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WEATHER IMPACTS ON SPACE OPERATIONS

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INTRODUCTION

The 45th Weather Squadron of the United States Air Force provides weather support to Patrick Air Force Base, Cape Canaveral Air Force Station (CCAFS), Eastern Range, and Kennedy Space Center (KSC). The support includes weather observations, forecasts, climatological studies and consultant services to a wide variety of Range users. The most visible to the general public is weather support to space vehicles, particularly the Space Shuttle. That support includes resource protection, ground processing, launch, and Ferry Flight; as well as consultant to the Spaceflight Meteorology Group (at Johnson Space Center) for landing forecasts.

PRELAUNCH PROCESSING WEATHER

Although launch (and landing for Space Shuttle) are the most visible space launch operations, there is much weather sensitive work to be accomplished between flights, such as moving vehicles, moving/stacking Solid Rocket Boosters (SRBs), fueling, etc. Any loss of production during this processing cycle impacts launch schedules. The single greatest time loss due to weather results from weather warnings/advisories which restrict certain work (such as any work on tall structures). The major weather item of concern in the Cape Canaveral area is lightning, since the KSC/CCAFS area is near the area of maximum thunderstorm occurrence in the United States (Figure 1). Thunderstorm occurrence peaks in the summer afternoons as indicated in Table I, reaching 17.4% of the time between 3PM and 5PM (local Standard Time) in the month of August. Various people have looked at lightning detection networks to better define actual frequency of lightning. While there is no long term national climatology of such strike frequencies, Orville (91) determined for 1989 the maximum peak annual frequency was 9 to 10 flashes per square kilometer "north-east of Tampa" and M. Maier (92) indicated for 1990 the KSC/CCAFS area varied

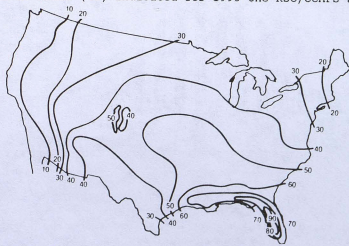


Figure 1. Thunderstorm Frequency (days per year) (Court and Griffiths, 1982)

from 10 per square kilometer on the coast to more than 30 per square kilometer over Titusville, with an average around 20 per square kilometer over the entire KSC/CCAFS area. Actual Titan processing time losses due to weather warnings/advisories 1989-1991 for launch complex 40/41 (CCAFS) are summarized in Figure 2 (Shuttle is similar). Note: The average shown is only a three year average.

TABLE I
FREQUENCY (PERCENT) OF HOURLY SURFACE OBSERVATIONS WITH THUNDERSTORMS AT THE SHUTTLE LANDING FACILITY (ETAC, PERIOD OF RECORD 78-89)

21-23					1.2	1.1	4.2	3.6	1.7	2.3				
18-20	-	-	-	-	1.6	4.5	7.7	9.4	8.6	4.9	1.7	-	-	-
15-17					2.3	6.3	12.4	16.2	17.4	7.4	2.2			1.0
12-14	-	-	-	-	1.3	1.0	2.2	4.4	8.6	13.2	11.0	5.6	-	-
09-11							1.0	1.3	1.6	3.1	2.8			
06-08	-	-	-	-	-	-	-	-	1.2	-	-	-	-	1.3
03-05											2.0			
00-02	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	J	F	M	A	M	J	J	A	S	O	N	D		

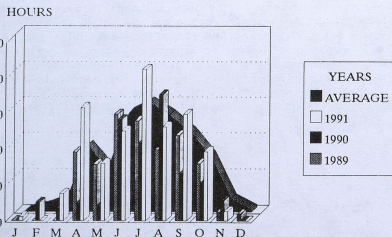


FIGURE 2. LIGHTNING DOWNTIME AT THE TITAN LAUNCH COMPLEXES

LAUNCH SUPPORT WEATHER

Lightning, both natural and potential for triggered lightning, also present a major concern during launch countdowns. Table II lists the constraints developed to protect against damage or loss of vehicle during launch. While

lightning may be the single most frequent weather item of concern, there are others as listed in Table III. A summary of weather impacts to launch countdowns is contained in Table IV for Shuttle and Table V for other space launch systems.

