Investigation on Improvements in Lightning Retest Criteria for Spacecraft

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***Abstract*—Spacecraft are generally protected from a direct strike by launch the vehicle and ground structures, but protocols to evaluate the impact of nearby strikes are not consistent. Often spacecraft rely on the launch vehicle constraints to trigger a retest, but launch vehicles can typically evaluate the impact of a strike within minutes while spacecraft evaluation times can be on the order of hours or even days. For launches at the Kennedy Space Center where lightning activity is among the highest in the United States, this evaluation related delay could be costly with the possibility of missing the launch window altogether. This paper evaluated available data from local lightning measurements systems and computer simulations to predict the coupled effect from various nearby strikes onto a typical payload umbilical. Recommendations are provided to reduce the typical trigger criteria and costly delays.**

Keywords—nearby lightning; coupling; ring criteria; spacecraft; launch complex; transmission line matrix method;

I. Introduction (*Heading 1*)

The launch vehicle industry has been historically reliant on launch complex systems and launch weather constraint to prevent direct lighting attachment. Accordingly, the focus for lighting effects protection is on nearby strikes and direct strikes to the vehicle support structure/facility. It is important to well characterize the launch vehicle immunity to this lightning environment. Although simulation tools and measurement options exists, lightning evaluation criteria based on coupling to a simple loop is used to allow for crisp go, no-go, and retest decision points once the vehicle is on stand. This paper compares these typical back-of-the-envelope (BoE) loop induced currents to electromagnetic full wave simulations and available measured data. The calculations are based on magnetic induction of voltage and current equations performed with classical electromagnetics theory where the open circuit voltage and short circuit loop current are given by (1).

$$I_{loop} = -\frac{1}{L}\int Voc\, dt = -\frac{BA}{L} \qquad (1)$$

Where $V_{oc} = -\frac{d\emptyset}{dt}$, $\emptyset$ = BA, L is the loop inductance and B = µH. The magnetic field, H, is derived from the current magnitude of the lightning strike with assumed reference waveform given in MIL-STD-464for the A component. This is based on $i(t) = I_0(\varepsilon^{-\alpha t} - \varepsilon^{-\beta t})$ where the time, t, is in seconds and the constants for the A component waveform are α = 11,354 and β= 647,267 [1,2].

Another method is to use mutual inductance coupling [5-6] as shown in (2) [5,6].

$$I_{loop} = I(L_m/L_s) \qquad (2)$$

Where *I* is the current magnitude of the lightning strike, L_m is the mutual inductance between the conductor and the loop and L_s is the loop self-inductance. In [6] this mutual inductance method was found to be representative of the magnitude of a strike for a loop 1 meter away and a 0.454 µs rise time. In this paper both methods and simulations are examined for launch vehicle representative cases.

A brief discussion of the evaluation process is provided followed by comparisons between this process and measured or simulated data. Additional simulations are performed to evaluate the shielding launch complex structures. Finally recommendations on trigger criteria for retest procedures are made. Since common mode to differential mode coupling and shield transfer impedance are widely varying factors in such analysis, the current coupled in the loop will be used to compare the models, measured data, and calculated levels.

II. Lightning Criteria

A. Launch Vehicle

Transient testing is typically performed at the equipment level to characterize the vehicle immunity to induced currents and voltages. MIL-STD-461 and RTCA_DO-160 provide industry lightning transient immunity tests [1,7]. The lightning magnitude and location data is available from the launch site or range and includes the lightning magnitude and location either though on-site systems such as Cloud-to-Ground Lightning Surveillance System (CGLSS) or through national lightning measurement systems such as the National Lightning Detection Network (NLDN) [8]. Note the accuracy of these systems vary and should be accounted for the in the retest criteria. An analysis is performed using the range data

