Fifty Years of Radio Science at Arecibo Observatory: A Brief Overview.

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Abstract

As the 50th anniversary of Arecibo Observatory (AO) approaches it is appropriate to note the vast influence the many radars and ionospheric heaters that have been deployed on or near the 305 m dish have had on radio science and related fields. Of course William E. (Bill) Gordon's original idea concerning incoherent scattering is the seed from which all this grew; although, that Gordon was Henry Booker's student and then colleague, set the stage. Much of this history is found in a recent paper by the author [1]. Here we summarize a few high points and include some material—particularly concerning the ionospheric heating facilities—that was not available for the earlier publication. And, as noted in the earlier paper, this history surely has some gaps. The community is encouraged to fill these gaps and to help complete the history.

Introduction

As is true in all areas of research, we benefit from understanding the history of the subject and often become aware of still open but forgotten questions. Put another way, the radio science community will benefit from understanding how various science and engineering questions arose and were solved or left open. And, perhaps most importantly, we gain insight into the personalities who pioneered, in this case, Arecibo Observatory. The journal History of Geo- and Space Sciences (HGSS; http://www.history-of-geo-and-space-sciences.net) has initiated a special series on "The history of ionospheric radars" [2]. Here we introduce this series to the URSI community as well as introduce an occasional "History of Radio Science" series to appear in the URSI (International Union of Radio Science) Radio Science Bulletin (RSB).

In their HGSS article Pellinen and Brekke [2] give a thumbnail history of radar beginning with the first patent for what we now know as radar and, not surprisingly, by citing Marconi as a pioneer of the field. A more complete history of radar is given by Buderi [3] with various more specialized histories given by Butrica [4] and in the introduction of another of the author's papers [5]. Again, this article on AO serves to introduce the RSB history series and to update [1] that gives a much more complete history of geophysical radar at AO. In this paper we give some details from a famous, to this community, 1958 URSI meeting held at Penn State as well as update the evolution of AO on-dish HF heater feeds and transmitters.

Before Incoherent Scatter Radar

As is well documented [[1] and references therein], the initial manifestation of Arecibo Ionospheric Observatory (AIO) was built over the period from June 1960 through August 1963 with the formal dedication of the facility occurring on 1 November 1963. Cornell managed AIO—first for the Air Force and then, beginning in 1969, for NSF (National Science Foundation)—from its inception through 30 September 2011 after which new management under the lead of SRI International began operations.

AIO with the 305 m dish and 430 MHz radar was primarily intended for incoherent scatter radar studies of the Earth's ionosphere. The story of the path William E. Gordon traversed on the way to AIO first light is given by [6], [7], [8], [1], and others. Professor Gordon conceived of the concept of incoherent scattering and ultimately of the Arecibo 305 m dish in the spring of 1958. The rapid evolution of Gordon's idea of incoherent scattering from free electrons in the earth's ionosphere is reflected in the 29 May 1958 Cornell School of Engineering seminar announcement reproduced as Figure 6 in Cohen [8]. Cohen also reports an April 1958 presentation to the Cornell ionosphere group on these earliest ideas. The idea progressed further with Gordon's submission of the first paper on the subject to the Institute of Radio Engineers (IRE). This was received on 11 June 1958 and published in November 1958 [9].

