15.4 Lightning Characteristics and Lightning Strike Peak Current Probabilities as Related to Aerospace Vehicle Operations

Dale L. Johnson[1]
NASA, Marshall Space Flight Center, Huntsville, Alabama

William W. Vaughan
University of Alabama - Huntsville, Huntsville, Alabama

1. INTRODUCTION

A summary is presented of basic lightning characteristics/criteria for current and future NASA aerospace vehicles. The paper estimates the probability of occurrence of a 200 kA peak lightning return current, should lightning strike an aerospace vehicle in various operational phases, i.e., roll-out, on-pad, launch, reenter/land, and return-to-launch site. A literature search was conducted for previous work concerning occurrence and measurement of peak lighting currents, modeling, and estimating probabilities of launch vehicles/objects being struck by lightning. This paper presents these results.

2. LIGHTNING CHARACTERISTICS

On a cloudless day, the potential electrical gradient in the atmosphere near the surface of the Earth is relatively low (less than 300 V/m). When clouds develop, the potential gradient near the surface of the Earth increases as water droplets of sufficient size develop. The atmosphere potential gradient may then result in a lightning discharge, i.e., gradients greater than 10,000 v/m at the surface.

A variety of charge separation processes occur at microphysical and cloud-size scales and vary in importance depending on the developmental stage of convective clouds (Beard and Ochs, 1983). It has been suggested that both induction and interface charging are the primary electrification mechanisms in convective clouds (Leteinturier, 1990). Inductive charging involves bouncing collisions between particles in the external field. The amount of charge transferred between the polarized drops at the moment of collision depends on the time of contact, contact angle, charge realization time, and net charge on the particles. Interface charging involves the transfer of charge due to contact or freezing potentials during the collisions between riming precipitation particles and ice crystals. The sign and magnitude of the charge transfer depends on the temperature, liquid water content, and ice crystal size and impact velocity.

Gradients may be considerably higher with altitude than just above the surface. The Earth-ionospheric system is considered a large capacitor with the Earth's surface the negatively charged plate, the ionosphere the positive plate, and the atmosphere the dielectric.

When a cloud develops into the cumulonimbus state, lightning discharges result. For a discharge to occur, the potential gradient at a location reaches a value equal to the critical breakdown value of air at that location. Laboratory data indicate this value is as high as one million v/m at standard sea-level atmospheric pressure. Electrical fields measured at the surface of the Earth are much lower than one million v/m during lightning discharges. The measured electrical field at the Earth's surface is limited by discharge currents arising from grounded points, such as grass, trees, and structures, which ionize the air around the points thus producing screen space charges.

Lightning is a secondary effect of electrification within a thunderstorm cloud system. It is a giant electrical spark that can have a peak current flow greater that 200,000 amperes during a period of a few microseconds. Thunder results from the sudden heating of the air to about 20,000 K by the flow of current along a narrow channel. This flow can be from cloud to ground with several individual strokes separated by a tenth of a second. Or it can be from cloud to cloud strokes which diffusely illuminate the cloud. Strokes can also be from cloud through an aircraft or aerospace vehicle operating in the vicinity.

When lightning strikes a protected or unprotected object, such as an aerospace vehicle on pad, the current flows through a path to true Earth ground. The voltage drop along this path may be great enough over a short distance to be dangerous to people and equipment.

A static charge may accumulate on an aerospace vehicle from its motion through an atmosphere containing raindrops, ice particles, or dust. A stationary object, if not grounded, can also accumulate a charge from small windborne particles, or rain, or snow particles striking the object. This charge can build up until the local electric field at the point of sharpest curvature exceeds the breakdown field and trigger a lightning discharge. The quantity of maximum charge depends on the size and shape of the object.

If a charge builds up on a not-grounded structure, any discharges could ignite explosive gases or fuels, interfere with radio communications or telemetry, or cause severe shocks to people. Static electrical charges occur more frequently during periods of low humidity and at any geographical area.

Lightning protection assessment and design consideration are critical functions in the design and development of an aerospace vehicle. The project's Lighting Protection Engineer must be involved in preliminary design and remain an integral member of the design and development team throughout vehicle construction and verification tests. For an overview of the guidelines to be considered for an adequate lightning protection design see (Goodloe 1998).

