Science case for ATCA 7 mm receivers

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The CA's frequency coverage has a large gap between 25 GHz and 85 GHz. This document outlines the scientific opportunities and the technical feasibility of a 7 mm receiving system for the Compact Array. Here, the term "7 mm" refers to a receiver system which allows one to observe between the upper edge of the "12 mm" (16 GHz to 25 GHz) band and the oxygen lines between 50 GHz and 70 GHz.

1 Scientific opportunities in the 7 mm band

1.1 Star formation and stellar evolution

The transition from molecular cloud to high-mass ($M>8\,M_\odot$) star is poorly understood, in contrast to the well-established scenario of the formation of lower-mass stars. The two competing scenarios predict that massive stars either form via a scaled-up version of the processes in low-mass stars, i.e., accretion into a disk accompanied with outflows or jets, or via collision of lower-mass stars. The debate suffers from observational constraints for several reasons.

Massive stars have shorter lifecycles and their numbers are relatively small, hence they are usually more distant and more difficult to observe. Furthermore, they are always embedded in clusters and cluster gas, making it difficult to separate the emission from massive stars and their smaller companions. Then there is a variety of emission from protostars: thermal emission comes from dusty disks, free-free emission from Strömgren spheres and/or ionized outflows, and there may even be synchrotron emission from jets and shocks. All of these contributions have optical depth effects, and to disentangle them requires good frequency coverage and high resolution.

Specifically, jets and outflows, signposts of low-mass star formation, have only been observed in a couple of massive stars yet. So do disks, jets, and outflows not generally exist in massive stars? Are they very different from their counterparts in low-mass stars? Are they shielded from our view? Or do they actually form via coalescence of lower-mass stars?

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The 7 mm system will combine several advantages to investigate regions of massive star formation. It will fill a large frequency gap which helps to determine the SEDs of these objects and to disentangle the emission processes. At 7 mm, the free-free emission from jets and the blackbody emission from dusty disks have similar optical depths, hence it is the wavelength which lets one observe processes as close to the star as possible. The higher resolution will allow to pinpoint massive stars and to align their positions with maser or IR observations, and to carry out proper motion studies of jets.

When high-mass stars have finally formed, they ionize their surroundings, forming HII regions of various degrees of size, density, and temperature. The spectra from the free-free emission of these regions peak in the radio regime, the exact frequency ν_0 depending on the emission measure and temperature. For the most copmpact regions, ν_0 is expected to be several tens of GHz, probing regions with densities of $10^6\,\mathrm{cm}^{-3}$ and diameters of only several mpc. However, radio surveys of Ultra-Compact HII regions were made predominantly at wavelengths of several cm, resulting in considerable bias towards regions with densities of the order of $10^4\,\mathrm{cm}^{-4}$. Dense frequency coverage up to 100 GHz is essential to determine ν_0, yielding measures for the density and temperature.

In the later stages of stellar lifecycles, SiO masers in the atmospheres of evolved stars can be observed at 7 mm. As these masers are strong, they can be observed almost throughout the entire Milky Way, and help to determine its stellar dynamics. At distances of 10 kpc, in the galactic bulge, stellar masers have luminosities of several tenths of Jy, which is easily detected with the CA. The relative strengths of 43 GHz and 86 GHz masers give useful information about physical conditions in the masing regions.

SN1987A is the brightest supernova in 400 years and has been intensively studied. Since the radio emission was re-detected in 1990, it has been observed with HST, Chandra, MOST and the CA. With the CA at 12 mm, SN1987A is currently only marginally resolved (diameter of $2''$ compared to a beam size of $0.4''$), and very high signal-to-noise ratios are required to make superresolved images which show details in the expanding shell. At 7 mm, the resolution would be almost doubled, matching that of the HST and Chandra, and one will be able to resolve forward and reverse shocks and to study shock acceleration as the spectral index of the radio emission slowly increases. The inverse correlation between radio and X-ray is puzzling and requires highest resolution to be studied in detail. Given the importance of SN1987A and the CA's uniqueness in the southern hemisphere, this is a great opportunity.

1.2 Observations of molecular lines

There are hundreds of molecular lines in the 25 GHz to 50 GHz regime, which can be mined for information about temperature, density, and chemical reaction chains in a variety of environments. It should be pointed out that a large number of lines in this part of the spectrum have not even been identified and conversely the 7 mm transitions of many molecules have not yet been calculated. A few examples are listed here, together with their astrophysical application.

