THE POTENTIAL OF MICROWAVE LINKS FOR PROVIDING INFORMATION CONCERNING THE AMOUNT AND TYPE OF PRECIPITATION

Graham J. G. Upton, Rob J. Cummings, Anthony R. Holt

Department of Mathematical Sciences
University of Essex
Wivenhoe Park, Colchester, Essex. CO4 3SQ. UK

ABSTRACT

In this paper we summarize the findings of three research contracts undertaken in the period 1999-2008. We show that microwave links can provide accurate estimates of path-averaged rainfall and that they can be used for the remote detection of snow and melting snow. They are also shown to be effective in online adjustment of weather radars.

Index Terms— Attenuation, Phase measurement, Radar measurements, Rain, Snow

1. INTRODUCTION

Over the last ten years, investigators at the University of Essex, in collaboration with many organizations in the UK, and with teams in Denmark, Germany, and Italy, have been investigating and developing the use of microwave links for precipitation measurement. In this paper we outline the previous work that has been described more fully in [1, 2, 3, 4, 5, 6] and then describe some of the results of our most recent research.

2. THEORY

2.1. Attenuation by rain

Suppose that a linearly polarised electromagnetic (*em*) wave with wavelength λ (cm) is scattered by a raindrop of equivolume diameter D (cm) to give a (complex) co-polar forward scattering amplitude $\mathrm{f}(D)$. Suppose that the wave passes through a precipitation region for a distance of 1 km, with the dropsize distribution being $\mathrm{N}(D)\mathrm{d}D$ (cm^{-4}). The resulting specific attenuation A (dB km^{-1}) is proportional ([7]) to the imaginary part of

$$\frac{2\pi}{\lambda} + \lambda \int_0^{D_{max}} \mathrm{N}(D)\mathrm{f}(D)\mathrm{d}D \qquad (1)$$

where D_{max} is the maximum drop diameter. The specific attenuation is dependent on temperature, drop shape, the drop size distribution (*dsd*) and, crucially, the frequency and plane of polarization of the em wave. In general, if these parameters are held constant whilst the rainrate is increased then the specific attenuation will increase non-linearly (see e.g. Fig 3 in [3]) and, more importantly, in a way that varies with dsd. The dependence on dsd appears to be least at around 24 GHz where the relation is slightly non-linear. The relation is closest to linearity near 35 GHz, though here the variation with dsd is greater. For frequencies much below 17.5 GHz the rainrate for a given attenuation is both non-linear and dependent on the dsd. Since gaseous absorption is at a peak at about 22.3 GHz, the most useful commercial frequencies are likely to be in the ranges 17.5 GHz to 20 GHz, or 24 GHz and above.

2.2. Attenuation difference

The genesis of the UK work was the chance observation that the *difference* in the attenuation between two frequencies used by the Olympus satellite appeared to be linearly related to the on-path rainfall [8]. Following this observation, pairs of frequencies (and polarizations) for which the attenuation difference was approximately linearly related to rain rate and was insensitive to changes in dsd or temperature were identified [3].

The desirable consequence of a linear relation is that, for example, a uniform rainrate of R along the entirety of a microwave link will result in the same attenuation as a rainrate of $2R$ on one half of the link and zero on the other half. The total attenuation thereby provides a direct measure of total rainfall along the link.

2.3. Phase and differential phase

In our recent research we have transmitted an em wave with a 45° polarization and have received its separate horizontal and vertical components. The phase of a wave is slowed by its passage through media, with the amount being proportional to the real part of quantity given in Equation (1).

If the media consist of (small diameter) spherical raindrops then the retardation will be the same for each component. However, with large raindrops (shaped like oblate

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spheroids) the retardation will be greater for the horizontal component than for the vertical component. Thus the differential phase (the difference between the phases of the two components) provides an indication of the shape (and hence the size) of the particles through which the wave has passed. However, it should be noted that, for rain, differential phase is only of use for frequencies below around 13GHz, since at higher frequencies the contribution from large drops becomes negative, whereas that for smaller drops is positive.

In snow (where attenuation is negligible) the differential phase (which depends on the refractive index of the scattering medium) can be appreciable. Thus differential phase provides a remotely sensed snow detector.

2.4. Attenuation ratio

When an em wave polarized at 45° passes through spherical rain droplets, the attenuations of the horizontal and vertical components will be the same, so that the attenuation ratio (attenuation in the horizontal plane divided by attenuation in the vertical plane) will be unity. However, for aspherical droplets, the attenuation ratio will be greater than 1.0 (and is typically around 1.1). The greater the ratio, the larger must be the typical on-path droplets.

3. PRACTICAL DETAILS

Theory is one thing; practice can be rather different. Theory has one looking at a signal received at constant power (no rain) interrupted by occasional power reductions (rain). Practice sees a signal arriving with constantly fluctuating power. Paradoxically, the major problem in determining the rainfall in an event is the determination of when it is raining!

