# CLOUD BACKSCATTER PHASE FUNCTION AND EMITTANCE OF LOW AND MIDLEVEL CLOUDS FROM LIRAD-TYPE MEASUREMENTS FROM CALIPSO

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## ABSTRACT

Lidar/Radiometer (LIRAD) observations from the ground have yielded values of the cloud backscatter-to-extinction ratio and emittance of midlevel and boundary layer clouds, as well as of the more common cirrus observations. The cloud backscatter-to-extinction ratio is numerically equal to the cloud particle backscatter phase function, when suitably normalised.

CALIPSO will be launched in early 2005 and will carry a two-wavelength depolarisation lidar together with a scanning infrared filter radiometer. Thus CALIPSO is ideal for LIRAD-type observations. Although midlevel and boundary layer water clouds tend to have higher optical depths than cirrus clouds, LIRAD observations of midlevel clouds [1] and boundary layer clouds [2] indicate that cases of semitransparent water clouds do occur. The backscatter phase function of water clouds is also much more constant than that for ice clouds. Theoretical studies [2,3] indicate that the total variation of backscatter phase function in water clouds is about ±5%. An advantage of this small variation is that the integrated backscatter can be used also for calibration of the lidar instrument or, alternatively, estimation of the multiple scattering factor in the backscatter.

An inherent difficulty in observations of water clouds is that the typical cellular nature of stratocumulus and altocumulus clouds implies that the field of view of the lidar may not be cloud-filled at any one time. Thus a signal from an unfilled field of view could be confused with that from a cloud of lower optical depth. Further, the field of view of the infrared radiometer is different from that of the lidar. In order to calibrate the lidar, a cloud-filled field of view is required. These issues are explored in this paper and a method for separating the two cases is presented.

## 1. THE LIRAD METHOD

The LIRAD method involves simultaneous observations in a narrow field of view, and along the same axis, of lidar backscatter and infrared radiance. Observations from the ground are traditionally made in the vertical. In the case of CALIPSO they would be made close to nadir.

The LIRAD method involves combining the lidar and infrared observations to give the cloud visible and infrared optical depth. These benchmark observations can then lead to an assessment of the total radiation balance of the cloud. Additional quantities that are derived are the cloud lidar backscatter-to-extinction ratio and the ratio of visible-to-infrared optical depth. Details of instrumentation and numerous LIRAD observations made are summarised in [4].

The integrated backscatter through the cloud $\gamma'$ at the lidar wavelength is related to the cloud infrared emittance $\varepsilon$ by the equation [5],

$$\gamma' = \frac{k}{2\bar{\eta}}\left\{1-\exp\left[-2\alpha\eta\ln\left(\frac{1}{1-\varepsilon}\right)\right]\right\} \tag{1}$$

When $\varepsilon$ tends to unity, $\gamma'$ tends to $k/2\bar{\eta}$ where $k$ is the backscatter-to-extinction ratio and $\bar{\eta}$ is the effective multiple scattering factor for the cloud depth [6]. The term $\alpha$ gives the ratio between the visible (lidar) optical depth and the IR absorption optical depth. The visible (lidar) extinction coefficient of the cloud is obtained from a retrieval of the cloud profile of backscatter coefficient [4] using the measured value of $k$.

The calculation of the cloud emittance $\varepsilon$ employs the profile of backscatter coefficient through the cloud as a surrogate to the profile of infrared optical extinction coefficient. The calculation then iterates successive values of the infrared absorption to visible extinction coefficients until the calculated cloud radiance matches the measured value. Full details are given in [4].

## 2. LIRAD METHOD FROM SPACE

The lidar backscatter profile from space will be similar to that from the ground except that the highest clouds will be encountered first. This implies that at times clouds at a greater altitude will obscure the lower clouds. The major difference is that the cloud infrared radiance is observed against the warmer background of the Earth's surface, plus atmosphere, below the cloud. As the spacecraft orbits, this background will tend to change, causing uncertainties in the measurement. However, the lidar returns will be able to distinguish more constant backgrounds, that is, the ocean, from variably emitting ground surfaces. The lidar can also determine when lower cloud decks are present.

