Blue.Sky@AreciboObservatory
Where does the future lie?

Introduction

As a component of the Arecibo Observatory 50th anniversary celebrations in late October 2013, an ASAP sponsored "blue sky" session on the future of AO was held with considerable success. Some of the results of this session and updates to it are summarized below.

Arecibo Observatory in the Next 30 Years.

AO has been reinvented many times over its 50-year lifetime. The first 430 MH radar antenna at AIO (Arecibo Ionospheric Observatory) is shown in Figure 1 [*Mathews*, 2013a; b]. AO has since been upgraded with new radars, receivers, feeds, and surfaces all of which led to new science—both planned and serendipitous. The consensus achieved at the AO 50th "blue sky" session was and is that the AO reinvention should and must continue as the possibilities are remarkable as is outlined below.

Figure 1. The first functioning radar feed at AIO. This 430 MHz hornfeed was constructed to test the full radar system before the dish was completed. This feed had a ~10° half-power beamwidth and was in operation in mid-October 1962. It was used to receive the sun in transit and to obtain lunar echoes as the moon transited near zenith [*Gordon*, 1962]. Photo courtesy of Carmen G. Segarra-Saavedra [*Mathews*, 2013b; *Segarra-Saavedra*, 2012]. Figure 4, [*Mathews*, 2013a].

Reinvention Topics

It is clear that for AO to remain cutting-edge over the next 20-30 years the AO managers and Puerto Rican government must become and remain fully involved in preserving and, hopefully, expanding the radio quiet zone. Additionally, and as critically, as much land as possible must be acquired and protected to preserve room for AO to expand.

For example, AO requires upgraded geophysical radars to support heating campaigns and to fully capitalize on having far and away the best incoherent scatter radar. Combined with a LALO-like (see below) lidar capability and various airglow imaging etc. systems, AO would provide cutting-edge space and atmospheric science results for decades.

PR Space Initiative

The PR Industrial

Development Company (PRIDCO) is promoting the development and growth of the aerospace industry in Puerto Rico. Their vision statement reads: "Puerto Rico's vision is to posture the local industry to become a vital link in the global aerospace supply chain including research, design/development, manufacturing, and aerospace-based services." This vision includes redevelopment of the airfield at the former Roosevelt Roads Naval Station in Ceiba (on the east coast) into a possible upper atmosphere and space systems launch facility that AO could utilize and must at minimum involve in strategic planning.

LALO

The Large Aperture Lidar Observatory (LALO) began with a meeting in Chicago, hosted by Chet Gardner & Gary Swenson. The workshop link (http://rsss.csl.illinois.edu/workshop) lists a number of planning documents that impact AO strategic planning. The LALO concept combines a 10-m class telescope (or more likely multiple 2-m class telescopes) with laser and detection systems that will allow it to probe the upper atmosphere well above 100 km altitude. LALO should be able to make measurements of relative density, wind, temperature, abundances of Na and/or Fe, acoustic-gravity waves, tides, etc. in the neutral atmosphere from ~30-130 km altitude as seeing permits and 150+ km when conditions produce extended metal layers—a completely new area of research. A world-class lidar system located at or near AO with the world's most sensitive incoherent scatter radar would uniquely enable new aeronomic science.

Broadband Backends.

The successful but now limited Mock Spectrometers and WAPPs need to be replaced with following broadband backend capabilities that would greatly extend at relatively low cost AO observing flexibility:

- 2 GHz instantaneous bandwidth (preferably 4 GHz)
- Want 1 kHz resolution (for C-band Galactic work) at as high a bandpass as possible (more than the ~100 MHz currently possible with both the Mocks and the WAPPs).
- Match or improve on the frequency resolution of the Mock spectrometers (10 kHz at 1 GHz bandwidth)
- Match or improve on the time resolution of the Mock spectrometers (i.e. higher max data rate)
- Cleaner bandpass than the Mock spectrometers – no DC spike or baseline steps
- Can produce full polarization products
- The broadband backend is primarily for single-pixel use, but if a design could be made that would work with a possible C-band array or with AO40 that would be an advantage (both could have ~40 beams)

C-band Focal Plane Array.

