Report SDSMT/IAS/R-92/09

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SUMMARY REPORT OF T-28 DEPLOYMENT TO COLORADO (JUNE 1992)

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1. INTRODUCTION

The armored T-28 aircraft was deployed to Greeley, Colorado, for the two-week period 15 June through 27 June, 1992. The purpose of the deployment was a combination of instrumentation testing and participation in a program to test multi-parameter radar hail detection algortihms.

Funding for the deployment was derived from two sources. The National Science Foundation (NSF), Division of Atmospheric Sciences facilities deployment pool provided funds for one week of the deployment; the purpose was testing aircraft instrumentation and performing exercises in thunderstorm studies in coordination with the Colorado State University/NSF CHILL multiparameter research radar, located at Greeley. Aircraft instruments undergoing tests included the South Dakota School of Mines and Technology (SDSMT) Institute of Atmospheric Sciences (IAS) hail spectrometer, the National Center for Atmospheric Research (NCAR) reverse-flow temperature sensor, a newly-installed combination LORAN/GPS aircraft positioning unit, and a research data telemetry system acquired in 1991 that had yet to perform up to its specifications. The aircraft telemetry system was to be used to transmit location information to the CHILL radar, where it would be displayed on the operational PPI displays in real time.

Funds for the second week of the deployment were provided by the NCAR Research Applications Program (RAP) for support of their study of hail detection using multiparameter radars. This study is described in Appendix E by Dr. Edward Brandes. The role of the T-28 in this study was to provide *in situ* precipitation particle measurements in volumes of cloud under surveillance by one or more multiparameter radars and thought to contain hail.

The prime area for operations was determined by the siting of the three radars supporting the RAP project. These were the NCAR Mile High radar, near Stapleton International Airport on the northeast side of Denver, the NCAR CP-2 radar at the NCAR Marshall field site northwest of Denver, and the CSU/NSF CHILL radar located northeast of Greeley, about 100 km northeast of Denver (see Fig. 1). The CHILL radar is described in Appendix F. The T-28 penetrations were to be focused on storms evolving in the region between these three radars.

Research flights were directed from the RAP operations room at the NCAR Foothills Laboratory in Boulder. Radio communications were set up between a meteorologist in the operations room, with access to Mile High or CP-2 radar displays, and the T-28. A secondary communications link was also established between another scientist in the CHILL operations

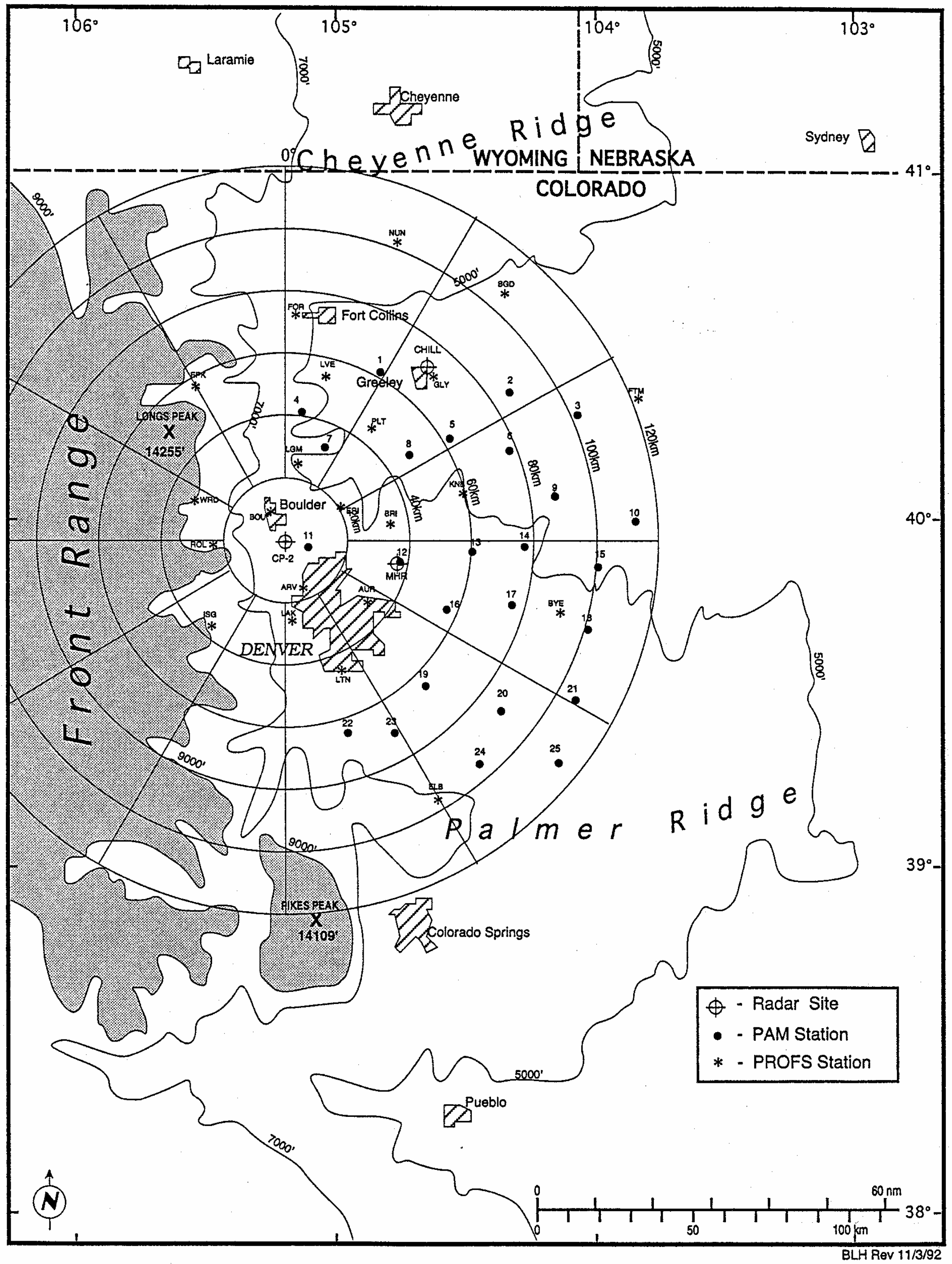

Fig. 1: The RAPS-92 project area is shown with a superimposed spiderweb centered on the CP-2 radar. T-28 operations were based in Greeley. Flight operations were directed from Boulder.

trailer at Greeley, with access to the CHILL radar display, and the T-28. The two scientists on the ground were able to communicate with each other over a ground radio link or via the commercial phone network.

The frequency of hailstorms within the target region during the two- week period was well above climatological expectations. The T-28 flight activity is summarized in Table 1. The first few days of the first week were used for preliminary clear-air flight tests to debug instrumentation and telemetry systems. Beginning at the end of the first week, there were five research flights in a 7-day period, with hail-bearing storms in the operational area on each of these days.

This report summarizes operations and instrumentation performance during the two-week deployment. Section 2 describes operations on the five days during which research flights in hailstorms were performed. Section 3 summarizes the data obtained on these flights and describes the performance of the aircraft instrumentation during the deployment. Section 4 includes a brief summary of data analysis up to the time of this report. Additional information concerning the data and operations is included as appendices.

TABLE 1

Flight Activity

Date (1992)	Flight No.	Hours	Purpose
2 June	582	1.4	Ferry RAP - BIS
9 June	583	1.4	Ferry BIS - RAP
15 June	584	2.0	Ferry RAP - GXY
17 June	585	1.1	Test
18 June	586	1.3	Test
20 June	587	2.2	Research RAPS-92
21 June	588	1.6	Research RAPS-92
22 June	589	1.6	Research RAPS-92
24 June	590	2.3	Research RAPS-92
26 June	591	1.9	Research RAPS-92
27 June	592	1.7	Ferry GXY - RAP

Total flight hours: 18.5
Total CSU/test and ferry hours: 6.1
Total RAPS-92 hours: 9.6

2. OPERATIONS

The T-28 Facility Staff for this project included Dan Custis (DCP), pilot; Andy Detwiler (AGD), scientist; Ken Hartman (KRH), programmer; Gary Johnson (GNJ), engineer; Richard Kelley (RFK), scientist; Jon Leigh (JEL), mechanic; and Dennis Musil (DJM) meteorologist.

The T-28 was hangared at PL Flyers at Greeley Municipal Airport; it is shown on the ramp in Fig. 2. Telemetry and secondary communications were based at the CHILL radar site north of the Greeley Airport. Figure 3 shows, at the CHILL site, the radom and the user trailer, with telemetry and communications antenna attached.

Below are brief summaries of research flights performed on 20, 21, 22, 24 and 26 June 1992 from Greeley Municipal Airport. The T-28 was directed from Boulder by Dennis Musil, who had available in the RAP operations room a display of either Mile-High or CP-2 radar data and the T-28 flight track, obtained from the Federal Aviation Administration (FAA) radar aircraft tracking system, displayed on top of the radar PPI's. These summaries were extracted from his notes plus the pilot's comments recorded during the flight. Times are Mountain Daylight.

<u>20 July 1992</u>

1200 - Briefing at Boulder. Weak southeast low level flow exists with a convective temperature of about 30°C. Looks like good potential, but it appears to be a waiting game.

1255 - Radio at Greeley won't transmit; appears to be a bad microphone or microphone connector. There is no transmit key when the microphone is plugged in. The Greeley people plan to bring down an exchange microphone from the other radio at CHILL.

1400 - Fairly cloudy outside. Echoes exist over the mountains to the west, especially stronger to the southwest. Some clouds come off the mountains but dissipate rapidly.

1420 - AGD arrived with the exchange microphone and it appears to work okay. There is little visible difference between the two plugs.

1500 - Talked to DPC about possible flight around 1730 or so, unless something develops sooner. A storm is located at azimuth 275/51 nmi from GLL vortac, movement east-southeast/20 kts.

Fig. 2: The T-28 is shown on the ramp at Greeley municipal airport.

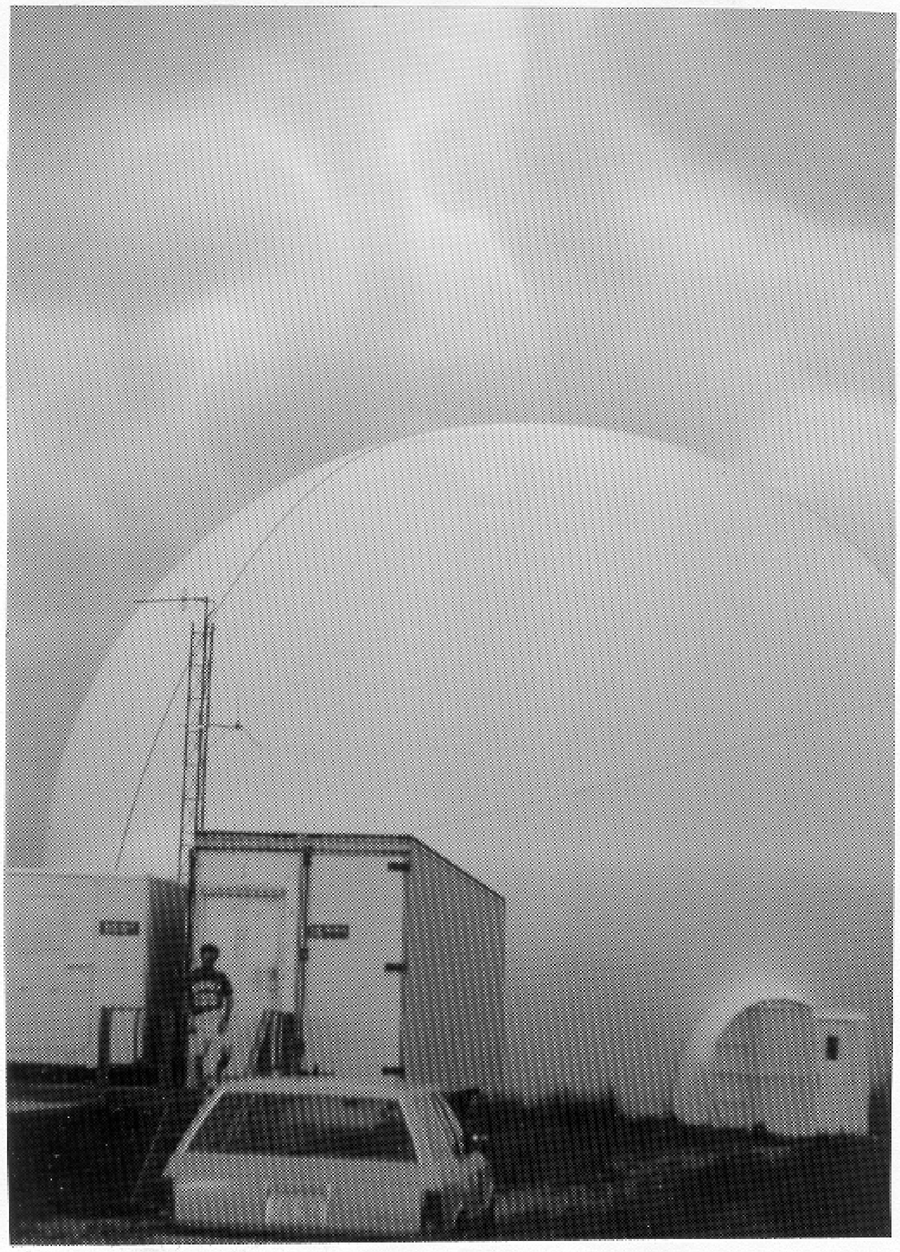

Fig. 3: The CHILL radome is shown with support trailers and communication antenna mast in the foreground. The view is to the east northeast.

1620 - Echo 260/45 GLL. All echoes seem to be weakening. They don't seem to want to move off the mountains.

1655 - Alerted T-28. Plan is to fly into Flight Level (FL)150 for penetration work. The intended storm is located at 210/15 nmi GLL.

1705 - Tracking program is questionable.

1723 - T-28 airborne. Climbing to N then back to S for target storm S of Greeley.

1730 - Transponder code is 5131.

1731 - Track acquired.

1733 - Climbing through 14 kft.

1735 - Level off at 15 kft, 0°C. Heading for S end of a line extending SW->NE over Greeley.

