1 A Full-Stokes ALFA Continuum Survey

1.1 Introduction

Arecibo is the biggest single-dish radio telescope in the World, thereby providing full spatial frequency coverage, high surface brightness sensitivity, and arcminute scale resolution at decimeter wavelengths - a unique and powerful combination. The ALFA multi-beam receiver system will allow these unique properties to be used to image large areas of the sky at $\lambda 21$ cm, thereby enabling new and exciting scientific directions.

To set the case for a large-area, full-Stokes, ALFA continuum survey in context, a compendium of most of the existing medium- and high-resolution continuum surveys made with the presence of full spatial-frequency coverage is presented in the Appendix to this document.

1.2 Scientific Motivation for an ALFA Continuum Survey

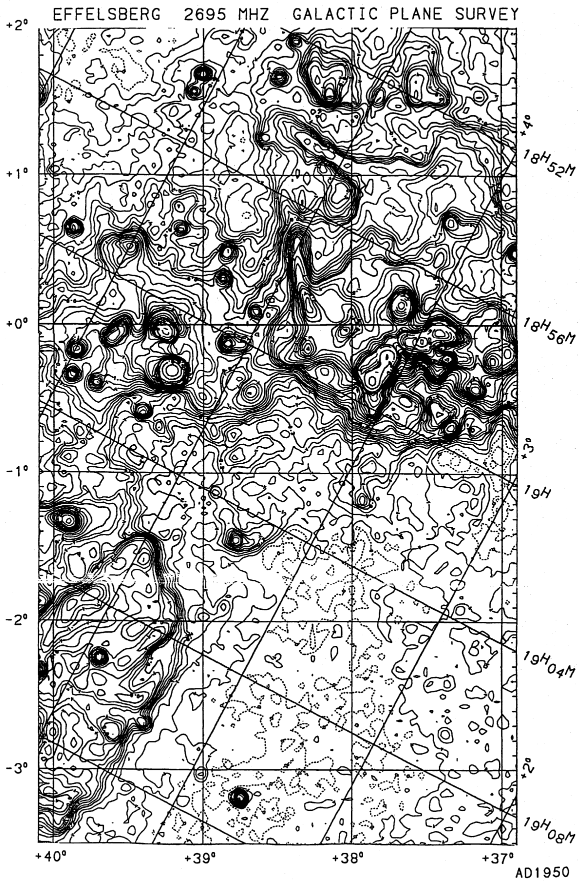


Figure 1: The low-latitude continuum emission at 2.7 GHz for $37° < l < 40°$ measured with the Effelsberg 100-m telescope (Reich et al., 1990, A&AS, 85, 633). The image is in Galactic coordinates, and the HPBW$\sim$ 4.3 arcmin.

A full-Stokes continuum survey of the wider Galactic plane using the full ALFA band (1225 - 1525 MHz) would provide a unique database in a number of ways. Firstly, it would yield full spatial frequency mapping with unsurpassed resolution at such a long wavelength of extended features such as the Galactic background emission itself, HII complexes, and middle-aged and old supernova remnants (SNRs), with simultaneously recorded linear polarization measurements being of especial importance. Many new extended, low-surface brightness objects can be expected to be found. Analysis of the variation of intensity as a function of frequency within the 300-MHz ALFA band and comparison with the existing Effelsberg Galactic plane surveys at 2.7 (Fig. 1) and 5.0 GHz would allow accurate estimation of the spectral index distribution of individual objects, as well as of the radiation from the Galactic disc, providing the ability to perform an accurate and full thermal-nonthermal separation on angular scales of a few arcminutes. This would allow the study of energy injection and energy losses of relativistic particles in the ISM associated with SNR, and the mechanisms of vertical transport and diffusion of energy from the disk of the Galaxy to the halo and intergalactic space.