- Ammonia (NH_3) with transitions between 25 GHz and 35 GHz is used as a measure for temperature in dense, hot environments like star forming regions.

- Carbon chains with four and more carbon atoms produce a wealth of lines. They are mainly used as probes for cold and dense gas, as tracers of molecular cores and can be used to study the outflow chemistry in AGB/Mira stars.

- Cyanoacetylene (C_3HN) and its derivatives can be used to trace chemically young, prestellar material. It therefore is a kinematic probe of early cloud evolution. As its transitions are available over a wide frequency range in the 7 mm band, it can be used as a thermometer for both cold and hot gas.

- Dicarbon monosulfide and tricarbon monosulfide (C_2S and C_3S) are important tracers of prestellar cores. It has the potential of acting as a probe for magnetic fields in dense gas via a small Zeeman effect.

- Cyclopropenylidene (C_3H_2) is a tracer of infalling gas in young stars.

- Unsaturated carbon chains can test chemical models of the evolution of low-mass cores. H-saturated cyanoethane may do likewise in the warmer massive cores.

- Formaldehyde (H_2CO) is an important discriminator of different density regimes, as each transition has a very distinct critical density for excitation, which does not depend strongly on temperature. Combining these with matched-resolution maps in other transitions at other wavebands can "peel away" the density structure of a cloud. Formaldehyde has only very few lines between 4 GHz and 200 GHz, hence every transition is precious.

- Sulphur monoxide and sulphur dioxide (SO and SO_2) trace regions of shock chemistry in dense gas.

- Various other molecules useful for stellar astrophysics are Silicated carbon-chains (SiC_4 and SiC_2), Dimethyl ether (CH_3OCH_3), magnesium isocyanide ($^{24}MgNC$), methyl cyanide (CH_3CN, CH_2CN), silicon monoxide (SiO) and carbon monsulfide (CS).

Methanol (CH_3OH) is an especially interesting molecule, as it has by far the most detected transitions of any molecule (both thermal and maser). Interstellar methanol masers are associated with regions of active star formation, and fall into two classes. Class I methanol masers are normally seen apart from compact continuum sources, while Class II methanol masers are found close to ultra-compact H II regions. The difference between the two classes is likely due to a difference in pumping mechanism: collisional excitation produces Class I masers while radiative excitation produces Class II masers. Studies of methanol masers therefore are an important tool to study star formation and the density and temperature distribution in interstellar matter. Blind methanol surveys could be used to reveal star formation regions at their earliest stages.

1.3 Very Long Baseline Interferometry (VLBI)

VLBI delivers images of AGN and their surroundings with a spatial resolution that is unachieved by any other instrument. VLBI observations are essential for studies of radio jets and the interaction with their environments, nuclear absorption and emission lines, and H_2O and SiO masers. The mechanism by which gas is fed into the central supermaasive black hole in the centre of AGN is still not understood. This is primarily due to a lack of imaging observations with sufficient resolution, because regions of the order of a few Schwarzschild radii have to be resolved in other galaxies. Higher frequencies are desireable because it is the easiest (and often only) way to increase the resolution, and because synchrotron emission becomes optically thin towards higher frequencies. 7 mm VLBI observations provide extremely high resolution whilst still having good sensitivity, and hence are superior to 3 mm VLBI observations when weak (sub-Jy) sources are targeted.

The largest benefit would accrue if other Australian antennae would also be outfitted with 7 mm receivers. Mopra will most likely get a 7 mm receiver in the course of the CA upgrade, and there is good prospect that Tidbinbilla may have a receiver with good bandwidth in the next few years. LBA-only observations would yield an angular resolution of 5 mas, and the future e-VLBI upgrade of the LBA would then yield very sensitive images at this resolution.

The CA at 7 mm would have a resolution of the same order as the LBA at 20 cm. This would allow one to study the spectra of sources with moderate brightness temperatures (starburst galaxies, radio galaxy jet interaction regions, galactic X-ray binaries) without resolution effects.

VLBI observations of SiO masers have yielded impressive results of dynamics in stellar atmospheres, and the CA could collaborate with the Japanese VERA project to map SiO masers in the Milky Way. The CA would contribute long north-south baselines, and increase the coverage of the inner galaxy. The space-VLBI mission VSOP-2 is planned with 8 GHz, 22 GHz and 43 GHz receivers, and the CA, together with Mopra and Tidbinbilla, would be the only souther-hemisphere option for VSOP-2 at 43 GHz, yielding an angular resolution of 40 μas at 43 GHz.

