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CALCULATING THE LIGHTNING PROTECTION SYSTEM DOWNCONDUCTORS' GROUNDING RESISTANCE AT LAUNCH COMPLEX 39B, KENNEDY SPACE CENTER

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ABSTRACT

A new Lightning Protection System (LPS) was designed and built at Launch Complex 39B (LC39B), at the Kennedy Space Center (KSC), Florida, which consists of a catenary wire system (at a height of about 181 meters above ground level) supported by three insulators installed atop three towers in a triangular configuration. Nine downconductors (each about 250 meters long) are connected to the catenary wire system. Each downconductor is connected to a 7.62-meter-radius circular counterpoise conductor with six equally spaced, 6-meter-long vertical grounding rods. Grounding requirements at LC39B call for all underground and aboveground metallic piping, enclosures, raceways, and cable trays, within 7.62 meters of the counterpoise, to be bonded to the counterpoise, which results in a complex interconnected grounding system, given the many metallic piping, raceways, and cable trays that run in multiple directions around LC39B. The complexity of this grounding system makes the fall-of-potential method, which uses multiple metallic rods or stakes, unsuitable for measuring the grounding impedances of the downconductors. To calculate the grounding impedance of the downconductors, an Earth Ground Clamp (EGC) (a stakeless device for measuring grounding impedance) and an Alternative Transient Program (ATP) model of the LPS are used. The EGC is used to measure the loop impedance plus the grounding impedance of each downconductor, and the ATP model is used to calculate the loop impedance of each downconductor circuit. The grounding resistance of the downconductors is then calculated by subtracting the ATP-calculated loop impedances from the EGC measurements.

1 FLUKE 1630 EGC MEASUREMENTS

The FLUKE 1630 EGC works under the principle that in parallel/multi-grounded systems, the net resistance of all ground paths will be extremely low as compared to any single path (the one under test). So, the net resistance of all the parallel return resistances is effectively zero. The type of measurement done by the EGC is a "stakeless" measurement, and it only measures individual ground rod "resistances" in parallel to earth grounding systems, as stated by the manufacturer. If the ground system is not parallel to an earth grounding system, then you are measuring either an open circuit or a ground loop resistance.

The equivalent circuit of the grounding resistance measurement, given by the Ground Clamp manufacturer, is shown on Figure 1.

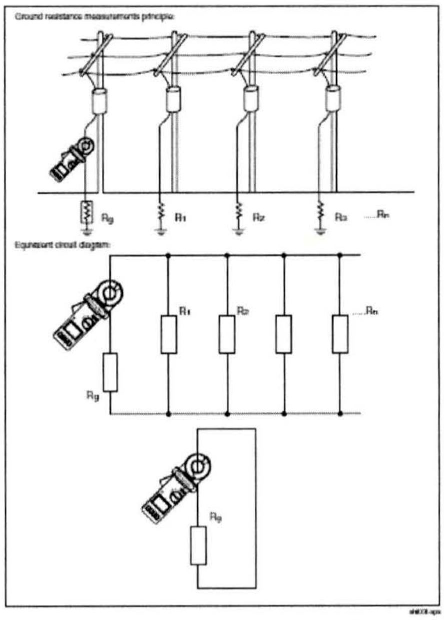

Figure 1 Ground Resistance Measurement Principle, adapted from the FLUKE 1630 user manual.

1.1 LC39B LPS's Downconductors Measurements

EGC measurements were performed at the LC39B LPS downconductor locations on different days and their corresponding values are shown on Table 1.

1.2 EGC Measurements Test

The EGC used to take the measurements shown on Table 1 was used in the laboratory to measure three different RL series circuits: A-Mostly resistive, B-Balanced resistive-inductive impedance, and C-Mostly inductive, to determine if the measured value (*ClampMeas*) was either the loop "resistance" or "impedance" of the circuit.

Table 1 LC39B LPS downconductors' grounding measurements using the EGC FLUKE 1630.

