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The Compendium*

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Star trails over the Bracewell Radio Sundial.

Time wasted is existence, used is life.

– Edward Young

Front cover: star trails circling about the North Celestial Pole during a one-hour exposure, as viewed over the Bracewell Radio Sundial at the Jansky Very Large Array in New Mexico. This image was NASA's Astronomy Picture of the Day on 13 July 2018. Photo: Miles Lucas.

A "Radio Sundial" for the Jansky Very Large Array in New Mexico

Woody Sullivan (Seattle WA), W. M. Goss (Socorro NM), and Anja Raj

Introduction

A unique sundial has appeared in the Plains of San Agustin at the Karl G. Jansky Very Large Array (hereafter the VLA), about fifty miles west of Socorro, New Mexico, USA.[1] The VLA consists of 27 dishes of 25 meter (82 ft) diameter, all connected by fiber optics and movable on 21-km-long railroad tracks in a "Y" configuration (Fig. 1).[2] The array produces exquisitely sensitive and detailed images of the radio astronomy sky.

Fig. 1. Looking south, the 27 dishes of the VLA cast long, evening shadows across the Plains of San Agustin in southern New Mexico. In this configuration each arm extends ~2000 ft (600 m). Photo: NRAO/AUI/NSF/Dave Finley.

In 2010, the idea emerged of a unique "radio sundial" at the VLA Visitor's Center as a way of honoring one of the great early radio astronomers, Ronald N. Bracewell (1921 - 2007, Fig. 2). He developed much of the fundamental mathematics that underlies the operation of the VLA; moreover, he loved sundials and had a keen sense of history. In this regard, he had collected chiseled-in-concrete "signatures" of over 200 astronomers who visited his radio telescope in California over the 1960-75 period.

The key principles for designing the Bracewell sundial (Fig. 3) were:

- to provide an attractive and educational feature for visitors to the VLA
- to accurately indicate the time and many other quantities
- to display the historic signatures
- to incorporate the history of radio astronomy
- to directly involve celestial sources of radio emission

This paper tells the story of Bracewell, his radio telescope and its signatures, the preservation of the signatures and their move over a thousand miles, and the design and construction of the sundial, leading to its dedication in 2013.

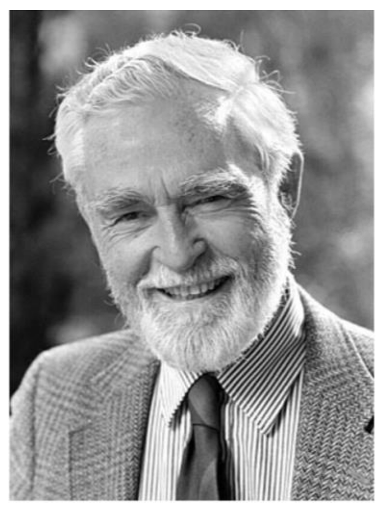

Fig. 2. Ron Bracewell in 1997. Photo: L.A. Cicero and Stanford University.

Bracewell and the Stanford Radio Telescope Array

Born in Australia, Ron Bracewell designed radar equipment during World War II at the Radiophysics Laboratory in Sydney, afterwards receiving his Ph.D. from Cambridge University in England. He became one of the key figures who turned their wartime expertise in physics and electrical engineering toward establishing Australia as a world leader in the emerging field of radio astronomy.

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[1] Latitude 34° 04.4´ N, Longitude 107° 37.4´ W, Altitude 7000 ft (2120 m).

[2] The Jansky Very Large Array is operated by the National Radio Astronomy Observatory (NRAO). The NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

In the 1950s and 1960s, Bracewell made major contributions to developing the mathematical techniques for combining the radio signals received by multiple antennas to produce detailed images of astronomical objects. These techniques remain at the heart of how the VLA and many other radio telescopes operate today. In addition, Bracewell adapted these same techniques to making computer-assisted tomography (CAT) images of the interior of the human body.

Fig. 3. The Bracewell Radio Sundial's gnomon casts a faint shadow on the afternoon of a cloudy day. In the background, the VLA observes a radio source unaffected by the clouds. Photo: Sullivan.

Bracewell moved to Stanford University in 1955, where he built a radio telescope comprising a cross-shaped array of thirty-two 10 ft (3.0 m) diameter dish antennas — each arm is 400 ft (122 m) long (Fig. 4). He called this instrument a microwave spectroheliograph and dubbed his field site near the campus "Heliopolis."

Over the period 1962-73, he monitored and mapped variations in the Sun's radio intensity on almost a daily basis; one great advantage of radio waves is that they penetrate clouds and rain, allowing solar monitoring to be undisturbed by weather. Active regions on the Sun as small as an unprecedented 3 arcminutes could be radio-imaged at a wavelength of 9.1 cm.[3] In addition to helping understand the Sun's workings, his system provided warnings of powerful solar bursts that could affect satellites or endanger the Apollo astronauts during their Moon voyages.[4]

Fig. 4. Bracewell's 32-dish spectroheliograph array seen from the Southwest, observing the sun in the 1960s from his Heliopolis site near the Stanford University campus. Each cross arm is 400 ft (122 m) long. Photo: Bracewell Archives, NRAO.

A true polymath, he wrote about such disparate subjects as the search for extraterrestrial intelligence (*The Galactic Club*, 1975) and trees (*Trees of Stanford and Environs*, 2005). He also produced fundamental textbooks such as *Radio Astronomy* (1955, with Joseph Pawsey) and *The Fourier Transform and its Applications* (1965); later editions of the latter are still consulted by engineers and scientists around the world.

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3 A typical solar map of that era, for 8 Jun 1968, is in Appendix F on our website. References in this paper to Appendixes on "our website," are to https://science.nrao.edu/about/publications/sundial

4 Construction and operation of the array was funded by the Air Force Office of Scientific Research from 1956 onwards.

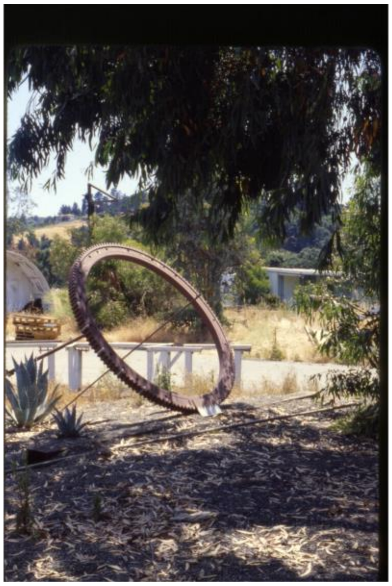

Fig. 5. *One of Bracewell's sundials at the Heliopolis site in 1979, constructed from a radio telescope gear wheel. Photo: Sullivan.*

