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CLOUD PHYSICS OBSERVATIONS INSIDE HAILSTORMS WITH AN ARMORED AIRCRAFT DATA SYSTEM

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1. INTRODUCTION

Several years ago, a project was initiated to develop a research vehicle capable of flying through hailstorms (Sand and Schleusener, 1974). The purpose was to gather meteorological data from the interior regions of such storms, which could lead to a clearer understanding of hail formation and possible hail suppression mechanisms. The result of this project was the T-28A aircraft shown in Fig. 1.

The modifications required to the standard T-28 included armoring all leading edges, strengthening wing and tail structures, and installing a larger engine and stronger propeller. In addition, the rear seat and interior compartments of the airplane were stripped to make room for instruments and data acquisition hardware. To insure the aircraft could indeed withstand the harsh environment through which it was supposed to fly, a "hail cannon" was used to propel iceballs of various

Fig. 1. The armored T-28 hail research aircraft.

sizes (up to 7.6 cm diameter) against exposed portions of the plane at speeds of 100 m sec^{-1}. No significant damage resulted from these tests.

Instrumentation and data acquisition systems carried aboard the T-28 have been in a constant state of evolution since the aircraft became operational. Originally, the airplane was used to acquire rather general information about the structure of storms, such as temperature, total water concentration, and updrafts. However, as newer and more specialized instruments have become available, the T-28 has been used to study other areas of interest, such as turbulence, hydrometeor concentrations and size distributions, and detailed case studies.

Since 1972, the T-28 has made more than 200 thunderstorm penetrations and has been an important data gathering facility for the National Hail Research Experiment (NHRE).

2. INSTRUMENTATION

The instruments carried aboard the T-28 may be grouped into three categories according to the type of quantity being measured:

1. State variables.
2. Aircraft navigation and performance variables.
3. Hydrometeor sensors.

A complete list of instruments carried and the ranges of measurement are shown in Table 1.

2.1 State Variables

Because of the importance of the temperature and static pressure measurements within and around the storm clouds, these variables are redundantly measured. The primary static pressure instrument, the Rosemount

TABLE 1

T-28 Instrumentation Complement

Variable	Instrument	Range of Measurement
State:		
Static Pressure (Altitude)	Rosemount 1301-A-4-B	0 to 15 PSI
	Ball Engineering EX-210-B	0 to 27,000 ft (8.2 km) MSL
Total Temperature	Rosemount 102AU2AP	-25 to +25°C
	NCAR Reverse Flow	-25 to +25°C
Aircraft Navigation & Performance:		
Attitude	Servomechanisms angle-of-attack vane	-15 to +15°
	Pitch (Humphrey vertically-stabilized accelerometer)	-50 to +50°
	Roll (Humphrey vertically-stabilized accelerometer)	-50 to +50°
Navigation	IAS heading indicator	0 to 360° magnetic
	NARCO UDI-2ARD DME (2 units)	0 to 100 n mi
	NARCO MK12 VOR (3 units)	0 to 360° from
Performance	Ball Engineering 101A variometer (rate-of-climb)	-6000 to +6000 ft/min (-30 to +30 m/s)
	Rosemount 1301-D-1-B dynamic pressure (ind. airspeed)	-3 to +3 PSI
	NCAR True Airspeed Computer	0 to 250 knots (128 m/s)
	Humphrey SA09-D0101-1 vertically-stabilized accelerometer	-1 to +3 g's
	Giannini 45218YE manifold pressure	0 to 50+ in Hg
Hydrometeors:		
Cloud droplets	Johnson-Williams LWC	<50 μm dia (liquid only); 0 to 6 g/m^3
	Particle Measuring Systems FSSP	3 to 45 μm dia; adjustable
	Rosemount 871 Ice Detector (icing rate)	0 to approx. 0.15 in/min (0.06 mm/sec)
Rain, graupel, snow	Williamson Foil Impactor	1 to 20 mm dia
	Particle Measuring Systems OAP-2D	31 to 1000 μm
	Cannon Particle Camera (alternates with hail spectrometer)	Approx. 50 μm up
Hail	IAS Laser Hail Spectrometer (alternates with Cannon camera)	4.5 to 50+ mm dia

1301-A-4-B, has a basic accuracy of ±0.1% and response time of a few tens of milliseconds, whereas the Ball EX-210-B used as a backup is accurate to within ±1%, and has similar response. To provide higher resolution pressure data from which aircraft rate-of-climb can be determined by differentiating, the Rosemount output for the normal operating range of the T-28 (5 - 7 km MSL) is also amplified by a factor 5 and recorded separately.

