RAL Configuration Science Requirements for the Allen Telescope Array

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Purpose

This document describes the science requirements for the configuration design of the Allen Telescope Array, from the perspective of Radio Astronomy Laboratory users. It is an outcome of a series of meetings of the RAL faculty and research astronomers. When reconciled with SETI Institute requirements, these requirements will form the basis for evaluating telescope configuration options and choosing the final configuration.

Science Drivers

The key to selecting the appropriate configuration for the ATA seems to be to optimize for a few important, high-profile science drivers, while retaining a reasonably versatile general-purpose instrument for a variety of experiments both foreseen and unforeseen.

The attached table of science drivers indicates the variety of projects in which RAL astronomers are interested. Broadly, these require good sensitivity at arcminute scales, or simply point-source sensitivity. Most projects are concentrated towards the low end of the expected ATA frequency range. These projects are already matched to the other specifications of the ATA, and selected to be within the range of configurations practical on the presently available land. From the table, the meetings focused on two key scientific areas for the ATA:

- Wide-area surveys: HI in the Milky Way, nearby galaxies, and at cosmological distances, and continuum polarization surveys of the Milky Way.
- Monitoring of sources variable on timescales from milliseconds to days (pulsars, intra-day variables, extreme scattering events, GRBs, extragalactic supernovae, etc.)

These stem from more than just the interests of the astronomers: the wide field-of-view and sensitivity to extended structure will be a unique combination in the ATA, while the opportunity to influence the design for monitoring variable sources together with the expected synergy with SETI processing equipment will make the instrument well-placed to pursue time-domain studies.

Wide-area surveys

These major surveys would cover the entire sky visible from Hat Creek. In a large mosaic, the effective survey area contributed by each ATA pointing is 3 square degrees. Thus a complete northern ($\delta > 0^{\circ}$) survey to match sensitivities with a single 8-hour pointing would be possible with 6.3 years of continuous observing. In 8 hours ($70''$ beam, 1 km s^{-1}) the ATA will achieve a line sensitivity (1σ) of 0.19 K. A wide bandwidth HI survey would provide an unprecedented study of nearby galaxies, with a mass sensitivity of 6×10^2 M$_{\odot}$ (d/Mpc)^2 in typical linewidths of 30 km s^{-1}. This corresponds to a sensitivity of 1.5×10^7 $M_\odot$ at 160 Mpc, i.e. the Milky Way would be detected (in a single wider channel) at about 100σ. A similar survey of our own Galaxy would also be uniquely sensitive (8×10^{-5} $M_\odot$ in 0.5 km s^{-1} at 1 kpc) at the resolution of the ATA. Sensitive existing surveys (Leiden-Dwingeloo, Burton & Hartmann 1994) have resolutions much lower (30′), while interferometric surveys such as the Canadian Galactic Plane Survey fall far short of the desired sensitivity (cf. Normandeau et al. 1997). A companion northern sky continuum imaging survey would also be important. Even a 1MHz continuum correlator would reach the background confusion limit of 0.1 mJy $beam^{-1}$ (Bower 2000) during this survey—but with imaging performance far superior to any existing continuum survey at this resolution (cf. NRAO VLA D-array sky survey). The confusion limit in linear polarization will be much lower, but the correlator is expected to have a bandwidth $\gg$ 10 MHz.

Monitoring of sources variable on timescales from milliseconds to days

Many radio telescopes have add-on hardware for measuring variable sources (generally pulsars). But few have been designed with transient source monitoring in mind, while the correlation hardware for interferometers typically makes it difficult to coherently detect variations not well sampled by the correlator integration cycle. The availability of the RF signals at the central laboratory is an important capability for such projects, since it allows searching for and monitoring of such sources at various frequencies while observing for other projects, as well as maximum flexibility for upgrading hardware as computing capabilities improve.

Since the telescope will used principally for major projects by a few research groups, it should be relatively easy to arrange interruptions to the schedule to monitor important new transient sources as they are announced. The synergy between transient, unresolved sources and the SETI detection hardware will make cooperation on the backends important for these projects.

Configuration requirements

The requirements for the HI surveys can be met by an array that has excellent sensitivity in the range from DC to 70′′. Since the observations would in general be long (8 hrs/field), the snapshot *uv* coverage is not in principle critical, provided a long track produces a high quality beam. However, in order to maintain flexibility when observing for this long-term project simultaneously with other ATA experiments, it would be highly desirable to have good snapshot coverage so that integration may be made at any collection of hour angles. With antennas evenly distributed within the inner Hat Creek site (Figure 1), it is possible to meet these criteria with arrays having near sidelobes of approximately 5%. It is probable that this figure can be reduced somewhat with some fine tuning of the antenna positions: studies of this aspect should form part of the final configuration selection process. A small increase in the size of the interferometer beam might an acceptable tradeoff for much reduced sidelobes; this also requires further investigation. Configurations with a more uniform *uv* coverage (e.g. doughnuts) have been contemplated. These would provide a compromise between projects requiring high sensitivity at the extremes of the available spatial scales. However, the sidelobes of such arrays are significantly higher (>10% even for ideal doughnuts with smooth edges). The

ATA will find it difficult to compete with other instruments for raw sensitivity at the largest and smallest spatial scales, so it seems desirable to focus on the uniquely low sidelobes that the ATA can provide with a more evenly spread configuration. Configurations satisfying these requirements can be designed to keep shadowed baselines to below 15% during a 2-hour observation of the Galactic center.

