JP1.20 CLOUD RADAR OBSERVATIONS AT KENNEDY SPACE CENTER DURING THE ABFM EXPERIMENT

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1. INTRODUCTION

NASA's Airborne Field Mill (ABFM) experiments at Kennedy Space Center (KSC) in 2000 and 2001 were designed to study cloud electrification processes and to assess various lightning launch commit criteria (LLCC) regulations (Merceret and Christian 2000) . In February 2001, the experiment included observations by a scanning 35-GHz cloud radar from NOAA's Environmental Technology Laboratory (ETL) to augment data from the project's cloud physics aircraft, ground-based electric field mill network, and operational weather surveillance radar. Its role in the ABFM was to provide a clearer context for interpreting the aircraft and field mill network data and to assess the cloud information content of the permanent weather surveillance radar that is routinely used as part of KSC launch commit decisions. This article encapsulates a much more thorough description by Martner *et al.* (2002a).

Although Florida was suffering through a prolonged extreme drought in February 2001, two noteworthy cases presented themselves. On 03FEB01 coordinated aircraft, radar and electric field mill measurements were made of a mid-level stratiform cloud. The radar revealed that the cloud layer was approximately 2 km thick and extended upward to the -5 C altitude at 4.5 km MSL. As such, this cloud qualified as an LLCC "thick cloud" rule case and would have prevented a rocket launch at KSC. To paraphrase, this rule prohibits rocket launches, for fear of triggered lightning strikes, if a cloud is present that is more than 4500 ft thick and any part of it is within the 0 to -20 C temperature interval.

Data from the 03FEB01 case and from another case of weaker clouds on 13FEB01are also examined to compare observations by the visiting high-resolution cloud radar and those of the permanent, coarser resolution WSR-74C weather surveillance radar. The WSR-74C is a C-band radar that is routinely used by KSC meteorologists to assess cloud conditions over Cape Canaveral for LLCC decisions. Its ability to detect clouds over KSC is investigated using the cloud radar data as a baseline for comparison.

ETL's transportable NOAA/K cloud radar is a Ka-band Doppler, polarization-diversity system designed to provide detailed information about the structure, kinematics, and microphysical properties of nearby clouds (Martner *et al.* 2002b). During the ABFM, the NOAA/K radar was located at KSC about 1 km east of the Shuttle Landing Facility, well within the permanent KSC network of ground-based electric field mills and within 25 km of all launch pads on the Cape. An electric field mill from the University of Arizona was also temporarily installed adjacent to the radar. Scan images from NOAA/K were posted on the Worldwide Web in near realtime, and radio communications between the radar crew, the research aircraft, and the project command center were established to facilitate experiment operations.

2. THICK LAYER CLOUD CASE OF 03FEB01

On 03FEB01 a weak frontal system moved into central Florida creating a stratiform overcast and cold, northerly winds at KSC. At times, the clouds produced drizzle and very light rain. The morning radiosonde marked the 0C and -20C levels at 4 and 7 km MSL, respectively. By mid-afternoon, NOAA/K radar scans showed that the layer was about 2 km thick and its top had risen to the -5 C level at 4.5 km MSL. Low elevation scans of the WSR-74C radar at Patrick AFB (~42 km to the south) indicated a somewhat banded and cellular appearance of the echoes, characteristic of embedded convection within widespread stratiform clouds. Based on the NOAA/K scan images, the University of North Dakota Citation aircraft was dispatched to investigate these clouds.