Electromagnetic waves are subject to absorption by mist or fog, to refraction by the earth's atmosphere, to reflection from the ground, hillsides, trees and buildings. All these factors are constantly changing. The most extreme scintillation that we have observed occurred on windless nights, when the air was settling in layers and small changes in the layers were causing big changes in refraction of the beam, and hence in the multipath reflections received.

3.1. Equipment requirements

If the link transmitter and receiver are not shielded, then there will be additional attenuation due to precipitation lying on the instruments. In the case of snow this can result in a steady increase of attenuation followed by a sharp drop when the snow falls off the instrument. In the case of rain the attenuation through an event, and for a period afterwards,(as the equipment dries) will have been slightly enhanced.

3.2. Baseline estimation

As noted above, with wet equipment the apparent baseline immediately after the event may differ from that when the equipment is dry. In earlier work we have described procedures for identifying dry periods on either side of an event [5] with the baseline through the event itself being estimated by linear interpolation. However, while this may give the most accurate link-based estimates, such estimates would not be available until the event has finished. For real-time purposes the baseline estimated just prior to the event must be used.

With dual-frequency links it is possible to get an idea of when rain is falling by studying the correlations in the two attenuations [2, 9, 4]. However, accuracy is increased if there are direct observations (e.g. through raingauges) in the neighbourhood of the link [5]. Although gauges give good time coverage, they cannot indicate what is happening along the entirety of a link. By contrast, a radar gives a clear indication of when rain is falling on the link (albeit only at, say, 5-minute intervals). There is therefore a nice synergy in our current research since the radar 'calibrates' the link with respect to baseline identification and the link then 'calibrates' the radar with respect to the amount of rain falling (see Section 5.2 below).

4. ASSESSING ACCURACY

To test agreement between hourly rainfall totals (either path averages estimated by link or radar, or point values measured by gauges or estimated by radar) we use three standard measures used by the UK Met Office. Denoting the sets of N values being compared by X and Y, these are:

$$\text{RMS} = \sqrt{\frac{1}{N}\sum(X-Y)^2} \tag{2}$$

$$\text{RMSF} = \exp\left\{\sqrt{\frac{1}{N}\sum\left\{\ln\left(\frac{X}{Y}\right)\right\}^2}\right\} \tag{3}$$

$$\text{Bias} = \frac{1}{N}\sum(X-Y) \tag{4}$$

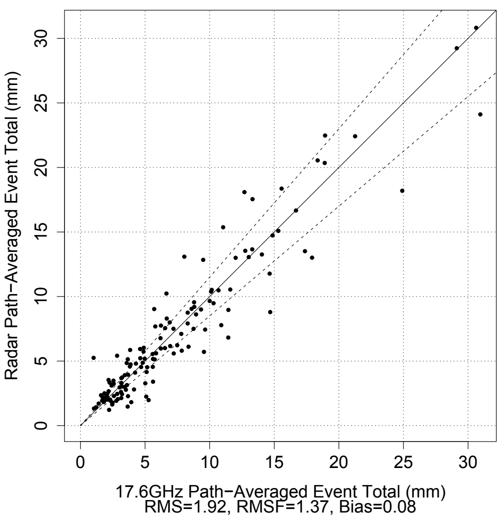
5. APPLICATIONS

5.1. Rainfall measurement

A summary of dual-frequency results has been provided by [5], who also provide results for single-frequency estimation using a horizontally polarized 22.9 GHz link on a 14 km path. Our more recent research has focused on a 23.3 km link near Bolton in North West England, using a horizontally polarized 17.6 GHz link. The nearby Hameldon Hill radar was used to determine the wet and dry periods, and the baseline before an event was taken for reference through the event.

Fig. 1 summarizes the results for the 140 rain events from October 2005 to February 2007. On the x-axis is the estimate

Fig. 1. Scatter diagram of estimates of path-averaged rainfall from radar and from the horizontally polarized 17.6 GHz link



obtained from the 17.6 GHz link, while on the y-axis is the corresponding radar-based estimate using a weighted combination of the values recorded over 14 cells of the radar's 2 km $\times$ 2 km Cartesian grid. The dotted lines correspond to $\pm 15\%$ of the link value. On average there is negligible bias, though the agreement between the estimates is not as close as had been found with the dual-frequency procedure.

