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Engineering Notes

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Radar Evaluation of Optical Cloud Constraints to Space Launch Operations

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I. Introduction

WEATHER constraints to launching space vehicles are designed to prevent loss of the vehicle or mission caused by weather hazards (e.g., see Ref. 1). Constraints include lightning launch commit criteria (LLCC) designed to avoid natural and triggered lightning. The LLCC currently in use at most American launch sites including the Eastern Range and Kennedy Space Center require the Launch Weather Officer to determine the height of cloud bases and tops, the location of cloud edges, and cloud transparency. The preferred method of making these determinations is visual observation, but when that is not possible because of darkness or obscured vision it is permissible to use radar.[2]

This Note examines the relationship between visual and radar observations in three ways: 1) a theoretical consideration of the relationship between radar reflectivity and optical transparency, 2) an observational study relating radar reflectivity to cloud edge determined from in situ measurements of cloud particle concentrations that determine the visible cloud edge, and 3) an observational study relating standard radar products to anvil cloud transparency. It is shown that these three approaches yield results consistent with each other and with the radar threshold specified in Ref. 2 for LLCC evaluation.

II. Theoretical Relation of Reflectivity and Transparency

The optical transparency of a cloud depends on the optical extinction coefficient (OEC) of the cloud and its geometric thickness. The cloud particles determine both the OEC and the radar reflectivity. Thus, there is a theoretical basis for a relationship between cloud optical transparency and radar reflectivity. Atlas et al.[3] provides a theoretical approach for expressing the OEC of a cloud composed of ice crystals in terms of the radar reflectivity (Z mm^6 m^{-3}) and D_0, the mass weighed average diameter of the cloud particles. The following equation is consistent with Fig. 8 in Atlas et al.[3]:

$$\mathrm{OEC}\ (\mathrm{km}^{-1}) = 196{,}200^* Z/(D_0)^{1.8} \tag{1}$$

where D_0 is expressed in μm. Figure 1 shows curves of the OEC as a function of D_0 for three dBZ ($\mathrm{dBZ} = 10 \log_{10} Z$) values: 5, 0, and -5. The OEC increases with increasing dBZ, but decreases with increasing D_0.

Data from anvil clouds presented by McFarquhar and Heymsfield[4] suggest D_0 values increasing downward from 100 μm or less near cloud tops, to 300 to 500 μm several kilometers below the tops. Figure 1 indicates a D_0 value of 400 μm would produce an optical extinction coefficient of 1.29 km^{-1} at -5 dBZ, 4.06 km^{-1} at 0 dBZ, and 12.85 km^{-1} at $+5$ dBZ. Multiplying by a realistic geometric thickness of 3 km (9,843 ft) would produce corresponding optical thicknesses as follows: 3.87 at -5 dBZ, 12.18 at 0 dBZ, and 38.55 at $+5$ dBZ. The relation between optical thickness and transparency is explored next.

Determining the threshold of optical thickness that precisely separates transparent from nontransparent is beyond the scope of this study. Nevertheless, a useful optical thickness threshold can be obtained by considering an idealized optical medium and highly idealized viewing conditions.

For a medium that scatters and absorbs visible radiation, such as haze or fog, an optical thickness of 3.912 is considered sufficient to obscure an object from the view of a typical human observer.[5] This assumes that the limiting value of contrast for the human eye is ± 0.02, where the contrast between the brightness of an object B and its background (B_0) is defined as $(B - B_0)/B_0$. The optical thickness is the product of the OEC of the medium and the observer's distance from the object (the visual range), consistent with the discussion of Fig. 1.

