A Transit Dish Design for High-Redshift 21cm Intensity Mapping Experiments

ABSTRACT

1. Introduction

- importance of frequency smoothness
- collecting area

2. Background

- τ-modes, wedge, EoR window
- geometric interpretation of τ-modes

3. Geometric Constraints

- first principles of EoR window, how that maps to a specification for design
- cost analysis
- critically constrained design
- symmetric on-axis parabaloid, for reasons of symmetry in polarization response

4. Design and Construction

4.1. bent pipes as approximation to parabola

The construction method is based on the use of a reasonably stiff spar supported at a few points as a low-pass spatial filter. Additionally, a moment-loaded beam naturally attains a parabolic shape, depending on the loading, the moment of intertia and the material's Young's modulus (see *e.g.* http://ruina.tam.cornell.edu/ Courses/ ME4730/ Rand4770 Vibrations/ BeamFormulas.pdf). In this instance we fix the angle at the rim (r_e) of 7m and at a hub radius (r_h) of about 45 cm, so between those two points, the effective angle is $(r_e - r_h)/(2F)$, where F is the focal length (4.5m). Equating that angle to the angle of the cantilevered beam (using scenario 5 of the web-site) we find

$$y = \left(\frac{r_e - r_h}{L}\right)\frac{x^2}{4F} \tag{1}$$

where L is the length of the beam. Assuming, $(r_e - r_h) \approx L$ (in this case, the ratio is 0.91) we find we have the equation for our desired parabola. Note that we do not contend that this figure over the entire length of the actual beam achieves this, but merely that if properly held and loaded it tends to the right shape.

In our construction, we hold the spar at three locations at the proper location and angle and then rely on the fairly stiff spar to "filter" out any higher frequency ripples and on the physics to give us the overall general shape.

4.2. faceting

The construction of the surface stretches mesh panels over adjacent spars, so the surface is not a true paraboloid but rather a faceted parabola, although note that the construction does pull down the mesh mid-panel to both better approximate a paraboloid as well as to hold the mesh.

If we assume an actual faceted parabola (*i.e.* the mesh if perfectly flat between adjacent spars) we can calculate the rms deviation from a paraboloid for various spar configurations. For this antenna, we chose 12 spars out to 1.45m, then transitioning to 24 spars. Choosing just 12 spars all the way out to the rim yields an rms of 6.9cm (corresponding to a Ruze loss of almost 18% at 150 MHz), as opposed to 1.7cm (for about 1 % loss).

4.3. shielding

The panels across the dish surface are made out of 6 different dimensions of galvanized wire cloth $\frac{1}{4}$"; employing different dimensions at different heights to reduce the surface bumps produced during installation.

4.4. splash cone

4.5. hub

The central hub has an overall diameter of 37", the inner sono tube has an interior diamater of 18", the outer sono tube has an interior diameter of 36". The launch angle of the spar sleeves is $+2.86°$ from the inner sono tube to the outer sono tube, the supporting sleeves (botton sleeves) do not have any launch angles.

4.6. feed suspension

The feed suspesnsion mechanism consists of a back plane made out of wire cloth and $\frac{3}{4}$" schedule 40 white PVCs bolted on a metal structure, and a mast from the metal structure connects the dipole feed to the back screen. The whole feed structure is suspended above the hub by attaching kevlar wires from the three telephone poles to the back of the metal structure.

Each telephone pole has a reel with kelvar ropes wrapped, adjustments to feed height can be made by cranking the reels.

4.7. material, PVC selection

The dish structure is made out of schedule 40, white PVCs to minimize the bending effect under sunlight exposure; PVCs are subject to thermal contraction and expansion with a linear thermal coefficient of $50.4 \times 10^{-6}\ \frac{m}{m^{\circ}C}$.

- bent pipes as approximation to parabola
- faceting
- shielding
- splash cone
- hub
- feed suspension (feed with mast, back screen by kevlar wire)
- materials, PVC selection
- design lifetime (wood, PVC)

5. Simulated Performance

5.1. Beam Pattern

- beam pattern
- delay performance (E-M modeling)

6. Fabrication and Deployment

- lessons/principles
- process to precision to specifications on precision

7. Reflectometry Test Setup

During the contruction process for the HERA prototype, we use Time Domain reflectometry(TDR) to measure the reflections on the dish as a function of time due to impedance mistmatch between the feed electronics and the sky signal. The feed characteristic impedance from the VNA and cable is 50 $\Omega \times 4$ (4:1 passive balun at each dipole) and that of the free space $120\pi\Omega$. Each polarization is fed into one port connected to the VNA which provides a frequency swept signal and inverse Fourier transform is then performed. In this prototype, the focal length is 4.5m, thus for 2 reflections, i.e. 4 crossings attenuation is 59.0ns in time domain.