1745 - Heading for Initial Point (IP) of 170/36 followed by penetration heading of 010.

1746 - Heads into cloud.

1749 - End Penetration 1. Heading was 360 then became 010 later in penetration. Turned out to west to steer clear of excessive reflectivity after going through southernmost cell. Then turned back into next cell.

1749 - Heading back into cloud.

1749:40 - In cloud again.

1750:50 - Out again. Not much to it. The T-28 appears to be located on the west side of the cloud. Turning to east and trying to hit more of the echo, but looks like it is dissipating.

1752 - Heading 170 for Penetration 2. Under a cloud with large vertical electric fields.

1756 - Data acquisition computer dies. All digital data up to this time in the flight is lost.

1801:27 - In cloud. Heading 360 for Penetration 3. Hail spectrometer is picking up particles.

1802:50 - Out of cloud. 170 deg/34 nmi from GLL.

1804 - Pilot reports funnel to southwest, will attempt to penetrate through cloud over it.

1810 - In cloud. Heading of 340. Pilot reports 3,000 feet per minute updraft during the penetration with light to moderate turbulence.

1814 - Out of cloud on north side. There were some clear spots in this penetration. Was lifted to 15.3 kft. Appeared to go through on west edge of highest echoes.

1818 - In cloud, heading 160, altitude 14 kft. Heading more to SE to get closer to echoes. Looks like he's going through the northernmost cell in a N->S line of 3 cells.

1500 fpm (feet per minute) up, moderate rain, then 2000 fpm up.

1821 - Moderate turbulence, light rain.

1822 - Out of cloud. A tornado was 2 mi S of Mile High. T-28 should have gone right over it.

Turning to E then will head back thru to N.

1825 - In cloud, heading 340.

Moderate precip/moderate turbulence.

1828:07 - Out of cloud. Probably missed the target on the east side, but in the echo.

Left turn to 160 deg to go back thru to S.

1830:46 - In cloud, across an extension of the main echo. Heading 160, altitude 14 kft.

Light precip and a little hail.

1832:08 - Out of cloud. Turning right to come back north. Telemetry reception degrades when tail is pointing away from CHILL.

1834 - New penetration, heading 330. Good tower ahead.

1836 - Out on N side and turning.

1837 - Rolling out on 070 heading. Trying to go through a new tower off to east.

1839 - In clear but thinks he's picking up light hail.

1842 - 180 turn to heading 240.

1842:50 - Possible hail.

1843 - Coming right to 270. Heading thru a 50 dBZ echo.

1844 - Intermittent radio contact for about the last 4 minutes. New heading 270.

1846 - Out of cloud. 180 deg turn to right to heading 090.

1850 - In cloud.

1850:10 - P-static.

1850:50 - P-static.

1851:40 - Out of cloud. 180 deg turn to right. Still working storm to N of Mile High. Pretty much in the bottoms of what little cloud is left.
Steady on heading 260. Is S of last pass.

1856 - In cloud on a heading of 260. Just S of Mile High, going through new growth on S side of line.
Pretty high hail counts during this penetration.

1900 - Out of cloud.

1903 - T-28 heading back to Greeley airport.

1920 - T-28 touches down.

Summary:

Computer on the aircraft quit during the flight, around 1756. Aircraft was highly charged at the time. First attempted reboot failed. Second one succeeded. The data on the data tape were lost prior to that time, except for 8 variables that were recorded on the telemetry computer on the ground.

Foil ripped early in flight. Most of the roll was wrinkled. Could distinguish particle impressions, but background is pretty wrinkled. Other instrumentation appeared to function well.

21 July 1992

1200 - Weather briefing: southeast flow is weaker today with less moisture than yesterday; convective temperature is around 27°C with the current temperature at 23°C. Activity is expected, but there is more uncertainty today; plan is to update at 1330.

1330 - Back at RAPS operations. Echo located at 250/35 nmi GLL. Movement east-southeast slowly. Storm is still in the mountains.

1345 - Updated DPC and CHILL people.

1425 - Storm movements appear to be toward the southeast now.

1500 - Echoes west of GLL dissipate when moving eastward off the mountains. Cumulus clouds are developing E-S of GLL. Best activity southwest of DEN.

1515 - Echoes 275/45 and 270/40, movement SE/40.

1600 - Echo 270/30-40; another 310/30, tops greater than 35 kft. Movement is still southeast, but most intense part stays in the mountains.

1700 - Talked to DPC. The plan is to file for an 1800 takeoff. Echo 350/15 moving south with reflectivities 55-60 dBz. Nowcasters expecting cloud to form along a convergence line in the vicinity of 150/35.

1745 - Alerted T-28. Developing storm 155/50. Weak yet, but launching on forecast. Storm near Greeley is dissipating. Target storm is forming on northern edge of RAPS radar area.

1805 - T-28 airborne, trying to get clearance.

1810 - 5156 transponder. No track, problem unknown.

1815 - Transponder shows 4156 even though 5156 was selected.

1817 - A little below 14 kft. 20 nmi out of Greeley.

1819 - At 15 kft. Something about 5 nmi ahead.

1822 - In and out of bases. T-28 has target being watched by ops center.

1825:45 - Penetration 1, heading 210. Altitude 15 kft. 170 deg/55 nmi from GLL.

Barely in the bases. Not picking up anything.

1829 - Out of cloud.

1832:30 - In-cloud, heading 010, Penetration 2.

1834 - Change to 030 heading.

1836:41 - Out of cloud. Some radio problems during the penetration, unable to hear each other at times.

1840 - Storm 1 loses RAP ops. CHILL radios to have him continue on course (090 heading) as per instructions from RAP ops.

1845 - In cloud. Storm at 138 deg/58 nmi from GLL. Small cloud.

1846 - Out of cloud.

1849 - Penetration 4. Heading 275.
Hail, 500 fpm up, light turbulence.

1850:50 - Out of cloud. Will go back through at a lower altitude.

1855:39 - Penetration 5, heading 090 (visual), altitude 12 kft; T-28 is under cloud at the present time, will enter cloud little later.

1856:45 - Hail encountered.

1857:30 - Out of cloud. Was just in bases of storm at 137 deg/62 nmi from GLL.

1859 - Doing a 90/270 turn. Will come out westbound.

1901 - Rolling out on heading 270 deg. Then comes right to 280 deg. Altitude 13 kft.

1903 - Heading 280, Penetration 6, at 13 kft. Really below cloud base. There was a little precip, but generally very little activity.

1904 - Out of cloud. Return to base.

1925 - Reaches ground at Greeley.

Summary:

A few penetrations were performed in weak clouds east-southeast of Denver. The clouds were in a weakening, dissipating stage; most penetrations were in rain below cloud base. Radio communications with Boulder were marginal at times, probably because of long range and P-static on the aircraft. Data appeared to be okay, except JW liquid water sensor was out. There were fairly strong electric fields in spots.

22 July 1992

1200 - Arrived at Boulder for the weather briefing. The outlook is not too good, as it is quite dry in the mountains. The atmosphere is much clearer than yesterday and hotter. There is some moisture over the prairie, but it is expected to mix out.

1330 - Back at RAPS operations following lunch.

1415 - Echoes located on Palmer divide, movement southeast.

1450 - Echoes northwest and west of I-25, movement southeast. Very small and weak.

1500 - Review of potential conflict with newly arriving research aircraft:

1. CP-2 will provide primary support for the T-28 and will operate in sector scan mode with interspersed RHIs.

2. Operations will attempt to get the *zeb* display operational for use of T-28 controller. This might happen as early as tomorrow.

1505 - Little change in echoes.

1600 - Best echo north of CHILL moving in from Wyoming. Max 50-55 dBz. Movement southeast/speed unknown.

1623 - GNJ called, wants to work on computer, but I declined because the echo to the north of Greeley is still a possible candidate; however, getting the storm in range in time for an operation may be a problem.

1720 - Alerted T-28, storm about 25 nmi north of Greeley.

1750 - T-28 airborne. Heading for cells to the north of CHILL which, according to the radar, contain hail at this time.

1756 - Transponder code 5173.

1758 - No track yet.

1800 Display program at RAP ops is down, still not working. T-28 altitude block from 12 -> 16 kft. Leveling at 14 kft. Lining up on N side of storm.

1804 - 30 nmi N of GLL.

1806 - 34 nmi N of GLL. Communication and coordination problems.

1808 - Track is okay now.

1810 - Storm still contains hail, according to radars.

Setting up to run down the 34 deg radial toward GLL. Should be right through storm starting on the N side.

1814:51 - In cloud, lots of lightning. Heading 200 deg, altitude 14 kft.

1819 - Possible hail encountered.
Maximum vertical motions 3000 fpm up and down

1821:30 - Having trouble staying within block, pushing over.

1824:40 - Out of cloud.

1827 - Reversing course with a 90/270. Going to head back north.

1829 - Rolling out on 030 heading. Will fly along 040 radial from GLL.

1831 - In cloud for Penetration 2, moderate to heavy rain encountered, turbulence is strong with good updrafts reported. Pretty much through bases of clouds.

1837 - Possible hail.

1839 - Turning in cloud using a 90/270. Will come back through along 050 radial from GLL.

Seem to be on western edge of storm. Heavy precip with mainly downdrafts. Hail is detected just west of CHILL on the CHILL radar.

1844 - Out of cloud on south side for Penetration 3 at 11 kft. Will turn and go back to north on 050 radial from GLL.

1845:40 - In cloud, good precipitation reported again. Some possible hail sounds on windscreen mike. Lightning and +/- 1000 fpm vertical motions.

1847:25 - Heavy rain and lightning

1849 - Out of cloud. Doing 90/270.

1852 - In cloud. Heading 220 deg, altitude 12 kft. Coming to 230 deg heading. Lightning and updrafts to 3000 fpm reported. Looks like a good hit on the echo.

1856:48 - Out of cloud, T-28 will return to base, too dark to read the instruments in the cockpit.

1910 - On ground.

Summary:

Four penetrations were performed in a storm that moved north and east of Greeley. Penetrations were generally along radials from GLL and a couple were through the hail signal reported on the CP-2 radar. Instrumentation appeared to work properly, although there was some question about random hail counts in the large categories of the hail sensor.

<u>24 July 1992</u>

1145 - Arrived at Boulder. Clouds are already building along the edge of the mountains. Looks like a good day.

1200 - Weather briefing. Atmosphere is much drier today, dewpoint temperature is ranging between 0-4°C. A small positive area exists, and there is northwest flow at the surface. On the positive side, a low over Kansas-Nebraska border shows strong moisture advection back toward northeast Colorado; things could change rapidly. At the present time, they do not look too good for the development of hail.

1330 - Called DPC to go on standby. Also talked to KRH.

1400 - Echo forming southeast of Greeley. Convergence line moving southwest into area; the dew points to the eastern side of the line are much higher.

1445 - Alerted T-28.

1455 - Storm at 135/29 nmi GLL. Tops near 30 kft.

1515 - T-28 airborne.

1524 - Transponder code 5103.

1525 - No track, problem unknown.

1533 - Track is okay now.

1535 - Penetration 1 on a heading of 360, FL 140. Storm is WNW of Greeley.

1537 - T-28 reports hail.

1538 - Heading 030.

1539:30 - 4,000 feet per minute updrafts reported, hail encountered. Frequent lightning.

1542 - Turning 90/270 in cloud for new penetration.

1543 - Picking up 150 deg heading on N side of storm.

1544 - Penetration 2 on a heading of 150.
Heavy precip

1544:30 - 20 deg right so heading is now 170.

1546 - Heading 190.

1547 - Hail encountered. Lightning.

1549 - Out of cloud. Peak upward motion 1000 fpm.

1551 - Doing 90/270, then lining up on heading 010 in the clear on the south side.

1555:56 - In cloud. Heading 010 for new penetration, reflectivity exceeds 55 dBz. Aircraft is at 12 kft.

1556:40 - Hail encountered.

1557:28 - More hail encountered.

1558:45 - 3000 fpm up.

1600:24 - Out of cloud. Will do 90/270 and come back through at 12 kft.

1604:28 - In cloud for Penetration 4 on a heading of 170. Storm is moving SEwd right over CHILL.

1608 - Track jumped east about 3 nmi.

1608:10 - Hail encountered.

1609 - More hail encountered.

1609:46 - Hail again.

1612 - Hail again.

1613 - Out of cloud. Asking for new block as he reverses course to come back north.

1615:40 - Rolling out on heading 350.

1616:20 - CHILL trailer being buffeted by winds.

1618:20 - In cloud for Penetration 5 on a heading of 010 at FL 095.

1622 - The track jumps around a lot, but so far I'm able to sort it out.

1623:30 - Below bases.

1624:35 - Out below cloud base on north side. Penetration encountered moderate precip, moderate turbulence, some lightning. Will do 90/270 and go back through to south.

1627:25 - In cloud for Penetration 6 on a heading of 190; severe turbulence encountered, as well as heavy precipitation and lightning.
3000 fpm down

1630:10 - Hail.

1632 - Under cloud base. Can see off to east.

1634:32 - Out on south side. Will reverse course.

1637:37 - Penetration 7 on a heading 010.

1644:54 - Turning in cloud (actually in bases), end of Penetration 7. Encountered heavy precip and mod turbulence on this leg, with some lightning. Could see a lot of dirt being kicked up to east as he turned.

1648:25 - Begin Penetration 8 on a heading 190. This penetration encountered moderate turbulence and precip with some lightning.

1653:52 - Out of cloud on south side. Will return to base. Storm began to weaken noticeably near 1618 (Penetration 5) and succeeding penetrations.

1710 - On ground.

Summary:

Good penetrations with hail encountered during the first four penetrations. Reflectivities were also high, exceeding 60 dBz in some cases. Reflectivities were highest during the early penetrations and decreased gradually after that. Radio communications were poor at times, especially during penetration 1 when the reflectivity exceeded the T-28 limits. Oil cooler and J-W hot wire LWC sensor were damaged during the flight and must be replaced.

<u>26 July 1992</u>

1150 - Arrived at Boulder.

1200 - Weather briefing. Dew points are in the mid to high 50's range, very good for northeast Colorado. Convective temperature is about 80°F, which is expected to be reached late in the day. CAPE of 1200 joules/kilogram, corresponding to a lifted index of about -5, shows lots of energy in the atmosphere. Expect lots of convective activity, but probably late.

