Science drivers for W-band in the EVLA Phase II

Claire J. Chandler

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This memo seaks to answer the question of whether the imaging of circumstellar dust disks will be a good science driver for including 86 GHz (W-band) receivers in the New Mexico Array. Certainly, the resolution provided by a W-band system on baselines of 100 km or more is extremely exciting for studies of planetary system formation in the nearest star forming clouds — a few milliarcsec is < 1 AU in Taurus. Whether W-band will be a better choice for such studies compared with 43 GHz (Q-band) depends on the relative brightness temperatures of the dust emission from the disks at these two frequencies, and the relative surface brightness sensitivities of the instrument.

I assume that the surfaces of the existing VLA antennas will not be good enough to contribute any significant effective collecting area at W-band, and compare the relative surface brightness sensitivities of only the PT and LA VLBA antennas and 8 new 25-m antennas at Q and W-band, assuming the VLBA and the new antennas have comparable aperture efficiencies. Note that this will underestimate the surface brightness sensitivity of the New Mexico Array at Q-band compared with W-band, since the VLA is not included. The number of antennas is the same at each frequency in this analysis, so the rms brightness temperature, $T_{\rm rms}$, depends only on the relative values of the system temperatures, $T_{\rm sys}$, beam efficiencies, η, and the amount of integration time spent on source, t. The maximum bandwidth for continuum observations is assumed to be determined by the correlator, and so is the same at both frequencies. Thus,

$$T_{\rm rms} \propto \frac{T_{\rm sys}}{\eta\sqrt{t}}.$$

The brightness temperature of the dust emission depends on the dust opacity, which is a power-law function of frequency, so that $T_{\rm B} \propto T_{\rm dust}\nu^{\beta}$, where $0 \leq \beta \leq 2$. The ratio of the required sensitivities at Q and W-band is therefore

$$\frac{T_{\rm rms,W}}{T_{\rm rms,Q}} = \left(\frac{\nu_{\rm W}}{\nu_{\rm Q}}\right)^{\beta}$$

and for measurements of equal signal-to-noise ratio at both frequencies the relative on-source observing time needed is

$$\frac{t_{\rm W}}{t_{\rm Q}} = \left(\frac{T_{\rm sys,W}}{T_{\rm sys,Q}}\right)^2 \left(\frac{\eta_{\rm Q}}{\eta_{\rm W}}\right)^2 \left(\frac{\nu_{\rm Q}}{\nu_{\rm W}}\right)^{2\beta}.$$

Using the optimistic estimates $(T_{\rm sys,W}/T_{\rm sys,Q}) \sim 2$, $(\eta_{\rm Q}/\eta_{\rm W}) \sim 4$, and the most optimistic case for the dust opacity, $\beta = 2$, we find

$$\frac{t_{\rm W}}{t_{\rm Q}} \sim 4.$$

Or, perhaps more realistically, we should use $\beta \sim 1$ and $(T_{\rm sys,W}/T_{\rm sys,Q}) \sim 3$, giving

$$\frac{t_{\rm W}}{t_{\rm Q}} \sim 40.$$

Q-band will therefore be best suited for experiments of imaging circumstellar or protoplanetary disks, but whether the increase in observing time needed for imaging at W-band makes it completely infeasible will depend sensitively on the distribution of the new antennas (or stations) throughout New Mexico. For the 10 antennas described above, a continuum bandwidth of 8 GHz, and 12 hours on-source, the point-source sensitivity at Q-band for natural weighting is around 4 μJy/beam. Assuming an average baseline $b \sim 200$ km this will give a synthesized beam $\theta \sim \lambda/b \sim 7$ mas, and $T_{\rm rms} \sim 50$ K. This is a useful sensitivity for imaging the inner parts of a circumstellar disk, where the optical depth is relatively high and the dust temperature may be 200–300 K. This sensitivity does not include the VLA antennas, but the signal-to-noise ratio achieved ($\sim$ few) is the value to be scaled to W-band using the relationships above. Thus it seems that for W-band to be useful for imaging circumstellar disks it is likely that days to weeks of on-source integration time will be needed. On the other hand, Q-band will potentially provide an extremely valuable tool for such projects.