Down Conductor	*ClampMeas* [Ω]		
Number	08/27/2010	10/13/2010	12/02/2010
1	12.46	12.42	12.72
2	12.26	12.21	12.53
3	12.51	12.45	12.75
4	12.37	12.28	12.53
5	12.40	12.33	12.61
6	12.19	12.15	12.37
7	13.62	13.55	13.79
8	13.62	13.47	14.26
9	13.29	13.19	13.39[a]

[a] This measurement was taken on 11/23/2010

Table 2 shows the results of these tests and Figure 2 shows the electrical circuit and component values used to achieve the desired resistance and inductance values. The combination of resistor(s) and inductor(s) used for these cases were selected so that the magnitude of the resulting impedance was approximately 12.68 Ohms (the average of the EGC measurements from 08/27/2010 to 10/13/2010, see Table 1).

Additionally, a LeCroy waveRunner 104MXi oscilloscope was used to obtain the measuring frequency of the EGC. This was achieved by measuring the voltage across the resistor, the measured frequency was 3.3 KHz.

Since electrical impedance is represented by its magnitude and phase (Equation 1)

where R is the resistive and X is the reactive component of the impedance, respectively.

In the case of a RL circuit the reactance is only inductive (Equation 2)

where f = Frequency [Hz] and L = Inductance [H].

From the measurements shown in Table 2, it can be seen that the FLUKE 1630 EGC overestimates the loop impedance of the circuit by about 3% (when the RL test circuit was mostly resistive), by about 7% (when the RL test circuit was balanced), and by about 8% (when the RL test circuit was mostly inductive).

Table 2 RL test circuits measurements with the ECG FLUKE 1630

RL Nominal Circuit Elements			*ClampMeas*[b]	Calculations: $Z = \|Z\|\angle\phi$	
Resistance R [Ω]	Inductance L [μH]	Reactance[a] X [Ω]	$\|Z\|$ [Ω]	$\|Z\|$ [Ω]	ϕ [degrees]
12.4 (Fig. 3a)	100 (Fig. 3a)	2.0735	12.9	12.5722	9.49
8.125 (Fig. 3b)	470 (Fig. 3b)	9.7452	13.53	12.688	50.18
1.4691 (Fig. 3c)	603 (Fig. 3c)	12.5029	13.6	12.5889	83.29

[a] Reactance calculated using Eq. 3 and f = 3.3 KHz.

[b] Measured values from the EGC. After measurements were taken, the inductor was removed from the circuit, and the EGC measured 12.6 Ω, 8.18 Ω and 1.5 Ω.

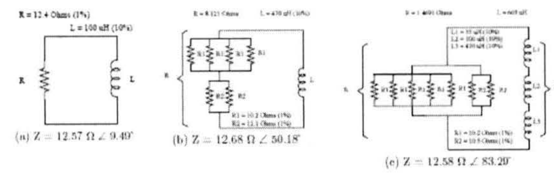

Figure 2 RL Measurements Equivalent Circuits

2 DOWNCONDUCTOR IMPEDANCE CALCULATION

An equivalent circuit for a grounded downconductor connected to the LPS catenary wire system at Pad B can be seen in Figure 3, where Rg is the grounding resistance, Zdc is the down conductor's loop impedance, and Zeq_dc is the equivalent impedance of the ground system connected in parallel to the down conductor under test, in this case the LPS catenary wire system and the remaining eight (8) downconductors. The difference between this equivalent circuit and the one shown on the Ground Clamp measurement principle (see Figure 1) is the presence of the down conductor's loop impedance in series with the grounding resistance. If we assume that all of the downconductor's loop impedances and their corresponding grounding resistances are similar, we can say that Zeq dc << Zdc + Rg. If this is true, then the EGC measurement principle still applies and the assumption that Zeq_dc ≈ 0 can be made.

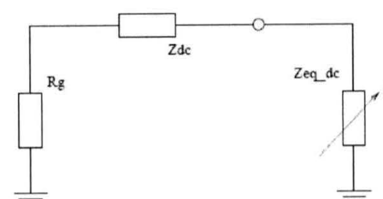

Figure 3 Ground resistance measurement equivalent circuit considering the downconductor's impedance

From the EGC laboratory test (see Table 2) it was verified that the EGC measures the impedance, which can be overestimated by as much as 8 %. If we try to use the EGC to measure the ground resistance at any downconductor, we would expect the EGC to measure the series of the grounding resistance and the down conductor's loop impedance (Rg + Zdc (see Figure 3)):

$$ClampMeas = Zg = Rg + Zdc \qquad (3)$$

Equation 3 gives us the relation between the values measured using the EGC (*ClampMeas*), the ground resistance Zg, and the downconductor's loop impedance.

2.1 Cable data

The cable used for the LC39B LPS downconductors is 6 × 19 Class, preformed 316 Stainless Steel wire rope. Table 3 shows the dimensions and lengths of each segment of cable used for each downconductor.

Table 3 Downconductor's dimensions

DC #	Diameter [inches]	Radius [cm]	Length [m]
1	$1\frac{1}{4}$	1.59	243.55
2	$1\frac{1}{4}$	1.59	245.13
3	$\frac{5}{8}$	0.7938	246.12
4	$\frac{5}{8}$	0.7938	244.25
5	$1\frac{1}{4}$	1.59	257.31
6	$1\frac{1}{4}$	1.59	251.05
7	$\frac{5}{8}$	0.7938	262.75
8	$1\frac{1}{4}$	1.59	264.98
9	$1\frac{1}{4}$	1.59	257.31

Figure 4 shows a plan view of the LPS identifying all the downconductor's location. The height of the towers plus the insulator (installed atop the tower which support the catenary wire system and one end of down conductors 1, 2, 5, 6, 8 and 9) is 596 feet [181 meters]. It is worth noting that the height of the down conductors 2, 3 and 7 is effectively less than that of the down conductors connected to the insulators (atop the towers) due to the sag of the catenary wire system. This difference in height is not considered here.

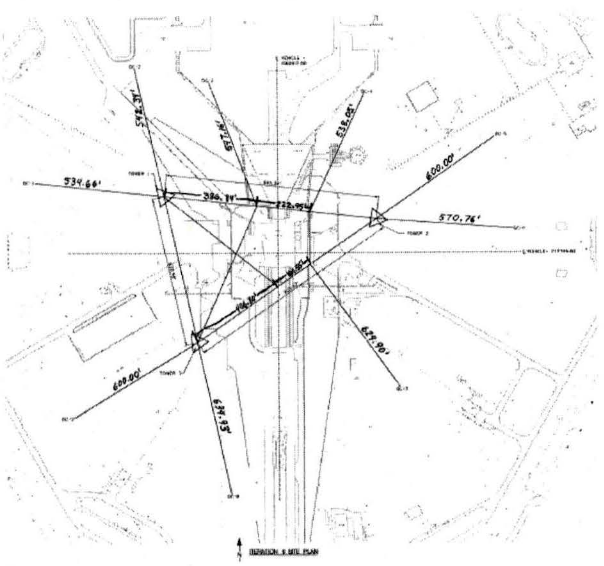

Figure 4 KSC Pad 39B Lightning Protection System (LPS) sketch identifying tower and downconductors

The resistivity of 316 Stainless Steel (ρ) 7.5E-7 Ω-meter.

The DC resistance of a cylindrical wire conductor of uniform cross section can be calculated using Equation 4

where: R = Resistance [Ω]; ρ = Resistivity [Ω- meter]; L = Length [meter], and r = radius [meter]. A = Cross sectional area, a cylindrical conductor, then $A = \pi r^2$.

Then with both values of radius for the down conductor cable (see Table 3) we can get the downconductor cable DC resistance per kilometer (required by the transmission line model of the ATP program) as shown in Equations 5 and 6.

Temperature dependence It has not being taken into consideration the fact that the specific resistance of a material may change with temperature. If this would be taken into consideration, then further calculations should be done using Equation 7.

$$R = R_{ref}\,[1 + \alpha(T - T_{ref})] \qquad (7)$$

where: R = Conductor resistance at temperature "T"; R_{ref} = Conductor resistance at reference temperature T_{ref} , usually 20°C, but sometimes 0°C; α = Temperature coefficient of resistance for the conductor material; T = Conductor temperature in degrees Celsius, and T_{ref} = Reference temperature that α is specified at for the conductor material.

2.2 ATP model

To calculate the down conductor's loop impedance an Alternative Transient Program (ATP) model was built where the downconductor is discretized in four sections. Each section is modeled with a single phase over-head transmission line (with no sag) and heights corresponding to 20, 40, 60 & 80% of the maximum height of the downconductor (181meters). All these sections are connected in series (single phase transmission line sections from lowest to highest height). Figure 4 shows a graphical description of the downconductor's model.

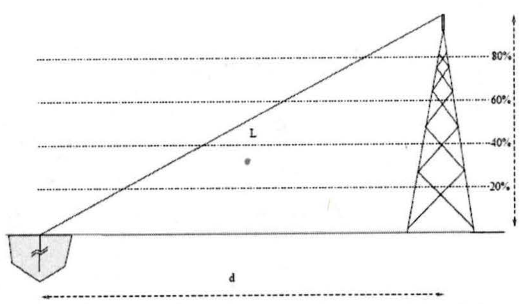

Figure 5 Model used to calculate the downconductor's loop impedance using ATP.

The ATP simulation for each downconductor has a single phase Alternating Current (AC) source (with the same frequency as the one used by the EGC, 3.3 KHz) connected to one end of the downconductor model (the one corresponding to the lowest height, 20% of the tower height) and the other end of this model (the one corresponding to the highest height, 80% of the tower height) connected to ground (see Figure 5). The downconductor loop impedance can be estimated (or calculated) by dividing the source's voltage by the current flowing through the system.

This ATP model (for each downconductor) uses the following components:

- Sources: Single Phase AC type 14 (AC1PH)
- Lines/Cables: Single Phase LCC PI model[1]
- Probes & 3-phase: Probe Volt and Probe Current

Figure 6 shows the above mentioned components as part of the downconductor 1 simulation (using the PI Model for the transmission line segment), also, a plot of the source voltage and system current is shown with the peak current value.

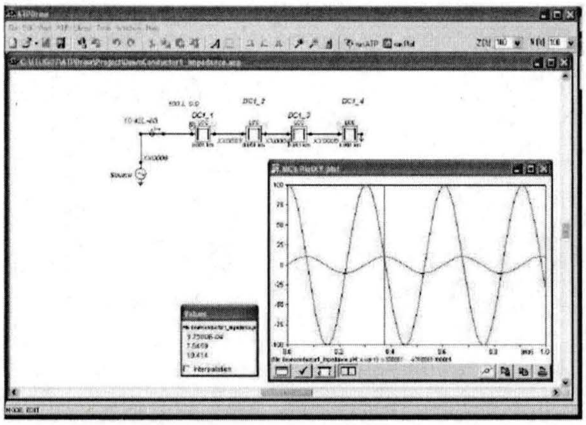

Figure 6 ATP model for downconductor 1. The transmission line sections (DC1_1, DC1_2, DC1_3 & DC1_4) correspond to the four different height levels (20%, 40%, 60% & 80%) respectively.

2.2.1 Single Downconductor Model

Since the EGC measurements (ClampMeas see Table 1) correspond to a grounding impedance (see Section 1.2), each downconductor's grounding resistance can be estimate from the EGC measurements and the calculated impedance (from the ATP model Zdc = Rdc + Xdc) see Equation 8

Equation 8 is solved for x by using MATLAB® function fzero (see Equation 9)

Results are shown in Table 4.

