Shape of LWA station: A study of the synthesized beam shapes and weighting scheme

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Abstract

The LWA is a tracking aperture synthesis telescope composed of a number of aperture array stations. Each station is composed of 256 dipoles and the celestial source will be tracked by phasing these dipoles for the desired direction in the sky. Away from the local zenith, the shape of the station beam is determined by the projected shape of the distribution of the dipoles at each station. Consequently, as the stations track a fixed astronomical co-ordinate, the station beam shape changes continuously as a function of time. A time-variable beam-forming weighting scheme can be used to minimize the variations in the station beam at the cost of loss of sensitivity. In this memo we present results from the simulations to determine the variation in sensitivity and beam shape as a function of time for two proposed shapes for LWA stations: (1) circular and (2) elliptical.

1 Overview

The LWA is composed of a number of aperture-array stations with phased-array beam forming hardware and software at each station to form and steer the station beam in the desired direction in the sky. Since the station beam is a Fourier Transform of the project shape of the station towards the tracking direction, the shape of the beam as well as the sensitivity in the main lobe of the beam varies as a function Hour Angle (HA) and Declination. Away from the local-zenith at each station, the main-lobe of the beam becomes elongated. There is also significant variation in the near side-lobes of the power pattern, which is also an important consideration given the frequency at which LWA will operate. This variation of the beam shape as a function HA is shown in Fig.1.

Imaging with aperture synthesis telescopes like the LWA requires deconvolution of the telescope Point Spread Function (PSF) from the raw image. This is a non-linear operation and the final imaging performance depends on the accuracy of the model of the station beam as a function of time (Bhatnagar, 2008). The computing load for image deconvolution also depends on the rate of change of the shape of the station beam. It is therefore important to determine an optimal shape for the station and beam-forming weighting scheme that minimizes the temporal variations in the beam shape. Due to inevitable geometrical projection effect, the sensitivity of the main-lobe of the station beam varies with declination and HA irrespective of the station shape. Since this change in sensitivity is fundamental to tracking with aperture-array stations, it is useful to explore beam-forming weighting schemes that minimize variations in the station beam shape.

In this memo, via simulations, we did detailed comparisons between the shape of the all-sky station beams as a function of HA and declination for two proposed shapes for the distribution of the dipoles at each LWA stations: (1) circular and (2) elliptical. The circular station we used has radius of 50 m with 4m dipole spacing (Kogan & Cohen, 2005) while the major and minor axis of the elliptical station were 110m and 92m with 4m dipole spacing respectively with the position angle in the north-south direction (Kogan, 2008). For each of these station shapes, a beam-forming weighting scheme was also used which minimize the variations in the beam shape with time (HA). The results were compared with those obtained without a beam-forming weighting scheme. The radiation pattern for the Big Blade LWA dipole with 3m x 3m ground screen calculated with NEC4 software (Paravastu, in prep) was used.

2 A weighting scheme for station beam forming

As shown in Fig.1, the station beam changes while tracking a target direction because the projected area of the station varies. The projected area of physically circular station is circular only for the local-zenith direction and becomes elliptical away from this direction. Consequently the resultant station beam also is circularly symmetric only for the local-zenith direction. The ellipticity of the beam depends on the elevation of a target direction and the position angle of the beam ellipse is along the line of the longitude which, of course, varies as one tracks a fixed direction astronomical co-ordinate. In order to keep the beam shape (the main-lobe as well as the side-lobes) stable, and the main-lobe of the beam circular, we devised a weighting scheme which corresponds to an aperture plane tapering such that project area of the station is circular as a function of elevation. The radius of the major axis of the projected area is determined by $rsin\delta_{el}$, where r is the radius of the major axis of the ellipse and δ_{el} is the elevation of the target direction (Fig.2). Fig.3 and Fig.4 show simulated station beams when tracking from -30° to 0° in HA (-2^h to 0^h) and from -70° to 0° (-4.7^h to 0^h). For the beams shown in Fig.4, the projected radius is $r_{-70^\circ} \sin \delta_{el_{-70^\circ}}$ [1], as the radii of a major axis of an effective elliptical

[1] $\delta_{el_{-70^\circ}}$ is the elevation at the hour angle of -70° (-4.7^h).

area in a station are fixed as follows.

$$r_{x^\circ} = \frac{r_{-70^\circ} \sin \delta_{el_{-70^\circ}}}{\sin \delta_{el_{x^\circ}}} \qquad (-70^\circ < x < 0^\circ)$$

Note that it is important to keep r_{-70° as the maximum allowed length [2] , as shown in the Fig.4 for beam corresponding -70° (-4.7^h). The fixed-projected radius has to be the one at the lowest observing elevation of interest. For the simulations presented here, this was $\sim 27.5m$ ($r_{-70^\circ} = 50m$, $\delta_{el_{-70^\circ}} = 33.4^\circ$).