TABLE II
RANGE SAFETY CONSTRAINTS FOR NATURAL AND TRIGGERED LIGHTNING

The Launch Weather Officer (LWO) must have clear and convincing evidence the following constraints are not violated:

A. Do not launch if any type of lightning is detected within 10nm of the launch site or planned flight path within 30 minutes prior to launch unless the meteorological condition that produced the lightning has moved more than 10nm away from the launch site or planned flight path.

B. Do not launch if any of the planned flight path will carry the vehicle:

1. Through cumulus clouds with tops that extend to an altitude at or above the plus 5 degree Celsius level; or

2. Through or within 5nm of cumulus clouds with tops that extend to an altitude at or above the minus 10 degree Celsius level; or

3. Through or within 10nm of cumulus clouds with tops that extend to an altitude at or above the minus 20 degree Celsius level; or

4. Through or within 10 nm of the nearest edge of any cumulonimbus or thunderstorm cloud including its associated anvil.

C. Do not launch if, for Ranges equipped with a surface electric field mill network, at any time during the 15 minutes prior to launch time, the one minute average of absolute electric field intensity at the ground exceeds 1 kilovolt per meter within 5nm of the launch site unless:

1. There are no clouds within 10nm of the launch site; and,

2. Smoke or ground fog is clearly causing abnormal readings

NOTE: for confirmed instrumentation failure, continue countdown.

D. Do not launch if the planned flight path is through a vertically continuous layer of clouds with an overall depth of 4500 feet or greater where any part of the clouds are located between the zero degree and the minus 20 degree Celsius temperature levels.

E. Do not launch if the planned flight path is through any cloud types that extend to altitudes at or above the zero degree Celsius level and that are associated with disturbed weather within 5nm of

the flight path.

F. Do not launch through thunderstorm debris clouds, or within 5nm of thunderstorm debris clouds not monitored by a field mill network or producing radar returns greater than or equal to 10dbz.

G. Good Sense Rule: If hazardous conditions exist that approach the launch constraint limits or if hazardous conditions are believed to exist for any other reasons, an assessment of the nature and severity of the threat shall be made and reported to the test director or launch director.

DEFINITIONS:

1. DEBRIS CLOUD - Any cloud layer other than a thin fibrous layer that has become detached from the parent cumulonimbus within 3 hours before launch.

2. DISTURBED WEATHER - Any meteorological phenomenon that is producing moderate or greater precipitation.

3. CUMULONIMBUS CLOUD - Any convective cloud that exceeds the minus 20 degree Celsius temperature level.

4. CLOUD LAYER - Any cloud broken, overcast layer, or layers connected by cloud elements; e.g., turrets from one cloud to another.

5. PLANNED FLIGHT PATH - The trajectory of the flight vehicle from the launch pad through its flight profile until it reaches the altitude of 100,000 feet.

6. ANVIL - Stratiform or fibrous cloud produced by the upper level outflow from thunderstorm or convective clouds. Anvil debris does not meet the definition if it is optically transparent.

TABLE III
SHUTTLE LAUNCH COMMIT CRITERIA
(IN ADDITION TO LIGHTNING)

AMBIENT TEMPERATURE RESTRICTIONS

Prior to external tank loading--propellant loading will not be initiated if the 24 hour average temperature has been below 41° F.

From external tank loading to launch -- countdown will not continue (i.e. launch is not allowed) if the temperature exceeds any of the following for more than 30 minutes:

A. Temperature greater than 99° F.

B. Temperature less than 37° F for wind equal to or greater than 5kts.

- C. Temperature less than 47° F for wind less than 5kts.

PRECIPITATION CONSTRAINT

The Shuttle vehicle will not be launched if:

- A. Precipitation exists in the flight path.
- B. Ice accumulates in zero-ice or restricted thickness areas on the external tank.

SURFACE WIND LIMITS FOR LIFT-OFF MEASURED AT 60 FT LEVEL

The Shuttle vehicle will not be launched if launch pad peak winds are greater or equal:

- A. 20 kts -- 150 degrees through 200 degrees
- B. 21 kts, increasing to 34 kts as winds become more northerly

UPPER AIR WINDS

The launch vehicle will not be launched if the Launch Systems Evaluation Advisory Team (LSEAT) makes a "no-go" call in the L-30 minute time frame. This call will be based on a systems performance evaluation of the vehicle versus the launch site winds profile measurement. The procedure and decision criteria are documented in NSTS-08211, LSEAT Integrated Support Plan.

