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SUBMILLIMETER-WAVE RADIOMETRIC SENSING OF CIRRUS CLOUD PROPERTIES: THE JPL PROTOTYPE CLOUD ICE RADIOMETER

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1. INTRODUCTION

The difficulty of remote sensing cirrus ice mass from a satellite is a major problem for observing the climate system. With climate models now predicting cloud water and ice content, global measurements of cirrus ice water path (IWP) are needed for GCM validation]), as well as for understanding the upper tropospheric hydrologic cycle. While some optical properties of ice clouds can be measured from satellites, there are large inaccuracies in relating optical depth to IWP because of uncertainties in cirrus phase functions, size distributions, and spatial inhomogeneity.

Recently a new technique for remotely sensing cirrus IWP and characteristic particle size was proposed (Evans and Stephens, 1995). This method relies on the scattering of upwelling microwave radiation by ice crystals, reducing the brightness temperature from clear sky values. Theoretical calculations at frequencies up to 340 GHz showed that the sensitivity of microwave radiometry to cirrus IWP increases with frequency and that characteristic particle size is the major factor in relating brightness temperature depression to IWP. The differential sensitivity of two radiometer frequencies was found to be useful in estimating characteristic particle size.

Based on this theoretical work internal Jet Propulsion Laboratory funds were obtained to begin constructing a prototype dual frequency (500 GHz and 630 GHz) submillimeter-wave radiometer for remote sensing of ice clouds from an aircraft platform. The advantages of moving to submillimeter wavelengths are discussed below.

2. SUB-MM RADIOMETRY AND CIRRUS

In the microwave portion of the spectrum the absorption by atmospheric gases, outside of isolated oxygen bands, is from water vapor. Thus the radiation emitted by the surface and lower tropospheric water vapor is affected little by the dry upper troposphere. The absorption by water vapor increases with frequency, but the transmission from typical cirrus levels to space is still high in the submillimeter-wave atmospheric windows (Fig. 1).

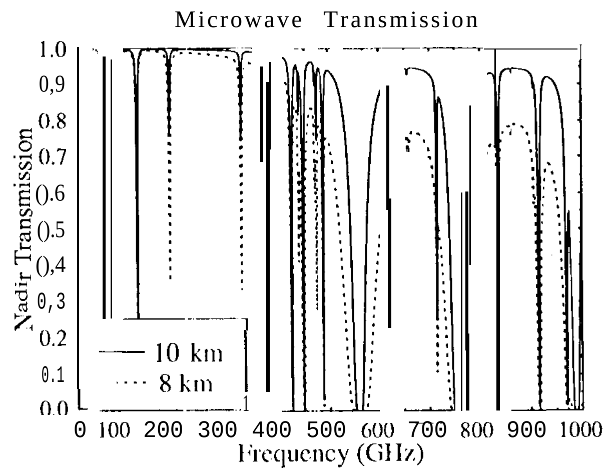

Figure 1: Transmission from space to 10 and 8 km in a standard midlatitude summer atmosphere.

Unlike in the infrared, ice particles in the microwave (< 1000" GHz) interact with radiation primarily by scattering rather than emission. Cirrus clouds scatter some of the upwelling radiation from the lower atmosphere back down, while emitting little, and so cause a reduction in the power measured by a downward looking radiometer. It is this change in brightness temperature from the clear sky value (ΔT_b) that is the observable quantity related to the cirrus IWP. Given the tenuous nature of cirrus clouds, microwave radiative transfer will usually be in the linear regime. This means the sensitivity, defined as the ratio of the brightness temperature change to the ice water path ($\Delta T_b/IWP$), is nearly constant.

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Figure 2 snows the sensitivity for various particle size distributions for a range of' microwave frequencies. The characteristic particle size of these gamma distributions of spheres is given by the median mass diameter D_{me}. The sensitivity increases dramatically with frequency for all size distributions for the longer wavelengths (< 300" GHz). Above 300 GHz the sensitivity still increases rapidly with frequency for the smaller particles, but much less so for the larger sizes, so the range of sensitivity narrows with frequency in the submillimeter region. Thus in the submillimeter region the particle size dots not need to be known as accurately in order to retrieve the cirrus IWP. The increase in sensitivity with frequency depends on the characteristic particle sire, with less increase for larger particles. It is this property that allows the brightness temperature change at two frequencies to be used to retrieve the characteristic particle size.