While Gordon was refining the Arecibo designs, he was famously in contact with Dr. Kenneth Bowles, a recent Cornell PhD, then at the National Bureau of Standards (NBS) in Boulder, Colorado. Bowles had access to an NBS 41 MHz forward-scatter transmitter/antenna system located near Long Branch (Havana) Illinois. All he needed was a suitable zenith-looking antenna system of sufficient gain and capability to handle the 4-6 MW peak power. The 116 m × 140 m half-wave dipole array (1024 elements) was quickly built and the experiment to test for incoherent scattering was conducted with positive results [10]. On 22 October 1958 Gordon, then chairman of the US National Committee URSI and attending the URSI/IRE (Institute of Radio Engineers) Joint Meeting at Penn State University, gave the fourth paper of the 2-5 PM Session 3 on "Scattered Signals" titled "Incoherent Scattering of Radio Waves by Free Electrons with Applications to Space Exploration by Radar" [11]. This talk featured the announcement that Ken Bowles had earlier that day observed incoherent scattering from the ionosphere [6]. Bowles' paper on this result was received at Physical Review Letters on 12 November 1958 and published in the 15 December 1958 edition [10]. Figure 1 shows the cover page of the Penn State meeting program while Figure 2 gives the USNC URSI meeting attendees—a veritable Who's Who of our community. Figure 3 gives the abstract of Gordon's talk during which Bowles's detection of incoherent scattering was announced. The full program for the meeting and the URSI meeting minutes will be available online.

From Early On-Dish HF Heating to Now

Ionospheric heating occurs when intense medium frequency through HF (high frequency) and even VHF [12] and UHF [13] radio waves accelerate the electrons in the ionosphere causing collisional heating, plasma wave generation, and related interesting phenomena. As the heating or modification levels can be controlled, ionospheric modification *experiments*—rather than the usual incoherent scatter radar *observations* of the natural ionosphere—become possible. The AIO incoherent scatter radar was uniquely capable of probing heating phenomena and thus use of the AIO dish for ionospheric heating was of great early interest. Further details are given in [1]; however, missing in the earlier paper was a photo of the earliest heating system over the AIO dish. This is given in Figure 4 that shows the 5.62 MHz crossed-dipole with reflector (dual-polarization, two-element Yagi) system described in Gordon et al. [14]. The Gordon et al. article describes O-mode HF ionospheric heating with this system at transmitter power levels of 100 kW CW or pulsed (at any duty cycle) and a ~10° beamwidth. L. M. LaLonde designed and built the feed. Further results derived from this system are given in [15].

As the Figure 4 crossed-dipole feed was restricted to a single frequency (5.62 MHz), it was replaced by a dual-polarization log-periodic HF feed system mounted at zenith above the Arecibo dish. This system, shown in *Mathews* [1] Figure 6, was plagued by arcing and other reliability issues. Additionally, both this feed and the earlier dipole feed were mounted at center of the elevation track and thus restricted carriage house #1 pointing to zenith angles greater than ~4º thereby limiting access to the full heated volume. This blocking issue is visible in Figure 4. These issues together with the need for even higher heater power led to the construction of the very successful, off-site Islote heater described in Section 6 of [1].

The stand-alone Islote HF heater array was located ~17 km NNE of AO on the Atlantic coast of Puerto Rico. Construction on the Islote heater facility began mid-1980 with operations commencing in September 1981 [16]. In its initial manifestation this system operated at frequencies of 3-12 MHz with an effective radiated power (ERP) of up to ~120 MW. This was accomplished with HF transmitters supplying up to 600 kW (4 × 150 kW transmitters) continuous power depending on the diesel generators and the state of the transmission lines to the two sets of ~20 dBi gain 4 × 4 log periodic antenna arrays shown in Figure 7 of [1].

Various issues resulted in peak power limitations with a maximum at or below 400 kW. Later upgrades allowed reliable use at the full 600 kW CW. Early use of the Islote heater included the 25 November and 8 December 1981 observations of HF-enhanced plasma lines using the 140 kW peak-power 46.8 MHz Max-Planck radar on the 305 m AO dish [17, 18]. Many of the science results from the Islote heater and the main instrument cluster are discussed in [1] and references therein.

Unfortunately, the Islote facility was severely damaged by Hurricane Georges on 21-22 September 1998 [NAIC/AO Newsletter No. 26, November 1998] and this, combined with the government decision to return the wetlands on which the facility was located to a natural state, led to decommissioning of the facility in 1999.

