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RADIO ASTRONOMY AT CORNELL UNIVERSITY: THE EARLY YEARS, 1946 TO 1962

Donald B. Campbell
Department of Astronomy, Space Sciences Building, Cornell University, Ithaca, NY 14853, USA.
Email: dbc7@cornell.edu

Abstract: In 1946 the Microwave Astronomy Project was initiated by the School of Electrical Engineering at Cornell University, the first university in the United States to enter the new field of radio astronomy as it was later called. While the Engineering School's Director, Charles Burrows, led the project, the initiative came from Charles Seeger, a faculty member in Electrical Engineering, and two instructors in the Department of Astronomy, Ralph Williamson and Donald McRae, both of whom left Cornell in 1946. With funding from the U.S. Office of Naval Research, two World War II SCR-268 radar systems, which operated at 200 MHz, were acquired and plans made to construct a 6-m diameter parabolic antenna that would operate at frequencies up to 10 GHz. A site was chosen about 8 km from the Cornell university campus. The parabolic antenna was completed in 1948 although using a borrowed 5-m reflector that, initially, could only operate up to 200 MHz. Its completion in October was in conjunction with the first conference on radio astronomy held in the United States, which attracted considerable publicity for this new research field. Initial observations of the Sun were made in June 1948 using the two receiving 4 × 6 dipole arrays from the SCR-268 radars mounted on the elevation arm of one of the radar systems. This was followed by routine solar observations from July 1948 to December 1949. Initial results were published by Martha Stahr, Assistant Professor of Astronomy at Cornell. During the summer and fall of 1948 two more observational programs were started. Charles Seeger and Ralph Williamson determined the direction of the radio pole of our Galaxy using the SCR-268 mattress array and Seeger did extensive observations of the strong variable source Cygnus A using, initially, the mattress array and, later, the 5-m antenna. In late 1949 Leif Owren joined the project to pursue a doctoral degree based on solar radio observations. These started in mid-1950 and continued until December 1952, initially with the 5-m antenna and, later, with the mattress array while the 5-m antenna was being resurfaced to allow operation at 1,420 MHz. Owren also built a two element interferometer to study the relationship between solar radio bursts and optically observed plages and sunspots. Charles Seeger left Cornell in 1950 and Owren in 1952, leaving no astronomers with a strong interest in the radio astronomy program until Marshall Cohen joined the faculty in 1954. Cohen initiated studies of the polarization properties of solar radio emission with the 5-m antenna that continued into the 1960s both at the original site and, after 1962, at a new site south-east of Cornell University in the town of Danby. Only the 5-m antenna was moved to this site and it was decommissioned when the radio astronomy technical group, which by this time was primarily working in support of the newly built Arecibo 305-m telescope, was again moved to a site closer to Cornell University.

Key Words: Radio astronomy, Cornell University, Sun, Galaxy, Charles Seeger, Ralph Williamson, Donald McRae, Martha Stahr Carpenter, Leif Owren, Marshall Cohen

1 INTRODUCTION

On 11 July 1956 Bart J. Bok, Professor of Astronomy at Harvard University and the mentor of many of the first graduate students in radio astronomy in the U.S., gave an address at the U.S. National Science Foundation titled "Radio Astronomy Research in the United States". Bok (1956) began with a brief history of radio astronomy:

> Radio astronomy had its birth in the United States in the early 1930s, when Karl G. Jansky discovered radio static reaching us from the center of our Milky Way System. Some of the basic early discovery work was done in the United States by Grote Reber and by J.C. Southworth, but in the postwar period the lead was taken by Great Britain, Australia, the Netherlands and Canada. Ten years ago, only a single university—Cornell—devoted major attention to research in radio astronomy and the Naval Research Laboratory (NRL) had then only just entered the field.

A general account of the early years of radio astronomy can be found in the book *Cosmic Noise: A History of Early Radio Astronomy* (Sullivan, 2009).

Why did Cornell University get involved in the very early days of this new field? It appears to have been the chance association of three young faculty members in the last years of World War II and the following year combined with a receptive Director of Cornell's School of Electrical Engineering, Charles Burrows (1902–1970; Figure 1). Burrows came to Cornell in June 1945 from Bell Laboratories. He had worked on radar during the war and his interests were in radio wave propagation for communications purposes so he was likely receptive to the idea of getting involved in this new field of astronomy, which utilized radio techniques that he was familiar with.

The suggestion undoubtedly came in late 1945 or early 1946 from Charles Seeger (1912–2002; Figure 2), an Instructor until 1946 and then Assistant Professor of Electrical Engineering, and Ralph Williamson (1917–1982; Figure 3), an Instructor in the Department of Astronomy. Seeger was the elder brother of the future folk

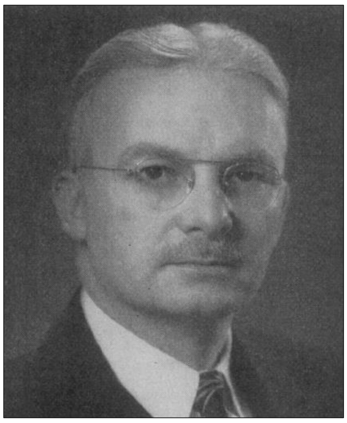

Figure 1: Charles Burrows in about 1957 (courtesy: IRE, September 1957).

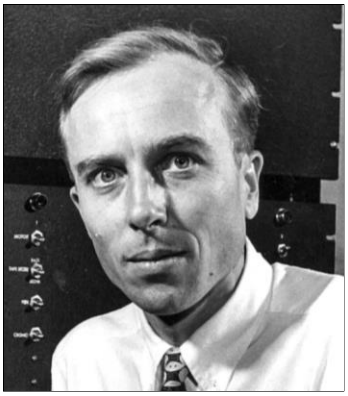

Figure 2: Charles Seeger in about 1948 (courtesy: Cornell University).

Figure 3: Ralph Williamson in 1943 (courtesy: University of Chicago).

Figure 4: Donald MacRae probably in the early 1950s (after Seaquist, 2007).

music icon Pete Seeger, had a strong interest in anything connected to radio. After graduating from high school he worked in a variety of radio stations and other industry jobs related to radio techniques before earning a Bachelor of Electrical Engineering degree from Cornell University in 1946 at the age of 34. In what now seems like an unusual arrangement, Seeger was an Instructor in Cornell's School of Electrical Engineering from 1943, while he was still an undergraduate, and was promoted to Assistant Professor as soon as he graduated. This likely came about because of the need to train wartime service people in electronics and, after the war, to teach the very large number of veterans attending university under what was known as the GI Bill, the Servicemen's Re-adjustment Act of 1944.

During the late war years there were two instructors in the Department of Astronomy at Cornell interested in radio astronomy, Donald MacRae (1916–2006; Figure 4), a Canadian who obtained his PhD at Harvard University in 1943 working with his advisor, Bart Bok, on galactic structure, and Ralph Williamson, a theorist who had obtained his PhD from the University of Chicago also in 1943 working with the eminent astrophysicist Subramanyan Chandrasekhar. In his obituary of Ralph Williamson, Arthur Covington (1983: 98) mentions that "Williamson was associated with Charles L. Seeger and C.R. Burrows in the founding of the Cornell radio observatory". While a graduate student at Chicago, Williamson had attended a talk by Grote Reber about his observations of radio emission from our Galaxy. Covington (ibid.) believed that

> … Williamson's intense desire to participate in radio astronomy was stimulated by hearing Grote Reber present his Wheaton observations at a seminar in the Astronomy Department at the University of Chicago.

In his obituary of MacRae, Seaquist (2007) states that Williamson introduced MacRae to radio astronomy, so it was the theorist who introduced the observer to this new field. However, it is clear that MacRae, Williamson and Seeger shared a common interest in the new field of radio astronomy.

Both Williamson and MacRae left Cornell in 1946, a significant loss of two very bright young astronomers but it does not appear that their departure caused any questioning at Cornell as to why they left. In his obituary of Williamson, MacRae (1982) says:

> Apart from some elementary radio astronomy studies sparked by Charles L. Seeger Jr. in the Electrical Engineering faculty, astronomy at Cornell seemed unlikely to develop, and both of us left with regrets in 1946.

Williamson joined the faculty at the University of Toronto and MacRae eventually also ended up on the faculty at Toronto where he had a distinguished career supporting many of the major Canadian radio astronomy programs. During his years at Toronto, before he left in 1953 for a position at the Los Alamos National Laboratory, Williamson maintained a collaboration with Seeger and was appointed a consultant to the Microwave Astronomy Project at Cornell. MacRae also maintained a relationship, spending the summer of 1948 at Cornell and collaborating with Seeger on searching for an optical counterpart for the variable radio source Cygnus A.

The departure of Williamson and MacRae from Cornell left William Shaw, the Chair of the Astronomy Department, as the only faculty member in the Department. This led to the hiring of Martha Stahr (1920–2013; Figure 5) in January 1947 as an Assistant Professor. Stahr received her PhD from the University of California at Berkeley in 1945 with a thesis based on measurements of stellar radial velocities using the 36-inch telescope at Lick Observatory. She spent two years as an Instructor at Wellesley College before coming to Cornell, where she was the first woman to be a faculty member in Cornell's College of Arts and Sciences (Rossiter, 1995).