Temperature measurements out-of-cloud are obtained from both the Rosemount 102AU2AP and the NCAR reverse-flow sensors. However, in-cloud temperatures cannot be measured with the Rosemount unit due to wetting of the sensing wire. The NCAR reverse-flow thermometer with a basic accuracy similar to that of the Rosemount device (less than 1.0°C), but with a slower response (on the order of a few seconds), is used for in-cloud measurements.

2.2 Aircraft Navigation and Performance Variables

Instruments which measure aircraft position, attitude, and motion are used in determining storm dynamic characteristics, such as vertical and horizontal air motions and turbulence. In addition, the aircraft navigation equipment is used by the pilot in locating the desired penetration point of a storm from instructions given from ground radar.

Redundancy is an important feature of the dynamic instrumentation system since only a few storms a year are studied in detail and the data are sufficiently important to warrant the added expense. For the study of vertical air motion, for example, the primary system consists of aircraft rate-of-climb determined from differentiated static pressure measurements, but in the event of a malfunction, the variometer (rate-of-climb indicator) is used instead. If both instruments should fail, the integrated accelerometer output could be used to calculate rate-of-climb. Corrections for engine power setting and airspeed are used in computing true vertical air motion as opposed to the simple rate-of-climb of the aircraft.

2.3 Hydrometeor Sensors

One of the most important features of the aircraft instrumentation package is its ability to measure the numbers and sizes of particles present within a hailstorm. These particles may range in size from a few microns diameter for cloud droplets up to several centimeters diameter for hailstones.

Typically, cloud physicists are interested in particle size distributions, and this information can be obtained from the PMS probes, the foil impactor, the hail spectrometer, and the Cannon camera. In addition to numbers and sizes, the particle phases (ice or water) can be determined through the use of the PMS OAP-2D and the Cannon camera data. Supporting information about the phase of particles less than 50 μm diameter is obtained by comparing the output of the J-W liquid water indicator with liquid water concentrations calculated from the PMS-FSSP probe. With larger size particles (greater than 5 mm diameter), which are measured mainly by the foil impactor, Cannon camera, and hail spectrometer, we assume ice phase only because raindrops in this size category break up very quickly in nature due to dynamic instabilities.

3. DATA RECORDING SYSTEM

Data are recorded by two separate digital systems aboard the T-28. The primary recording system consists of an analog and digital multiplexer connected to a 7-track computer-compatible incremental recorder. This system records all analog and digital data from the instruments carried, with the exception of the PMS particle data. In addition, time of day, flight number, and various event codes are recorded by this system. A second, 9-track, recording system is carried for the primary purpose of storing PMS particle data. It also records backup data from some of the more important analog instruments, plus the hail spectrometer. Here again we have attempted to achieve higher system reliability through the use of dual redundancy.

All data from analog instruments such as the temperature, pressure, and attitude transducers are normalized to an output of ±5 volts DC for full-scale measurements. All digital instruments, such as the hail spectrometer and PMS probes, output data in a BCD format.

A small Sony stereo voice recorder is also carried for the dual purposes of recording pilot comments and the sound of hailstone impacts upon the windscreen of the aircraft. This recorder has proven to be extremely valuable in providing supporting data for the other instruments and also allows the pilot to concentrate entirely on flying the aircraft without the burden of taking notes.

A UHF telemetry system, which has seen only limited usage thus far, is carried also. This system permits selected variables to be recorded on the ground and additionally allows the ground radar observer to gain a fuller understanding of the conditions in which the aircraft is flying in real time.

4. OPERATIONAL PROCEDURES

The general objective of the T-28 program is to use the aircraft to obtain data within and in the immediate vicinity of hailstorms. Primary use of the aircraft to date has been in cooperation with NHRE in the study of mature storms. The objective of the mature storm studies is to locate and characterize the hail growth region for different types of storms. This involves many studies, such as determination of the particle size distributions in various stages of storm development and determination of the trajectories of hailstones and their growth environment. The underlying idea is to gain sufficient knowledge to address specific questions as to whether the beneficial competition hypothesis of hail suppression is viable in northeast Colorado storms.

To accomplish the above objectives, various flight patterns have been developed for penetrating mature storms. The penetration procedures have been of an evolving nature, but generally consist of making repeated penetrations at a single level near a temperature of -15C (approximately 6 km MSL). Safety is of primary importance in any of the penetration procedures designed for the T-28. Accordingly, portions of the storms with reflectivity factors greater than 55 dBz at or above the level of penetration are avoided. This limit has worked satisfactorily and has produced encounters with hail up to 2.5 cm diameter, and a few larger stones on occasion.