5.2. Radar adjustment

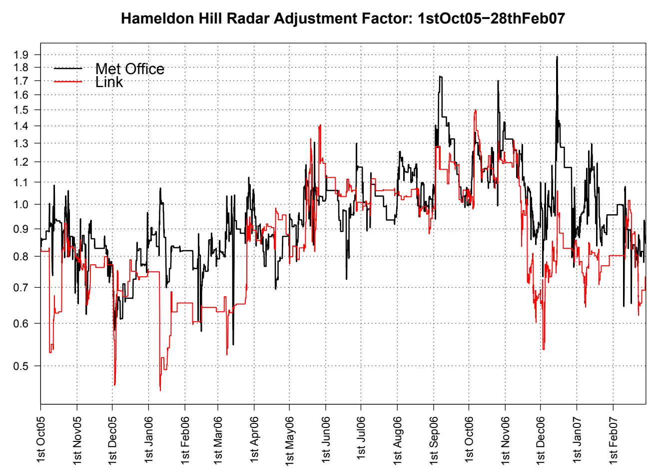
Weather radars collect reflectivity data on a polar co-ordinate basis. Those data are adjusted for range and height effects with cluttered cells being ignored. A power-law relation converts reflectivity to rainfall and the data are then converted to Cartesian coordinates. The final step is a comparison of the radar estimates with ground truth, where 'ground truth' has meant raingauge data. The UK Met Office uses a modification due to [10] of a procedure introduced by [11] that involves a weighted combination of the individual one-hour gauge/radar ratios, updated every hour. The calculations, are carried out separately using nine alternative integration times ranging from 1 hour to 2000 hours. An algorithm determines which integration time is relevant and the corresponding multiplicative factor, θ, is used to provide the final adjustment to the radar-based estimates of rainfall.

We have adapted the existing procedure for use with the integrated link rainfall values. Let θ_i be the multiplicative factor in hour i, during which the hourly accumulations estimated from link and radar data are, respectively, L_i and R_i. We have used

$$\theta_i = \theta_{i-1}^{(1-w_i)} \left(L_i/R_i\right)^{w_i} \tag{5}$$

where w_i is an estimate of the proportion of the link that experiences rain in that hour. Fig. 2 shows the adjustments for the UK Met Office's Hameldon Hill weather radar using their current gauge-based procedure and the link-based procedure of Equation (1).

Fig. 2. Time series of gauge-based and link-based adjustments (values of θ_i)



The results in Table 1, which refer to the alternative radar estimates of one-hour rainfall at test gauges, suggest that the link-based procedure is at least as effective as the current gauge-based procedure.

Correction	RMS	RMSF	Bias
Gauge-based	1.39	1.58	−0.24
17.6 GHz radial link	1.35	1.61	0.02

Table 1. The comparative accuracy of gauge-based and link-based adjustments of the Hameldon Hill Met Office radar

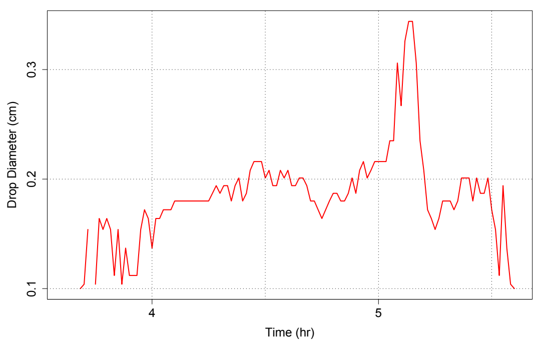
5.3. Radar calibration

Attenuation affects radars just as it affects microwave links. X-band radars, which are useful for monitoring small catchments are particularly affected. In an experiment at Essen in Germany, a 29.6 km vertically polarized 10.5 GHz link was situated with one end beside the 9.47 GHz horizontally polarized X-band radar. At these frequencies the radar's attenuation is about 90% of that experienced by the link. The attenuation experienced for the radar cell at the far end of the link can be determined and the rain in that cell estimated. The contribution of that rain to the total attenuation is then estimated and the reduced attenuation experienced by the penultimate cell is estimated. This is repeated in the direction of the radar. The details are given by [12].

5.4. Dropsize information

The monotonic relation between attenuation ratio and dropsize implies that the combination of transmission at $45°$ and the separate reception of horizontal and vertical components enables one to plot changes in the typical drop size through a storm. Figure 3 shows the plot for an event on Jan 17th, 2007.

Fig. 3. Time series of changes in typical drop size through a single event



5.5. Detection of melting snow

Melting snow has a complex physical structure [13], but its effect on a microwave link is easy to describe. A melting snowflake will 'appear' to an em wave as though it were an enormous raindrop, and will therefore attenuate the wave disproportionately to the volume of water that it contains. By comparing the attenuations at two different frequencies it is possible to identify when melting snow is affecting a link without recourse to other measurements [6].

5.6. Information from phase

Our current research has shown that, at 12.8GHz, differential phase is a useful complement to attenuation for the measurement of path-integrated rainfall and can provide information about humidity. In a snow storm the time series of differential phase has a similar appearance to that seen in rain, but without any comparable change in attenuation.

6. REFERENCES

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