While her interest was in optical astronomy, Stahr became the Department of Astronomy's participant in the Microwave Astronomy Project and immediately launched into assembling a comprehensive *Bibliography of Radio Astronomy*, all the papers published to date on microwave emission from the cosmos. The first bibliography was published on 15 December 1948 (Stahr, 1948) as a Cornell School of Electrical Engineering Radio Astronomy Report. Subsequently, two supplements to the *Bibliography of Radio Astronomy* were published (Stahr, 1949; 1950). In 1951 Stahr married Jesse Carpenter, a Cornell Professor in the School of Industrial and Labor Relations, and she continued to publish supplements under her married name through the mid-1960s under the titles *Bibliography of Extraterrestrial Radio Noise* and, after 1957, *Bibliography of Natural Radio Emission from Astronomical Sources* (see Larson (2012) for a comprehensive list of the supplements). The *Bibliography* through 1949 was issued as part of the Report of Commission V to the IXth General Assembly of the International Scientific Radio Union (URSI) and the *Supplement* covering 1950 was issued as part of the Commission V report for the Xth URSI General Assembly held in Sydney (Australia) in 1952. Charles Burrows

Figure 5: Martha Stahr Carpenter in the receiver hut of the Australian CSIRO Radiophysics Laboratory Potts Hill 11-m (36-ft) antenna while she was on sabbatical leave from Cornell University in 1955. (caption detail thanks to Wayne Orchiston, W.M. Goss and Jessica Chapman; photograph courtesy: CSIRO Radio Astronomy Image Archive).

led the U.S. delegation and William E. Gordon was also a member. An paper about the life of Martha Stahr, or Martha Stahr Carpenter after she married in 1951, has been written by Susan Larson (2012).

2 FIRST STEPS

The Cornell 'Microwave Astronomy Project' as it was called, was formally established on 1 May 1946 with support from the newly established Office of Naval Research (ONR) (Burrows and Gordon, 1954). It was to be based, initially, on two army SCR-268 wartime radar systems but with plans to build a fully steerable parabolic dish antenna up to 6-m in diameter.

In early 1946 ONR had initiated a program to support university research. It was under the direction of Rear Admiral H.G. Bowen, Chief of Research and Invention, and a number of universities were requested to submit proposals. Cornell submitted 28 of which 12, including, apparently, the Microwave Astronomy Program, had been funded by late 1946. This support was the seed funding needed to initiate the project leading to a long-term contract (N6-onr-264) that was awarded to Cornell by ONR about 1 August 1947. ONR was a significant funder of civilian science before the creation of the U.S. National Science Foundation in 1950 and continued to fund university research until the Mansfield amendment of 1973 limited the U.S. military to only funding research with direct military application. The basic objective of the Microwave Astronomy project, quoting from the contract document, was

> … the determination of radio noise magnitudes and apparent source directions, an investigation of high altitude reflections, and determination of absorbing bands, over as wide a frequency range as possible. Correlations of these measurements with weather, diurnal and seasonal variations and astronomical position is to be made. This work is to include measurements of radiation from the sun, and correlation of these with astronomical observations, especially those of sunspots. In the course of the work, a microwave telescope is to be designed and assembled, and a survey of its usefulness is to be made.

What was meant by "investigation of high altitude reflections" is not clear but it may indicate an intention to pursue radio propagation studies as well as radio astronomical ones, as did turn out to be the case.

From the first status report to ONR dated 31 October 1947, initial plans for work under the contract and the achievements up to that date were:

(1) Make a bibliographical survey of previous work on solar and cosmic noise. This was being pursued by Martha Stahr and was extremely important as the knowledge of what other groups in the U.S. or, more importantly, abroad was often delayed by months or longer due to poor or slow communications at the time. By 31 October 1947 Stahr had completed the initial cosmic noise survey and had started on a survey of solar noise observations.

(2) Construct a building for the operational equipment—a 15 × 7.5-m Quonset building was completed by 31 October (see Figure 6).

(3) Design and construct the microwave telescope mount (i.e. without the reflector) to cover the frequency range from 200 MHz to 10 GHz.

(4) Design and construct Dicke type radiometers for various frequency ranges, initially at 200 MHz to use with the SCR-268 antennas and, during the next year, for 10 cm wavelength because of the possibility of a spectral line of atomic hydrogen at 9.26 cm. Finally, at 20 cm and 3 cm due also to possible lines of atomic hydrogen. As of 31 October 1947 the 200 MHz radiometer was under construction.

(5) Construct or obtain antennas for these same frequency ranges, and calibrate them as to directivity and power gain.

(6) Investigate methods of obtaining the types and sense of polarization of the incoming radiation. As of 31 October, a "… satisfactory method of determining the type and sense of polarization for horn type antennas has been designed".

These initial work plans indicated an ambitious and well thought out program, a significant improvement on the plan presented in the ONR proposal. It is not clear why the wavelength of 9.26 cm, a spectral line due to a first excited state fine structure transition in atomic hydrogen, was preferred in order to detect atomic hydrogen. It is possible that the Cornell group was not fully aware of H.C. Van de Hulst's (1945) paper—which was in Dutch—that discussed the possibility of detecting the 21 cm line of atomic hydrogen, although it was close to one of their planned frequencies. A concerted effort to detect the 21 cm line would have put Cornell at the forefront of the new field of radio astronomy.

The financial support from ONR was substantial since it supported two faculty members, one research associate, four full time technicians, one secretary, two consultants and three additional technicians during the summer.

Because of radio frequency interference problems on the Cornell campus, a site was chosen about 8 km north of the campus on the east-

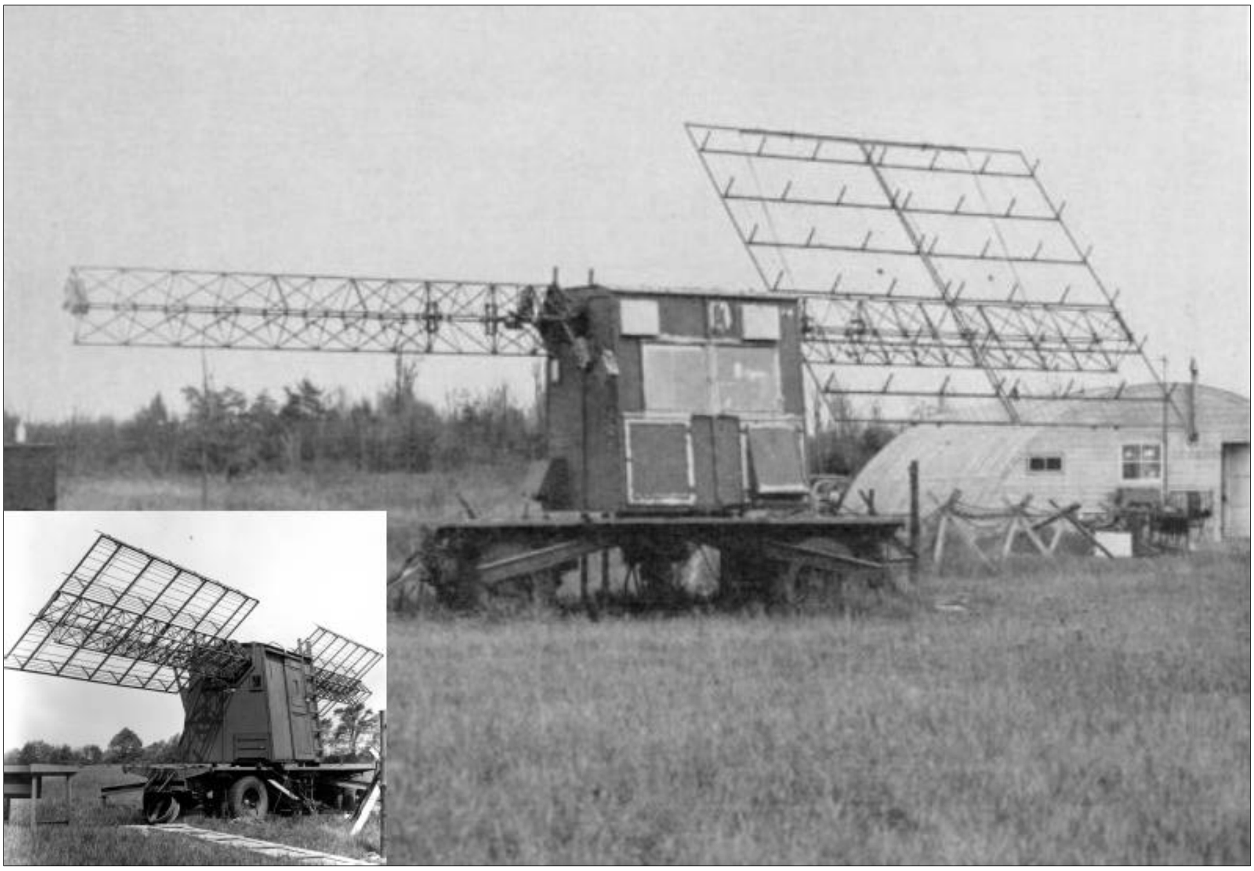

Figure 6: Two configurations of the modified SCR-268 radar systems. The radar system had a separate transmitting array plus elevation and azimuth receiving arrays. Only the 4 × 6 205 MHz dipole receiving array was retained. Two of these are mounted on the elevation arm of one of the units, with the insert showing the configuration as of late 1948 or early 1949. The main image shows the two arrays side-by-side to form a 6 × 8 dipole (5 m × 5 m) configuration used starting in October 1949. There was an intermediate configuration with one array rotated to give dual linear polarizations for solar observations. A bearing under the cabin allowed rotation in azimuth and the arm holding the arrays rotated in altitude (elevation), both initially manually operated. The Quonset hut housing the receiving equipment is in the background (courtesy: Cornell University Archives).

ern edge of the new Ithaca airport, which was then under construction. By late 1947, the two US Army SCR-268 radar systems had been acquired and modified keeping just the two receiving dipole mattress arrays on one of the mounts for use as a cosmic radio wave receiver operating at a frequency of 205 MHz (Mc/s at the time, as the unit Hz was not adopted until 1960). As shown in Figure 6 several configurations of the 4 × 6 mattress arrays were used. Single 4 × 6 dipole arrays, probably using the configuration with the two arrays at right angles to give horizontal and vertical linear polarizations, was used for the initial solar observations starting in June 1948, but the 6 × 8 array was in operation by October 1949.