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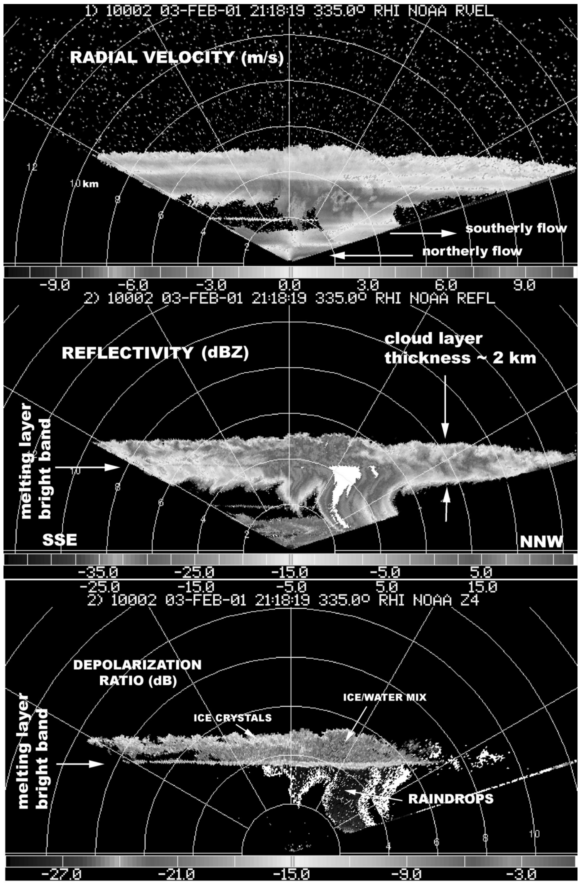

Figure 1. An RHI scan parallel to the aircraft penetrations on 03FEB01. Top panel is radial velocity (m/s), middle panel is radar reflectivity (dBZ) and bottom is deopolarization ratio (dB).

Virga and drizzle fell at the NOAA/K site during parts of the 2-hour flight of the Citation. The total accumulation measured with a gauge at the site was no more than 1 mm. Maximum observed reflectivity factors were about 25 dBZ in drizzle and virga streamers. RHI scans at 21:18 UTC shown in Figure 1 indicate a melting layer bright band was present at 3.7 km above ground level (AGL ≈MSL). The depolarization ratio data in the lower panel of the figure show this feature most clearly. Thus, the cloud layer was more than 4500 ft thick and its top was within the 0 to -20C interval. It definitely met the criteria for suspension by the LLCC thick cloud rule.

The Citation took off at 20:40 UTC and conducted 18 penetrations of the cloud over the radar vicinity, between 21:30 and 22:34, on flight track legs oriented approximately north-south, before landing at 22:55. The cloud penetrations were all between 4.5 and 3.5 km AGL (-5 C to +1 C). Almost the full cloud depth over the radar was sampled in 64 minutes. During the Citation overpasses, NOAA/K conducted a continuous series of RHI scans through the zenith, thereby providing vertical cross-sections through the sky at azimuth increments of 30 degrees and time increments of 1 minute.

The Citation aircraft's *in situ* hydrometeor measurements were limited by the malfunction of some of its probes. However, it is clear that both liquid water cloud droplets and ice crystals were present on nearly every pass. Mean cloud droplet sizes, derived from the Forward Scattering Spectrometer Probe (FSSP) were about 25 microns and concentrations were generally less than 100 cm^{-3}. The mean ice particle size, inferred from the 1D-C probe, was about 150 microns and concentrations were highly variable from pass to pass. The presence of large ice crystals or snowflakes, some as large as 1 cm, was documented by the High Volume Particle Sampler (HVPS).

Ground-based and airborne mills monitored the electric field strength. During the Citation flight, all measured fields, including those from the three KSC mills closest to the radar were weak, as shown in Figure 3. Except for one mill that briefly measured a field of 400 Vm^{-1}, all of the nearby KSC mills and the University of Arizona mill registered less than 300 Vm^{-1}. Similarly weak E fields were detected aloft in the cloud by the Citation on all of its 18 penetrations. It is reasonable to conclude that these very weak electric fields presented minimal threat of triggered lightning and virtually no threat of natural lightning strikes. No lightning strikes occurred anywhere in central Florida on this day.