7.1. Choice of Hardware

The dipole feed element consists of the PAPER feed, a mating board, one 4:1 passive balun for each polarization, 50Ω LMR400 cables of length 10m where the singal attenuation over 10m is $\sim$0.5dB at 150MHz. The cables are connected to the two ports of an Agilent VNA ES8753 for reflectometry measurements.

7.2. Calibration of VNA

Calibration is performed prior to taking measurements to eliminate the effects caused by cables and connectors. Performing calibration shifts the reference plane to the SMA connectors of the cables that are connecting the baluns with zero phase, zero loss and zero mistmatch, the measurements taken are showing only the effects of the feed and baluns under different configurations. The full two port calibration is done by attaching the calibration standards (Short, Open, Load, and Through) to the end of the 50Ω cables, the VNA calculates the correction coefficients by calibrating out at the calibration standards' impedances and applies the coefficients subsequently to each measurements.

7.3. Configurations

The measurements are taken with 401 data samples between 50MHz to 1000MHz, giving a time resolution of 1.05ns; each set of data is averaged by 16 measurements for higher SNR.

The feed height test is carried out at three different heights above the dish: 67", $10'3.5$", and $14'0.5$". See Delay Spectrum for Configurations under result section for images

The cone test is carried at height $14'6$", measurements with and without cone, 2 metal sheets covering the entrace to the dish, covering panel A, B.

7.4. Window Functions

To deal with real-life situations of a finite bandwidth which results in spectral leakage in time domain, the Kasier-Bessel window is applied to the frequency domain data prior to the inverse Fourier transform in order to increase the dynamic range of the measurements in time domain; the disadvantage however, is the widening of space between data points.

- reflectometry
- hardware
- calibration of the good
- feed height test
- configurations
- window function used in delay transform

8. Results

8.1. Delay Spectrum for Configurations

The VNA results:

results@ height 14' 6" Dish with and without cone, with screen covering panel A, B

======== dish different heights h1 = 67" h2 = 10'3.5" h3 = 14'0.5"

8.2. Cone test

show May 5th cone helped on reduce backlobe, see Figure 9

8.3. RFI investigation

Replacing the passive balun by the PAPER active balun and mating board, 75Ω cables are fed into the receiver, and the receiver outputs 50Ω through the LMR 400 cables to the Agilent E4407B spectrum analyzer. 401 points, 100MHz - 200MHz, average by xx measurements, sweep time is xx ms, bandwidth resolution is xx kHz.

What are the gains for the balun, the receiver?

VHF list, see bmail (FM 100-200MHZ), see if any matches

8.4. How well did we place everything

Resurvery the center for hub after telephone poles were stabilized in the ground. The telephone poles have varying diamater and along the length.

The surrounding posts are not equidistant to the center of the hub; within 5' between maximum post to center distance and minimum post to center distance.

- delay spectrum for configurations
- cost
- photos of constructed element
- XXX hook up receiver and to a sky test?
- measured parabolicity
- why were we right in the antenuation per reflection?
- does the cone help?
- how well did we place everything?
- ways to ensure spec in field
- mention extender as unnecessary in flat deployments

9. Conclusion

- relevance to HERA, project cost
- link Pober et al. (2014) sensitivity/science

- polarization matching
- frequency coverage, need for a feed re-design.

10. Acknowledgment

We would like to thank SKA-SA for the site infrastructure, maintenance, and observing support that has made this work possible, as well as the significant efforts of the staff at NRAO's Green Bank and Charlottesville sites. AP would like to thank M. McQuinn and A. Lidz for helpful discussions and ionization models. The PAPER project is supported by the National Science Foundation (awards 0804508, 1129258, and 1125558), and a generous grant from the Mt. Cuba Astronomical Association.