3 THE 5-m RADIO TELESCOPE

The initial plans were to construct a parabolic dish-type telescope with a reflector diameter of up to 6 m operating at frequencies from 200 MHz to 10 GHz. A four-axis mount was designed by Professor Hinkle of Cornell's School of Mechanical Engineering. The mount, possibly the most complex one ever built for a radio telescope, was indicative of the ambitions of the project. The telescope had a standard equatorial mount but it was also supported on an azimuth track and the reflector could be rotated about its principal axis for polarization studies. As of 31 October 1947, the design had been completed, the large concrete base finished, and construction of the mount begun in the mechanical engineering shops at Cornell. Possibly for reasons of cost and, especially, time, it was decided to borrow an SK-2 5-m reflector from the U.S. Navy, the same reflector that was used on large navy ships such as the battleship *USS Missouri*. Due to its relatively small size and a surface made up of 0.32 cm steel rods welded into a 7.6 × 10 cm mesh, which limited its maximum frequency to about 200 MHz, this decision made moot immediate plans for observations at 20, 10 and 3 cm wavelengths. The mount was designed to support a reflector up to 6-m in diameter and it could probably have supported a

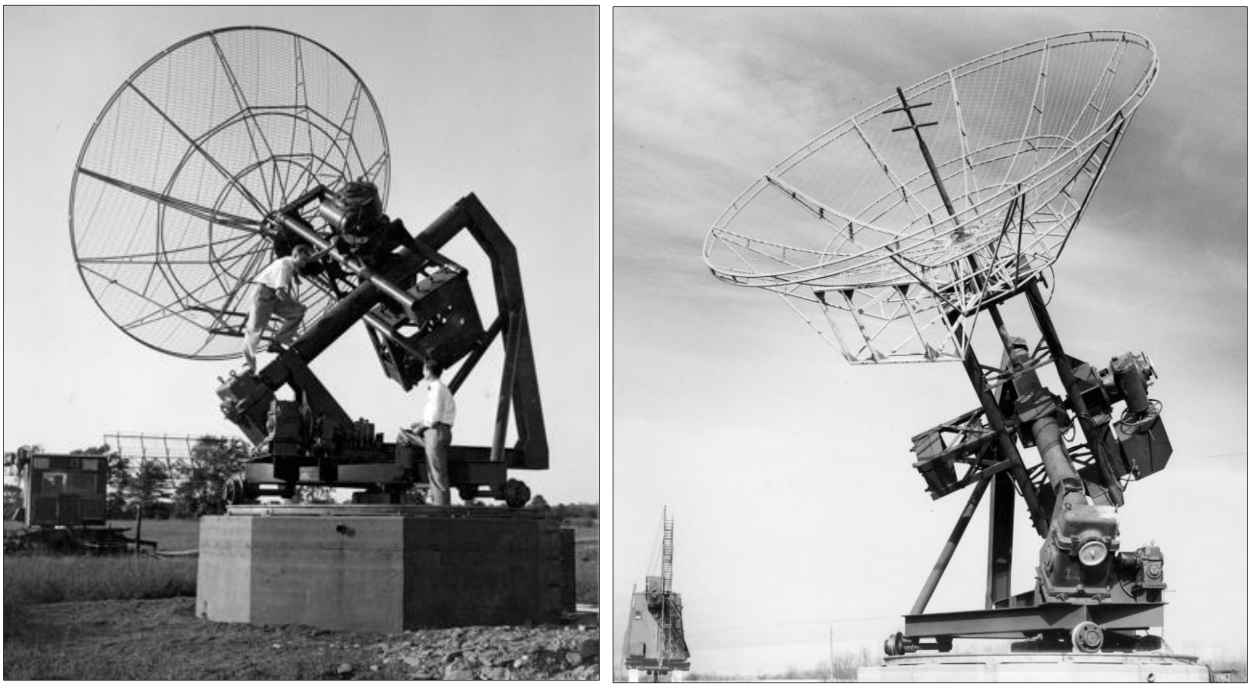

Figure 7 (Left): Charles Seeger and William Gordon on the almost-completed 5-m antenna in August/September 1948. The modified SCR-268 radar system can be seen in the background. Right: The completed 5-m antenna with a single polarization rotatable feed in October 1948. The hour angle and declination axes can be clearly seen equipped with manual controls and the whole mount sits on an azimuth track. Automatic tracking was to be done from the control building using selsyns for positional readouts (courtesy: Cornell University Archives).

larger one since it was designed to allow operation in winds up to 100 km/hr and its survival wind speed would have been much higher. Perhaps the major impact of the decision to use the borrowed reflector was that it prevented any attempt to detect the 21 cm line of atomic hydrogen until it was too late.

By the summer of 1948 the mount for the telescope was completed and by October the 5-m Navy dish had been attached to the mount (Figure 7). As discussed later, the dedication ceremony in early November coincided with the first radio astronomy conference held in the United States.

Plans for the radiometers included a Dicke switched system based on R.H. Dicke's July 1946 paper in *Review of Scientific Instruments*, which was only a little over a year old at this time. The plan was to switch between the source and a constant temperature load at low frequencies and use a rotating chopper with a resistive sector in waveguide similar to Dicke's setup, at higher frequencies with the switching and chopper rates being about 30 Hz. The receivers were to use balanced mixers, automatic gain control and adjustable time constants on the detected outputs. Esterline-Angus chart recorders were used to record the data. Time marks were based on a clock that was calibrated using WWV time signals transmitted by the then National Bureau of Standards (now the National Institute of Standards and Technology).

Burrows recruited Edwin Hamlin, Professor of Electrical Engineering and Director of the Electrical Engineering Research laboratory at the University of Texas at Austin, to be Professor of Electrical Engineering and Director of the Microwave Astronomy Project. Hamlin arrived at Cornell in September 1947. Like Burrows, his interests were in radio wave propagation for communications purposes and he had no background in radio astronomy. Unfortunately, Hamlin died suddenly on 27 April 1948. However, prior to his death, he had recruited William E. (Bill) Gordon (1918–2010; Cohen and Lane, 2011), his former Associate Director at the Electrical Engineering Laboratory at the University of Texas at Austin, to join the Cornell group.

Bill Gordon had a Master's degree in meteorology from New York University and had served in the Army Air Force during the war working primarily on the effects on radar of refraction in the Earth's atmosphere. He joined the University of Texas after the war was over. As recounted by Gordon in a 1979 self-interview, he was told by Hamlin that he needed to get a PhD and Hamlin offered to bring him to Cornell to work on the Microwave Astronomy Project while at the same time pursuing his PhD degree under Hamlin. Gordon represented the University of Texas at Hamlin's funeral where Burroughs renewed the offer with Burroughs now the thesis advisor. Gordon arrived in July 1948 with an appointment as a Research Associate and, simultaneously, as a graduate student pursuing a doctoral degree. His interests were also in radio wave propagation and after Henry Booker, a well-known British expert on radio wave propagation at Cambridge University, joined the School of Electrical Engineering in early 1949 Gordon worked primarily with him on his thesis research. Gordon went on to conceive and build the Arecibo 305-m telescope (Cohen, 2009) but, as he recounted in his self-interview, during his early years at Cornell he supported himself by doing some observing and data reduction for the radio astronomy project.

On 5 and 6 January 1948, Joseph (Joe) Pawsey (1908–1962; Lovell, 1964), the noted Australian radio astronomer, visited Cornell while on a tour of institutions in North America working on radio astronomy projects. At Cornell he would have met with Burrows, Hamlin and Seeger. In a report on his trip he commented that the Cornell plans included "… measurements in the decametric range, a search for the 1420 Mc/s line of hydrogen, and measurements on a separate 200 Mc/s set." (Pawsey, 1948). He felt that the Cornell group was spending too much time on developing elaborate equipment rather than getting on with observations. However, his report does make it clear that the Cornell group was now aiming at trying to detect the 21 cm line of atomic hydrogen.

