as input to computer models for weather forecast in particular nowcasting, and for predicting future changes in climate.

5 Conclusion

In this paper, we have proposed a hypothesis of 3D rainfall tomography using satellite signals. Along

7 <http://www.vortex2.org/home/>.

with the deployment of LEO satellite constellations (e.g., the OneWeb constellation) for global broadband Internet services, it is possible to use small satellite receivers (e.g., size of a pizza box) to achieve 3D rainfall tomography anywhere on the Earth, including remote terrestrial and ocean areas. We believe that such a system, if successful, will pave the way for many practical applications and atmospheric research.

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