In a separate application, the 7 mm-upgraded CA could contribute to the upgraded International Celestial Reference Frame (ICRF). The ICRF provides the reference for all other astronomical reference frames and is essential if observations from different wavebands are to be compared. It is also needed for (spacecraft) navigation, VLBI data correlation, and pulsar observations. The current ICRF has been derived from 2.3 GHz/8.4 GHz VLBI observations, but the next generations will be derived from 24 GHz/43 GHz observations as accuracy demands increase. The 7 mm-upgraded CA will be the only station in the southern hemisphere that can contribute to the ICRF.

1.4 The high-redshift Universe

1.4.1 Redshifted CO

One of the primary scientific goals of 7 mm receivers is the study of redshifted CO, tracing the Universe's star formation history, which is only poorly constrained at redshifts higher than about 1. CO is an excellent tracer of H_2, thus indicating the masses of gas reservoirs which fuel star formation. Although redshifted CO has been found in sub-mm galaxies, quasars, radio galaxies and Lyman break galaxies, the total number of objects only amounts to 35, and the detections are heavily biased towards objects for which dust emission had already been found. CO is very versatile, as multiple transitions are in principle observable and yields densities and temperatures. Some of the redshifted CO lines showed double-peaked profiles which can be used to determine the dynamical mass of the host galaxy. Also, the redshift derived from CO is a better measure of the intrinsic redshift because it is largely at rest with respect to the host galaxy.

However, todays CO observations are mostly carried out in the 3 mm band and so most of the lines are higher-order transitions. These observations tend to underestimate the amount of low-density gas, and so observations of lower (J=2-1, J=1-0) transitions are essential for accurate models. This is also important as the lower transitions are easier to observe in local galaxies, teaching us how to interpret the results from the same transitions at high redshifts.

With today's receivers, the CA can observe the CO $J(1{-}0)$ line at redshifts of $0.1 < z < 0.4$ (using the 3 mm band) and $3.4 < z < 6.2$ (using the 12 mm band). Continuous frequency coverage between 26 GHz and 50 GHz will narrow that gap considerably and will allow astronomers to observe CO $J(1-0)$ at redshifts as low as $z = 1.3$. Modelling of CO clouds requires multiple transitions to be observed, and the 7 mm-capable CA will be able to observe two CO transitions in galaxies with $1.3 < z < 1.7$ and $2.3 < z < 3.1$. At redshifts between 3.6 and 6.2, three transitions will be observable (Fig. 1).

The importance of the 7 mm band is best illustrated with Fig 2 which shows the relative detection sensitivity for redshifted CO. With increasing frequency, it accounts for the increasing line luminosities as well as decreasing system sensitivity, and so shows which band is most likely to yield a detection of CO if the approximate redshift of the object is known. It turns out that at almost *any one redshift above 1.5, a CO line in the 7 mm band is the easiest to detect.* The 7 mm receivers will turn the CA into a detection machine for high-redshift CO, and its capability to study other CO transitions will allow astronomers to accurately model the gas contents in these objects.

One should also note that a CO survey would be most efficient in the 7 mm band. The synthesized beamsize decreases as ν^{-2}, and the surveyed velocity

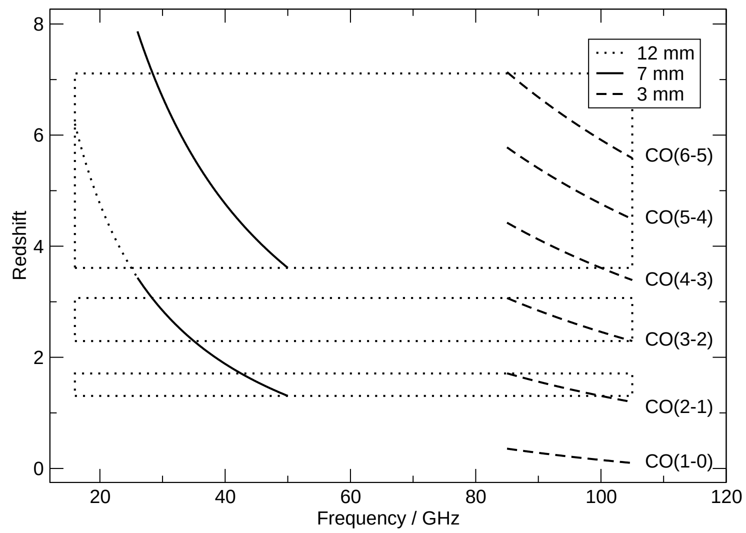

Figure 1: CO transitions at various redshifts and where they fall into the 7 mm band. Dotted boxes indicate redshifts at which the 7 mm system adds substantial information about the CO.