1315 - Oil cooler is installed, testing taking place. No activity yet.

1325 - NWS has issued a tornado watch in the vicinity of CYS-TAD.

1500 - Towers visible from roof northeast and south, but each is a long way away.

1530 - Called DPC, aircraft is ready for duty. Hail sensor is out with a bad power supply.

1600 - Echo 65 km north-northwest of CP-2 is hung up in the mountains. Other stuff is south of Stapleton.

1630 - Nowcasters expect things to go soon; uncertain why it hasn't gone already.

1654 - Alerted T-28, IP 150/30 at FL 140.

1715 - Storm located near 170/48, but appears to be weakening.

1723 - T-28 is airborne, squawking 5165 transponder code.

1730 - Echo now at 165/40 with old echo near 165/47 nmi.

1733 - Trouble obtaining clearance to area; will work northern echo near 150/30.

1742 - In cloud on 085 deg heading at 15 kft.

1743:15 - Heavy hail. Also moderate turbulence and lightning.

1744 - In wrong storm. Located at 140/30, reversing course to right.

1745:30 - Begin penetration 2.

1746 - Hail encountered during Penetration 2. Heading 265 deg, altitude 14 kft.

1748 - More hail encountered, along with heavy rain.

1750:20 - Out of cloud. Went through a very tough storm with 60 plus dBz, 2500 fpm updrafts and moderate turbulence. Poor radio communications caused the mis-communication.

Orbiting while talking to ATC.

1758 - Track tends to drop out. Clearance obtained for storm at 150/30. Will penetrate east to west from IP located at 165/30.

1804:07 - In cloud for Penetration 3 on a heading of 075 at 14 kft.

1804:50 - Heading 055.

1808:33 - Out of cloud, track still flaky. Pilot reports not much activity on that penetration. Will reverse course to 250 deg.

1814:30 - In cloud for Penetration 4.

1818:06 - Out of cloud, track is gone again. Encountered light turbulence, light precip, lightning and 1000 fpm updrafts. "Not much in it."

Going left 270 deg.

1820 - Track is back again.

1821:30 Rolling out on heading 060.

1823 - In cloud for Penetration 5 at 150 deg/28 nmi from GLL.

1824:25 - Hail encountered.

1826:36 - Reversing course. Encountered 2000 fpm updrafts, moderate precip and light turbulence on that pass.

1827 - In cloud for Penetration 6 on a heading of 240. Believes he's in hail.

1831 - 1,000 fpm updrafts reported.

1831:45 - Hail encountered.

1833 - Out of cloud. Encountered moderate turbulence, light precip, and 1500 fpm updrafts on that pass. Sees tower ahead about 4 nmi.

1833:50 - In cloud again.

1834:10 - Out of cloud.

1837:55 - Rolling out on heading 060. Will go northeastward through a line of cells.

1839:23 - In cloud for new penetration, heading 060.

1841:40 - Hail encountered.

1842:45 - Changed course 30° to the left.

1844:30 - Hail encountered. Two cells 145/28 and 130/26.

1846:05 - Out of cloud. Encountered 2000 fpm updraft and moderate precip and turbulence on that pass.

1849 - Transponder is out, return to base.

Summary:

Good case with eight penetrations, but many problems with radio communications (P-static). Several penetrations had hail, including two in one storm that was very strong. Penetrated while radio communications were lost. Foil data look good but no hail spectrometer data were obtained.

3. DATA

Herein follows a summary of data obtained during the operations described in Section 2.

Flight 587 (20 June 1992)

A data system crash midway through this flight caused the loss of most data obtained before 1800 Mountain Daylight Time. This summary is based on data obtained after that time.

Electric field mills showed that the storms were fairly highly charged, with fields approaching 40-50 kV/m during short periods between 1800 and 1900.

Updrafts encountered during the period 1800 to 1900 tended to be fairly narrow. Many were only a few seconds long (i.e., less than a kilometer wide) as the airplane went through them. There were a couple of broader ones with the computed updraft speed approaching 30 meters per second.

The 2D-C probe image data and the 1D hail spectrometer data both look good. The FSSP data look a little bit suspicious. The JW data look good.

Unfortunately, the foil impactor jammed and the foil ripped early in the flight. Most of the subsequent foil was rolled up on top of this rip, which caused the foil to wrinkle. The particle impressions can be recognized but the background is pretty wrinkled. Maximum sizes approach 1 cm, while the most common sizes are down around 5 mm. Due to the wrinkling and the fact that the foil was apparently jammed at one point during the flight, the punch marks are not all there and timing of this foil will be impossible.

Flight 588 (21 June 1992)

All data save the FSSP look good.

Flight 589 (22 June 1992)

Foil data from this flight look good. Punch marks came through fine and the foil was not excessively wrinkled. All other data, except for the FSSP data, look generally pretty good.

Flight 590 (24 June 1992)

Hail was reported by the pilot during all penetrations except for penetration number 5. One-inch hail and 2 inches of rainfall were reported in the Fort Collins area from this storm, prior to the time the T-28 was flying in it. Peak wind gusts at the CHILL radar were 67 mph as the outflow reached it.

Maximum sizes recorded on the hail spectrometer exceeded 2 cm, while the largest foil impressions appeared to be about 1 cm in diameter. The audio tape only lasted through the first seven out of eight penetrations. Research data look good, except for the FSSP. During this flight, the T-28 oil cooler was damaged and the aircraft was leaking quite bit of oil when it got to the ground. The J-W hot wire liquid water concentration sensor was broken.

Flight 591 (26 June 1992)

The pilot reported hail around 1742 and 1743 during his first penetration. During this period, hail could be heard both on the windscreen mike and on the pilot's mike. He reversed course in cloud, came back through, and found a little bit of hail and mostly rain on the reverse track. During these two penetrations he observed updrafts exceeding 2500 feet per minute. The third penetration was not very exciting, but on the remaining penetrations, updrafts in excess of 2,000 feet per minute and hail were encountered each time. The flight was terminated early due to a failure of the aircraft transponder, which made it impossible for either the FAA or RAP ops to know the position of the T-28.

Data from this flight were generally good. Two exceptions are the hail spectrometer, which had a failed power supply and provided no data on this flight, and the FSSP, which was still not giving proper sizes to the droplets it sampled. The foil data from this flight, however, are quite good and should allow an analysis of the hail content of these storms.

Table 2 contains a collection of summary statistics organized by segments in the flight between the times the aircraft entered and left cloud.

In some cases when several small cloud elements were penetrated in quick succession, multiple cloud episodes are lumped into one penetration period. In some other cases, the aircraft reversed course to pass back through an interesting portion of a cloud without ever leaving the cloud. In these latter cases, a new "penetration period" is started in the middle of the reverse-course maneuver. Only rudimentary quality checks have been performed on the data at this time, so these numbers should be treated as first-look data that require further evaluation.

Appendix B lists all of the variables recorded or routinely computed from the T-28 observations, while Appendix C provides details on how each is determined. The variables tabulated in Table 2 are as follows:

Time - times, in Mountain Daylight Time, 24-hour format, when the aircraft began and ended a cloud penetration. Attempts are made to keep the aircraft data system clock set to WWV. Small deviations (plus or minus a second) may be present on any given flight.

Dur - duration, in seconds, of the cloud penetration.

z - average altitude, in geopotential meters in a standard atmosphere, during the penetration period. There may be significant differences (hundreds of meters) between this altitude and actual geometric altitude.

T - average temperature, in degrees Celsius, during the penetration as determined from the Rosemount aircraft temperature sensor. This sensor is subject to wetting effects and the average temperature may be biased low on many penetrations.

LWC - maximum 1-s value of total cloud liiquid water concentration, in g/m^3, as determined by the cloud water meter. This instrument has been shown to respond mainly to droplets with diameters less than 30 micrometers.

Up/Down - peak positive and negative vertical winds, in m/s, during the period, estimated from changes in aircraft pressure altitude computed from centered 2-s differences with some corrections applied. The peak downdrafts tended to occur near the beginnings of penetrations and are probably not reliable estimates of the actual air motion. As the aircraft rolls out of a turn there is a period of ~30 s where the pilot regains altitude lost in the turn and the aircraft is not in an attitude of straight and level constant-speed flight. Updraft estimates are only reliable at steady-state constant attitude flight settings.

Ez +/- - vertical electric field, kV/m, as determined from the T-28 electric field mills and corrected for aircraft shape effects and the roll angle of the airplane. Peak positive and negative values during the period are given. A positive vertical field component would force a positive test charge to drift upward, and is indicative of positive charge below the aircraft and/or negative charge above the aircraft.

Max Sh/Or Conc - maximum precipitation particle concentration, number per cubic meter, observed during the penetration. This estimate is based on the maximum value of 1-s counts of the number of particles entering the PMS 2D-C probe sample volume, per second. This probe responds to particles larger than roughly 25 micrometers diameter. Only the edge of a particle need be in the sample volume to trip the probe. The probe sweeps out 5 ℓ/s. The concentration is computed assuming all particles activating the probe are entirely within the geometric area scanned by the probe. This assumption is not strictly true and can lead to overestimates of the particle concentrations. The 2D-C probe exhibited some electronic problems during this project; one of its two buffers was often full of noise. Therefore, high shadow/or counts may, in some cases, represent noise rather than high particle concentrations.

Max 2DC Img Conc - maximum particle concentration, number per cubic meter, computed from the 2D-C image data for particles larger than ~50 μm. These estimates are based on periods over which the probe was active for a total of 1 s, which may involve several seconds of flight time. Artifact images are rejected and some particles partially in the field of view are reconstructed and included in the count. This approximately doubles the volume sampling rate of the probe for the largest particles compared to the volume sampling rate obtained if only images entirely within the field of view are included. These maximum concentration estimates are typically similar to the ones based on the shadow/or counts when the probe is operating properly. The peak values are somewhat dependent on the time chosen for the beginning of the penetration as the sample accumulation process for each 1-s period will involve different portions of the cloud if it is started at different times. The noisy buffer data were eliminated from consideration when making these estimates.

Max Hail Conc - maximum concentration, number per cubic meter, of particles with diameters larger than ~5 mm as determined by the T-28 hail spectrometer. This is a non-imaging, one-dimensional

TABLE 2

Penetration Data Summary

RAPS-92	Time (MDT)		Dur (s)	Hdng (deg mag)	z (m)	T (C)	LWC (g/m3)	Up (m/s)	Down (m/s)	Ez+ (kV/m)	Ez- (kV/m)	2D-C Sh/Or Conc (#/l) (for d>25μm)	2D-C Img Conc (#/l) (for d>50μm)	Hail Conc (m^{-3}) (for d>5mm)	Max 2D-C Size (mm)	Max Hail Size (mm)
Flt 587 20 June	(data prior to 18:00 lost due to data system crash)															
	18:01:37	18:02:53	76	360	4250	-0.3	0.2	10	10	7.2	-6.7	34	25	6.4	4.5	14
	18:10:34	18:14:32	238	335	4570	-2.7	1.5	17	-14	0.0	-1.6	29	15	3.8	4.7	10
	18:17:60	18:22:18	258	164	4320	-1.3	0.9	13	-15	1.1	-6.0	30	12	5.9	3.7	17
	18:25:55	18:28:09	134	345	4260	-1.1	0.5	9	-15	10.7	-14.5	64	34	8.2	5.6	45
	18:30:46	18:32:11	85	162	4310	-1.5	0.7	12	-15	0.9	-1.7	34	7	2.0	3.7	10
	18:35:44	18:36:09	25	337	4290	-0.3	0.4	2	-5	0.0	-1.6	1	0	0.0	1	0
	18:39:15	18:45:56	401	182	4260	-0.8	0.5	11	-15	45.6	-0.6	55	29	10.1	4.8	9
	18:50:02	18:51:20	78	89	4290	0.1	0.2	12	-18	38.1	-19.2	91	38	0.4	4.1	6
	18:56:23	19:00:34	251	264	4260	-0.2	0.4	9	-17	4.0	-29.6	55	27	5.8	4	14
Flt 588 21 June																
	18:25:34	18:29:04	210	210	4530	-3.4	0.0	10	-11	29.5	-27.8	104	86	6.4	4.1	9
	18:32:29	18:36:44	255	25	4540	-3.1	0.0	7	-11	7.5	-41.9	59	48	22.5	3.7	12
	18:44:49	18:45:42	53	86	4590	-4.8	0.0	4	-6	35.7	0.0	48	40	12.1	2.1	36
	18:49:52	18:50:56	64	276	4540	-4.0	0.0	12	-11	7.9	-4.4	39	21	11.6	3.5	20
	18:55:41	18:57:32	111	94	3630	3.7	0.0	14	-14	15.4	-0.1	31	9	9.4	4.9	45
	19:02:46	19:03:36	50	282	3930	1.4	0.0	3	-5	18.1	-0.6	42	12	10.7	4.8	10

TABLE 2
(continued)

RAPS-92	Time (MDT)		Dur (s)	Hdng (deg mag)	z (m)	T (C)	LWC (g/m3)	Up (m/s)	Down (m/s)	Ez+ (kV/m)	Ez- (kV/m)	2D-C Sh/Or Conc (#/ℓ) (for d>25μm)	2D-C Img Conc (#/ℓ) (for d>50μm)	Hail Conc (m^{-3}) (for d>5mm)	Max 2D-C Size (mm)	Max Hail Size (mm)
Flt 589 22 June																
	18:14:53	18:24:45	592	220	4360	-0.9	0.5	14	-14	62.5	-14.1	142	69	26.1	5.8	45
	18:31:05	18:39:30	505	68	3770	3.7	1.0	16	-15	47.0	-16.3	130	73	25.0	4.8	45
	18:39:30	18:44:00	270	225	3550	6.0	0.6	4	-17	41.5	-29.4	178	73	50.1	5.5	45
	18:45:45	18:49:18	213	53	3800	2.0	0.4	17	-14	33.6	0.0	62	31	12.2	4.5	45
	18:51:57	18:56:55	298	227	3710	3.0	0.6	10	-21	33.5	-25.8	62	32	10.7	4.6	45
Flt 590 24 June																
	15:35:08	15:42:30	442	82	4420	-1.1	0.8	17	-14	55.8	-78.0	486	201	39.3	4.3	45
	15:42:30	15:49:02	392	175	4480	-1.8	1.3	14	-13	29.5	-17.8	292	117	5.3	3.7	20
	15:55:56	16:00:26	270	19	3800	2.6	0.5	18	-11	35.9	-16.9	96	51	30.6	4.6	45
	16:04:28	16:13:05	517	172	3730	3.4	0.5	12	-11	24.3	-26.4	156	73	50.9	4.65	45
	16:18:10	16:24:38	388	11	2910	9.1	0.1	12	-12	17.1	-18.1	131	90	18.0	5	45
	16:27:27	16:34:53	446	191	2950	9.2	0.0	11	-11	29.1	-23.1	80	54	0.4	6	36
	16:37:36	16:44:57	441	11	2910	9.8	0.0	10	-14	32.0	-35.9	120	94	0.0	4.8	0
	16:48:26	16:53:56	330	192	2890	10.0	0.0	8	-8	23.5	-8.9	66	42	0.0	4.6	0
Flt 591 26 June																
	17:41:52	17:45:30	218	79	4720	-3.6	1.5	15	-14	30.4	-7.3	238	75	M	4.9	M
	17:45:30	17:50:22	292	260	4470	-1.6	1.2	18	-14	8.9	-5.3	364	45	M	4.6	M
	18:04:07	18:08:34	267	62	4340	-1.7	0.3	9	-13	12.0	-18.6	113	44	M	3.8	M
	18:13:53	18:18:05	252	244	4340	-1.7	0.1	10	-9	17.6	-22.6	89	39	M	4.6	M
	18:23:02	18:27:00	238	84	4440	-2.6	0.7	14	-11	22.5	-35.2	121	35	M	5	M
	18:27:00	18:34:05	425	247	4380	-1.9	0.7	10	-18	23.3	-17.9	132	25	M	5.1	M
	18:39:22	18:46:08	406	60	4320	-1.8	0.3	9	-13	41.1	-5.4	106	59	M	4.5	M

optical array probe. Large liquid drops may be counted by this probe as well as snow, graupel, and hail.

