An Astronomer's Guide to the Arecibo 305-m Telescope

(Prepared by Chris Salter. Last revised 23 July 2009)

1 Introduction

The Arecibo 305-m radio telescope is the largest single-dish radio telescope on our planet, and is available to the global scientific community for astronomical observations at wavelengths between λ6 m and λ3 cm (frequencies of 47 MHz to 10 GHz). Over the past few years it has contributed significantly to the investigationly of solar system bodies via radar imaging, the discovery and subsequent study of new pulsars, the use of binary pulsars as laboratories for general relativity, the measurement of celestial magnetic fields via the Zeeman effect, the compiling of huge redshift surveys of galaxies, the detection of OH megamasers and other molecules in ultra-luminous infra-red galaxies, and much more besides. The study of a large number of molecular species (e.g. OH, CH, H_2CO, HCN, HC_3N, CH_2NH and CH_3OH) is now possible, the high end of the Arecibo frequency range having been "opened up" by the telescope upgrade of the mid-1990s. Additionally, new instrumentation has allowed the telescope's participation in wide-band Very Long Baseline Interferometry (VLBI) studies, adding enormously to the sensitivity of this endeavor for the imaging of the smallest scale structure in both line and continuum radio emitters. The Arecibo Telescope is a regular contributor to the HSA, EVN and Global VLBI Arrays, and participates in EVN eVLBI sessions.

With the arrival at the Observatory of the Arecibo L-band Feed Array (ALFA) in mid-2004, an exciting new facility with wide user-community appeal was added to the telescope's receiver ensemble. ALFA is a seven-feed receiver system that allows large-scale surveys of the sky to be conducted with unprecedented sensitivity. In the past, use of the telescope as a survey instrument has been limited by the relatively small field of view of its single-pixel receivers. ALFA, operating over the band 1225 - 1525 MHz, enables deep surveys for a variety of Galactic and extragalactic investigations.

The present document is intended to provide an introduction to Arecibo Observatory and the 305-m telescope both for radio astronomers wishing to have an overview of telescope capabilities, etc., and for other interested parties wanting to know whether the instrument could be an appropriate tool with which to further their research. It also aims at informing potential new users concerning the procedures for obtaining observing time.

We note here that for U.S.-based scientists without financial support from other sources, and with a scheduled research program on the telescope, NAIC will reimburse transportation costs associated with the conduct of the research program, NAIC budget permitting. The details and conditions of this are to be found at
`http://www.naic.edu/~astro/proposals/proposal.shtml#11`. (Travel support cannot

be provided for investigators not based in the U.S.A.) Similarly, NAIC will contribute towards the publication costs of results from observations carried out at Arecibo. Details of this are at `http://www.naic.edu/~astro/proposals/proposal.shtml#12`.

In Section 2, we provide an introduction to the Observatory, the telescope and its instrumentation. Section 3 lays out how to compute expected sensitivities as required for justifying the time requirements in a proposal. Section 4 deals with VLBI use of the 305-m telescope, while Section 5 informs the potential user as to when and how to submit a telescope proposal, and elaborates on the proposal procedure. Section 6 provides general information and a list of contact addresses.

2 The Arecibo Observatory and its Telescope

The Arecibo Observatory (AO) is part of the National Astronomy and Ionosphere Center (NAIC), which is operated by Cornell University under a cooperative agreement with the National Science Foundation (NSF). Use of the AO is available on an equal, competitive basis to all scientists from throughout the world to pursue research in radio astronomy, radar astronomy and atmospheric sciences. Observing time is granted on the basis of the most promising research as adjudicated by a panel of anonymous referees.

The Observatory is located in the karst hills of the Caribbean island of Puerto Rico, some 10 miles south of the coastal city of Arecibo. It was constructed in 1960-63 and upgraded, first in 1972-74, and again in 1992-98. Table 1 lists basic information on the observatory site and the telescope. The Arecibo 305-m telescope is a general-purpose meter-to-centimeter wavelength instrument. Among its many possibilities, it supports the following types of investigation;

- spectral line observing, both "pointed" observations at specific targets, and "on-the-fly" mapping,
- continuum observing in total-intensity or full-Stokes mode. Beam switching is not presently available at any frequency,
- pulsar observing, including pulsar search (targeted and survey), timing measurements, single-pulse studies, investigations of interstellar scintillation, and polarization measurements,
- VLBI observing as part of all the major VLBI networks (i.e. HSA, EVN and Global). Recording is currently made via a VLBA4 data-acquisition rack and a Mk5A recorder,
- planetary radar observing, and,
- atmospheric physics investigations.