3 Results

3.1 FOV (HPBW)

As explained in Section 2, a radius of a fixed-projected area is determined by $r \sin \delta_{el}$ of the lowest observing elevation in the tracking range, which decides the FOV of the beam. As known by comparison between Fig.3 and Fig.4, the FOV in Fig.4 is approximately two times bigger than the one in Fig.3, due to the difference of the fixed-projected area size.

3.2 Relative Directive Sensitivity

The simulation results of the relative directive sensitivity [3] are shown in Figs.5-10. The sensitivity of the station also was approximately flat after applying the tapering to keep the beam shape constant, compared to the one without the tapering as shown by the continuous red curve. This was a surprising result indeed which can be understood intuitively as follows. As shown in Fig.4, at low elevations (hour angle -70deg), the attenuation of the cosmic signal by the dipole beams is significant though more dipoles are used, and at high elevations (hour angle 0deg) the signal is received by near the beam center though the number of the used dipoles is smaller. As a result, the sensitivities become more or less flat. From the summary figure (Fig.11), the sensitivity of the circular station becomes better than that of the elliptical one as the observing declination draws nearer to 34°. At the declination of 34°, the sensitivity of circular station is up to approximately 20% better than the elliptical. Around the declination of 0°, both sensitivities are almost same. The elliptical station is approximately 10% better than the circular one at around -26°.

4 Conclusion

With tapering scheme at mid-latitudes, the sensitivity of the circular is up to approximately 20% better, but at northern and southern declinations, the

[2] In the case of a 100m circular station, the maximum length is 50m.

[3] The relative directive sensitivity is defined as $\frac{n}{256} \frac{D(\vec{s})}{D(\vec{z})}$, where D is the directive gain, the vector $\vec{s}$ points at the phased beam direction, $\vec{z}$ points at the zenith, and n is the number of the used dipoles.

elliptical has up to better sensitivity ($\sim$10%). The tapering scheme used in this paper is only representative of the technique available to improve imaging performance of LWA. It is not claimed or concluded here that the weighting scheme shown here is optimal in anyway (though this scheme may be optimal for some cases). The weighting is in the online software for the LWA stations not in the hardware. Hence the weights can be changed in the future depending upon the available computing and scientific requirements. We also note that an overall comparison of stations must take into account scientific drivers (e.g. Galactic, solar, and ionospheric science) as well as available sky area, both of which could affect how much weight is given to various declination ranges.

References

[1] Bhatnagar, S.; Cornwell, T. J.; Golap, K.; Uson, J. M. Astronomy and Astrophysics, Volume 487, Issue 1, 2008, pp.419-429

[2] L. Kogan, A. Cohen, and E. Polisensky, "Elliptical LWA Station Configurations Optimized to Minimize Side Lobes", Long Wavelength Array Memo #139 June 24, 2008.

[3] L. Kogan and A. Cohen, "Optimization of the LWA Antenna Station Configuration Minimizing Side Lobes" #21 May 2005,

