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MEASUREMENT OF AIRBORNE VOLCANIC ASH USING MILLIMETER-WAVE RADARS

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1. INTRODUCTION

Radars have been used to measure volcanic ash plumes for some time, and the technique is becoming increasingly mature (See, for example, Harris and Rose (1983), Rose et al. (1995)). However, it typically relies on data from existing weather radars, designed for the detection of rain rather than volcanic ash. These radars are often far from the volcano, and can only offer fairly low resolution.

The two key applications of remote measurement of volcanic ash are: (i) to estimate the mass of ash being emitted in a given ash plume and (ii) the detection and measurement of airborne ash in areas where the ash may interfere with aircraft operation. The first application provides critical data as input to atmospheric dispersion models, allowing (if the source term is accurately measured) very good modelling of where the ash will go, and in what concentration. The importance of the second application is self-evident and well known – to detect a hazard to aircraft. Additionally, it would be of scientific interest to be able to determine the particle size distribution (PSD) and mass loading of the ash in various parts of the cloud.

The work described here aims to show that ground-based millimeter-wave radars have considerable potential for the measurement of volcanic ash plumes, compared with existing low-frequency weather radars. It also suggests the use of a dual-frequency measurement technique to determine the Particle Size Distribution (PSD) of the volcanic ash without resorting to measurement of ash once it lands on the ground. This would allow for more precise estimation of the mass concentration of the volcanic ash being measured.

The potential millimeter-wave radar system requirements for measurements of ash suspended high in the atmosphere at the very low mass concentrations that might affect aircraft are also examined.

2. SIMULATION METHOD

It has been suggested (Marzano et al. 2006) that the PSD of volcanic ash clouds can be described by a normalized gamma distribution. Marzano has further shown that this can be expressed in terms of the concentration C_a, mean particle diameter D_n and shape parameter μ:

$$N(D) = \frac{6\, C_a D_n^{\mu}}{\pi \rho_a (3+\mu)!}\left(\frac{(\mu+1)!}{D_n(\mu!)}\right)^{3+\mu+1}\left(\frac{D}{D_n}\right)^{\mu} \times \exp\left(-(\mu+1)\left(\frac{D}{D_n}\right)\right) \qquad (1)$$

where ρ_a is the density of the solid ash (taken to be 1×10^6 g m^{-3}). μ is taken to be 1.

The ash particles will have somewhat arbitrary shapes and orientations, which would be very challenging to simulate. Instead, the particles are treated as spherical, with Mie scattering assumed. This will inevitably introduce some additional error, but it is thought that the net effect on averaged results should be small.

The bulk permittivity of the ash is taken to be $6.15 - 0.135j$, the average result of W-band (75 - 110 GHz) measurement of many different dry volcanic ash samples reported by Rogers et al. (2011). While these measurements were only performed at W-band, the value measured by Rogers corresponds well with that measured by others at lower frequencies, for example Adams (1996). As a result, and for the purposes of modelling, this value is assumed to hold across frequencies from 1 GHz to 1 THz. Note that Rogers' permittivity measurements made the assumption that the ash is non-magnetic, which may well not be strictly true, so this will introduce a small error. It should also be highlighted that Roger's values were for dry ash and that in reality, ash in plumes will exist in the presence of water vapour and other gases which will modify the permittivity. These effects are currently unknown and have been ignored for this analysis.

Since the volcanic ash is a collection of small, moving, randomly oriented particles of similar RCS values, it can be expected to behave as a Swerling 2 target (Richards, 2005). As a result, the measured