for a 99th percentile strike of 200 kA, umbilical loop size and vehicle immunity data to develop the outer boundary of concern. Then inner boundaries are established for the more likely lower magnitude strikes. These boundaries are often formed by the radius around the launch vehicle and are referred to as rings. The criteria are set conservatively with worst case coupling to the loop too add confidence during real-time retest decisions. When violations occur, the launch vehicle providers have set retest procedures to evaluate the most sensitive circuits and can be "launch ready' within a short window. Retest decisions are made by applying range data to a ring criterion; however, range data is not infallible. When a strike is recorded there are uncertainty levels associated with the data, ±500m from the recorded distance and ±35%kA of the measured flash magnitude [14]. Evaluating the worst case scenarios based on these uncertainties yields a very conservative estimate, possibly leading to unnecessary retest and a missed launch opportunity. An alternate approach, employing statistical analysis, should be considered. Table 1 includes standard deviations of these uncertainties propagated through a typical data reduction equation using the Monte Carlo Method. The standard deviations below are calculated from the BoE B-field equation (1). These uncertainties are still conservative due to the use of the 99th percentile 200kA strike in the calculation. While this table is clearly not a replacement for range data, such as a current monitor, it could prove useful for a quick BoE calculation, evaluating individual ring criteria, and determining the validity of a simulation.

TABLE I. STANDARD DEVIATION USING B-FIELD EQN.

Standard Deviation (σ) of Current (A) for a 200kA Strike		
Distance	***B-Field Method (σ)***	***Uncertainty (95% confidence)***
4km	3.0	±6.0 A
3km	4.5	±9.0 A
2km	7.0	±14.0 A
1km	24.0	±28.0 A

[a.] Assuming a Gaussian distribution, the uncertainty is ±2σ with 95% confidence.

B. *Spacecraft*

Spacecraft on the other hand typically do not characterize their transient immunity by test other than to the typical load switching transients that are tested in MIL-STD-461. The payload umbilical is typically the highest umbilical on the launch platform and hence has the worst case loop area for induced currents and voltages. The spacecraft only flies once and thus does not have lightning sensitive circuit based retest procedures established. Instead, the spacecraft relies on full system retest checks which can take many hours or days to complete. Performing a worst case coupling analysis can lead to over prediction of the impact and thus lost launch opportunities. Hence, we are evaluating typical spacecraft configurations to provide additional resources and techniques to evaluate the impact of a nearby strike on the sensitive equipment housed inside the spacecraft. This is not to say that a retest should be avoided, especially after a strike very near the launch site because the safety and functionality of the spacecraft are of the utmost importance. These recommendations are designed to allow the spacecraft provider to make their own assessment on a retest decision rather than following a blanket conservative criterion established without any knowledge of the equipment in question.

III. SIMULATION COMPARISONS

All simulations were performed using the hexahedral mesh transmission line matrix solver in CST [9]. This option allows for circuit layout and grounding modifications of the umbilical cable. Comparisons were made with regard to distance from the strike, rise time, and cable layout. Currents in CST were taken from the over braid of a simulated cable bundle.

A. *Distance comparisons*

The standard model distance used in this study was 500 meters. Typically, strikes closer than this distance would be a direct strike to the launch support or lightning protection structure simply because it would be the tallest structure within that radius. However, to evaluate the sensitivity of simulations and lightning criteria equations have to the distance from the strike parameter, closer and further distances were used and compared with both BoE equations. The results in Table II reveal a correlation between the model and equation across the range of distances with some systematic error. It is worth noting that all of the values fall nearly within the uncertainties established in Table I, showing the utility of a modeling effort and statistical analysis. As with the uncertainties in Table I this comparison indicates a larger margin of error for closer strikes.

TABLE II. CST AND B-FIELD EQN. CURRENTS ON A STANDARD LOOP

Comparison of Current			
Distance	***CST Peak Current***	***Eqn. (1) Current***	***Eqn. (2) Current***
4km	9.5 A	15.1 A	16.6 A
3km	8.5 A	20.1 A	22.1 A
2km	19.0 A	30.2 A	33.1 A
1km	37.0 A	60.4 A	66.2 A

B. *Waveform comparisons*

The rise time typically assumed for the ring criteria is 6.4x70 µs based on MIL-STD-464 lightning definition for the initial stroke. That standard rise time was used in all of these simulations unless noted otherwise. In order to evaluate the coupling into a 150m^2 cable loop for different waveforms, the rise times were extrapolated from the double exponential constants (α and β from MIL-STD-464) and compared with CST simulations. The results in Table III show that the performance is similar in the two

BoE methods because they are both based on the peak level and not the rise time. Comparison to the simulation shows that the BoE methods remain conservative except for the faster H component. Since strikes with magnitudes of concern will likely be component A or D waveform, the BoE equations bound the simulation.

