Detection and Localization of L-Band Satellites Using an Antenna Array

Steven W. Ellingson*,[1] and Grant A. Hampson[2]
[1] *Virginia Polytechnic Institute & State University*, ellingson@vt.edu
[2] *The Ohio State University*, hampson.8@osu.edu

I. Introduction

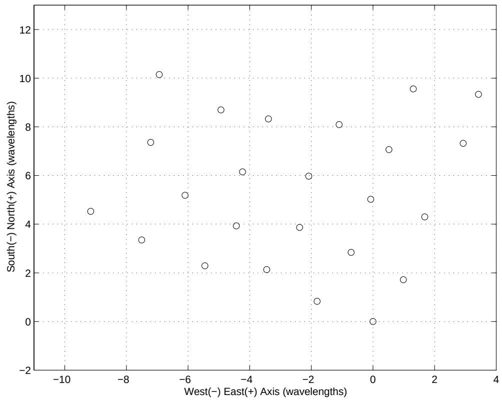
At last year's symposium we presented our work on the development of Argus, an experimental L-band radio telescope consisting of a large number of low-gain antennas networked together to facilitate detection and localization of astronomical transients over the entire sky instantaneously [1]. An initial operational capability was achieved during Summer 2003 and a series of commissioning experiments have been conducted since. In this paper, we report an experiment in which we used Argus to observe man-made satellites, namely the 1691 MHz WEFAX signal from the GOES-12 satellite and the combined 1575.42 MHz signal from the US GPS constellation. This is a useful interim step to astronomical observations because WEFAX and GPS are strong relative to astronomical sources, yet weak enough to provide a meaningful test of the ability to operate with high sensitivity in field conditions.

The experiment consists of two parts. First, we imaged the sky at 1691 MHz to demonstrate that an all-sky map is possible, and that sources present (in this case, GOES-12) can be identified in this map. Second, we observed at 1691 MHz and two additional frequencies, 1691.03 MHz (nominally signal-free) and 1575.42 MHz (a GPS center frequency), to understand to what extent it was possible to determine the actual number of sources (1, 0, and 9, respectively) directly from an analysis of the correlations among the array elements, without imaging. In addition to being a first step towards a demonstration of the ability to detect and localize astronomical sources, this experiment also suggests other possible applications of this technology, including automated detection and tracking of space-borne radio frequency interference (RFI) in support of traditional radio astronomy, and passive bistatic radar.

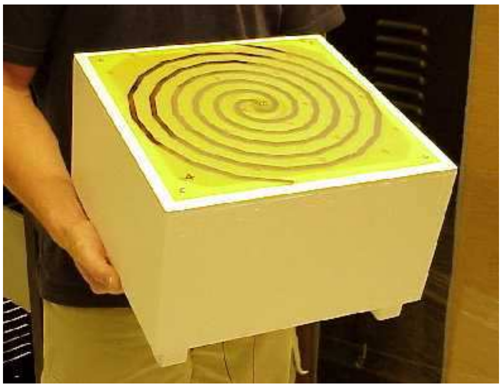
II. System Description

Argus is located on the West Campus of the Ohio State University in Columbus OH USA. For the experiment, the 24-element Argus array was arranged as shown in Figure 1. The array elements are RHC-polarized spirals in enclosures which are 33 cm across. The size of the elements precludes Nyquist sampling of the aperture, so to help mitigate aliasing a pseudorandom arrangement of elements is chosen. Integral to each antenna is an uncooled 170 K PHEMT low noise amplifier, followed by a 6-ft cable to a line amplifier which drives a 100-ft cable to a receiver room located underneath the array. There, direct conversion receivers are used to convert a 14-MHz swath of spectrum from within the L-band tuning range into a complex-valued digital signal consisting of 8-bit + 8-bit samples at 20 MSPS. A bandwidth of 60 kHz is selected from the digital passband, decimated to 78.125 kSPS, and combined with samples from the other 23 elements to form a single array snapshot. Groups of 16,384 array snapshots (209 ms) are collected and continuously transmitted to a cluster of general purpose computers using a UDP broadcast protocol over a dedicated 100 Mb/s ethernet LAN. The general purpose computers run Linux and are used to perform all subsequent processing using C language programs. For additional details, see [1].