The appearance of the polarized sky at $\lambda 21\,\mathrm{cm}$ wavelength is surprising, and at first seems bewildering (Fig. 2). As seen by both the Westerbork 327-MHz synthesis observations at high Galactic latitude and the Canadian Galactic Plane Survey with the DRAO Synthesis Telescope, there is little relationship between total intensity and polarization structures. We expect to detect SNRs as polarized objects, and the diffuse Galactic synchrotron emission, but the bulk of the area of the Galactic Plane when imaged at L-band on arcminute scales is filled with highly structured polarization features with no counterpart in Stokes I. The accepted interpretation is that the distributed polarized emission arises from the Galactic synchrotron emission, and is intrinsically quite smooth. Differential Faraday rotation in the intervening magneto-ionic medium, the so-called Faraday Screen, imposes fine structure on the polarized emission. In fact, the sky is dominated by the effects of the medium through which the signals have traveled rather than by intrinsic structure in the polarized synchrotron emission itself. This emerging field of study is gradually moving from phenomenology to astrophysics. The signatures of the Faraday Effect on polarization are revealing details of the magnetic field (rotation measures of compact sources) and of the magneto-ionic medium (imaging of extended emission).

The signals produced by the Faraday Screen are rather weak, typically a few 100 mK at most (a fraction of the polarized signal from the synchrotron background). The limited surface brightness sensitivity of interferometric observations samples only the strongest features, and even in these areas, derived RM measures are very noisy due to low signal-to-noise per channel. Moreover, the lack of zero-spacing flux in the interferometric observations leads to complications in interpreting the polarization signals. The high brightness sensitivity of the Arecibo telescope coupled with the few arcminute beam size promises major advances in the study of the magneto-ionic medium, particularly at mid-to-high latitudes where the signals become weaker due to the fall off in the background synchrotron brightness. It is precisely in regions at these latitudes where critical information about the vertical structure of the Galactic magnetic field can be measured. At higher latitudes, the magnetic field is even more significant in the energy budget of the ISM and is likely to play a dominant role in the vertical energy transport, and in the pressure equilibrium of the medium. Such studies are important in a wider context of the astrophysics of galaxies. The radio-infrared correlation of starburst and normal galaxies must be a result of the relationship between massive star formation and supernova rates in evolving galaxies. The radio luminosity

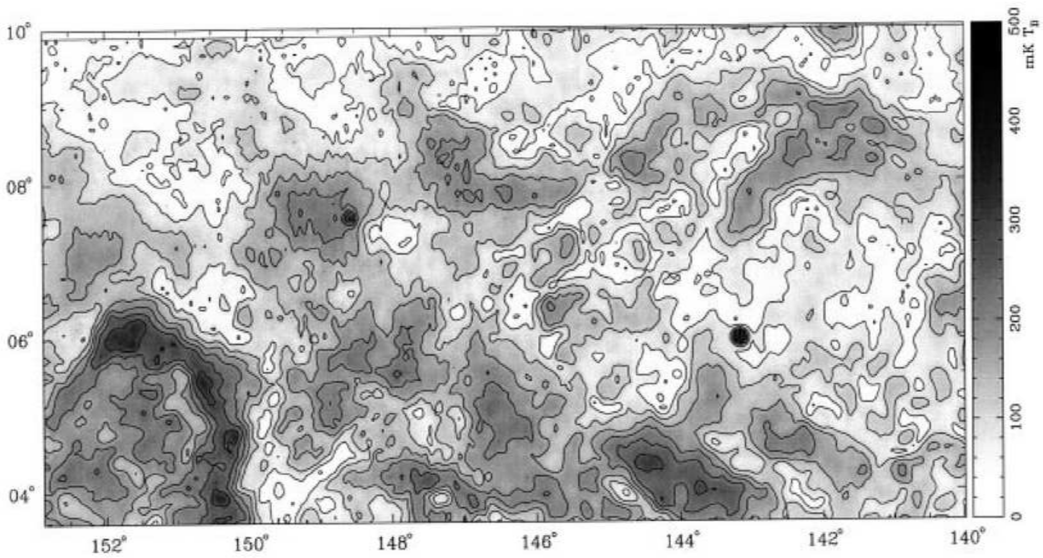


Figure 2: Polarized intensity of the 1.4-GHz emission at $l \sim 140°$ measured with the Effelsberg 100-m telescope (Uyaniker et al., 1999, A&AS, 138, 31). The image is in Galactic coordinates, and the HPBW$\sim$ 9.4 arcmin.

resulting from injection of relativistic particles must in turn be related to both the life time of energetic particles and the rate of bulk flow of energy out of the galaxy. Both are directly linked to the galactic magnetic fields, in particular the vertical structure of the field.