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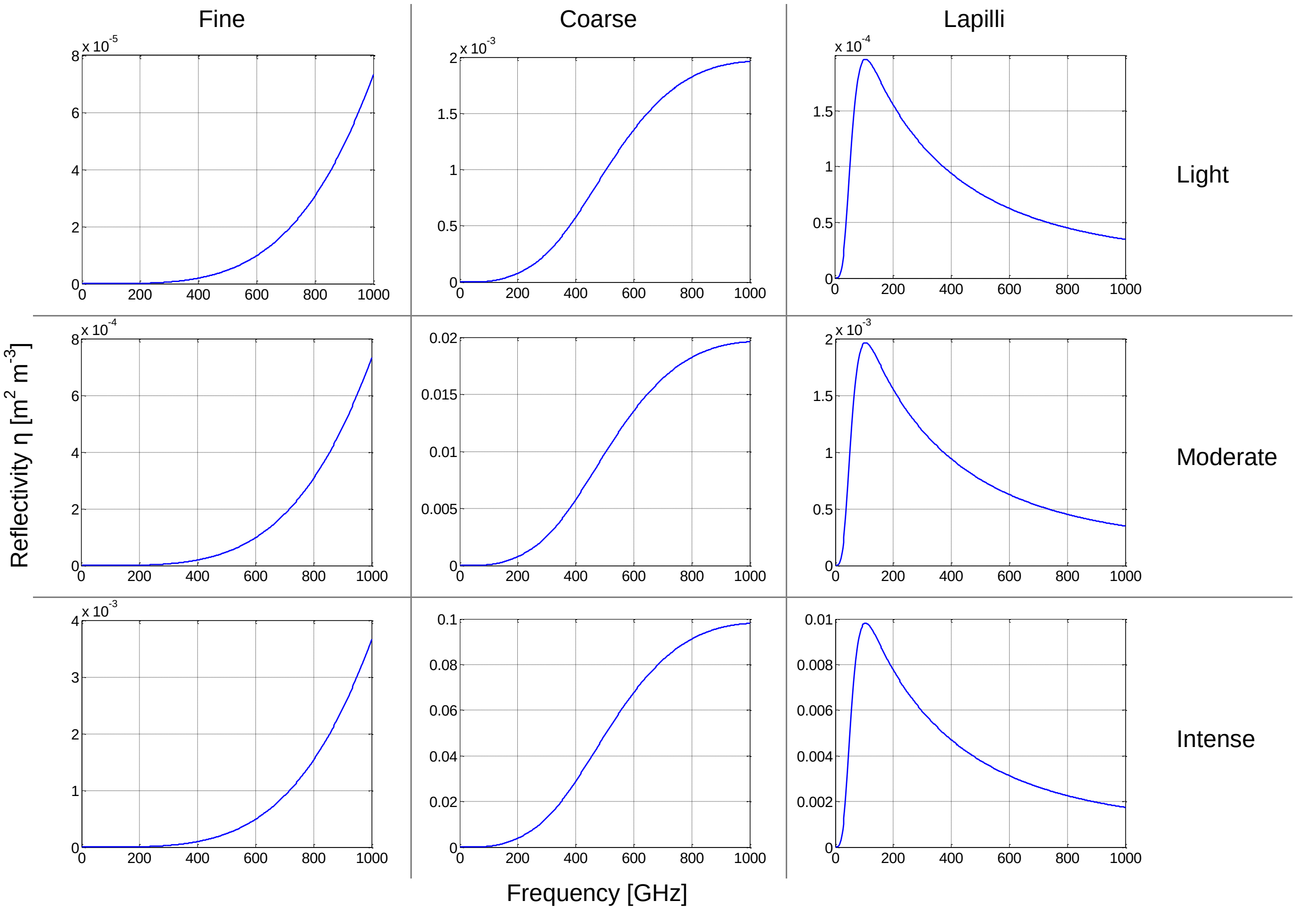

Figure 1 The reflectivity of the volcanic ash as a function of frequency for the nine different Marzano ash categories considered. Note that, due to the form of equation 1, increasing concentration results only in a multiplicative factor, not affecting the shape at all.

volume reflectivity can be expected to vary according to an exponential distribution. However, over the many averages that will be needed, the measured value will tend towards the expectation value given by the standard expression:

$$\eta(f) = \int_0^{D_{\max}} N(D; D_n, C_a)\sigma(D; f, \epsilon)dD \qquad (2)$$

with $\sigma(D, f, \epsilon)$ being the RCS of a sphere of diameter D, frequency f and permittivity ϵ.

The expectation value of the power received by the radar is calculated by application of the Probert-Jones equation (Probert-Jones, 1962).

Whether or not the ash is detectable, for a chosen acceptable probability of false alarm (P_{FA}) and probability of detection (P_D), is determined using the method given by Richards, (2005), again assuming that the ash is a Swerling 2 target. This does not show how accurate the measurement will be *per se*, but the level above the minimum detectable signal does give a measure of this.

3. SELECTING AN APPROPRIATE PLUME DETECTION FREQENCY

In order to provide some representative values for concentration and diameter pairs, the set of nine ash categories used by Marzano (2006) are used. These are listed in table 1 below.

	Fine	Coarse	Lapilli
Light	0.1 g/m^3 0.01 mm	0.1 g/m^3 0.1 mm	0.1 g/m^3 1 mm
Moderate	1 g/m^3 0.01 mm	1 g/m^3 0.1 mm	1 g/m^3 1 mm
Intense	5 g/m^3 0.01 mm	5 g/m^3 0.1 mm	5 g/m^3 1 mm

Table 1 The nine ash categories proposed by Marzano (2006).

