VLBI at Arecibo

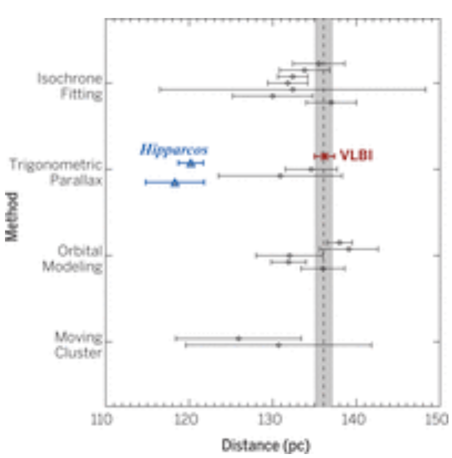
Very Long Baseline Interferometry (VLBI) technique allows images to be made with angular resolutions of milliarcsec or finer. Over the past two decades, the Arecibo 305-m telescope has made very significant contributions to VLBI science, bringing greatly increased sensitivity to the relevant arrays.

Arecibo regularly participates in two major VLBI arrays; (a) the High Sensitivity Array (HSA), comprising of the VLBA, GBT, EVLA, Bonn & Arecibo, and (b) the European VLBI Network (EVN).

Arecibo has also co-observed with space-radio telescopes, (a) the Japanese VSOP (1997-2000), and the Russian RadioAstron (2012-?). Over the years, Arecibo has upgraded its electronics and data recorders in steps with the world's other radio telescopes. At the moment, Arecibo is able to provide a maximum of 2Gbps data recording rate from all Arecibo receivers which could also be used as baseband-sampled (2-bit) data for single-dish applications. A two-times faster mode will be implemented in the near future.

Arecibo is also deploying a 12-m diameter antenna to aid in correcting for atmospheric phase fluctuations. This will make Arecibo's VLBI observations considerably more time-efficient.

A recent hallmark result has been, "**A VLBI Resolution of the Pleiades Distance Controversy**"



The Pleiades is the best studied of all open clusters. It is also one of the primary open clusters used to define the "Zero Age Main Sequence", and thus serves as a cornerstone for programs that use main-sequence fitting to derive distances. This role has been called into question by the "Pleiades distance controversy" i.e. the distance to the Pleiades according to the Hipparcos satellite is about 120 pc, significantly different from the value of 133 pc derived by ground-based techniques. Although this amounts to only a 10% difference in the distance, the resultant discrepancies, as propagated into the Pleiades HR-diagram, and the necessary revisions of physical models to obtain agreement with the Hipparcos result, are quite significant. To resolve this, a two-year long VLBI observing campaign is being carried out using the HSA. This will provide an independent, trigonometric parallax distance to the Pleiades (Melis et al. 2013, IAUS

289, 60). Weekly VLBI observations of several, very weak double/triple radio stars have been used to decouple proper motion from the motion of each binary (or tertiary) system. The first three Pleiades parallaxes derived from these measurements have now been determined yielding distances that are incompatible with the cluster distance suggested by Hipparcos.

Science areas that benefit from Arecibo's participations in a VLBI array include:

- **Jets and radio structures of all classes of AGNS at all redshifts finding evidence for (even triple) blackholes, providing constraints for theoretical models of such objects and their cosmic evolution.**
- **Mapping gravitationally lensed objects, occasionally helping to detect the so-called, "dark lenses".**
- **Astrometric measurements of proper motions and parallaxes of pulsars and other objects, providing model-independent distance (thence luminosity) estimates.**
- **Pulsar scintillations studies allowing the delineation of detailed structure of the magneto-inonic interstellar matter.**
- **Observations and monitoring of Gamma Ray Burst (GRB) afterglows.**
- **Connecting the Celestial and Terrestrial Reference Frames.**
- **Tracking spacecraft through cloudy planetary atmospheres.**

When fully functional, the 12-m telescope will aid in phase-referencing VLBI observations making these up to 50% more time efficient. It will also be used in geodetic VLBI, search of variable and transient sources, mapping the sky at C or X band, and for "hands-on" training of local and visiting students.

