Estimation of the Asymmetry Parameter from microphysical observations

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Abstract:

A new method of calculating the asymmetry parameter from aircraft microphysical observations is discussed and has been applied to aircraft data where direct measurements are available. Recent parameterizations of the asymmetry parameter often are based on theoretical ray-tracing results for simple particle shapes. One recent theory, which has gained prominence, is the use of equivalent surface volume/area spheres to estimate the scattering properties of ice particles. In this paper a new technique is described for determining the properties necessary for calculation of appropriate equivalent spheres. These calculations have been applied to aircraft in-situ data from the Cirrus Regional Study of Tropical Anvils and Cirrus Layers - Florida Area Cirrus Experiment (CRYSTAL-FACE) mission. The results were in poor agreement with direct asymmetry parameter measurements. Considering the near field interactions of radiation within a cluster of spheres as opposed to considering each sphere individually is not likely to improve the agreement.

1. Introduction:

Accurate knowledge of the scattering properties of ice particles is critical to understanding the radiation budget of the atmosphere. Numerous research projects have been completed in an effort to determine appropriate values of the asymmetry parameter

In an effort to simplify calculations numerous researchers have used equivalent spheres to represent ice particles in the atmosphere. Researchers rarely use the scattering properties of equivalent spheres for calculation of an asymmetry parameter. A new equivalent sphere definition has been suggested by Grenfell and Warren (1999), has shown reasonable results compared to ray tracing calculations. Warren et al (2002) noted that this technique did not work well at non-absorbing wavelengths compared to ray-tracing results. This paper uses a new approach for calculating the equivalent volume/surface area sphere size from raw aircraft data and tests whether these spheres are reasonable for asymmetry parameter estimates for real world data. We do this by comparing calculated asymmetry parameter values with direct measurements.

Section 2 gives an overview of the aircraft data and the nature of the particle observations used for this study. Section 3 shows how equivalent volume/surface area spheres were calculated from aircraft observations. Section 4 gives the results and conclusions.

2. Overview of aircraft data:
The UND Citation aircraft collected the aircraft data used in this study during the
CRYSTAL-FACE field project in Florida during the summer of 2002. For particle
observations the 2-Dimensional Cloud probe (2DC) and High Volume Precipitation
Sampler (HVPS) cloud probes were used. These probes are both imaging probes, which
facilitate the calculation of the area ratio of each particle, which is critical to the
investigation. Additionally the Cloud Particle Imager (CPI) was used for detailed particle
imagery. The Cloud Integrating Nephelometer (CIN) probe was also used for direct
measurements of the asymmetry parameter of a volume of cloud particles. Data from all
probes was averaged over 30 second time periods for the purposes of this study.

Asymmetry parameter parameterizations are often based on simple particle types.
Simple shapes are easily modeled using ray-tracing techniques. Figure 1 (upper) shows
some CPI images from the CRYSTAL-FACE mission. The crystals shown are examples
of near-perfect hexagonal plates. The crystals were imaged over a 45 second time period.
Ray-tracing of the most simple of these particles would be easy. Some particles,
however, have surface markings, which make the calculations more difficult. The
crystals shown in figure 1 (upper) represent approximately 1/3rd of the crystals observed
during the 30 second time period. The remaining 2/3rds were similar to those shown in
figure 1 (lower). The crystals shown in figure 1 (lower) represent what is more common
in ice cloud observations. Korolev et al (2000) showed that commonly up to 80% of
observed ice particles would be classified as ‘irregular’ in most situations. These
observations are in line with observations by the authors who have completed numerous
habit classification studies.
Figure 1 Ice crystal images from the CPI. Upper particles are rarely seen pristine plates. Lower panel contains more common irregular particles.

For the CRYSTAL-FACE project the effective particle size as defined by Fu (1996) has been calculated for particle size distributions for 30-second time periods for six UND Citation research flights. The asymmetry parameter calculated using the parameterization from Fu (1996) is shown compared to the CIN measured asymmetry
parameter in figure 2. In general, Fu’s parameterization over-estimates the observed asymmetry parameter. This is likely due to the fact that Fu used ray-tracing of hexagonal plates for his parameterization.