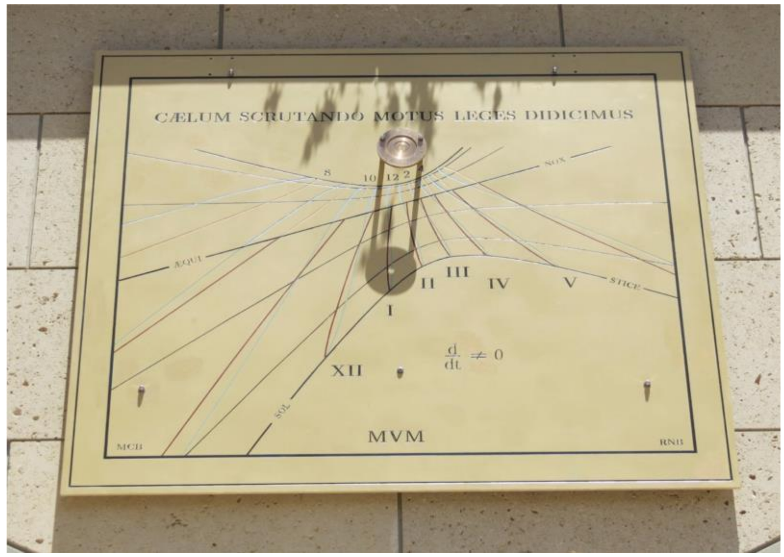

Fig. 6. A 1995 vertical sundial that Bracewell designed and built with his son Mark, on the Stanford University campus. See text for details. Refurbished in 2013 by Mark; NASS Catalog No. 482; Photo on 25 May 2013 by Doug Korns.

Bracewell designed several sundials, including in the 1970s one at the array, fashioned from a large radio telescope gear wheel (Fig. 5). An extant dial built in 1995 is on the Jen-Hsun Huang Engineering Center at Stanford (Fig. 6).[5] It is on a southwest-facing wall (azimuth of 195°) and features an analemma for each hour line, allowing Pacific Standard Time to be read. The date is a palindromic "MVM" and the motto "Caelum scrutando motus leges didicimus" translates as "We learned the laws of motion by studying the heavens." Bracewell, who was a member of the Department of Electrical Engineering but whose research was primarily in astronomy, wanted to emphasize to his colleagues and students the fundamental importance of astronomy for our historical understanding of the physical world and for the development of technology. The dial's second "motto" is $d/dt \neq 0$, an equation whose meaning is more obscure; those knowing calculus will see that it can be interpreted as "Everything is always changing."[6]

Saving the Concrete Piers and their Signatures

Each dish of the Stanford array was originally mounted on a 5 ft (60 cm) tall concrete pier. Bracewell invited many visitors to his radio observatory to inscribe their name on the side of a pier, wielding hammer and chisel (Figs. 7 and 8). From about 1960 to 1975, he collected over 200 signatures in this unique "Guest Book." When painted white, they looked quite handsome (Fig. 9), not unlike a team-autographed baseball, but in this case the "team" represented many of the most important astronomers and physicists of the mid-20th century. Among the signatories were two Nobel Prize winners (Harold Urey and William Fowler), observatory directors from around the world (including traditional optical observatories), and a large fraction of the pioneers who established the revolutionary field of radio astronomy after World War II. Fully 40% of the signatures were by overseas visitors; twenty-six came from Australian colleagues who had worked with Bracewell on radar development during World War II.

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[5] Further details are be found in the NASS Registry, http://sundials.org/index.php/component/sundials/oneDial/482.

[6] Further information on Bracewell's career can be found in Bracewell (1984), Bracewell (2005), Thompson and Frater (2005), and Frater, Goss and Wendt (2017). The last also features the Bracewell sundial. For the early history of radio astronomy, see Sullivan (2009). Bracewell's archived papers are at the National Radio Astronomy Observatory (NRAO) in Charlottesville, VA. (https://www.nrao.edu/archives).

Fig. 7. Ron Bracewell instructs Marcel Minnaert (1893-1970), prominent astronomer from the University of Utrecht in the Netherlands, on mallet and chisel technique, while others in the back beaver away (1961). Photo: Bracewell Archives, NRAO.

Fig. 8 Astronomers carve their names on the piers. During the construction of the spectroheliograph in 1958, Bracewell supervises his former boss Joseph Pawsey (leader of the radio astronomy group at the Division of Radiophysics in Australia), with Govind Swarup from India looking on.

Inset: At another time, John Bolton works on his inscription. He was a radio astronomer who made fundamental discoveries in Australia in the decade after World War II (see Table 1 at article's end). Photos: Bracewell Archives, NRAO.

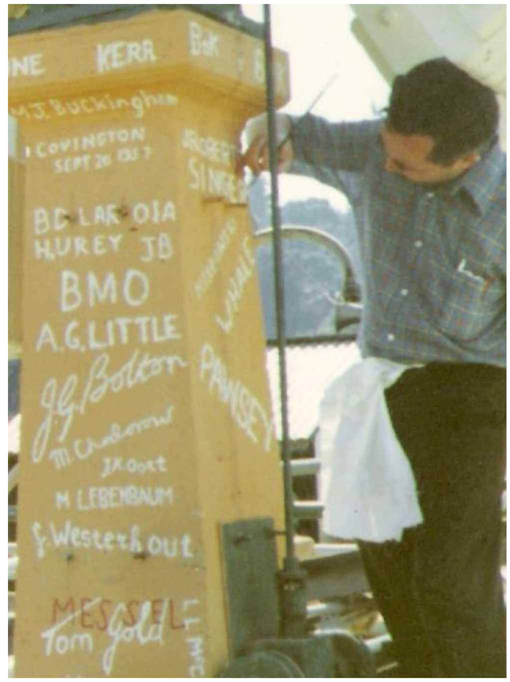

Fig. 9. Bracewell touching up the signatures on the first pier of the spectroheliograph's East arm. Note John Bolton's script signature (compare Fig. 8). Another prominent name is that of the Dutchman Jan Oort, one of the greatest astronomers of the twentieth century. Photo: Bracewell Archives, NRAO.

By 1980 the array, with all of its historical signatures, had become obsolete and was abandoned for decades to the vicissitudes of weather and entangling poison oak and moss (Fig. 10). Shortly before Bracewell's death in 2007, co-author Goss discussed with him the idea of moving the best signature piers to a permanent site for display, perhaps for a "sculpture garden" of some sort at the VLA. In 2010, Judy Stanley, the VLA Education and Public Outreach Officer, suggested that the piers might be somehow used as elements of a sundial. Co-author Sullivan, who had designed and supervised the construction of a number of sundials in Washington state and elsewhere, and who had also been a longtime colleague of Bracewell's, next joined the team. Soon this project of gnomonic archaeology moved forward with Goss as spark plug, and support from Associated Universities, Inc., and the National Science Foundation. Bob Lash, head of Friends of the Bracewell Observatory, played a vital role in California.