VLBI at the Arecibo Observatory

Tapasi Ghosh

Over the past decade, the Arecibo 305-m telescope has made very significant contributions to VLBI science. Its unparalleled sensitivity is every bit as relevant to these endeavors as it is to its single-dish contributions.

A VLBI Resolution of the Pleiades Distance Controversy :

The Pleiades is the best studied open cluster in the sky. It is also one of the primary open clusters used to define the "Zero Age Main Sequence", and hence serves as a cornerstone for programs which use main-sequence fitting to derive distances. This role is called into question by the "Pleiades distance controversy" i.e. the distance to the Pleiades from Hipparcos of about 120 pc is significantly different from that of 133 pc derived from other techniques. Although this amounts to only a 10% difference in the distance, the resultant discrepancies, as propagated into the Pleiades HR-diagram, and the necessary revisions of physical models to obtain agreement with the Hipparcos result, are quite significant. To resolve this, a two-year long VLBI observing campaign using the HSA is being carried out to derive a new independent, trigonometric parallax distance to the Pleiades (Melis et al. 2012). Weekly observations of several double/triple (weak) radio stars have been made to decouple proper motion from the motion of each binary (or tertiary) system. The first three Pleiades parallaxes derived from these measurements have now been determined yielding distances that are incompatible with the cluster distance suggested by Hipparcos.

Unique Scattering media revealed by Space-VLBI observations of PSR B0950+08 :

Space-ground VLBI observations of the pulsar PSR B0950+08 made with the RadioAstron, an 10-m orbital radio telescope, Arecibo and the WSRT at 324 MHz, with a maximum baseline length of 220, 000 km, were used to investigate plasma inhomogeneities in the direction of this nearby pulsar. Analysis based on fundamental behavior of structure and coherence functions reveal that the scattering originates in two distinct plasma layers at 4.4 – 16.4 pc, and 26-170 pc, and that the ensuing modulation is also dispersive due to refraction in a wedge structure. The refraction angle in this "cosmic prism" is measured to be 1.4 – 4.4 mas. The spectra of the density fluctuations in the two scattering layers are found to differ significantly from those expected for a Kolmogrov spectrum.

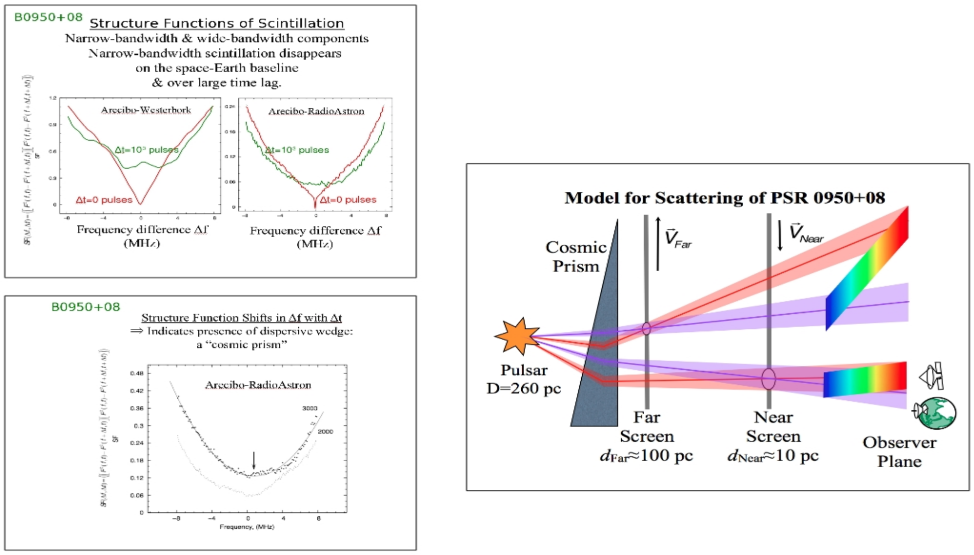


Fig.1: *The nature of the Scintillation Structure functions for space-earth and earth-earth baselines, as well as the frequency shift with time, has been used to derive the unique scattering geometry towards PSR B0950+08* ***(Courtesy:*** *Carl Gwinn, UCSD)*