![Image](image_url)

**Figure 2** Asymmetry parameter calculated using Fu (1996) parameterization versus CIN direct measurement.

3. Calculating equivalent sphere sizes from aircraft data:

In cloud physics it has become common to use equivalent spheres to model the radiative properties of cloud ice particles. Ebert and Curry (1992) used spheres with projected areas equal to the projected areas of ice particles in their study. Sun and Shine (1995) tried to adjust Mie theory (for spheres) to calculated scattering properties to
account for asphericity in ice particles. Grenfell and Warren (1999) suggest that the use of equal volume/surface area spheres is best. Equal volume/surface area spheres were used to successfully simulate the infrared emission properties of laboratory ice clouds, which were generally composed of pristine plates or columns by Schmitt and Arnott (1999). Foot (1988) suggested that equal volume/surface area spheres were appropriate for calculating the radiative properties of cirrus. Warren et al (2002) showed excellent results in comparing equal volume/surface area spheres to ray tracing calculations for pristine ice particles for calculating extinction, asymmetry parameter, and single scattering albedo. Results were good except when a large quantity of radiation is transmitted directly through the particle without any deviation of direction such as in a thin plate at visible wavelengths where absorption is negligible.

It is easy to calculate the radiative properties of ‘equivalent spheres’ because of Mie theory. Common problems for equivalent sphere types are shown in table 1.

<table>
<thead>
<tr>
<th>Replacing ice particles with spheres of:</th>
<th>Correctly predict Mass?</th>
<th>Correctly predict Extinction?</th>
<th>Correctly predict asymmetry parameter?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equal maximum dimension</td>
<td>No, Too high</td>
<td>No, Too high</td>
<td>No, Too high</td>
</tr>
<tr>
<td>Equal projected area</td>
<td>No, Too high</td>
<td>Correct</td>
<td>No, Too high</td>
</tr>
<tr>
<td>Equal Volume</td>
<td>Correct</td>
<td>No, Too low</td>
<td>No, Too high</td>
</tr>
<tr>
<td>Equal Surface area and volume</td>
<td>Correct</td>
<td>Close (correct for convex particles)</td>
<td>?</td>
</tr>
</tbody>
</table>
From table 1 it is obvious that the equal volume/surface area spheres are the best choice for ice crystal representation. The remainder of this paper will deal with the calculation of the asymmetry parameter using this equivalent sphere definition.

For the calculation of equal volume/surface area spheres it is necessary to determine the surface area of the particles. Imaging particle probes such as the 2DC, CPI, and HVPS give a two dimensional image of the particle. The technique described below assumes that the variation of the perimeter of the two-dimensional image is representative of the three-dimensional variation of the particle surface. This technique was developed using CPI data since the CPI has the highest resolution of any of the imaging probes.

This technique builds on the fact that the ratio of the area of a sphere to its surface area is 4. The value of 4 is commonly used for estimation of surface area of convex particles as well.

\[ A_s = A \times 4 \]  
\[ \text{(1)} \]

where \( A \) is the projected area and \( A_s \) is the surface area of the particle. Most of the particles observed in the atmosphere have concavities and this relationship breaks down. Since \( A = \pi r^2 \) we can break that down into \( A = \pi r^2 r \) which can again be broken down to \( A = \pi r^2 p/2 \) where \( p \) is the perimeter of the particle. Substituting this into equation 1 we get:
\[ A_s = 2r \times p \]  \hspace{1cm} (2)

where \( r \) is the radius and \( p \) is the perimeter of the projected 2D particle.

In development of this technique the above equation was applied to each point on the perimeter of the particle. For each point on the perimeter the distance to the center of the particle is known (\( r \)), the perimeter length for the segment is known (based on its orientation to other perimeter points around it) and therefore \( A_s \) can be summed using equation 3.

\[ A_s = \sum_{i=0}^{n} r_n \times p_n \]  \hspace{1cm} (3)

where \( n \) is the number of points on the perimeter, \( r_n \) is the radius to the \( n \)-th perimeter point and \( p_n \) is the perimeter length represented by that perimeter point. Because we are using the 2-D image of the particle and not a 2-D cross section, this is probably an overestimate of the surface area. Analysis of various theoretical irregular particles indicates that this technique over-estimates the actual surface area by about 10% on the average. This error is counteracted to some extent by variations in the surface, which are not detected in by the CPI (i.e. variations smaller than the pixel size).