Burrows had plans for a conference at Cornell in March 1948 on Microwave Astronomy, perhaps the first stand-alone conference ever planned on this subject, and, shortly after he arrived in Washington, Pawsey received an invitation from Burrows. In a letter dated 31 December to his boss, Dr E.G. Bowen, Chief of the Division of Radiophysics of the Australian Commonwealth Scientific and Industrial Research (CSIR, later CSIRO), Pawsey discusses the meeting and his plans to present a number of papers about the solar and cosmic noise research being done by CSIR researchers. The meeting would take place just prior to an Institute of Radio Engineers (IRE) meeting in New York that Pawsey was also attending. As detailed in Wendt (2008), Bowen sent a supportive reply but commented, "I don't think much of Burrow's invention of the title "Microwave Astronomy". A lot of it is certainly not microwave and I am not sure that it is astronomy". A session at the May 1948 URSI meeting had the title 'Radio Astronomy' (a term first proposed by Pawsey in 1948), and Bowen liked this much better. In 1949 the term 'radio astronomy' was formally adopted by Radiophysics (see Wendt, 2008). Possibly because the 5-m antenna was not yet in operation, the Cornell meeting was rescheduled from March to October 1948 and so Pawsey did not get to re-visit Cornell in March, as originally planned.

4 EARLY SOLAR OBSERVATIONS

By the summer of 1948 significant progress had been made in both the construction of the 5-m antenna (Figure 7) and with the start of solar observations at 205 MHz with the modified SCR-268 radar system (Figure 6). Test observations of the Sun were made in June 1948 using the receiver system that had been completed except for the chopper which was still under development. However, stability was not a problem given the strength of the solar emission. Figure 8 shows observations of the quiet and active Sun made on 5, 18 and 28 June 1948. A single 4 × 6 dipole SCR-268 mattress array was used, vertically polarized with respect to the horizon and with a beamwidth of 15° in azimuth and 20° in elevation. The antenna was visually aligned with the Sun at intervals of 15 minutes or less.

With the success of the June solar observations, regular 'solar patrol' measurements of radio emission from the Sun at 205 MHz over a two-hour period centered on local noon were begun in July 1948 and carried out almost daily until October 1949. Results of observations between July 1948 and June 1949 were reported by Martha Stahr (1949) at the 81st Meeting of the American Astronomical Society in Ottawa in June 1949. It was found that the fluctuations in the base level of the emission at 205 MHz were stronger than at 2,800 MHz by comparing observations made at Cornell and by Covington's group at Ottawa, Canada. It was also found that the base level is correlated with sunspot numbers but less strongly at 205 MHz than at 2,800 MHz.

Statistical analysis of this data-set was carried out by Hans Mayer (1895–1980), Professor of Electrical Engineering at Cornell. Mayer (Figure 9) had been Director of the German electronics firm Siemens and Halske until 1943 when he was sent to a concentration camp for listening to the BBC and criticizing the Nazis. Released at the end of the war he briefly returned to Siemens but was then required in 1946 to go to the United States to work at the Air Material Development Command at Wright Field in Dayton, Ohio. Cornell was interested in hiring him to a faculty appointment, and after two years succeeded. Mayer joined the faculty in January 1948. His main interest was in electronic communications, but he also became involved with the Radio Astronomy project. He returned to Germany in 1950, and again worked for Siemens. It was only after his death that it became known that in late 1939 while on a visit to Oslo, Norway, he had passed significant information to the British about the state of electronics in Germany, in what was known as the 'Oslo Report'.

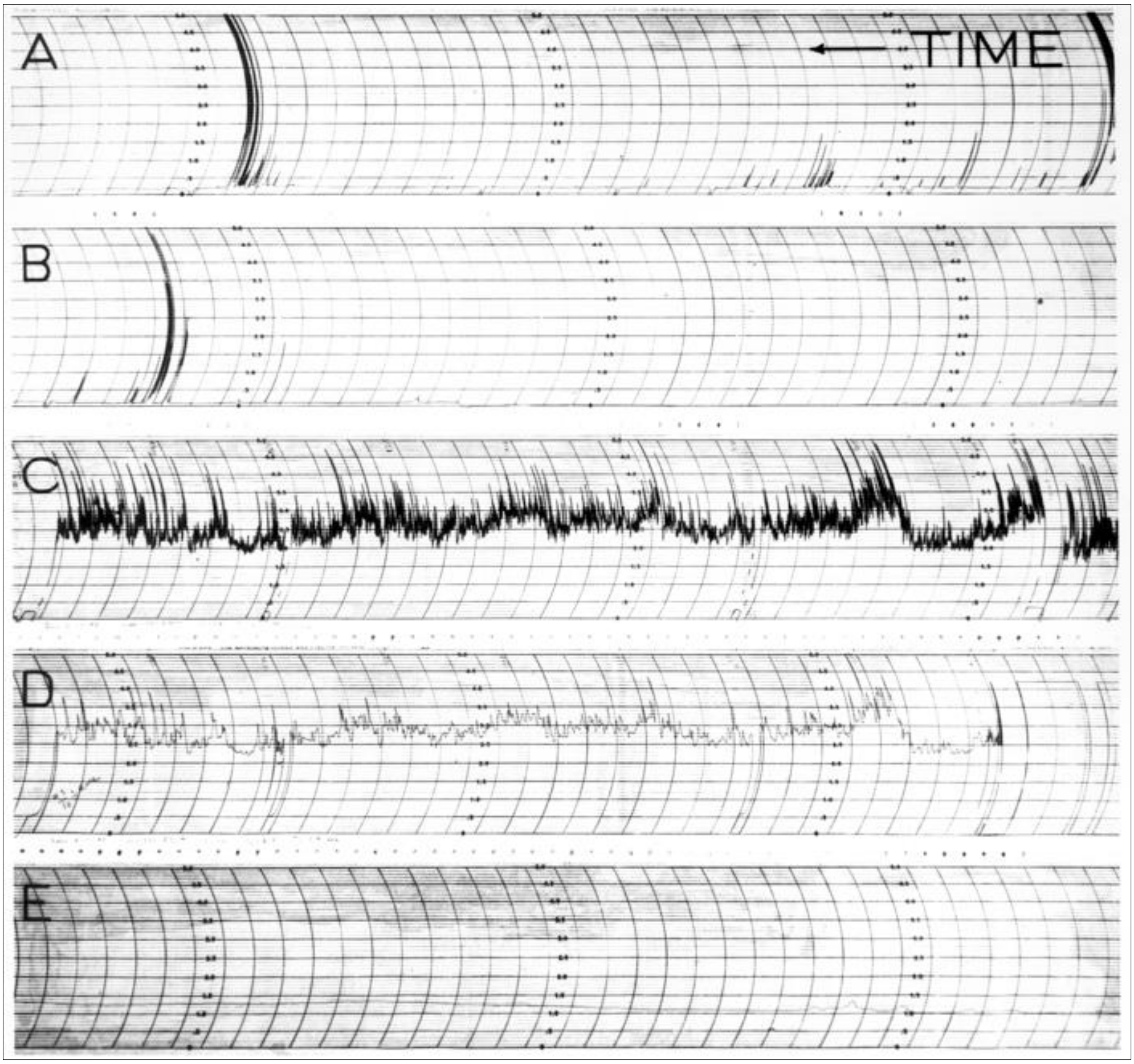

Figure 8: Chart recordings of observations of solar emission at 205 MHz in June of 1948. A and B are consecutive covering an elapsed time of 4 hr 40 min from late morning to mid-afternoon on 28 June. The base level of the emission is along the bottom of the chart interspersed with three large bursts of emission and some smaller ones. Tape C ran from 10:53 to 13:02 local time on 18 June showing part of a solar storm. The chart recorder scale is 2.5 times more sensitive than for A and B, 1 volt vs 2.5 volts full scale. D is a duplicate of C except that the time constant was changed from 0.5 sec to 4 sec. E shows the quiet Sun on 5 June with full scale only 0.5 volts (after Anonymous, 1948: Figure 5).

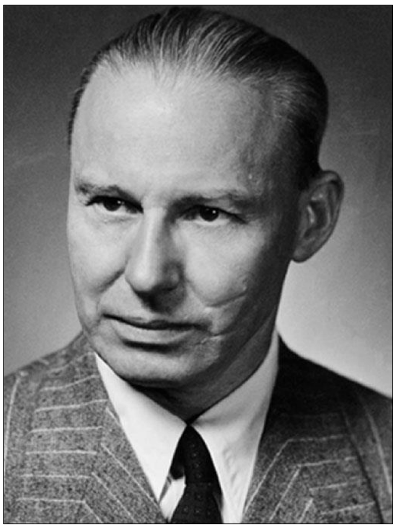

Figure 9: Hans Mayer, likely at about the time that he was on the faculty at Cornell (courtesy: Alchetron Encyclopedia).

Mayer's analysis of the solar radio noise data (unattributed in Statistical Analysis of Solar Noise Observational Data, Radio Astronomy and Solar Noise, Joint Report No. 1, School of Electrical Engineering, Cornell University, 15 May 1950) was based on the Sun being in four principle states, which occur with roughly equal probabilities: very quiet, small activity, medium activity and large activity. He looked at the average time that the Sun remained in a given state and transition probabilities from that state to one of the other three states.