Space VLBI Measurement of the Brightness Temperature of 3C 273 requires revisions of quasar models:

The 18-cm VLBI observations by Kovalev et al. (2014) between the RadioAstron spacecraft and both Arecibo & the GBT on projected baselines of up to 1.8 x 10^9 λ show a directly measured brightness temperature of greater than 10^{14} K. This high brightness temperature greatly exceeds the 10^{12} K limit expected from inverse Compton cooling, or the 10^{11} K expected if there is equilibrium between particle and magnetic energy. Such high observed brightness temperatures are difficult to understand in terms of Doppler boosting since VLBA monitoring of 3C 273 over the past 15 years indicate Lorentz factors of only about 10 to 15. Thus, this observation requires other explanations in terms of the continual acceleration of relativistic particles, incoherent radiation from relativistic protons, coherent radiation such as from a synchrotron maser, and/or differences between the observed pattern velocity and the relativistic flow velocity giving rise to Doppler boosting in excess of the Lorentz factor.

The Closest Triple Black-hole system in a distant galaxy :

Galaxies are believed to evolve through merging, which should lead to some being hosts to multiple supermassive black holes. Until recently, only four triple systems were known, making them rather rare objects. Using multiple epochs of VLBI observations at 6 and 18 cm wavelengths and the Global VLBI array including Arecibo, Dean et al. (2014) have discovered a triple black hole system at redshift z= 0.39, with the closest pair separated by only about 140 parsecs.

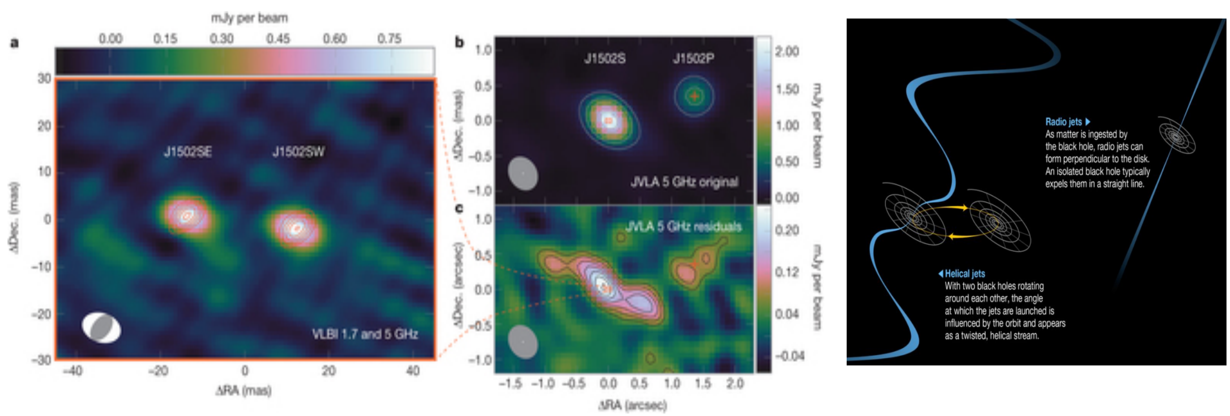


Fig 2: 5_GHz VLBI and JVLA maps and a cartoon of the triple system in J1502+1115

The effect of the tight pair is to introduce a rotationally symmetric helical modulation on the structure of the large-scale radio jets which provides a useful way to search for other tight pairs without needing extremely high resolution observations. As the authors found this tight pair after searching only six galaxies, they conclude that tight pairs are more common than hitherto believed. This provides an important observational constraint for low-frequency gravitational wave experiments.