Fig. 10. One of the ten piers at Stanford in 2012, before their extraction and removal to the VLA. Photo: Bob Lash.

Fig. 11. The lone surviving 10-ft dish of the original 32, after refurbishment and placement near the VLA sundial. Photo: Goss.

Fig. 12. Moving the piers and single dish ~1000 miles from Stanford to the VLA. Photos: Bob Lash and Guy Stanzione.

During 2010-11, the basic sundial design was established and a specific site near the VLA Visitor Center was chosen. In July 2012, under the guidance of Lash, ten of the most interesting piers, plus the lone surviving 10 ft dish (Fig. 11), were cleared of brush and poison oak, sawed off, and trucked 1000 miles (1600 km) from the Bay Area to the Plains of San Agustin (Fig. 12). Construction of the sundial took place over the following year with the indispensable know-how and skillful supervision of Guy Stanzione, facilities engineer at the VLA site (Fig. 13). Sullivan made several visits to the VLA for consultations, tests, and measurements as the project proceeded. Appendix D on our website gives a detailed project timeline.

We faced a major challenge in the identification and restoration of the 225 signatures on the ten piers. The clarity of most of the inscriptions suffered from 55 years of fading, weathering and enveloping moss. Because of the possibility of damaging the indistinct signatures, the piers were gently cleaned with only a kitchen water-spray bottle. Some signatures had chisel indentations only a few mm deep, which made the lettering very difficult to discern. Others were by persons who had written their names on a piece of paper or cardboard and then pasted this on the side of a pier before chiseling. These interesting signatures were thus often representative of the handwriting style of the author (examples can be seen on the pier shown in Fig. 9).

Fig. 13. Key persons for the project on "First Shadow" Day, 23 September 2013: (l. to r.) Woody Sullivan, Guy Stanzione, Miller Goss, Bob Lash and Judy Stanley. Photo: Dave Finley.

Fig. 14. Angelica Vargas of the New Mexico Tech Astronomy Club re-paints Bracewell's signature on the sundial's noon pier. Photo: Judy Stanley.

Stanley led the painstaking cleaning and repainting, assisted by members of the New Mexico Tech Astronomy Club (Fig. 14). An alphabetical list of all the revealed signatures is given in Appendix A in the Digital Bonus and on our website. Appendix B presents photos and identifications of all the signatories pier by pier; only about 17 signatures remain unidentified. Appendix C discusses many of the most interesting signatures and signatories. Appendix D provides a detailed timeline for the entire project. Appendix E lists NRAO staff members and private donors who were vital for the project's success. Appendix F has many details of the Dedication Ceremony in 2013, and Appendix G is a large color brochure describing the sundial and available for downloading as a PDF file. Finally, Appendix H contains jpg images of all figures in this article.

The Radio Aspect of the Sundial

The most straightforward way to actively involve the radio sky would have been to use radio waves from the Sun itself, which is by far the strongest radio source in the sky at the microwavelengths used by the VLA (0.75 to 30 cm). Why not somehow use the sun's "radio shadow" in exactly the same way we use the sun's more familiar shadow at visual wavelengths? Such a radio sundial would have one huge advantage: because clouds do not appreciably absorb radio waves, the dial would reliably work on cloudy days, even in the rain! We would have to devise a radio-opaque object for the gnomon,[7] and then somehow determine the location of the Sun's radio shadow, which would be at the minimum of radio intensity on the dial's face. This might be done, for instance, using a small hand-held microwave detector with a display indicating signal strength; the sundial user would then move the detector over the dial face, keeping it pointed at the Sun (but how?), until a minimum signal was located. All this would be feasible in theory, but we deemed it not practical. First, in a public setting the microwave detector would undoubtedly often break (or be stolen). Second, the detector would create its own radio noise which would interfere with the extraordinarily sensitive measurements being made by the nearby VLA dishes (not even cell phones are allowed on the site). Third, the achievable accuracy of time determination would be much less than with a standard visual shadow.

Rather than the radio Sun, we decided to involve radio waves by using three of the strongest radio sources outside of our solar system, all of which were extremely important in the early history of radio astronomy. And rather than directly telling time with the radio shadows of these sources,[8] we turned things around: we instead guide users to find the radio shadow's location at any time, and then use the sundial's gnomon as a *sighting device* for the radio source's current sky position. The gnomon now has a twofold purpose: (a) to indicate time (and date) in the usual fashion via the Sun's visual shadow, and (b) to show at any time the location in the sky of three strong radio sources.

For this scheme to work, however, the user must somehow know the current *sidereal time*, i.e., time by the stars (and radio sources), not the more familiar solar time indicated by almost all dials (see Box on the following page).[9] The two types of time run at different rates and the difference between them depends only on the date.

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[7] The shadow-caster of the VLA sundial is technically a *nodus*, an object at a single reference point, rather than a *gnomon*, which usually refers to a linear edge or rod aligned with the celestial pole. In this paper, however, we call the VLA shadow-caster a gnomon.

[8] The three radio sources that we employ are the strongest available, but nevertheless many hundreds of times weaker than the Sun (and vastly farther away). They would thus be far too weak to locate via a simple radio shadow technique.

[9] Sundials indicating sidereal time by a nodus's solar shadow can rarely be found. One nice example is at the Lycée Louis-le-Grand in Paris. For the Bracewell dial, however, we judged that the necessary pattern of numerous crossed lines would make the dial face too complex.

Sidereal Time

Sidereal time and solar time run at different rates. Suppose that the Sun is due south (on the meridian) and it is therefore solar noon. Coincidentally, there is a distant radio source (or a star) far "behind" the Sun and simultaneously crossing the meridian. Due to the Earth's rotation, the Sun will next cross the meridian *on average*[10] 24.0000 (solar) hours later, whereas the radio source will cross it 3.9344 minutes earlier. The *sidereal day*, consisting of 24.0 sidereal hours, is thus equal to 0.99727 *mean solar days*. As more days pass, the Sun will continue to be 3.9344 minutes late each day with respect to the radio source, and thus appear to shift relative to the source (and the stars). This causes the Sun to apparently move steadily eastwards through the constellations of the zodiac, eventually returning, exactly one year later, to where it started.[11]

The procedure to find the location in the sky of a radio source, day or night, is:

1. Find the current solar time and date from the sundial (or other sources).
2. Use the diagram shown in Fig. 15 to find the current sidereal time.
3. Go to the appropriate radio source marker (each is labelled with source name and sidereal time - see Fig. 22 for examples[12]) and, putting your eye as close as possible to the marker on the concrete pad (Fig. 16), look upwards at the gnomon, which then indicates the direction to the radio source (day or night). [13]

At night, such a line-up even reveals the pattern of the appropriate constellation (Figs. 17 and 18)!