3.0 STATEMENT OF PROBLEM

The NASA Johnson Space Center (JSC) Shuttle Systems Integration Office requested probabilities for

[1] Corresponding author address: Dale Johnson, NASA, Marshall Space Flight Center, Mail Code: EL23
Huntsville, AL 35812;
e-mail: dale.johnson@msfc.nasa.gov

three peak lightning strike currents (i.e., 200kA, 100kA and 50kA) if the Space Transportation System (STS) was hit by a lightning cloud-to-ground (CG) return stroke during roll-out, on-pad, and for triggering lightning on ascent. This is Question A. The Shuttle Program needs this STS lightning criteria for a new STS avionics box. Question B asked, is if all lightning launch commit criteria (LCC) rules are followed, what is the probability of a 200kA, 100kA, and 50kA peak current lightning strike if the STS is hit while in the boost/launch phase? This paper respondes to these questions. Annual probabilities are expressed in percent and in terms of a mean return period (RP) in years. Currents are expressed in kiloamps (kA).

4.0 RESPONSE

Table 1 is the response to these questions.

Table 1: Response:
Question A:

For Roll-Out To Pad (during evening hours, with no forecasting considered):

Lightning Peak Current:	>200kA		>100kA		>50kA	
Point Probability:	Prob. %	RP yr	Prob. %	RP yr	Prob. %	RP yr
Worst Case	0.00218	45,963	0.00590	16,934	0.01150	8,696
KSC SLC40	0.000037	2,681,000	0.00031	322,000	0.00404	24,749

For On-Pad (STS protected by Pad Lightning System):

Lightning Peak Current:	>200kA		>100kA		>50kA	
On-pad Point Probab:	Prob. %	RP yr	Prob. %	RP yr	Prob. %	RP yr
Worst Case	0.00226	44,220	0.06138	1,629	0.11953	837
KSC SLC40	0.00039	258,000	0.00323	30,954	0.04200	2,381

For Launch (Lightning triggered by vehicle): (See Section 4.5 - Vehicle Triggered Lightning)

Lightning Peak Current:	>200kA		>100kA		>50kA	
Point Probability:	Prob. %	RP yr	Prob. %	RP yr	Prob. %	RP yr
Worst Case	TBD		TBD		TBD	
KSC SLC40	TBD		TBD		TBD	

Question B:

For Launch (STS protected by LCC storm distance rule only):

Lightning Peak Current:	>200kA		>100kA		>50kA	
Point Probability:	Prob. %	RP yr	Prob. %	RP yr	Prob. %	RP yr
Worst Case	0.000304	329,000	0.000825	121,000	0.00161	62,274

5.0 RATIONALE FOR RESPONSE

BACKGROUND:

NASA documents that reference natural lightning criteria and current lightning models used in the STS program are published (Bankson 1991, Johnson 1993, NSTS 16007). However, no document completely answers the questions concerning the probability of peak return stroke current magnitudes possible. Hence, a literature search for lightning statistics and procedures produced five reports dealing with lightning probabilities that can be applied to the Florida/KSC/Pad area, and were used for this paper. They are (Stahmann 1991), (Mach 1989), (Chai 1997), (Santis 1998), and (Gabrielson 1988). Three key general references consulted regarding extreme lightning peak current cummulative percentage frequencies (CPF) are (Uman 1987), (Volland 1995), and (Fisher 1990). A technical summary of the KSC references (Stahmann, Mach, & Chai) follows. An in-depth analysis of this literature search is in an upcoming NASA research publication (Johnson 1998).

KSC AREA/PAD LIGHTNING:

The lightning protection system (LPS) at KSC's Pad 39A has been struck by lightning an average of 3 times per year since 1979 (Stahmann 1991). Stahmann's theoretical probability calculations for lightning striking the 122 m (400 ft) tower is 2.0 strokes/yr., producing an average peak current amplitude of 122 kA with all calculations based on a pad stroke density of 20 strokes/km^2/yr.

Six years (1990-1995) of CG Lightning Surveillance System (CGLSS) measurements for Cape Canaveral Space Launch Complex 40 (SLC 40) were analyzed and published (Chai 1997). Chai's paper presents a summary of ~6200 CG events occurring within 5 nmi of SLC 40. The absolute maximum peak current measured was -284 kA (negative), the positive current peak was +144 kA. The 5-year total mean current peak was ~30.5 kA (with a SD value of ~14.5 kA). The associated negative mean peak current was -30.9 kA and the positive was +23.3 kA. A plot of the lightning peak current cpf for SLC 40 is shown in figure 1 (200 kA peak current ~99.9 percentile). Of the 6186 flashes; 94.5% of the flashes measured were negative, and 5.5% positive. Also, 91% of flashes occurred from June through September and 9% from October through May. Only three SLC 40 flashes carried current > 200 kA (i.e., -284 kA, -281 kA, and -203 kA; all negative). These strikes ranged from 1.9 to 4.9 nmi from SLC 40. The probability for natural lightning current >200 kA to occur within 5 nmi of SLC 40 per year is estimated to be 0.0513% (or 1 event in ~1,950 yrs.) (Chai 1997). This is an "area" probability, not a "point" probability.

