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

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1 Introduction

The 305-m William E. Gordon radio telescope at Arecibo is one of the two largest single-dish radio telescope on our planet, and is available to the global scientific community for astronomical observations at wavelengths between λ1 m and 3 cm (frequencies of 300 MHz to 10 GHz). Over the past few years it has contributed significantly to ;

- investigations 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 search for long-wavelength gravitational waves,
- the discovery and study of the only known repeating Fast Radio Burst (FRB),
- the determination of celestial magnetic fields via the Zeeman effect,
- the large-area mapping of HI and continuum emission,
- 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 frequency range having been "opened up" by the Arecibo telescope upgrade of the mid-1990s. Additionally, appropriate instrumentation has allowed the telescope's participation in wide-band Very Long Baseline Interferometry (VLBI), 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, Global VLBI Arrays, and also participates in EVN eVLBI.

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. Previously, use of the telescope as a survey instrument was limited by the relatively small field of view of its single-pixel receivers. ALFA, operating over the band 1225 – 1525 MHz, facilitates the making of deep surveys for a wide variety of Galactic and extragalactic investigations.

The present document is intended to provide an introduction to Arecibo Observatory and its 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.

In Section 2 of this document, 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 the University of Central Florida under a cooperative agreement with the National Science Foundation (AST-1822073), and in alliance with Universidad Ana G. Méndez and Yang Enterprises. 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 lies 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, are support of the following types of investigation;

- spectral line observing, both “pointed” investigations of specific targets, and “on-the-fly” mapping, Total-intensity or On-Off observations are the standard observing modes.
- continuum observing in total-intensity or full-Stokes mode. Beam switching is not presently available at any frequency,
- pulsar and Fast Radio Burst (FRB) observing, including pulsar search (targeted and survey), timing, single-pulse, interstellar scintillation, and polarization studies,

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

Site	
Longitude (Geodetic)	$66^{\circ}45'11.1''$ W
Latitude	$18^{\circ}20'36.6''$ 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	$2\overset{\circ}{.}4$/min
Pointing Limits:	
Azimuth	0°–720°
Zenith Angle	0°–$19\overset{\circ}{.}7$
	($1\overset{\circ}{.}06$ –$19\overset{\circ}{.}7$ in tracking mode)
Declination range	$-1^{\circ}20' <$ Dec $< +38^{\circ}02'$
Pointing Accuracy	$\sim 5''$ (rms)

- VLBI observing as part of the major VLBI networks (i.e. HSA, EVN and Global). Recording is currently made via a RDBE digital backend and a Mk6 recorder.
- planetary radar observing, and,
- atmospheric physics investigations.

Neither planetary radar nor atmospheric physics will be specifically mentioned in this document, (although some information included here may be of use to scientists active in these disciplines). Those requiring more details of the instruments available for such studies are directed to `http://www.naic.edu/~pradar/` for planetary radar studies, and `https://www.naic.edu/ao/space-atmospheric-sciences` for atmospheric physics.

General information can be found on the NAIC web site, `http://outreach.naic.edu/ao/landing`, including;

- Driving directions and observer lodging bookings: (`http://outreach.naic.edu/ao/lodging-facilities`),
- 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 × 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 suspended from 3 reinforced concrete towers. Each tower is back-guyed to ground anchors via 7 × 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 $\sim 20^\circ$ 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 Galactic, B1950, J2000 and current coordinates to telescope azimuth and zenith angle is provided.

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

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

- A 96-ft long line feed tuned to 430 MHz 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. (N.B. This line feed was severely damaged by the passage of Hurricane Maria in Sept. 2017. As of today – August 4, 2020 – the feed is not available for observations. However, planning for its repair and recommissioning is underway.)
- 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 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 S-band 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 many 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.)