The intrinsic sensitivity of the Arecibo dish could be much more efficiently utilized with a C-band focal plane array comprised of as many as 35 beams. At C-band (4 – 8 GHz) Arecibo has a beam size of ~35 – 70 arcsec. This is comparable to that of the GBT K-band Focal Plane Array (KFPA; 32 arcsec at 23 GHz). There are a number of interesting spectral lines in C-band. At the low end these include formaldehyde (H_2CO; 4.83 GHz), OH (4.66, 4.75, & 4.77 GHz), and HCN (v_2=1; 4.49 GHz); while at the high end there is methanol (CH_3OH; 6.67 GHz), OH (6.02, 6.03, 6.04, 7.76, & 7.82 GHz), and HCN (v_2=1; 6.73 GHz). There are also numerous radio recombination lines across the entire band.

It would be easiest to build a relatively narrow-band system. ALFA has $\Delta\lambda/\lambda \sim 0.2$, while a C-low multi-beam system that that included formaldehyde, HCN and OH would only require $\Delta\lambda/\lambda \sim 0.1$ (4.66 GHz ± 0.233 GHz). A wider bandwidth would leave more 'discovery space' for other lines and give better sensitivity for co-added radio recombination lines and continuum, both total intensity and polarization.

Raising the Upper Frequency Limit of the 305-m Telescope?

In 2002, José Maldonado and Paul Goldsmith noted that the upper frequency limit of the 305-m telescope could be raised by replacing the primary surface, with one "long panel", (with smaller holes), in place of each of the four smaller panels that span the distance between main surface support cables. At that time, a price of $4-5,000,000 was mentioned, we presume for just the resurfacing?

Astronomical Rationale:

Some potential astronomical justifications for pushing up the highest operating frequency of the 305-m telecope are:

a) Spectral-Line: A few of the molecules that would be of interest should the frequency range of the 305-m telescope be extended beyond 10 GHz are:

Frequency (GHz)	Molecule	Notes
10.15	HC7N	
10.65	HC5N	
12.16	OCS	
12.18	CH3OH	Strong masers star-forming regions
13.04	SO	
13.44	OH	
14.49	H2CO	
14.66	HC7N	
18.15	SiS	
18.20	HC3N	
18.34	C3H2	
~19.05	C4H	
~19.8	NH3	
19.97	CH3OH	Maser
20.17	CH3OH	
20.37	NH3	
20.79	C6H	
~20.8	NH3	
21.98	HNCO	
22.23	H2O	Strong Masers (galactic & extragal)
22.34	C2S	
22.65 - 24.14	NH3	The "Perfect" Molecule!
23.12	CH3OH	Maser
23.96	HC5N	
~25.0	CH3OH	

Searches for H_2O masers at $0 < z < 1.22$ would be especially exciting. (Very highly red-shifted H_2O masers, i.e. $z > 1.22$, can even now be searched for at Arecibo using existing receivers.) The importance of such observations to cosmology and the nature of dark energy have been highlighted by the present Megamaser Cosmology Project which uses the GBT, the VLBA, and the Effelsberg 100-m telescope (Henkel et al, 2012, IAU Symp. 287 301). In addition, ammonia, with its profusion of hyperfine levels, is looked on as the "perfect molecule" for deriving physical conditions in molecular clouds. We probably would need to at least double the GBT's gain at a given frequency to be the "leader in the field". Of course, even with the same gain as the GBT at some frequency, we would still have a considerably smaller main beam area, (and there is a lot of sky to go round.) The value of spectral line surveys of both Galactic and extragalactic sources have recently been demonstrated by the GBT PRIMOS survey (e.g. Remijan et al., 2013, BAAS, 221.352.08) and the Arecibo spectral scan of Arp220 (Salter et al., 2008, AJ, 136, 389).