In the studies of the Faraday Screen made so far, the spectral signatures of the polarized intensity have been examined to seek only a single RM value per image pixel, which would correspond to a RM in the foreground of the most dominant polarized emission component along the relevant sight-line. However, the Faraday Screen is spread out in depth along each line of sight, and different regions, or slabs, of polarized emission at different distances along the sight-line will make contributions with their corresponding foreground Faraday rotation signature across the observed spectrum. Because of depolarization effects, bandwidth integrated polarization will show a lower degree of polarization than that intrinsic to individual slabs. With an appropriate combination of observing frequency, bandwidth and spectral resolution, it should be possible to perform Faraday tomography, wherein the spectral polarized intensity modulations along a given sight-line can be transformed to a set of polarized intensities as a function of Faraday depth (i.e. RM). Thus, it should be possible to derive a polarized-intensity data cube (quite like the spectral-line data cube) with two dimensions being the sky coordinates and the third being the RM. The spectral resolution dictates the RM–range that can be probed, while the total bandwidth determines the resolution attainable in RM. The wide bandwidth (300 MHz) and fine spectral resolution (1024 channels) combination available through ALFA would allow us to probe an RM range of a few thousands rad/m^2 with a resolution of 140 rad/m^2 or finer depending on the signal-to-noise, values that are appropriate to low-latitude regions of high RM.

Apart from the polarized emission structure from the Galactic magneto-ionic medium, i.e. the Faraday Screen, the high latitude region visible from Arecibo contains known non-thermal emission structures. The North Polar Spur (Loop 1) runs along more than 6 hr of RA within the Arecibo sky. Lower resolution measurements have shown this object to contain rich small-scale structure, both on its main arc and in internal ridging (Fig. 3). Above $b = 45^\circ$, even the low resolution Dwingeloo measurements have shown this nearby ($\sim$100 pc distant), old SNR to be above 70% linearly polarized at 1.4 GHz.

Further, full-Stokes mapping of the continuum emission of large, nearby, spiral galaxies and giant radio galaxies would add considerable information on the very extended structures and magnetic field configurations within these objects.