5 GALACTIC OBSERVATIONS: THE POLE OF OUR GALAXY AND THE VARIABILITY OF CYGNUS A

During the summer and fall of 1948 two more observational programs were started. Seeger and Williamson (1951) measured the direction of the pole of our Galaxy at 205 MHz and Seeger (1951) carried out extensive observations of the strong variable radio source Cygnus A. For the determination of the pole of our Galaxy at radio wavelengths they used the SCR-268 antenna with the two mattress arrays side-by-side as shown in Figure 6 making an approximately 5-m square array with a beam of 15° × 15° ± 0.5° at the operating frequency of 205 MHz. As described in their paper, the basic objective was to measure the position of the centroid of the galactic emission, the mean galactic latitude, when sweeping the antenna beam as closely as possible perpendicular to the galactic equator. This would be done for all galactic longitudes observable from the telescope site, resulting in a best fitting small circle on the celestial sphere from which the pole direction could be deduced. The scans were done when the galactic equator passed through the zenith, with the antenna being scanned through 360° in azimuth with a fixed altitude (elevation) angle.

As also pointed out in the paper, success depended on the stability of the receiver system. By stabilizing the cathode and plate voltages of the tubes in the amplifiers (Figure 10), Seeger and Williams claimed that the receiver stability was close to 1% of the peak galactic signal during the 6 minute scan, which was preceded and followed by comparison with the output of a resistive load. The peak signal was about 7% of the receiver and background sky noise. Given that the r.f. bandwidth was 4.5 MHz and the post-detection time constant was 0.4 secs, the theoretical r.m.s. noise fluctuations were about 7 $\times 10^{-4}$ of the receiver and background sky noise, very close to the claimed receiver stability which is impressive for that time. As shown in Figure 10 the frontend amplifier and frequency converter (mixer) were housed at the antenna with 60-m of coaxial cable bringing the I.F. signal to the equipment rack in the Quonset hut (Figure 10) containing the I.F amplifier, detector, post detector amplifier and Esterline-Angus chart recorder with its 0.4 sec time constant and time marks good to a fraction of a second.

The observations were made from 17 to 21 October 1948 with a total of about 320 measurements made of the galactic latitude and longitude of the centroid of the galactic emission using the then International Astronomical Union (IAU) defined coordinate system. These were then converted to obtain the galactic latitude and longitude of the pole of the Galaxy. The latitude was determined to be 87°.43, indicating that the IAU defined pole based on optical observations differed from the one defined by the galactic radio emission at 205 MHz by about 2°.6.

In August 1946, Hey et al. (1946) published a paper in *Nature* describing a fluctuating radio source in the direction of the constellation Cygnus. Their observations were at a frequency of 60 MHz and the fluctuations had variable time scales. Subsequent observations of this source were made by Bolton and Stanley (1948) in Australia at four frequencies between 60 and 200 MHz and included the use of a sea interferometer at 100 MHz. They found that the variability had time scales between 0.1 and 1 minute and was stronger at the lower frequencies with no fluctuations observed at 200 MHz. They also determined a position accurate to about a minute of arc in Right Ascension and 7

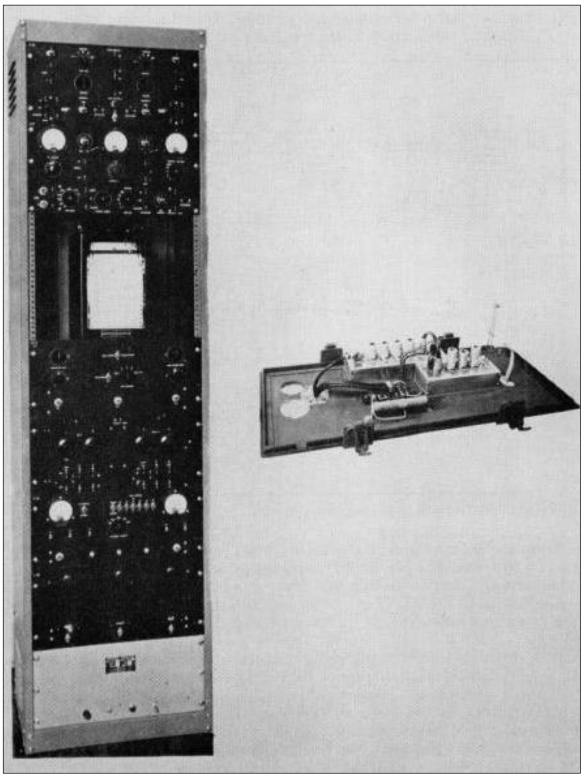

Figure 10: The 205 MHz front end amplifier and mixer (right), which was mounted at the telescope, and the rack with the I.F. amplifier, detector, post-detector amplifier and Esterline-Angus chart recorder located in the Quonset hut (after Seeger and Williamson, 1951: Figure 1).

minutes in Declination, but there was no obvious source of the emission in the field. Ryle and Smith (1948) also observed the variable source in Cygnus, and discovered several others, including Cassiopeia A.

Despite Bolton and Stanley's (1948) report of no fluctuations for the source (now named Cygnus A) at 200 MHz, Seeger decided to observe it, initially with the same mattress array operating at 205 MHz that he and Williamson used to determine the radio pole of the Galaxy and, after 1 June 1949, with the 5-m parabolic antenna. Some observations were made between May and October 1948 with the first indication of large variability at 205 MHz occur-

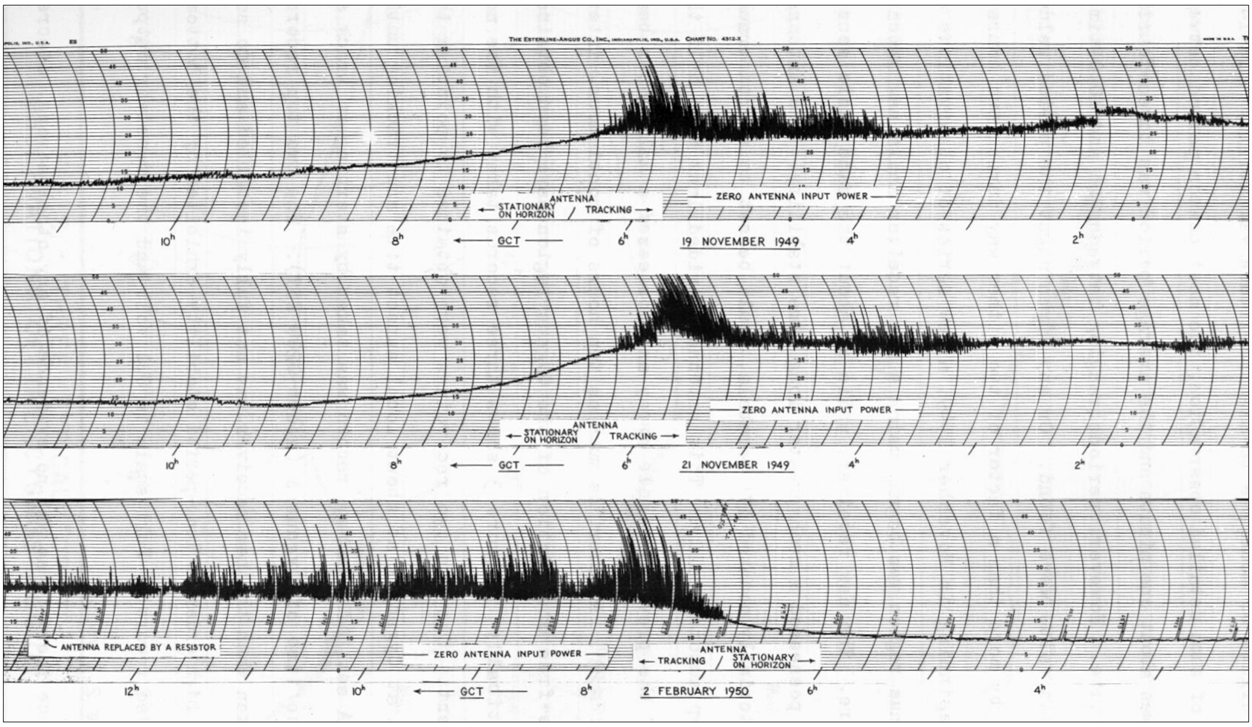

Figure 11: Two setting and one rising low elevation observations of Cygnus A in November 1949 and February 1950, respectively, showing strong variability (after Anonymous, 1950: Figure 3).

ring during the scans of galactic emission on 18 October aimed at determining the position of the pole of the Galaxy (Seeger and Williamson, 1951). Given the 15° beam size the best Seeger could say was that the position of the fluctuating source was close to that of Cygnus A. This began a series of three sets of observations of Cygnus A. The first, from 22 November 1948 to 9 February 1949, using the SCR-268 mattress array (Figure 6) were 30 minute observations on almost every day until 4 January and then on two groups of days in late January and early February. The observations were made at altitude (elevation) angles from greater than 70° for the first observations to about 30° at the end except for the last two which were at 46° and 47°. Seeger developed an activity index from 0 to about 15 to characterize the variability with 0.5 being the minimum for a detection of activity. During the period only 23 out of 42 days had zero index and of the remaining days the index never exceeded 5. There was no clear indication of a correlation with altitude angle.

For the second set of observations from 2 April to 31 May 1949 the SCR-268 antenna was set at a fixed altitude angle of 30° and Cygnus A allowed to drift through the beam. Of the 45 observations 3 were made at an altitude of 60°. Significant activity was detected on all but three days (for another two no index was recorded) with values as high as 15 on 8 April.