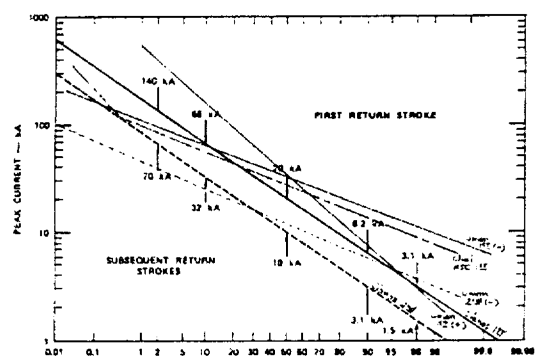

Fig. 1. Distribution of peak currents for first return stroke and subsequent strokes [Cianos 72, Uman 87 + Chai 97]

Mach's paper entitled: "Shuttle Lightning Threat Analysis" (Mach 1989), gave lightning probability estimates for various Shuttle operational phases. Mach emphasized all his probabilities are estimates and can be in error by more than an order of magnitude. In addition, his estimates do not take into account all possible pathways for lightning to damage STS systems. The three operational phases analyzed in his paper are roll-out, on-pad, and launch.

For roll-out, high current damage (200 kA) to the Solid Rocket Booster (SRB) and continuing-current to the External Tank (ET) are the greatest possibilities for major Shuttle damage (Mach 1989). The probability for lightning damage to an SRB is 1 in 3,200,000 years (or 3.1x10-7). For ET damage is 1 in 55,000 years (or 1.9x10-5).

On-pad it is estimated the lightning protection system's (LPS) catenary wire will shield the STS from ~97.2% of all pad area strikes (i.e.,~2.8% not diverted), (Mach 1989). If there are ~1.8 pad strikes/yr, and each STS spends ~2 weeks on the pad, Mach calculated the probability for SRB damage from lightning is 9.5x10-5 (RP=11,000 yrs). The probability for ET damage is 5.6x10-3 (RP=178 yrs).

Therefore, the maximum probability of a lightning strike of "any" current magnitude hitting the STS directly while protected on the pad is 0.028 (2.8%). Mike Maier of Patrick AFB/CSR stated, "Since 1990, the NASA OTV has documented two direct strikes to the pad structure which have bypassed the catenary wire LPS. Neither event resulted in a strike to the vehicle; one struck the gaseous oxygen (GOX) vent arm, and the other the far corner of the partially retracted RSS." (Maier,1998 pers. commun.).

On the boost-phase of launch the probability of the STS vehicle and exhaust intercepting a "natural" (not triggered) lightning flash from a nearby storm was calculated assuming the following conditions: a low flash rate (1/min) to a high flash rate (60/min), distance from the storm edge of 2 nmi, 5 nmi and 10 nmi standoffs, ascent time of ~50 s, and 8 launches per year. Mach's probability estimates are presented in table 2.

Table 2: Probability Estimates for Natural CG Lightning to Strike STS on

Exposure Time t(sec.)	Standoff From Storm Edge(nmi)	Storm Severity Flash Rate(min-1)	Probability per yr.(%)	Probability RP(yrs)
50	2	high = 60	0.625	160
50	5 (LCC)	avg.= 6	0.00434	23,000
50	10 (LCC)	low = 1	0.00007	1,300,000
50	10 (LCC)	high = 60	0.00434	23,000

* assuming 8 STS launches per year (Mach.
RP = mean return period (yrs.) LCC = launch commit criteria.

If Shuttle lightning launch commit criteria (LCC) are followed during countdown/launch, the estimated probability of the STS being struck by <u>any</u> magnitude lightning is 1 in 23,000 (or 0.0043%). The only LCC rule applied herein is the 5- and 10- nautical mile limit to thunderstorms (LCC/NSTS-16007). Not included are triggered lightning from anvils, cloud thickness, ceiling, and other LCC rules.

PROBABILITY FOR A >200 kA ETC. CURRENT STRIKE:
<u>Question A</u>:

The three mentioned references (Stahmann 1991, Chai 1997, Mach 1989) provided the main statistics to develop the conclusions arrived at in this section. To estimate the probability for "any" peak current strike to the STS, the following assumption was used: the highest probability of lightning intercepting the STS (either on-pad (2.8%), or in-flight (0.0043%)) was applied. In multiplying the average strikes to pad per year (3.0) x probability of lightning striking the STS (0.028) x 2-week pad exposure (0.03846 yr) gives:

$$3.0 \times 0.028 \times 0.03846 = 0.00323 \text{ strikes/yr} \quad (1)$$
or (0.323% or RP=310 yr)

This estimated probability includes "all" possible strike currents. To estimate the probability of >200 kA, >100 kA, or >50 kA strike, the most representative peak current cpf was used. The probability of strong CG negative and stronger CG positive lightning currents was applied (not the lower current triggered lightning current probabilities). The "Lightning Protection of Aircraft" (Fisher 1990) used the older 1972 Cianos peak current plot (figure 1), which gives 140 kA current at the 98th percentile; Lightning peak currents fit a log-normal probability distribution well (Fisher 1990). Uman's peak current summary curves of first return stroke peak current cpf for both negative and positive flashes (Uman 1987) and Chai's KSC Pad 40 peak current cpf (Chai 1997) are shown in figure 1. There is still some disagreement about these exact peak current statistics (Uman 1987). Figure 1 indicates these differences.