Penetration procedures have been outlined for the following storm types:

1) quasi-steady-state storms;
2) multicell storms; and
3) line storms.

Most storms in northeast Colorado are multicellular, but even so it is difficult to make real-time identification of storm type because many storms exhibit properties of the other types at one time or another during their lifetimes.

If a storm is relatively steady-state, the plan calls for penetrations starting from the southern quadrant of the storm followed by a right turn through the weak echo region (WER) and out to the leading edge of the storm through the so-called embryo curtain (EC) region. If all works well, this process can be repeated and several passes will be made through various parts of the WER and EC region.

Penetration procedures for multicell storms are somewhat simpler because they can usually be carried out along the direction of motion of the storm through cells that are in various stages of development. In the event that reflectivity factors are too high along the desired flight path, the penetration can be carried out parallel to, but displaced from it while avoiding the high reflectivity factors. An alternative procedure is to pick a cell expected to merge with the main cloud mass and penetrate it in a direction perpendicular to the line of cell formation. In this way, an individual cell can be followed through its life cycle.

For line storms, the plan calls for penetrating along and in front of a line of cells in the inflow region. Thus, several cells in various stages of development are penetrated. An alternative here would be to concentrate on a particularly well identified cell in the line and penetrate it according to either multicell or supercell procedures.

Aircraft penetration paths are determined by a project meteorologist located at a ground control facility, in close coordination with the pilot of the T-28 and other personnel involved with the project. In order to accomplish the penetrations with desired accuracy, it is necessary to have access to high resolution tracking and conventional weather radar data in a near "real time" mode.

5. SUMMARY OF DATA

Many different types of data presentations for analysis are possible from the T-28 system, but space is not adequate to show them all. Instead, three examples of data available from the system are presented here; they were selected because of their demonstrated utility and/or uniqueness.

5.1 Standard Data Reduction

An example of T-28 reduced data is shown in Fig. 2. The data are from a segment during one of the hailstorm penetrations on 22 July 1976. Of the ten variables shown, only temperature (RFT) and cloud liquid water concentration (JW LWC) are measured directly. Altitude (ALTX5-1) is computed from high resolution pressure measurements and vertical air velocity (UPDR-ALT) is obtained essentially from aircraft rate-of-climb (Musil et al., 1977). The hail water equivalent concentrations (HAIL H2O) are obtained from measurements by the laser hail spectrometer, assuming spherical ice particles, and ECHO is the hail radar reflectivity factor computed assuming a thin water film. TURB is a measure of the turbulence encountered by the T-28 and is based on Fourier analysis of the fluctuations in airspeed (Sand et al., 1976). The remaining variables are all derived from temperature measurements. Equivalent potential temperature (THETA E) assumes water saturation, TV-1 is virtual temperature, and D TEMP is a temperature deviation which is obtained by adjusting temperature moist adiabatically to a reference level outside the cloud.

The variables shown in Fig. 2 have proven to be the most useful for analysis purposes, but many others can be displayed. In fact, a larger presentation of the data, including measurements from essentially all equipment on the aircraft, is used on a quick-turnaround basis to diagnose equipment problems in the field.

5.2 Particle Size Distributions

The T-28 has instrumentation for measuring hydrometeor sizes between about 30 μm and 5 cm in diameter. The measurements are taken from the PMS OAP-2D probe, a foil impactor, and a laser hail spectrometer. An example of the composite hydrometeor spectrum is given in Fig. 3. The size distributions are for a 10-sec time period taken from the time period shown in Fig. 2.

The foil impactor data must be hand-reduced prior to computer processing, but data from the other two sources are entirely computer reduced. Procedures used in analyzing the 2-D PMS data are described by Heymsfield and Parrish in a forthcoming NCAR Tech Note. The hail spectrometer sizes the particles passing through its field of view in the same way as the PMS probes, so it is a simple task to develop particle size distributions from it. An encouraging feature of Fig. 3 is that all three data sources fit together very well.

5.3 Particle Photography

Figure 4 shows an example photograph from a particle camera developed by Cannon (1976) which is flown alternately on the T-28 with the hail spectrometer. The Cannon camera produces pictures of particles in the cloud and can distinguish between ice and water. Although the sample volume is limited and the camera data must be reduced by hand, the device does give excellent pictures of the particles and is capable of determining hydrometeor composition.