It is only in the last eight years that serious planning and now construction of a new on-dish HF heating facility has commenced. The new heating facility will operate in a campaign mode at initially only 5.1 MHz and 8.175 MHz as the feeds will be crossed-dipoles. The reason for this is that the design is radical as the feeds will be mounted just above the dish—with the dish surface as ground plane—and illuminate, in Cassegrain geometry, the convex sub-reflector suspended under the line/Gregorian feed system already in place. Figure 5 (upper left) shows the side-view geometry in schematic form—the remainder of Figure 5 shows the whole system viewed from above. Each individual dipole is feed from an individual, circa 1989, 100 kW (class A) Continental transmitter via ~1000 feet of 3 inch, unjacketed heliax cable. Figure 6 shows the first fully deployed 5.1 MHz dipole system. The arrangement at the top of the tower allows the dipoles themselves to fold umbrella-like down and against the tower for normal observing operations of the observatory. In a similar fashion the sub-reflector mesh of stainless steel cables that will be winched in/out of position by a set of winches at the base of each of the three towers. The 5-foot mesh spacing of the sub-reflector will allow the 430 MHz (70 cm) radar to work through the mesh. The same will be true for some radio and S-band radar astronomy observations if needed.

13. Conclusions

This brief history serves to introduce the "History of Radio Science" initiative of the Radio Science Bulletin as well as to note and celebrate the 50th Anniversary of the dedication of Arecibo Observatory. A more formal version of this history [1] is given in the journal History of Geo- and Space Sciences (HGSS; http://www.history-of-geo-and-space-sciences.net) that has initiated a special series on "The history of ionospheric radars" [2]. Here we add a few items missing from the earlier history.

As is inevitably the case, this history remains incomplete with gaps and mysteries that the community should fill and solve. However, in this paper we update the earlier history to give some details from the portentous 1958 URSI meeting held at Penn State. We have also given an update on the evolution of on-dish HF heater feeds and transmitters. The latter includes a few details regarding the new on-dish heater now under construction.

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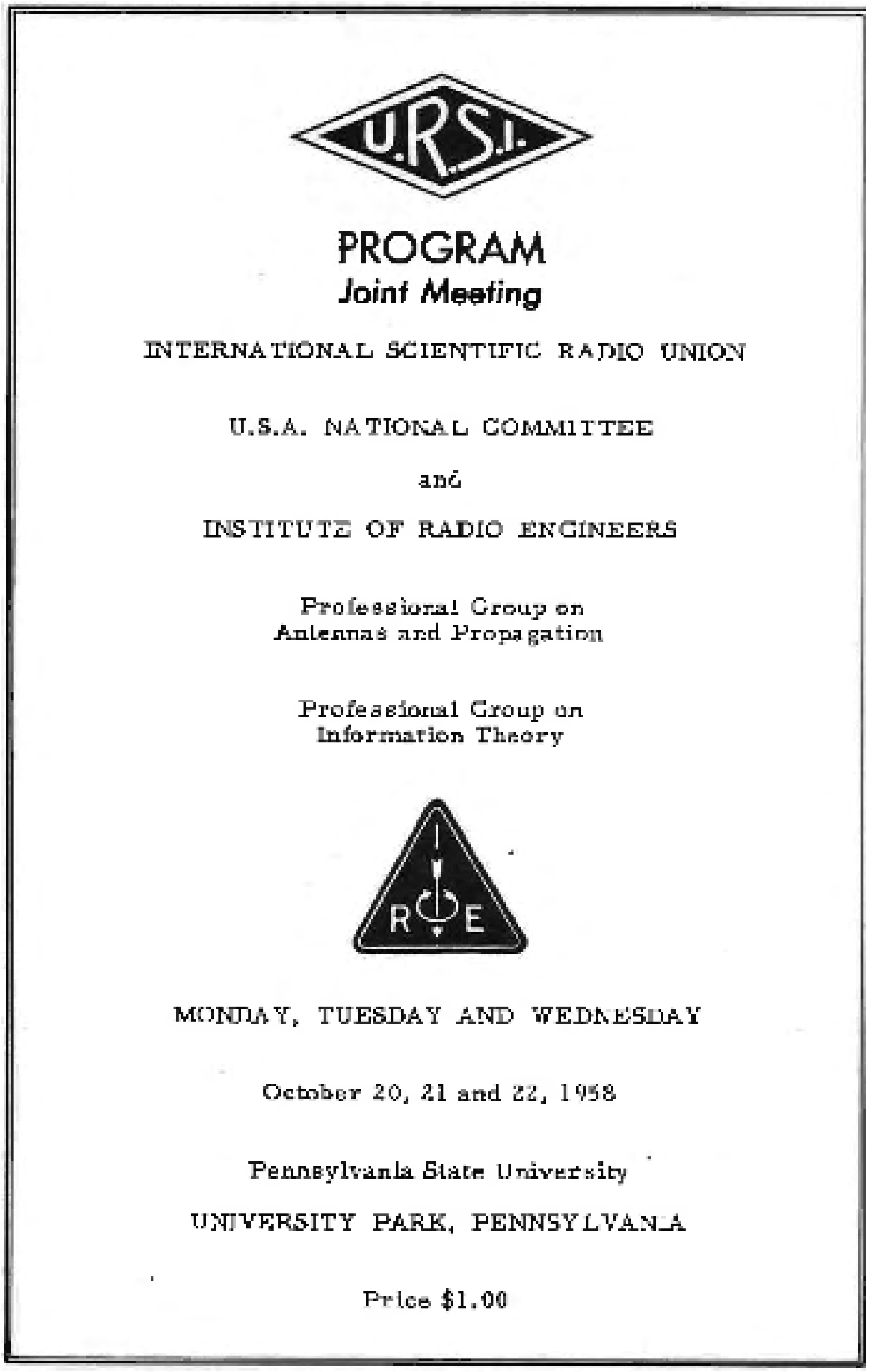