Uman's first return stroke peak current has a median value in the range 20 to 40 kA (median ~30 kA for negative flashes and ~35 kA for positive strokes) with <200 kA occurring at about the 99% level. The Uman 95th percentile negative first stroke peak current is <80 kA, while for positive first strokes is <250 kA. With exception of Uman's positive stroke curve, the more recent cpf current plots seem to parallel each other, and slope differently from the standard, 1972 Cianos plots. Table 3 presents the various extreme probabilities for a <200, <100, and <50 kA peak return stroke CG lightning current given by Uman, Cianos, and Chai.

Table 3: Estimated Cumulative Percentage Frequencies (CPF) of:
<100kA & <50kA Peak Lightning Current Occurrences : (Extracted from Figure

Peak Current	Uman87' Positive	Cianos72' 1st Return	Uman87' 1st Negative	Chai97' 1st Return
<200 kA	93.0%	99.35%	99.98%	99.88%
<100 kA	81.0%	95.6%	98.2%	99.0%
<50 kA	63.0%	84.0%	80.0%	87.0%
	(Worst Case)	(Standard)		(KSC)

One could use any of the first return stroke peak current CPF curves of figure 1 for negative or positive strokes, and apply them for the KSC area. This answers Question A. However, the Chai KSC CGLSS Pad 40 lightning current statistics may be more applicable/realistic for the SLC 39 area, and were used in this study.

Maier provided insight to the lightning climatology at SLC 40 compared to Pad 39. He stated: "The situation around 39A and 39B is almost the same. We have found the two Shuttle pads are exposed to slightly higher flash densities than the Titan pads, since they are a bit farther north and closer to the mean "storm track" which extends ENE from the local lightning frequency maximum west of KSC. However, the peak current distributions don't seem to have any significant (at least within our area) spatial variations so the Cape area distribution would apply." (Maier 1998 personal communication).

Therefore, using the Chai lightning current statistics at SLC 40 to represent the Pad 39 area, we can assume a <200 kA return stroke peak current at the 99.88% level (table 3). Multiplying the equation 1 value by 0.0012 (0.12% is the probability of >200 kA), we calculate a probability of 0.000388% (or RP=258,000 yr). This provides a response to Question A. However, the worst-case situation might arise if a rare, strong, positive current lightning strike occurs at KSC generating much higher currents. If the Uman positive stroke curve applies to KSC, the table 3 worst-case probability of 93.0% for a <200 kA peak current would be used with equation 1. We then would arrive at a resulting worst-case probability of 0.00226% (or RP=44,220 yr) for a >200 kA current event. This is a more conservative answer to Question A (a greater factor of safety). Probabilities for occurrence of peak lightning stroke currents >100 kA and >50 kA are similarly computed (table 1).

<u>Question B</u>:

To answer Question B the Mach report (Mach 1989) probabilities (table 2) were applied directly to the worst-case cpf values. The main assumptions are first the lightning 5- and 10- n mi storm distance LCC rules used, and then only CG (not triggered) lightning is assumed.

Therefore, in calculating the point probability that the STS would get struck "naturally" on ascent by a >200 kA lightning induced peak current, multiply the table 2 probability (0.00434) for "any" current, by the worst-case probability (0.07), to compute a resultant vehicle-hit probability of 0.0003038% (or RP= 1 in 329,164 yr).

STS ROLL OUT RISK:

To calculate the probability of a 200 kA current lightning strike to the STS during roll-out, the following assumptions were used. The height of the Shuttle atop the mobile launching platform (MLP) and crawler is ~235 feet (72 m agl). The horizontal dimensions of the MLP are 135 ft x160 ft giving an ~21,600 ft^2 (~2007 m^2) striking area. The ground/terrain is assumed flat for the ~6-hour trip over the 4.2-mile distance from VAB to Pad 39B.