III. Observed Reflectivity and Cloud Boundaries

In 2000 and 2001, an extensive field program was undertaken to determine the relationship between in-cloud electric fields and other cloud properties including radar reflectivity to improve the LLCC. This Airborne Field Mill program flew an aircraft carrying six electric field mills and a full suite of cloud physics instrumentation into central Florida thunderstorm anvil clouds during the summer convective season.[6] Details of the aircraft and its instrumentation are found in Dye et al.[7] All flights took place in the field of view of two weather radars: the Air Force WSR-74C 5-cm system at Patrick Air Force Base, Florida, and the National Weather Service WSR-88D 10-cm Doppler system in Melbourne, Florida. The aircraft and radar data were carefully synchronized in both time and space before analysis. All measurements were subject to the intensive calibration and quality control procedures described in Dye et al.[7] The radar data are estimated to be accurate to within about ± 1 dBZ. For a detailed discussion of Z and its relation to cloud properties, see Doviak and Zrnic.[8]

Using an automated cloud edge detection algorithm based primarily on the airborne cloud physics data,[9] the radar reflectivity measured by the ground-based radars was measured as a function of distance from cloud edge. The results are shown in Fig. 2 based on data from both the WSR 74C and WSR 88D with redundant data eliminated.

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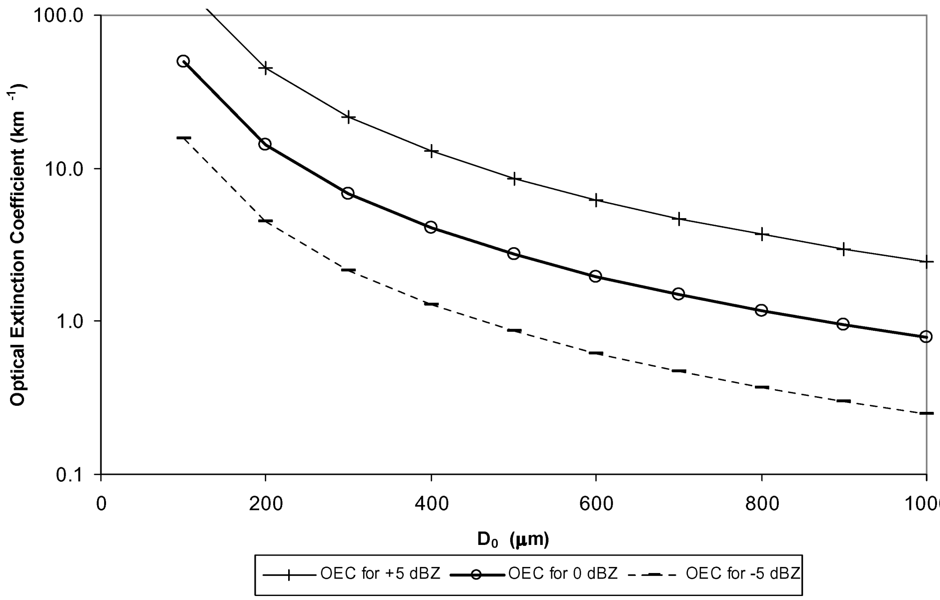

Fig. 1 Optical extinction coefficient vs D_0 for dBZ values of +5 (+), 0 (o), and −5 (—), computed from Eq. (1) (using results from Atlas et al.[3]).