Fig. 1.— THIS FIGURE SHOWS THE ANALYSIS ON PARABOLA

Fig. 2.— THIS FIGURE SHOWS THE PHOTGRAMMRY ANALYSIS

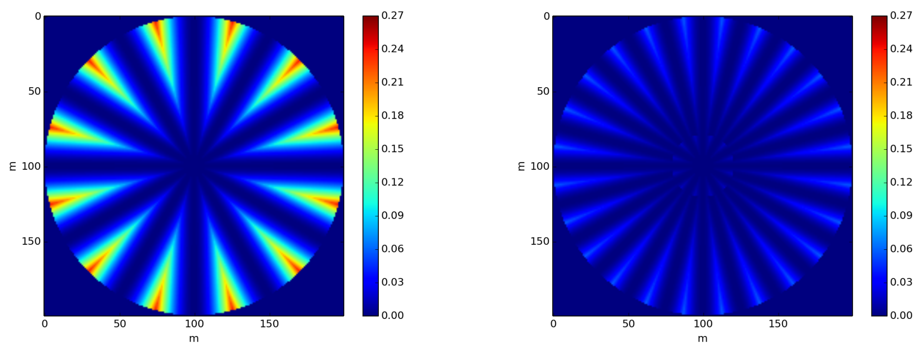

Fig. 3.— Contour plots of the facet deviations from a paraboloid for 12 spars (left) and the 12-to-24 spar design (right).