The first item to determine is what is the probability of "any" magnitude lightning strike (str) to hit "any" square area (A) on the ground (between the VAB and Pad 39) of 2007 m^2, using the KSC annual flash density (f) of 20 strikes/km^2/yr? Assuming a poisson distribution (Santis 1998), the probability that any flat surface area will be hit by any magnitude lightning in a certain number of years is:

$$Y(yrs) = 1/(A \times f), \quad \text{(Santis 1998)}. \qquad (2)$$

Therefore: Y = 24.91 yr/str, or P_{yr} = 0.04014 str/yr, (or 4.01%). However, to calculate the resultant probability of a 200 kA current strike at KSC, apply the table 3 worst case probability (0.070) with other key parameters (i.e., elevated vehicle, worst month, a 6-hr exposure period, and best diurnal time to roll out).

For an elevated object of height 235 ft, Viemeister presents a strike/height chart (Fig. 50 Viemeister 1972) for an isolated tower or object to 600 feet tall (on level terrain), located in a moderate (30 thunderstorm days/yr) lightning environment. The charts probability of lightning strikes is directly related to height. An object 235 ft. tall will be hit twice at often as an object 117 ft. tall. Viemeister's strike value for 235-ft height is 1.0 lightning strikes/yr. Since the KSC area has more thunderstorm days (72) than Viemeister's 30, this strike value of 1.0 is multiplied by 2.533 (72/30) resulting in 2.533 strikes per year. This figure is close to reality because elevated Pad 39 gets hit directly by lightning ~ 2 to 3 times per year, indicated earlier (Stahmann 1991). Therefore:

$$P_{(yr\ elev)} = (0.04014 \text{ str/yr}) \times (2.533) = 0.10167 \text{ str/yr},$$
$$(\text{or } P_{(yr\ elev)} = 10.17\%). \qquad (3)$$

This yearly probability should be converted to a monthly probability. Dividing by 12 gives

$$P_{(mo\ elev)} = 0.008473, \quad (\text{or } P_{(mo\ elev)} = 0.847\%). \qquad (4)$$

Now the remaining parameters can be applied to this probability value:

(1) To obtain a 200 kA current for the worst case (table 3), use 0.070.
(2) For "any" 6-hr exposure period during a month, an exposure period of 6/720 = 0.008333 month is used.
(3) Since the roll-out vehicle should be exposed during the peak lightning season, July KSC data is used. The average monthly KSC thunderstorm days is ~6.333 (KSC July averages ~16.0), giving a factor of 16/6.33 = 2.53 applying to July (Mailander 1990).
(4) Finally, assume that the STS will be rolled out during the 6-hour time frame when thunderstorm activity is minimal, i.e., between 0200 and 0900 LST when the probability of July KSC thunderstorm occurrence is ~1.0% (Golde 1977). The July KSC probability peaks at ~23% at 1600 LST. Since The average KSC July hourly thunderstorm probability is ~6.9%, a factor of 1.0/6.9 = 0.145 is applied during the early morning hours for conservative roll-out purposes.

The "final" resultant probability combines all four above mentioned procedures.

$$P_{(mo\ elev)} = 0.008473 \times 0.07 \times 0.008333 \times 2.53 \times 0.145 = 0.000001813 \text{ str/mo}. \qquad (5)$$

Converting this probability back to an annual value results in a yearly probability and return period.

$$P_{(yr\ elev)} = 0.002176\%, \text{ and } (45{,}963 \text{ yrs/str}). \qquad (6)$$

Computed lightning current probability values associated with STS roll-out for 200 kA, 100 kA, and 50 kA, using table 3 worst-case and KSC/SLC40 conditions, are presented in table 2.

Note: If the Shuttle roll-out did not occur during the evening hours, but during the peak July afternoon hours, the resultant nominal probabilities for a 200 kA and 50 kA lightning strike are 0.04% (RP = 2,508 yr), and 0.21% (RP = 475 yr), respectively. Thus it does matter "when" the Shuttle is rolled out.

VEHICLE TRIGGERED LIGHTNING:

If the STS vehicle is launched under LCC storm distance rules, Mach has given a "non-triggered", natural CG lightning hit probability of 0.00434 (23,000 yrs).

Since the peak stroke current measurements from the KSC rocket-triggered program is 99 kA (Jafferis 1995), this seems to follow the subsequent peak current curve for return strokes (of half the value of an initial return stroke current). Using the Cianos subsequent-stroke curve (figure 1) for estimating the <200 kA, <100 kA and <50 kA triggered current cpf's, one derives ~99.94%, ~99.35%, and ~96.2%, respectively. This implies a 0.06% risk would have to be applied (multiplied) to the probability of a rising vehicle triggering a >200 kA stroke at KSC. But this ascent-triggered probability has not yet been determined. See next paragraph for more insight concerning ascent vehicle triggered lightning.