PROGRAM

Joint Meeting

INTERNATIONAL SCIENTIFIC RADIO UNION

U.S.A. NATIONAL COMMITTEE

and

INSTITUTE OF RADIO ENGINEERS

Professional Group on
Antennas and Propagation

Professional Group on
Information Theory

MONDAY, TUESDAY AND WEDNESDAY

October 20, 21 and 22, 1958

Pennsylvania State University

UNIVERSITY PARK, PENNSYLVANIA

Price $1.00

Figure 1. URSI/IRE 1958 Meeting program found at the National Academies archives.

USA NATIONAL COMMITTEE, URSI

Minutes of October 20, 1958 meetings
Pennsylvania State University
University Park, Pennsylvania

The first meeting was called to order by Chairman W. E. Gordon at 9:30 a.m. October 20 in Room 111, Electrical Engineering Building; the second meeting at 5:00 p.m. in the same place.

The following members were present at one or both sessions:

W. E. Gordon, Chm.	H. E. Dinger	A. H. Schooley
E. W. Allen	I. H. Gerks	A. H. Shapley
J. I. Bohnert	R. A. Helliwell	Samuel Silver
W. Q. Crichlow	G. D. Lukes	R. J. Slutz
J. H. Dellinger	L. A. Manning	J. B. Smyth
F. H. Dickson	E. F. McClain	A. H. Waynick
	M. G. Morgan	

Others present were: D . W. W. Atwood, Jr., Director, Office of International Relations, National Academy of Sciences-National Research Council, Mrs. A. MacIntyre.

The following members were not present: S. L. Bailey, R. W. Beatty, L. V. Berkner, H. H. Beverage, Marvin Chodorow, R. G. Fellers, H. W. Grant, F. T. Haddock, J. P. Hagen, A G. Jensen, E. C. Jordan, J. E. Keto, K. A. Norton, Brian O'Brien, J. D. O'Connell, W. G. Shepherd, L. C. Van Atta, Frank Virden, Ernst Weber, H. W. Wells.