RANGE SAFETY WEATHER RESTRICTIONS

A. BLAST focus (based on simulation using weather balloon and wind data):

- (1) if more than 1 fatality per 100,000 -- hold or scrub,
- (2) values between 1 per 100,000 and 1 per 1,000,000 require Range Director evaluation.

B. Ceiling and visibility (required to aid radar acquisition): ceiling equal to or greater than 8000 ft and visibility equal to or greater than 5 mi.

C. Lightning (protection of range destruct system) same as natural and triggered lightning constraints.

TABLE IV
WEATHER EFFECTS ON SHUTTLE LAUNCHES
NOV 87 TO DEC 91

COUNTDOWNS	40
LAUNCHES	19 (47% OF COUNTDOWNS)
NON-WX SCRUBS	14 (35% " ")
WX SCRUBS	7 (18% " ")
WX DELAYS	11 (58% OF LAUNCHES)
WX SCRUBS & DELAYS	18 (45% OF COUNTDOWNS)

TABLE V
WEATHER EFFECTS ON EXPENDABLE VEHICLE LAUNCHES
NOV 87 TO DEC 91

COUNTDOWNS	73
LAUNCHES	43 (59% OF COUNTDOWNS)
NON WX SCRUBS	8 (11% " ")
WX SCRUBS	22 (30% " ")
WX DELAYS	7 (11% OF LAUNCHES)
WX SCRUBS & DELAYS	29 (40% OF COUNTDOWNS)

LIGHTNING ASSESSMENT INSTRUMENTATION

To reduce lost manpower costs and maintain the highest safety standards, the CCAFS and KSC developed a highly sophisticated network of instrumentation described in detail by Boyd et. al. (88) and Boyd and Dye (89). Wind/temperatures sensors located on 46 towers at heights ranging from 2 to 165 meters as shown in Figure 3 are referred to as the Weather Information Network and Display System (WINDS). The ground based field mill network is deployed as shown in Figure 4. The cloud to ground Lightning Detection System (LDS) is a network of five Lightning Location and Protection, Inc. (LLP) Model 141 Advanced Lightning Direction Finders (ALDF) in a relatively short baseline configuration (Figure 5). The ALDF data are processed by a LLP Model 280 Advanced Position Analyzer (APA). The APA generates a least squares estimate of the optimum lightning location using all available ALDF data whenever two or more of the ALDFs respond in time coincidence. The effective range of the LDS is about 100 km. A WSR-74C (5cm wavelength) radar was modified to produce volumetric data sets (Austin et. al.,88). These data are created at 24 elevation angles ranging from 0.6 degrees to 35.9 degrees over five minute intervals. Data digitization allows forecasters to construct and display Constant Altitude Plan Position Indicator (CAPPI), vertical cross-sections, and echo tops; animate displays; and extract point information such as maximum tops and radial location. The digitized data is also transmitted to the Meteorological Interactive Data Display System (MIDDS) for processing and display over Closed Circuit Television (CCTV) and merged with other data such as lightning plots or satellite imagery. Location of the radar antenna at Patrick AFB, 21 miles south of Cape Canaveral, reduces ground clutter data loss and produces a full volume scan over CCAFS/KSC. Real time GOES satellite data, routinely received each 30 minutes is updated each 5 minutes during the final phases of the Space Shuttle launch countdown.

UPPER LEVEL WIND REQUIREMENTS

In addition to lightning assessment, a second major requirement to support launch is evaluation of the upper atmosphere. Measurements are taken and input to the user for load analysis and to safety for support programs (including debris footprint, toxic dispersion, and sonic blast focusing). Measurements are currently made with Jimspheres, rawinsondes, and weather rockets. The Shuttle "balloon" requirements are listed in Table VI.

TABLE 6
SHUTTLE BALLOON REQUIREMENT

	(1)	(2)	(3)
COL (1):			
TIME (IN HOURS)	L-72	ROCKET	240K
RELATIVE TO LAUNCH	L-52	JIMSPHERE	55K
	L-36	RAWINSONDE	100K
COL (2):	L-28	JIMSPHERE	55K
TYPE INSTRUMENT	L-24	RAWINSONDE	100K
	L-13	RAWINSONDE	70K
COL (3)	L-8.5	RAWINSONDE	100K
HEIGHT REQUIREMENTS	L-6.75	JIMSPHERE	55K
(IN THOUSANDS OF	L-5.5	RAWINSONDE	70K
FEET)	L-4.25	JIMSPHERE	55K
	L-3.5	RAWINSONDE	50K
	L-3	JIMSPHERE	55K
	L-2	RAWINSONDE	20K
	L-2	JIMSPHERE	55K
	L-1.5	RAWINSONDE	20K
	L-70 (MINS)	JIMSPHERE	55K
	L-1	RAWINSONDE	10K
	L-0.5	RAWINSONDE	100K
	L+0.25	JIMSPHERE	55K