range as ν^{-1}, if the bandwidth is fixed. Hence the detection efficiency decreases as ν^{-3}, an effect that by far offsetts the increasing line strength towards higher frequencies as J increases. Only the 7 mm and 3 mm bands cover enough redshift space for such a survey, but the ν^{-3} dependence of efficiency and the higher system sensitivity make the 7 mm band the first choice for such a survey.

Furthermore, redshifted lines of HCO^+ and HCN as well as hydrogen recombination lines can be observed.

1.5 SZ effect measurements

The Sunyaev-Zeldovich (SZ) effect, the scattering of CMB photons in hot galaxy cluster gas, provides insight into cluster mass and their physics independent of redshift throughout the Universe. Dedicated SZ-effect surveys will be carried out in the next few years, expected to detect hundreds of new clusters. The 7 mm band is ideal to study these clusters, because the relatively high frequency minimises the non-thermal contamination from galactic and extragalctic sources, while the sensitivity is still high. In a 12 h observing run in H75 configuration, the CA will yield a $10\,\sigma$ detection of a typical SZ-signature with a surface brightness of several mK.

1.6 CMB foreground measurements

Upcoming high-precision CMB measurements suffer from considerable foreground emission which needs to be removed to filter out the CMB variations. The main foreground emission comes from vibrating dust and point sources,

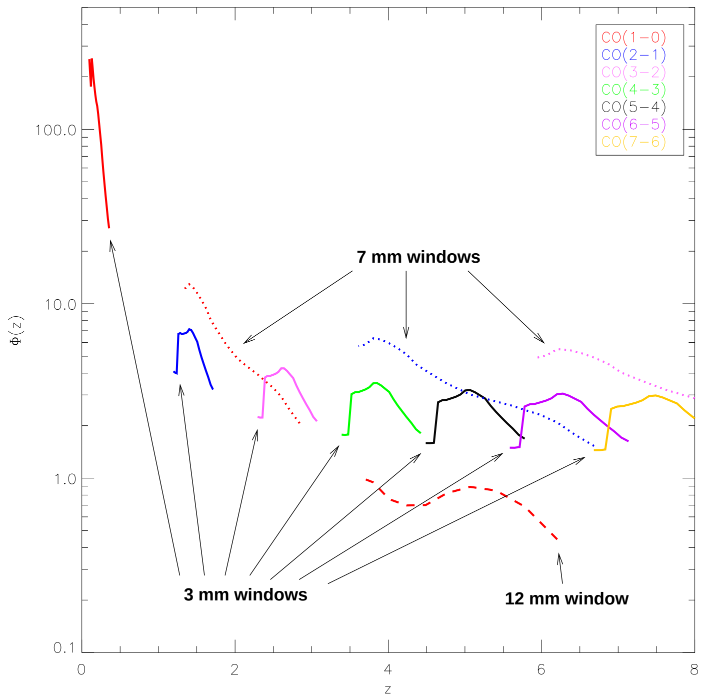

Figure 2: Sensitivity of the CA at 12 mm, 7 mm and 3 mm to various CO transitions, in arbitrary units. Higher $\Phi(z)$ means that CO is easier to detect. The diagram shows that at almost any one redshift above 1.5, lines in the 7 mm band will be the easiest to detect. The 12 mm and 3 mm sensitivities were taken from the CA's sensitivity calculator, and the 7 mm sensitivity has been estimated from laboratory measurements of the LNA and predictions of noise contributions from waveguides, feed horns, and other electronics. The brightness of the atmopshere at 7 mm (which is already included in the 12 mm and 3 mm sensitivities) has been estimated using Miriad's OPPLT for 50 % humididty at the Narrabri site. The frequency range at 7 mm band has been assumed to cover 30 GHz to 45 GHz. The quantum number J increases towards higher redshifts, hence for 3 mm, the transitions $J = 1-0$ (left) through to $J = 7-6$ (right) are shown, for 7 mm the transitions $J = 1-0$ to $J = 3-2$ and for 12 mm the $J = 1-0$ transition only.

both of which can be significantly polarized. At 7 mm, the CA will be an excellent instrument to determine the contribution of point sources on an angular scale of $1'$, or multipoles of the order of 10^4. Furthermore, the CA's polarization characteristics allow one to determine the contribution of these sources to the polarized signal, which contains information about reionization and gravity waves.