Using the above technique the surface area of particles from a large dataset has been calculated. The data used for this calculation was from the February 17, 1998 Tropical Rainfall Measurement Mission (TRMM) flight over Brazil. The imaged data was taken in a convective region and the particles were similar to particles observed in CRYSTAL-FACE. The particle surface area to particle projected area ratio was then plotted versus the particle’s area ratio (defined as the particle’s projected area divided by
the area of the smallest circle which would completely cover the particle). Additionally, the same parameters were calculated for randomly oriented bullet rosettes of different aspect ratios and different numbers of bullets. The TRMM data as well as the rosette data are plotted in figure 3. As one would expect, a high area ratio leads to a surface area to projected area ratio of 4.0. A fit to the data in figure 3 is given in equation 4.

\[ \frac{S_a}{A} = 3.9169 \times A_r^{-.5861} \]  

Figure 3 Surface area to projected area ratio plotted versus particle area ratio for TRMM irregular particle data (X’s) and theoretical rosettes (+’s).

The projected area to surface area ratio can therefore be estimated using equation 4 when area ratio and the area of the particle are known. It is expected that this equation...
would not produce accurate results for an individual particle, but with large numbers of particles the errors will balance out.

Numerous mass-dimensional relationships have been developed for atmospheric ice particles (Mitchell et al, 1990, Heymsfield et al, 2002). It was found that the choice of mass-dimensional relationship had little effect on the final results of this project. The mass-dimensional relationship used for the final calculations is given in equation 5.

\[ \rho = 0.49 \times (Ar)^{2.26} \]  

(5)

where \( \rho \) is the particle density and \( Ar \) is the area ratio of the particle. This relationship is from Heymsfield et al (2002).

4. Results and conclusions:

The UND Citation dataset for the CRYSTAL-FACE experiment contains combined particle size distributions from the 2DC and HVPS as well as area ratio averages for each size bin. For 30-second time intervals the data was averaged and an equivalent sphere size was calculated using equations derived and sited in section 3. Typical equivalent sphere sizes ranged from size parameters of 5 to 500. The number of spheres was determined using equation 2 from Grenfell and Warren (1999). Mie theory for spheres was then used to calculate the asymmetry parameter for each individual sphere size, and an area averaged asymmetry parameter was then calculated for the entire particle size distribution. The equivalent sphere asymmetry parameter is plotted
compared to the directly measured asymmetry parameter in figure 4. The agreement is very poor and concurs with the observations of Warren et al (2002) for hexagonal particles at non-absorbing (visible) wavelengths.

**Figure 4** Equivalent sphere (Rva) calculated asymmetry parameter plotted versus CIN measured asymmetry parameter.

The technique used above does not account for near field interactions of electromagnet radiation for spheres, which are in close proximity. Using the equivalent volume/surface area spheres will yield large numbers of spheres to represent each individual particle. Treating these spheres as individual particles and not considering near-field interactions could pose a problem. A cluster of spheres could be used to represent each individual ice particle. T-matrix code was used to investigate the
possibility of clustering giving different results. Due to computer limitations it was not possible to run the T-matrix code on large clusters of spheres. A few simple tests on four-sphere clusters of various sizes and separations resulted in similar asymmetry parameters, as one would expect from the individual spheres. This leads the authors to believe that the near-field interactions do not significantly affect the scattering properties of sphere clusters compared to individual spheres when size parameters are large.

Given that the particle surface area is estimated, further experimentation was done to see how much affect this had on the resulting asymmetry parameter calculation. A factor of 10 increase in particle surface area led to small enough particles which generated an asymmetry parameter comparable to measured values. A cloud of equivalent spheres created with a factor of 10 increase in surface area led to an overestimate in extinction by a factor of 5 assuming geometric optics. It seems unlikely that near-field electromagnetic interactions could account for the necessary differences to make this a viable technique for calculation of asymmetry parameter. Use of T-matrix code is also very time consuming and therefore would be of little use to the modeling community.

References:


