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To: EDGES Group

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Subject: Theoretical approximations and simulations of a slot resonance in the ground plane.

A ground plane made of individual panels has the potential for the formation of capacitively loaded slots at the corrections between panels. A slot antenna is formed when a slot cut in the metal plate. The antenna is "dual" of the electric dipole. The "complementary" antennas have the following relationship of impedance.

$$Z_d Z_s = \eta^2 / 4 \text{ where}$$

$$Z_d = \text{ wire dipole antenna}$$

$$Z_s = \text{ slot antenna}$$

$$\eta = \sqrt{\mu_0 / \varepsilon_0} = \text{free space impedance} \approx 377 \text{ ohm}$$

Slot antennas have become very popular in recent years as they can be miniaturized to fit into cell phones. The slot antenna has the complementary polarization so that a slot that is perpendicular to the dipole has the same polarization and strongest mutual coupling with EDGES dipole. The impedance of a short wire dipole is approximately given by

$$Z_d \sim -j\eta Nk$$

Where N is the ratio of center frequency to a lower frequency of interest. k is a factor which depends on the length, L, to width, 2a, of the antenna or slot.

$$k \sim \left(2/\pi^2\right)\left(ln\left(L/2a\right)-1\right)$$

$$Z_s \sim j\eta/\left(4kN\right)$$

using the Babinet's principle. If the antenna panels joints are modeled as 2 parallel wires of radius a, separated by distance d. The capacitance per unit length is

$$\pi\varepsilon_0 \Big/ ln\left(d/2a + \sqrt{d^2/4a^2 - 1}\right)$$

For a frequency of 100 MHz and capacitance over a length of 20 cm.

$$N = \pi\varepsilon_0 \eta L 2\pi f \Big/ \left(4kln\left(d/2a + \sqrt{d^2/4a^2 - 1}\right)\right)$$

$$= 4 \text{ for L=0.2, } f = 10^8, d/2a \sim 1.01, k \sim 1$$

The capacitance of 39 pf per 20 cm length is augmented with the capacitance between the coplanar panel plates due to the electric field lines away from the gap. This amounts to about 20 pf per 20 cm.

In this case N could be higher than 10 which makes a 20 cm long gap (4 sections of 5×5 cm grid) resonate at 150 MHz or lower. A slot between panels at the edge of the ground plane can resonate as a "quarter wave slot" if the slot is open at the edge of the panel. This lowers the resonant frequency by a factor of 2 to 75 MHz for the same slot length and capacitance per unit length.

Modeling the overlapping panels with FEKO is limited by the ability to accurately model a close separation of the panels because a ratio of d/2a equal to 1% corresponds to a wire separation of only 30 microns. With wire separation of 1mm, which can be modeled, the lowest resonant frequency with 20 cm long gap is around 250 MHz. In the case of an open gap at the edge of the ground plane which forms a "quarter wave" slot a resonant frequency around 150 MHz is obtained. These simulations show that it is difficult to get a resonance below 100 MHz without very close contact between overlapping panels, or a gap longer than 20 cm. Based on FEKO models it is unlikely that a resonance as low as 70 MHz can be produced by the overlap unless a welded joint every fourth wire has failed which would result in a 40 cm long gap.

Additional simulations show that a non uniform slot can lead to a significantly lower resonant frequency. A very simple model of a non uniform slot is shown in Figure 1. In this case the FEKO results are approximately given by the resonance of an inductance ℓ and capacitance c in series

$$\ell = \frac{\mu_0 L_1 h_1}{w}$$

$$c = \frac{\varepsilon_0 L_2 w}{h_2}$$

Since the slot looks like a single turn solenoid with a parallel plate capacitor at the end.

In this case the resonant frequency is

$$f = (2\pi)^{-1}\left(\mu_0 \varepsilon_0 L_1 L_2 h_1/h_2\right)^{-1/2} MHz$$

$$\sim 48\left(h_2/h_1\right)^{1/2} \Big/ \left(L_1 L_2\right)^{1/2} MHz$$

The FEKO results are given in table 1.

Resonant frequency MHz	h1 cm	h2 cm	L1 cm	L2 cm
122	3.0	0.2	10	10
83	3.0	0.2	20	15
100	3.0	1.0	20	15

Table 1.

In each case the overlap was 10 cm. Increasing the overlap to 20 cm only reduced the resonant frequency from 83 to 72 MHz consistent with the simple expression above. While these simulations show a resonance at 70 MHz is possible it would need a long open slot or very close contact in the overlap region at the edge of the ground plane without reaching actual ohmic contact. A model of the antenna and the entire ground plane with the region of the slot is not practical although it can come close by using the FEKO "RM" card to decrease the mesh in the region of the slot. However even in this case I found it necessary to add a 10 pf load to the gap at the edge of the ground plane. The beam effects which result from a 20 cm slot length and 10 pf added capacitive loading are shown in Figures 2a and 2b for comparison with figures 1b and 2d of memo 208. While these simulations don't agree in detail with the low band data they do show similar trends. The observed resonance appears to move down from 72 MHz to 67 MHz in January/February when there is more moisture in the ground which suggests that the soils dielectric is involved in an increased capacitive loading. The simulations assumed a soil dielectric constant of 3.5 and conductivity of 2e-2 below the ground plane. The presence of soil in the overlap region would have the effect of additional capacitive loading.

Added information from simulations and tests made in March 2020

In looking into the design of a large 48x48m ground plane for EDGES-3 it was discovered that the zinc paint used after the welding between mesh panels is probably nonconductive and instead of filling the "slots" between the wires it could result in a thin dielectric layer in the 20 cm long slots.

Further analysis using

the analytic expressions for inductance per unit length

$$L = (\mu_0/(2\pi))\ln(((2d - a)/a)^2)$$

and capacitance per unit length

$$C = \pi\varepsilon_0/[\ln(d/(2a) + \sqrt{(d^2/(4a^2) - 1)})]$$

and the standard transmission line equations which treat the slot as a transmission line, of two parallel cylindrical wires of radius a meters and whose centers are d meters apart, driven from the center and shorted at each end. The results show that a resonance occurs at 80 MHz when the gap between the conductors is filled with a 2 micron thick dielectric with relative permittivity of 2.

It is unlikely that slots with this precise width will be formed. If there is evidence of a problem the slots could be soldered or additional welds added to reduce the distance between welds to 10 cm. Also, the ground screen could be scanned for resonances using with an antenna probe connected to a VNA.

This analysis has been checked with FEKO simulations with wire radius, a, equal 3 mm.. For example, with a 200 microns wide slot between the wires in air FEKO finds the slot resonance at 80 MHz with an added 236 pf capacitance across the center of the slot while the transmission line analysis requires 180 pf of added capacitance for a resonance at 80 MHz.

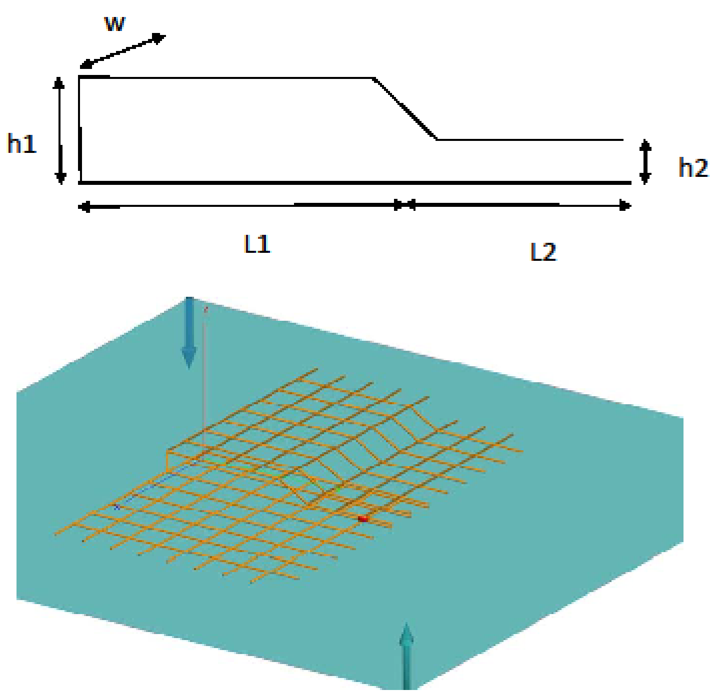

Figure 1. Model of an open slot at the edge of a ground plane. The resonant frequency can be significantly reduced if the panel separation in the overlap region is smaller near the edge.

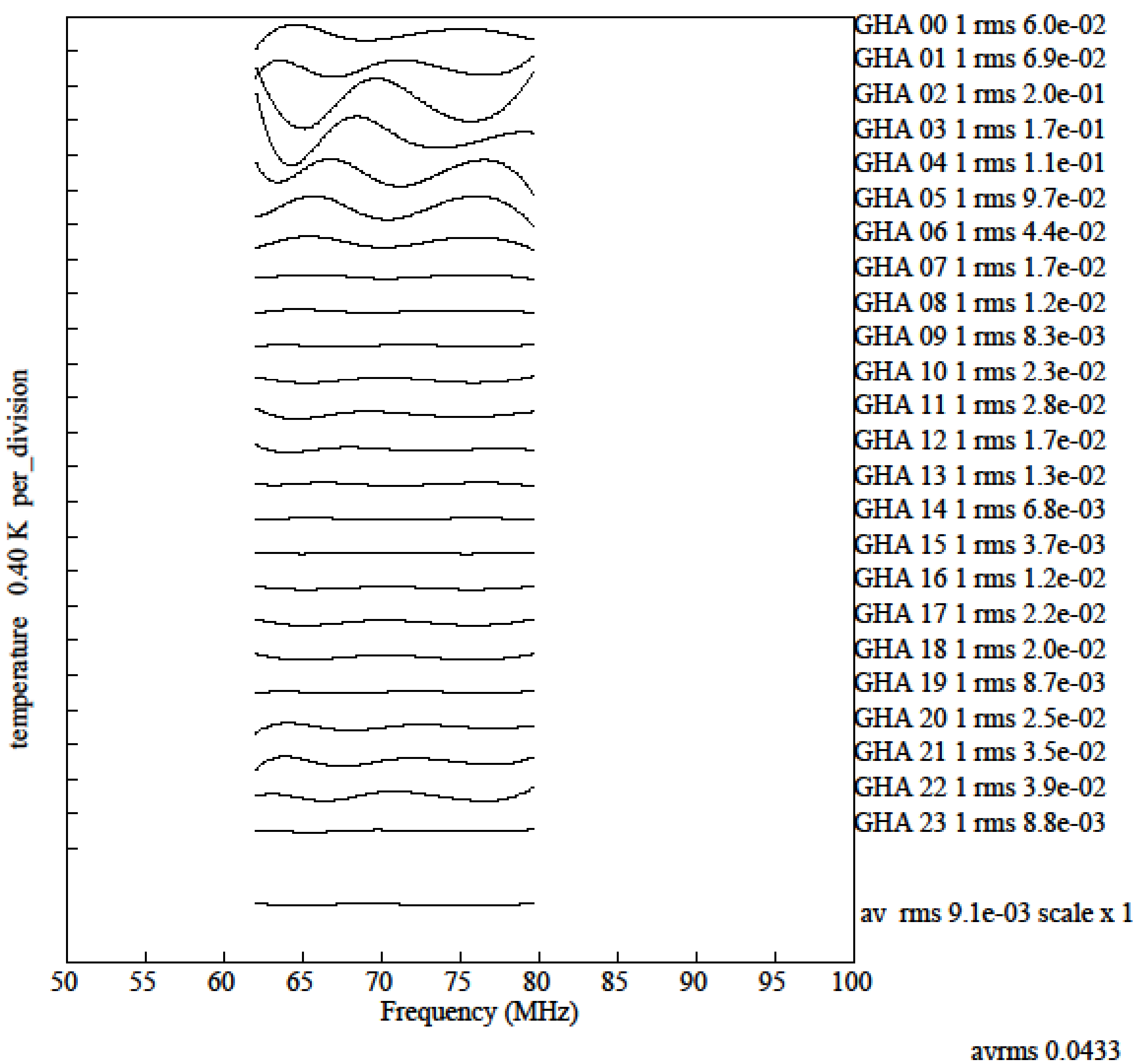

Figure 2a. Simulation of the residuals of the beam effects of the slot with 4-term polynomial fit.