The third set of observations making use of the newly commissioned tracking capability of the 5-m antenna, began in November 1949 and lasted about six months. Observations were made either from sunset to Cygnus A set or from Cygnus A rise to sunrise (Figure 11). There was already a suggestion from the first and second set of observations based on the activity index at low and high altitude angles that the variability of Cygnus A may be related to scintillations in the ionosphere. The new data from the third set of observations, where the activity index used for these observations is clearly correlated with the altitude angle, made this abundantly clear.

During 1949 observations of Cygnus were also made at Jodrell Bank radio observatory by Little and Lovell (1950) and at Cambridge University by Smith (1950) at wavelengths of 3.7m and 6.7m, which showed that the fluctuations in Cygnus' intensity were partly or completely due to scintillations in the Earth's ionosphere. Seeger's results seemed more definitive, and Status Report #10 of 1 March 1950 clearly states that the variation with antenna altitude

> … must mean that an important part, and possibly even the whole, of the variability of Cygnus A arises in the earth's atmosphere, presumably due to scattering by random inhomogeneities.

This conclusion was backed up by theoretical work by the Cornell radio propagation group. Despite Seeger's early observations being coincident with those of the British groups he did not publish his results until 1951 and then only in the *Journal of Geophysics Research*, or *JGR*

(Seeger, 1951). The paper was received by the *JGR* on 18 March 1951, exactly one year after *Nature* published the papers by Smith (1950) and by Little and Lovell (1950). It was also one year after Seeger 'published' his result in Status Report #10. Curiously, Seeger did not reference either of the *Nature* papers, perhaps because he was unaware of them. This was an unsettled time in his life, as he resigned his position at Cornell in 1950 to accept a post at Chalmers University in Sweden. In his *Cosmic Noise* …, Sullivan (2009) recounts that Seeger left Cornell due to disagreements with Burrows. These may have been over the issue of the directorship of the Radio Astronomy Project. Upon his arrival in July 1948, Gordon—who was then a Research Associate and graduate student—was appointed director of the project and not Seeger, who was the only faculty member with a direct interest in this new field. Yet in the 1 December 1949 Status Report #9 to ONR, Seeger is listed as the Project Supervisor and Gordon is not listed as being involved. In Status Report #10 of 1 March 1950, Gordon is now the Project Supervisor and Seeger is merely listed as an Assistant Professor. In relation to Seeger's move to Chalmers University it is not clear whether this was the cause or the effect.

There is also the matter of Seeger's choice of journals when it came to publishing his Cynus A results. Most likely he selected the *JGR* because the detection of ionospheric scintillations offered a new way of studying the Earth's upper atmosphere.

Seeger's departure for Sweden, coupled with Cornell's very strong radio propagation group, caused a shift in emphasis for the Radio Astronomy Project with considerable effort going into studies of refraction and scintillation for the strong radio stars Cygnus A and Cassiopeia A as a means of studying the ionosphere. Solar observations continued but no significant research on galactic radio emission or radio stars took place after Seeger's departure.

6 THE OCTOBER 1948 CONFERENCE

The planned Cornell March 1948 conference on Radio Astronomy was delayed until 5 and 6 October 1948. It coincided with the dedication of the 5-m radio telescope and the 80th anniversary of the first undergraduate classes at Cornell University. It was possibly the first conference anywhere dedicated to radio astronomy, and was certainly the first in the United States.

Unfortunately, no agenda or complete list of attendees has been located. However, based on press reports, there were about 20 attendees, including A.E. Covington from Canada, R.E. Burgess from Britain, J.P. Hagen of the Naval Research Laboratories, Donald Menzel from Harvard College Observatory, J.F. Denisse from the École Normale Supérieure in Paris, and R.E. Williamson from the University of Toronto. Attending from Cornell were Burrows, Gordon, Seeger, W.R. Jones, Carl W. Gartlein (Physics), Dr Menzies (Physics) and, likely, Martha Stahr. As reported in the press, much of the discussion revolved around the connection between optically observed activity on the Sun and solar radio emission. Donald Menzel, the well-known Harvard solar physicist, showed a movie made at Harvard's coronograph station at Climax, Colorado.

The meeting was attended by many science writers, including William Laurence of the *New York Times*, perhaps the leading science writer of the time, and Harry Davis, the science correspondent for *Newsweek*. There was, of course, a tour of the radio astronomy facility at the airport, where the 205 MHz radio signal from our Galaxy was detected and sent to a loud-speaker. That you could actually listen to the cosmos excited the science writers, with Texas' Malcolm Bingay of the Houston *Chronicle* equating it with the 'Music of the Spheres' in an article published on 22 October. He also quoted Donald Menzel as saying: "… the 'music' is like a combination of gravel falling on the roof and a howling of wolves". Laurence wrote an article on the first day of the meeting that appeared on Page 1 of the *New York Times* on 6 October titled "Radar Yields New World of Sound; Brings "Music of Spheres" to Earth". He initially discussed the conference and, especially, Menzel's movie, but towards the end branched off into a discussion about picking

> … out of the vast variety of cosmic frequencies a selection of sounds that would constitute a Beethoven symphony. In the true sense of the word, the stars would thus be made to sing, and man may dance to the "music of the spheres".

Laurence came back to Earth with an editorial that appeared on Sunday 10 October in which he looked to the future of radio astronomy: "Only a rash pessimist would question the scientific potentialities that lie in this radio spectrum."

7 FURTHER SOLAR OBSERVATIONS

In the fall of 1949, Leif Owren (Figure 12), a Norwegian from the University of Oslo, joined the radio astronomy group to pursue a PhD degree in Electrical Engineering centered on radio observations of the Sun. He was supported by a Norwegian Government grant for study abroad, plus some support from the Norwegian Research Council for Science and the Humanities.

Owren's solar radiometric observations at 200 MHz, not 205 MHz due to TV interference at this frequency, were conducted from April 1950 to December 1952 for 6–8 hours per day with occasional interruptions due to equipment problems. From April 1950 to June 1951 the 5-m antenna was used for solar observations. After June 1951 the 200 MHz observations were transferred to a dipole array with 6 dipoles in the horizontal direction and 8 in the vertical direction attached to one of the SCR-268 mounts that had been made remotely steerable by synching the azimuth and elevation to a small equatorial mount that tracked the Sun (Owren, 1954). "Daily means of 3-hourly values for the median flux, daily values for the 'variability', and information on outstanding occurrences were published in the IAU's *Quarterly Bulletin of Solar Activity* (Owren, 1954). Starting on 23 January 1951, daily reports on the median flux and hourly

Figure 12: Leif Owren in 1948 at the 7th General Assembly of the International Astronomical Union in Zurich (courtesy: University of Chicago Photographic Archive).

burst frequency were also sent to the Central Propagation Laboratory of the National Bureau of Standards for their weekly "Solar Activity Report" (Radio Astronomy Status Report 14, 1 March, 1951). A detailed correlation between the occurrence of flares on the Sun and the onset of fluctuations in the 200 MHz emission from the Sun done by Helen Dodson and Ruth Hedeman from the McMath-Hulbert Observatory at the University of Michigan and Leif Owren showed, based on 194 flares, that there was an association 78% of the time (Dodson et al, 1953).

In early 1951, a parabolic dish of approximately 1.3-m diameter was installed on the 17-ft mount and positioned next to the edge of the 5-m reflector so that both could track the Sun simultaneously. The small dish was equipped with a 1,420 MHz receiver, thereby allowing routine observations of the Sun at 200 and 1420 MHz, with the likely primary purpose being to test the 1,420 MHz receiver. The 200 MHz solar observations were transferred to the SCR-268 6 × 8 dipole array after June 1951 so that the 5-m reflector could be resurfaced with a fine mesh that would allow it to be used at 1,420 MHz. By realigning the original coarse mesh and using it as the backing for the fine mesh the Cornell group achieved an RMS error of about 1.2 cm, adequate for 21 cm observations. However, persistent stability problems with the 1,420 MHz receiver limited its usefulness, and it is not clear whether routine solar observations were ever initiated.

Given the very broad response patterns of the antennas that were used to monitor the solar radio emission at 200 MHz, it was not possible to identify the locations of the radio burst emissions, which originated in the solar corona, to verify if they were directly associated with optically observed plages and sunspots in the photosphere or chromosphere. Flares could only be observed optically when they were on the limb of the Sun, so the objective was to determine whether the 200 MHz solar emission was mostly associated with plages or sunspots (Owren, 1954).