An ascent vehicle-triggered lightning probability can be "implied" (Gabrielson, 1988). Gabrielson calculated a probability for any lightning strike to directly hit a standing 10-m tall vehicle on the ground during moderate storm/lightning conditions, to be

$$P_d = 2.9 \times 10^{-9}, \text{ and } (RP = 3.45 \times 10^{-8} \text{ yrs}) \qquad (7)$$

He based his probability estimate of either a direct strike (P_d) or a nearby strike (P_n) on thunderstorm day data only. The probability is estimated using three independent parameters - flash density (fD), vulnerability area (A_v), and exposure time (t), i.e., P_d = fD x A_v x t. Gabrielson neglected exposure time in calculating P_d.

Gabrielson also calculated the probability of any nearby (within 10 km of the craft) vehicle-triggered lightning strike during flight, resulting in either a cloud-to-cloud or cloud-to-ground discharge. In this second case, Gabrielson kept all inputs the same except he assumed the presence of exhaust gases after launch extends the vehicle's effective height 10 times, thereby affecting the vulnerability area. Also, he included an additional 5% to the calculated flash density to account for discharges (intercloud) triggered on nonstormy days. Vehicle exposure time during ascent was assumed to be 50 seconds. The nearby strike threat estimate (probability) for this vehicle ascent case is:

$$P_n = 4.06 \times 10^{-4}, \quad (RP = 2{,}463.\text{yrs}) \qquad (8)$$

Note that this resultant probability value is still a very conservative, small probability of occurrence compared to the reality at KSC of two major vehicle triggered strikes (Apollo 12 and the Atlas-Centaur) within ~20 years. However, from these two probabilities one can see that a "nearby" triggered lightning estimate (P_n) for "any" magnitude current strike is 140,000 times greater than the direct hit to a vehicle on the ground estimate (P_d). This is a factor to be considered when launching. Another factor to consider is KSC test-rocket triggered lightning discharges generally indicate that large currents (>100 kA) are extremely rare compared to natural CG lightning discharge currents.

6.0 SUMMARY

KSC "worst case" probability estimates are summarized here. Table 1 presents the "KSC SLC40" results.

Answer to JSC Question A is the probability of a >200 kA peak lightning strike current occurring to the STS vehicle, while protected on the pad is 0.00226% (or a RP of 1 in 44,220 yr).

Answer to JSC Question B is The probability of a >200 kA peak natural lightning current occurring on or near the launched STS while following (only) the lightning LCC distance to storm rule is 0.0003038% (or a RP of 1 in 329,000 yr). Other lightning LCC rules such as anvil, thick cloud, ceiling, etc. are not applied here.

Answer to JSC question regarding Roll-Out is the probability of a >200 kA peak lightning strike current occurring during roll out, and exposed for 6 hours during the worst KSC lightning month (July), during the most lightning inactive time of day (night hours), is 0.00218% (or a RP of 1 in 45,963 yr). Man forecasting is not considered here. In reality a weather forecast always precedes an STS roll-out at KSC. The best-condition real-time forecast still allows for a ~10% chance of lightning strike.

Answer to JSC question regarding Launch-Triggered Lightning is that the probability of a >200 kA lightning strike current occurring has not yet been determined. However, a "triggering" factor (a factor of 140,000 increase in probability and RP) was determined from one case found in the literature, and will be looked into further to see if it applies.

Lightning strike possibilities to the STS exist during Shuttle exposure at locations other than KSC, i.e., while on the Edwards AFB runway for up to a week and while flying atop the Boeing 747 aircraft on the trip back to KSC (must fly with no clouds or weather present). These two operational categories were not dealt with in this paper.

The concluding probabilities in this report are only estimates and may be greatly in error (author's and Mach 1989).

ACKNOWLEDGEMENTS:

The authors would like to acknowledge Dr. Doug Mach, and Dr. Bill Koshak and their MSFC/GHCC colleagues for advice, references, inputs, and review of the lightning probability section of this report. Also appreciated are inputs and comments by Ms. Carolyn Goodloe, and Ms. Margaret Alexander of MSFC/EL23. Thanks go to our NASA KSC colleagues, Mr. John Madura at the KSC Weather Office and to Mike Maier of CSR, Patrick AFB.

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MANUSCRIPT INSTRUCTIONS

EIGHTH CONFERENCE ON AVIATION, RANGE, AND AEROSPACE METEOROLOGY

79TH AMS ANNUAL MEETING

10–15 January 1999 Wyndham Anatole Hotel Dallas, TX

A preprint volume for the **EIGHTH CONFERENCE ON AVIATION, RANGE, AND AEROSPACE METEOROLOGY** will be published and distributed in **Dallas, Texas, 10–15 January 1999**. We encourage all presenters to submit a manuscript since time for oral presentations is limited. The preprint provides an excellent opportunity to include more detailed information, figures, and graphs that may require more time for study than is available at the meeting. The preprint volumes will also be made available on CD-ROM, therefore exposing your research to an even broader audience.