Fig. 4.— THIS FIGURE SHOWS THE SPLASH CONE STRUCTURE

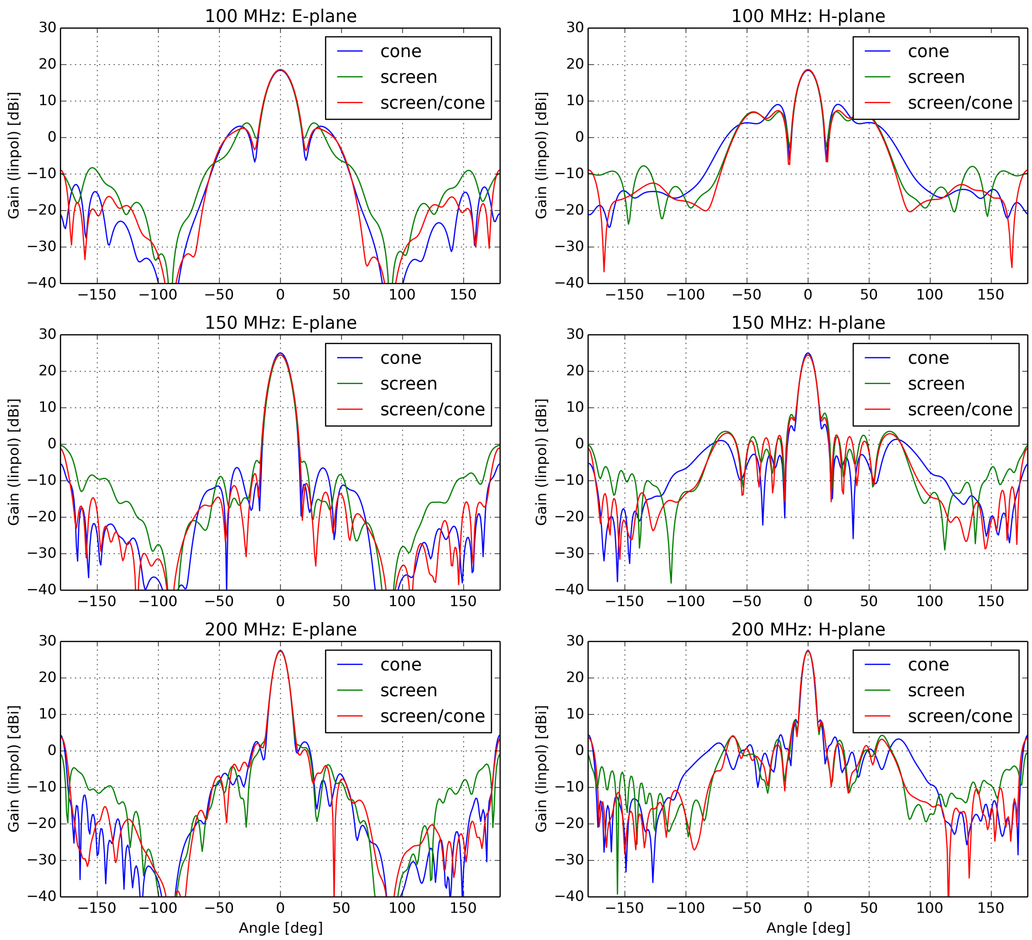

Fig. 5.— THIS FIGURE SHOWS THE BEAM PATTERN

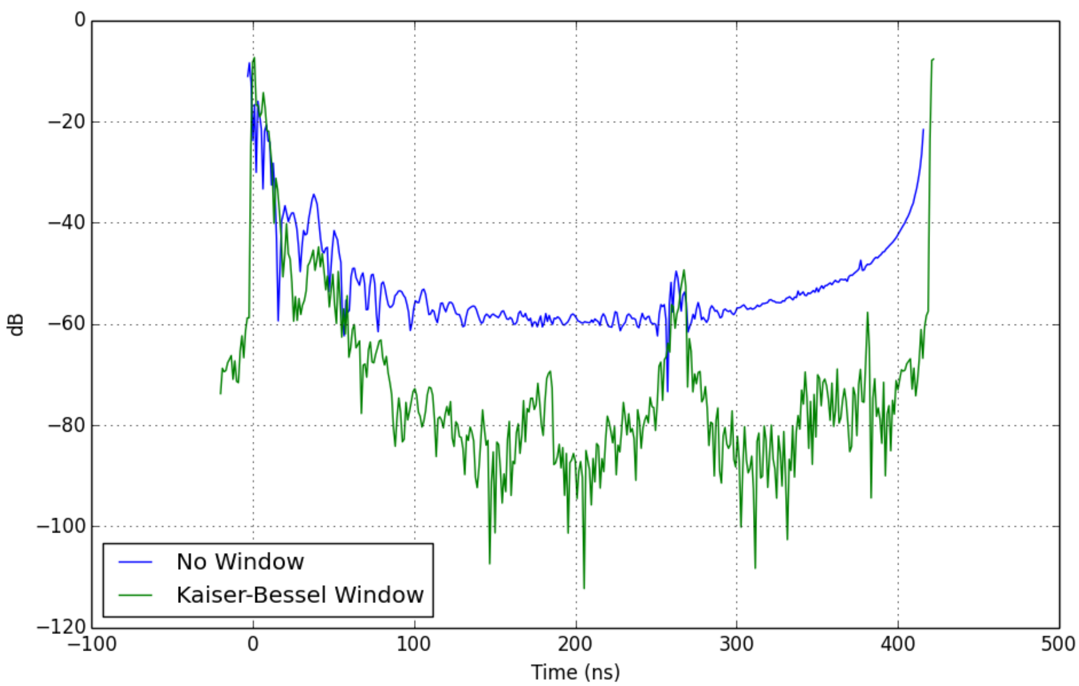

Fig. 6.— PUT FIGURE SHOW WINDOW in TIME domain, oplot with Kaiser - Bassel and without Kaiser Bessel (NA Time LOG VS FREQ IFFT without window)