Although one of the common ingredients for cloud electrification was present (*i.e.* ice), the NOAA/K Doppler measurements indicate that there was little in the way of vertical motions in this cloud to separate charges and produce threatening electric

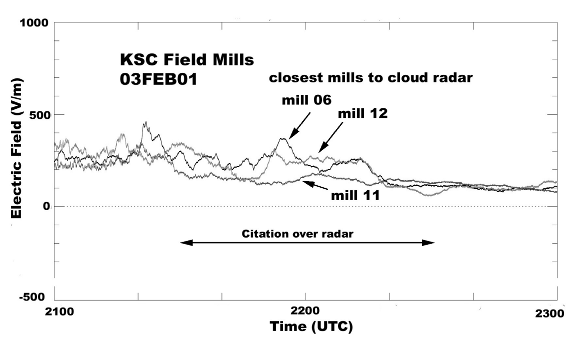

Figure 2. Ground-based electric field measurements from the KSC network of mills near the NOAA/K radar during the 03FEB01 aircraft flight.

fields. There was also no upstream thunderstorm from which charged particles could have advected.

Coordinated operations and combined observations by the cloud radar, research aircraft, and electric field mills provide strong evidence that the 03FEB01 case was one in which the existing LLCC thick cloud rule would have prevented a launch unnecessarily. Of course, it is only a single case, and generalizations should not be drawn from one case. Before the thick cloud rule is allowed to be relaxed, it is important to know how often thick cloud situations pose no threat (100% of the time?, 90% of the time?), and to develop dependable ways to routinely identify the benign circumstances and distinguish them from hazardous ones.

However, 03FEB01 is at least one well-documented case that confirms thick-cloud-rule false alarms do indeed occur, as had been surmised by general experience of scientists at KSC. The case study also provides a more detailed knowledge of the structure and microphysical characteristics of this kind of cloud than was available previously.

3. RADAR COMPARISONS

The NOAA/K cloud radar data were also applied to assess how well the precipitation radar used for KSC operations is able to detect and delineate cloud layers. In practice, cloud conditions are assessed as well as possible by KSC meteorologists using realtime scan images from the WSR-74C C-band precipitation radar at Patrick AFB, (augmented by scan images from the National Weather Service WSR-88D radar at Melboune, FL). Often these data are inconclusive for LLCC decisions, and a reconnaissance airplane must be launched to provide *in situ* observations of clouds, winds, and other factors.

The sensitivity the ETL cloud radar, its close proximity to the clouds of interest, and its 37.5-m range resolution, allowed it to reveal weak cloud boundaries and structure with intricate detail. Furthermore, it conducted RHI scans, which are ideally suited to observing the vertical structure of clouds directly. In contrast, the WSR-74C conducted a sequence of PPI scans, from which cloud heights and thicknesses are more difficult to determine directly. Vertical sections can be constructed from a volume of these scans, but they suffer some loss of resolution and detail from the original PPI data and require some time lag to produce. Also, millimeter-wave radars, such as NOAA/K, characteristically suffer less from side lobe problems that commonly infuse even high scan data with ground clutter contamination and exaggerate indicated storm top heights (Kropfli and Kelly 1996).

Only the clouds on 03FEB01 and 13FEB01 were strong enough and persistent enough for the radar data intercomparisons. Data from the WSR-74C's PPI scans were carefully mapped onto the NOAA/K RHI scan planes to enable comparisons in a common volume of space. The NOAA/K data extended to 19 km range; no comparisons were possible beyond that radius. Figures 3 and 4 show the results for selected times on the two days as informative examples.

The 03FEB01 comparison in Figure 3 indicates that the cloud radar (gray points) detected two layers, the thick mid-level cloud discussed in the previous section and a much weaker cirrus layer near 11 km AGL. The precipitation radar (white squares) detected stronger portions of the lower layer fairly well; both radars indicated echo top at about 4.5 km (confirmed by the Citation) for that layer. But the WSR-74C was unable to delineate weaker parts of this layer and it failed to detect the overlying cirrus. Numerous points within the cloudless 5-10 km interval were found in the WSR-74C data, apparently the result of noise or ground clutter contamination. In regions where the reflectivity exceeded about 5 dBZ, both radars agreed fairly well. In weaker regions, the precipitation radar data were not reliable indicators of cloud boundaries or existence. Similar analyses for other times on this date corroborate this finding.