Table 1: Basic Information on the AO Site and the 305-m Telescope

Site	
Longitude (Geodetic)	66°45′11.1″ W
Latitude	18°20′36.6″ N
Elevation of reflector center of curvature	497 m (1630 ft) above MSL
Telescope	
Primary Reflector	
Diameter of Spherical cap	305 m (1000 ft)
Radius of Curvature	265 m (870 ft)
Illuminated Area (at zenith):	
Gregorian Feeds	213 × 237 m (700 × 776 ft)
430-MHz Line Feed	305 m (1000 ft)
Surface Accuracy	2 mm (rms)
Frequency range	300 MHz $< \nu <$ 10 GHz (Gregorian)
Wavelength range	1 m $> \lambda >$ 3 cm (Gregorian)
Slew Rates:	
Azimuth	24°/min
Zenith Angle	2.°4/min
Pointing Limits:	
Azimuth	0°–720°
Zenith Angle	0°–19.°7
Declination range	−1°20′ < Dec < +38°02′
Pointing Accuracy	∼5″ (rms)

Neither planetary radar nor atmospheric physics will be specifically mentioned in this document (though some of the information included here may be of use to interested parties). Those requiring more details of the instruments available for such studies are directed to `http://www.naic.edu/~pradar/pradar.htm` for planetary radar studies, and `http://www.naic.edu/aisr/sas/sashomeframe.html` for atmospheric physics.

Additional information for all users can be found on the NAIC web site, `http://www.naic.edu`, including;

- road maps (`http://www.naic.edu/public/mapmenu.htm`),
- lodging fees (`http://www.naic.edu/science/usrweb/general/visiting.htm#roomrates`),
- telescope schedules (`http://www.naic.edu/vscience/schedule/scedfra2.htm`).

2.1 The Telescope Optics and Pointing

The main reflector of the telescope is a *fixed spherical cap*, 305 m (1000 ft) in diameter and 51 m (167 ft) deep. Its surface consists of 38,778 perforated doubly-curved aluminum panels, each measuring about 3 ft $\times$ 6 ft, supported by a network of steel cables strung across an underlying karst sinkhole.

Suspended 137 m (450 ft) above the reflector is a 900-ton triangular platform, supported by 18 cables strung from 3 reinforced concrete towers. Each tower is back-guyed to ground anchors via 7 $\times$ 3.25 inch diameter steel cables. Another system, consisting of 3 pairs of cables, runs from each corner of the platform to large concrete blocks under the reflector. These "tie-downs" are attached to giant jacks which allow adjustment of the height of each platform corner with millimeter precision, retaining the optimum focus and pointing despite changes in the ambient temperature.

Just below the triangular frame of the platform is a circular track on which the azimuth arm turns. The azimuth arm is a bow-shaped structure 100 m (328 ft) long, whose curved lower girders carry a second track, on opposite sides of which a carriage house and a geodetic (Gregorian) dome can be independently positioned anywhere up to $\sim 20°$ from the vertical. Electric motors drive the azimuth arm, the Gregorian dome and the carriage house to point to and track any requested celestial position with millimeter precision (3 mm $\sim$ 5 arcsec). Celestial tracking duration (rise to set) is given in Table 2. Tracking accuracy is about 5 arcsec (rms) at night. The pointing corrections needed to achieve this include individual offsets for each feed, as well as analytic and tabular corrections for measured errors. Coordinate conversion from B1950, J2000 and current coordinates to telescope azimuth and zenith angle is provided.

Two methods are used to correct the spherical aberration inherent in the use of a spherical primary reflector:

Table 2: Tracking Time

Declination (deg)	Tracking Time (h:mm)
–1°	0:31
0°	0:58
2°	1:30
5°	2:18
10°	2:27
15°	2:42
20°	2:46
25°	2:40
30°	2:20
35°	1:35
37°	0:57
38°	0:07

- A 96-ft long line feed tuned to 430 MHz, (and a 47-MHz point feed system), is located on the carriage house and used for ionospheric radar and some pulsar observations. This 430-MHz feed has the unique advantage of illuminating the entire reflector (at zenith), but has a bandwidth of only 10 MHz with system temperature and gain that degrade rather rapidly with increasing zenith angle.
- The system housed in the Gregorian dome provides continuous frequency coverage from 300 MHz to 10 GHz using a pair of shaped (secondary and tertiary) subreflectors, plus standard point feeds and receivers. The dome also provides weather protection. The feeds and receivers themselves are mounted on a rotating turret within the dome, allowing rapid changes (of order 30 sec) from one frequency band to another. Consecutive use of multiple receivers during an observing run is straightforward.