We have experimentally confirmed effective aperture and antenna temperature, each on a per-element basis, to be $\sim$60 cm^2 (1420 MHz) and $\sim$ 215 K respectively. Given $N = 24$ antennas, bandwidth $B = 60$ kHz, and integration time $\tau = 209$ ms, we estimate the sensitivity of this system in this configuration to be $\sim(2.4 \times 10^{-22}$ W m^{-2} Hz$^{-1})\cos\theta$ where θ is the angle from zenith. In astronomical terms, this corresponds to $\sim$ 24 kJy at the zenith.



(a) Array Geometry (λ @ 1691 MHz).



(b) A single antenna element.

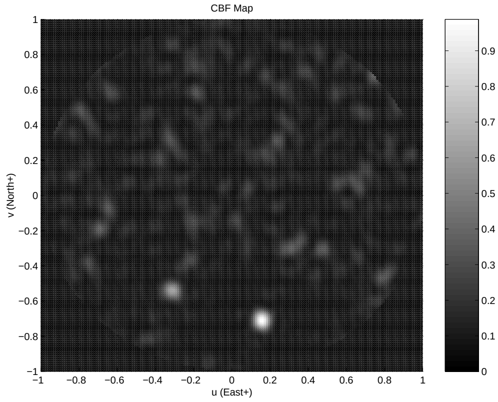
Fig. 1.

III. All-Sky Imaging

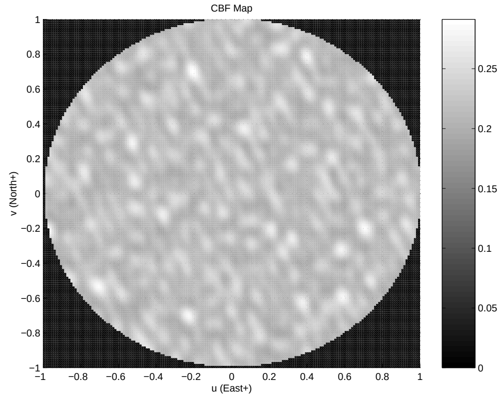
Imaging requires calibration of the array. The desired calibration consists of a measurement of the *array manifold*; that is, the response of the system to a plane wave arriving from every possible direction of arrival $\{0 \leq \theta \leq \pi/2,\ 0 \leq \phi \leq 2\pi\}$ where ϕ corresponds to azimuth. For Argus, such a measurement is simply not practical. Instead, we make the simplifying assumption that the element antenna patterns are uniform in θ and ϕ, differing by no more than complex constant. Under this assumption, the measurement of a single known source in the near field combined with knowledge of the array geometry is sufficient to define the entire array manifold. For the source, we used a small log yagi antenna mounted on a mast 122.4 cm (6.9λ) to the west, 68.1 cm (3.8λ) to the south, and 169.5 cm (9.6λ) above the southern-most element shown in Figure 1. This antenna was used to broadcast a locally-generated noise signal. The observation bandwidth of 60 kHz was large enough that we were able to position the WEFAX signal of about 30-kHz occupied bandwidth entirely in the lower half of the passband, leaving the upper half free to observe the noise source. When turned on, the noise source allows us to estimate – using just the upper (signal-free) half of the passband – the calibration magnitudes using the measured self-power per element, and the calibration phases from the inter-element correlations.

To form the map, we constructed a covariance matrix $\mathbf{R}$ from the inter-element correlations associated with the lower 30 kHz of the passband, applied the calibration determined above, and then computed the image as the angle power spectrum $\mathbf{a}^H(\theta,\phi)\ \mathbf{R}\ \mathbf{a}(\theta,\phi)$ where $\mathbf{a}(\theta,\phi)$ is the assumed array manifold (derived from the measured array geometry) sampled at θ,ϕ. The expected resolution using this technique is on the order of 6° at the zenith, degrading with decreasing elevation due to the planar configuration of the array.