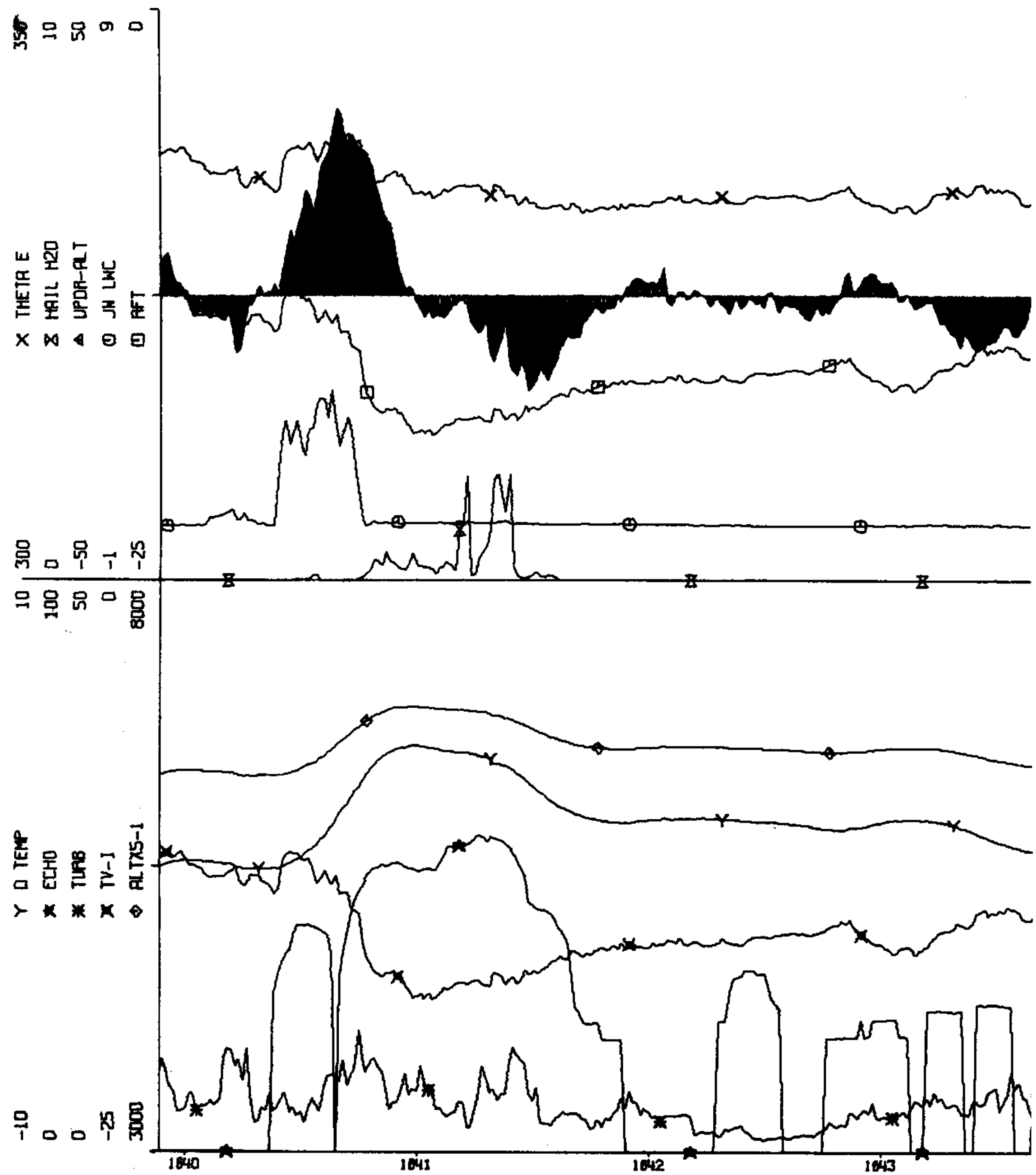

Fig. 2. Example of reduced meteorological data from 22 July 1976. Variables explained in text.

6. CONCLUSIONS

Data gathered by the armored T-28 have played an important role in developing a better understanding of the nature of hailstorms. The T-28 system was developed for the primary purpose of gathering data from the interior regions of convective storms. As instrumentation has evolved, this system has been used to gather finer scale and more accurate information concerning the microphysical and dynamic characteristics of hailstorms. Analysis of these data has helped to develop a better understanding of hail formation and growth processes.