1.7 7 mm source population

Only little is known about the source population at high (> 20 GHz) frequencies, as most surveys have been undertaken at lower frequencies and extrapolations are uncertain (for example, the integral source count of 15 GHz sources matches that of 8.4 GHz, which contradicts simple predictions). These sources are of particular importance for several reasons. A significant fraction of sources exist whose inverted spectra extend far into the tens of GHz regime. These sources may be a significant contaminant in CMB (polarization) measurements, but they also promise to be valuable calibrators for the ATCA at 3 mm, and for ALMA. A fraction of these sources are likely to be very young (10 yr to 1000 yr) AGN, which peak at tens of GHz.

The broadband upgrade of the CA will allow to survey reasonably large areas of the sky at 7 mm with good sensitivity.

2 Technical considerations

The CA antennas have been designed to operate at frequencies of up to 60 GHz, and their surface rms is currently of the order of 0.2 mm. This is true also for CA06, the surface of which was not part of the millimetre upgrade. However, at frequencies below 60 GHz, an rms of this order is not the limiting factor on the antenna efficiency, but other factors like illumination, blockage, and diffraction. The antenna efficiency, η_{A}, should exceed 0.55 at 50 GHz, and is probably around 0.60 over most of the band.

Noise measurements of the LNAs and estimates of contributions from feeds, waveguides, and electronics indicate that the receiver temperature, T_{rec}, will be of the order of 30 K to 40 K. Atmospheric emission and ground spillover add another 5 K to 15 K, so that a conservative estimate yields a system temperature, T_{sys}, of 55 K. These data suggest that a 12 h of integration will yield an image rms noise of between 0.031 mJy beam^{-1} and 0.033 mJy beam^{-1}. This is about a factor of two less than the 12 mm system, but factors of 10 to 30 better than the current (2005) 3 mm system.

As NASA requires sensitivity to circular polarization, both orthogonal linear polarizations have to be recorded to form the circular polarization. Hence the CA will have full polarization capabilities. Simulations of the orthomode transducers show that the receiver's cross-polarization (i.e. from feed horn on) is below 0.1 %. However, imperfections in the antenna structure will increase the cross-polarization of the entire system to be of the order of 0.5 %.

Commercially available components have bandwidths of 26 GHz to 40 GHz or 33 GHz to 50 GHz. Fractional bandwidths exceeding 1.5 are problematic, so one has to decide which of these two options is going to be implemented. A poll among the speakers and the audience at the 7 mm workshop showed that a majority of more than 90 % opted for the higher frequency range.

Frequency agility is no problem. The built-in LOs are tunable between 11.2 GHz and 15.6 GHz with a 4-12 GHz bandwidth, and hence provide LO frequencies between 21.6 GHz and 58.8 GHz

3 Other considerations

3.1 Atmospheric transparency

There is an atmospheric opacity trough between the 22 GHz water vapour line and the absorption by oxygen at frequencies higher than 50 GHz. Depending on the atmospheric water vapour content, the opacity in this window is a factor of two to five lower than in the 3 mm band. The opacity forecasts for the Green Bank Telescope[1] predict zenith opacities of the order of 0.1 Nepers at 34 GHz to 0.25 Nepers at 48 GHz. This converts into transparencies of 90 % to 78 %. However, these values depend very sensitively on the local weather conditions and should be slightly better for the drier location of the Compact Array.