b) VLBI: Apart from ad-hoc arrays to study such maser transitions as CH_3OH at 12.2 GHz, there are popular VLBA bands at 12.0 - 15.4 GHz and 21.7 - 24.1 GHz. VLBA observations in the second of these bands have produced the best evidence to date for the existence of Massive Black Holes (MBHs) in the center of galaxies via VLBI of H_2O maser emission, also providing very accurate distances for the relevant galaxies. Highly red-shifted H_2O masers detected in single-dish mode could be followed up using the HSA/Global arrays. Even if the Arecibo sensitivity at the highest frequencies were to be only a couple of K/Jy, this would still be very useful in an array with other large telescopes (e.g. the HSA and the Global Arrays) for water maser studies.

c) Pulsars: Above 10 GHz is largely unexplored territory for pulsar studies. The spectra of pulsars drop rapidly with frequency, and the collecting area of Arecibo could be vital for making meaningful observations of many pulsars at high frequencies. There are indications that the spectra of at least some pulsars may flatten (or even turn up?) above 10 GHz (Xilouris et al., 1996, A&A, 309, 481). Polarization properties above 10 GHz could also be interesting as, contrary to normal continuum emitters, the percentage polarizations of pulsars appear to fall with increasing frequency.

d) Continuum: Flux density and polarization measurements are less available above 10 GHz. Flat spectrum sources are more variable here, sometimes on time scales much shorter than 1 day. The polarization percentages of extragalactic sources and SNRs rise with increasing frequency, and polarization position angles are close to their intrinsic orientations, allowing direct derivation of magnetic field directions in the objects.

e) Solar System Radar: A powerful 12-GHz radar for solar system studies would be unique (Goldstone included!) if 10K/Jy sensitivity available.

MK6: A Major VLBI Upgrade

Over the past decade, the Arecibo 305-m telescope has made very significant contributions to VLBI science. Its unparalleled sensitivity is as relevant to these endeavors, as it is to its single-dish contributions. A spectacular example of this has been Arecibo's participation to the RadioAstron project, obtaining fringes out to about 20 Earth diameters (220,000 km) for both pulsars and AGNs in collaboration with the Russian 10-m diameter orbital dish, RadioAstron. The successes of this period were initially achieved using disk recording rates of up to 1 Gbps using a MK5A recording system. The MK6 VLBI data system is a COTS (Commercial-Off-The-Shelf)-based 16-Gbps recording system that is necessary for AO VLBI observations. The MK6 is now fully functional and is being used for geodesy (VLBI2010) development work. While early MK6 operations are already underway within the geodesy community, adoption of MK6 by Arecibo should await decisions on VLBI development plans within the global VLBI community, i.e. both within the US and by the EVN. The former depends very much on the future of the VLBA, which is currently under active consideration.

The need for the MK6 upgrade is well illustrated by this following example. Arecibo has been participating in the HSA program to resolve the "Pleiades Distance Controversy" via weekly astrometric observations. These are aimed at resolving the disagreement over the distance to the Pleiades star cluster between that derived by the Hipparcos satellite and those from various ground-based measurements. Five very weak Pleiades stars (0.1 - 1 mJy at 8.4 GHz) were observed with the HSA over 2012 and into 2013 to unambiguously determine their parallaxes. A further five, even weaker stars (0.065 - 0.115 mJy), are being followed from 2013 through 2014. Arecibo's participation in these observations is crucial given the weakness of the targets. If the AO recording had been via the MK6 rather than the MK5C, then these observations would have been almost 6 times as sensitive as those with the MK5A!

We also note that 16-Gbps recording implies a dual polarization input signal of 2-GHz bandwidth. The planned widening of the Arecibo IF bandwidth is arriving at the perfect time to permit a MK6 upgrade.

Conclusions

There are many more examples of possible upgrades to the AO capability roster that are not included here. The point is that flexible instrument can and should continue to contribute to fundamental science for many decades into the future

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References

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