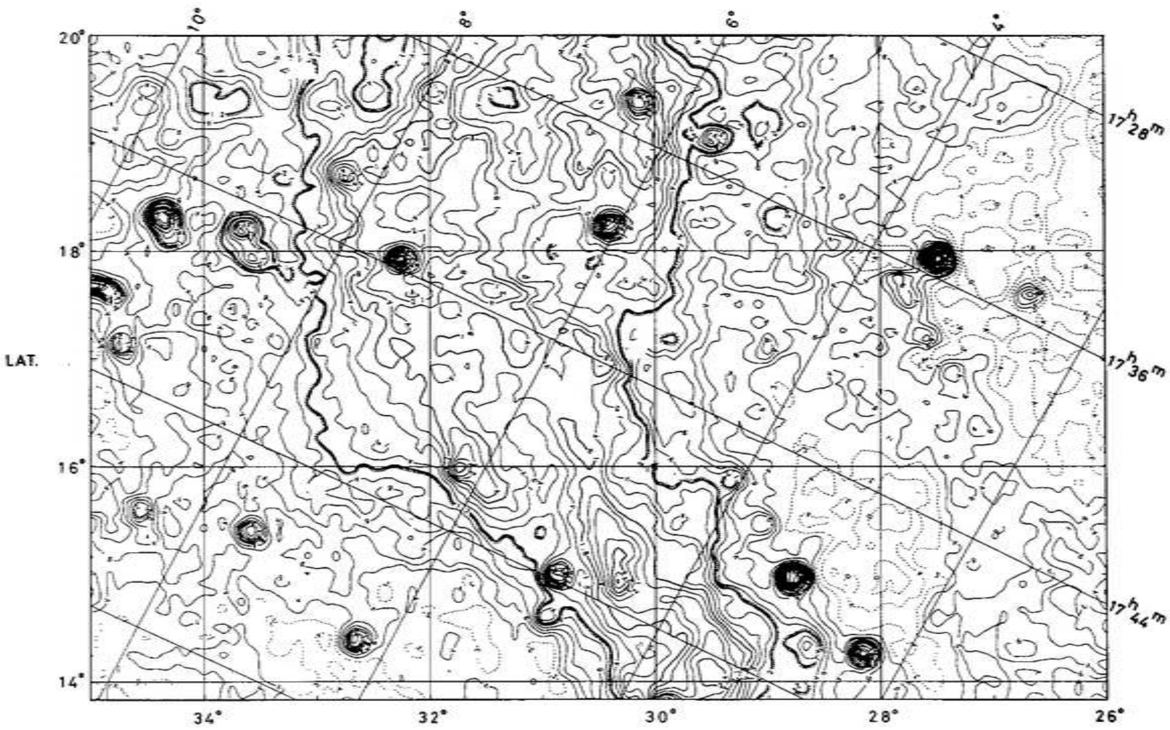


Figure 3: Contour maps of the intermediate latitude total-intensity emission from the North Polar Spur at 1.4 GHz made with the Effelsberg telescope (Sofue & Reich, 1979, A&AS, 38, 251). The image is in Galactic coordinates, and the HPBW$\sim$ 10 arcmin.

The Arecibo continuum survey would also measure the total-power and polarized intensities of the many "point-like" background sources seen through the Galaxy at both low and high latitudes. The sensitivity of Arecibo combined with the multiple channels across the 300-MHz bandwidth of ALFA would permit a complete RM survey to very low flux density levels and high RM accuracy. At low latitudes, combination of RM estimates for SNRs and extragalactic sources seen through the plane with those measured for pulsars will allow modeling of the magnetic field distribution through the whole depth of the galactic disk (center and anticenter) visible from Arecibo. Studies of the change in RM as a function of latitude will provide a measure of the total RM along lines of sight that are also probed by the Faraday screen effect, thereby allowing a measure of the relative Faraday depth of the screen features. The Canadian Galactic Plane Survey with a continuum RMS noise of 300 μJy/beam obtains a grid of background sources with sufficient polarized flux to provide a reliable RM with an area density of about 1 per square degree, over the restricted latitude range of 8 degrees. The Arecibo survey, at three times the sensitivity, will provide an area density almost an order of magnitude higher, over a large range of latitudes and with very high RM precision, thereby probing the vertical structure of the Galactic magnetic field with unprecedented sensitivity, precision and latitude range.

Finally, with multiple-passes of the survey region spread over a range of epochs, the Arecibo continuum survey would yield the most sensitive survey for variable and transient sources ever undertaken. Differencing the multiple passes would allow variable sources to be detectable well below the nominal confusion limit. Ideally we will be able to search to the noise limit of about 100 μJy/beam per pass of the region and detect variables at the level of about 500 μJy. The sky has never before been searched for variations systematically to this depth and over such a large area. We will also search the Stokes-V channel for evidence of highly circularly polarized sources such as pulsars and flares stars.

1.3 The GALFA Continuum Transit Survey (GALFACTS)

An example of what can be achieved with continuum mapping at Arecibo is shown by a recent L-band study with the 305-m telescope of the weak supernova remnant, G42.8+0.6, by Snezana Stanimirovic and her collaborators (Fig. 4). The map was fully sampled, with orthogonally scanned coverages being taken. These orthogonal coverages were subsequently "basket-weaved" to obtain optimum zero levels.