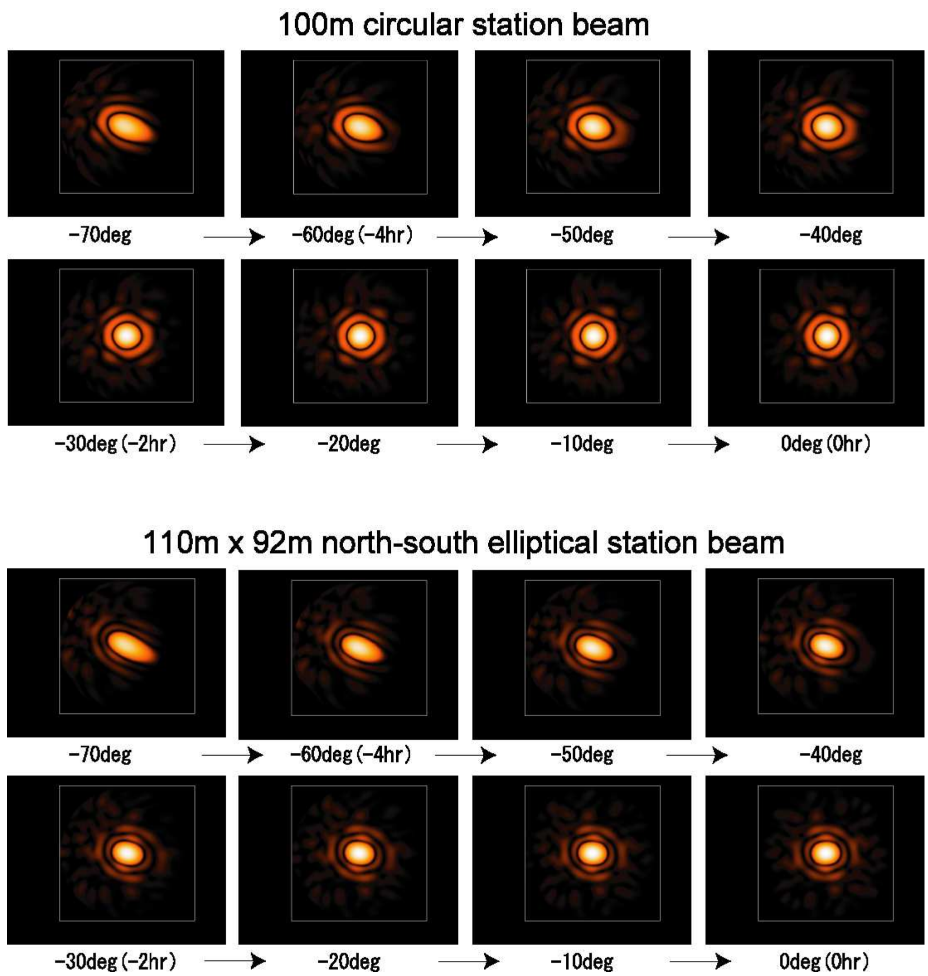

Figure 1: Above shows variations of a circular (top) and elliptical (bottom) station phased beam at 20MHz when tracking in the HA range from $-70°$ to $0°$ (-4.7^h to 0^h) at $\delta_{dec} = 34°$. The simulation was performed using the station located at the latitude of $\sim 34°$.

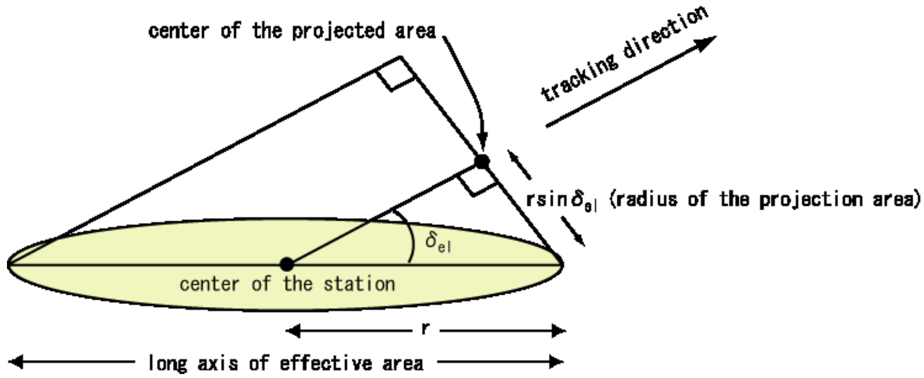

Figure 2: Above shows relations for a tracking direction, projected area, and effective area.