Agenda Item 1. Minutes of April 25, 1958 meeting

The minutes were approved as mailed out with modification as follows: On page 3, lines 13 to 15, "President" should be "Chairman". On page 10, an item should be inserted between paragraphs numbered 2 and 3: "The list of officers should include the Associate Editor of Information Bulletin."

Agenda Item 2. Report of the Secretary

Dr. Silver expressed satisfaction with the functioning of the D. C. office.

Dr. Atwood outlined the present responsibility of the Academy with respect to the office of the USA National Committee in Washington and stated that at the earliest practicable date the Academy would take over the full responsibility of providing Secretariat services which the Committee needs. The plan is that the office of the USA National Committee will be incorporated into the Office of International Relations in cooperation with the Division of Physical Sciences. This is for several reasons:

(1) If OIR is to be of greatest help to a Union, its experience with the others should be readily available and this may be best accomplished if the work of all the Unions is handled under one office. However, Dr. Atwood recognized that the USA National Committee's meetings twice a year impose a larger work load than the other Unions.

(over)

Figure 2. USNC URSI Business Meeting attendees 20 October 1958.

4. INCOHERENT SCATTERING OF RADIO WAVES BY FREE ELECTRONS WITH APPLICATIONS TO SPACE EXPLORATION BY RADAR -- W. E. Gordon, Cornell University, Ithaca, New York -- Free electrons in an ionized medium scatter radio waves weakly. Under certain conditions only incoherent scattering exists. A powerful radar can detect the incoherent backscatter from the free electrons in and above the earth's ionosphere. The received signal is spread in frequency by the Doppler shifts associated with the thermal motion of the electrons.

On the basis of incoherent backscatter by free electrons a powerful radar, but one whose components are presently within the state of the art, is capable of

(1) measuring electron density and electron temperature as a function of height and time at all levels in the earth's ionosphere and to heights of one or more earth's radii;

(2) measuring auroral ionization;

(3) detecting transient streams of charged particles coming from outer space; and

(4) exploring the existence of a ring current.

The instrument is capable of

(1) obtaining radar echoes from the sun, Venus, and Mars and possibly from Jupiter and Mercury; and

(2) receiving from certain parts of remote space hitherto-undetected sources of radiation at meter wavelengths.

Figure 3. Professor Gordon's 1958 URSI abstract on incoherent scattering.