To address this, Owren constructed a two-element interferometer that also operated at 200 MHz. The two antennas were constructed from surplus SCR-268 components and consisted of 5 × 4 full-wave dipoles mounted in the vertical and horizontal directions, respectively. They were facing south and were attached to horizontal bars about which they could be rotated to change the elevation angle depending on the declination of the Sun. No hour angle movement was possible but the beamwidth between nulls in the primary pattern of each antenna of about 30° allowed more than two hours of tracking about the zenith position of the Sun (Owren, 1954). Laid out on an E-W baseline the spacing between the two antennas of 51λ gave an interferometer interference pattern lobe spacing of 67.5 arc minutes, or a little over two times the angular diameter of the Sun. This meant that as Earth's rotation scanned the interferometer lobe pattern over the Sun the chart recording clearly showed the sinusoidal lobe pattern, and the position of the center of the solar disk assuming a uniform thermal emission. A localized persistent burst of emission would also show a lobe pattern that would be offset from that of the quiet Sun depending on the E-W location of the

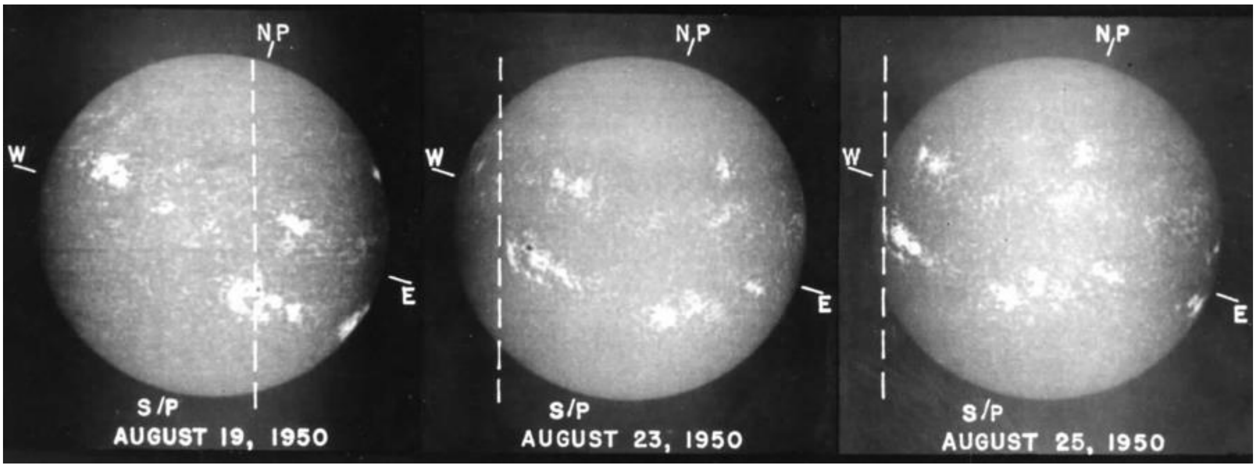

Figure 13: Three successive images of the Sun showing the interferometrically determined best fit E-W locations of the 200 MHz emission (the dotted lines) relative to the locations of the flares in the optical images (after Owren, 1954: 179).

burst relative to the Sun's center. Comparison of the phases of the two lobe patterns allowed the N-S position-line of the burst's location to be determined, i.e. its one-dimensional E-W location relative to the center of the Sun.

The accuracy of the measurement of the position-line was not good but was adequate to determine the frequency of radio emission from flares as a function of the E-W distance from the Sun's center (see Figure13). Owren discovered that the frequency declined beyond about 40° from the center, indicating that the radio emission from flares was directive with a polar diagram with a full-width half-maximum of about 80°.

Owren continued his solar observations and collaboration with Helen Dodson through 1952. In early 1953 he moved to the Division of Terrestrial Magnetism of the Carnegie Institution in Washington, DC where he participated in the construction of a phase-shifting interferometer system at 207 MHz for high-spatial-resolution observations of solar phenomenon. He continued some involvement with the Cornell solar observations, and completed his Cornell PhD thesis in 1954. The routine monitoring of the Sun at 200 MHz with both the SCR-268-based array and the interferometer continued after Owren's departure.

8 LOOKING FOR THE 21 cm EMISSION FROM NEUTRAL HYDROGEN

One of the early stated objectives of the Cornell radio astronomy program was the detection of 21 cm emission from atomic hydrogen in our galaxy. Despite developing detection equipment for this frequency, this was made impossible by the decision to use the 5-m reflector on loan from the U.S. Navy because its wire mesh setting and spacing limited its maximum operating frequency to about 200 MHz. However, in a letter dated 17 March 1951 to Joseph Pawsey, head of the Radio Astronomy group at the CSIRO's Division of Radiophysics, Frank Kerr, a senior scientist from Radiophysics who was visiting the United States, described two ongoing attempts to detect the 21 cm hydrogen line. One was at Harvard University by Harold Ewen (a graduate student working with Edward Purcell) utilizing a horn antenna, and the other was by Leif Owren at Cornell using a 2.4-m diameter antenna (but most likely this referred to the ~1.3-m antenna attached to the side of the 5-m reflector used to observe the Sun at 21 cm and referred to above). Kerr did comment that Ewen's equipment was more sensitive than Owren's, and it was only eight days after Kerr's letter that Ewen and Purcell detected HI line emission from the Galaxy at 1,420 MHz. Even after the 5-m reflector was modified to allow operation at 1,420 MHz in mid-1951 the receiver stability problems discussed earlier and lack of anyone with a strong interest were likely the reasons that no program of 21 cm observations of the Galaxy was ever initiated.

9 THE SACRAMENTO PEAK CONNECTION

In April 1948 the U.S. Air Force awarded a contract to Harvard University to establish a solar observatory on Sacramento Peak (Sac Peak) in New Mexico, a short distance from, and overlooking, Holloman Air Force base. Donald Menzel from Harvard College Observatory, along with Walter O. Roberts, the Director of the Climax Solar Observatory in Colorado, originated the idea of a new solar observatory to complement the one at Climax where severe weather was a serious problem (Bushnell, 1962). The contract monitor was the Air Force Cambridge Research Center (AFCRC) and in June 1948 AFCRC asked Cornell's School of Electrical Engineering to establish a radio observatory at Sac Peak to monitor solar radio emission in conjunction with Harvard's optical observations (ibid.). Bushnell (1962) states that routine radio observations at

50 and 200 MHz began in August 1949, using a modified SCR-268 radar system (see Figure 14). However, Zirker (1998) gives a date of August 1950 for the arrival of two Cornell engineers, and December as the start of routine observations at 50 and 200 MHz. Given the state of development of the observatory infrastructure on the mountain in 1949 (Zirker, 1998) the 1950 date seems much more likely.

However, a major disadvantage of having a direct line-of-sight to Holloman air force base was that radio interference from the base severely affected the quality of the solar radio observations. This was so detrimental to the program that the decision was made to establish a solar radio emission monitoring station at Fort Davis in western Texas under an Air Force contract with Harvard University (see Thompson, 2010) and, in 1954, observations with the Cornell antennas on Sac Peak ended (Zirker, 1988).

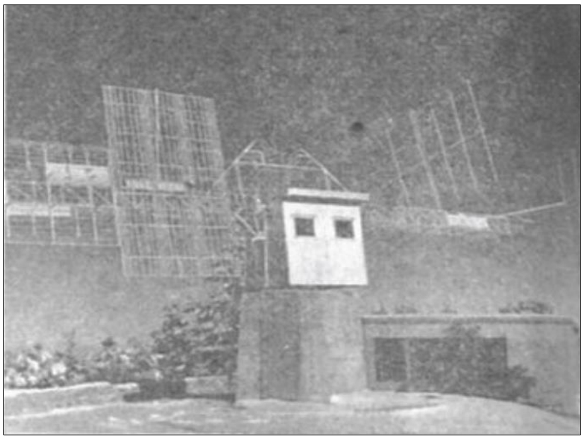

Figure 14: Photo of the Cornell equipment at Sac Peak showing a 3-frequency system, 50, 200 and 3,200 MHz. If it was installed, the small 3,200 MHz dish at the center is hard to see in this poor-quality photograph. Two 200 MHz mattress antennas at left are at right angles in order to measure circular polarization. Two yagis on the right are for 50 MHz observations. The alt-azimuth mounting was driven from a clock motor on an equatorial mount (after Burrows and Gordon, 1954: 168).

10 THE LATER YEARS

In 1954 Marshall Cohen joined the faculty of the School of Electrical Engineering as an Assistant Professor. Cohen had been an under-graduate student in electrical engineering and a graduate student in physics at Ohio State University obtaining his PhD in 1952, and was the first faculty member at Cornell since Charles Seeger's departure with a direct interest in radio astronomy. Cohen developed a strong interest in studying the polarization properties of the solar radio emission and developed both the theory behind the measurements and spearheaded the development of polarimeters that could measure the Stokes' parameters that define the polarization state of a radio wave. He was supported by grants from ONR, the Air Force and the National Science Foundation over many years for this work and published some of the ground-breaking papers in this field (e.g. Akabane and Cohen, 1961; Cohen 1959).

Martha Stahr, who married Jessie Carpenter in 1951, was promoted to Associate Professor in 1953. Both Martha Stahr Carpenter and her husband spent sabbatical leaves from 1954 to 1955 in Australia on Fulbright Scholarships. Martha Stahr Carpenter worked with Frank Kerr at the CSIRO's Division of Radiophysics, making observations at Potts Hill field station (see Wendt, 2009; Wendt et al., 2015), and mapping the distribution of HI emission from our Galaxy (see Figure 5). Shortly after their return to Cornell she resigned her faculty position because she was anticipating having children, and she reverted to being a Research Associate (Larson, 2012).

Charles Burrows resigned his positions at Cornell in the summer of 1956 to become Vice-President for Engineering at the Ford Instrument Co., a division of Sperry Rand Corp. He was succeeded as Director of the School of Electrical Engineering by Henry Booker.