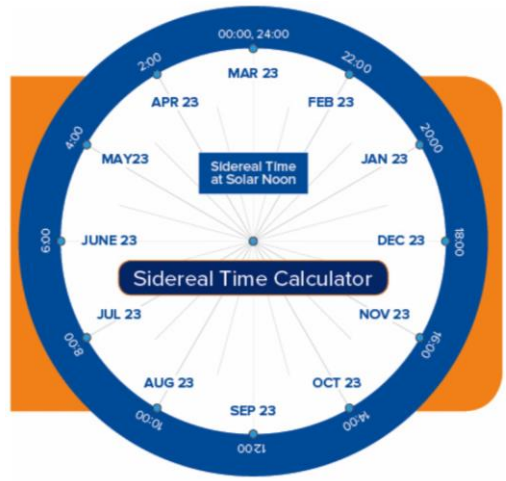

Fig. 15. Visitors to the VLA use this sidereal time calculator in order to locate the current positions of radio sources in the sky. Diagram: NRAO/ AUI/ NSF.

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[10] The length of a solar day actually varies over the year — as much as 30 seconds longer or 20 seconds shorter than the *mean solar day*. The accumulation of these variations on any given date leads to the familiar equation of time.

[11] How can the Earth apparently have *two* different rotation periods? And which is the "real" one? The answers involve the annual *orbital* motion of the Earth; physicists consider the sidereal day more fundamental, but biologists (and non-astronomical humans) care more about the solar day. Consult the Web for diagrams explaining why the two types of day exist.

[12] A radio source of course is, in general, not always above the horizon, so at a given time it may not be possible to "see" it. Indeed, the range of sundial markers for each source informs the user about the sidereal time interval when it can be viewed. The intervals are: 12:30 to 14:30 for Centaurus A, all but 03:00 to 13:00 for Cygnus A, and all but 09:00 to 13:00 for Cassiopeia A. Note that the radio source markers are separated by *sidereal* hours, not the more familiar solar hours as on the main dial pattern.

[13] Another consideration for this sundial is that the coordinates of radio sources (and stars) in fact steadily change because the direction of the Earth's Pole, on which the coordinates are anchored, drifts with time. This *precession* of roughly 14° (0.9 hour) per millennium means that in the very distant future the radio sundial's line-up will noticeably *not* point to the radio sources. This could be fixed by simply adjusting the sidereal time values on each disk — we recommend to our descendants that the first adjustment (of 10 minutes) be made in the year 2190. (Further long-term trouble: since a radio source's *declination* also slowly drifts because of precession, the radio shadow tracks will also slowly shift.)

Normal sundials also slowly become inaccurate as the centuries pass, due to the fact that the obliquity of the ecliptic ε (the "tilt" of the Earth's axis) is slowly decreasing at a rate of 47" per century. Thus, the dates and times read on a dial built in ancient times are not accurate today; ε was about 24° in Ptolemy's time and is 23.44° today.

The spherical coordinate system used by astronomers for radio sources (and stars) is aligned with the sidereal day and the North Celestial Pole; the coordinates analogous to longitude and latitude on Earth are right ascension and declination. For these coordinates, in which any distant radio source has a fixed right ascension and declination, the Sun apparently moves steadily eastwards through the year even as it moves north and south by 23.4° with respect to the (celestial) equator. Sundials thus only need to deal with declinations between 23.4° S (December solstice) and 23.4° N (June solstice). Radio sources, however, can be located well outside this declination range, and therefore their "shadows" can occur far outside the hyperbolic, solstitial borders of the familiar pattern on the face of a horizontal (or vertical) sundial with a nodus. In fact, the sun's apparent annual path around the sky (the ecliptic) never does pass near any of our three chosen radio sources, which are at declinations of 59.0° N (Cassiopeia A), 40.8° N (Cygnus A), and 43.1° S (Centaurus A). [14]

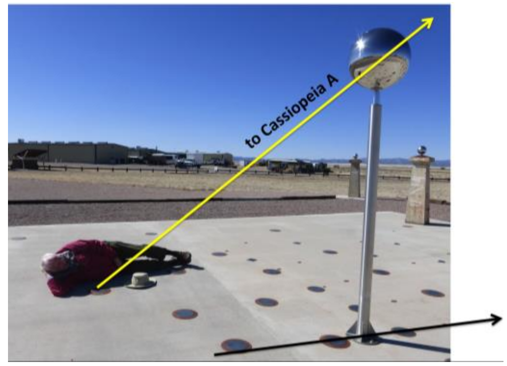

Fig. 16. Goss demonstrates how the sundial can be used as a sighting device for where each of three radio sources lies: place your eye as close as possible to the relevant radio source's disk and look on past the gnomon. Photo: Sullivan.

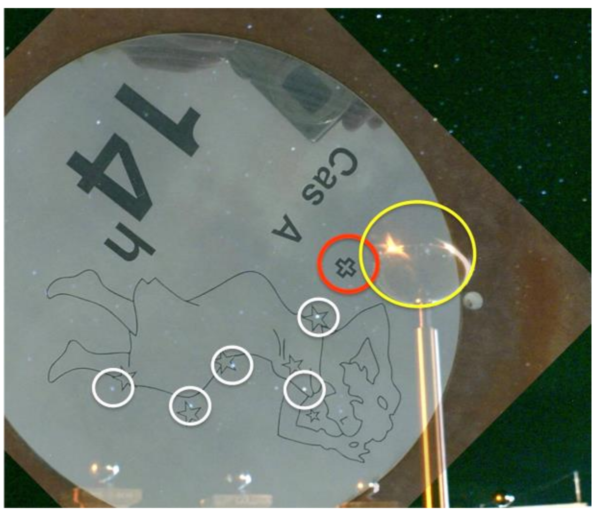

Fig. 17. A demonstration of locating the radio source Cassiopeia A at night on 22 July 2017. Taken at 14h sidereal time, the photo shows the camera's view of the gnomon (yellow circle) and the sky behind it as seen from the 14h sidereal time disk. This disk (shown in Fig. 22) is here superimposed on the sky. The familiar "W" of Cassiopeia's brightest stars is indicated by white circles, and the location of Cassiopeia A (red circle) is seen to align closely with the gnomon. Glare reflected off the gnomon is from a nearby security light. Photo: Kelsey Lund and Anya Raj.