The upper air processing system as described by Bauman et. al. (92) is briefly summarized as follows:

Real Time Winds Aloft Processing System (RTWAPS) is used to receive, process, format, and transmit upper air wind speed and direction data from the two balloon systems commonly used to provide Range users with near real-time upper air data: Jimspheres and rawinsondes. The data is quality assured by a US Air Force meteorologist (Upper Air Director) in 5000 ft segments as the balloon ascends. Each segment is sequentially sent to the appropriate user at a rate dependent on the number of balloons being concurrently processed and number of users requiring access to the system.

Jimspheres are specially designed aluminized mylar constant volume balloons tracked by a metric radar (Wilfong and Boyd, 89). Jimsphere data from a tracking radar is received at the Data General MV15000 computers in the CCAFS weather station for processing and transmission. Output of the metric radar is received via the radar switch located in the Central Computer Complex controlled by the radar controller in the Single Point Acquisition Radar and Control (SPARC) area of the Range Control Center at CCAFS. There are presently three communication lines from SPARC to the CCAFS Weather Station of which two are routinely used with a third held as a spare. Both lines are fed directly into each MV15000.

Rawinsondes used at the Range are atmospheric sensors with transponding capability normally carried aloft by a neoprene balloon and tracked by one of CCAFS's two Meteorological Sounding Systems (MSS's). The MSS's connect to the MV15000 computers via the NOVA 3/12 minicomputer. The final output from the rawinsonde system includes pressure, temperature, relative humidity, wind speed, and wind direction and other data derived from these basic parameters. RTWAPS uses only the wind speed and wind direction data from the rawinsonde. By convention of CCAFS, these rawinsondes are called High Resolution Rawinsondes (HRR's) to denote processing by RTWAPS for space launch vehicle trajectory and dynamic airloads calculations.

Data coming in from the MSS or tracking radar is processed by the appropriate data reduction programs (WVWSRV for HRR's and WVRTJS for Jimspheres) on either MV15000 where it is then shipped to the graphical editing terminal for quality control by the Upper Air Director. The capability exists to output data to as many as six users sequentially. The MSS trackers, both MV15000's, data transmission modems, and the Upper Air Directors are all located at the CCAFS Weather Station.

Location of instrumentation used to obtain upper air data is shown in Figure 6. Note: the Doppler radar Wind profiler shown is a 50 mhz system currently being tested by NASA.

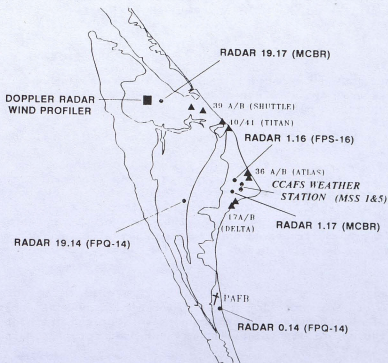


FIGURE 6. UPPER AIR SUPPORT EQUIPMENT LOCATIONS

FERRY FLIGHT SUPPORT

A Shuttle landing at any location other than KSC requires transporting (ferrying) the Orbiter back to KSC where ground processing for the next mission is accomplished. The Orbiter is perched atop a modified Boeing 747, the Shuttle Carrier Aircraft (SCA), piloted by a NASA crew from Johnson Space Center (JSC). Due to the fragile nature of the Orbiter's Thermal Protection System, stringent weather constraints are imposed. Operations are limited to daylight hours only; no flight through visible moisture or within 25nm of thunderstorms; flight level limited to 16,000 ft and temperatures above 15°F; and no threat of precipitation, greater than light, at any enroute stops. Restrictions are required since flying through visible moisture, i.e. clouds, is sufficient to erode the Shuttle tile surface causing millions of dollars of damage. An Air Force C-141 is the designated Pathfinder for the mission. The Pathfinder flies 100nm ahead of the SCA to ensure suitable route weather and advise for deviations from expected flight path.