As well as the single-pixel receivers which cover essentially the complete range 1.1 – 10 GHz and two bands below 1 GHz, the Gregorian dome contains the Arecibo L-band Feed Array (ALFA). This 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. Full details of the ALFA observing system, its performance, and the latest ALFA news are 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

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,f] Az × ZA (Arcmin)
Carriage House					
430ch[g]	0.425 – 0.435	70 - 120	10 - 20	3.5 - 10	10 × 12
Gregorian Dome: Single-Pixel Receivers					
327	0.312 – 0.342	$90 + T_{\text{sky}}$	10.5	11	14 × 15
430	0.425 – 0.435	$35 + T_{\text{sky}}$	11	5	10 × 12
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
sbn	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	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
cbw[d]	4.000 – 8.000	–	–	–	–
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	3.3 × 3.7
Outer Pixs	1.225 – 1.525	30	8.5	3.5	3.3 × 3.7

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) The C-Band Wide receiver was installed in the Gregorian Dome in July 2017, and is currently (August 4, 2020) being commissioned. When the receiver is ready for observations, performance figures across the band will be added to this table.

e) At 9 GHz.

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

g) The 430-MHz CH line feed was severely damaged by the passage of Hurricane Maria in Sept. 2017. As of today (August 4, 2020) this feed is not available for observations. However, planning for its repair and recommissioning is underway.

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/`

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.

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 (i.e. all four Stokes parameters).

2.4.2 The "WAPP" Correlator

The WAPP, (so-named for "Wideband Arecibo Pulsar Processor", it having first become available to astronomers as a pulsar processor, with standard spectral-line modes appearing later), was nominally 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 3- and 9-level operations, 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://www.naic.edu/alfa/gen_info/wapp_fact_sheet.shtml`, with the WAPP 8-board mode being described at `http://www.naic.edu/~cima/cima_dual_board.html`.

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%.

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 per board. Initially, the Mock spectrometer was only 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 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.

The Mock spectrometer is also available in “single-pixel mode” for use with the observatory’s single-pixel receivers. Details can be found at
`http://www.naic.edu/~phil/hardware/pdev/singlePixelSpecs.html` .

General details of Mock spectrometer operations can be found at
`http://www.naic.edu/~astro/mock.shtml` .

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 PUPPI Pulsar Backend

The “Puertorican Ultimate Pulsar Processing Instrument” (PUPPI) is a backend built with off-the-shelf hardware designs, and custom FPGA “Gateware”. This gateware is compiled and loaded into the 7 Xilinx FPGA’s used for PUPPI’s implementation. It is a clone of the Green Bank Observatory GUPPI instrument.

PUPPI is fully integrated into the Arecibo observing software, and non-expert users are encouraged to include its usage in their telescope proposals. In search mode, the PUPPI backend provides a maximum bandwidth of 800 MHz, up to 2048 spectral channels, and 40.96 μsec minimum sampling time. In addition, 20.48 μsec sampling is possible in on-line folding mode. For more details, potential users can refer to the GUPPI on-line manual at
`https://safe.nrao.edu/wiki/bin/view/CICADA/GUPPiUsersGuide` .

2.4.6 Continuum Observing

Continuum observing at Arecibo can be made in two ways. Firstly, via 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 a spectral-line spectrometer, and the measurements treated as spectral-line observations in which the spectral channels are subsequently collapsed across frequency during data analysis to give a broad-band continuum signal. This has the great advantage that radio interference can be edited out before the broad-band signal is derived.