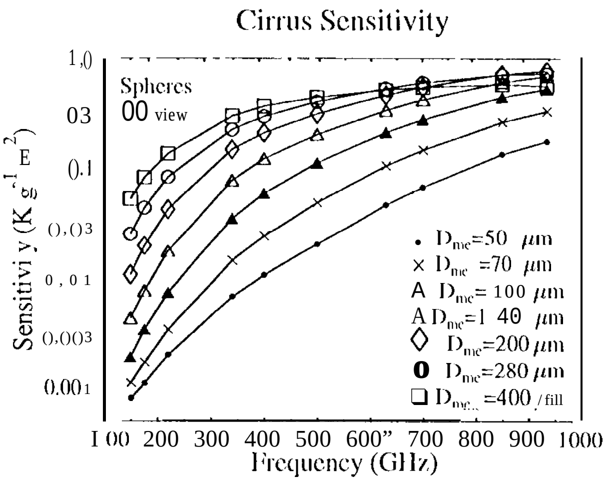

Figure 2: Sensitivity for different size distributions of spherical particles.

The submillimeter-wave sensitivity is high enough that cirrus of moderate visible optical depth will be detectable. For a given 1 WI' the microwave sensitivity increases with particle size, while the optical depth decreases. Thus the brightness temperature change for a visible optical depth of one (Fig. 3) varies considerably with the size distribution. However, even a size distribution with moderately small particles (D_{me} = 100μm) is detectable at 630 GHz (ΔT_b = 2.6 K).

'1'0 summarize, the advantages of submillimeter wavelengths are 1) there is much greater sensitivity to cirrus IWP, 2) there is less dependence on the characteristic particle size, 3) surface emissivity variations are unimportant because there is virtually

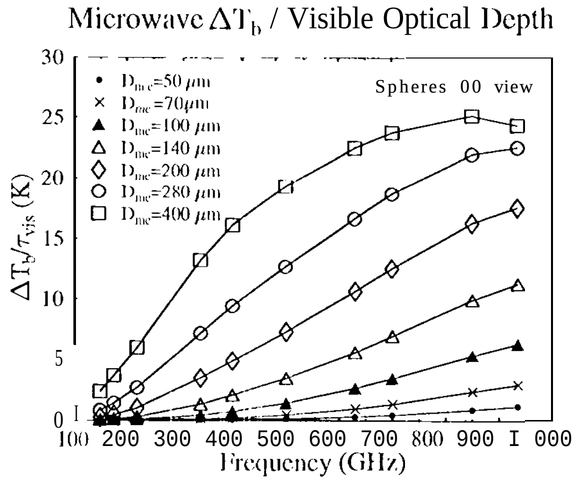

Figure 3: Ratio of brightness temperature change to visible optical depth for various size distributions of spherical particles.

110 surface contribution. A plausible set of frequencies for a multichannel instrument can be chosen by select ing atmospheric window frequencies that are about a factor of 1.4 apart (for particle size determination; Gasiewski, 1992), such as 210, 290, 410, 630, and 880 GHz.

3. THE JPL CLOUD ICE RADIOMETER

The Jet Propulsion Laboratory is a world leader in submillimeter-wave radiometry. Ultra low-noise heterodyne receivers for astrophysical and earth remote sensing applications have been developed in recent years. Costs for this prototype instrument were greatly reduced by using two existing receivers operating at 55(I GHz (Febvre et al., 1994) and 626 GHz (Salez et al., 1994), which are being retuned t o the atmospheric windows at 500 and 630 GHz. These receivers employ superconductor-insulator-superconductor (S1S) detectors. They are cryogenically cooled to 4 K and have noise temperatures around 200 K some 5-30 times lower than uncooled Schottky barrier diodes. This low noise characteristic is useful, though not strictly necessary for cloud ice radiometry.

A high f-number optical system will couple the atmospheric signals to the receivers. The radiometer will measure two orthogonal linear polarizations at 500 and 630 GHz with matched 3° beamwidths. The radiometer beam will scan along one axis to view both upward and downward from the aircraft. With the S1S recievers an integration time of 35 milliseconds should yield a measurement precision of ().2 K.

Two temperature-controlled blackbody targets will be inserted into the beam periodically for receiver calibration.