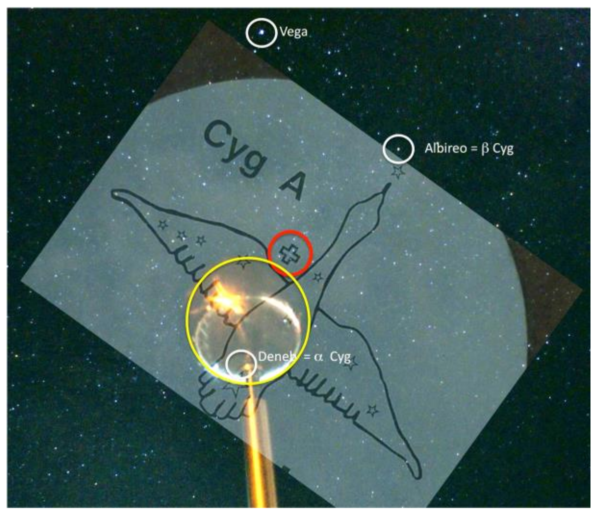

Fig. 18. A similar demonstration of locating the radio source Cygnus A at night. Once again the location of the radio source (Cygnus A, red circle) is seen to align closely with the gnomon. Deneb, the brightest star in the constellation Cygnus, is hidden behind the gnomon. Photo: Kelsey Lund and Anya Raj.

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[14] The "A" notation originated in the 1940s when the strongest radio source within any constellation was called A, the second strongest B, etc.

The fact that the radio shadow tracks can occur well outside the range of solar tracks over the year, aided the dial's clarity in that such tracks do not intermix with solar tracks (date lines). In fact, we specifically did *not* choose radio sources Taurus A (the Crab nebula) and Virgo A because their declinations are within the Sun's range.

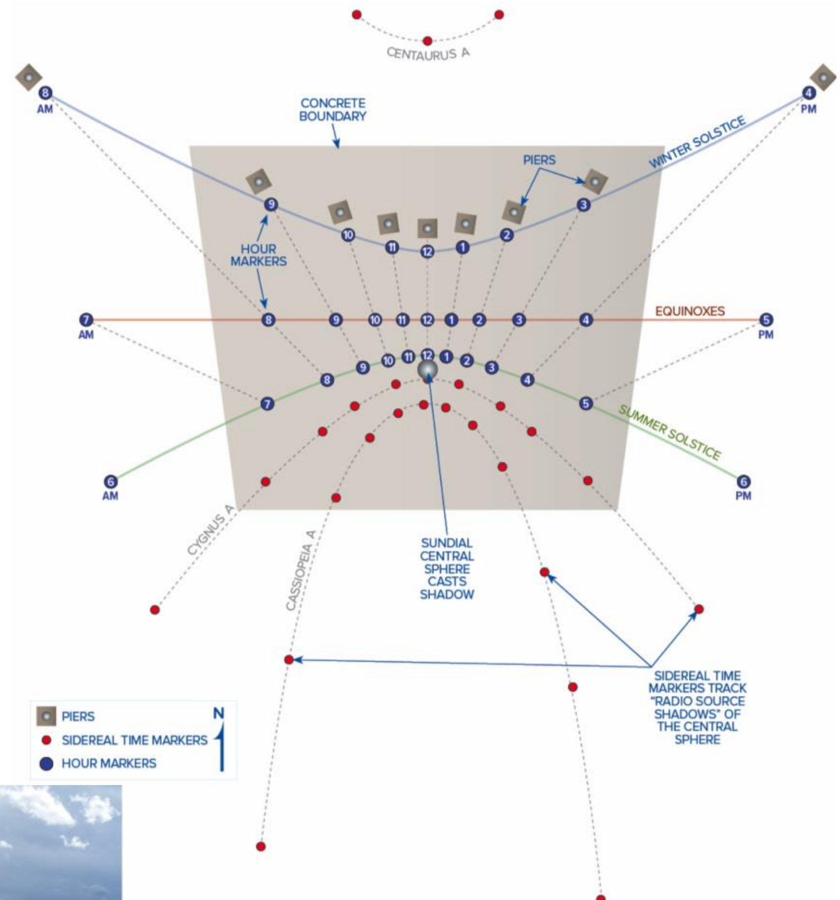


Fig. 19. Layout of the various markers for the sundial — the legend explains the symbols. The southern edge of the concrete pad is 37 ft (11 m) in length. Note how the paths of the "shadows" of the three radio sources fall outside the range of the usual solar shadow. The sidereal time disks (red dots) are at 1h intervals except near the center where they are 2h due to crowding. Compare the aerial view of Fig. 29. Diagram: NRAO/ AUI/ NSF.

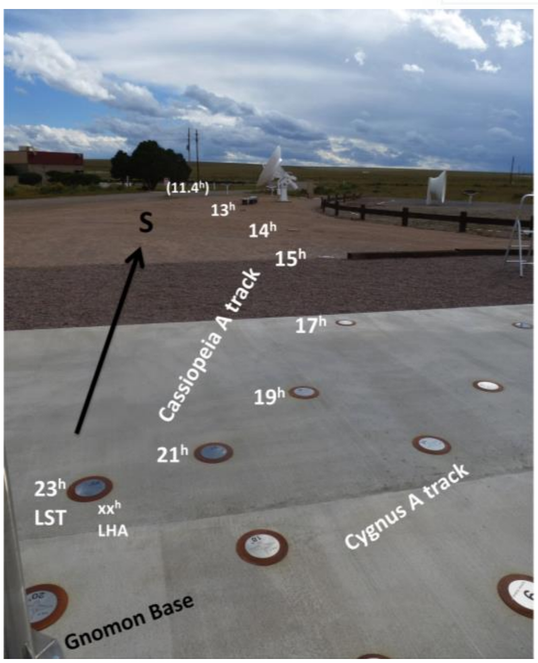


Fig. 20. The long, ellipsoidal arc of Cassiopeia A's radio shadow track (Fig. 19) stretches out into a road, although for practical purposes the plaques do not extend quite so far. A portion of the Cygnus A radio shadow track is also seen. Photo: Sullivan.

Radio sources have the convenient property that their declinations remain (almost) constant, so the daily tracks of their radio shadows, unlike solar tracks, do not change through the year. The tracks on the sundial for the radio shadows of Cygnus A and Centaurus A are both hyperbolas, while that for Cassiopeia A is an ellipse (Fig. 19) because it is so far north that it never sets at the VLA's latitude — even when it is due north, it is still 3° above the horizon.[15] The ellipse of Cassiopeia A, if completely marked, would have extended to 135 ft (40 m) south of the gnomon, squarely in a nearby road (Fig. 20). We thus reluctantly had to omit three hour markers for Cassiopeia A. Conversely, the portion of the hyperbola for Centaurus A extends over only two hours because the source is so far south that it barely peeks above the horizon (at 13° peak altitude). Radio images of the three sources are shown in Fig. 21 and further information about each is given in Table 1 at article's end. Fig. 22 shows close-ups of the radio source/sidereal time markers whose locations are illustrated in Fig. 19.

[15] An analogous situation obtains for the *Sun* on a sundial above the Arctic Circle — because the Sun never sets on the summer solstice, its shadow track is a complete 24-hour ellipse.