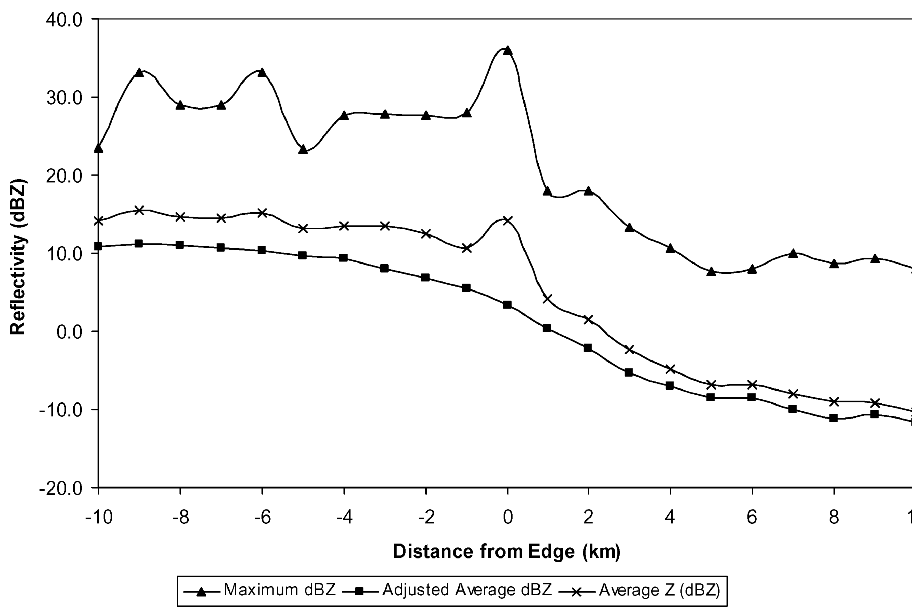

Fig. 2 Maximum and average radar reflectivity as a function of distance from the edges of anvil clouds. Positive distances are in clear air and negative distances in cloud.

The average reflectivity was calculated in two ways denoted in the figure as "Average Z (dBZ)" and "Adjusted Average dBZ." The first method converted the dBZ values reported by the radar to the equivalent values of Z and averaged them. The result was converted back to dBZ. This methodology is quite sensitive to large outliers, which is why the shape of this curve in Fig. 2 tends to track the shape of the maximum reflectivity curve.

The second method averaged the dBZ values reported by the radar. This produces a more representative average in the interior of clouds because it is less affected by a few large outliers, but it has a major weakness for our application. When the reflected signal drops below the noise floor of the radar, the radar reports "no signal." When averaging Z as in the first method, Z can be replaced with the value zero with little error. When averaging dBZ, there is no equivalent finite value to insert for dBZ when the data are missing. In this case the average was corrected by adjusting the average for the missing clear air data as follows:

$$\text{Adjusted Average dBZ} = \text{Average dBZ} + 10\,\text{Log}_{10} R_p$$

where R_p is the active pixels/total pixels.

The figure shows that the two methods give essentially equivalent results. In both cases, the sampling error ranges from less than 1 dBZ in cloud to a maximum of 2.4 dBZ in clear air. In clear air the two methods are within the sampling error. In cloud, the average Z is slightly higher because of its sensitivity to peak values, but the difference is not significant to this discussion. Both methods yield average reflectivity that drops from 10 dBZ or more in cloud to less than −5 dBZ outside of cloud. The transition takes place within 4 km of the cloud boundary.

IV. Observed Reflectivity and Transparency

In the summer of 2003, an observational campaign was conducted at Kennedy Space Center to explore the relation between the transparency of anvil clouds, as determined by ground-based observers at the Shuttle Landing Facility (identifier KTTS), and a standard radar reflectivity product from the National Weather Service radar (WSR-88D) in Melbourne, Florida. The observers subjectively determined the transparency of high cirriform clouds overhead and recorded them as transparent when higher clouds, blue sky, the sun's disk, etc. could be distinctly seen or if the sun cast distinct shadows of objects on the ground. These guidelines are consistent with those used during space launch and landing operations by pilots of reconnaissance aircraft to determine the transparency of anvil clouds. Satellite imagery was analyzed afterward to determine if the clouds were anvil clouds originating from thunderstorm activity. Data for 45 days with anvil clouds were obtained during the months of June, July, and August.

The WSR-88D layer reflectivity maximum (LRM) product displays the maximum radar reflectivity (dBZ) detected within a discrete vertical layer over each defined grid cell. It has been used to provide a quick assessment of the potential severity of thunderstorms.[10] The grid cells have horizontal dimensions of 2.2×2.2 n miles. The LRM product is available for two layers that encompass the altitude range where anvil clouds are typically observed over Florida: mid (24,000–33,000 ft) and high (33,000–60,000 ft). The product is color coded into seven categories, with the lowest category being 0–4 dBZ and the next highest category being 5–18 dBZ.

LRM mid and high products from the Melbourne WSR-88D were obtained for our 45 case days from the National Climatic Data Center. Of the 45 days, 41 had LRM products available, and on those 41 days a total of 313 daylight hourly observations of thunderstorm anvil clouds were found with coincident LRM products and anvil transparency remarks from the KTTS observers.