The available receiver systems mostly operate with considerable cryogenic cooling to minimize the noise level against which celestial sources are observed. For more details of these see Section 2.2. The 1-MW planetary radar transmitter, located in a special room inside the dome, is used to transmit radio signals to objects within our solar system. Analyzing the echoes provides information about surface properties and object dynamics.

A powerful scripting language, Tcl, has been used to develop coordinated pointing and data acquisition procedures that are constantly evolving. Our experience has been that most observers desire some tailoring of the standard procedures to their specific needs, and a graphical user interface named CIMA is available for spectral-line, continuum and pulsar observing, and to perform calibration continuum cross-scans. CIMA considerably simplifies the observing process for a majority of astronomical observations. For full details on using CIMA, go to `http://www.naic.edu/~cima` .

2.2 Available Receivers

The properties of the currently available receivers are given in Table 3. The columns of the table give the receiver name, frequency range, the typical System Temperature (T_{sys}), Gain, System Equivalent Flux Density (SEFD) and Half Power Beamwidth (HPBW) for zenith angles below 15° as measured by Arecibo staff. For more extensive performance descriptions, including the detailed changes of T_{sys}, Gain and SEFD with zenith angle (and possibly azimuth), consult `http://www.naic.edu/~astro/RXstatus/` (and there click on the link for the receiver of interest.)

Apart from single-pixel receivers covering the complete range 1.1 – 10 GHz and three bands below 1 GHz, the Gregorian dome now contains the Arecibo L-band Feed Array (ALFA), which was installed in April 2004. ALFA is a seven-feed survey instrument, covering a band of 1225-1525 MHz. It offers excellent performance, with rapid sky coverage. To exploit this instrument to the full, a number of consortia have been set up to use ALFA for Extragalactic HI (EALFA), Galactic line and continuum (GALFA) studies, and Pulsar (PALFA) searches. Results are now appearing in all these disciplines. Full details of the ALFA observing system, its performance, how to join an ALFA Consortium, and the latest ALFA news is to be found via, `http://www.naic.edu/alfa/`

2.3 Local Oscillators (LOs) and the Intermediate Frequency (IF) Chain

All receivers at the Arecibo telescope use local oscillators locked to the station hydrogen maser frequency/time standard. Commercial synthesizers in the dome and carriage house are remotely controlled to provide the first LO. The upstairs and downstairs IF chains are linked by optical fibers to bring the signal from the telescope to the control room, providing an instantaneous bandwidth of up to 1 GHz per polarization. Up to eight dual-polarization IF sub-bands (or all seven dual-polarization ALFA beams) can be selected for transmission to the observatory spectrometers, or other signal processing equipment. Doppler offsets can be applied at the first and/or second (downstairs) LOs.

Observers can select any of the receivers available in the dome feed turret or the carriage house from the control room. The selection process includes the routing of the LO reference signal, the IF signal, the positioning of the feed turret, and the loading of the appropriate pointing model.

To access detailed schematics of the IF/LO system, go to;
`http://www.naic.edu/~astro/techinfo/iflo/index.shtml/`

Table 3: Available Receivers

Receiver Designation	Freq Range (GHz)	System Temp[a] (K)	Gain[a] K/Jy	SEFD[a,b] Jy (at zenith)	HPBW[a,h] Az × ZA (Arcmin)
Carriage House					
47	-	T_{sky}	-	-	94 × 110
430ch	0.425 - 0.435	70 - 120	10 - 20	3.5 - 10	10 × 12
Gregorian Dome: Single-Pixel Receivers					
327	0.312 - 0.342	90 + T_{sky}	10.5	11	14 × 15
430	0.425 - 0.435	35 + T_{sky}	11	5	10 × 12
800[f]	0.705 - 0.800	110	9.5	12	∼6 × 7
lbw	1.120 - 1.730	25	10.5	2.4	3.1 × 3.5
sbw	1.800 - 3.100	32	9.5	3.4	1.8 × 2.0
sb	2.240 - 2.340	25	10	2.5	1.8 × 2.0
	2.330 - 2.430	25	10	2.5	1.8 × 2.0
sbh[g]	3.000 - 4.000	29	8.8	3.3	1.35 × 1.5
cb	3.850 - 6.050	31	8	3.9[c]	0.9 × 1.0
cbh[g]	6.000 - 8.000	28	5.5	5[d]	0.65 × 0.75
xb	8.0 - 10.0	33	4.5	7.5[e]	0.5 × 0.6
Gregorian Dome: Feed Array					
ALFA					
Center Pix	1.225 – 1.525	30	11	2.8	3.5 × 3.9
Outer Pixs	1.225 – 1.525	30	8.5	3.5	3.5 × 3.9