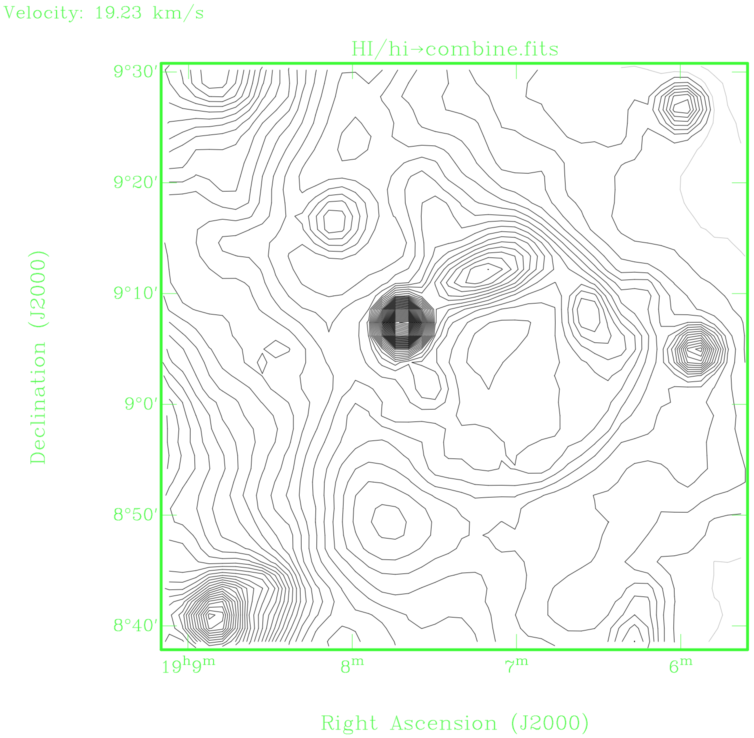


Figure 4: The continuum emission at 1640 MHz in the field of SNR G42.8+0.6 as measured with the Arecibo 305-m telescope. The HPBW∼ 3 arcmin. (Courtesy: Snezana Stanimirovic)

For an ALFA continuum survey we assume that a spectrometer would be available with about

1000 channels covering the full 300-MHz ALFA bandwidth, a full-Stokes capability, and the ability to dump data "slowly" (say, a few dumps per sec).

If we assume an integration time of 1.33 sec per Nyquist sampling interval (see below) and the expected ALFA System Equivalent Flux Density (SEFD) of $\sim$ 3 Jy, then combining both polarizations would give an rms noise of about 100 μJy/beam on cold sky. In Stokes–I this would be well below the confusion level due to the point source background, RMS(confusion)$\sim$ $2\,mJy$/beam, implying weakest believable detections at S(min)$\sim$ $10\,mJy$/beam. (A recent confusion limited Arecibo Stokes-I continuum survey at L-band is that of Giovanelli et al., see Fig. 5) However, the confusion level in polarization will be well below this value (about a factor of 100 less, $\sim$$20\,\mu Jy$/beam). Hence, we can certainly make a very sensitive survey of polarization. For the signals caused by the diffuse Faraday Screen, with no counterpart in Stokes I, the spurious polarization will not generally be a problem. However to measure polarization percentages of strong Stokes-I sources well we must deal with the high spurious polarization responses expected for ALFA. It is not clear to what degree spurious polarization will affect RM measurements, since RM is derived from the frequency dependence of the polarized signal across the band. Instrumental effects on RM measurements may be substantially smaller than on polarization percentage. We will measure the effect of systematics on RM as part of the pilot project described in the next section. To emphasize the power of having available a 300-MHz bandwidth for polarization measurements, the change of position angle across the band is $\delta\theta$ =1.22*RM *deg*, (or one full 180 *deg* turn for an RM of $\sim$$150\,rad/m^2$). The relatively small spectrometer channel width would prevent decorrelation across a channel, with $\delta\theta$ = 0.0012*RM *deg* for each 300-kHz channel.