A 3×3 grid of LRM cells was analyzed over the KTTS area to match the effective area monitored by the ground-based observers and to take into account navigation errors in the radar product caused by daily variations in the refractive properties of the atmosphere. For each hourly KTTS observation with transparency remarks, the nine values of each LRM product within the 3×3 grid were recorded as integers, 0 for <0 dBZ, 1 for ≥ 0 dBZ. The record of anvil transparency remarks was merged with the integer values for the LRM mid and high products and classified as follows for a categorical analysis: The observer evaluation was classified as "yes" for opaque anvil clouds and "no" for transparent anvil clouds. The radar indication was classified as yes if any of the nine cells for either product had a value >0 and no if all of the nine cells for both products had a value equal to 0.

Table 1 shows a standard contingency table used for computing verification statistics of the observer evaluation and radar indication of anvil transparency. The categorical data were entered in the 2×2 table of counts of the four possible combinations of yes/yes, yes/no, no/yes, and no/no.

Table 1 shows five measures of performance as follows:

1) False alarm rate (FAR) of 10.1% shows that an LRM indication of anvil cloud has a high probability of being nontransparent.

2) Probability of detection of yes (PODy) of 49.7% shows that only about half of the anvil clouds classified as opaque by the observer were detected in the radar product.

3) Critical success index (CSI) of 0.471 gives the proportion of yes/yes events to the sum of yes/yes, yes/no, and no/yes.

4) True skill statistic (TSS) of 0.532 provides a measure of the radar's ability to discriminate between transparent and nontransparent observations. A TSS of 0 would result if the radar indications were random.[11]

5) Heidke skill score (HSS) of 0.437 gives the fraction of radar observations that were correct, adjusted for the number expected to be correct by chance.

Table 1 reflects a total of 313 evaluation/indication pairs corresponding to the hourly observations on 41 case days. The CSI, TSS, and HSS indicate that the LRM provides a modest degree of skill in detecting nontransparent anvil clouds.

Reasons for the discrepancy between the observer's assessment of cloud transparency and the LRM product appear to be in the nature of the LRM product. It provides the maximum radar reflectivity detected throughout the depth of a predefined layer but provides no information on the geometric thickness of cloud within the layer, and it has a lower cutoff at 0 dBZ. The lower cutoff and geometric thickness are important variables because theoretical calculations show that a cloud with a radar reflectivity below the cutoff (<0 dBZ) could appear nontransparent to an observer if the cloud were sufficiently thick. An additional important variable is the size of the ice crystals composing the cloud. Small crystals tend to produce weaker radar echoes but are highly effective in obstructing visibility. Large ice crystals produce stronger radar echoes, but are less effective than small crystals in obstructing visibility.

Table 1 Contingency table of anvil transparency based on the KTTS observer's remarks and a combination of the LRM high or mid radar product indication[a]

	Observer evaluation		
Radar indication	Yes	No	Total
Yes	80	9	89
No	81	143	224
Total	161	152	313

[a]FAR = 10.1%, PODy = 49.7%, CSI = 0.471, TSS = 0.532, and HSS = 0.437.

V. Conclusions

Since the original publication of Krider et al.,[2] the definition of the radar cloud edge in the LLCC has been changed from 10 to 0 dBZ. The observed average radar reflectivity (dBZ) at cloud edge was between 0 and 5 dBZ. This suggests that the recent revision of the limit specified in the LLCC was appropriate. The previous 10-dBZ limit meant that the radar boundary was actually about 5 km inside the cloud on the average, a potentially unsafe condition. The 0-dBZ limit places the average boundary a kilometer or two outside the cloud whichever averaging method is used, a safe but not overly conservative distance.

The analysis of ground-based observer assessments of cloud transparency and the LRM radar reflectivity product support the notion that anvil clouds with radar reflectivity values as low as 0 dBZ are likely to be nontransparent. These empirical results are consistent with theoretical calculations of radar reflectivity, optical extinction coefficient, cloud geometric thickness, and optical thickness.

The observational data are consistent with the theory and each other, lending confidence in the use of radar for determining cloud boundaries and transparency when visual observations cannot be made.

Acknowledgments

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