The following pages contain instructions to help you prepare your camera-ready manuscript, which should be no more than **FIVE** (5) pages in length. The **deadline** for receipt of your manuscript at AMS is **1 October 1998.** It is very important that you adhere to our deadlines. If you cannot submit your manuscript by this date, please contact the Meetings Department immediately via e-mail: kmorrissey@ametsoc.org or by telephone (617) 227-2426, ext 226. The success of the preprint volume is wholly dependent upon your cooperation in preparing and mailing your manuscript in a timely fashion.

If your manuscript contains a color photo, the cost for printing color is $1,500 per page (contact the Meetings Dept. for cost of color reprints). Color preprint covers (relating to the conference theme) may be sponsored by you or your organization. If you would like to submit a color photograph for consideration as a cover, please contact the Meetings Department at the number above.

Please complete and return the Publication Page/Reprint Charge Form with your manuscript. Be sure to include your paper number (which is found by searching your name or title in the preliminary program). **Your manuscript, Page/Reprint Charge Form, and payment should be sent together**. If it is necessary to submit your manuscript without a hard copy of your purchase order, please attach a photocopy of your Page/Reprint Form and check the box "Purchase order to follow" (hard copy must be received within 30 days of date of submission of your manuscript). When submitting payment separately from your manuscript, always include a copy of your Page/Reprint Charge Form.

Your general information and hotel information are available at this site. You will be notified once the preliminary program, registration form, and audio/visual & computer request form are updated on the Web. Thank you for your participation in this conference. We look forward to seeing you in Dallas!

MANUSCRIPT DEADLINE DATE:
1 OCTOBER 1998

Tips for Formatting your Manuscript for the AMS Preprint Volume

1a. **WHAT IS YOUR PAPER NUMBER** — AMS will inform you when the preliminary program is posted on the AMS home page. At that time, please search your name in the program to find your paper number (which is different from the log number you received when submitting your abstract via the Web).

Example: **7.2**
7= Session number
2= paper number
7.2 = YOUR PAPER NUMBER

- ★ If you are presenting a **poster** a "P" will precede your paper number (**P7.2**)
- ★ If you are presenting in a **joint session** a "J" will precede your number (**J7.2**). Presenters in a joint session, should submit TWO ORIGINALS of their manuscripts as it will appear in TWO different preprint volumes.

1b. **PLACEMENT OF PAPER NUMBER**

- ★ Type your **BOLDFACE** paper number at 1"/1" margin in the UPPER LEFTHAND CORNER of the first page of your manuscript

2. **BASIC FORMATTING TIPS:**
   - ★ **MARGINS:** 1" all around (8/12 x 11); 1 3/4" bottom (A4 paper)
   - ★ **COLUMNS**: 2 columns with 1/4" space in between
   - ★ **TEXT**: Helvetica or Arial, 9 point (or similar font to this page)

3. **TITLE**
   - ★ Type at 1" top margin in center of first page, all CAPS

4. **HALFTONES**
   - ★ All photographs must be converted into halftones by our press.
   - ★ In most cases, it is not necessary to halftone a shaded computer-generated figure (rule of thumb: if original does not photo copy well, then we recommend halftoning)

5. **DON'TS**
   - ★ do not STAPLE or FOLD YOUR MANUSCRIPT
   - ★ do not PRINT OR TYPE THE CONFERENCE NAME ON YOUR MANUSCRIPT
   - ★ do not PRINT OR TYPE PAGE NUMBERS ON YOUR MANUSCRIPT

Please Refer To The Following Instructions For More Detailed Information

10.2 DOPPLER RADAR VELOCITIES

Andrew A. Andrews *
University of Missouri, Columbia, Missouri

1. INTRODUCTION

To assist you in preparing your camera-ready manuscript for publication in the preprint volume, please adhere to the following instructions. Manuscripts should be printed directly on 8 ½" x 11" paper (216mm x 279mm), which is standard size in the United States or A4 paper which is standard in Europe.

2. MANUSCRIPT DEADLINE & SUBMISSION

Manuscripts must be received by **1 October 1998** at AMS, Meetings Department Attn: **8 AVIATION**, 45 Beacon Street, Boston, MA 02108-3693.

2.1 *Length Of Text & Page Charges*

Text, including illustrations and references, should be no longer than **FIVE (5) PAGES IN LENGTH**.

Publication page charges have been assessed to help defray the cost of printing preprints (see Table 1 below). When submitting your manuscript, include your payment, along with the Publication Page Charge/ Reprint Form.