[1] A second simulation was also run using the Jmarti Line model, see results in Table 4.

Table 4 Ground Resistance R_g [Ω] obtained from the calculated downconductor impedance Z_{dc} [Ω] and the measured ground impedance *ClampMeas*, see Figure 3 and Eq. 9

DC #	PI model				JMarti model			
	$\|Z_{dc}\|$ [Ω]	$\Phi_{Z_{dc}}$ [Degrees]	R_g [Ω] Approx.[a]	R_g [Ω] Calc.[b]	$\|Z_{dc}\|$ [Ω]	$\Phi_{Z_{dc}}$ [Degrees]	R_g [Ω] Approx.[a]	R_g [Ω] Calc.[b]
1	9.7276	85	7.7862	6.9844	9.3371	86.5	8.2505	7.7002
2	9.7943	85	7.3742	6.5698	9.3985	86.5	7.8725	7.3196
3	10.6519	81.9	6.5603	5.2289	10.2543	85	7.1658	6.3277
4	10.5820	81.9	6.4061	5.0863	10.1926	85	7.0091	6.1768
5	10.2754	85	6.9409	6.1029	9.8619	86.5	7.5168	6.9388
6	10.0351	85	6.9204	6.1009	9.4967	86.5	7.6426	7.0848
7	11.3792	81.9	7.4846	6.0511	10.8932	84.9	8.1757	7.2645
8	10.5955	85	8.5581	7.6842	10.1709	86.5	9.0586	8.4589
9	10.2754	85	8.4286	7.5804	9.4967	87.2	9.2972	8.8448

[a] Assuming the calculated impedance is 100% inductive ($R_{dc} = 0$) then: $R_g = \sqrt{ClampMeas^2 - Z_{dc}^2}$

[b] Calculated using Equation 10

2.2.2 LPS Model

Based on the individual downconductor model presented on Section 2.2.1, now all the downconductors and the catenary wire system are modeled connected together (see Figure 7).

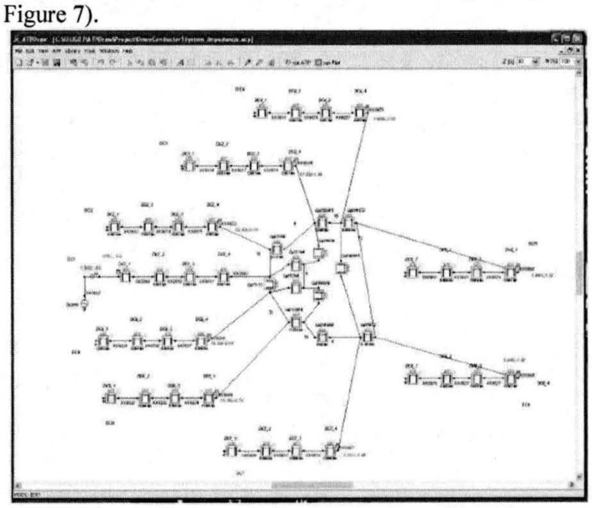

Figure 7 ATPDraw model for downconductor 1 impedance calculation with the full LPS.

All the individual downconductor models are integrated into the LPS model and connected to ground at the transmission line lowest height section (20% of the total height). The transmission line section with the highest height section (80% of the total height) is connected to the catenary model. To calculate the impedance for any downconductor, then the lowest height transmission line section of the downconductor model will be connected to the same source used for the individual downconductor models while the other downconductors are kept connected to ground (see Section 2.2.1).

The transmission line model used for the LPS's catenary wire system simulation is the same ATP PI model used for the individual downconductor simulations taking into consideration the following:

1) the catenary system uses a conductor of 1 inch in diameter, so the DC resistance (per kilometer) used in the model will be given by Equation 10.