2.4.7 Pulsar Observing

A number of pulsar back-ends are available to Arecibo users. These consist of "facility" instruments maintained by NAIC, namely the WAPP, the Mocks, and PUPPI. These pulsar backends 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]	8 × 100	1024	25	Search, Timing, Poln, Single Pulse
Mocks	7 × 300	per box 8192	65	ALFA Search
	1000	per box 8192	65	Single-Pixel Search & Timing
PUPPI	800	2048	41	Single-Pixel Search
	800	2048	20.5	On-line folding

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	ALFA or Single-pixel
Mocks	FPGA FFT Spectrometer	Facility	ALFA or Single-pixel
PUPPI	FPGA Spectrometer	Facility	Single-pixel

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, $\sigma_{\mathrm{T}}(\mathrm{K})$, 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, $\sigma_{\mathrm{T}} = \mathrm{T}_{sys}/\sqrt{(\beta\tau)}$ per polarization, or $\sigma_{\mathrm{T}} = \mathrm{T}_{sys}/\sqrt{2\beta\tau}$ 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: Traditional 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, $\sigma_{\mathrm{T}} = \sqrt{2}\mathrm{T}_{sys}/\sqrt{\beta\tau}$ for a single polarization, or $\sigma_{\mathrm{T}} = \mathrm{T}_{sys}/\sqrt{(\beta\tau)}$ 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, $\sigma_{\mathrm{T}} = 2\mathrm{T}_{sys}/\sqrt{\beta\tau}$ per polarization, or $\sigma_{\mathrm{T}} = \sqrt{2}\mathrm{T}_{sys}/\sqrt{\beta\tau}$ 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 simple position-switching 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, especially for any telescope with a partially blocked aperture. The Arecibo telescope represents an extreme case of aperture blockage, with the suspended platform and a good fraction of its support cables being situated within the volume traversed by the incoming rays focused on the telescope feed. This structure also scatters significant amounts of radiation from the surrounding hills, and other sources of radiation arising outside the telescope main beam.

  For simple ON/OFF position switching on a target possessing significant continuum radiation, the standing-wave pattern due to the continuum emission from the target source is not at all cancelled by subtracting the source-free OFF data from the ON. A standing-wave residual whose amplitude is proportional to the source intensity remains to degrade the spectrum. To minimize the effects of this residual standing wave when observing a strong continuum source, another (reference) continuum source, (preferably of different redshift to avoid it having an emission/absorption line near the line frequency of the target), is also observed in ON/OFF mode. The azimuth-zenith angle track followed during this observation should be as near as possible that for the target source. Division of the (ON $-$ OFF) target spectrum by that of the reference source then cancels the residual standing wave, and yields a spectrum whose magnitude is proportional to the ratio of the target and reference flux densities across the observing band, 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 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 details of the technique and sensitivity considerations, see;
  `http://www.naic.edu/~astro/aotms/performance.shtml`, , 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;

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

Where, T_{sys} is the system temperature, including the contributions from the celestial back-ground 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) at Arecibo

Arecibo presently supports VLBI for up to a maximum of 4% of its astronomy observing time. A hydrogen maser frequency standard is available for VLBI (Model No. SOHM-4A). The maser also serves as the Observatory master clock.

Arecibo VLBI backend was upgraded in 2019. The new backend consists of a dual Roach Digital Back End digital receiver (RDBE) and a 64 GB RAM Mark6 ethernet recorder. The system can process 512 MHz bandwidth both in PFB (Polyphase filter Bank) and DDC (Direct digital conversion) modes of operation, supports 4096 Mbps recording speed, and has 32 TB of disk capacity. With this upgrade, the 305-m telescope is compatible with European VLBI network (EVN) and High sensitivity array (HSA). The system supports data e-shipping to the EVN software correlator at JIVE. For HSA, the data is transported by shipping the disk packages.

Any proposer wishing to include the 305-m telecope in their VLBI observations should submit a proposal to the HSA or EVN, rather than to Arecibo. All proposals should contain special justification for inclusion of Arecibo. (Observations with "ad-hoc" arrays will also be considered. 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 all observing facilities involved.)

5 Submitting a Telescope Proposal

Potential users of the 305-m telescope should submit their proposals via the web-based submission procedure described below. Proposals should describe the desired observations and justify the scientific aims and telescope time request. Proposals are accepted for 2 deadlines per year. They are evaluated by a panel of anonymous referees associated with neither NAIC nor the Observatory's "management troika".