The optical system and mounting hardware are designed for the NASA DC-8 aircraft. We hope to fly the submillimeter-wave radiometer on DC-8 atmospheric research flights in Spring 1996, specifically those of the NASA Subsonic Assessment program (SASS) and/or the test flights for the JPL cloud radar.

A dedicated radiometer for sensing cirrus clouds would have the characteristics of the prototype radiometer discussed here, but in addition have 1) more widely separated frequencies for better particle size determination, 2) multiple frequencies for good sensitivity over a wide range of IWP, and 3) lower frequency channels (such as around the 183 GHz water vapor line) to be used for determining variations in the upwelling radiation below cirrus layers.

4. MODELING FOR THE JPL RADIOMETER

A modeling study is underway to improve the previous analytical work and extend it to the frequencies of the JPL radiometer. The ice crystal scattering properties are modeled with the discrete dipole approximation (DDA) (see Evans and Stephens, 1995 and references therein). Here 21 logarithmically spaced particle sires from 10 to 1000 μm are computed for 11 shapes (solid column, hollow column, solid column with a different aspect ratio formula, lower density $\rho = 0.6\ g/cm^3$ column, 4 bullet spatial rosette, 5 bullet rosette, 6 bullet rosette, 5 bullet rosette with modified bullet aspect ratio, randomly oriented 5 bullet rosette, $\rho = 0.6$ stick-ball cylinder with a sphere on one end, $\rho = 0.6$ prolate spheroid). A polarized plane-parallel radiative transfer model calculates the radiance (and hence brightness temperature) for several angles at any level in the atmosphere. For the results shown here a standard midlatitude summer atmosphere is used with the relative humidity of the cirrus layer set to 75%. The particle size distributions are characterized by equivalent sphere gamma distributions:

$$N(D) = aD_e^{\alpha} \exp[-(\alpha + 3.67) D_e/D_{me}] ,$$

where D_e is the diameter of the equivalent mass sphere, D_{me} is the median mass diameter of the distribution, α controls the width of the distribution, and a is found from the ice mass concentration. Tests have shown that using gamma distributions fit to observed size distributions (from FIRE 1991, $D_{me} < 150 \mu m$) gives rms fractional differences in sensitivity of only 6% when D_{me} is fit to the 5'th moment of D_e and α is fixed at 1.

The sensitivity for 9 gamma size distributions and 4 representative particle shapes for an upward viewing geometry is shown in Fig. 4. For these horizontally oriented particles the brightness temperature change for vertical polarization is smaller than for horizontal polarization. The range in sensitivity due to shape increases with particle size, and at 49° view angle is about a factor of 2.0 for H pol and 1.7 for V pol. Most of this range in sensitivity is from the high density assumption for the column shape. Other modeling results indicate that the range in sensitivity from the distribution width (α = 0, 1, 2) is much smaller than that from shape.

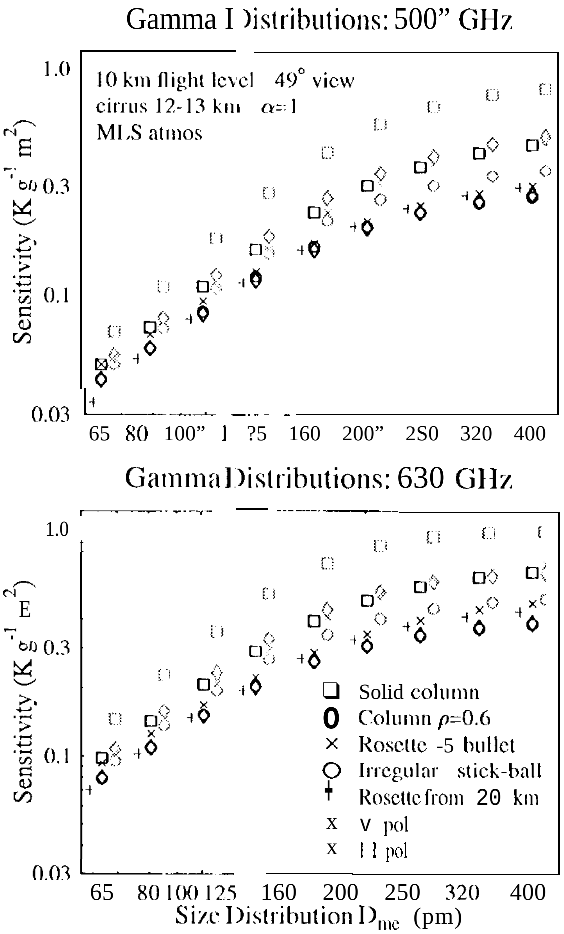

Figure 4: Sensitivity for four particle shapes and different size distributions at 500 GHz and 630 GHz for two polarizations.