The 45th Weather Squadron is responsible for providing detailed weather support to Ferry Flight operations. The challenges of supporting NASA's most weather sensitive mission are met by implementing a team support concept. A USAF Weather Officer flies on board the Pathfinder to directly advise NASA managers of enroute options. Enroute base weather stations provide access to weather data and input on local weather conditions. The Cape Canaveral Forecast Facility (CCFF) is responsible for monitoring enroute weather and making route recommendations to the Pathfinder Weather Officer.

FUTURE ENHANCEMENTS

Both the Air Force and NASA are constantly striving to improve weather support to space systems. Several projects recently completed, underway, or in the planning stage are summarized below:

Radar Improvements: A WSR-88D (formally referred to as NEXRAD) will become operational at the Melbourne National Weather Service office. One of the ten Limited Production Phase Systems is currently installed at Melbourne with expected operational acceptance mid to late 1992. The Cape Canaveral Forecast Facility (CCFF) has a Principal User Processor (PUP) (one of the primary workstations) used to display WSR-88D data (consisting of reflectivity, radial velocity, and spectrum width information). The WSR-88D, S-band (10 cm) Doppler radar, should provide increased warning capability for such dangerous weather hazards as tornadoes, high surface winds, low level wind shear, hail, and thunderstorms.

Advanced Ground Based Field Mill (AGBFM) System: New more efficient and reliable field mills are being developed as a joint Air Force/NASA project. These mills will replace the current network and have improved graphics and independent processing capability versus the current need for processing on the Range Cyber computer.

Weather Information Network Display System (WINDS): WINDS is being modernized with new sensors, better data transmission, and data processing independent of the Range Cyber computer.

Airborne Field Mill (ABFM) Program: The ABFM program was recommended by the

AC 67 investigation committee. Purpose of the ABFM platform is to gather data to better understand/quantify the meteorological conditions favorable for electric charge aloft and then: (1) evaluate/revise current launch constraints and (2) possibly develop a concept of operation to use an ABFM on day of launch. The ultimate goal is to safely increase launch availability and to reduce the chance for weather holds and delays. A NASA Lear Jet with extensive instrumentation has been flying to 50,000 feet to obtain cloud electrification data in the vicinity of CCAFS. Forty missions were flown in July and August 1990 to calibrate the Lear Jet's five field mills and gather data to revise the LCC. A data analysis is currently underway for data gathered in 1991. (A winter deployment is in place as this paper is being written) (Jan 92).

Improved Weather Dissemination System (IWDS): IWDS is a minicomputer based system designed to simplify and accelerate the transmission of weather forecasts, observations, advisories, and warnings directly to individual user groups. System software is currently under development for CCAFS and KSC. Installation is expected by summer 1992. IWDS will eliminate time consuming dissemination processes and allow for increased forecaster concentration on convective activity.

Lightning Mapping System: A new Lightning Detection and Ranging (LDAR) System is under development at KSC. The system will map the location of in-cloud and cloud-to-ground lightning based on the time of arrival (TOA) of VHF radiation (Lennon and Maier, 91).

Applied Meteorology Unit (AMU): The AMU will facilitate the development and transition of new techniques and equipment into the CCFF. The AMU, managed by KSC, will address both the CCFF and the Spaceflight Meteorological Group Shuttle weather requirements. The AMU also includes the National Weather Service's Melbourne office which will cooperate in solving local weather forecast problems.

Automated Weather Distribution System (AWDS): An integrated imagery, graphics, alphanumeric and data processing system capable of automating many forecasting and observing requirements. An Air Force wide program, local installation is expected mid 1992.

Use of wind and temperature profilers of varying frequencies, polar orbiting satellite data, artificial intelligence, mesoscale models, and improved forecasting algorithms are in various stages of planning.

SUMMARY AND RECOMMENDATIONS

Because of the high visibility of the space program and its importance to both the advancement of science, engineering, and technology in the U.S. and the national pride, it is imperative we continually strive to provide the best meteorological instrumentation, expertise and general support available. While it is true, as the National Research Council Report (88) agrees, "Air Weather Service and National Weather Service forecasters have been supporting space operations with skill and dedication", more stringent future requirements will outdistance current capabilities. Both research and operations activities must be willing to commit resources -- manpower, money and time -- to upgrade the meteorological support to a level sufficient to meet the demands of accuracy and timeliness necessary for space operations.

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