Max 2DC Size - maximum particle size (mm) observed by the 2D-C probe during the period. Since an attempt is made to reconstruct partial images, and the maximum dimension may be in the along-flight direction, the maximum size may exceed the nominal 800 μm effective width of the 2D-C array. Attempts are made to exclude artifact images such as splashes and streakers, but the automated rejection scheme is not 100% effective. These data have been checked with one pass of visual inspection through the most-probably misclassified images, but further examination would be prudent before basing any detailed analyses on these values.

Max Hail Size - maximum-size particle (mm) detected by the hail spectrometer during the penetration. Timing criteria are used in an attempt to reject counts due to water streaming off the probe housing, although this has been shown to be insufficient to eliminate all artifacts from the data. The maximum measurable size is 45 mm. Values this large in the presence of rain are probably artifacts due to water streaming off the housing. Detailed examination of the measured size spectra should be done in order to further verify the maximum sizes listed here. Maximum sizes determined from this probe are typically larger than maximum sizes determined by the 2D-C due to the larger size range sampled and the higher volume sampling rate.

Appendix D provides the recorded GPS flight track for each T-28 research flight.

4. PRELIMINARY ANALYSIS

The Colorado flights were very successful in providing data from a range of environments suitable for the various instrumentation tests discussed in the Introduction.

A calibration equation was verified for the new MINCO Platinum Resistance Temperature Detector (RTD) sensor element installed in the reverse-flow housing. The total temperature indicated by this sensor was used along with the static temperature indicated by the Rosemount temperature sensor, for clear sections of several flights, to establish a new recovery factor of 0.797 $\pm$ 0.040 for the reverse flow instrument with its new element. This agrees well with the value of 0.765 that was previously used with a semiconductor diode in the same reverse flow housing.

The telemetry system worked reasonably well on the first test flight. Reliable signals were obtained out to a range of 40 n mi and usable signals were obtained beyond 50 n mi. Performance then became progressively worse with each successive flight. Post-season examination by the system's manufacturer, DataRadio, confirmed that mechanical vibration probably caused a shift in a frequency setting that would have resulted in the observed symptoms. Steps will be taken to fix this problem before the next deployment.

The display of telemetered aircraft positions on the CHILL operational PPI display worked well. Voice communications between the ground and the aircraft were hampered by interference from precipitation static (P-static). The T-28 facility is now looking into the acquisition of FM radios to use for ground-air communication. It is hoped that these units will suffer less from precipitation static and will perform better than our aging VHF AM communications radios.

The new combination GPS/LORAN unit worked well with one minor problem. The old unit with GPS capability only, updated position and related quantities such as groundspeed, ground heading, etc., every second. The new unit provides values every second, but updates them only every 3 seconds. There appears to have been a difference in the internal programming of the unit, compared to the unit we used last year. We would prefer more frequent updates and are working with the manufacturer, Trimble Navigation, to get them. We are also working to retrieve geometric altitude from the GPS.

The new imaging interface between the IAS hail spectrometer and the aircraft data acquisition system did not function properly. Imaging capability was not demonstrated during the deployment, but three months later, after further work in the lab, images were finally obtained.

A data reduction routine obtained from Darrel Baumgardner at NCAR is being used to obtain better estimates of cloud water droplet population statistics from our FSSP than have been retrieved using our past algorithms. The effect of the FSSP response on the actual droplet distribution can be characterized by a response matrix which accounts for the optical (nonuniform laser beam intensity cross-section) and electronic (electronic response times) properties of the FSSP. The routine from Baumgardner uses Markowski's modification to Twomey's aerosol data inversion algorithm to calculate an estimate of the actual distribution and the response matrix. When these are multiplied together, they give an estimate of the measured distribution. The estimated actual distribution is adjusted until the difference between the estimate of the measured distribution and the actual measured distribution is minimal. An example of this is shown in Fig. 4, where the numbers of droplets per channel are plotted as a function of FSSP channel number for the distribution observed at time 154702 of T-28 Flight 590 on 24 June 1992. Increasing channel number corresponds to increasing droplet size. The measured distribution is plotted as a solid line with pluses (+), the estimate of the measured distribution as circles, and the estimate of the actual distribution as a dashed line with asterisks (*).

In addition to the calculation of the estimate of the actual distribution, the sampling volume must be modified to account for dead-time and edge effect losses. The corrected sampling volume and the estimated actual distribution are then used to compute the droplet concentration and liquid water concentration (LWC). These calculations are incorporated in the front-end software to the routines from Baumgardner.

Generally better agreement in LWC values is obtained between FSSP and Johnson-Williams instruments when Baumgardner's routines are used. Figure 5 is a plot of LWC as a function of time for about 2.5 minutes of T-28 Flight 590 on 24 June 1992 with no hail and few or no water droplets larger than 30 μm. Time is plotted as xxyy.zz where xx is hour, yy is minutes, and zz is fraction of a minute; each time tic is 3 seconds. The J-W LWC is plotted as a solid line, the FSSP LWC before the correction routine is applied as asterisks (*), and FSSP LWC after correction as circles with the dashed line.

There is some question about some of the optical characteristics of our FSSP probe (serial number 1 of Particle Measuring Systems, Inc's FSSP line) and further measurements of these characteristics are underway.

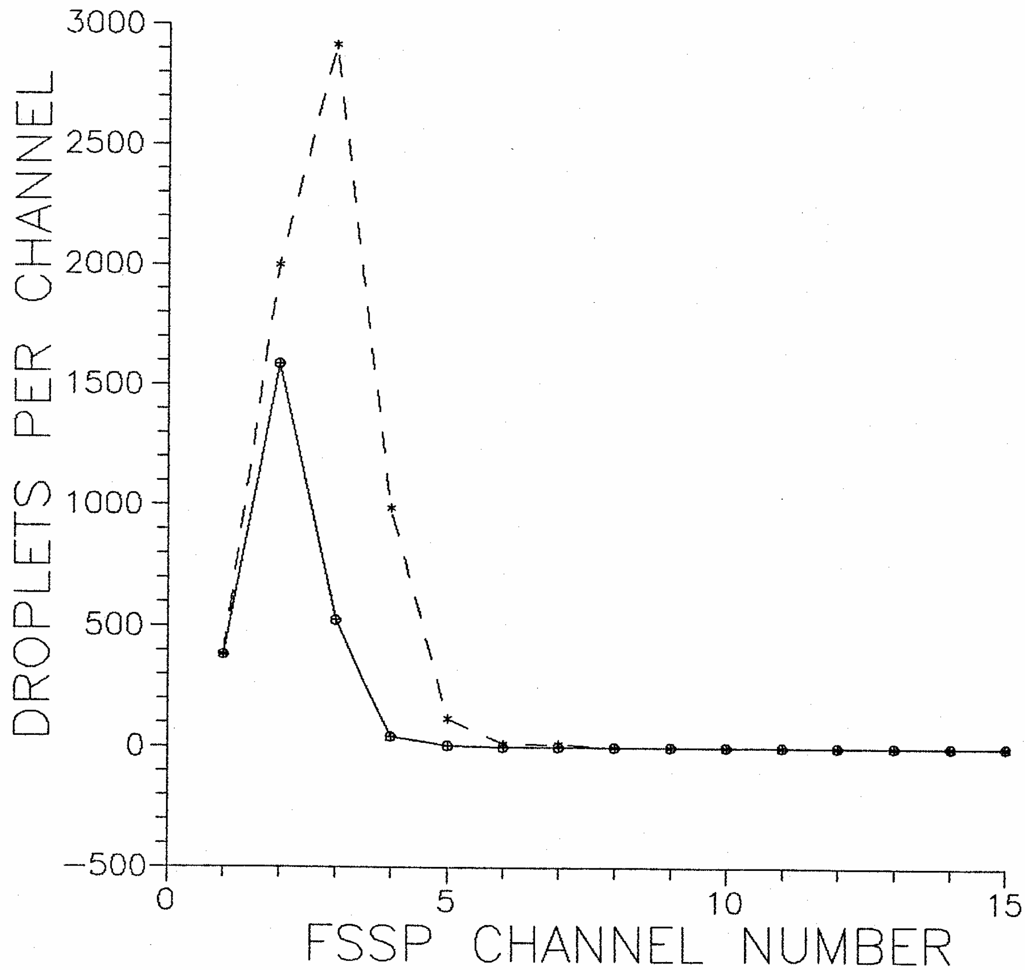

Fig. 4: Number of droplets per channel as a function of FSSP channel number (increase in channel number is increase in droplet diameter) for distribution at time 154702 of T-28 Flight 590 on 24 June 1992. Solid line with pluses (+) is measured distribution, circles are estimate of measured distribution, and dashed line with asterisks is estimate of actual distribution from correction routine.

As of the date of this report, RAP project scientists have begun to isolate the best periods of the research flights for in-depth analysis. Their field project continued through 7 August with radar and ground surveillance, as described in Appendix E. A large volume of data was obtained and the operations in which the T-28 participated represent only a small portion of the interesting data. It is hoped that instances can be found where a region of a cloud containing hail was under surveillance by two of the three project

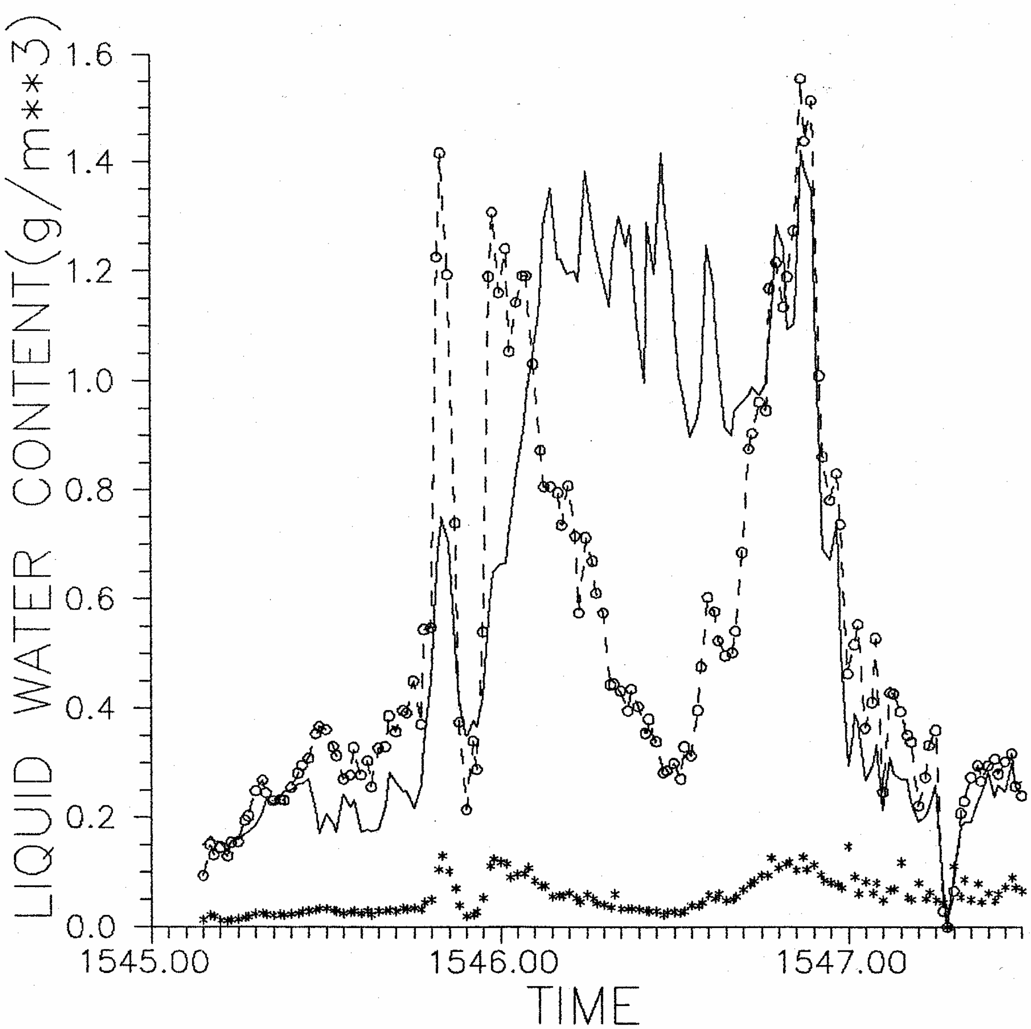

Fig. 5: Liquid Water Concentration (LWC) in g m^{-3} as a function of time for a portion of T-28 Flight 590 with no hail and little or no water droplets greater than 30 microns. The solid line is the J-W LWC; asterisk (*) is the FSSP LWC before correction; and the dashed line with circles is the FSSP LWC after correction. Time is plotted as xxyy.zz where xx is hour, yy is minutes, and zz is fraction of a minute. Each time tic is 3 sec.

radars as it was penetrated by the T-28. This would enable one to test the robustness of the hail detection schemes outlined in Appendix E, with independent measurements from two radars and an *in situ* aircraft.