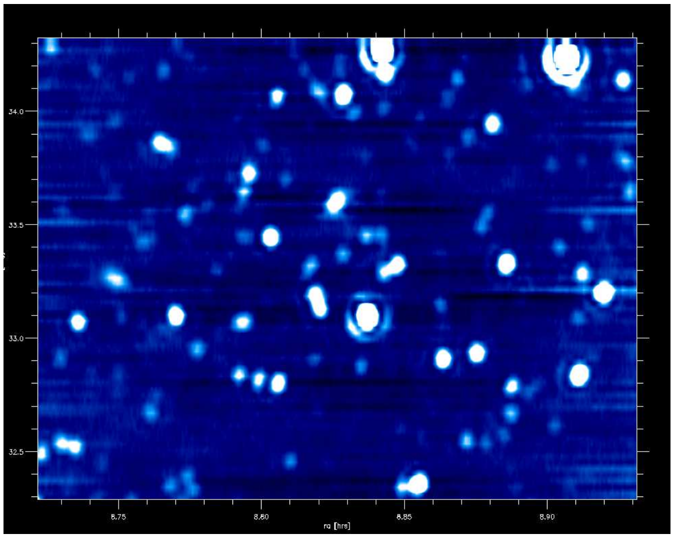
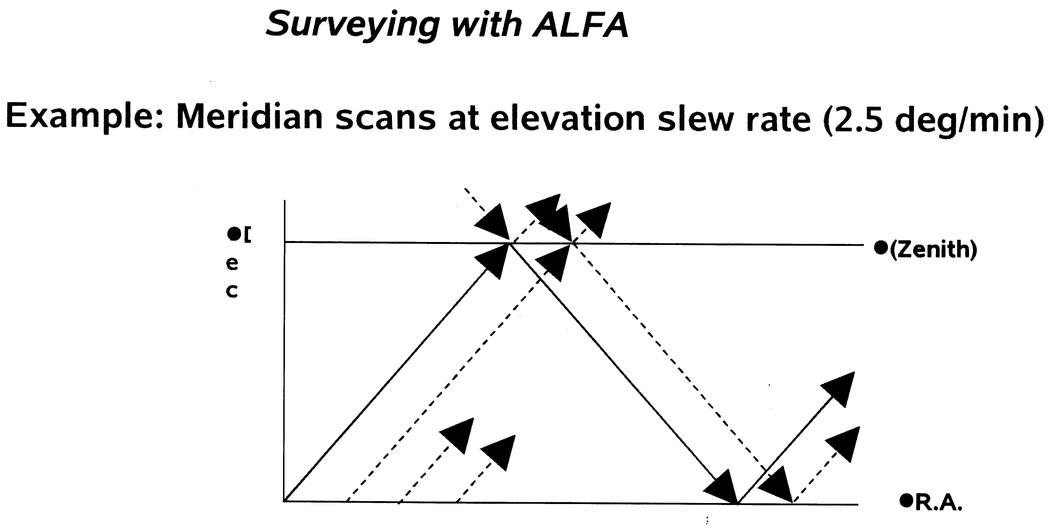


Figure 5: The continuum emission (over a band from 1415–1425 MHz) of a region in the vicinity of the nearby (7.6 Mpc) galaxy NGC 2683. The axes are R.A. (hr), and Dec (deg). Each horizontal strip is normalized to its average flux, leading to the spurious horizontal stripes. The map was obtained in "On-The-Fly" mode with a R.A. drive rate of 6 s per beam, and spaced in Dec each 1.65 arcmin. The map covers 2° × 1.5°. (Courtesy: Martha Haynes)

The biggest problems for any ALFA continuum survey would be; a) temporal zero-level drifts along a scan, b) the $\sim$8-dB coma lobes for the outer horns, and c) the high spurious polarization responses.

The most satisfactory way to deal with temporal zero-level drifts is to minimize them by scanning the telescope beam across the sky as fast as possible. However, to deal with the sidelobes and polarization artifacts, the data needs to be acquired as systematically as possible. An attractive possibility for achieving this is to fix the telescope on the prime meridian and NOD it in zenith angle at the maximum drive rate of ~2.5 deg/min (thus minimizing drifts). The scan pattern projected on the sky is then a zig-zag, where each "zig" is crossed by many "zags" (Fig. 6). This permits the minimization of residual zero level drifts through "basket-weaving". With such an observing strategy, the variations of T_{sys}, antenna gain, sidelobe pattern, and spurious polarization are now purely dependent on declination (because on the meridian, zenith angle maps into declination), and their characterization and correction is much simplified. For example, if one can characterize the coma lobe patterns for all feeds such that they can be interpolated to 10% at any declination (i.e. Zenith angle), then the 8-dB spurious responses could be reduced through CLEANing to some 18 dB. This is similar to, or better, than the normal Effelsberg beam. The meridian NODding technique has the additional benefit that all sky positions are observed with the telescope at the minimum possible zenith angle, thus minimizing the SEFD and maximizing the sensitivity.