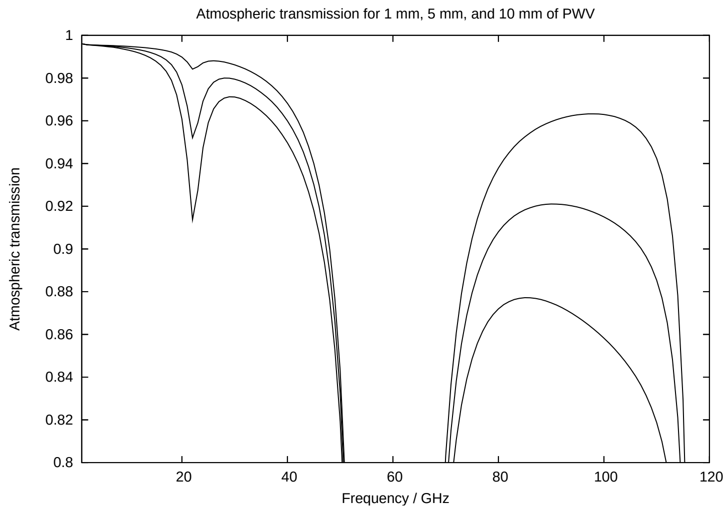

Figure 3: Atmospheric transparencies between 1 GHz and 120 GHz for values of precipitable water vapour (PWV) of 1 mm, 5 mm, and 10 mm. The higher the PWV, the lower the transparency.

[1] http://www.gb.nrao.edu/ rmaddale/Weather/opacity.html

3.2 The 7 mm-upgrade CA compared to other telescopes

While it is unlikely that ALMA will be outfitted with 7 mm receivers, the Expanded VLA (EVLA) will be operational in this regime, although this band does not have a very high priority for the EVLA, and may take as long as 2012 to be installed. The estimated effective surface area of the CA at 7 mm, 1140 m^2, is one quarter of the VLA's effective surface area of 4640 m^2 at this frequency, and hence can compete in areas where sensitivity requirements are not extreme. Still the Compact Array will be the only instrument in the southern hemisphere.

4 User Requirements

The expected performance of the system, indicated by noise estimates based on laboratory tests and summarized in Table 1, has been presented to the community at a workshop on 31 May 2005. It was generally felt that the system performance is excellent and will be a benefit to the ATCA and its users.

The availability of commercially manufactured waveguides makes it impossible that the entire frequency range of 25 GHz to 50 GHz is covered by the 7 mm system. The options are either to cover 25 GHz to 40 GHz (Ka band) or 30 GHz to 50 GHz (Q band). A poll among the speakers and the audience at the workshop showed that a vast majority of users would want to have the higher-frequency option implemented. This decision was mainly influenced by the higher resolution, more important molecular lines in the 40 GHz–50 GHz range, or too little advantage over the existing 12 mm system.

The primary beams of the antennas will have FWHM of $112''$ to $56''$. Using reference pointing, the RMS of the pointing error of the CA antennas is around $5''$, or between 4 % and 8 % of the primary beams. Pointing errors therefore will cause amplitude errors of less than 3 %.

5 Version history of this document

1. Version: 23 August 2004, science case presented at AT projects meeting
2. Version: 6 December 2004, minor revisions
3. Version: 13 April 2005, added performance estimates based on early LNA tests
4. Version: 6 June 2005, major changes, including results from 7 mm workshop
5. Version: 8 February 2006, update of plot showing CO detectability

	32 GHz		43 GHz	
	Configuration-independent parameters			
$T_{\rm sys}$	48 K		51 K	
SEFD	630 Jy		670 Jy	
Baseline sensitivity (1 σ in 1 min)	3.2 mJy		3.4 mJy	
Array sensitivity (1 σ in 12 h)	0.031 mJy		0.033 mJy	
Primary beam size	88 arcsec		65 arcsec	
cross-polarization	0.5 %		0.5 %	
	Configuration-dependent parameters			
	H75 array	6A array	H75 array	6A array
Synthesized beam (minor axis, $b_{\rm min}$)	$19.9''$	$0.43''$	$14.8''$	$0.32''$
Surface brightness sensitivity (12 h)	0.093 mK	100 mK	0.18 mK	190 mK

Table 1: Expected performance of the 7 mm system. SEFDs (System equivalent flux density) are the flux densities needed to produce the same noise temperature as the system, with $SEFD = 2kT_{\rm sys}/\eta_{\rm A}A$. Baseline sensitivities were calculated using $\sigma = \eta_{\rm corr}\frac{SEFD}{\sqrt{2\Delta\nu\tau}}$ with $\eta_{\rm corr} = 0.88$ and $\Delta\nu = 416$ MHz (208 MHz per polarization). Surface brightness sensitivities were calculated using $T_{\rm b} = 1.36\frac{\sigma\lambda^2}{b_{\rm min}b_{\rm max}}$ assuming circular beams in H75 arrays and $b_{\rm max} = 2b_{\rm min}$ in 6 km arrays, corresponding to a source declination of $-30°$.