The reflectivity of volcanic ash can then readily be determined as a function of frequency for these nine value pairs, as shown in figure 1. If this were all that mattered in detecting the volcanic ash then it can be seen that for the lapilli cases a frequency of around 100 GHz would be appropriate. For the fine and coarse cases it would appear that the higher the frequency the better.

However, atmospheric attenuation is significant at these frequencies, and so must be considered. For this purpose, the Liebe (1989) atmospheric attenuation model is assumed, combined with path attenuation through the US standard atmosphere (per ITU-R P. 835-2).

In order to make these calculations it is necessary to make some assumptions about how the measurement would be made. It would be prohibitively expensive to install one or several fixed ash monitoring radars at every potential site of an eruption. Instead, it is thought that it would be better to have a smaller number of radars that could quickly be moved near to the site of an eruption as it begins. Thus the radars would have to be small enough to be portable. In order to obtain high resolution data, and to maximise the systems performance, ideally the radar would be sited reasonably close to the volcano. For the purpose of these calculations it is assumed that the radar will be sited 3 km laterally away and that the ash being imaged is at a height of 500m above the ground. A 100m range bin depth has been assumed.

The portability requirement dictates that the radar has a small antenna and in the following calculations this has been set at 0.5 m diameter. The gain of the antenna is then calculated from $G = \left(\frac{\pi d}{\lambda}\right)^2$, and the beamwidths from $\theta_0 = \phi_0 = \sqrt{\frac{26000}{G}}$ (Skolnik, 2001).

The potential need to operate far from mains power for long periods suggests that a lower power solid state radar would be required. For this reason, it is assumed that a frequency-modulated continuous wave (FMCW) system is used with a transmit power of 20 dBm, a 1ms chirp (leading to a bandwidth of 1 kHz) and that the system has a noise figure of 10 dB. These figures are plausible at frequencies of up to around 300 GHz, and become easier to exceed at lower frequencies. However, they would be somewhat challenging to achieve at the highest frequencies considered here.