Consider an extended cloud, filling the fields of view of the instruments and with IR emittance changing with horizontal distance. The radiance $L_S$ at the satellite can be written in terms of the cloud and ground radiances:

$$L_s = \varepsilon B_c + (1-\varepsilon) B_g \qquad (2)$$

where $B_C$ is the blackbody radiance at cloud temperature and $B_g$ is the radiance below the cloud. Consider now a cloud that is optically dense but is broken and fills the fields of view of the instruments by a variable amount C. The radiance is given by

$$L_s = C B_c + (1-C) B_g \qquad (3)$$

However, the effective integrated backscatter from the cloud alone is given by,

$$\gamma_e' = C\gamma' \qquad (4)$$

Fig. 1 shows a plot of integrated backscatter versus radiance $L_S$ from equations 1 and 2, and 3 and 4 respectively. Two values of $\alpha$ are specified for the former case of a variable emittance. Clearly, the two cases of variable emittance and broken cloud are very well separated and should be identifiable in the data.

However, a problem arises here that in the case of the lidar, CALIOP, and the IR radiometer, IIR, the fields of view are not equal. The lidar has a surface footprint of 100 m whereas the IIR has a footprint of 1000 m. Thus several backscatter profiles must be averaged to be compatible with the IIR footprint. Again, the lidar profiles are separated by 250 m, so that the full horizontal range is not covered. Four lidar profiles will impact on the IIR footprint as shown in Figure 2. The lidar profiles within the IIR footprint will give some indication of the uniformity of the cloud and of its extent.

The above technique will be most successful in cases of extended stratocumulus cloud as found off the west coast of the USA. [7] for example, have indicated frequent extended stratocumulus cloud sheets in the Eastern Pacific and [2] utilised stratocumulus in high-pressure regions between frontal zones. Although not considered here, the technique should also be suitable for cases of cirrus cloud that are frequently known to be extensive.

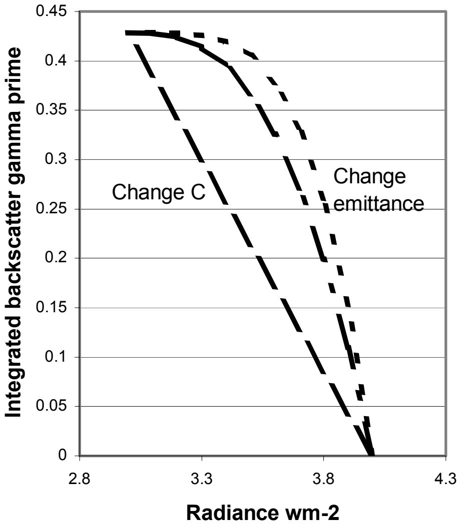

Fig.1 Plot of $\gamma'$ versus radiance $L_S$ for a cloud with variable amount C and two cases with variable emittance $\varepsilon$ and $\alpha$ = 2 and 3 (outer curve). Cloud and surface temperatures are 10 and 30 degrees C respectively

However, the lidar can be utilised on its own to collect values of cloud effective integrated backscatter $k/2\overline{\eta}$. As the range of values of the stratocumulus backscatter phase function is known to be small then values of $\gamma'$ will cluster around a maximum value representative of a dense cloud. The mean cloud phase function of water droplet clouds was found [2] to give a value of $k$ of 0.65±4.4% depending also on depth into the cloud. If a good calibration is already available, then the mean maximum value of $\gamma'$ can be used to obtain a value of effective multiple scattering factor $\overline{\eta}$. This value will give a check on theoretically calculated values [6]. We require a better understanding of the variability of the backscatter phase function of stratocumulus clouds before we can be confident in the level of uncertainty inherent in the results.

## 3. CONCLUSIONS

The technique described for separating cases of variable cloud optical depth and variable cloud amount will be successful for cases of extended boundary layer cloud. The cloud scales need to satisfy the two fields of view of the instrument. However, the lidar, on its own, can obtain a value of effective backscatter-to-extinction ratio. Given that we know the theoretical value of $k$ to some estimated uncertainty, we can determine either a lidar calibration or multiple scattering factor. If the lidar has been calibrated by other means, which is likely, the effective multiple scattering can be determined.

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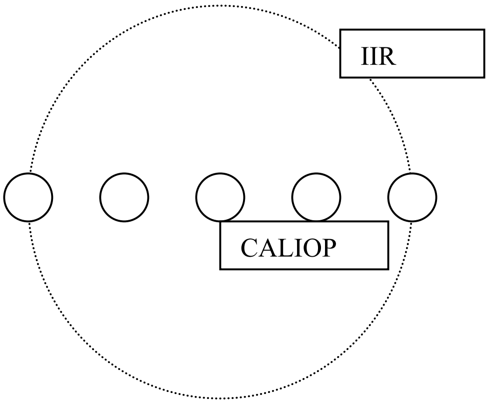

Fig. 2. Schematic of the Infrared Imaging Radiometer (IIR) (1000m) and CALIPSO Lidar with Orthogonal polarisation (CALIOP) (100m) footprints