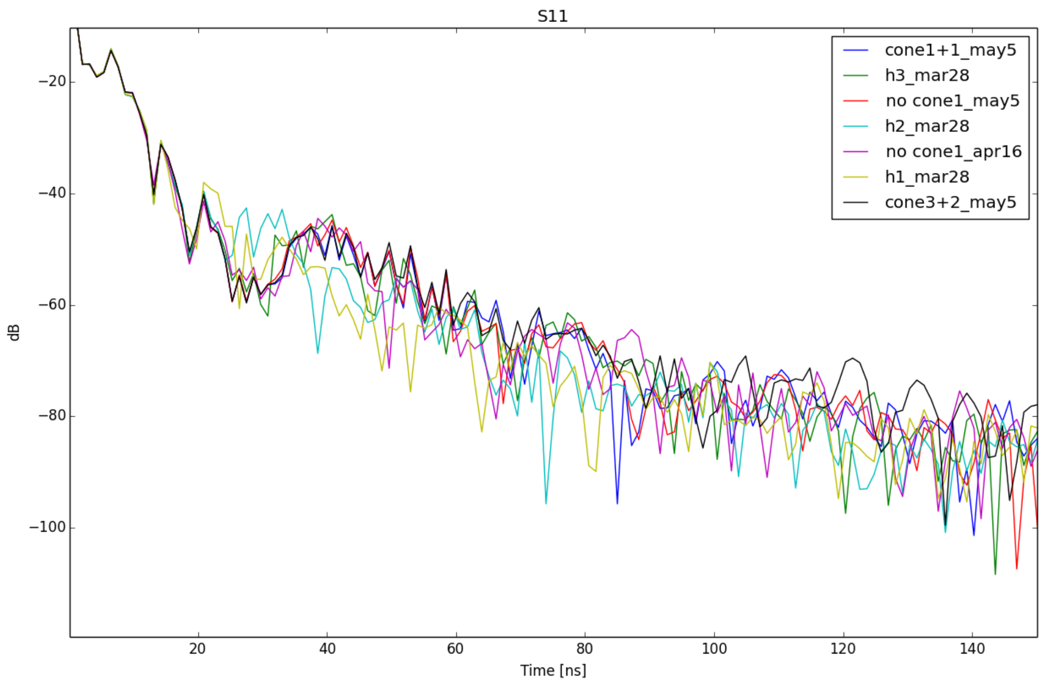

Fig. 7.— Shows height tests, cone test zoomed on 10-150ns, can see height test changed the delay, each configure is plotted on different plots below

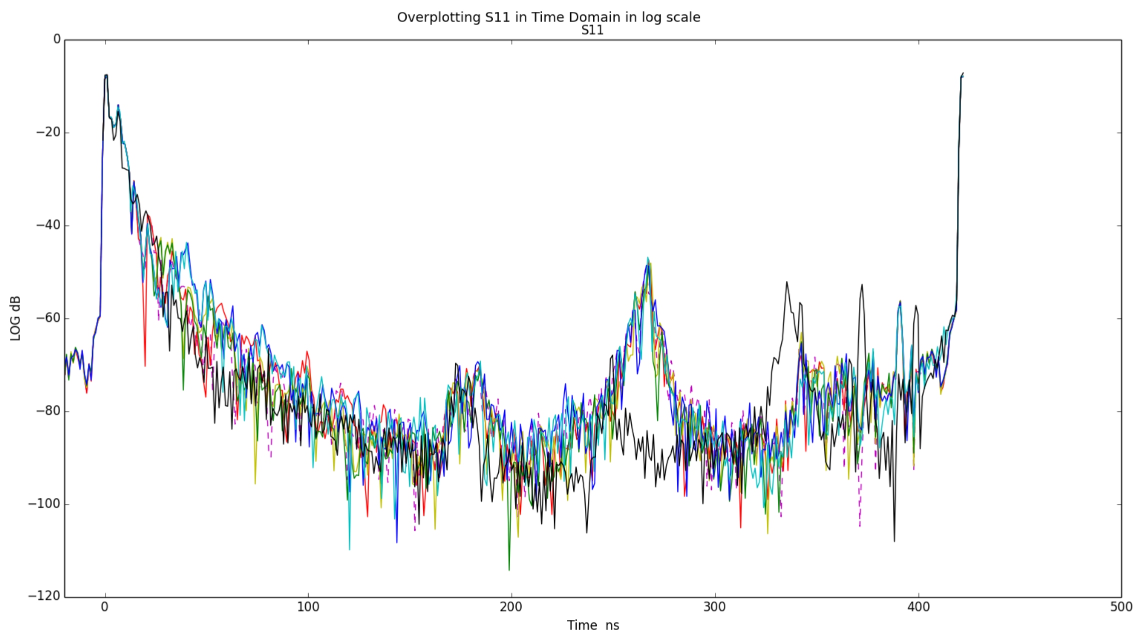

Fig. 8.— Shows height tests on dish, test not on dish, shows bump is reflection due to surroundings. mountain bumps 60' - 80'