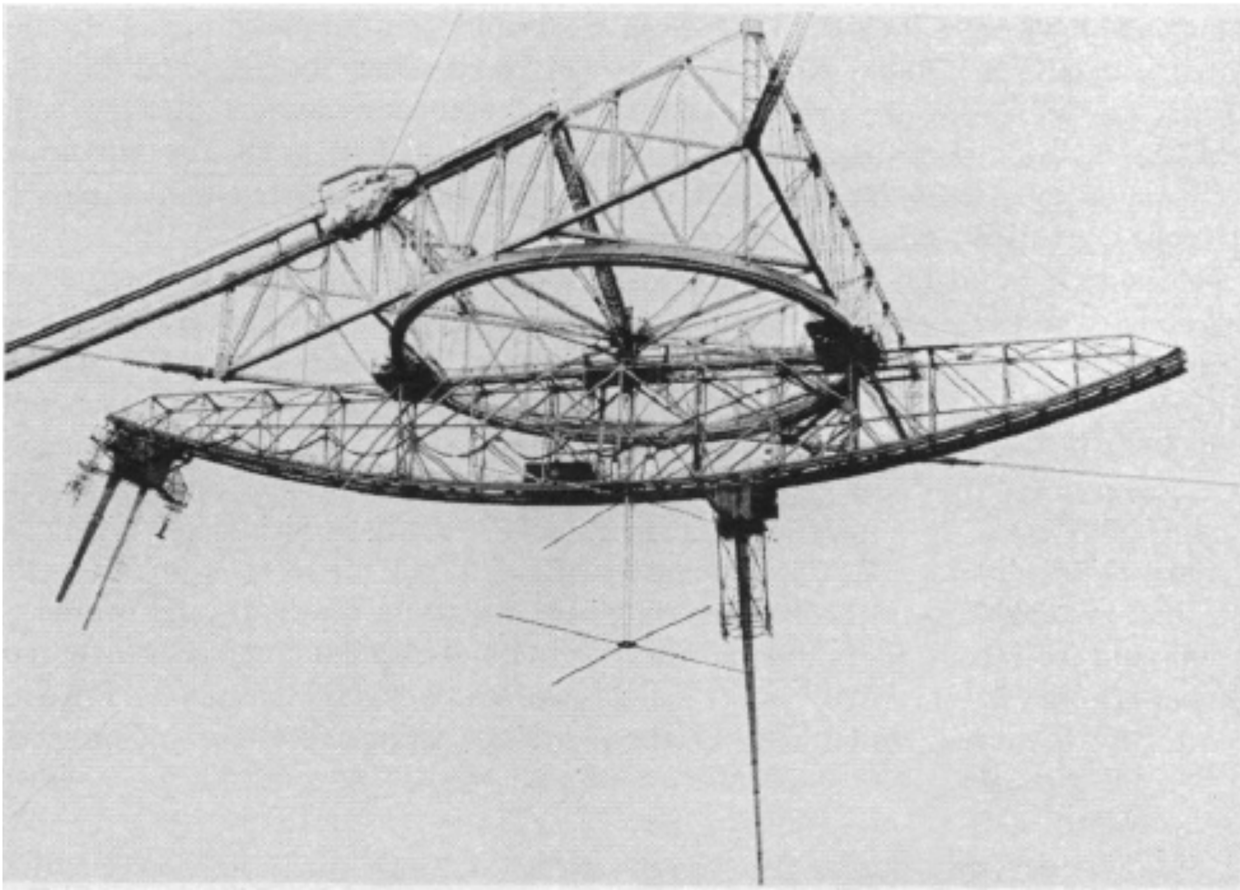

Figure 4. Antenna feeds deployed over the AO dish circa 1970. The crossed-dipole feed with reflector elements at center of the elevation arc is the first HF (5.62 MHz) heating antenna described sans photo in Section 5 of [1]. L. M. LaLonde designed and built this feed. Results from this early heating system are given in [14] and in [15]. Carriage house #1 to the right of center supports the original square cross-section 430 MHz linefeed and the coaxial 40.12 MHz radar Yagi feeds. Carriage house #2, now replaced with the Gregorian dome system, shows a variety of radio astronomy feeds. Photo courtesy of D. B. Campbell and Cornell University.

