Towards a Full-Stokes ALFA Continuum Survey: A Pilot Study

1 Background

This proposal is to carry out a pilot study for the GALFA Continuum Transit Survey (GALFACTS). A complete description of GALFACTS can be found in the GALFA White paper. Here we briefly summarize the scientific background.

Arecibo is the world's biggest single-dish radio telescope possessing continuous spatial frequency coverage, high surface brightness sensitivity, and arcmin-scale resolution at decimeter wavelengths. The ALFA multi-beam receiver system will allow these unique properties to be used to image large areas of the sky at $\lambda 21\,\mathrm{cm}$. Presently, the highest resolution L-band continuum surveys are those of Reich et al. (1997, A&AS, 126, 413) for $|b| \leq 4^\circ$ ($\theta_{\mathrm{HPBW}} = 9.4'$), the identical resolution images of Uyaniker et al. (1999, A&AS, 138, 31) of a few selected regions at intermediate latitudes, and Reich et al. (2001, A&AS, 376, 861) for the whole sky ($\theta_{\mathrm{HPBW}} = 35'$). Of these, only Uyaniker et al. include polarization information. In comparison, an all-sky ALFA continuum survey would provide full-Stokes data, much better sensitivity, a resolution of $3.3'$, and cover a band of 1225 – 1525 MHz, allowing imaging of Faraday Rotation. An all-sky ALFA continuum survey would have unsurpassed resolution for extended features, i.e. the Galactic background emission, HII complexes, and supernova remnants (SNRs). Many new low-surface brightness objects will be discovered. Analysis of the spectral variations over the 300-MHz ALFA band, and comparison with existing Galactic plane surveys at 2.7 & 5.0 GHz, would determine spectral-index distributions, and enable a full thermal-nonthermal separation on a few-arcmin scale. This would permit a study of relativistic electron injection and energy losses in the ISM, and vertical transport and diffusion of energy from disk to halo and into intergalactic space.

A key objective of the ALFA continuum survey is images of the linearly polarized emission over the full range of Galactic latitudes from the mid-plane to the pole. The appearance of the λ21-cm polarized sky at arcminute-scale resolution is at first bewildering. Both WSRT 327-MHz observations at high Galactic latitude and the Canadian Galactic Plane Survey (CGPS, Taylor et al. 2003, AJ, 125, 3145) at 1.4 GHz with the DRAO Synthesis Telescope, find polarized emission with little relationship between total-power and polarized intensities. We expect to detect polarization for SNRs and the diffuse Galactic synchrotron emission, but the bulk of the Galaxy imaged at L-band on arcmin scales is filled with highly structured polarization features with *no Stokes-I counterparts*. The accepted interpretation is that the distributed polarized emission arises from the intrinsically-smooth Galactic synchrotron emission, but differential Faraday rotation in the intervening magneto-ionic medium (the Faraday Screen) imposes fine structure on this; i.e. propagation effects dominate over intrinsic polarized structure. This emerging field is now moving from phenomenology to astrophysics, the signatures of the Faraday Effect on polarization revealing details of the interstellar magnetic field (RMs of compact sources) and of the magneto-ionic medium (imaging of extended emission).

Features produced by the Faraday Screen are faint – a few 100 mK at most. The limited surface brightness sensitivity of interferometers reveals only the strongest, for which derived rotation measures (RMs) are noisy. Moreover, interferometers lack short spacings, leading to complications in interpretation. ALFA promises major advances in the study of the magneto-ionic medium, particularly at mid-to-high latitudes where the background synchrotron brightness falls off. Yet this is just where critical information on the vertical structure of the Galactic magnetic field can be obtained. At higher latitudes, the magnetic field is even more significant in the ISM energy budget and likely plays a dominant role in both vertical energy transport, and the pressure equilibrium of the ISM – important factors in the wider context of galaxy astrophysics.

In existing Faraday Screen studies, the linear polarization spectrum has been used to derive a single RM value per pixel. However, the Faraday Screen is distributed in depth, and different regions of polarized emission along a sight-line contribute to the observed spectrum according to their individual RMs. With an appropriate combination of frequency, bandwidth and spectral resolution, it should be possible to perform Faraday tomography, in which the modulations of a linear-polarization spectrum can be transformed to a set of polarized intensities and position angles as a function of Faraday depth (i.e. RM). Thus, it should be possible to derive a (complex) polarized-intensity data cube, the sky coordinates being two dimensions and RM the third. Spectral resolution sets the RM range probed, while the total bandwidth determines resolution in RM. The wide bandwidth (300 MHz) and fine spectral resolution (1024 channels) combination planned for ALFA would probe RMs up to many thousand rad/m^2 with a resolution of 140 rad/m^2, or finer depending on the signal-to-noise.