Surveying with ALFA

Example: Meridian scans at elevation slew rate (2.5 deg/min)

Figure 6: The "zig-zag" scan pattern produced on the sky by NODding the telescope on the prime meridian. Note that the areas of sky north and south of the Arecibo zenith have to be observed at different times as the telescope cannot "scan through the zenith".

With the NODding approach suggested above, each zig and each zag would take about 0.67 sec to cross a Nyquist sampling interval. Hence, after averaging the (fully sampled) map of "zigs", and the map of "zags", there would be an integration time of 1.33 sec per Nyquist interval. From this, the time to map the whole Arecibo sky would be about 1000 hr. The time to map smaller areas would be proportionally less, e.g. 100 hr to cover a 2.5 $hr \times 40^{\circ}$ strip containing the inner Galactic plane.

The optimum parallactic-angle setting for the ALFA feed table needs to be established such as to give the best possible sampling between adjacent ALFA beams.

1.4 GALFACTS Pilot Observations

The GALFA Continuum Survey group will soon propose for a pilot observation using the current single feed L-band system. We will observe a 1° × 10° area of the sky at mid-latitudes using the observing technique described above. The region will be observed twice (two independent passes), with each pass taking 20 hours. The region to be observed will be chosen to contain a strong compact source with known polarization properties to assess the polarimetric response of the system. However, we will also image the effects of the Faraday screen RM variations which occur in the absence of corresponding polarized signals and are thus largely independent of the Stokes-I leakage terms. Comparison of the two images will provide an assessment of the reliability and reproducibility of the results, allow refinements of the processing and imaging techniques, and allow for algorithms for detection of variables and transient sources to be developed.

We would use the available L-Wide receiver and select 4 bands of 50 MHz each, centered at 1170, 1410, 1510 and 1610 MHz, using an available combination of two front-end filters (1120–1220 MHz bandpass and 1320-MHz highpass filters) to eliminate the strong Radar-RFI. The IF filter would have 1-GHz bandwidth (1-2 GHz), instead of the usual 500-MHz bandwidth, to allow the above bands without any in-band cutoffs. The WAPPs would provide a suitable backends, with 256 channels per 100-MHz band and about 2 millisecond integration (9-level sampling at input, and 32-bit output), for recording full Stokes parameters.

Continuous-switching, correlated CAL (switching rate: 25 Hz; Step-size: 2 K) would enable monitoring of gain and system temperature variations for the two polarization channels.

1.5 Commensality of the GALFA Continuum Survey with other Surveys

The possibility of commensality with other ALFA surveys for a GALFA continuum survey needs to be considered. An immediate constraint is that no ALFA survey can easily be commensal with any other that requires the same spectrometer. A GALFA continuum survey would need the same 300-MHz bandwidth spectrometer as is planned for the pulsar search projects (only with full Stokes capability). As those pulsar search projects suggested to date all need relatively long integration times of at least a few minutes per point, while a continuum survey would collect data as rapidly as the telescope can be practically driven, the two classes of survey are not anyway candidates for mutual commensality.

While the proposed recombination-line ALFA survey uses a different spectrometer to the continuum survey, it again requires relatively long integration times, and does not seem suitable for mutual commensality. The constraint of long integration times would also seem to eliminate the possibility of commensality with a number of E-ALFA projects, such as the proposed deep extragalactic surveys, a ZOA survey and a Virgo cluster survey.