Figure 4 also shows the sensitivity of rosettes for a downward viewing geometry from a 20 km flight level. The downward looking sensitivity is slightly lower, especially for smaller particle sizes. This can be explained with a simple first order scattering radiative transfer model. Assuming no downwelling incident radiation on the top of the cloud this model gives:

$$\Delta I_{1,up} = -\tau \; [(1 - \omega f) I_{0,up} - (1 - \omega) B_{cld}] \; ,$$

$$\Delta I_{0,dn} = \tau \; [(1 - \omega f) I_{0,up} - (1 - \omega)(I_{0,up} - B_{cld})] \; ,$$

where τ is the sub-mm optical depth of the cloud, ω is the single scattering albedo of the cirrus particles, f is the forward scattering ratio, B_{cld} is the Planck emission for the average cloud temperature, $I_{1,up}$ is the upwelling zenith radiance from the top of the cloud, and $I_{0,dn}$ is the downwelling nadir radiance from the bottom of the cloud. For this simple two-stream model the upward and downward radiance change are the same magnitude (but opposite sign) if the ice particles do not absorb ($\omega = 1$). If the ice particles are small and therefore emit then this model shows that the downwelling delta radiance would be greater. The simple model can also explain why the sensitivity for solid columns is substantially greater than that for rosettes. For a given IWP and size distribution the columns have a higher optical depth but a lower forward scattering ratio and these effects combine to give a larger AI.

The effects of various atmospheric humidities and cirrus layer heights was examined. The change in sensitivity for cloud base heights varied from 10 to 14 km in a standard midlatitude summer atmosphere is 25% for the downward viewing geometry but only 8% for upward viewing from 10 km. As the cirrus layer, or aircraft instrument, moves lower in the atmosphere the transmission between the cloud and radiometer decreases, thus lowering the sensitivity. One way to think about this is that the transmission curve for a downward viewing geometry is a kind of weighting function selecting for upper tropospheric ice clouds.

A simple approach to remote sensing cirrus properties is to consider the effects of particle shape and density as error sources, and try to retrieve characteristic particle size and ice water path using two radiometer frequencies. One way to do this is to relate the ratio of ΔT_b at 630 GHz and 500 GHz to the sensitivity as in Fig. 5. This relation is fairly linear, though there are substantial uncertainties in sensitivity as seen in the scatter in the plot.

The linear regression relation for sensitivity (S) at 630 GHz for vertical polarization at 49° is

$$S = 0.837 - 0.820(\Delta T_{b\,630}/\Delta T_{b500} - 1) \pm 0.075$$

(the standard error of the regression is after the ±). For a 00 viewing angle from 10 km in this summer

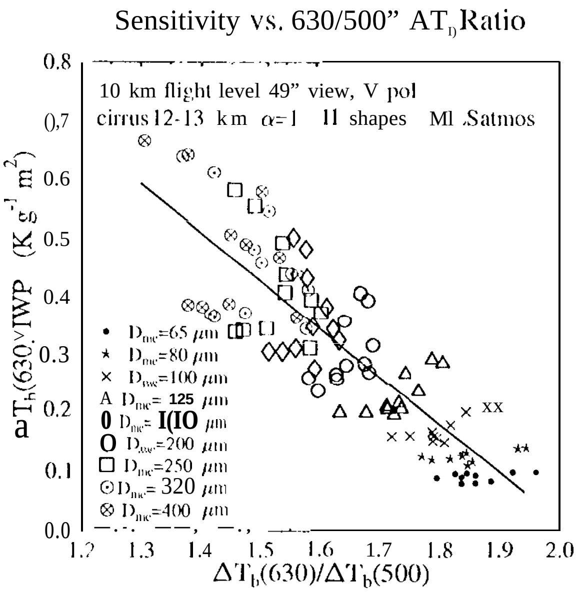

Figure 5: Sensitivity at 630 GHz as a function of the ratio of ΔT_b at 630 GHz to 500 GHz for various particle shapes and size distributions.