Receiver Notes

a) T_{sys}, Gain and SEFD all vary with zenith angle (and to a lesser degree with azimuth). T_{sys} and SEFD increase with zenith angle, while Gain decreases. The HPBW in ZA increases with zenith angle.

b) SEFD, the System Equivalent Flux Density (= T_{sys}/G) is the system temperature expressed in Jy/beam.

c) At 5 GHz.

d) At 6.9 GHz.

e) At 9 GHz.

f) Receiver being characterized in July 2009.

g) Receiver available on a "campaign" basis.

h) HPBW is the Half-Power Beam-Width.

2.4 Back-End Signal Processors

The Observatory provides a range of signal processing equipment, including a number of correlation and Fourier transform spectrometers, high-speed direct sampling, a variety of pulsar processors, and VLBI equipment. It also supports the use of visitor-supplied equipment, and in some cases this equipment can be made available to other users,
(cf. `http://www.naic.edu/~astro/general_info/backends.shtml`).

2.4.1 The "Interim" Correlator

For spectral-line observing, the original post-upgrade "interim" correlation spectrometer provides four independent sub-correlators, each having eight chips with 1024 lags per chip. Each sub-correlator can be set up with its own independent bandwidth and configuration. Table 4 specifies the available configurations. The maximum bandwidth per sub-correlator is 50 MHz, with 8 other alternative bandwidths being available in decreasing octave steps. Popular configurations combine chips in groups of four to provide 9-level sampling (96% efficiency), interleaved operation (50-MHz bandwidth) or auto+cross correlation (all four Stokes parameters).

2.4.2 The "WAPP" Correlator

The WAPP (Wideband Arecibo Pulsar Processor, as this device first reached astronomers as a pulsar processor, with standard spectral-line operation appearing later), is the replacement for the "interim" correlator. The WAPP provides eight sub-correlators, each of these sub-correlators having sixteen 1024-lag chips. Each of 4 pairs of sub-correlators can be set up with their own independent bandwidths and configurations. Table 5 specifies the available configurations. The maximum bandwidth per sub-correlator is 100 MHz, with 9 other alternative bandwidths being available in decreasing octave steps. The WAPP offers both 3- and 9-level operation, both for standard autocorrelation (total-power) and auto+cross correlation (all four Stokes parameters) modes. The WAPP also offers a direct-sampling option. Details of the many WAPP capabilities are to be found at
`http://alfa.naic.edu/hardware/backend/wapp_fact_sheet.html`, with the WAPP 8-board mode being described at `http://www.naic.edu/~cima/cima_dual_board.html`.

2.4.3 The "Mock" Spectrometer

The FPGA-based Mock spectrometer (named after its designer/builder, the Late Jeff Mock) contains 14 boxes, each of which contains 2 boards handling bandwidths up to 172 MHz each. To date, the Mock spectrometer has only been available for use with the ALFA 7-beam L-band array, for which the 14 boxes are divided into 2 groups of 7 boxes, each of which can be configured as an independent spectrometer. These will support all ALFA observing

Table 4: "Interim" correlator configurations with all 4 digital filter boards

Config	Max Bw per Sbc* (MHz)	Pol/Sbc*	Boards Used	Lags/Sbc* & Resn – (kms^{-1} @ 1420 MHz)
9-level	25	1	4	2048 (2.6)
9-level	25	2	4	1024 (5.2)
3-level	25	2	4	2048 (2.6)
3-level interleaved	50	1	4	4096 (2.6)
3-level interleaved	50	2	4	2048 (5.2)
3-level Stokes	25	Full Stokes	4	2048 (2.6)

* Sbc = Subcorrelator

Notes:

1) The spectrometer has its available bandwidths defined by the following filters: a) Analog filter – 50 MHz, b) Digital filters – 25, 12.5, 6.25, 3.125, 1.563, 0.781, 0.391, 0.195 MHz

2) Double Nyquist sampling can be used with all configurations except interleaved, but decreases the maximum bandwidth by a factor of two.

3) 3-level, double Nyquist, 12.5-MHz bw and below will give 4 sub-bands with better resolution than the corresponding 9-level configuration.

4) 9-level operation achieves 96% of the signal-to-noise of analog correlation, whereas 3-level achieves 81%.

5) Different correlator boards can operate with different configurations to each other.

6) The fastest dump rate for spectral-line usage is about 10 Hz.