Solar Time and Date

As can be seen in Fig. 19, the solar time and date are indicated in the conventional manner for a horizontal dial. An explanatory brochure for visitors (Appendix G on our website) provides a graph for adjusting solar time to clock time because of the equation of time and the VLA's 10.5 minute offset from the center of the Mountain Standard Time zone. Time can be read to an accuracy of about 5 minutes with little effort. Furthermore, the solstices and equinoxes (Fig. 23), as well as intermediate months, are marked so that one can typically read the shadow to an accuracy of about a week.

The entire pattern is centrally anchored by the oversized (20-inch (51 cm) diameter) noon/equinox marker (Fig. 24). This contains one of two mottos for the dial:

I measure the hours by our nearby star,

While the dishes around you look light-years afar.

The second motto is:

A complex array transforms radio skies;

A creeping shadow shows us time flies.

The first line of the second motto pays homage to Bracewell and the VLA through the technical meanings of the terms “complex” and “transform”. Bracewell was a master of understanding the power of Fourier Transforms, a mathematical operation at the heart of the VLA. And “complex” refers to the standard practice of representing electromagnetic waves (and much of the behavior of modern electronics) as complex numbers.

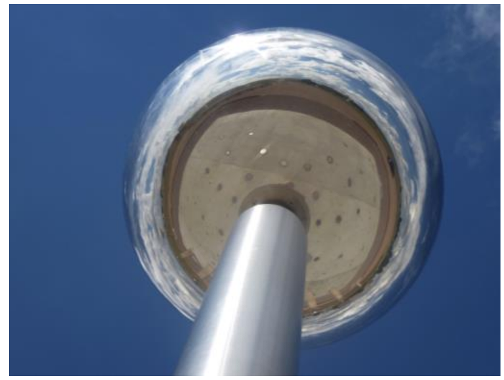
Fig. 21. The radio sources Cassiopeia A (top left), Centaurus A (top right) and Cygnus A (bottom). The strength of the radio emission has been color-coded and superimposed on each image at visual wavelengths. In each case the ultimate source of radio energy is an object near the image center. Cassiopeia A is the remains of a star that exploded as a supernova in the 17th century in our own Milky Way galaxy. Centaurus A is a distorted galaxy, thought to be the result of two galaxies merging around one-half billion years ago (the bluish colors represent the radio emission). Cygnus A is a faint galaxy with a giant black hole at its center that gives rise to two large regions of radio emission (colored red) well outside the galaxy. More information is given in Table 1 at article's end. Images: NRAO/ AUI/ NSF.

Fig. 22. Sample sidereal time markers for the radio sources Cassiopeia A, Cygnus A and Centaurus A. The sidereal time at which the disk would fall in the gnomon’s "radio shadow" is indicated beneath a drawing of the traditional constellation (and its brightest stars) in which the source can be found. The exact location of the radio source within the visible constellation is indicated by a plus symbol. Each stainless steel disk is bordered by a beveled “rust-bloom” steel border. Photos: Sullivan.

The sundial's gnomon deserves special mention. It is a highly polished 18-inch (46 cm) diameter stainless steel sphere (fabricated in China) that casts a clean elliptical shadow whose center can be estimated quite accurately by eye. It also looks superb perched 86 inches (219 cm) above the concrete pad on its stainless steel pole, a pipe of diameter 3 inches (7.6 cm).[16, 17] Gazing into it at close distances produces spectacular wide-angle vistas of the horizon and sky, as well as the dial (examples are shown in Figs. 25, 26 and 27). Skilled photographer Colleen Gino produced the beautiful image shown in Fig. 28.

Fig. 23. Sample solstice and equinox markers with subtle seasonal patterns decorating the outer rims. Photos: Sullivan.

Fig. 24. The large, central disk (20-inch (51 cm) diameter) anchoring the entire pattern at noon on the equinoxes (see Fig. 29). One of the two dial mottos can be read along the bottom edge. Photo: Sullivan.



Figs. 25, 26, 27. The polished stainless steel gnomon (18-inch (46 cm) diameter) reflecting the photographer, the sundial, and the near-horizon skies above the Plains of San Agustin. Photos: Sullivan.

[16] Our original idea for the gnomon was to mount it on one of the piers or perhaps on a slender pyramid. But mock-ups showed that such a large object covered too many of the planned radio source markers, and also seemed too dominant from an aesthetic point of view.

[17] The pipe supporting the pole also serves as a conduit for a ground cable, protecting against a lightning strike.

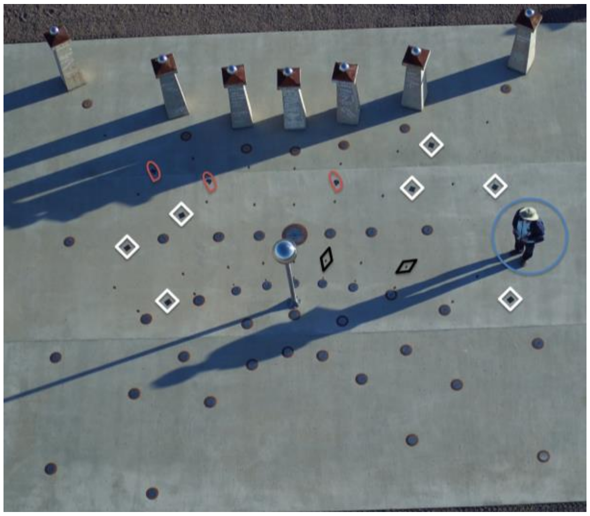


Fig. 29. A drone view of the concrete pad portion of the dial early on the morning of 24 Jun 2018 (compare Fig. 19). White diamonds enclose the 7 commemorative markers, red ovals the 3 observatory markers, and 2 black diamonds typical month/hour indicators. The blue circle marks a human gnomon. Photo: Jeff Hellerman and Brian Kent.

Fig. 28. A night-time composite image of the Milky Way in the southern sky and the gnomon with its reflection of the northern sky, showing star trails circling about the North Celestial Pole during a one-hour exposure. Photo: Colleen Gino.

Commemorated Dates

Given that the sundial is infused with the history of early radio astronomy, it seemed natural to commemorate dates important in that history. Each of seven 4.5-inch-square (11.4 cm) engraved brass markers is positioned such that the gnomon's shadow passes over it on the event's anniversary. Details of these seven events are given in Table 2 at article's end. Their marker locations are seen in Fig. 29 and the markers themselves are shown in Fig. 30.

