DESIGN CONSIDERATIONS FOR A DUAL-FREQUENCY RADAR FOR SEA SPRAY MEASUREMENT IN HURRICANES

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1. INTRODUCTION

Of several factors contributing to hurricane intensity, air-sea interaction and specifically the effect of sea spray, are poorly understood [1]. The fundamental parameter required for characterizing the impact of sea spray on air-sea exchange processes is the size dependent source function for droplets, or the number of droplets of a given size produced at the sea surface per unit surface area per unit time as a function of wind speed. However, the extreme environment makes measurement of either the source function or the droplet size distribution (DSD) as a function of height, $n(r, z)$, extremely challenging. Instead, remote-sensing radar techniques are uniquely suited to tackle this problem. Specifically, multiple millimeter-wave frequencies are sensitive to small particles and can provide particle size information. The objective of this paper is to present the results of a feasibility study for a dual-wavelength Air-sea Spray Profiler (termed ASAP) that could be deployed both in manned aircraft (such as C-130, WP-3 or similar) and in unmanned aerial vehicles (UAVs).

2. RADAR MEASUREMENT CONCEPT

We would like to use radar to measure droplet size distribution parameters that can, in turn, be used to estimate heat and moisture flux for hurricane research. To get information about the DSD, we need at least two parameters of the DSD and, therefore, at least two radar measurements [2], [3]. To understand what a dual-frequency spray radar can measure, we couple backscattering calculations with the source function and DSD profile model of Fairall et al. [4]. Only droplets produced by spume are considered here. These droplets range from a few μm to nearly 1 mm. Smaller droplets produced by other mechanisms have an extremely small radar cross section. The sea spray droplets are assumed to be salt water; the dielectric function of Meissner and Wentz [5] is used. Since sea spray particle diameters are typically well below 1 mm, 94 GHz backscatter is strongly dominated by Rayleigh scattering. Radar technology is also well-developed, making it a good choice for the lower frequency. The second, higher frequency is chosen to provide a non-Rayleigh frequency, as needed for dual-frequency measurements [3]. Our calculations have shown that an acceptable differential reflectivity can be obtained with a second frequency of 220 GHz; the differential reflectivity at 140 GHz is too small to be reliably measured. The differential reflectivity using 300 GHz is even larger. However, using humidity profiles made by NOAA P-3 aircraft dropsondes and the model in [6], we have found that the attenuation at 300 GHz in the hurricane environment is typically so large (approach 40 dB two-way) that 220 GHz is the better choice. Technology is also more straightforward at 220 GHz.

3. DSD, HEAT FLUX, AND ATTENUATION RETRIEVAL

The retrieval algorithm, as previously mentioned, uses independent reflectivity measurements at two separate frequencies operating in different scattering regimes to derive the DSD of sea spray at several discrete altitudes above the ocean surface for the wind conditions observed. Here, as is commonly done in raindrop size distribution estimation, we assume that the DSD can be approximated by a gamma distribution. We developed an efficient procedure to fit the reflectivities predicted by the DSD to dual-frequency data. The retrievals were performed over a reflectivity profile, ranging from 30 m to 300 m, adding to the profiles four different levels of noise and performing the retrievals over 1000 noise realizations. From the retrieved spray DSD parameters, we used the method in [7] to derive sensible and latent heat flux. Results show that the DSD can be derived with sufficient accuracy to provide useful estimates of heat flux.

The retrieval technique assumes that the unattenuated reflectivities are available at both frequencies. As noted in Section 2, the attenuation due to water vapor can be quite large, potentially swamping the dual-frequency signal due to the particle size. Hence, accurate correction of attenuation must be accomplished prior to DSD retrieval. Our approach is to use a 37 GHz radiometer to estimate the water vapor attenuations at 94 and 220 GHz. To determine the feasibility of this approach we have developed a simple model for the brightness temperature of the ocean surface. The model also calculates the clear air attenuation at both 94 and 220 GHz. The slope of the 220 GHz attenuation versus the 37 GHz brightness temperature is roughly 0.5 dB per K for one-way attenuation. Since the radar reflectivity is affected by the two-way attenuation, this would be roughly 1 dB of differential reflectivity error for each K error in the radiometer measurement. Hence, sub-dB errors would require sub-K radiometer accuracy, along with accurate surface wind estimates. This is challenging, although feasible with current technology [8], [9].

