GALFACTS: The Galactic ALFA Continuum Transit Survey

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Abstract. The Arecibo Radio Telescope has been equipped with a seven feed horn array operating at 1400 MHz - the Arecibo L-band Feed Array (ALF A). This new feed system, combined with a 300 MHz digital spectrometer back end, enables the large collecting area of the Arecibo reflector to be utilized for sensitive, wide-area imaging. A consortium of over 40 researchers from around the world is working together to use this system to carry out a spectro-polarimetric imaging survey of the entire sky visible to the Arecibo Telescope; the Galactic ALFA Continuum Transit Survey (GALFACTS). GALFACTS covers 13,000 square degrees of sky, creating over this area full-Stokes image cubes at angular resolution of 3.5′ with several thousand spectral channels covering 1225 to 1525 MHz, and band-averaged sensitivity of 90 microJy. The complete survey will require about 2000 hours of observing time. Observations began in 2009 and are now 80% complete. The data will provide a rich new database for exploration of the magnetic field of the Galaxy, the properties of the magneto-ionic medium and the polarization properties of over $10^5$ extragalactic radio sources.

1. Introduction

The Arecibo 305-m antenna is the world’s largest single-dish telescope, achieving continuous spatial frequency coverage, high brightness sensitivity, and arcminute-scale angular resolution at decimetre wavelengths. The new ALFA multi-beam receiver system allows these properties to be used to efficiently image large areas of the sky at λ21 cm. The GALFACTS Consortium is using the Arecibo telescope and ALFA to carry out a sensitive, high resolution, spectro-polarimetric survey of the region of the sky visible with the Arecibo telescope – the GALFA Continuum Transit Survey, GALFACTS.

A key observational objective of the GALFACTS is to image the polarized emission from both discrete objects and the diffuse interstellar medium of our Galaxy and to derive polarization properties, including Faraday Rotation Measures for a vast population of extragalactic sources. Wide-field polarimetric imaging of Galactic emission has enjoyed a surge of activity over the past decade with the detection of highly-structured, arcminute-scale polarized radiation in interferometric images, both at high Galactic latitude, e.g. in WSRT 349-MHz images (Haverkorn 2003), and in the plane of the Galaxy with the Canadian Galactic Plane Survey (Taylor et al. 2003, Landecker et al. 2010) and Southern Galactic Plane Survey (Haverkorn et al. 2006) at 1.4 GHz. Similar structures are seen at 5 GHz by (Sun et al. 2007). These structures are superposed on the polarized emission from the diffuse Galactic synchrotron emission, but themselves have no Stokes-I counterpart. 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 due to the resulting spatial variation in polarization position angle. Propagation effects in the interstellar medium dominate over intrinsic polarized emission structure. Observations of diffuse polarized emission and of the propagation effects of the ISM on the Rotation Measures of background sources are thus powerful probes of both the relativistic and thermal plasmas of the interstellar medium.

GALFACTS is a major observational advance by virtue of its high brightness sensitivity compared to interferometric surveys, the high angular resolution compared to other single-dish telescopes and the large spectral bandwidth, which combined with high spectral resolution will allow accurate measurement of the frequency dependence of the polarization state of the emission at 1.4 GHz. Presently, the highest resolution, single-dish, L-band continuum surveys are those of the northern sky by the Effelsberg telescope (Reich et al. 1997) and in polarization by (Uyaniker et al. 1999) of a few selected regions at intermediate latitudes, both with resolution of 9.4′ and brightness sensitivities of 10’s of mK. For surveys covering a significant fraction of the sky in polarization, only significantly poorer resolution data are available; θ_{HPBW} = 35′, (Wolleben et al. 2006) at similar sensitivity (12 mk). In comparison, GALFACTS will provide full-Stokes image cubes at resolution of 3.5′, at a brightness sensitivity an order of magnitude deeper than previous work, and covering a frequency band from 1225 – 1525 MHz in spectral-line mode, allowing imaging of Faraday Rotation Measure.

2. Observations
The observations are carried out with the Arecibo L-band feed array system, ALFA. The seven feed horns of the ALFA provide seven beams on the sky with six beams arranged in a hexagonal pattern around a central on-axis beam. Each feed horn detects two nominally orthogonal states of linear polarization. Data is acquired simultaneously in each polarization channel while the feed system is alternately scanned north and south along the meridian at a rate of 1.53 degrees per sidereal minute. Combined with the Earth’s rotation, this tracking speed creates a zig-zag track pattern on the sky with the tracks from individual beams separated by 1.83′, close to Nyquist sampling for the 3.5′ FWHM beams. The tracking geometry is illustrated in Figure 1. On consecutive days the track of the central beam is shifted by 51 seconds of Right Ascension. For 18 degree long Declination scan, 28 separate days/tracks provides complete coverage.