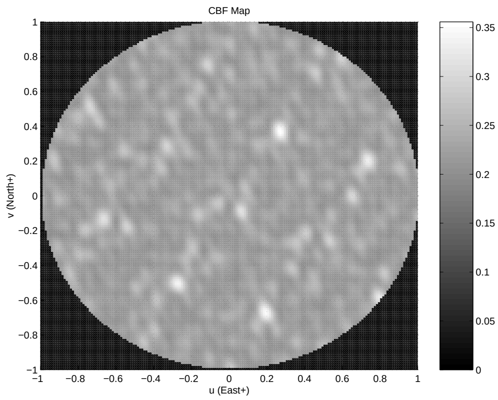
From the Argus site, the sky at 1691.0 MHz is dominated by a weather fax (WEFAX) signal, transmitted from the satellite GOES-12, which is geostationary, appearing fixed in the sky at a position of 168° north azimuth and 43° elevation [2]. (A related satellite, GOES-10, transmits on the same frequency but appears only 19° above the horizon and thus is effectively squelched by a combination of increased path loss and element antenna patterns.) The anticipated image, determined by simulation assuming infinite signal-to-noise ratio (SNR), is shown in Figure 2(a). GOES-12 appears as the bright spot at $\{u,v\} \sim \{+0.2,-0.7\}$. The sub-Nyquist array spacings result in a complex sidelobe distribution including a particularly strong peak appearing at $\sim \{-0.3,-0.6\}$. The image obtained from a 209 ms observation before and after calibration is shown in Figures 2(b) and (c), respectively. Note that the calibration is quite effective in resolving GOES-12 (as well as



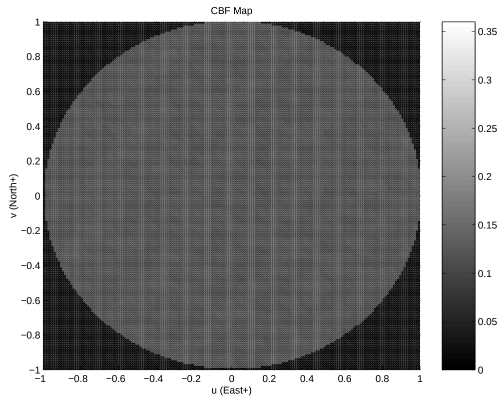
(a) 1691.0 MHz, simulated



(b) 1691.0 MHz, uncalibration



(c) 1691.0 MHz, calibrated



(d) 1691.03 MHz, calibrated

Fig. 2. Axes $\{u, v\}$ are direction cosines such that $u = v = 0$ is the zenith and $u^2 + v^2 = 1$ is the horizon.

the expected alias), although there is clearly room for improvement. The high spurious sidelobe levels evident in the calibrated image can be attributed to a combination of model assumptions (i.e., the element patterns are of course not exactly uniform in $\{\theta, \phi\}$) and errors in determining the actual array geometry.

Figure 2(d) shows the results of the same procedure applied to the upper half of the passband (centered at 1691.03 MHz) only, which is nominally signal-free, using data collected while the calibration noise source was off. Note that the resulting image is relatively uniform and dark, which confirms that the calibration is reasonable and that all structure in Figures 2(b) and (c) are due to GOES-12 and not some other source.

IV. Blind Detection

As reported in [1] and [3], it is not our intent to detect astronomical transients by means of imaging, for the reasons that the calibration necessary for imaging is relatively onerous, and that localization by imaging is not necessarily required until *after* detection. Instead, it is possible to detect the presence of sources, and to some degree the number of sources, directly from an analysis of the measured inter-element correlations represented by $\mathbf{R}$. To demonstrate this, Figure 3 shows the eigenvalues of $\mathbf{R}$ computed from 209 ms of measured (but uncalibrated) data at 1691.0 MHz, 1691.03 MHz, and 1575.42 MHz. At 1691.03 MHz, we expect to see only spatially-white noise, since detection of the strongest astronomical sources (not including the Sun, since this experiment was conducted at night) requires an increase of integration time by at least another two orders of magnitude. As a result, the associated eigenvalues are expected to be relatively uniform. Note that this is the result shown in Figure 3. At 1691.0 MHz, we expect to see only one source – GOES-12 – and this