5.1 Proposal Deadlines and Procedures

Proposal deadlines are the first Thursday in March and September of each year. The corresponding scheduling terms are July 1 – December 31 and January 1 – June 30. After refereeing, each proposal is allocated a "broad ranking" and a recommended amount of observing time should the proposal be scheduled (see Section 5.2).

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

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 summary, a proposal is composed of:

- a cover sheet containing, among other information, the proposal title, scientific and outreach abstracts, 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 form to be found at, `http://www.naic.edu/~astro/proposals/cover.html`. Full details of the submission procedure are also to be found at this web address.
- A scientific and technical justification in pdf format should be submitted separately from the cover sheet. This is uploaded via the above web page,

Following the submission of a proposal, the Observatory will notify the authors that it has been received and specify an identification number. Proposals will be sent out to a number of anonymous referees (neither NAIC nor “management troika” staff, but with different referees for planetary radar, pulsar, non-pulsar astronomy, and space and atmospheric physics.) The recommendations of the referees serve to guide the Arecibo Scheduling Advisory Committee (ASAC) in respect of the time allocation and relative ranking of all proposals. The ASAC meets as soon as the referees' grades and reviews have all been received. Subsequently, proposers are 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: Such proposals will be put into the scheduling queue and scheduled for the time awarded during the semester for which they were accepted, or if that proves impossible during the subsequent semester.

B: These proposals will often be scheduled in the semester(s) for which they were accepted. If they are not scheduled during that period, they expire and resubmission will be required. Allocation of the full requested or allocated observing time is not guaranteed.

C: Such proposals are not considered ”approved projects” but may be scheduled owing to low proposal pressure within the relevant LST range. They are in effect ”filler” projects. They will only be considered for scheduling in the semester(s) for which time was originally requested. The proposer is invited to submit a revised version.

D: These proposals will not be scheduled.

The scheduler (Hector Hernández) 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 accommodating every priority. Nor is it possible to schedule everything some 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, PR 00612-8346
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 introductory message. A staff directory can be found at `https://www.naic.edu/ao/general-tools/staff-finder`. 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. Where non-naic.edu e-mail addresses are preferred, these are given in the table below.

Function	Name	Tel Ext	e-mail @naic.edu	Org.
NAIC/Arecibo Director	Francisco Cordova	212	Francisco.Cordova at ucf.edu	UCF
Science Operations Director	Christiano Brum	242	cbrum	UCF
Telescope Scheduler	Hector Hernández	308	hhernand	YANG
Radio Astronomy Lead	Anish Roshi	315	aroshi	UCF
Planetary Studies Lead	Anne Virkki	337	avirrki	UCF
Dept. Head Computing	Arun Venkataraman	340	arun	YANG
Dept. Head Electronics	Luis Quintero	320	lquintero	YANG
Telescope Ops. Head & Spectrum Mgr.	Angel Vazquez	304	angel	YANG
Office Manager	Carmen Rosario	267	crosario	UCF

Questions on specific technical topics for astronomy and planetary studies can also be addressed to the following points of contacts, whose e-mail names (@naic.edu) and phone extensions are in parentheses after their names;

- Spectral line: Anish Roshi (aroshi; ext 315, or 434-284-2647),
- Continuum: Anish Roshi (aroshi; ext 315, or 434-284-2647), P.K. Manoharan (mano.rac at gmail.com, ext 617)
- Pulsars: Benetge Perrara (bhakthiperera at gmail.com; ext 204), P.K. Manoharan (mano.rac at gmail.com, ext 617)
- VLBI: Anish Roshi (aroshi; ext 315, or 434-284-2647), P.K. Manoharan (mano.rac at gmail.com, ext 617)
- Solar System Radio Astronomy & Planetary Radar: Anne Virkki (avirkki; ext 337)
- Radio Frequency Interference (RFI): Angel Vazquez (angel; ext 304).

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/`.