An ALFA continuum survey would also measure full Stokes emission from the many background sources seen through the Galaxy at all latitudes, with the high sensitivity and multiple channels across the ALFA bandwidth, permitting a complete RM survey of background sources to very low fluxes. At low latitudes, combination of the RMs for SNRs, extragalactic sources and pulsars will allow modeling of the magnetic field distribution through the entire depth of the Arecibo-visible galactic disk. The CGPS, with a continuum rms noise $\approx$300 μJy/beam, finds a grid of background sources with sufficient polarized flux to provide a reliable RM with an area density of $\approx$1 per deg^2 over a latitude range of 8° (Brown and Taylor, 2001, ApJ 563,L31). The ALFA survey, at three times this sensitivity, gives an area density almost an order of magnitude higher over a wide latitude range, and with high RM precision, enabling an unprecedented study of the vertical structure of the Galactic magnetic field.

In addition to using RM images to probe the magneto-ionic structure of the Galaxy, the ALFA continuum survey will sample known non-thermal emission structures in the Arecibo-visible high-latitude regions; for example the North Polar Spur (Loop 1), which runs along more than 6 hr of RA visible from Arecibo. Lower resolution mapping show Loop 1 to contain rich small-scale structure on both its main arc and internal ridging. For $b > 45°$, even low-resolution Dwingeloo measurements show this nearby ($\sim$100 pc distant), old SNR to be $\approx$70% linearly polarized at 1.4 GHz. Additionally, full-Stokes mapping of the emission from nearby spiral galaxies and giant radio galaxies will add considerable information on their structures and magnetic fields.

2 The GALFA Continuum Transit Survey (GALFACTS)

An example of what is achievable with Arecibo continuum mapping is a recent L-band study of the weak SNR, G42.8+0.6, (Fig. 1). For this, orthogonal coverages were "basket-weaved" to give consistent zero levels.

An ALFA continuum survey requires a full-Stokes capable spectrometer with $\approx$1000 channels covering the 300-MHz ALFA bandwidth. For the expected performance of ALFA and the NODding approach detailed below, summed polarizations give an rms noise of $\approx 100\,\mu$Jy/beam on cold sky, well below the Stokes–I rms confusion level of $\sigma_{\rm confusion} \sim 2\,$mJy/beam. However, the linear polarization confusion level is about a factor of 100 less ($\sim$20 μJy/beam), and a very sensitive polarization survey can be made. For the signals caused by the diffuse Faraday Screen, with no Stokes–I counterparts, spurious polarization will not generally be a problem. However, to

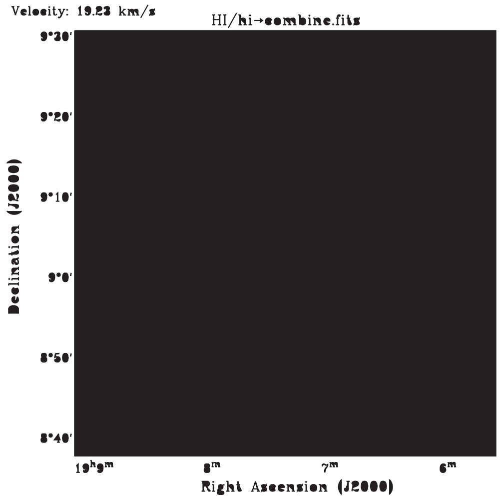

Figure 1: The 1640-MHz continuum emission from SNR G42.8+0.6 measured with the Arecibo telescope; HPBW$\sim 3'$ (Stanimirovic et al., Priv. Comm.).

measure polarization percentages for Stokes-I sources well, we must deal with the high spurious polarization responses expected for ALFA. It is unclear 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 estimates may be substantially smaller than on polarization percentage. We will measure the effect of systematics on RM as part of the pilot project described below.

The biggest problems for any ALFA continuum survey will be; a) zero-level drifts along a scan, b) $\sim$-8-dB coma lobes for the outer horns, and c) high spurious polarization responses. To minimize temporal zero-level drifts we plan to scan the telescope as fast as possible, bearing in mind that to deal with sidelobe and polarization artifacts, the data needs to be acquired as systematically as possible. A possible means to achieve this is to fix the telescope on the prime meridian and NOD it in zenith angle (ZA) at the maximum drive rate of $\sim 2.4^\circ$/min. The scan pattern projected on the celestial sky is then a zig-zag, with each "zig" crossed by many "zags" (Fig. 2). This permits 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 essentially functions of declination only (ZA mapping into Dec), 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 Dec (i.e. ZA), then the expected -8-dB spurious responses can be CLEANed to an acceptable -18 dB. Meridian NODding also assures that all sky positions are observed at their minimum ZAs, thus maximizing sensitivity. With the NODding approach, the time to map the whole Arecibo sky would be $\approx$1000 hr. Additional $cost\text{-}free$ commensal coverages could be used to study source variability.