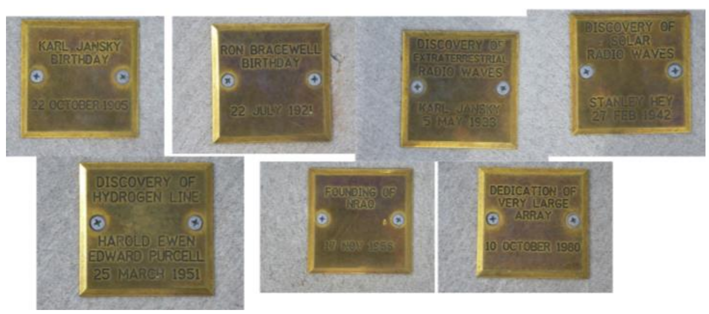


Fig. 30. The 7 miniature plaques commemorating dates important in the history of radio astronomy; details are given in Table 2 at article's end. The sun's shadow passes over each marker on the date it commemorates. Photos: Sullivan.

Related Observatories

Three ~5-inch (13 cm), engraved brass markers in the form of radio dish antennas refer to other important observatories (see Figs. 29 and 31, and Table 3 at article's end). Their positioning is such that the gnomon's shadow passes over a marker's hour when solar noon occurs at the corresponding observatory. For instance, Bracewell's original array at Stanford in California was located 14.55° or 58.2 minutes west of the VLA, meaning that solar noon at Stanford occurs 58.2 minutes after solar noon at the VLA.[18]

Fig. 31. The 3 antenna-shaped markers indicating related radio astronomy observatories, including Bracewell's Heliopolis; see Table 3 at article's end. They are positioned at the VLA solar time corresponding to each observatory's local solar noon. Photos: Sullivan.

[18] The commemorative date markers are placed at arbitrary solar times, and the observatory markers at arbitrary dates. The locations of these markers are shown in Fig. 29.

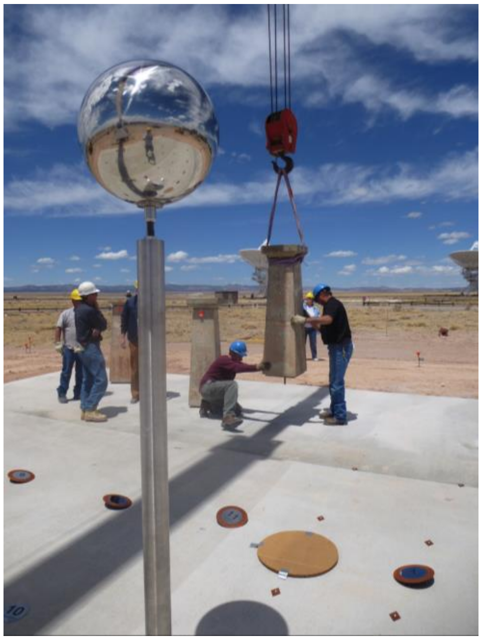


Fig. 32. A pier is gently lowered into place by a crane. Photo: Sullivan.

Fig. 33. Sullivan uses a 1940s era surveyor's transit to establish the locations of all markers and piers. The midday sun, used to determine true north, is at an uncomfortably high altitude. Photo: Goss.

Fabrication and Construction

The 86 inch (219 cm) height of the sphere above the dial face was chosen to provide a not-too-crowded dial pattern, as well as to place the sphere largely out of harm's way. A trapezoidal concrete pad of approximate dimensions 41 × 35 ft (12.5 × 10.7 m) accommodates most of the dial face, but 17 markers beyond this pad (see Fig. 19) were positioned on small concrete footings. Altogether, ~30 cubic yards (23 m^3) of concrete were required. [19, 20]

The surfaces of the 62 inch (1.6 m) high signature piers, although an outstanding feature of the sundial, proved not suitable to receive the dial shadow. Rather, we placed a pier directly behind the winter solstice line for each of the nine hour lines from 8 to 4 (see Fig. 19). The 1600-pound (700 kg) concrete structures were carefully positioned by a crane at distances ranging from 14 to 47 ft (4 to 14 m) from the gnomon (Fig. 32). We decided not to put large numbers for the hours on the piers, since that would have detracted from the signatures — rather, the user reads the hours from the disks on the concrete pad. The piers have been given decorative caps and 8 inch (20 cm) diameter stainless steel balls.

Fig. 34. A long shadow cast by the gnomon on the winter solstice of 2013 almost reaches the base of the 4h pier; the front edge of each hour-pier was placed 20 inch (51 cm) beyond the center of the winter solstice shadow (see Figs. 19 and 29). Photo: Goss.

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[19] *Colored* concrete was seriously considered as a possibility for the dial, but in the end rejected based on its increased cost and the uncertainty about durability of the colors in harsh desert conditions.

[20] It was necessary to pour the concrete pad on three separate days. This resulted in slightly different shading on the three sections (visible in Fig. 29).

The dial pattern was laid out based on a survey using Sullivan's 1940s-era transit (Fig. 33); north was determined using the Sun's position, of course! Various checks have indicated that the resultant dial can be read to an accuracy of ~1 minute when crossing a marker. The most sensitive check was an observation at 4 hours solar time on the winter solstice (solar altitude of 9°), when the shadow extended 45 ft (14 m) to the farthest marker from the gnomon (Fig. 34).

A major decision was whether to create, for the usual hour and date indicators, continuous connecting *lines*. Continuous lines can be made using inlaid metal strips or paint, but the former is costly for a large dial and the latter requires frequent maintenance, especially in a desert environment. We favored instead sequences of 6 inch (15 cm) diameter stainless steel disks (Fig. 23) bordered by beveled "rust-bloom" steel borders for a total diameter of 9 inch (23 cm) [21]. These were attached to the concrete surface along the two solstice lines and the equinox line for each hour. Intermediate dates can be estimated more accurately using small ~2-inch (5 cm) diamond-shaped markers (see Fig. 29; one is visible close-up in Fig. 23) placed at one-month intervals along each hour line. We also decided to greatly simplify construction and have a less cluttered design by foregoing any separate large labelling (such as "Equinox"); rather, all lettering is laser-engraved on the stainless steel disks themselves. Altogether, 101 markers were fabricated and attached using a combination of screws, epoxy and pins to deter souvenir hunters.

"First Shadow" Day

After more than three years of planning and construction, the sundial was dedicated on 23 September 2013 at precisely solar noon on a sunny, breezy day (Fig. 35). Present were Ron Bracewell's son Mark and daughter Wendy (Fig. 36); Karl Jansky's daughter Moreau Parsons (see Table 2 at article's end); Joseph Pawsey's son Stuart (see the caption for Fig. 8); the Director of NRAO Tony Beasley; and two of the pier signatories, Barry Clark and Barney Ricketts (Fig. 37). The pole and spherical gnomon had colorful ribbons extending to each of the piers; after a ceremonial countdown and cutting, we had a joyful impromptu "May Pole" to dance around (Fig. 38)!

Fig. 35. The crowd gathered on 23 Sep 2013 for the sundial's dedication ceremony, as reflected in the gnomon. Photo: Dave Finley.