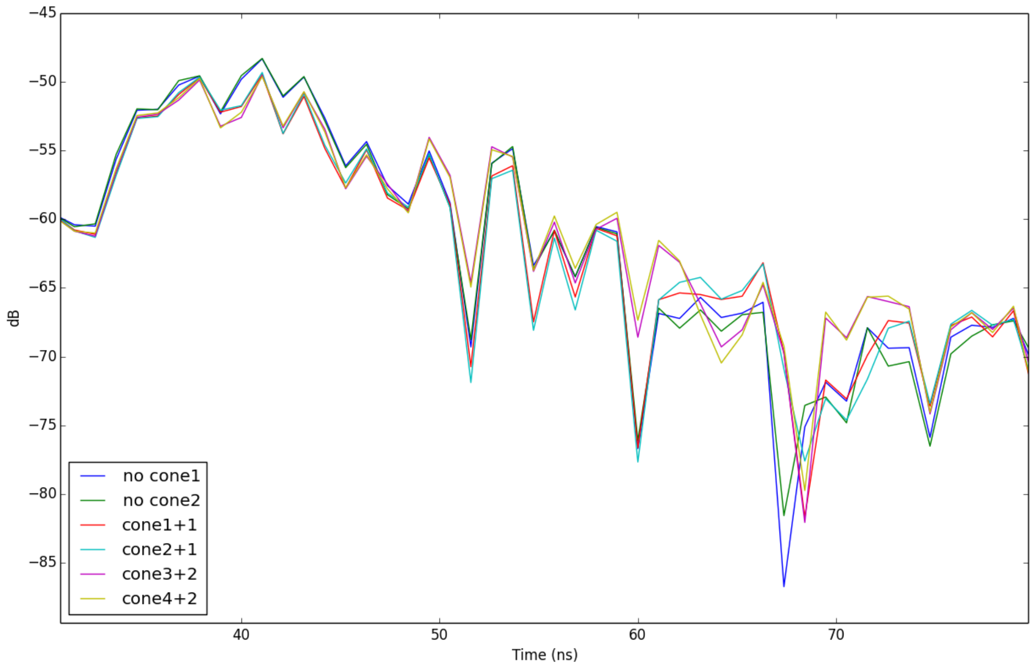

Fig. 9.— Shows cone VS no cone, combine 2 plots above, apparent difference cone make, but needs redesign for better backlobe minimization as seen from 45ns.

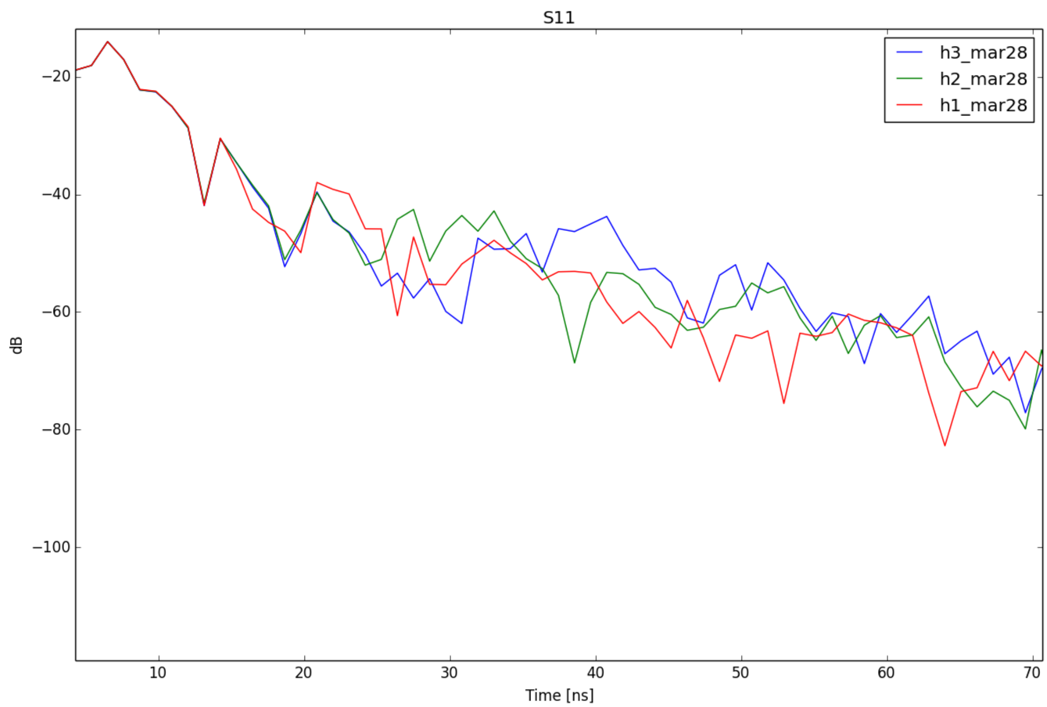

Fig. 10.— height test showing delay depending on feed height

Fig. 11.— SHOW SPECTRUm ANALYZER 100MHz - 200 MHz plot, radio stations, VHF showed up