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It was a pleasure to cooperate once again with the CHILL radar crew, and to have the opportunity to participate in the RAP hail detection product development project.

APPENDIX A

T-28 Instrumentation

VARIABLE	INSTRUMENT	RANGE	ACCURACY	RESOLUTION (as recorded)	NOTES
STATIC PRESSURE	ROSEMOUNT 1301-A-4B	0-15 psi (0-103 kPa)	±0.015 psi (±0.1kPa)	0.0002 psi (0.002 kPa)	• Bench calibration, 3/89
	ROSEMOUNT 1301-A-4B	5-15 psi (35-103 kPa)	±0.015 psi (±0.1kPa)	0.0002 psi (0.002 kPa)	• Bench calibration, 3/89
TOTAL TEMPERATURE	ROSEMOUNT 102AU2AP	-30 - +30°C	±0.5°C	0.001°C	• Platinum wire • -2 sec time constant
	NCAR REVERSE FLOW	-30 - +30°C	±0.5°C	0.001°C	• New platinum resistance element
CLOUD WATER AND CLOUD DROPLETS	JOHNSON-WILLIAMS LIQUID WATER CONCENTRATION	0 - 6 g/m2	±20%	0.0001 g/m3	• Accurate if all droplets have d <30 μm
	PARTICLE MEASURING SYSTEMS, INC. FORWARD SCATTERING SPECTROMETER PROBE	Size -1 < 57 μm Concentration 0 - -2000 droplets/ cm^3	±1 size channel in size and ±1% in concentration at -50/cm^3	1 size channel	• 15 discrete size channels spread over an adjustable range • Sampling rate 300 cm^3/km • Accuracy of computed liquid water concentration ~ ±20%. Depends on processing.
PRECIPITATION PARTICLE SIZES AND CONCENTRATIONS	WILLIAMSON FOIL IMPACTOR	1 - 20 mm	0.2 mm	0.2 mm	• Sampling rate 1.4 m^3/km
	PARTICLE MEASURING SYSTEMS, INC. 2D Cloud Probe	Size 25 - 800 μm	±25 μm	25 μm	• Computed ice and water concentration can vary ±50% with processing technique • Sampling rate: 0.1 m^3/km; DAS can accept ~250 particles/sec (2500/km)
	HAIL SPECTROMETER	Size 4.5 mm - 4.5 cm Concentration 0 - 100/m^3	±1 size class	1 size class	• 14 size classes • Sampling rate 100 m^3/km • Alternates with particle camera
AIRCRAFT MOTION	NCAR TRUE AIRSPEED COMPUTER	0 - 250 kts (0 - 130 m/s)	±3 kts (±1.5 m/s)	0.125 kt (0.07 m/s)	• True airspeed
	HUMPHREY SSA09-D0101-1 VERTICALLY STABILIZED ACCELEROMETER	-1 to +3 g's pitch -50° to +50° roll -50° to +50°	0.004 g 0.2° 0.2°	0.00006 g 0.002° 0.002°	
	ROSEMOUNT 1301-D-1B DYNAMIC PRESSURE	-3 to +3 psi (-20 to +20 kPa)	±0.1%	0.0001 psi (0.0006 kPa)	• Indicated airspeed • Bench calibration, 3/89
	ROSEMOUNT 1221-F-2A DYNAMIC PRESSURE	-2.5 to +2.5 psi (-18 to +18 kPa)	±0.1%	0.0001 psi (0.0006 kPa)	• Indicated airspeed • Bench calibration, 3/89
	GIANNINI 45218YE MANIFOLD PRESSURE	0 to 50 in Hg	±2%	0.008 Hg (0.03 kPa)	• Used in one vertical velocity calculation • Bench calibration, 3/89
	BALL ENGINEERING 101A VARIOMETER	-6000 to +6000 ft/min (-30 to +3- m/s)	±200 ft/min (±1 m/s)	0.2 ft/min (0.001 m/s)	
AIRCRAFT LOCATION	NARCO NAV-122 VOR	0 - 360°	±2°	0.005°	
	CESSNA 400 DME	0 - 100 nmi (0 - 185 km)	0.1 nmi (185 m)	0.002 nmi (3m)	• Maximum 2 s to lock on and acquire range
	TRIMBLE TNL3000 GPS/LORAN	(global)	30 m	18 m	
ELECTRIC FIELD	NMIMT Model E-100 DC Electric Field Meter	- ± 200kV/m		0.01kV/m	

NOTE: Many of these instruments do not behave as ideal instruments. The use of one measure of accuracy over the entire range of measurement is, in many cases, questionable. An accuracy representative of the most useful part of the range is given here.

APPENDIX B

List of Variables Recorded or Routinely Computed
From T-28 Observations

Each different variable in the data stream is indexed with a unique tag number. Those used for COPS-91 are listed here.

Tag	Variable	Remarks
100	**Time**	The T-28 data system is always set to local time, and recorded in a 24-hour format. It is maintained within a second of WWV unless otherwise noted.
101	**Dynamic Pressure 1**	
102	**Dynamic Pressure 2**	Both dynamic pressures are read from the same pitot tube line (with the inlet out on the right wing) using two different but nearly identical sensors. [hPa]
103	**Rosemount Static Pressure 1**	
104	**Rosemount Static Pressure 2**	Both static pressures are read from the same static pressure line (inlet on the rear fuselage) using two different but nearly identical sensors. [hPa]
105	**Rate of Climb**	The instantaneous rate of change of aircraft altitude, read from a standard aircraft variometer. The recorded data are unfiltered and much noisier than the damped cockpit display. [m/s]
106	**Rosemount Temperature**	This is static temperature computed from the reading of a standard, de-iced, Rosemount aircraft total air temperature probe. It commonly suffers from wetting and reads low in clouds. [°C]

107	**Reverse Flow Temperature**	This is static temperature computed from the reading of a platinum resistance element placed inside a custom-design "reverse-flow" housing. It does not normally get wet in supercooled clouds, but may get wet in warm clouds or in regions of high precipitation water concentration. Apparently, ice may sometimes build up to such an extent on the housing that temperature readings are affected even though the sensor is not wetted. [°C]
108	**Manifold Pressure**	Pressure inside the engine manifold (an indicator of power being developed by the engine) is recorded from a standard aircraft engine pressure sensor. [inches of mercury]
109	**Acceleration**	Vertical acceleration is determined by a Humphrey accelerometer. [g's]
110	**Pitch**	The accelerometer also gives angle of the fuselage relative to horizontal. [deg]
111	**Roll**	Finally, the accelerometer gives angle of the wings relative to horizontal. Angle is positive for a left bank (left wing down). [deg]
112	**JW Liquid Water**	The JW probe yields concentration of water in clouds represented in droplets less than approximately 30 μm diameter. [grams per cubic meter]
113	**VOR**	The VOR gives the direction to the VORTAC (a radio direction-finding beacon used by aircraft) to which it is tuned. [deg]
114	**DME1**	This is distance to the VORTAC to which the #1 DME is tuned. [n mi]

115	**DME2**	This is distance to the VORTAC to which the #2 DME is tuned. If they are tuned to different VORTAC's, the recorded distances from the two DME's may be used to reconstruct the aircraft flight track. [n mi]
116	**Voltage Regulator**	Research system voltage. [volts]
117	**Heading**	Indicates direction (from magnetic north) towards which the aircraft is heading. [deg]
118	**NCAR true air speed**	True airspeed as computed by an analog computer built at NCAR during the NHRE project in the 1970's to clock the 2D-C imaging probe. [m/s]
121	**Interior Temperature**	Temperature inside the data acquisition system computer in the baggage bay. If it climbs much above 32°C, one should be wary for possible data system malfunctions. [°C]
130	**Event Bits**	Bits corresponding to various events recognized by the data system, including such things as the in-cloud switch activated by the pilot when visually entering cloud, activation of the cockpit voice recorder, etc.
131	**GPS Warning Codes**	Bits corresponding to various status messages from the GPS system.
140	**FSSP size counts**	This tag contains information concerning the number of counts in each of the 15 available FSSP size channels. [number per channel per second]
141	**FSSP total counts**	The total number of droplets counted by the FSSP during a second.
142	**FSSP average diameter**	The average diameter of all droplets recorded during a second. [μm]

143	**FSSP concentration**	The actual concentration of droplets computed from FSSP counts divided by the volume sampled in 1 s. A rudimentary correction for probe activity is made. [number per cubic centimeter]
144	**FSSP Water**	The liquid water concentration computed from the FSSP data for a second. [grams per cubic meter]
145	**FSSP Activity**	The fraction of time the FSSP is active during the current second.
147	**PMS 2DC Shadow Or Count**	The number of times the probe was triggered out of its wait state by the passage of a new particle. [number per second]
150	**Hail size counts**	This tag contains information on the number of particles in each of the 14 hail spectrometer size channels. [number per channel per second]
151	**Slow Particle**	The number of particles rejected because they passed through the hail spectrometer too slowly (indicating they were probably water or ice shed from the probe structure rather than hydrometeors). [number per second]
152 by	**Hail total counts (of 150)**	Total number of particles accepted the hail spectrometer. [number per second]
153	**Hail average diameter**	The arithmetic average diameter of all particles accepted by the hail spectrometer in the last second. [cm]
154	**Hail concentration**	The computed concentration corresponding to all particles accepted by the hail spectrometer in the last second. [number per cubic meter]

155	**Hail Water**	The mass concentration computed from the observed particle spectrum assuming a bulk particle density of 0.9 grams per cubic centimeter. [grams per cubic meter]
160	**Top Field Mill (low res)**	The electric field indicated by the low sensitivity channel on the field mill mounted in the aircraft canopy looking up. Field mill data are recorded at 20 Hz. [kV/m]
161	**Bottom Field Mill (low res)**	The electric field indicated by the low sensitivity channel on the field mill located in the baggage bay door looking down. [kV/m]
162	**Left Field Mill (low res)**	The electric field indicated by the low sensitivity channel on the field mill mounted in the left wing tip facing outward. [kV/m]
163	**Right Field Mill (low res)**	The electric field indicated by the low sensitivity channel on the field mill mounted in the right wing tip facing outward. [kV/m]
164	**Top Field Mill (high res)**	The electric field indicated by the high sensitivity channel on the top field mill. [kV/m]
165	**Bottom Field Mill (high res)**	The electric field indicated by the high sensitivity channel on the bottom field mill. [kV/m]
166	**Left Field Mill (high res)**	The electric field indicated by the high sensitivity channel on the left field mill. [kV/m]
167	**Right Field Mill (high res)**	The electric field indicated by the high sensitivity channel on the right field mill. [kV/m]
172	**Latitude**	Computed internally in the GPS receiver. [deg]

173	**Longitude**	Also computed internally in the GPS receiver. [deg]
174	**Groundspeed**	Computed internally in the GPS receiver (by differentiating the position data with respect to time). [m/s]
175	**Ground Track Angle**	The direction towards which the aircraft is moving relative to the ground, with respect to magnetic north. [deg]
176	**Magnetic Deviation**	The difference between magnetic north and true north as indicated automatically by the GPS receiver based on the current position. [deg]
177	**Time Since Solution**	The time since the GPS was last able to compute an accurate position solution based on a sufficient number of satellites. It updates position based on dead reckoning if it does not have a sufficient number of satellites in view. [s]
178	**Track Angle Error**	Angle between actual track and desired track between two GPS way points. This is meaningless if no way points have been selected. [deg]
200	**Date**	As indicated by the data acquisition system computer clock. [yymmdd]
201	**Month**	mm [integer number]
202	**Day**	dd [integer number]
203	**Year**	yy [integer number]
204	**Flight**	A serial number assigned to each T-28 flight beginning with the first flight. (Flight #1 occurred in 1972.)

205	**Altitude**	The altitude in a standard atmosphere corresponding to the recorded pressure. [m]
206	**Theta e**	The equivalent potential temperature corresponding to the recorded temperature and assuming saturation with respect to liquid water. [K]
207	**Saturation Mixing Ratio**	The mixing ratio of water vapor corresponding to saturation with respect to liquid water at the recorded temperature. [g/kg]
208	**Point dz/dt**	The rate of change of altitude of the aircraft computed by differentiating the pressure altitude with respect to time. This represents an independent estimate of the rate of climb to be compared to tag 105. [m/s]
209	**Indicated Air Speed**	What the airspeed would be if the aircraft were flying at sea level and indicating the observed dynamic pressure. [m/s]
210	**Updraft (uncorrected)**	The estimated upward speed of the air relative to the ground computed from changes in the aircraft altitude and other factors, but not corrected for horizontal aircraft acceleration. [m/s]
211	**Calculated TAS**	The true speed of the aircraft relative to the air computed from the observed dynamic and static pressures, and temperature. [m/s]
212	**Updraft Correction Factor**	A correction to the simple (uncorrected) updraft calculation that accounts for horizontal accelerations of the aircraft. [m/s]

213	**Cooper Updraft**	The sum of the uncorrected updraft and the correction factor. [m/s]
214	**Kopp Updraft**	An updraft calculated somewhat differently than the Cooper updraft. In most situations, it yields a less noisy and more physically plausible updraft result for the T-28. [m/s]
216	**Turbulence**	The turbulent energy dissipation rate estimated from observed fluctuations in true airspeed. [$cm^{2/3}/s$]
217	**Air Density**	Computed from the recorded temperature and static pressure. [kilograms per cubic meter]
218	**JW Mixing Ratio**	The mixing ratio of cloud water per unit mass of dry air based on the JW reading and computed air density. [g/kg]
219	**FSSP Mixing Ratio**	The mixing ratio of cloud water per unit mass of dry air calculated from the FSSP water concentration. [g/kg]
220	**Hail Mixing Ratio**	The mixing ratio of hail particles per unit mass of dry air based on the computed hail water and air density. [g/kg]
260	**Ambient Vert Electric Field**	The component of the ambient electric field that is vertical in the aircraft frame of reference. Positive means a positive test charge would drift upward relative to the aircraft in the field. [kV/m]
261	**Plane Vert Electric Field**	The field due to charge on the aircraft, computed by summing the readings of the top and bottom mill and normalizing based on self-charging tests. Positive means a positive test charge would be repelled away from the aircraft by the field. [kV/m]

262 **Ambient Hor Electric Field** The ambient field oriented perpendicular to the aircraft along the wings, positive meaning a positive test charge would drift to the right in the field. [kV/m]

263 **Plane Hor Electric Field** The field due to charge on the aircraft, computed by summing the wingtip mill readings and normalizing. Positive means a positive charge would be repelled away from the aircraft due to its charge. [kV/m]

264 **Ambient Vert Field (roll cor)** The component of the ambient field that is truly vertical with respect to earth coordinates. [kV/m]

265 **Ambient Hor Field (roll cor)** The component of the ambient field perpendicular to the aircraft path and truly horizontal with respect to earth coordinates. [kV/m]

272 **Latitude (deg)**

273 **Latitude (min)**

274 **Longitude (deg)**

275 **Longitude (min)** GPS coordinates broken into separate degree and minute components.