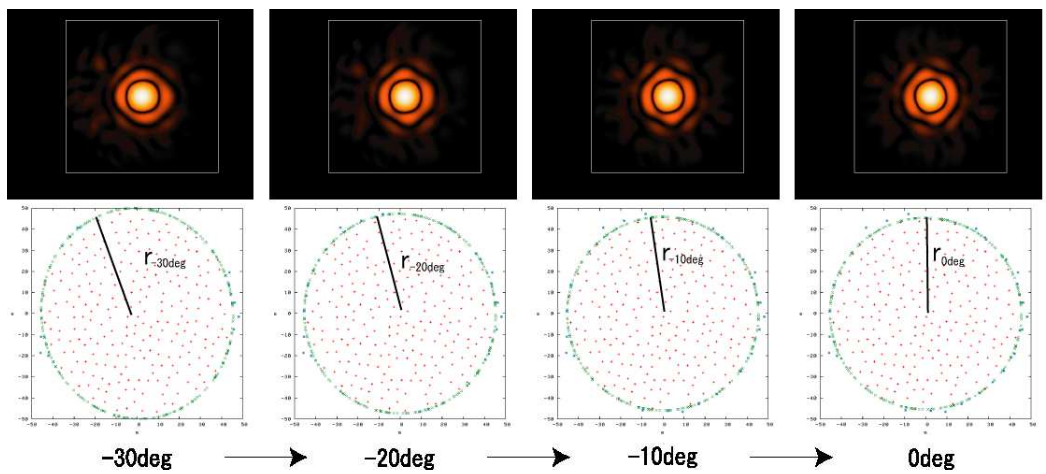

Figure 3: Above shows station phased beams at 20MHz produced by cutting out some dipoles (the blue dots) in a 100m circular station area. The beams are shown when tracking from $-30°$ to $0°$ in hour angles (-2^h to 0^h) at $\delta_{dec} = 34°$ (declination) with a possible core station located at the latitude of approximately 34°. Each dot in the bottom graphs shows the location of the dipoles. The red dots within a green line are the effective dipoles. The blue dots outside of the green line means the ineffective ones. Compared to the station beam from $-30°$ to $0°$ in Fig.1 using a whole area of a 100m circular station, the beams in this figure are a constant circular shape, though the sensitivities are lower (approximately 88 %).