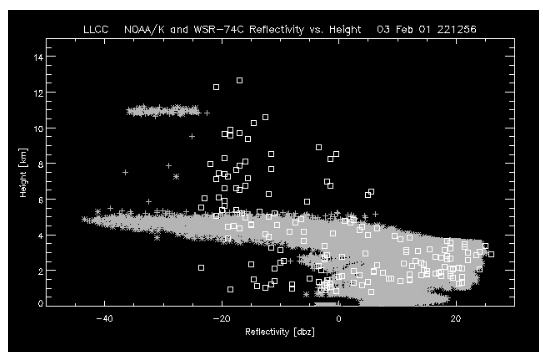

Figure 3. Reflectivity data as a function of height from NOAA/K (gray points) and the WSR-74C (white squares) at 2214 UTC on 03FEB01.

According to the NOAA/K observations, clouds on 13FEB01 included a persistent thin stratus overcast with occasional fog that was intermittently overlain by two to three layers of cirrus between 8 and 12 km AGL. The cirrus were not associated with a convective storm. These clouds were all much weaker (< -5 dBZ) than the mid-level cloud of 03FEB01. As such, they represent a demanding test of how well the C-band radar is able to detect non-precipitating clouds over KSC.

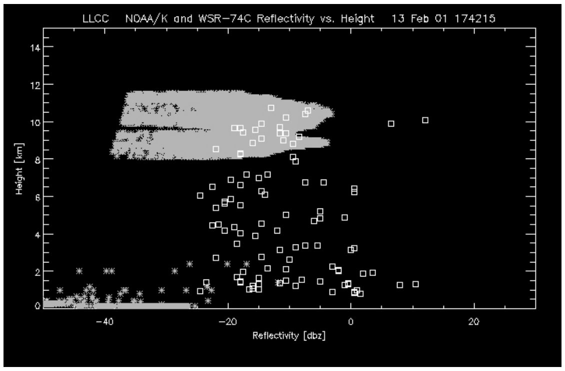

Figure 4. Reflectivity data as a function of height from NOAA/K (gray points) and the WSR-74C (white squares) at 1744 UTC on 13FEB01.

The 13FEB01 reflectivity-height comparison plots are shown in Figure 4. The gray points from the cloud radar clearly delineate the weak cirrus layers. The even weaker stratus (< -20 dBZ) is also evident just above ground level, although a few points above it are probably echoes from insects. In contrast, the WSR-74C data are dominated by clutter or noise and provide no clear indication of any cloud layer boundaries, and the existence of layers is only suggested. Thus, the radar used in operational LLCC decisions is not capable of usefully delineating cloud layers as weak as these. This is not necessarily bad, if these very weak clouds can be confidently dismissed as purely benign. However, the dramatically enhanced cloud depictions available from a cloud radar definitely offer more comprehensive, detailed, and reassuringly precise information about existing cloud conditions.

4. SUMMARY AND CONCLUSIONS

The NOAA-ETL millimeter-wave cloud radar was operated at KSC as part of the ABFM experiment in February 2001. Although the project took place during a severe drought, useful data from two cases were analyzed. NOAA/K documented cloud structure, such that concurrent research aircraft and electric field mill measurements could be better interpreted to study cloud electrification processes.

Assessment of the LLCC "thick cloud" rule was of particular interest. Mixed-phase clouds observed on 03FEB01 represent a well-documented case in which the thick-cloud-rule proved overly conservative. Data from the visiting cloud radar were also used as a "ruler" for assessing capabilities of the permanent WSR-74C precipitation radar for detecting clouds for LLCC decisions. These radar intercomparisons on two days show that precipitation radar defines cloud boundaries over KSC reasonably well where reflectivity exceeds about 5 dBZ, but yields ambiguous results for weaker clouds or misses them entirely.

It is clear from the limited ABFM experience and from deployments in other research programs, that cloud radars could be valuable tools for rocket range operations in the future. The NOAA/K operations in the ABFM were a step toward clarifying benefits and concerns in this regard. The technology to operate such an instrument as a long-term, fully automated cloud profiler has been demonstrated in the millimeter-wave cloud radars designed by ETL for the U.S. Dept. of Energy's Cloud and Radiation Testbeds (Moran *et al.* 1998).

ACKNOWLEDGMENTS

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