276 **Ground Track Angle (True N)** The direction of motion relative to the ground with respect to true north, derived from the GPS ground track angle with respect to magnetic north.

APPENDIX C

Reduced Data Items Computed for Greeley Deployment, 15-27 June, 1992 *0

Tag No.	Description		# Values Output	Units	Method of Computation	Last Mod
101	Dynamic Pressure #1	(10 Hz)	1	hPa	6.280525E-3 * Raw + 0.88244	
102	Dynamic Pressure #2	(10 Hz)	1	hPa	5.268222E-3 * Raw - 0.22955	
103	Static Pressure #1	(2 Hz)	1	hPa	1.5809E-2 * Raw + 528.1485	
104	Static Pressure #2	(2 Hz)	1	hPa	1.09617E-2 * Raw + 688.7589	
105	Rate of Climb		1	m/s	5.625E-4 * Raw, for Raw > = 0 5.287E-4 * Raw, for Raw < 0	
106	Rosemount Temp		1	deg C	mach2 = 5*((1 + dyn_pr/stat_pr)**(2/7)-1) divisor = 1 + 0.195 * mach2 temp = (1.83105E-3*Raw + 243.16)/divisor-273.16	
107	Reverse Flow Temp		1	deg C	divisor = 1 + 0.153 * mach2 temp = (1.7962E-3*Raw + 244.3775)/divisor-273.16	*3
108	Manifold Pressure		1	" Hg	3.1098E-3 * Raw + 0.159275	
109	Acceleration	(10 Hz)	1	g's	6.25E-5 * Raw + 1.0	*2
110	Pitch	(5 Hz)	1	deg	-3.05175E-3 * Raw + 50	
111	Roll	(5 Hz)	1	deg	3.05175E-3 * Raw - 50	
112	J.W. Liquid Water		1	g/m^3	1.83125E-4 * Raw	
113	VOR		1	deg	1.117534E-2 * Raw - 1.155475	
114	DME #1		1	naut mi	3.03269E-3 * Raw - 0.24536	
115	DME #2		1	naut mi	3.03269E-3 * Raw - 0.046623	
116	Voltage Regulator		1	volts	1.5258789E-4 * Raw	
117	Heading	(5 Hz)	1	deg	device not hooked up	
118	NCAR true air speed		1	m/s	3.96744E-3 * Raw	
121	Interior Temp (computer)		1	deg C	3.05175E-2 * Raw	
130	Event Code bits		1	flags	bit 0 = 1 --> system running bit 1 = 0 --> in cloud bit 2 = 0 --> foil on bit 3 = 0 --> voice recorder on	

APPENDIX C (continued)

Tag No.	Description		# Values Output	Units	Method of Computation	Last Mod
131	GPS warning codes		1	flags	11 bit codes	new 1991
140	FSSP counts		15	number	Raw	
141	FSSP total counts		1	number	Sum of tag 140s	
142	FSSP ave diameter		1	µm	sum of diams / number	
143	FSSP concentration		1	#/cm^3	vol = 0.229 * tas denom = 1 - .55 * activ / 100 conc = tot_count / vol / denom	
144	FSSP water		1	g/m^3	mass = sum of counts * volumes water = mass/vol/denom*1.E6	
146	FSSP Probe Activity		1	???	Raw / 10	
147	PMS 2d Shd Or		1	number	Raw	
150	Hail counts		14	number	Raw	
151	Slow particles		1	number	Raw	
152	Hail total counts		1	number	Sum of tag 150s	
153	Hail ave diameter		1	cm	sum of diams / number	
154	Hail concentration		1	#/m^3	tot_counts / (.1 * tas)	
155	Hail equiv water		1	g/m^3	mass = sum of counts * volumes * 0.9 water = mass / vol	
160	Top field mill, low res	(20 Hz) (*1)	1	kV/m	-1.982574E-2 * Raw + 0.026	Spring 1991
161	Bottom field mill, low res	(20 Hz) (*1)	1	kV/m	-1.982574E-2 * Raw + 0.104	Spring 1991
162	Left field mill, low res	(20 Hz) (*1)	1	kV/m	-9.7023E-2 * Raw - 0.5442	5/3/91
163	Right field mill, low res	(20 Hz) (*1)	1	kV/m	-9.7778E-2 * Raw - 1.9651	5/3/91
164	Top field mill, hi res	(20 Hz)	1	kV/m	-3.11585E-4 * Raw + 0.027 (*1)	Spring 1991

APPENDIX C (continued)

Tag No.	Description		# Values Output	Units	Method of Computation	Last Mod
165	Bottom field mill, hi res	(20 Hz) (*1)	1	kV/m	-3.10364E-4 * Raw + 0.04	Spring 1991
166	Left field mill, hi res	(20 Hz) (*1)	1	kV/m	-1.5323E-3 * Raw + 0.1614	5/3/91
167	Right field mill, hi res	(20 Hz) (*1)	1	kV/m	-1.5361E-3 * Raw + 0.0835	5/3/91
172	GPS latitude		1	deg	degree + (minute + hundredths/100)/60	new 1991
173	GPS longitude		1	deg	degree + (minute + hundredths/100)/60	new 1991
174	GPS groundspeed		1	m/s	1852 / 36000 * Raw	new 1991
175	GPS grnd track angle (mag N)		1	deg	Raw / 10	new 1991
176	GPS magnetic deviation		1	deg	Raw / 10 (Raw is 32-bits, not 16)	new 1991
177	GPS time since solution		1	s	Raw / 10	new 1991
178	GPS track angle error		1	deg	Raw / 10 (Raw is 32-bits, not 16)	new 1991
200	Date		1	yymmdd		
201	Month		1	number		
202	Day		1	number		
203	Year		1	2-dig		
204	Flight number		1	number		
205	Altitude		1	meters	4.43077E4*(1-(stat_pr/1013.3027)**.190284)	
206	Theta e		1	K	tempk = RFT temp in K svp = 6.1078*exp(17.26939*rft/(tempk-35.86)) smr = svp / (stat_pr - svp) * 0.622 ts = tempk * (1000/stat_pr)**0.286 thetae = ts*exp(597.3*smr)/(0.24*tempk))	
207	Saturation mixing ratio		1		smr from above	
208	Point dz/dt		1	m/s	alt - prev_alt	
209	Indicated airspeed		1	m/s	c = 1 + dyn_pr / 1013.3027 ias = sqrt(5.79E5*(c**(2/7)-1))	

APPENDIX C (continued)

Tag No.	Description	# Values Output	Units	Method of Computation	Last Mod
210	Updraft (uncorrected)	1	m/s	u1 = change in alt ((i+1)-(i-1))/2 u2 = (27 - man_pr) * 92 u3 = (1.94254 * ias - 140) * 17.7 updr = u1 + (u2 + u3) * 0.00508	
211	Calculated TAS	1	m/s	sqrt(rftuc*mach2*401.856/divisor)	
212	Updraft correction factor	1	m/s	calc_tas*(change in calc_tas)/2/9.775	
213	Cooper Updraft	1	m/s	updraft + updraft correction	
214	Kopp Updraft	1	m/s	dens = 0.34838 * stat_pr /tempk ang = pitch * 0.0174533 Kopp=u1+62.12*accel*9.775/(dens*calc_tas) -(0.02028+ang)*calc_tas	
216	Turbulence	1	$cm^{**2/3}/s$	Much too complicated to write here. Static and dynamic pressure values, along with temperatures, are fed into a fast Fourier transform routine. Consult program listing.	
217	Air density	1	kg/m^3	0.34838 * stat_pr / tempk	
218	JW mixing ratio	1	g/kg	jw_water / density	
219	FSSP mixing ratio	1	g/kg	FSSP_water / density	
220	Hail mixing ratio	1	g/kg	hail_water / density	
260	Ambient vert EF (*1)	1	kV/m	(tfm / 1.9 - bfm) / 5.6	5/5/91
261	Plane vert EF (*1)	1	kV/m	(tfm / 2 + bfm) / 4	5/5/91
262	Ambient lateral EF (*1)	1	kV/m	(rfm - lfm) / 44.8	5/5/91
263	Plane lateral EF (*1)	1	kV/m	(rfm + lfm) / 21.6	5/5/91

APPENDIX C (continued)

Tag No.	Description	# Values Output	Units	Method of Computation	Last Mod
264	Ambient vert EF (with roll) (*1)	1	kV/m	cosr = cos(roll_rad) sinr = sin(roll_rad) t264 = t260 * cosr + t262 * sinr	
265	Ambient lat EF (with roll)	1	kV/m	t265 = -t260 * sinr + t262 * cosr	(*1)
272	GPS deg lat	1	deg	integer portion of tag 172 (t172)	new 1991
273	GPS min lat	1	min	fractional part of t172 * 60	new 1991
274	GPS deg long	1	deg	integer portion of tag 173 (t173)	new 1991
275	GPS min long	1	min	fractional part of t173 * 60	new 1991
276	GPS true bearing	1	deg	mod(t175+t176+360,360)	new 1991

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*0 - In some cases the equation variables are averages. Consult the listing of REDUCE.C for exact details. All quantities are recorded at 1 Hz unless otherwise noted.

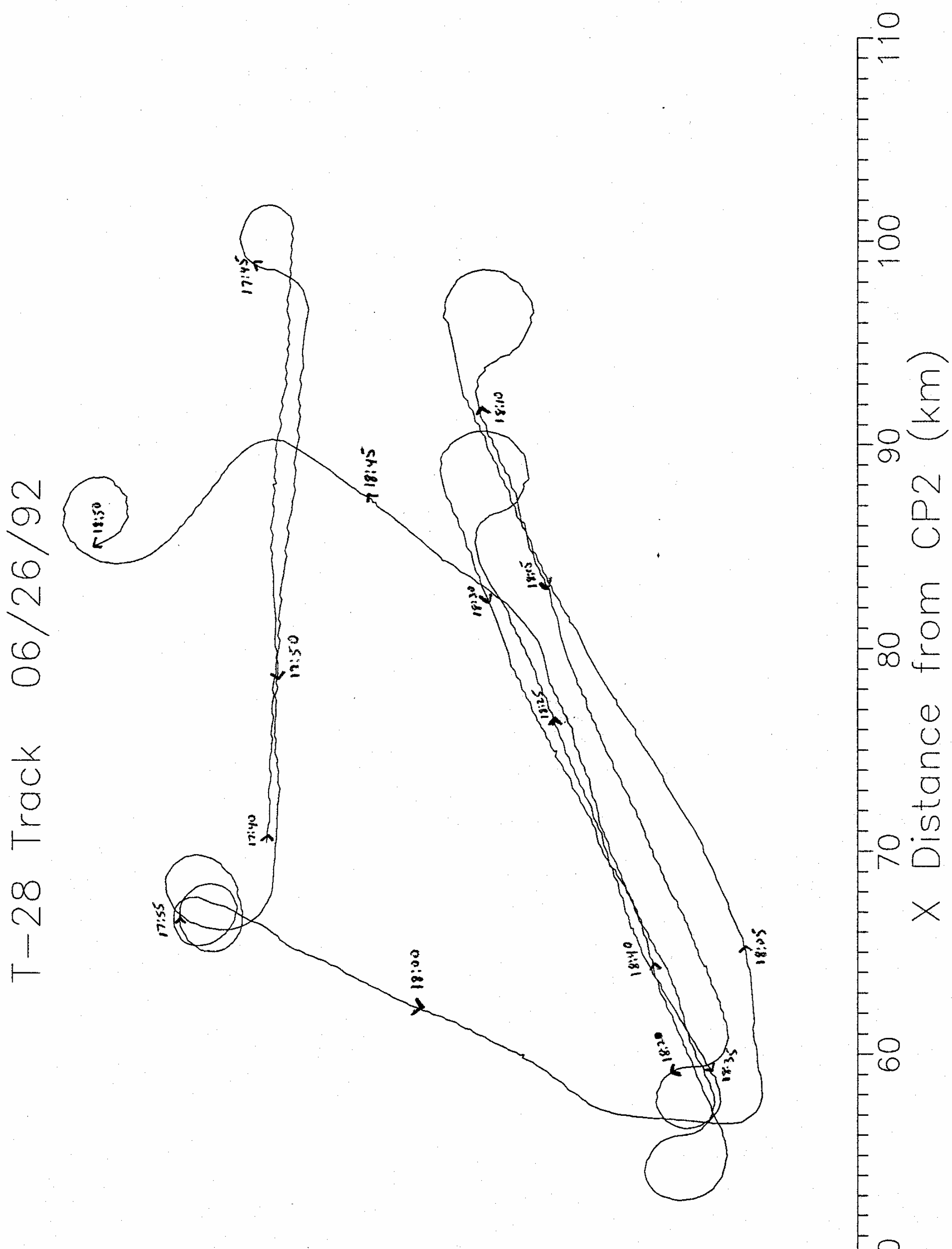
*1 - Currently electric field is reported, whereas prior to 1991 potential gradient was reported.