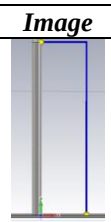
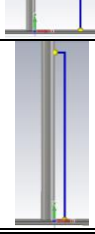
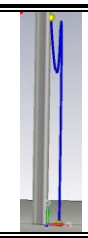
TABLE III. WAVEOFRM VS CURRENT ON A 150M^2 LOOP

Waveforms Coupling at 500m			
Waveform (MIL-STD-464)	***CST Current***	***Eqn. (1) Current***	***Eqn. (2) Current***
H: 0.25x4.5 µs	32 A	7.7 A	7.5 A
D: 3.2x35 µs	79 A	77 A	77 A
A_h: 5x50 µs	89 A	115 A	116 A
A: 6.4x70 µs	100 A	153 A	154 A

C. *Cable layout and grounding*

The standard ring criterion assumes the entire length of the loop made by the height of the umbilical cable, the rocket, the support structure and the ground. If details of the configuration aren't known, it is common to use the cable lengths to define the loop. This can lead to an overestimation of the currents when the cables are drooped. Three loop configurations with different areas were modeled and compared with equation (1): 1500m^2, 150m^2, and a drooped cable of the same length as the 150m^2 configuration with an effective area of 105m^2. The B-field equation takes into account the area of the loop and the magnetic flux, thus it is the equation used to calculate the values in Table III. Note that the inductance equation does not account for the difference between the small and drooped loops because the cable lengths are the same; however, there is a clear reduction in current for the smaller area, shown in both the BoE calculation and simulations.

TABLE IV. LOOP AREA VS CURRENT.

CST vs BoE for Various Areas			
Area	***CST Current***	***(1) Current***	***Image***
1500 m^2	267 A	1390 A	
150 m^2	100 A	153 A	
105 m^2	61 A	97 A	

The area reduction due to some amount of slack in the cable is not a negligible difference and should be taken into account to improve the accuracy of hand calculated results and modeling.

IV. FACILITY SHIELDING

When lighting protection systems are in place, significant additional benefit can be achieved from shielding from electromagnetic waves afforded by these facilities.

A. *Facility Shielidng*

Most launch vehicles at KSC are in enclosed buildings with large openings for vehicle roll-out to a launch pad. A typical structure housing a launch vehicle is made of steel. The energy propagating from the attachment point will couple to such structures resulting in some dB reduction in field and current levels measured within the building. The shielding effectiveness (S.E.) of such a steel building is discussed in [11] and validated through CST models and a comparison with range data. The study estimated the reduction due to the structure at 45dB and 46dB in the E-field and H-field respectively. Figures 1 and 2 are modeled to investigate the same phenomenon yielding results of -45dB and -39dB in the E-field and H-field respectively. This shielding may be applied to results derived from a model (excluding the presence of a building) or BoE equation to account for the significant reduction provided by the enclosure in order to calculate a value that reflects the conditions of the launch environment.

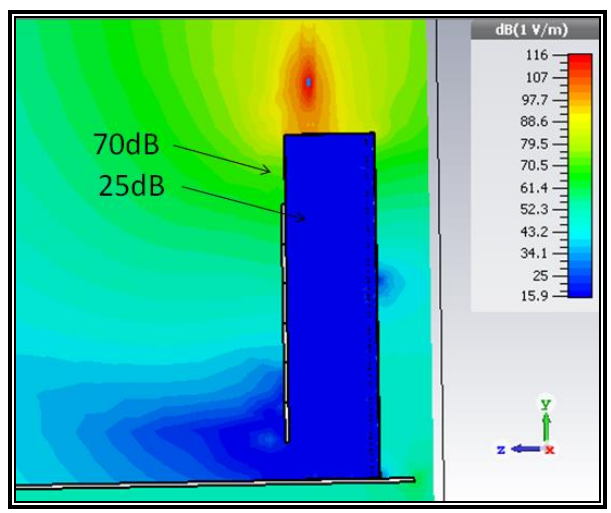


Fig. 1. Steel Building E-Field S.E.