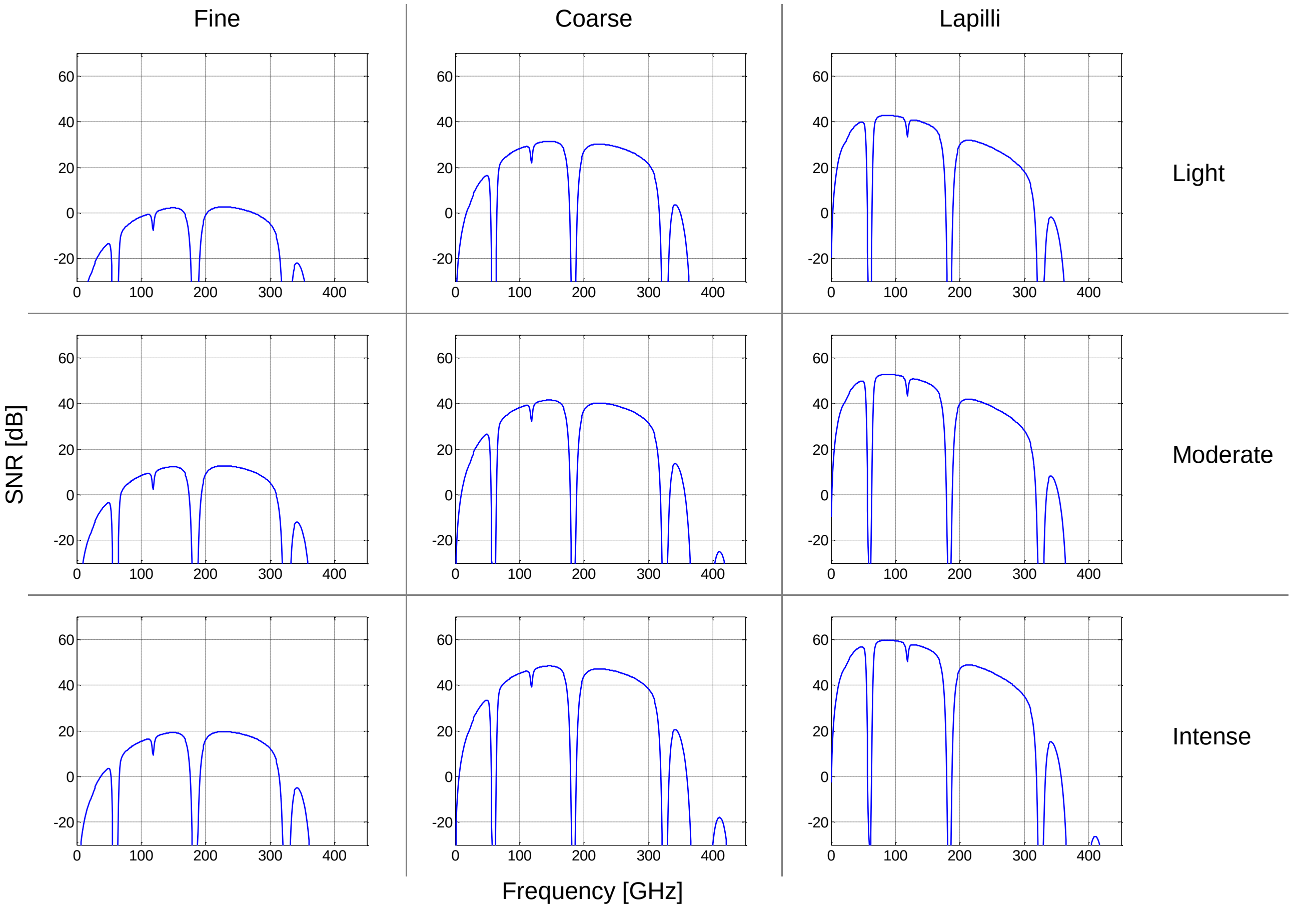

Figure 2 The signal to noise ratio (SNR) as a function of frequency for the sample radar system described in the text. It can be seen that different atmospheric windows are optimal for different ash categories, but that many of the lower millimeter-wave frequency windows offer good performance for all of the ash categories shown.

Nonetheless, the modelling is simplified through the use of these single compromise values.

With all of these assumptions, the expected signal to noise ratios (SNRs) from the nine ash categories are shown in figure 2**Error! Reference source not found.**. It can be seen that there are optimal windows for measurement at around 85 GHz and 150 GHz under these conditions. Note however that due to atmospheric attenuation, this is a function of range. By about 40 km, frequencies of around 40 GHz become optimal.

4. THE EXPECTED PERFORMANCE OF A CANDIDATE SYSTEM

The performance of the systems simulated in the preceding section could readily be met in practice, and it is perhaps useful to illustrate what the limits on such a system might be. An existing system that might be used to make some of these measurements is the AVTIS-2 radar system developed at St Andrews (description of AVTIS-2 not yet published, but the original AVTIS radar discussed in Robertson and Macfarlane, 2004). This is a 94 GHz (and hence in the 85 GHz frequency window) FMCW radar, with an antenna gain of 51.4 dBi, a 3dB one-way beamwidth of 0.5°, a transmit power of 20 dBm and a noise figure of 10 dB. It is ordinarily used for monitoring the changing topography of a volcano, but it is thought that it may also be useful for measuring volcanic ash.

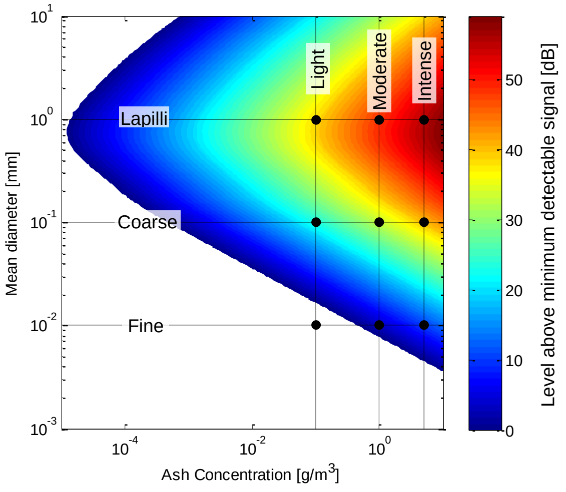

Figure 3 The shaded region indicates the detectable mean diameter/ash concentration value pairs with the AVTIS-2 system. The black points indicate the nine Marzano ash categories.

The finest possible range resolution with this system is around 1.8 m, but for the purpose of these measurements it is likely to be beneficial to consider a far larger sample volume, since this increases the reflected power per bin. Range bins of 10m depth have been assumed.

As before, the ash is assumed to be at a 3km lateral range and at a height of 500m. The acceptable P_D is set as 0.9 and P_{FA} is set as 10^{-3}. It is assumed that 500 averages would be taken along each line of sight (meaning that each line of sight would take around half a second).

The anticipated performance of this system is shown in figure 3. It can be seen that this would be able to detect 8 of the 9 Marzano categories, and in particular the larger, more concentrated cases are very comfortably within the detection region.