*3 - Reverse flow unit temperature sensing element was replaced with a new MINCO - element.

Data from this deployment are being used to derive a calibration equation and a recovery factor.

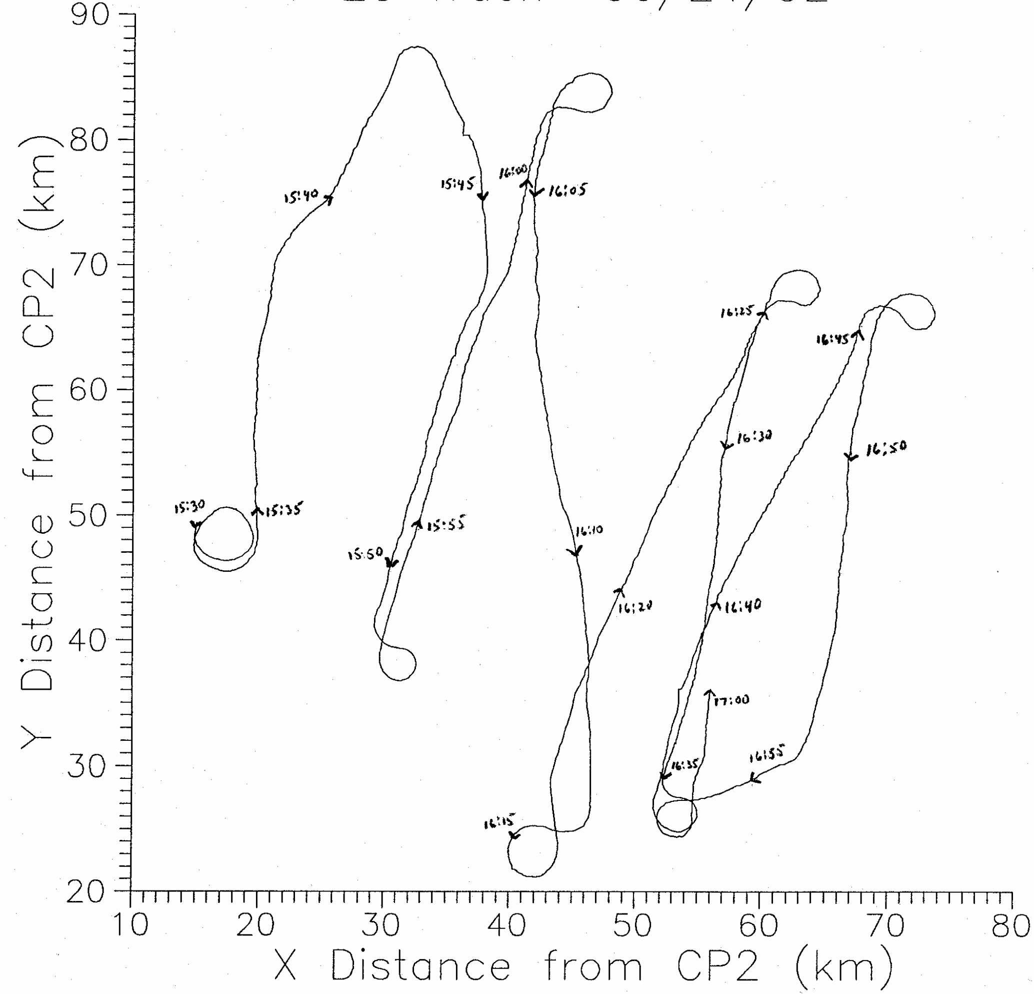
APPENDIX D

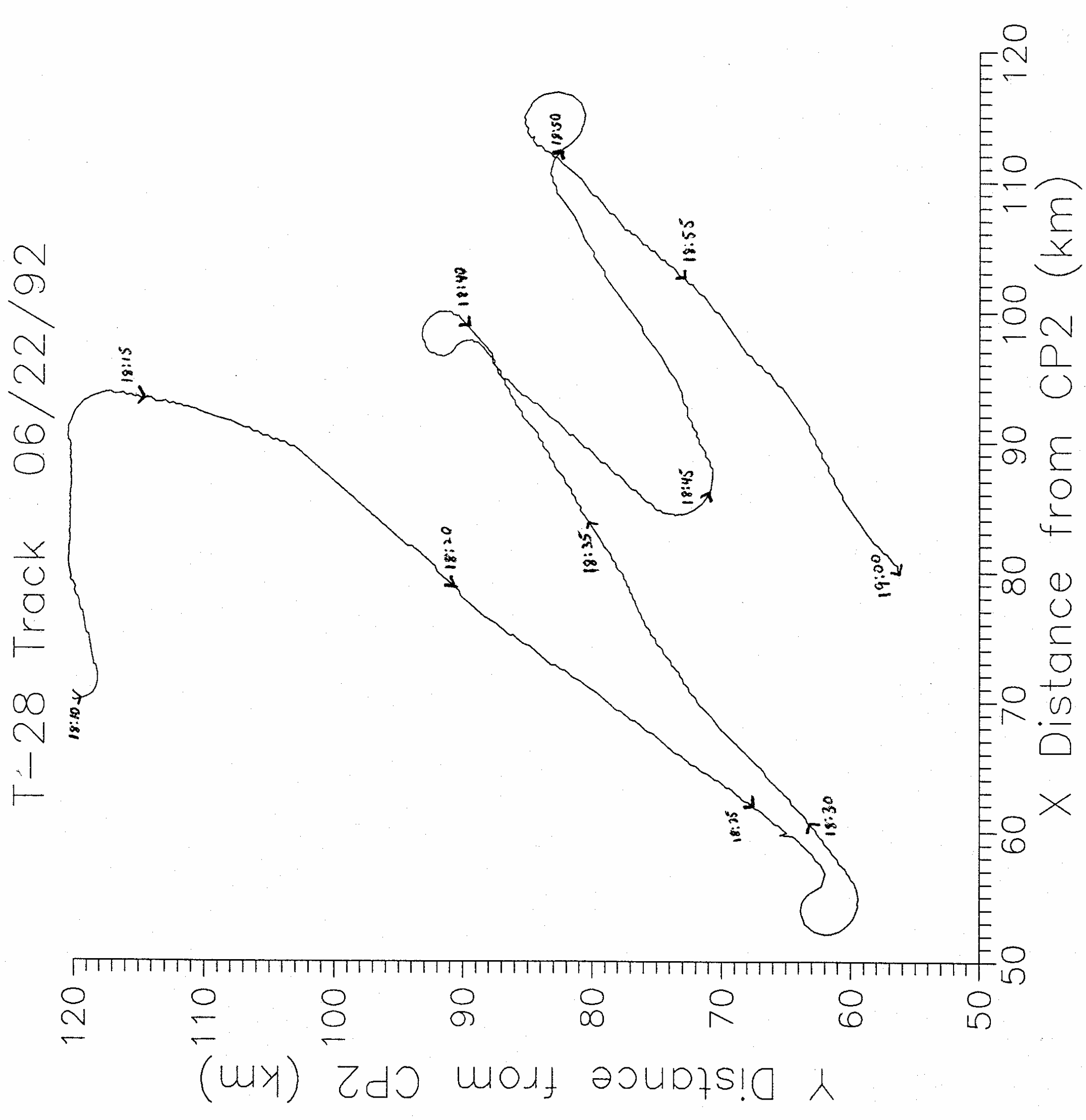
1992 Flight Tracks



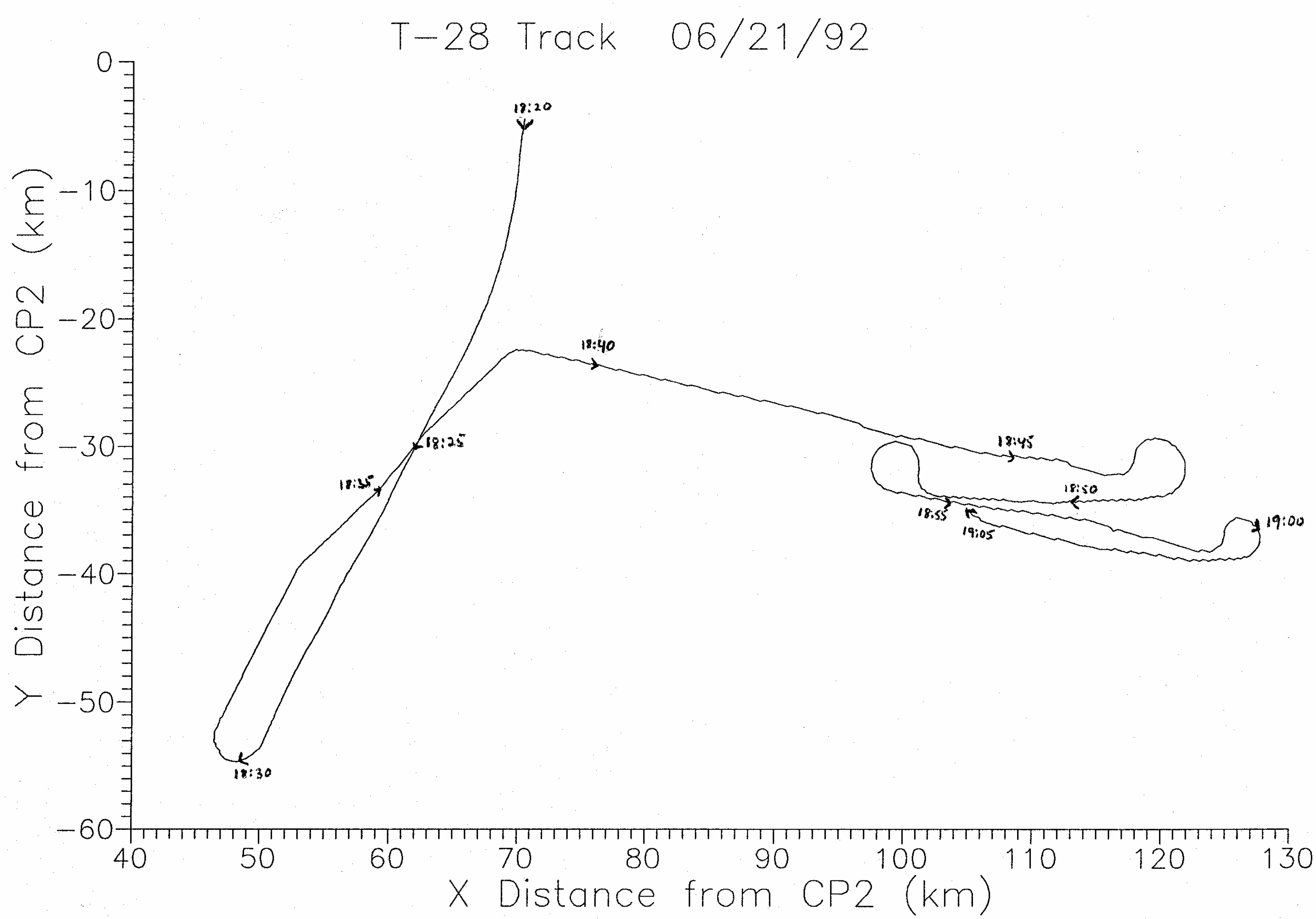
T-28 Track 06/26/92
X Distance from CP2 (km)
Y Distance from CP2 (km)
50
60
70
80
90
100
110
0
10
20
30
40
17:40
17:45
17:50
17:55
18:00
18:05
18:10
18:15
18:20
18:25
18:30
18:35
18:40
18:45
18:50

T-28 Track 06/24/92



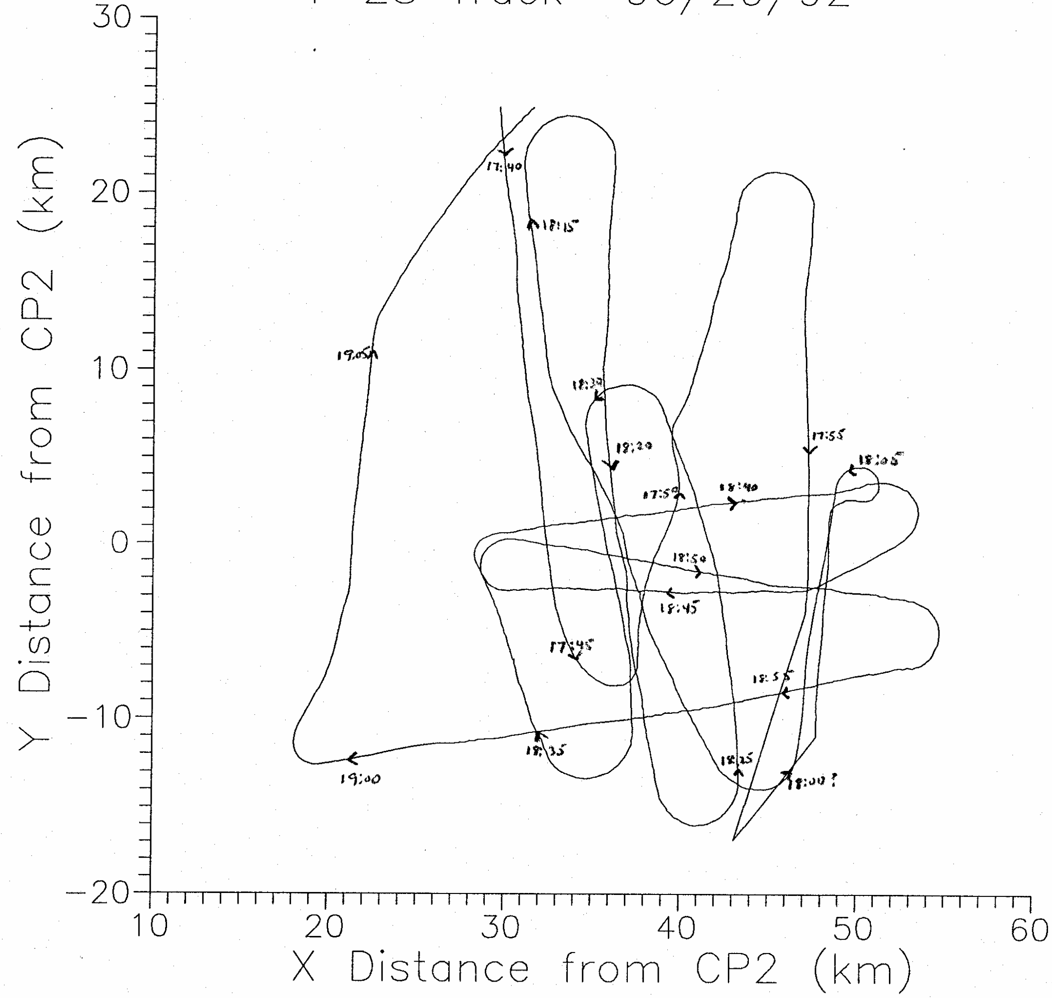


T-28 Track 06/22/92
X Distance from CP2 (km)
Y Distance from CP2 (km)
50
60
70
80
90
100
110
120
18:10
18:15
18:20
18:25
18:30
18:35
18:40
18:45
18:50
18:55
19:00



T-28 Track 06/21/92
Y Distance from CP2 (km)
X Distance from CP2 (km)
0
-10
-20
-30
-40
-50
-60
40
50
60
70
80
90
100
110
120
130
18:20
18:25
18:30
18:35
18:40
18:45
18:50
18:55
19:00
19:05

T-28 Track 06/20/92



APPENDIX E

Proposed Plan for a Hail Detection Product

by

Edward Brandes, Research Applications Program,
National Center for Atmospheric Research

1. INTRODUCTION

In the aviation sector, hail avoidance is of major concern not only for en route aircraft but also for aircraft on the ground. A hail detection product that provides timely warnings of a hailstorm's approach to an airport would have significant economic benefits. A capability to detect and predict hailfalls would also mitigate property losses experienced by the general public. Further, quantification of the hail contribution to radar reflectivity measurements would have import for hydrology and for detecting heavy rain.