More promising as prospective partners for commensal observing with an ALFA continuum survey are the proposed Galactic HI survey, and the shallow all-sky extragalactic survey for galaxies ("ALFALFA"). Both propose using a different spectrometer to the continuum survey, and both would have rather short integration times. In addition, the Galactic HI survey would clearly also benefit from acquiring its data as systematically as possible given the high ALFA sidelobes, as would the continuum survey. Similar considerations could also benefit ALFALFA. Discussion now needs to take place between the proposers of these three surveys to see if two- (or three-) fold commensality is practical.

In the possibility that commensality is possible with one or both of the above surveys, but that they require longer integration times than we are proposing for the continuum survey, there would be distinct benefits in arranging that a common observing strategy be chosen such that a number of passes are made to obtain the integration times required by the other (slower) surveys. The continuum data from the additional passes would then be obtained at no extra cost (the other survey/s would be observing anyway, and the continuum survey would literally "piggy-back"). To the other surveys, there would be the advantage that the probability of the data at a particular position being totally wiped out by RFI would be minimized by spreading the data-taking over several epochs, while an overall "first-look" could be obtained relatively rapidly, with sensitivity then being improved in a uniform fashion by subsequent passes. For the continuum survey, a number of complete, uniformly taken, passes would have the great advantage that each (free) coverage would be individually mapped, and a systematic search of the Arecibo sky made for both total-intensity and polarization variable sources, plus transient emitters. Searching for transient radio continuum sources is a planned objective for the next generation of large telescopes such as LOFAR and the SKA. Of course, the signal-to-noise ratio boost for the polarization measurements from the additional integration time would be a wonderful bonus.

Appendix

Existing Wide-Area Continuum Surveys

Freq. (MHz)	Resolution (arcmin)	Area	Reference
10	$156 \times 114\,\sec(\mathrm{za})$	$\delta > -5°$	Caswell, 1976, MNRAS, 177, 601
22	$66 \times 100\,\sec(\mathrm{za})$	$-28° < \delta < +80°$	Roger *et al.*, 1999, A&AS, 137, 7
38	$45 \times 45\,\sec(\mathrm{za})$	$\delta > +15°$	Williams *et al.*, 1966, Mem RAS, 70, 53
178	$23 \times 18\,\sec(\mathrm{za})$	$-1° < \delta < +64.5°$	Caswell *et al.*, Mem RAS, 72, 1
400	132×102	$\delta > -32°$	Seeger *et al.*, 1965, BAIN, 18, 11
408	$\leq 51 \times 51$	All Sky	Haslam *et al.*, 1982, A&AS, 47, 1 and references therein
820*	72×72	$-7° < \delta < +85°$	Berkhuijsen, 1972, A&A, 5, 263
1410	9.4×9.4	$-3° < l < 240°, \mid b \mid \leq 4°$	Reich *et al.* 1997, A&AS, 126, 413 and references therein
1410*	9.4×9.4	Intermediate latitudes	Uyaniker *et al.*, 1999, A&AS, 138, 31
1420	35×35	All Sky	Reich *et al.*, 2001, A&AS, 376, 861 and references therein
2326	20×20	$-83° < \delta < +32°$	Jonas *et al.*, 1998, MNRAS, 297, 977
2417*	10.6×10.2	$238° < l < 365°, \mid b \mid \lesssim 5°$	Duncan *et al.*, 1997, MNRAS, 291, 279 and references therein
2695*	4.3×4.3	$-2° < l < 240°, \mid b \mid \leq 5°$	Duncan *et al.*, 1999, A&A 350, 447 and references therein
2700	8×8	$46° < l < 61°, \mid b \mid \leq 1.55°$ $190° < l < 290°, \mid b \mid \leq 1.55°$	Day *et al.*, 1972, AJP Suppl., 25, 1
4800	2.6×2.6	Cygnus X	Wendker, 1984, A&AS, 58, 291
4875	2.6×2.6	$-2.5° < l < 60°, \mid b \mid \leq 1°$	Altenhoff *et al.*, 1979, A&AS, 35, 23
5000	4.1×4.1	$190° < l < 400°, \mid b \mid \leq 2°$	Haynes *et al.*, 1978, AJP Suppl., 45, 1

* Survey contains polarization information.