7) The number of lags used can be reduced by a factor of 2^n down to 16 lags. The size of the output file will be proportional to the number of lags.

Table 5: WAPP spectral-line configurations with all 4 digital filter boards

Config	Max Bw per Sbc* (MHz)	Pol/Sbc*	Lags/Sbc* & Resn – (kms^{-1} @ 1420 MHz)
Single-Pixel 100-MHz Bandwidth			
9-level	100	1	2048 (2.6)
9-level	100	2	1024 (5.2)
3-level	100	1	8192 (2.6)
3-level	100	2	4096 (2.6)
3-level Stokes	100	Full Stokes	2048 (2.6)
Single-Pixel 195-kHz – 50-MHz Bandwidth			
9-level	50	1	4096 (2.6)
9-level	50	2	2048 (5.2)
3-level	50	1	16384 (2.6)
3-level	50	2	8192 (2.6)
9-level Stokes	50	Full Stokes	2048 (2.6)
3-level Stokes	50	Full Stokes	8192 (2.6)
ALFA 100-MHz Bandwidth			
3-level	100	2	4096 (2.6)
3-level Stokes	100	Full Stokes	2048 (2.6)
ALFA 50-MHz Bandwidth			
9-level	50	2	2048 (5.2)
3-level	50	2	8192 (2.6)
9-level Stokes	50	Full Stokes	1024 (2.6)
3-level Stokes	50	Full Stokes	4096 (2.6)

* Sbc = Subcorrelator

Notes:

1) The WAPP has its available bandwidths defined by the following filters: 100, 50, 25, 12.5, 6.25, 3.125, 1.563, 0.781, 0.391, 0.195 MHz

2) 9-level operation achieves 96% of the signal-to-noise of analog correlation, whereas 3-level achieves 81%.

modes that are available via the WAPPs, with which they can be operated in parallel. As the WAPPs and the Mocks include both spectral-line and pulsar observing modes, this facilitates two-way (or more) commensal observing.

It is intended that the Mock spectrometer will soon be available to operate in "single-pixel mode" for use with the observatory's single-pixel receivers.

2.4.4 The "galspect" Spectrometer

The "GALFA" spectrometer (galspect) is an FPGA-based back-end, custom-built by Jeff Mock for Galactic HI spectral-line data acquisition with the ALFA 7-beam receiver. The "galspect" spectrometer acquires both a 512-point spectrum over 100 MHz, and a parallel 8192-point spectrum over 7.14 MHz, usually centered near 1420 MHz.

2.4.5 Continuum Observing

Continuum observing at Arecibo can be made in two ways. Firstly, via detecting the signal by square-law detectors, passing the output of these through integrators, and then recording the signal as a time series via the Radar Interface (RI). The RI consists of 4×12-bit Analog-Digital converters, a fifo buffer memory, packer, multiplexer, and control system. This can take dual-polarization data at a 10-MHz rate with quantization at 2 bits, or at slower rates with higher level quantization. To use this option, the user needs to set up the last part of the signal path manually via cables. The detailed procedure for this can be found in Astronomy User's Manual and is available via the link at `http://www.naic.edu/~astro/continuum.shtml`.

Secondly, the data can be recorded via the spectral-line correlator, and the measurements treated as spectral-line observations in which the spectral channels are collapsed across frequency at some point during the analysis to give a broad-band continuum signal. This has the advantage that radio interference can be edited out before the broad-band signal is derived.

2.4.6 Pulsar Observing

A number of pulsar back-ends are available for user experiments at Arecibo. These consist of a "facility" instrument built and maintained by NAIC, the WAPP, while some "user-owned public-access instruments" have been made available to the community by their owners. The pulsar backends currently accessible by general users are summarized in Table 6.

Table 6: Publically Available Pulsar Back-ends at AO

Machine	Max BW (MHz)	Max Chan	Min Samp (μs)	Usage
WAPP[a]	100	1024	25	Search, Timing, Poln, Single Pulse
PSPM	8	128	12	Search,
”	8	128	80	Timing
ABPP	112	32	varies	Timing
”	28	32	varies	Poln
ASP	64	16	-	Poln; 16 $\times$ 4 MHz channels via ABPP
FPDAS	2000	-	0.0005	Single Pulse

Notes:

a) For the WAPP, limits on the combination of number of channels and sampling rate used is set by the output rate of the machine.