4. RADAR SYSTEM DESIGN

The calculations in the previous section indicate that an airborne 94/220 GHz ASAP radar with a 37 GHz radiometer for attenuation correction could be used to measure sea spray water content, as well as sensible and latent heating. Two options for systems that meet the system requirements have been investigated. The first is a traditional short pulse system. The pulse length is 60 ns, for a resolution of 9 m. The receiver noise figures are assumed to be 5 dB at 94 GHz and 8 dB at 220 GHz. The transmitters are assumed to be extended interaction klystrons, with peak power 1.5 kW at 94 GHz and 100 W at 220 GHz, based on currently available technology.

Using the radar equation with a 0.5 second incoherent integration time and 40 cm diameter antenna, we find a minimum detectable reflectivity of -25 dBZ at 94 GHz and -37 dBZ at 220 GHz.

The pulse repetition frequency (PRF) for this option is 10000 Hz, allowing incoherent averaging of 5000 pulses during the integration time. Although the radar echoes themselves are not independent at this high PRF, the thermal noise added to these pulses is independent from pulse to pulse. Incoherent integration of many pulses allows an estimate of noise to be subtracted from the received signal plus noise, as done with CloudSat radar processing, for example [10]. At very low SNR the effective signal to noise improves as $\sqrt{N}$, where N is the number of pulses averaged. With these parameters, this radar design can meet requirements. Its implementation is straightforward at 94 GHz but challenging at 220 GHz due to the high power levels and required receiver isolation. Preventing receiver saturation or damage during each transmit event would require more than 50 dB isolation. This isolation can likely be achieved with a quasi-optical design [11] or with separate transmit and receive antennas. The quasi-optical design is preferable, since alignment of 40 cm antennas at 220 GHz is extremely difficult.

An option that eliminates the high power levels is a pulse compression radar system, using a linear, frequency modulated (FM) chirp [12]. The chirp bandwidth for ASAP is 18 MHz, giving a range resolution of 8.4 m. We assume a solid-state transmitter with 100 mW peak power at 220 GHz; this lower power level can be handled by current switch technology. At W-band a 1 W solid state transmitter is used. These power levels are 30-35 dB below the powers assumed for the short pulse option. To make up for this loss, we keep a similar bandwidth but lengthen the pulse from 60 ns to 60 us. This pulse length corresponds to a 9 km radar range. In conventional radar operation alternating between transmit and receive, a 9-km blind zone would occur during the transmit event. Since our nominal altitude is 2 km, the radar must receive while transmitting. This can be accomplished by separating transmit and receive antennas (undesirable, as explained above) or by using a quasi-optical circulator. At the expense of some power, a beam splitter can also be used to route half the transmit power to the receiver and half the receive power to the receiver. This results in a 6 dB loss but can be compensated by using an even longer pulse.

For pulse compression radars, range sidelobes from the ocean surface return can potentially obscure the reflectivity measurements at the lowest altitudes, thereby limiting the system's ability to retrieve the spray DSD down to the ocean surface. In FMCW radars (pulse compression with 100% duty cycle) this is the equivalent of phase noise due to a bright clutter target interfering with the desired target [13]. Currently, no measurements of ocean backscatter have been found reported in the literature for frequencies above W-band (94 GHz). Typically, ocean backscatter decreases weakly with increasing frequency. To be conservative, we take the 220 GHz backscatter to be the same as that at 94 GHz and use $\square^0$ as 10 dB. The surface return then exceeds the minimum detectable spray return by about 60 dB at 94 GHz and 50 dB at 220 GHz. Hence, system errors must be controlled to suppress the clutter (range sidelobes) from the surface to these levels [12].

A laboratory demonstration of a 220 GHz FMCW radar has been accomplished. It is based on an improved version of the terahertz radar described in [14]; the final frequency tripler has been removed to result in an output frequency near 220 GHz and the receiver mixer has been replaced with a sub-harmonic mixer that mixes the received signal down to a 3.6 GHz intermediate frequency (IF). This signal is IQ-detected by mixing with the transmitted chirp and Fourier transformed to change range to frequency. In testing, the system is stable enough to measure water spray from a spray dispenser at 4.3 m range.

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