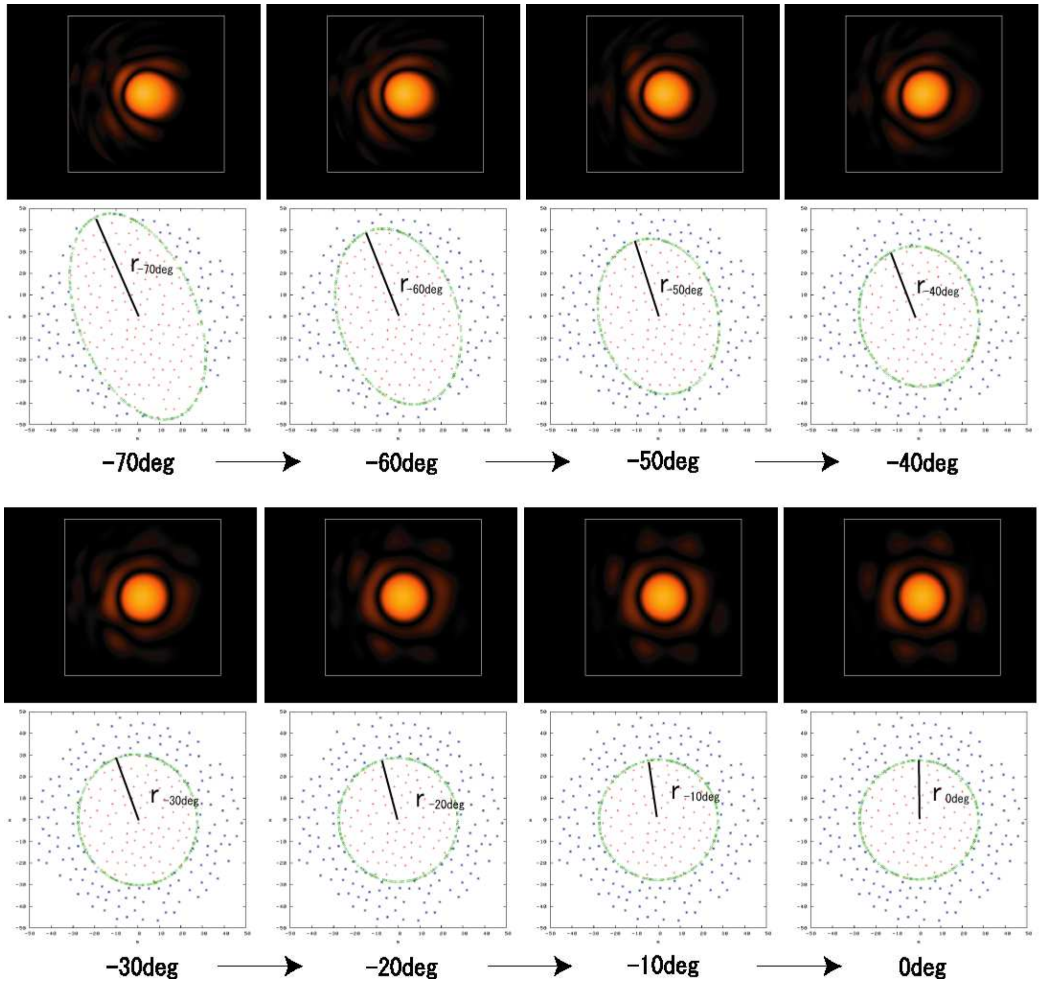

Figure 4: Above shows station phased beams at 20MHz produced by using dipoles within the green curve in a 100m circular station area. The beams are shown when tracking from $-70°$ to $0°$ in hour angles (-4.7^h to 0^h) at $\delta_{dec} = 34°$ (declination) with the core station located at the latitude of approximately 34°. Each dot in the bottom panel below the beams shows the location of the dipoles. The red dots within a green line is the effective dipoles. r_{deg} is the radius of the major axis. Compared to the station beam from $-30°$ to $0°$ in Fig.1 using a whole area of a 100m circular station, the beams in this figure are a constant circular shape, though the sensitivities are much lower ($\sim 32\%$).

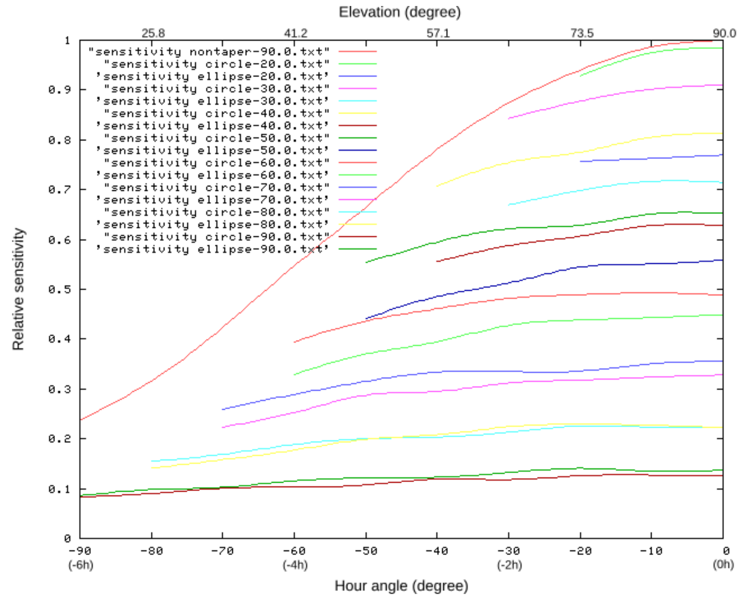

Figure 5: A Comparison of the sensitivities at 20MHz at the declination of 34° with the beams of a 100m circular tapered station, 110m × 92m elliptical tapered station and no tapered station (the red long steep line).

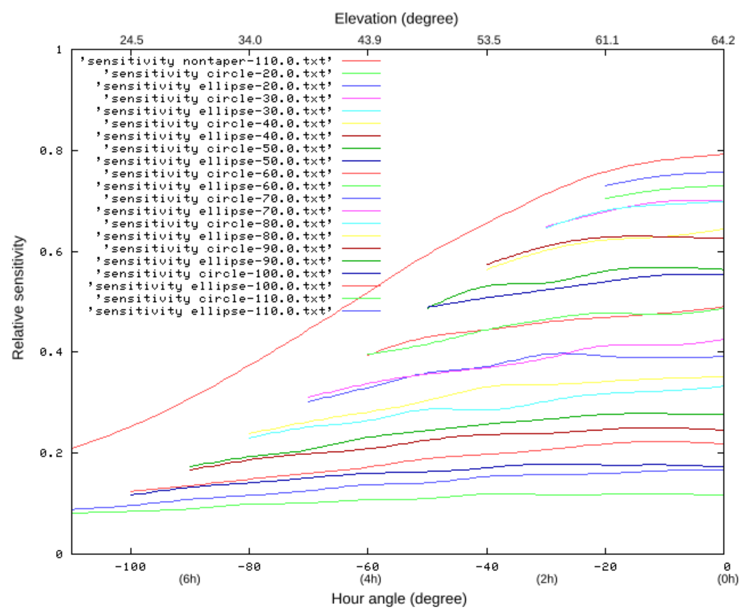

Figure 6: Above plot as in Fig.5, but for $\delta_{dec} = 60°$.