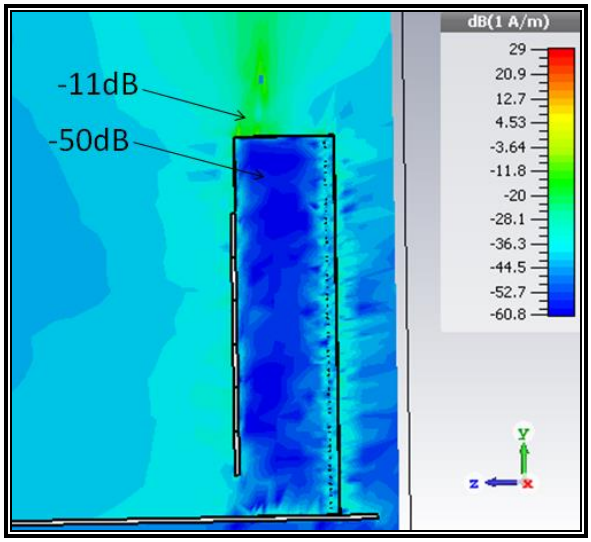


Fig. 2. Steel Building H-Field S.E.

Finally, to validate the results, data from a current monitor inside of a typical steel building was compared with a model of the strike occurring at the same time signature without the structure present. The loop area used in the BoE calculations in Table V was ~450m^2 the other data was taken from range reports that recorded the lightning events. The average difference between the current monitor and the predictive model was about -40dB of current (calculated from the results in Table V), this is in good agreement with the predictions in [11]. Although many other local flashes were recorded, no currents were reported on the umbilical during those events, showing the significant attenuation provided by the enclosure. Applying reductions of -30dB (-25dB for a very conservative estimate) to the E-field, H-field, and the predicted current will improve the accuracy of a quick BoE equation by accounting for additional factors in the launch environment, at the very least, providing a reference upon which to base further decision-making.

TABLE V. VERIFICATION OF DB REDUCTION IN CURRENT.

Steel Building Current Reduction				
Distance	***Magnitude***	***Eqn. (1)***	***Current Monitor*** [a]	***Decibel Difference***
400 m	-82.5 kA	230 A	2.09 A	-40.8 dB
650 m	-56.1 kA	96 A	1.63 A	-35.4 dB
2000 m [b]	-52.1 kA	29 A	0.5 A	-55.3 dB
120 m	-23.1 kA	214 A	9.64 A	-26.9 dB

a. The current monitor values are real measured values provided by a lightning monitoring system during actual lightning events. The table includes the associated distance and magnitude recorded by the same system for each strike.

b. The strike with a distance of 2000m was recorded after rollout while the Launch Vehicle was underneath the catenary, making this an excellent, example of the S.E. provided by the catenary in an actual launch environment during a natural lightning flash.

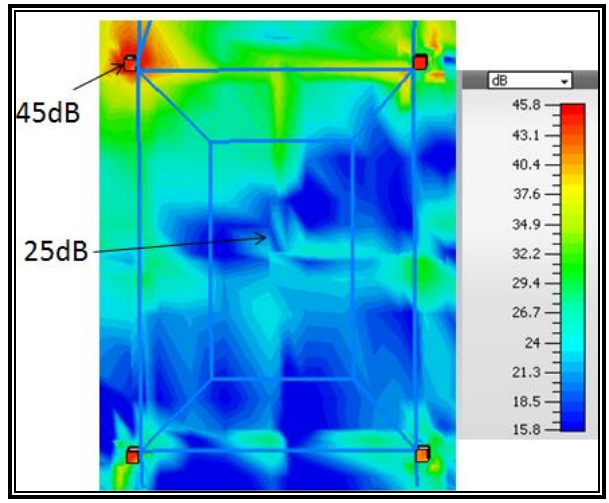


Fig. 3. Catenary S.E.

B. *Catenary systms*

Most launch vehicles have some catenary systems designed to mitigate the effect of a nearby flash. This study used a typical configuration including four metal towers topped with an insulating material (providing a safer location for lightning attachment) and conducting wires connected between the towers and to ground (carrying current away from the vehicle underneath the structure.) In addition to this more obvious protection from direct attachment, the catenary provides some shielding from the incident electric and magnetic fields directly after a flash. Determining the amount of shielding was carried out through modeling in CST and validated with [13]. The predictions made in [13] imply a 21dB reduction in the magnetic field. A CST model, displayed in Figure 3, predicted a 20dB reduction for B-fields in the middle of the catenary. As with the facility shielding, a reduction can be made for a launch vehicle or spacecraft sitting under a catenary system before launch. Reducing a calculated result by 20dB to account for the catenary is a conservative estimate, since a real example in Table V shows S.E. of -55dB in current.