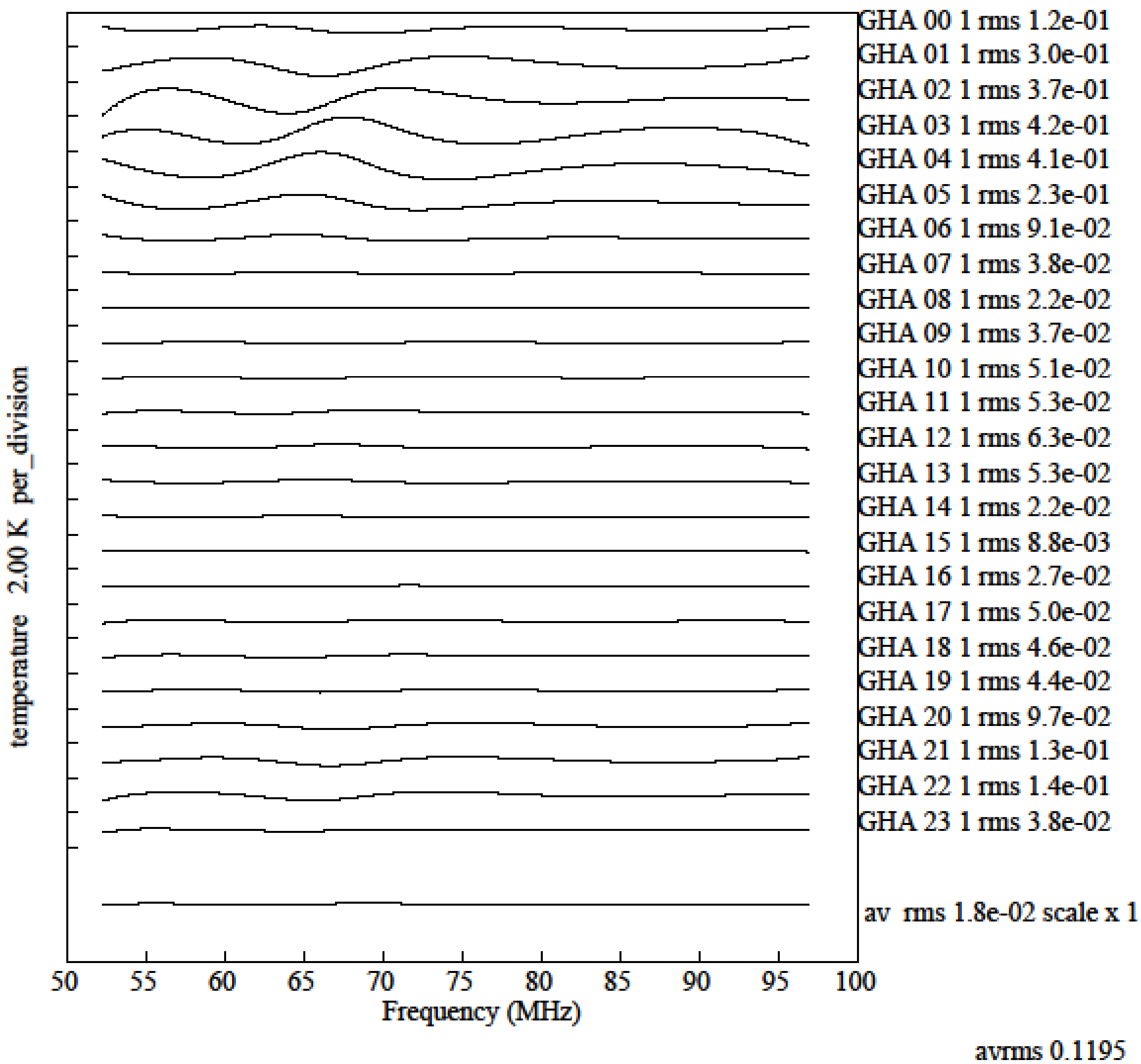

Figure 2b. Residuals to 5-term polynomial over wider frequency range.