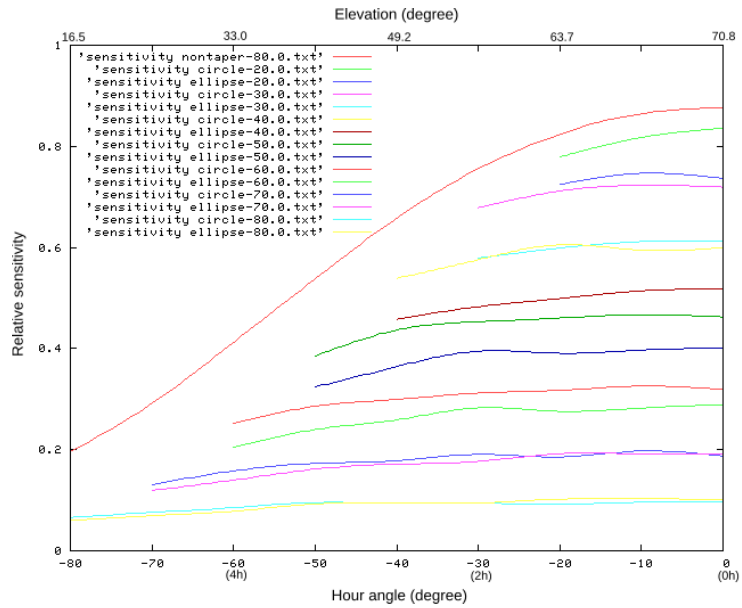

Figure 7: Plot as in Fig.5, but for $\delta_{dec} = 15°$.

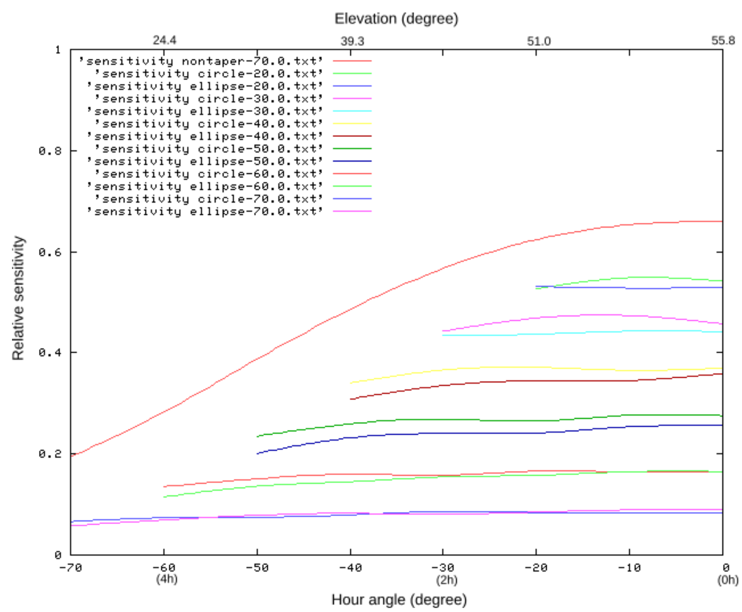

Figure 8: Plot as in Fig.5, but for $\delta_{dec} = 0°$.