Machine	Design	Owner	Remarks
WAPP	Correlator	Facility	Presently being replicated
PSPM	Filter Bank	Wolszczan, Penn State	
ABPP	Coherent Dedispersion	Backer, Berkeley	
ASP	Coherent Dedispersion	Backer, Berkeley & Stairs, UBC	PC Cluster
FPDAS	Coherent Dedispersion	Hankins, NMT	digital oscilloscope

3 Sensitivity Considerations

The prospective new user may be unfamiliar with computing the sensitivities to be expected from using the Arecibo telescope. Hence, we present here some formulae for calculating the rms noises that can be expected for various forms of observing at Arecibo.

3.1 Spectral-Line Observing

We will consider the rms, $\sigma_{\rm T}$(K), for observations with a receiver of system temperature, T_{sys}, frequency resolution, β per polarization, and total integration time per observing cycle, τ. Note that $\beta = 1.2B/N$, where B is the total bandwidth of the spectrometer per polarization, and N is the number of independent points in the computed spectrum (e.g. the number of spectrometer channels for an unsmoothed spectrum.) If the spectrum has been Hanning smoothed, then the effective frequency resolution is broadened by a factor of about 1.67. The sensitivity calculations given below represent the analog case, and it should be remembered that 9-level operation of our spectrometer achieves 96% of the signal-to-noise of analog correlation, whereas 3-level operation achieves 81%. For the following observing modes, the theoretical sensitivities are;

- **Total-Power Observations:** Here, all the observing time is spent looking at the target ("Point-and-Shoot"). This gives, $\sigma_{\rm T} = \mathrm{T}_{sys}/\sqrt{(\beta\tau)}$ per polarization, or $\sigma_{\rm T} = \mathrm{T}_{sys}/\sqrt{2\beta\tau}$ if both polarizations are averaged to obtain the final spectrum. Pure total-power observations are found to be adequate for many Arecibo observation, especially if narrow total bandwidth observing is to be used (say less than 1 MHz total), and has even been used for relatively short integrations on Galactic HI. Note that this is also the case for total-power continuum observations.

- **"In-Band" Frequency switching:** NOTE: Frequency switching is NOT presently supported, although its efficacy at Arecibo has been investigated.

  For "in-band" frequency switching, the line under investigation is always in the observing band. For each of the two positions where the line falls, only one half of the time is spent looking at the line, with noise being present all the time. Using a "flip, shift and average" operation on the raw frequency-switched spectrum, gives, $\sigma_{\rm T} = \sqrt{2}\mathrm{T}_{sys}/\sqrt{\beta\tau}$ for a single polarization, or $\sigma_{\rm T} = \mathrm{T}_{sys}/\sqrt{(\beta\tau)}$ if both polarizations are averaged to obtain the final spectrum.

- **Position Switching or "Out-of-Band" Frequency Switching:** Here the line is only observed for one half of the time, with noise being present all of the time. This gives, $\sigma_{\rm T} = 2\mathrm{T}_{sys}/\sqrt{\beta\tau}$ per polarization, or $\sigma_{\rm T} = \sqrt{2}\mathrm{T}_{sys}/\sqrt{\beta\tau}$ if both polarizations are averaged to obtain the final spectrum. Note that this is also the case for simple Dicke-switched continuum observations.

- **Position Switching on a Target Source, and a Band-Pass Continuum Calibrator:** When the simple position-switched technique is used to measure the emission or absorption line spectrum of a source that also has significant continuum emission, problems can arise due to residual standing waves for any telescope with a partially blocked aperture. An extreme case of aperture blockage occurs with the Arecibo 305-m radio telescope, where the feed support platform and a good fraction of its support cables are situated within the volume traversed by the incoming rays focused on the telescope feed. This large structure can also scatter significant amounts of radiation from the surrounding hills, and other sources of radiation arising outside the telescope main beam.

  The usual solution, to employ simple ON/OFF position switching, breaks down when the target is observed against significant continuum radiation. Under these circumstances, the component of the standing-wave pattern due to the continuum emission from the direction of the target source is not cancelled at all by subtracting the source-free OFF data from the ON, and a standing-wave residual whose amplitude is proportional to the source intensity remains to degrade the spectrum. To minimize the effects of the residual standing wave when observing a strong continuum source, another (reference) continuum source, (preferably chosen to have different redshift to avoid its possessing an emission or absorption line near the same frequency as the target), is also observed in the same ON/OFF position-switched mode. The azimuth-zenith angle track followed during this observation should be made to be as near as possible to that for the target source. Division of the target spectrum by that of the reference source then cancels the residual standing wave, and results in a spectrum whose magnitude is proportional to the ratio of the target and reference flux densities across the observing bandwidth, including any spectral-line component that may be present in the target.