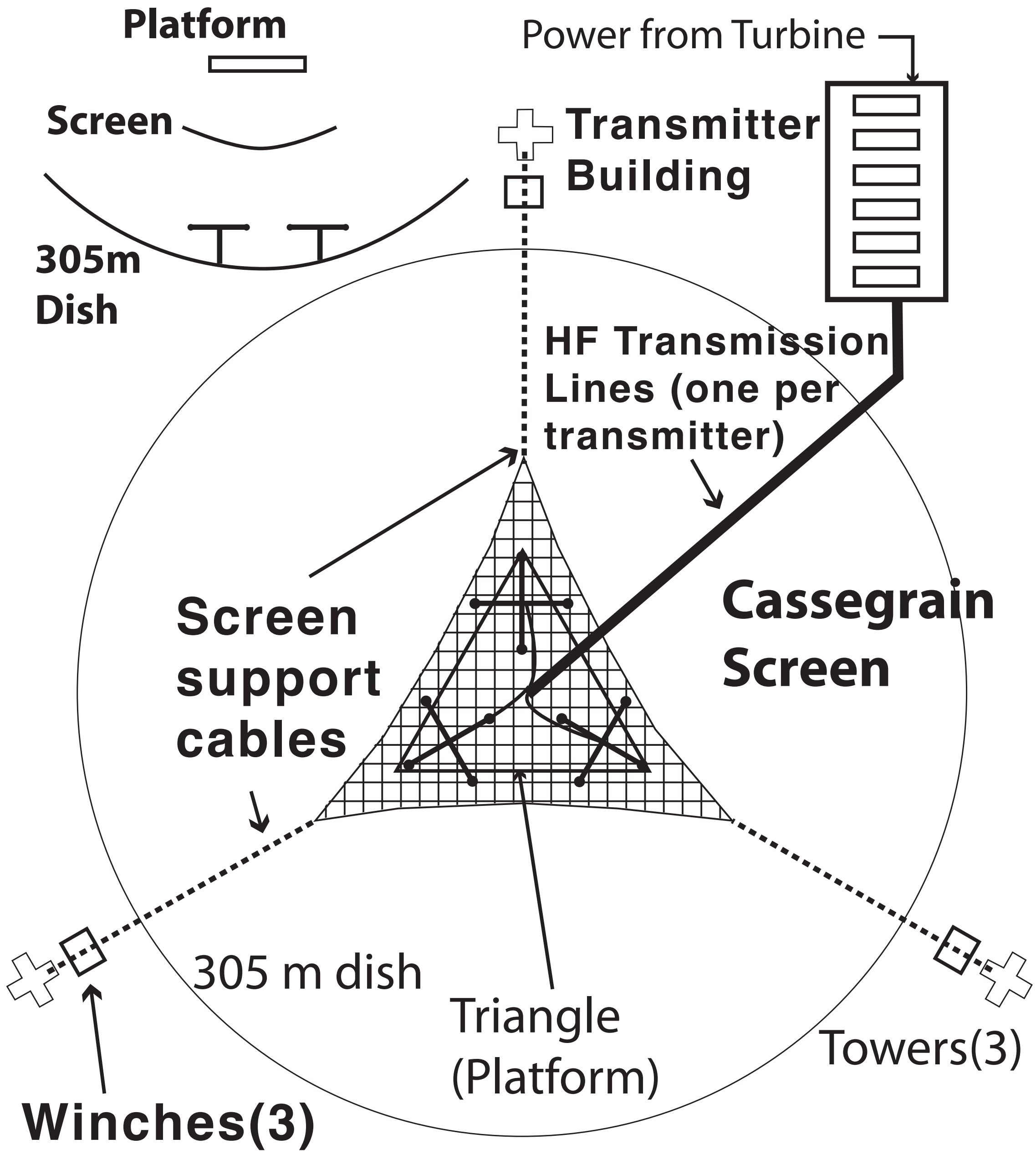

Figure 5. Schematic cartoon of the new AO on-dish heating facility. The upper left schematic shows the side-view with dipoles just above the dish surface and the convex sub-reflector mounted below the platform. The top view shows the wide-mesh Cassegrain sub-reflector and three of the six crossed-dipoles. The transmission lines are ~1000 ft in length. Figure courtesy of M. P. Sulzer, Arecibo Observatory.

Figure 6. The first of six crossed-dipole HF feeds to be deployed on the Arecibo Observatory 305 m dish. These feeds will illuminate a wire sub-reflector to be suspended from the towers that will turn illuminate the dish. Three feeds are sized for 5.1 MHz (λ = 58.8 m) and three feeds for 8.175 MHz (λ = 36.7 m). Modeling of the configuration suggests 22.2 dBi one-way gain at 5.1 MHz (~12° FWHM beamwidth) and 25.5 dBi gain at 8.175 MHz (~8° FWHM beamwidth). As six 100 kW CW transmitters are available, each polarization of each of the three feeds at a single frequency will be separately driven permitting full polarization flexibility. The transmitters are class-A however pseudo-pulsed operation will be possible. Later operations at 3.175 MHz may become possible. Photo 21 July 2013, JDM.