atmosphere the relation is

$$S = 0.569 - 0.383(\Delta T_{b\,630}/\Delta T_{b500} - 1) \pm 0.100 \; ,$$

and for a downward looking geometry at 49° V pol the relation is

$$S = 0.675 - 0.580(\Delta T_{b630}/\Delta T_{b500} - 1) + 0.072.$$

This type of plot can also give a relationship between the ΔT_b ratio and the characteristic particle size D_{me}, e.g.,

$$D_{me} = 1540 \exp[-3.43(\Delta T_{b630}/\Delta T_{b500} - 1)] \pm 24\%$$

for the case in Fig. 5. Assuming linearity, which is accurate to within about 10% for $\Delta T_b < 30$ K, the ice water path is simply the brightness temperature change divided by the sensitivity

$$IWP = \Delta T_{b630}/S_{630}$$

This defines a very simple cirrus retrieval algorithm for the JPL sub-mm radiometer.

It is important to estimate the errors associated with this simple algorithm. Potentially the largest source of error is determining the ΔT_b's from the measured brightness temperatures. This might be done by differencing nearby clear pixels or by using lower microwave frequencies, which are much less sensitive to cirrus, to measure water vapor and midlevel cloud variations. These type of errors are the

Table 1: Example IWP and particle size D_{me} retrievals with the simple algorithm. Included is the range of uncertainty in IWP from ΔT_b errors of about 2.0 K.

ΔT_b 500	ΔT_b 630	Sens	D_{me} μm	IWP g/m^2	IWP range	
5	7	0.509	390	13.8	12	26
5	8	0.345	197	23.2	19	77
5	9	0.181	99	49.7	27	105
10	14	0.509	390	27.5	24	32
10	10	0.345	197	46.4	38	82
10	18	0.181	99	99.4	61	225
20	28	0.509	390	55.0	48	65
20	32	0.345	197	92.8	76	123
20	36	0.181	99	198.9	134	451

focus of another ongoing modeling study. The other major error source in this simple scheme is the uncertainties in the sensitivity due to particle shape and density. The results of an illustrative error analysis combining these two error sources for the case in Fig. 5 are shown in Table 1. The range in IWP is computed for ΔT_b errors of ± 2.0 and ± 2.2 K for 500 GHz and 630 GHz with perfect correlation between the errors at the two frequencies due to water vapor variations. This ΔT_b error level should be readily achievable.

The IWP error ranges are quite favorable for the larger particle cases once the signal to noise is reasonable ($\Delta T_{b500} \geq 10$ K). The small size distributions have large error bars in IWP due to dividing by a sensitivity with a fractionally large uncertainty. This is not as much a concern as it might seem because the smaller particle sizes occur with low ice water content and generally won't be observable with a sub-mm radiometer. It is important to remember that the radiometer is making an integrated measurement and so the relevant size distribution is that of the whole cirrus cloud which would include the larger particles near the cloud base.

5. CONCLUSIONS AND FUTURE WORK

Passive microwave remote sensing of cirrus clouds becomes most attractive when considering submillimeter wavelengths. This is due to the much greater sensitivity to ice mass at higher frequencies and the decreased dependence on particle size. A prototype sub-mm radiometer with receivers at 500 and 630 GHz is under construction at JPL. This instrument will measure vertical and horizontal polarization and scan both upward and downward from the NASA DC-8 aircraft. Modeling realistic cirrus particle shapes and size distributions at these frequencies has shown that ice water path and characteristic particle size can be retrieved with usable accuracy with a very simple two channel algorithm.

In 1996 the prototype sub-mm radiometer should be finished and flown during atmospheric research flights (probably in late Spring). Future work will include developing more sophisticated retrieval algorithms for this new remote sensing technique, further characterization of the errors, and analysis and validation using the initial data collected. There is much to be gained in combining the sub-mm radiometer with a cloud radar to reduce the particle size/IWP uncertainties that limit both techniques. Looking farther ahead, the low power and space requirements of submillimeter-wave radiometers makes a satellite multichannel instrument an attractive option for global remote sensing of cirrus cloud properties.

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