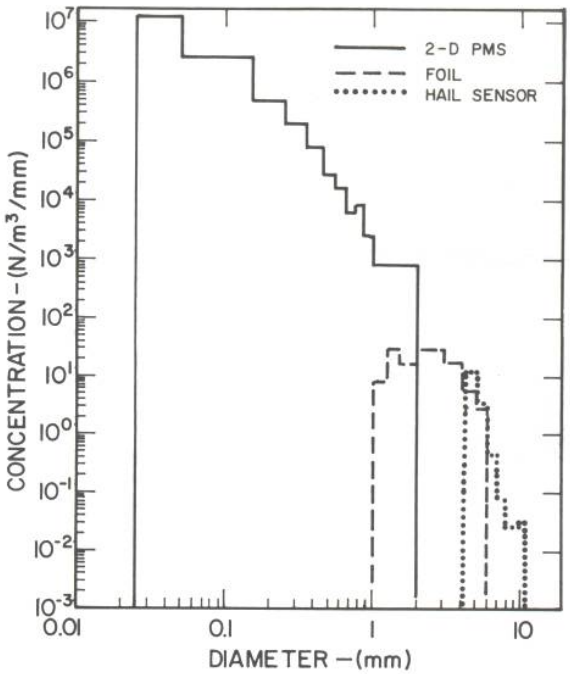

Fig. 3. Particle size distribution obtained from PMS (2-D) probe, foil impactor, and laser hail sensor for time period 164120-164129 MDT on 22 July 1976.

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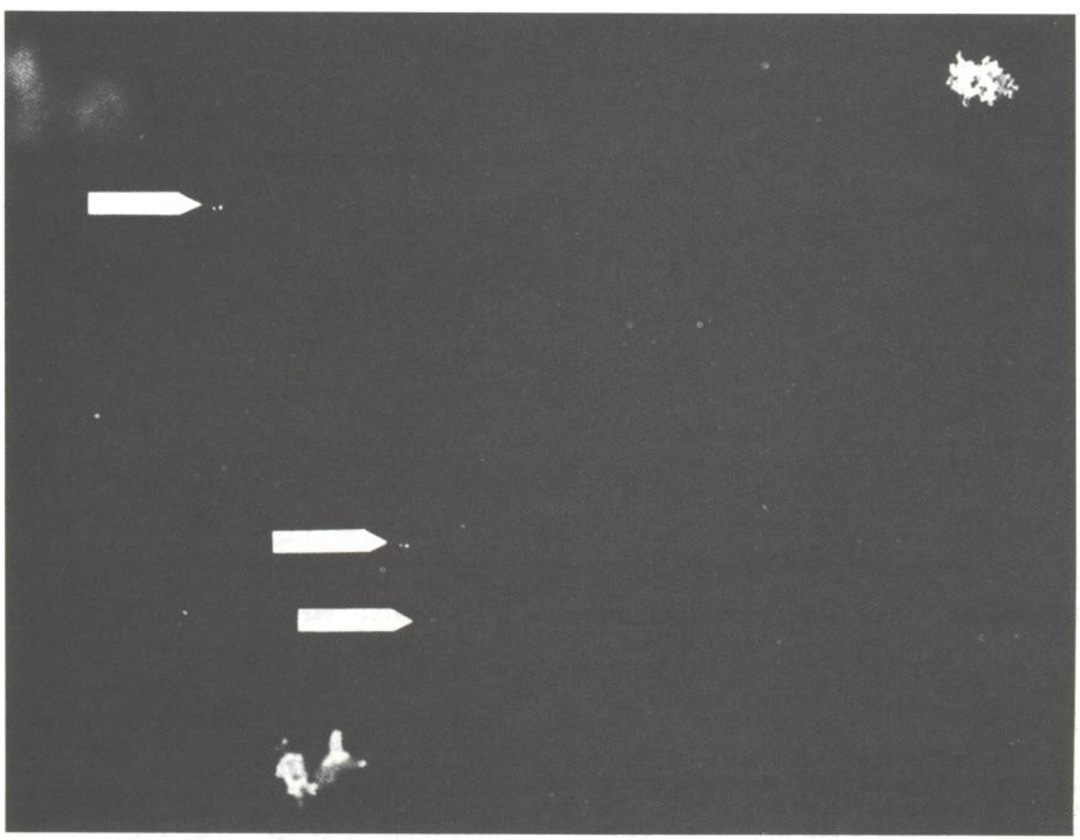

Fig. 4. Example of output from Cannon camera.