3 A GALFACTS Pilot Study: Observations & Time request

The GALFA Continuum Subconsortium here propose pilot observations using the single-feed L-Band Wide receiver. We will observe a $1^\circ \times 10^\circ$ area of mid-latitude sky using the NODding technique described above. The region to be observed is shown in Fig. 3. It contains two bright polarized "point sources" as well as highly structured emission from the magneto-ionic Faraday

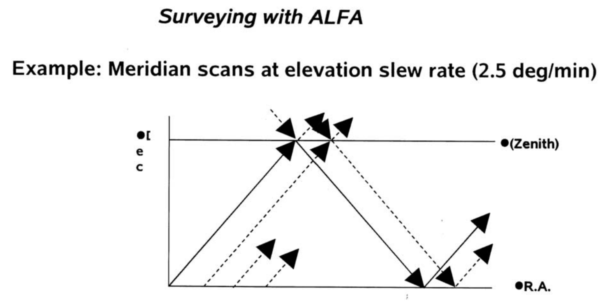

Figure 2: The "zig-zag" RA-Dec pattern produced by prime-meridian NODding. The sky north and south of the zenith must to be observed at different epochs as the telescope cannot "scan through the zenith".

Screen. In particular, dark channels are seen running down the length of the area. These channels arise due to rapidly varying Faraday Rotation either in space or frequency that leads to depolarization of the emission, especialy as observed at the low angular and spectral resolution of the Bonn observations. The much higher angular and spectral resolution Arecibo observations will probe this structure. The region will be observed twice (two independent passes), each pass taking 20 hr, including scan turnaround time, calibration, etc. Comparison of the images arising from each of the two passes will provide an assessment of the reproducibility of the results, and allow development of the processing and imaging techniques, as well as algorithms for detection of variables and transient sources. We note that apart from the technical aspects of this proposal, the high spectral resolution study of the "Faraday screen feature" will be unique to date.

We would use the L-Band Wide (LBW) receiver and select 4 bands of 100 MHz each, centered at 1170, 1405, 1475 & 1650 MHz (optimum re-RFI), using an available combination of two front-end filters (1120–1220 MHz bandpass and 1320-MHz highpass filters) to eliminate the strong radar RFI between 1220 and 1320 MHz. The WAPPs provide suitable backends, with 256 channels per 100-MHz band and we would record full-Stokes data using 2-msec dumps (9-level sampling at input, and 32-bit output) to allow interference editing through heavy oversampling. An rms noise of $\approx$65 μJy/beam is expected on each pass.

A continuously-switched, correlated CAL (switching rate: 25 Hz; step-size: $\approx$2 K) would enable continuous monitoring of gain, system temperature and polarization phase variations for the system. We would choose to make these observations at night to avoid the effects of solar interference.

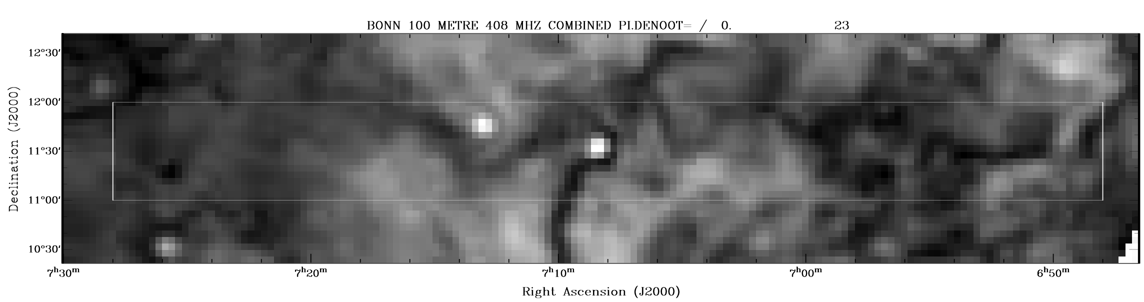

Figure 3: Polarized intensity of the 1.4-GHz emission of a region in the direction of the Galactic anti-centre (l = 205°, b = 8.5°), measured with the Effelsberg 100-m telescope (Uyaniker et al. 1999). The HPBW$\sim$ 9.4 arcmin. The area for the GALFACTS pilot study, shown by the white box, contains highly structure Faraday Screen "emission", including a dark filament where the Faraday Rotation is rapidly varying in space or frequency.