3. Data Acquisition and Processing
The FPGA spectrometer backend (the Mock spectrometers) produces data streams for each of four polarization states and 4096 spectral channels for all seven beams in two adjacent 172-MHz bands, which together cover the 300 MHz total band from 1225-1525 MHz. During the observations a continuous square-wave noise diode signal is injected into the two polarization channels at the feed horns at 25 Hz with 50% duty cycle to calibrate the time dependence of the complex gains of the receiver system. The noise diode is injected with equal strengths into the X and Y polarization channels. Each of the fifty-six (seven beams, four polarizations, two bands) 4096-channel data streams are sampled at 1 millisecond per sample to allow the on and off states of the noise diode to be detected in post processing. The aggregate data rate is 460 MB/s.

Data are recorded directly onto disk drives at Arecibo Observatory. After each observing day the data are run through first-stage processing which separates the on and off states of the noise diode signal and time averages the data to 0.2 s sample time diode-on and diode-off data streams. These time-averaged data are shipped to the University of Calgary at the end of each observing run for further processing.
Figure 1. GALFACTS observations are made by scanning the seven-feed ALFA receiver up and down the meridian at a rate of 1.53 degrees per sidereal minute. Each day of observations creates a zig-zag patterned set of up and down “scans”, each consisting of seven sub-tracks (see inset at upper right), one sub-track from each of the ALFA beams. Main tracks for successive days of observations are separate by 51 seconds of Right Ascension. Over 28 days a fully-sampled strip of sky is covered that is 18 degrees wide in Declination over 6 hours of Right Ascension.

Calibration of the data is simplified by the fact that we observe only along the meridian at a fixed feed rotation. There are thus only three independent variables for instrumental effects, frequency, time and elevation angle. The data from each day and beam are corrected for time variations of the receiver channel gains using the noise diode signals. This process converts the raw data into Stokes parameters in units of brightness temperature. Frequency-dependent baselines are removed by fitting high order polynomials to the elevation dependence of the signal amplitude in regions removed from strong sources for each day, beam and frequency channel. The Stokes I bandpass shape and the polarization leakage corrections derived from calibration observations are then applied and the corrected data are “basketweaved” to align total intensity offsets between days and gridded into images. The frequency-dependent baseline subtraction removes the emission on spatial scales of order 10 degrees and longer. These missing spatial frequencies will be recovered by integrating data from the Global Magneto-ion Medium Survey, GMIMS (Wolleben et al. 2009). Further processing, including cleaning the dirty images to remove sidelobes from the multiple beams (Guram 2008) is carried out on the gridded image data.

The final data products from GALFACTS are spectro-polarimetric image cubes, (intensity as a function of $\alpha$, $\delta$, $\nu$), in each Stokes parameter $I$, $Q$, $U$ and $V$, with $\sim$8000 spectral channels over a 300 MHz bandwidth. For a 3.5$'$ FWHM beamsize the effective integration time per scan for a given direction on the sky is 2.4s, or a total integration time per beam area of 4.8s. For an average SEFD over the seven beams of 3.4 Jy, the theoretical noise level per 42 kHz channel is 7.5 mJy per polarization. Integrated over the full 300-MHz band the theoretical 1$\sigma$ point-source sensitivity level is 90 $\mu$Jy per polarization, or a surface brightness sensitivity of 1 mK.

A preliminary set of GALFACTS images is shown in Figure 2. These images show total intensity as well as polarized emission in Stokes parameters $Q$ and $U$ over a 170 MHz bandwidth.
Figure 2. Sample GALFACTS images of one 1700 square degree sub-region covering 18 degrees of Declination and 6 hours of Right Ascension. The top panel shows the total intensity and the middle and bottom panels shows polarized emission in Stokes $Q$ and $U$ respectively.

at 1440 MHz. The band of highly-structured emission running vertically through the total intensity image is the Galactic plane, containing the Rosette Nebula and Λ Orionis. The polarized emission is structured throughout, primarily due to spatial variations in polarization position angle from propagation of Galactic synchrotron radiation through the Faraday screen of the Galactic magneto-ionic medium. As one moves away from the plane the polarization structures persist but become smoother and larger scale. The magneto-ionic effect of the Λ Orionis bubble is clearly seen in polarized intensity, defined by a smooth circular region internal to the bubble, surrounded by a ridge of polarized emission.

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