Technical Considerations:

The successes of this period were initially achieved using disc recording rates of up to 1 Gbps via a MK5A recording system for observations within the HSA, EVN and Global arrays. Up to 512-Mbps eVLBI data rates are also regularly achieved over the internet from Arecibo to the Joint Inatitute for VLBI (JIVE) in Netherlands in collaboration with the e-EVN. More recently, we have migrated to a digital VLBI back-end (the RDBE in Poly-phase filterbank, PFB, mode) and MK5C recorders, contributing 2-Gbps recording within the HSA. However, the complete utilization of Arecibo's full range of VLBI hardware awaits implementation of the Digital Down Converter (DDC) operating mode of the backend, and the deployment of the Arecibo 12-m phase-reference antenna. Considering these pending tasks, as well as the fact that the developers of the MK5 recorder series, Haystack Observatory, have set Sept. 1, 2015 as the date for the formal end of their MK5 support, we envisage below the future development of VLBI at Arecibo in two phases:

(a) The near-term pre-Sep. 2015 phase:

As soon as possible, the DDC mode of the RDBE will be deployed and commissioned allowing variable bandwidths (from 1 to 128 MHz in multiplicative steps of two) for up to eight recording channels. The independent tuning of individual channels can be set in steps of 15.625 kHz. The DDC mode allows high spectral resolution in combination with milliarcsecond spatial resolution.

For the Arecibo 12-m antenna, the receiver-chain electronics needs to be completed before the integration of the operations of the 12-m telescope into VLBI runs can be achieved. This will enhance Arecibo coherence times greatly, and increase the on-source integration times available with the 305-m telescope, allowing considerably fainter sources to be observed (in phase-referenced mode), and expanding the variety of astronomical objects that can be investigated via this method.

The eVLBI observations between Arecibo and the European VLBI Network will be continued, exploring improved connectivity. The possibility of VLBA soon joining eVLBI operations is being explored. This would pave the way to disk-free quasi-real-time observations. Arecibo can also foster collaboration with the US geodetic VLBI network, many of whose observations already utilize the internet. This phase of development would greatly enhance Arecibo's participation in projects for tracking space probes using the VLBI technique. Such an initiative is currently being developed by JIVE and ESA.

(b) Post-2016 - the MK6 era:

The MK6 VLBI data system is a COTS (Commercial-Off-The-Shelf)-based 16-Gbps recording system. It takes its input from four 100GigE data connections, with all its software being fully open source. Existing MK5 systems can be upgraded to MK6. In practice this represents a direct replacement for the MK5C, with much higher performance (and at a significantly lower price!)

The MK6 is now fully functional and is being used for geodesy (VLBI2010) development work, while Haystack Observatory develop test and operational software, and full documentation. Conduant Corp are handling sales of the MK6, and have taken first orders. Current pricing is, (i) a new 16-Gbps MK6 system is priced at US$13,285 plus taxes, while (ii) for upgrading an existing MK5 chassis into a 16-Gbps MK6 system chassis, the price is US$8,375. Delivery time is 60 days after receipt of an order.

Why Upgrade to MK6?

This is well illustrated by an example. As mentioned above, Arecibo has been participating in the HSA program to resolve the "Pleiades Distance Controversy" via weekly astrometric observations. 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 three , even weaker (0.065 - 0.115 mJy) stars are being followed from 2013 into 2014. Arecibo's participation in this is crucial given the weakness of the targets. As the project moved into its second year, and weaker stars, the recording migration from MK5A to MK5C with its doubling of sensitivity proved vital in enabling the targets even to be detected. If the recording migration had been to MK6 instead, then these observations would have been almost 6 times as sensitive as those made 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 bandwidths is arriving at the perfect time to permit a MK6 upgrade.

When to adopt MK6?

While early MK6 operations are already underway within the geodesy community, (which may be relevant in respect of the Arecibo 12-m Patriot antenna, for which geodesy use has been discussed), adoption of MK6 for the Arecibo 305-m telescope should await decisions on VLBI development plans by 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.

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