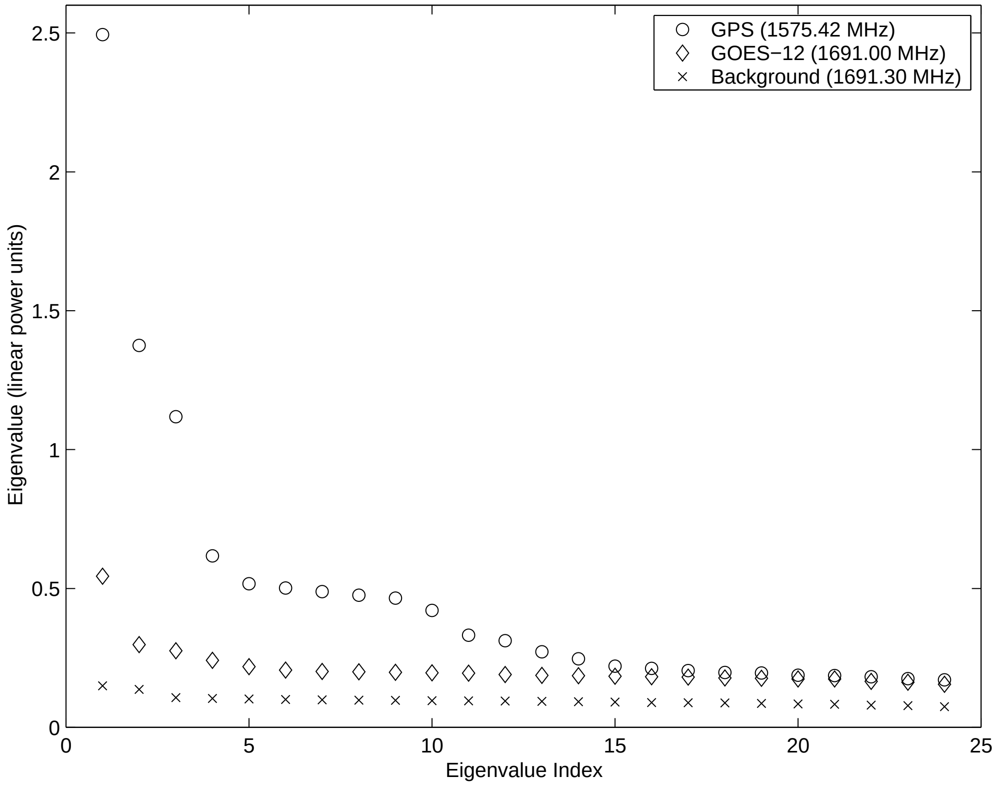


Fig. 3. Eigenvalues of the spatial covariance matrix for 30 kHz bandwidths centered at 1575.42 MHz (GPS), 1691.0 MHz (GOES-12), and 1691.03 MHz (no signal).

is reflected in the result as a 3 dB increase in the first eigenvalue relative to the second and higher-order eigenvalues. At 1575.42 MHz, we expect to see GPS satellites. At any given time, 3-4 satellites should be within the 3 dB beamwidth of the Argus elements, and an additional 3-6 satellites should be high enough in elevation to be within the 10 dB beamwidth [4]. In Figure 3, we find that the GPS constellation is detected as at least 9 eigenvalues exhibiting significant deflections from the expected noise-only values. Taking into account the 9 largest eigenvalues, the implied SNR $\sim$ 16 dB. Assuming 9 GPS C/A (narrowband) signals each being received at the typical (for a antenna temperature on the order of 290 K) value of -20 dB SNR per satellite [4], an array factor of 14 dB, and taking into account the integration time of 209 ms, the expected value is $\sim$ 24 dB. The 8 dB shortfall is attributable to the fact that the low elevation GPS satellites (there are at least 5) are not received with the nominal -20 dB SNR due to a combination of increased path loss and roll-off in the element patterns.

Acknowledgments

This project was supported in part by the SETI Institute, Mountain View, CA. Special thanks to R.S. Dixon and the volunteers of NAAPO, who have contributed substantial financial, material, and labor support to this project.

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