  If equal time is spent on the target and reference cycles, the line is observed for one quarter of the time, but noise is observed all the time. This gives, to first approximation, $\sigma_{\mathrm{T}} = 4\mathrm{T}_{sys}/\sqrt{\beta\tau}$ per polarization. Note that T here is not just the "blank-sky" system temperature, but should allow for the contribution due to the continuum reference emission of the target and reference sources, i.e. if both have a flux density, S Jy, then T_{sys} should be increased by $\Delta\mathrm{T}_{sys}(K) = S/2 * \mathrm{G}(za)$, where $\mathrm{G}(za)$ is the telescope gain (in K/Jy) at zenith angle, za.

  For full description of the technique and the detailed sensitivity considerations, see `http://www.naic.edu/~astro/aotms/performance.shtml`, and then click on report "2001-02.ps".

3.2 Pulsars

For a pulsar search observation, with the two polarizations averaged, a useful rule of thumb can be given for calculating the expected rms noise. If the rms noise, σ, is expressed in terms of the flux density of the target pulsar, then;

$$\sigma = \frac{T_{sys}}{G\sqrt{2\beta\tau}} \left(\frac{w}{P-w}\right)^{0.5} \text{Jy}$$

Where, T_{sys} is the system temperature, including the contributions from the celestial background and, if appropriate, any continuum emission from a host supernova remnant, etc., G is the telescope gain (in K/Jy), β is the system bandwidth, τ is the total integration time of the observation, P is the pulsar period, and w is the effective duration of the pulsar pulse.

4 Very Long Baseline Interferometry (VLBI) Observing at Arecibo

NAIC presently commits Arecibo to supporting VLBI observing up to a maximum of 4% of the 305-m's observing time. A hydrogen maser frequency standards is available for VLBI recording at Arecibo. The maser is a model from Symmetricon Inc. (ex-Datum/Sigma-Tau), Model No. MHM2010. For information on this unit see `http://www.symmttm.com/products_pfr_MHM2010.asp`. As well as being used as the primary Arecibo frequency standard, the maser serves as the master clock of the Observatory.

Arecibo is equipped with a a VLBA4 recording system, compatible with the VLBA, EVN and Global networks, and the 305-m telescope is now available for scheduling in conjunction with all 3 networks. Any proposer wishing to include the 305-m telecope in their VLBI observations should submit their proposals for the VLBA, the EVN or Global networks as usual, rather than to Arecibo. In all proposals, special justification for the use of Arecibo should be included. (Observations with ad-hoc arrays will also be considered, but in this case proposals should be submitted to Arecibo as specified at `http://www.naic.edu/~astro/proposals/proposal.shtml`. It is the proposers' responsibility to ensure that telescope time be granted by the other observing facilities involved.)

In the summer of 2004, Arecibo took delivery of a Mark-5A disk-based VLBI recording system. This uses the VLBA4 Data-Acquisition Rack, together with the Mark-5A unit. The Mark-5A system allows recording up to a 1 GBit/s data rate. The Mark-5A system allows Arecibo to participate in real-time e-VLBI with EVN.

5 Submitting a Telescope Proposal

Potential users of the 305-m telescope should submit their proposals via the web-based submission procedure described below (the preferred option) or, if this is not possible, send them by “snail mail” to the Observatory Director at Arecibo. In their proposal, they should describe the desired observations and give justifications for the scientific aims and the amount of telescope time requested. Proposals are accepted for 3 deadlines per year, and are evaluated by a panel of anonymous referees associated with neither NAIC nor Cornell University.

5.1 Proposal Deadlines and Procedures

The proposal deadlines are February 1, June 1, and October 1, although proposals may be submitted at any time. Following refereeing, each proposal will be allocated a "broad ranking" and a recommended amount of observing time should the proposal get scheduled.

Those interested in submitting a VLBI proposal using Arecibo should read Section 4.

5.2 How to Propose

Full details on the proposal procedure, etc., can be found at;
`http://www.naic.edu/~astro/proposals/proposal.shtml`.

In short, a proposal is composed of:

- a cover sheet containing, among other information, the proposal title, abstract, author contact information, time request, required instrument specifications, RFI considerations, and object(s) to be observed. The proposal cover-sheet should be submitted via a web-based form to be found at,
  `http://www.naic.edu/~astro/proposals/cover.html`, . Full details of the submission procedure will also be found at this web address.
- A scientific and technical justification submitted separately from the cover sheet as a postscript file via e-mail, or as a hardcopy by post.