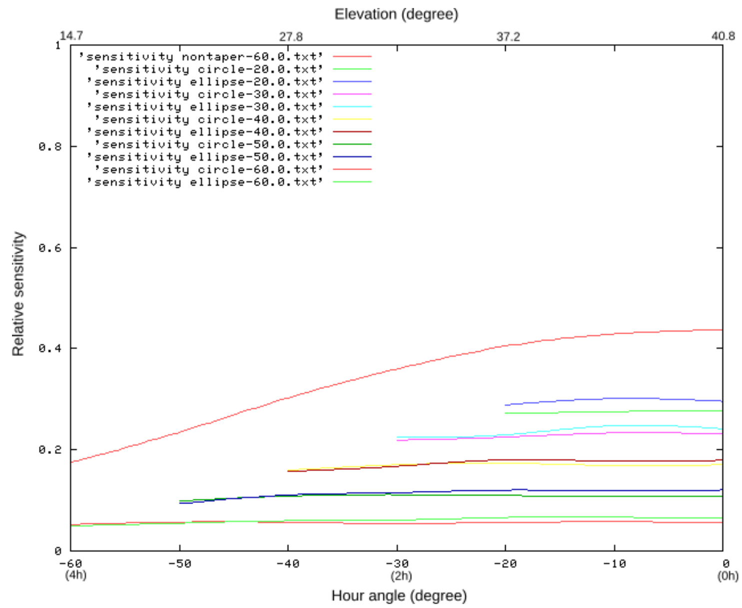

Figure 9: Plot as in Fig.5, but for $\delta_{dec} = -15°$.

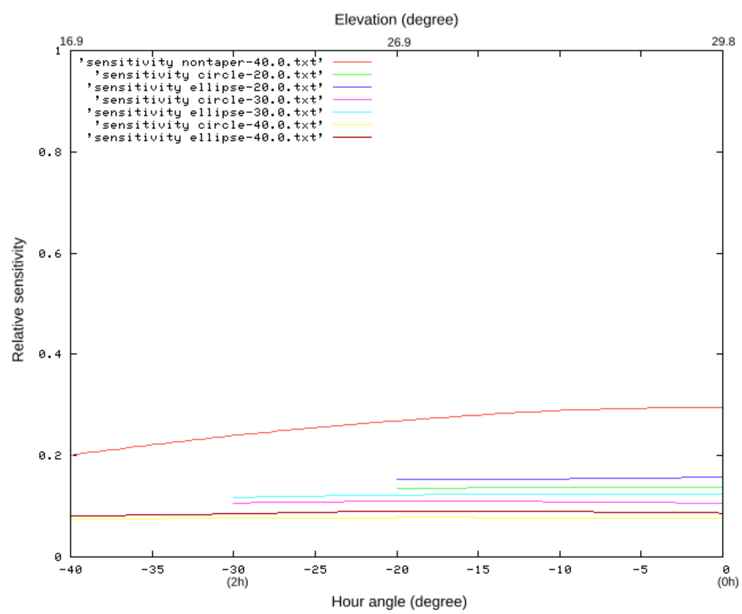

Figure 10: Plot as in Fig.5, but for $\delta_{dec} = -26°$.

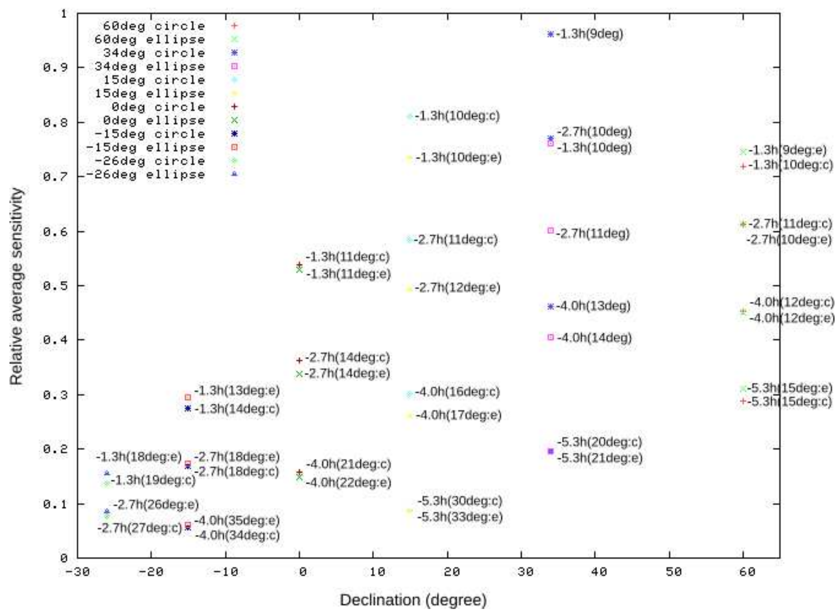

Figure 11: Summary of the averaged direction sensitivities and HPBW at the observing frequency of 20MHz. Each number, such as -1.3h, -2.7h, shows a tracking start hour angle. For example, a -1.3h means tracking from -1.3h to 0h.