2) the length of each catenary section (see Table 5) follows the distances shown on Figure 8.
3) the height of all the catenary sections will be the same (181 meters) and no sag will be considered.

Table 5 LPS catenary section's distances (see Figure 8)

From	To	Length [m]
T1	T3	189.7
T1	5	117.9
5	15	68
15	T2	84
T3	16	124
16	8	50.2
8	T2	101.4
T1	4	116.5
4	16	64.7
T3	4	121.4
4	5	66.5
15	8	67.5

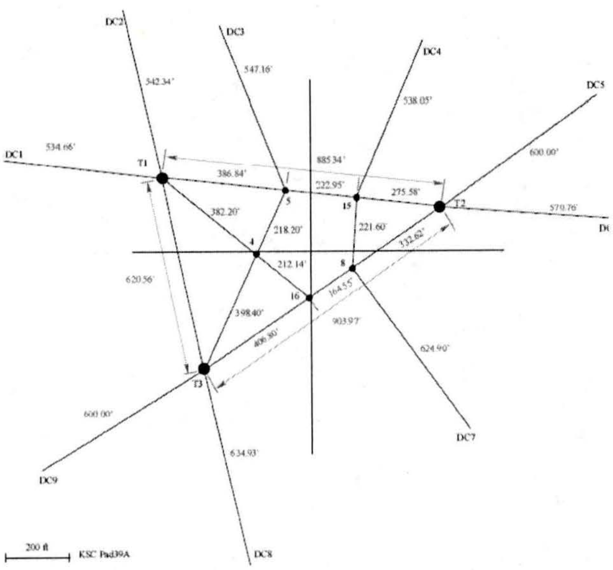

Figure 8 LPS components xy-plane distances. Note that the downconductors length should consider the height of the tower plus insulator mast.

Table 6 shows the calculated values of the downconductor impedance and the ground resistance (using Eq. 9) for two cases: individual downconductor models (see Section 2.2.1) and the whole LPS model. It is worth noting the similarity of both results, which validates the use of individual downconductor models for ground resistance calculation.

Table 6 Ground Resistance R_g [Ω] obtained from the calculated downconductor impedance Z_{dc} [Ω] and the measured ground impedance *ClampMeas*, see Figure 3 and Eq. 9 using the PI Transmission line model ATP and both simulations: individual downconductors and the whole system.

DC #	Individual down conductors				Full system			
	$\|Z_{dc}\|$ [Ω]	$\Phi_{Z_{dc}}$ [Degrees]	R_g [Ω] Approx.[a]	R_g [Ω] Calc.[b]	$\|Z_{dc}\|$ [Ω]	$\Phi_{Z_{dc}}$ [Degrees]	R_g [Ω] Approx.[a]	R_g [Ω] Calc.[b]
1	9.7276	85	7.7862	6.9844	9.7333	85.0526	7.7791	6.9848
2	9.7943	85	7.3742	6.5698	9.7953	85.0522	7.3729	6.5764
3	10.6519	81.9	6.5603	5.2289	10.6521	81.9004	6.5600	5.2287
4	10.5820	81.9	6.4061	5.0863	10.5820	81.9446	6.4060	5.0925
5	10.2754	85	6.9409	6.1029	10.2769	85.0032	6.9388	6.1011
6	10.0351	85	6.9204	6.1009	10.0354	85.0064	6.9200	6.1014
7	11.3792	81.9	7.4846	6.0511	11.3792	81.9446	7.4845	6.0579
8	10.5955	85	8.5581	7.6842	10.5954	85.0308	8.5581	7.6894
9	10.2754	85	8.4286	7.5804	10.2760	85.0320	8.4278	7.5847

[a] Assuming the calculated impedance is 100% inductive ($R_{dc} = 0$) then: $R_g = \sqrt{ClampMeas^2 - Z_{dc}^2}$

[b] Calculated using Equation 10

3 REFERENCES