TABLE 1

PAGES	1-2	3-4	5
COST	$95	$170	$235

3. PAGE LAYOUT & TEXT FONT

Text should be printed on ONE side of 8 ½" x 11" or A4 paper. Manuscripts must be formatted with 1" margins on all sides (1¾" bottom margin if using A4 paper). Please use 9 or 10 point Helvetica, Arial, or similar font for the text.

Place the text in newspaper style columns with a ¼" space between columns. If necessary, figures, photos, or charts may span the two columns adhering to the 1" outside margins.

The first page of your paper may begin on right or left. If it is essential that your paper be a double-page spread, please indicate if it should begin on the right or left page.

Please remember that your manuscript is CAMERA-READY and will not be edited. Also, please DO NOT STAPLE, FOLD, OR WRITE ON ANY OF THE PAGES.

4. MANUSCRIPT FORMATTING

The International System of Units (SI units) used in all AMS journals should be used in AMS conference preprint volumes.

4.1 *Paper Number*

If you are presenting a poster, a "P" will precede your paper number and if you are presenting in a joint session a "J" will precede your paper number (the "P" and the "J" are a part of your paper number, please be sure they appear on your manuscript).

Your **boldfaced** paper number should be typed at the 1"/1" margin in the upper lefthand corner of your manuscript (as shown on this page, i.e. **10.2**). Please also be sure to include your paper number on the page and reprint form.

4.2 *Titles, Headings & Footnotes*

The title of the paper should be centered and typed in CAPITAL LETTERS on the first line of the first page of your manuscript. Type the name of all author(s) in initial caps and center on the page two lines below the title. Type authors' business or school affiliation, city, and state and center on the line below the name in initial caps.

Major headings are Arabic-numbered and in CAPITAL LETTERS (as shown in these instructions).

Footnotes should be indicated in the text with an asterisk (*).

4.3 *Author's Corresponding Address*

Please type, within the 1" margin, the corresponding author's address in the lower left corner of your first page (see lower left corner of this page).

4.4 *References*

List all bibliographical references at the end of the paper in alphabetical order by first author. When referring to them in the text, type the corresponding author surname followed by the year of publication; e.g., Smith (1984). Use referencing style from any one of the AMS journals (see sample below).

Battan, L. J., 1971: Radar attenuation by wet ice spheres. *J. Appl. Meteor.*, **10**, 247–252.

* *Corresponding author address:* Andrew A. Andrews, Univ. of Missouri, Dept. of Meteorology, Columbia, MO 65211-1234; e-mail: aandrews@met.edu.com.

4.5 *Equation Numbers*

Enclose these Arabic (and sequential) numbers in parentheses and place flush with right-hand margin of column.

5. PAPER IDENTIFICATION & PAGE NUMBERING

Write the last name of the corresponding author and the page number on the back of each page (i.e. a 3-page paper would be marked as: 1 of 3, 2 of 3, 3 of 3). These markings are for handling and identification purposes only and will not be reproduced.

Please **do not** mark the front sides your manuscript with any page numbers. Final page numbering will be done when the complete volume is assembled at AMS.

6. BLACK/WHITE & COLOR PHOTOGRAPHS

All photographs should be converted into halftones by our press. In many cases, it is not necessary to halftone a shaded computer-generated figure (rule of thumb: if original does not photo copy well, then we recommend halftoning). There will be an additional $20.00 charge per illustration for photo/halftone processing for publication in the preprint volume and a $30.00 charge per photo/ halftone for reprints.

Contact the AMS Meetings Department if you are interested in submitting color photographs or illustrations. Cost per color page is normally $1,500.

7. ILLUSTRATIONS AND TABLES

Presentations at the conference do not usually allow enough time for in-depth explanation, therefore, it is important to include your most complex graphs, diagrams, illustrations, or tables in your manuscript.

All figures should be the **original or a high quality copy**. If you must affix your figure, table, photograph, etc., to your paper it must be glued (not taped) into position.

Figures and tables should be reduced so that they may be incorporated into the text along with the appropriate pages, with full captions typed below the figure.

A table or figure that cannot be placed in the same orientation as the text should be rotated 90° counter-clockwise so that the figure and caption may be read by rotating the published proceedings 90° clockwise.

Company logos and identification numbers are not permitted on your illustrations.

8. MAILING YOUR MANUSCRIPT

Authors are advised to make a copy of their manuscripts before mailing in the event that the original paper becomes lost in the mail. All Authors should send their papers via a TRACEABLE service to arrive at AMS Headquarters BEFORE the manuscript deadline date.

When submitting your manuscript to AMS, please include your Page Charge and Reprint Form, along with your payment. Thank you.

If you have any questions, please contact the AMS Meetings Department, e-mail: kmorrissey@ametsoc.org, or telephone (617) 227-2426, ext 226.