The issue of whether to place some fraction of the antennas to the north of the main array has been considered. This would provide a less elongated beam at the most southern declinations. The tradeoff is reduced sensitivity to the most extended north-south structure for higher-declination sources. The available land at Hat Creek implies that a northern extension would significantly degrade the beamshape at all declinations. Considering the desirability of retaining the lowest sidelobes, this last factor pushes the balance *against* adding any northern stations to the array. Future extensions of the ATA onto additional land would naturally address this issue.

Transient/variable source studies do not impose direct constraints on the array from the usual perspective, that of imaging performance. However, shadowing at low elevations remains an important constraint. The ability to complete the HI survey for southern sources will drive the design to minimize shadowing towards the south. To maximize the time during which variable sources can be observed, care needs to be taken to avoid severe shadowing over the full azimuth range. The desire to maintain a wide field-of-view in a broadband phased array mode points to minimum antenna separation. However, radio-frequency interference drives the antenna separation in the other direction. So the scale of the array can probably be set mainly by the imaging programs. Of concern, however, is the background confusion level (about 0.1 mJy) at 1.4 GHz. This would be reached in a few minutes within a bandwidth of 500 MHz. We leave aside the study of non-varying sources (convenient with existing, higher-resolution arrays). It should be possible to monitor variable sources well below the confusion limit, by obtaining a model of the constant background. This has been demonstrated in observations of Saturn at Arecibo (Yerbury et al. 1971). In any case, adjustments within the configuration parameter space presently under consideration would not significantly improve the situation.

References

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Normandeau, M., Taylor, A. R., & Dewdney, P. E. 1997, ApJS, 108, 279
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Figure 1: One possible (but not optimal) configuration satisfying the science requirements

topic	ν GHz	$\Delta\nu$ MHz	δv km/s	ch.	T_{int} or Sensitivity	pol.	θ	$\delta\theta$ arcsec	variability	ΔHA	prior.	who	notes
gamma ray bursts	C				10 uJy - 10 mJy	0.1%	10s/sq deg > 1uJy	pt	h-wks, or <?		high	Bower	
radio SNe	C				10 uJy at z=0.1	0.1%	many in FOV	pt	wks-yrs		high	Bower	
galactic black hole candidates	C				10 uJy, all in Galaxy	0.1%		pt	hrs-yrs		med.	Bower	
Milky Way HI survey	1.4	5	1	1000	2000 days / 115mK		MW survey	60				Blitz	cf Leiden/Dwing 70mK, 35' beam
ditto			0.5		0.3K			<180			1	Heiles	
nearby galaxies HI survey	1.4	50	30	300	240hrs/1.2x$10^6 M_{sun}$		2.5 deg	60				Blitz	
deep HI survey (cluster of galaxies z=0.3)	1.4	500	100	1000				60				Blitz	
continuum spectral index survey	1-10	25			30 days/0.28mJy		whole sky	45			med.	Bock	assumes 1 min/field, 75% of sky
extrag.contin.surv. (extended sources)	C(1)	25			10 days/0.28mJy		whole sky	60			med.	Bock	NVSS response 0.1 at 20'
comets	1667,4830	0.5	0.5		8 hrs		1 deg	30-60	highly		high	dePater	VLA sees 30% of emission, need total power
spectra of giant planets	1-10							50				dePater	
HI absorption in MW against continuum	1.4	3	0.14	5000	0.003Jy, 0.2K		6 arcmin	30			1	Heiles	need absorption and expected emission profile, for 10Jy sources, need opacities 1e-3 so that spin temps can be measured.
Zeeman splitting of above	1.4	3	0.14	5000	0.002Jy, 0.2K	yes	6 arcmin	30			1	Heiles	sensitivities for 10Jy sources
Zeeman splitting of HI emission in MW	1.4	3	0.15	5000	0.01K	yes	full primary beam	<180			1	Heiles	VLA meas. indicate possible interesting result, single field first.
Linear pol of HI in MW	1.4	3	0.5	1500	0.03K	yes	10s of sq deg	<180			1	Heiles	HI absorbs polarized background emission -> distances of HI and background
Map polarization of galactic bg contin.	0.5-2				1-0.05K	yes	whole sky	30			1	Heiles	new field
Pulsar timing	0.5-3	big	1MHz		>=1day/week	orth 30dB stab 40dB	not important	pt			1	Backer	10 year experiment
Extreme Scattering Events/Intra-Day Variables.	0.5-11	big	10%		1mJy					more	2	Backer	ESE weekly monitoring of 100s AGN/ISO; IDV month-long campaigns
High-b Synch. radiation and Magnetic Fields	0.8-2.4	100	10MHz		180-10mK, 0.2mJy/bm@2.4GHz	fidelity	full primary beam	60			3	Backer	remove Faraday rot. -> important for CMB
VLBI	1.4-10	100			10 hours		small	n/a				Backer	
Cosmic Deuterium/Hydrogen ratio	327				reach current limits in a few days		full primary beam	none				Blitz	autocorrelation observation

Table 1: Some projects brainstormed during the science requirements evaluation