Six years later, the sundial continues to engage visitors from around the world who are often surprised, while taking the Walking Tour (Fig. 39), to find this old technology amidst the very latest electronics of the VLA. [22] If you ever visit New Mexico, be sure to enjoy the VLA and its radio sundial in the beautiful high desert Plains of San Agustin.

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[21] The beveled edge and low profile of these markers mean that they present no tripping hazard, allowing visitors to wander safely all over the sundial. Attaching the markers to a standard concrete surface was also much less complex and expensive than insetting them.

[22] The Visitor Center (https://public.nrao.edu/visit/very-large-array) provides a large four-page color brochure (downloadable as Appendix G in the Digital Bonus and from our website) that fully explains how to use the sundial, as well as providing details of the history of radio astronomy and Bracewell.

Fig. 36. Ribbons are cut by Mark and Wendy Bracewell for the official "first shadow" at precisely solar noon. Note the gnomon's shadow covering the large central disk (Fig. 24). Photo: Sullivan.

Fig. 37. Radio astronomers Barney Rickett and Barry Clark stand by the signatures that they had chiseled into the Stanford piers under Bracewell's supervision a half century before. Photos: Goss, Dave Finley.

Fig. 38. An impromptu May pole dance immediately followed the sundial's "first shadow." Photo: Goss.

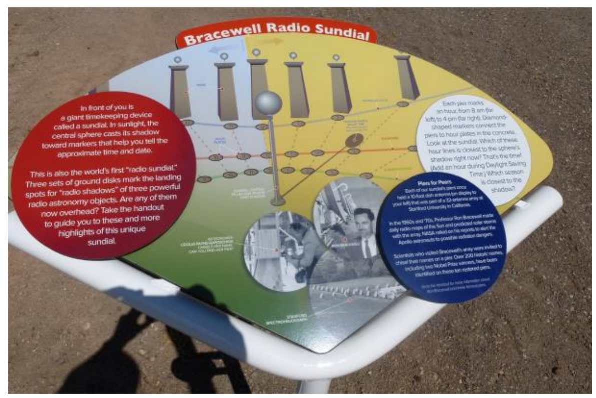

Fig. 39. A sign on the VLA's self-guided walking tour explains the radio sundial to visitors. Photo: Sullivan.

Acknowledgements

We thank Guy Stanzione, whose engineering advice and skill, as well as project management, was indispensable. Project coordinator Judy Stanley kept us on track over several years and contributed much labor and many excellent ideas. Bob Lash coordinated all aspects at the California end and raised needed financial support via Friends of the Bracewell Observatory (all donors are listed in Appendix E). Concept drawings by architect Robert Williams aided this fundraising. Chris Langley and Jon Thunborg of the NRAO staff were particularly helpful (all staff members who worked on the project are also listed in Appendix E). We also thank Jeff Hellerman and Brian Kent for their drone photography, as well as Robert Stephens and Bob Hayward for assistance with restoring the dish shown in Fig. 11. Finally, financial support from AUI, and its President Ethan Schreier, was vital.

Woody Sullivan woody@astro.washington.edu
W. M. Goss mgoss@nrao.edu
Anja Raj

/ continues

Table 1. Radio sources that can be located using the sundial

Radio Source	Identification	Discoverer	Date	Right Ascension[23]	Declination
Cygnus A[24]	Radio galaxy	J. S. Hey	1946	20.00 h	+40.77°
Centaurus A[25]	Radio galaxy	J. G. Bolton,[26] Stanley, Slee	1947	13.44 h	-43.09°
Cassiopeia A[27]	Supernova Remnant	M. Ryle & F.G. Smith	1948	23.40 h	+58.87°

Table 2. Commemorated dates on the sundial

Event	Date
Birth of Karl Jansky[28]	22 Oct 1905
Birth of Ronald Bracewell	22 Jul 1921
Announcement of Jansky's discovery of Milky Way radio waves	5 May 1933
J. S. Hey discovers radio waves from Sun[29]	27 Feb 1942
H.I. Ewen & E. M. Purcell discover hydrogen line[30]	25 Mar 1951
Founding of National Radio Astronomy Observatory	17 Nov 1956
Dedication of Very Large Array	10 Oct 1980

Table 3. Observatory noon markers on the sundial

Radio Observatory	Longitude	Latitude	Difference in Longitude from VLA	Time of Observatory's Solar Noon at the VLA
VLA	107.6184° W	34.0786° N	0	(12h0.0m)
Stanford	122.165° W	37.4° N	+14.55° = +0h58.2m	12h58.2m
Green Bank[31]	79.8394° W	38.4° N	- 27.78° = -1h51.1m	10h08.9m
ALMA[32]	67.7532° W	23.0° S	- 39.87° = -2h39.5m	09h20.5m

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23 The coordinates are given for the epoch 2013.5, the approximate dedication date for the sundial. The right ascension coordinate is identical to the sidereal time when the radio source crosses the meridian.

24 Cygnus A is a galaxy with a giant black hole at its center, at a distance of about 600 million light-years.

25 Centaurus A is a distorted galaxy (thought to be the result of two galaxies merging around 1/2 billion years ago), located about 9 million light-years from Earth.

26 Bolton's signature is prominent on the south side of the noon pier (Fig. 9).

27 Cassiopeia A is the high-energy remains of a star that exploded as a supernova in the 17th century in our own Milky Way galaxy, about 11,000 light-years distant. Co-discoverer F. G. Smith is a signatory.

28 Karl G. Jansky (1905—1950), for whom the VLA is now named, was an American physicist who serendipitously first detected radio waves of extraterrestrial origin, and then showed that they originated in the Milky Way.

29 James S. Hey (1909-2000) was an English physicist who, during World War II, accidentally discovered that the Sun emits radio waves.

30 Harold I. Ewen (1921-2015) and Edward M. Purcell (1912-1997) were American physicists who first detected an interstellar spectral line of hydrogen gas at a wavelength of 21.1 cm.

31 Green Bank, West Virginia, was the original home of the National Radio Astronomy Observatory and is still the home of the Green Bank Telescope, the world's largest fully steerable dish (100 m (328 ft) diameter).

32 ALMA is the international Atacama Large Millimeter Array, located in the Atacama Desert of Chile at an altitude of 5100 meters (16,600 ft). It is a new array operating on the same principles as the VLA, but at much shorter wavelengths.

Appendixes

These are made available at https://science.nrao.edu/about/publications/sundial

A. List of all signatories

B. Pier-by-pier & side-by-side signature listings & photos

C. Various aspects of the signatures

D. Sundial project timeline

E. Private donors, NRAO staff, and others who contributed to the project

F. Dedication ceremony in 2013

G. NRAO Sundial brochure (PDF)

H. This *Compendium* (2019) article (PDF) and JPG files for all figures

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