Research activity over the past 15 years indicates that multiparameter radars have potential for hail detection. Indeed, groups within the radar community have long argued that multiparameter capability be part of the NEXRAD (WSR-88D) and TDWR systems being considered for national deployment. However, a systematic independent evaluation of suggested hail-detection techniques is needed before they can be seriously considered for operational application. This proposal seeks to begin the necessary testing and has the ultimate goal of producing an operational, real time hail detection algorithm. NCAR's CP-2 radar is well equipped for this evaluation and an expert resident staff is in place to conduct the research.

2. SCIENTIFIC BASIS FOR THE STUDY

In recent years, a number of hail-detection techniques, based on the statistical properties of falling hydrometeors, on geometric relationships between hydrometeor size and radar wavelength, and on the propagation of radar signals through rain and hail have been suggested. Some techniques purport to differentiate between regions of rain and hail within precipitating weather systems, while others provide an estimate of the relative contributions of rain (liquid precipitation) and hail (solid precipitation) to the total radar reflectivity.

For example, hydrometeor shape and a tendency of some particles to fall with a preferred orientation result in a differential reflectivity (ZDR), defined as 10 log (Z_H/Z_V) where Z_H and Z_V are the polarized reflectivities in the horizontal and vertical planes, respectively. Raindrops deform into oblate spheriods as they fall. In rain, Z_H radar return signals are enhanced; and ZDR takes on positive values. Hailstones are thought to tumble as they fall. A random distribution of particle orientations causes ZDR to be zero even if the individual hydrometeors are highly asymmetric. Asymmetric hail falling with a preferred orientation would have a characteristic non-zero ZDR signature.

Empirical relationships for rain/hail discrimination have been developed by plotting Z_H versus ZDR. This technique makes use of the unique relationship between the median drop-size diameter and the flattening of raindrops as their diameter increases. Individual data points for rain tend to cluster. Large spurious values of Z_H, distinctly outside the clustered area, have been shown to be associated with hail.

The difference reflectivity parameter (Z_{DP}) [$\equiv$10 log (Z_H-Z_V), for $Z_H > Z_V$] may yield the percentage contributions of ice and water to reflectivity. The technique, much like the above empirical method, is based on the observation that a unique relationship (linear on a log-log scale) exists between Z_{DP} and the horizontally polarized reflectivity for rain Z_H^r. Deviations from this relationship at constant Z_{DP} represent the contributions of ice to the reflectivity (Z_H^i). The fraction of radar reflectivity factor contributed by ice is

$$1-\frac{Z_H^r}{Z_H^r+Z_H^i} .$$

Other properties of radar signals may also provide information concerning precipitation type. For example, one technique involves transmission of a horizontally polarized wave and measurement of both vertically and horizontally polarized echoes. A linear depolarization ratio (LDR), defined as 10 log (Z_{HV}/Z_H) where Z_H is the received horizontal reflectivity from the horizontally polarized transmitted wave and Z_{HV} is the cross-polarized reflectivity, is computed. Large negative LDR values are associated with light rain, while larger (moderately negative) values stem from heavy rain and mixed phase precipitation. Case studies indicate that tumbling, non-spherical hail produces relatively high LDR values which often concentrate in columnar-like regions within storms.

Another hail discrimination parameter available with the CP-2 radar is the dual frequency hail ratio (DFR). Defined as 10 log (Z_{10}/Z_3), where Z_{10} and Z_3 are the reflectivities at 10 and 3 cm, this parameter exploits geometric relationships between hailstone diameter and radar wavelength, i.e., large hailstones are in the Mie scattering region at 3 cm and Rayleigh scattering region at 10 cm. DFR is zero for rain and small hail but becomes increasingly positive for hail greater than 1 cm. Thus, crude estimates of hail size can be made. Unfortunately, 3 cm radar signals are severely attenuated by heavy rain. Signal loss, estimated from the 10 cm reflectivity measurements, must be subtracted from the measured DFR to retrieve the component due to hail.

Yet another parameter which may have value for identifying and quantifying hail is the differential propagation constant (K_{DP}). This parameter makes use of the fact that the propagation constants for vertically and horizontally polarized signals are different and the back-scattered signals have different cumulative phase shifts. Experiment suggests that the parameters K_{DP} and Z_H can be used to differentiate mixed-phase precipitation from pure rain and pure ice and that Z_H and ZDR can be used to determine the precipitation phase and particle orientation, if a hail-size distribution is assumed.

An often observed feature with severe hailstorms is the radar "hail flare" or "hail spike" that extends radially from the far side of the storm. Flares result from three-body scattering; i.e., transmitted signals scattered by the hail to the ground, from the ground to the hail, and then back to the radar. Radial velocity measurements from the hail core are influenced by ground returns and the terminal velocity of the hail. Thus, range distributions of reflectivity, radial velocity, and spectrum width may be useful for detecting large hail.

3. EVALUATION OF TECHNIQUES

Techniques described in Section 2 all show some promise for hail detection. However, the supporting research is largely a demonstration of specific techniques. Systematic comparisons of the various techniques have not been made. Sample sizes by necessity have been relatively small. We propose to test the parameters listed in Section 2 both singularly and collectively on a large data base obtained with the CP-2 radar.

The goal of this research is a product for operational use. Hence, a set of hail detection algorithms will be developed for testing in real time. Additionally, the Real time Echo Tracking and Applications (RETA) program developed at RAP will be modified to obtain time histories of the various hail detection parameters within storms and to monitor storm motion, echo coverage, maximum radar reflectivity, rain flux, and storm top. These data will be used to determine population statistics for hail and non-hail storms and to determine which (if any) variables have predictive value for hail.

Of particular interest are benefits which accrue from adding multiparameter measurement capability to the planned NEXRAD and TDWR systems. The WSR-88D hail detection algorithm, based on the reflectivity structure of Oklahoma hailstorms, weighs storm height, maximum radar reflectivity, storm tilt in the lower troposphere, angular differences between the tilt and storm motion, maximum reflectivity at middle storm levels, echo overhang at middle levels, and maximum storm top location relative to the overhang. Storms are categorized as (1) not producing hail, (2) definite hail producers, or (3) probable hail producers. The WSR-88D algorithm and an improved version developed by NSSL will be run real time on radar data from the Mile High radar. Results will be compared with the multiparameter techniques.

4. VERIFICATION

In-situ hail observations are essential for the testing of the hail signatures. Two mobile chase vehicles will be vectored from the RAP operations center to suspected hailstorms. Recorded documentation will include hail composition, size distribution and shape, the character of accompanying rainfall, the number density of hailstones per cubic meter, the onset and ending times of the hail event, and the vehicle location. An attempt will be made to move the chase vehicles with the storms so that the temporal evolution of the hail events is obtained.

Hail reports will be gathered from a nested, dense network of hail observers recruited from the general public. Such networks have been used previously with great success. Participants will be furnished with pre-printed report forms which are to be completed whenever hail or significant weather is observed and mailed to the operations center. The network will be distributed within the CP-2 observational umbrella.

5. TIME TABLE

The experiment will begin during the RAPS-92 summer program. While the effort outline here is designed to maximize the number of hail events, it is anticipated that the experiment may need to be repeated for two or three summers to ensure a sufficient number of datasets for a proper evaluation. Previously-acquired datasets will be incorporated into this study. However, the lack of verification data and the fact that many of these datasets cannot be used to determine all of the desired parameters limits their utility. In reality, the number of severe hail storms is likely to remain small. Nonetheless, it is crucial that these storms always be detected.

APPENDIX F

The CSU - CHILL National Radar Facility: An Overview
by
Pat Kennedy and Dave Brunkow, CHILL Facility Staff

1. HISTORY

The CHILL radar was jointly developed by the University of CHicago and the University of ILLinois with National Science Foundation funds in the early 1970's. The initial goal was to develop a high performance, transportable radar system that was capable of collecting a variety of data for meteorological research interests. From 1971 through early 1990 the CHILL participated in numerous research programs whose studies ranged from winter snowstorms to severe, hail-producing thunderstorms. During this period, the radar was staffed and operated by the Illinois State Water Survey. As of April 1990, the National Science Foundation transferred funding for the operation of the radar to Colorado State University. The goals of high quality research data collection and educational support continue at this new location.

2. DESCRIPTION

The CHILL is a Doppler weather radar with dual polarization capability. As in conventional incoherent radars, the CHILL can map the three-dimensional distribution of precipitation areas within a range of approximately 200 statute miles. The velocity component towards or away from the radar within these precipitation areas is measured by the radar's Doppler capability. The CHILL can also transmit either horizontally or vertically polarized microwave pulses. Information on the average shape of the precipitation particles can be deduced by examining differences in the returned signal when the transmitter polarization is rapidly switched between horizontal and vertical polarizations. State-of-the-art signal processing and display systems allow all of these precipitation parameters to be calculated and viewed in real time.

Characteristics of the CHILL RADAR SYSTEM
10/20/92

Antenna:	
Shape	Parabolic
Diameter	8.5 m
3 db beamwidth	0.96 degrees
Gain	42 dB
First sidelobe	-23 dB
Polarization	Horizontal and Vertical on a pulse to pulse basis Currently available sequences: H, V, VH
Rotation rate	Up to 27 degrees/second
Antenna Contoller:	(MicroVax)
Scan Modes	PPI, RHI, Manual Position, Seek Position, Hold Position, PPI-Man-El, RHI-Man-Az
Sector Limits	Adjustable
Fixed angle step	Fixed step, or optimized to maintain desired resolution
Swept angle sample	Adjustable - based on number of 'hits' in sample
Timers	9 available: (a) scan may be terminated after elapsed time (b) scan may be started at a specific time (c) scan may be repeated with a specific interval In case (b) and (c), the currently active scan is interrupted 10 seconds prior to scheduled start.
Scan memory	Up to 50 scan "segments" may be linked together to form complex scan sequences.
Transmitter:	Modified FPS-18
Wavelength	11 cm
Frequency	2725 MHz
Peak Power	700 kW typical
Pulse Width	0.2 to 1.0 μs (SP20 program controlled)
Pulse Repetition	800-2047 μs (SP20 program controlled)
Maximum Unambigous Range	375 km
Maximum Unambigous Velocity	+/- 34.4 m/s

Receiver:

Noise Figure	~4.25 dB
Transfer function	Linear and log available
Dynamic Range	90 dB
Band Width	1.8 MHz analog bandwidth (750-kHz optional)
Noise Intercept (SNR = 1.0)	-110 dBm
Clutter Filter	25 widths available from 0.01 to 0.25 of Nyquist velocity Four pole elliptical filter

Data Acquisition:

Number of Range Gates	100-2048 (SP20 program controlled)
Range Gate Spacing	.2 to 1.0 μs (SP20 program controlled) (current software supports 1 usec gates)
Recorded Word Length	
Velocity	8 bits offset binary
Width	8 bits offset binary (negative width estimates retained)
Intensity	8 bits binary 3/8 dB resolution
ZDR	8 bits 2's complement with offset 3/64 dB resolution optionally 3/8 dB resolution with greater range
PHIDP	8 bits offset binary (differential phase)
RHOHV(0)**2	8 bits unsigned (HV correlation at lag 0)
Correlations	16 bits real, 16 bits imaginary (top 16 bits of IEEE floating point number
Time Series	Same as correlations
Tape Recording Format	CHILL Modular format - may be converted to Universal on request
Tape	9-track 6250 cpi density 3600 foot or 8 mm cartridge
Block Length	Variable to 17000 bytes

Variables Available:

Reflectivity	Horizontal Polarization, Vertical Polarization
ZDR	Differential Reflectivty (Zh/Zv)
NCP	Normalized coherent power (Mag(R1)/RO)
Velocity	Mean velocity from pulse pair algorithm
Width	Spectral width from R1/R2 estimator
PHIDP	Differential phase shift

RhoHV(0)	HV correlation estimate at zero time
Complex Corelations	First and Second lag corelations RHV* and RVH* correlations in VH polarization mode RH2 (HH lag 2) correlation in VH polarization mode
Time Series	Adjustable range to 1st gate and gate spacing up to 63 gates at 1 kHz PRT continuous sampling

Much of the functionality of the system is determined by the SP20 program being used. Those items under SP20 control can, in most cases, be altered by arrangement with the CHILL staff.