However, a serious problem with such a measurement is that, while the reflected power value dictates which contour on the plot the volcanic ash lies on, it does not on its own determine which diameter/concentration pair has been measured. This could be done by making some additional assumptions about the ash being measured, perhaps by sampling the PSDs of the ash once it has fallen to the ground, but it would be rather more satisfactory to be able to make this measurement while the ash is still airborne.

5. DUAL-FREQUENCY MEASUREMENT

One possible way of resolving the diameter/concentration ambiguity would be the measurement of each ash sample volume at two frequencies. It can be seen by inspection of equations 1 and 2 that the ratio of the reflectivities is independent of the ash concentration and so dependent only on the mean diameter.

It is necessary to choose two frequencies at which the variation in reflectivity as a function of mean diameter are different. This is best achieved by working with one frequency that lies all or mostly in the Rayleigh scattering regime and one that is at least partially into the Mie scattering regime. It is also important to ensure that the mapping between mean diameter and reflectivity ratio is one-to-one over the expected plausible range of diameters.

The concentration can then be determined by substituting the mean diameter back into either of the two reflectivity relations and then solving for the concentration.

6. DETECTING ASH IN AIRSPACE

Detecting volcanic ash in the atmosphere at the heights and low concentrations that might affect aircraft is a far more challenging problem than detecting the ash plumes alone. This is a result of the concentrations of interest being around 25 to 500 times lower than the concentration of the least dense Marzano ash category.

Figure 4 shows figures for detectability for the AVTIS radar operating at 20dBm measuring volcanic ash at a height of 8 km, with the same basic specifications as given earlier. It can be seen that this low power portable radar is not able to reliably detect the very small particles and low concentrations that may be of concern to aircraft.

In order to make the measurement, AVTIS's transmit power would need to be increased to at least 60 dBm, all other specifications being the same. Such power levels are currently achievable in pulsed 94 GHz systems, but achieving them in an FMCW system would be far more challenging. Increasing the antenna size, upping the number of averages and lowering the noise floor would reduce the power requirement somewhat, but it would nevertheless be difficult to achieve in a small, portable system.

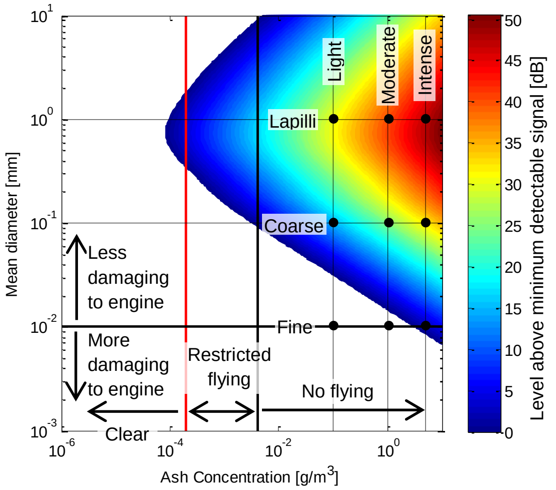

Figure 4 The shaded region again indicates the detectable mean diameter/ash concentration value pairs with the AVTIS-2 system. To be useful, the system would have to be able to detect distributions that have a mean diameter near to and less than 10 μm (below which they are more damaging to the engine) and concentrations at around 2×10^{-4} to 4×10^{-3} g m^{-3}, around which the clear/restricted/no flying zones are defined.

7. FINAL COMMENTS

For the measurement of volcanic ash plumes using small, portable radars it has been shown that millimeter-wave radars operating in the appropriate atmospheric windows have potential to offer measurements with far greater signal to noise than their lower frequency counterparts.

However, it should be noted that the analysis does not take into account the effects of any gases in the ash cloud. The volcanic ash has also been assumed to be dry, which is very unlikely to be true in practice. The water content of the ash particles/cloud could potentially have a substantial impact on both the reflectivity of the ash as well as the attenuation of the ash cloud (negligible with dry ash), given the high loss component of water's permittivity at these frequencies.

In principle, a dual frequency technique could be used to accurately determine the PSD of the ash, and hence provide a better estimate of the total mass contained in the cloud. However, in order to determine how feasible this would be, an analysis of the necessary measurement accuracies would be required.

Finally, it has been shown that portable, low power, millimetre wave radars are not suitable for the detection of ash at the low concentrations which restrict aircraft operations. Other techniques using optical wavelengths have been shown elsewhere to be effective in tackling this problem. However, less portable, higher power millimeter-wave radars could potentially be used, and would obtain higher measured volume reflectivities than lower-frequency radars.

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