Following the submission of a proposal, the Observatory will notify the proposers that the proposal has been received and specify an identification number. Astronomy proposals will be sent on to a number of anonymous referees (neither NAIC nor Cornell staff, but with different referees for pulsar and non-pulsar astronomy). The recommendations of the referees serve to guide the Arecibo Scheduling Advisory Committee (ASAC) in respect of time allocation and relative ranking of all proposals. The ASAC meets as soon as the referees' grades and comments have all been received. Subsequently, proposers will be notified of the outcome for their project. Referee comments and grades are made available to proposers at this time, as are the "broad rankings" allocated by ASAC. These "broad rankings" are as follows:

A: It is intended to schedule the proposal, which will remain active until this happens. Resubmission is not needed even if scheduling takes more than the usual 8 months.

B: The proposal will be scheduled only if time is available. If not scheduled within the next two 4-month scheduling periods (beginning 4 months after the proposal deadline), the proposers will need to resubmit. (In other words, "B-graded" proposals have an active life of 8 months before requiring resubmission, perhaps with modifications in the light of the referees' comments.)

C: The proposal is unlikely to be scheduled. The proposer is invited to submit a revised version.

The scheduler (Hector Hernandez) will now prepare the telescope schedule for the coming months, guided by the deliberations of ASAC. It should be emphasized that because of the special requirements of the different research areas which use the telescope, and the semi-transit nature of the instrument, scheduling is a difficult task requiring interaction with proposers and the flexibility to accommodate what are often conflicting demands. Therefore, it is not always possible to schedule in a "linear" fashion strictly following priorities, nor is it possible to schedule everything four months in advance. Depending on circumstances, some proposals will take longer to be placed on the schedule than others.

6 Observatory Contacts

6.1 General Information

The U.S. Postal Service (USPS) "snail mail" address for Arecibo Observatory is:

```
Arecibo Observatory
HC3 Box 53995
Arecibo
Puerto Rico, PR00612
U.S.A.
```

However, letters and parcels sent via "courier services" such as Fed-Ex, USPS, Airborne, etc., must use the physical address of the Observatory:

```
Arecibo Observatory
Route 625
Bo. Esperanza
Arecibo
Puerto Rico, PR00612
U.S.A.
```

All telephones at the Observatory have extensions to the basic observatory number (787)-878-2612. The extension should be dialed when prompted by the recorded introduction. FAXes to the Observatory should be sent to (787)-878-1861.

6.2 Points of Contact

Points of contact from whom information can be obtained are listed below. All can be reached by phone or e-mail, where local e-mail addresses take the form jastrono@naic.edu.

Function	Name	Tel Ext	e-mail @naic.edu	Remarks
NAIC Director	Don Campbell	-	campbell	Cornell based
Administrative Director	David Howe	-	dhowe	Cornell based
Observatory Director	Mike Nolan	212	nolan	
Telescope Scheduler	Hector Hernandez	308	hhernand	
Dept. Head, Planetary Sci.,	Mike Nolan	212	nolan	
Asst. Dir. Atm. Phys.	Sixto Gonzalez	252	sixto	
Dept. Head Radio Ast.	Murray Lewis	285	blewis	
Dept. Head Computing	Arun Venkataraman	340	arun	
Dept. Head Electronics	R. Ganesan	336	ganesh	
Travel, reimbursement, VSQs[a], logistics, etc.	Carmen Segarra Carmen Torres	210 303	csegarra ctorres	

a) VSQ = Visiting Scientist Quarters

Questions on specific technical topics can also be addressed to the following points of contacts, whose e-mail names and phone extensions are in parentheses after their names;

- Spectral line: Murray Lewis (blewis; ext 285), Tapasi Ghosh (tghosh; ext 289), Chris Salter (csalter; ext 281), Robert Minchin (rminchin; ext 283), Ji-hyun Kang (jkang; ext 305)
- Continuum: Chris Salter (csalter; Ext 281), Robert Minchin (rminchin; ext 283)
- Pulsars: Julia Deneva (deneva; ext -)
- VLBI: Tapasi Ghosh (tghosh; ext 289), Chris Salter (csalter; ext 281)
- Solar System Radio Ast.: Ellen Howell (ehowell; ext 282)
- Planetary Radar: Mike Nolan (nolan; ext 212), John Harmon (harmon; ext 284), Ellen Howell (ehowell; ext 282), Patrick Taylor (ptaylor; ext 280)
- Radio Frequency Interference (RFI): Murray Lewis (blewis; ext 285).

To find information concerning a particular receiver system, you may prefer to consult the "Friend of the Receiver", who is identified at; `http://www.naic.edu/~astro/RXstatus/`.