C. *Launch Tower*

Launch vehicles are generally accompanied by a launch tower before launch. This steel beam structure supports the vehicle itself and the umbilical cables terminated at the rocket, providing additional grounding points for the cable run. Some CST modeling (Figure 4) has shown that additional grounding points along the launch tower do not reduce the current observed on the over braid nor does the inclusion of multiple cable runs of various loop size all grounded on the launch tower. In modeling, we recommend using the largest loop attached to the launch vehicle grounded at the body of the rocket and a point on the ground plane that creates the desired loop area. While this is made of steel, a level of attenuation as seen with steel buildings is not expected due to the large aperture size between beams.

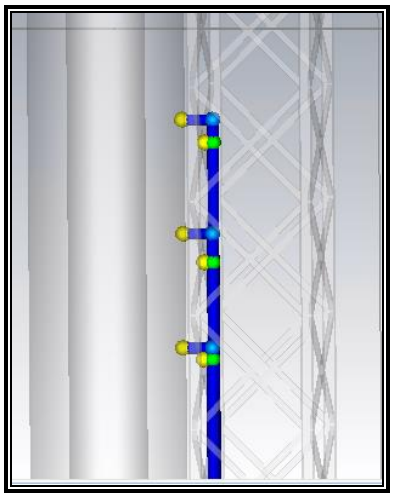


Fig. 4. Grounding Multiple Cables on Launch Tower

TABLE VI. LAUNCH TOWER S.E.

Current Reduction due to Launch Tower		
Configuration	***Current (A)***	***Current (dB Amps)***
With Tower	160 A	44 dB
Without Tower	177 A	45 dB
Difference	17 A	-1 dB

Table VI outlines the current difference based on the presence or absence of a launch tower. The S.E. calculated is insignificant at -1dB; calculations that do not include a launch tower will only be slightly conservative. It is not recommended to apply any reduction to equations (1), (2), or any model excluding the launch tower.

V. MEASURED DATA COMPARISONS

To add confidence in the CST results comparisons were made to currents coupled from a triggered lightning strike. Rocket-triggered lightning, described in [10], is an excellent validation example due to the well-defined magnitude and distance from the sample cable. In this case a 15kA strike was triggered 100m away from a 7m upright copper conductor. A current monitor on the conductor read a peak value of 7A during this triggered event. A similar model was created in CST using the specified magnitude, distance, and conductor. Fig 4 is the transient current induced on the conductor in the CST model also yielding a peak value of 8A.

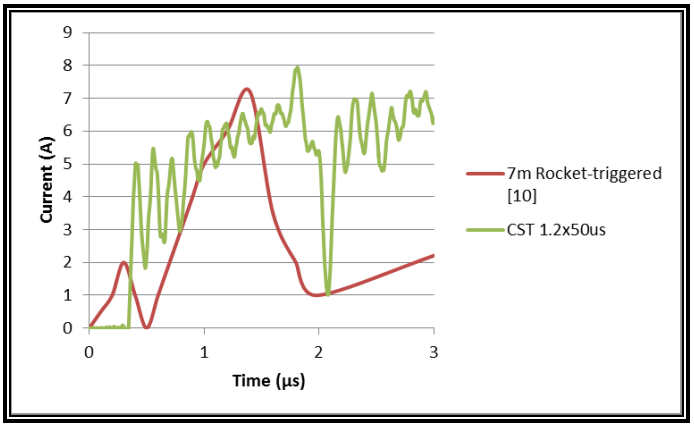


Fig. 5. Current on 7m Vertical Copper Conductor.

VI. CONCLUSIONS/ RECOMMENDATIONS

This study has shown some practical reductions and comparisons to simulated and measured results to support effective planning for launch readiness in the event of nearby lightning strikes. Applying the standard deviations in Table I can account for error in range reports without severely over predicting the coupled currents with an error stacking method. The basic coupling methods used today are shown to be a reasonable worst case bound for nearby strikes but over conservative at all distances when compared with CST models. The rise times are typically not known from range data so the standard 6.4 µs rise time is often used. Under that assumption, both (1) and (2) are conservative. Significant shielding effect was also shown for standard launch vehicle facilities and catenary systems allowing simple equations and models to account for complicated elements of the launch environment.

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