Under the direction of Marshall Cohen, Cornell participated in the International Geophysics Year providing daily records of solar activity and burst frequency. A Christiansen-type grating interferometer (cf. Wendt et al., 2008) was constructed to provide more accurate E-W positions on the solar disk of radio bursts than the two-element interferometer used by Lief Owren could provide. It had 16 dipole antennas operating at 200 MHz mounted on telephone poles positioned E-W over about 1,500 m. However, initially it did not very work well, and development ceased when Cohen became increasingly involved with the Arecibo telescope project (Marshall Cohen, pers, comm., 2019).

In May 1958 William E. Gordon gave a seminar in the School of Electrical Engineering in which he proposed that the University organize the construction of what became the 305-m Arecibo telescope with the primary purpose of studying the Earth's ionosphere but with secondary objectives to do radar studies of the Moon and nearby planets and to pursue radio astronomical observations. Funding for this radio telescope was obtained in late 1959 from the Advanced Research Projects Agency of the U.S. Department of Defense, and once detailed design work started the radio astronomy program under Marshall Cohen began to migrate from the Ithaca-based facility to planning for observations with the new telescope (see Cohen, 2009).

In the post-Sputnik era it was clear that the Department of Astronomy with just two faculty members, William Shaw as Chair and John Cox,

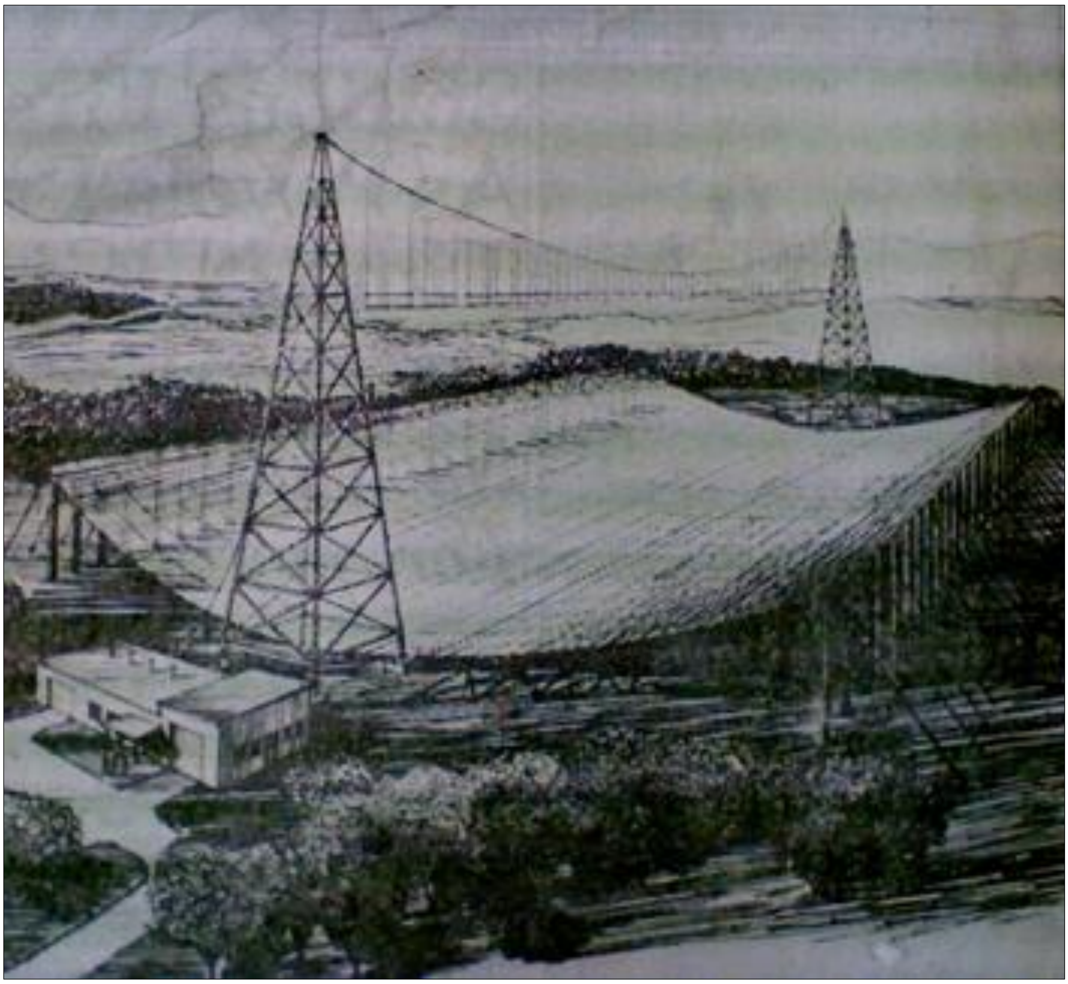

Figure 15: A concept drawing of a 500 ft (150 m) long cylindrical paraboloid to be located south of Ithaca. It was part of the publicity surrounding the establishment of the Center for Radiophysics and Space Research in November 1959 but was not built (courtesy: Cornell University Archives).

who joined the faculty as an Assistant Professor in 1954, was a poor match for the coming Space Age. A search for a new Department Chair who would revamp the Department was initiated, resulting in the appointment of Thomas Gold, a British astrophysicist of Austrian heritage and one of the originators of the Steady State Theory of cosmology. Gold, who arrived at Cornell in the summer of 1959, had a mandate to build a new Department and to create a research center. In November 1959 the Center for Radiophysics and Space Research (CRSR) was established combining, primarily, faculty in astronomy and electrical engineering. Gold was the Center's Director and Henry Booker the Associate Director. Plans for the Center included the construction of two radio telescopes in the Ithaca area (one is shown in Figure 15), but neither was built. However, the Arecibo radio telescope project was folded into the Center and, once completed, remained a major facility of CRSR until 1971, when its management came under the newly formed Cornell University based National Astronomy and Ionosphere Center.

By the late 1950s radio interference from other activity around the Radio Astronomy project's airport site forced a move to a site south of Ithaca in the town of Danby, the expected site of the proposed radio telescope shown in Figure 15. A new building was constructed in 1962 and only the 5-m radio telescope was moved and placed on top of the building (see Figure 16). Marshall Cohen continued to use this radio telescope for polarization measurements of solar bursts, but through the 1960s the Danby Laboratory (as it was called) became increasingly devoted to supporting the operation of the Arecibo 305-m Radio Telescope, primarily through the construction of receivers and digital equipment. As interest in using the 5-m radio telescope waned the Laboratory's remote site became an inconvenience and the Laboratory was moved to a building close to the airport. Sadly, the historic 5-m radio telescope was decommissioned and dismantled.

11 CONCLUDING REMARKS

Charles Burrows showed tremendous initiative in launching a radio astronomy program at Cornell University in 1946. The initial aims as outlin-

Figure 16: The new radio astronomy building at Danby south of Ithaca with the 5-m antenna on the roof (courtesy: Marshall Cohen).

ed in the first quarterly report to the funding agency, the Office of Naval Research in October 1948 were ambitious, well thought out and achievable and, if pursued vigorously, could have led to a program that put Cornell in a significant leadership position in this young research field. Unfortunately, the program seemed to suffer from a lack of strong commitment to this new field in either the School of Electrical Engineering or the Astronomy Department. Charles Seeger was the only faculty member with a strong interest. Martha Stahr did some initial solar observations but does not seem to have had much interest in making further observations. Once Seeger left Cornell in 1950 there was no effort to hire another faculty member with an interest in pursuing the development of radio astronomy at Cornell until Marshall Cohen was hired in 1954. The main interest of all the relevant faculty in Electrical Engineering, Burrows, Hamlin, Booker, Gordon, Ralph Bolgiano and others, was radio propagation for communications purposes, and active experimental programs in this area were pursued for many years, some of which utilized the radio telescopes. With the exception of Leif Owren, who clearly was largely self-directed, no doctoral degrees came out of the early programs.

The other very hard to understand decision that had a serious detrimental impact on the program was the one to place a borrowed 5-m reflector on the Cornell-built mount, a reflector that was both smaller than the mount was designed for and was incapable of being used at frequencies above 200 MHz. This may have been driven by the desire to get the radio telescope operational in 1948, but it made impossible many of the most interesting early aims of the program, such as the detection of the 1,420 MHz hydrogen line.

Curiously, the project that put Cornell 'on the map' in radio astronomy grew out of the radio propagation community in the School of Electrical Engineering through William Gordon's initiative to build a large enough radar system to detect incoherent scatter from the individual electrons in the ionosphere. As mentioned earlier, perhaps through his experience with the Cornell radio astronomy projects Gordon was prescient enough to realize that the new radio telescope would be a major contributor to the field of radio astronomy. He was correct.

12 ACKNOWLEDGEMENTS

Many thanks to W.M. Goss of the National Radio Astronomy Observatory for finding relevant documents in the archives of the Australian CSIRO especially the letters of Joseph Pawsey, E.G. Bowen and Frank Kerr. Many documents were also found in the Cornell University Archives, with special thanks to David Corson and Laura Linke for their assistance, and for kindly providing Figures 2, 6, 7 and 15. I am also grateful to the CSIRO Radio Astronomy Image Archives and the University of Chicago Archives for supplying Figures 3, 5 and 12, and to Marshall Cohen for Figure 16. Many thanks also to the unknown person at Cornell University who preserved a large binder containing the early project reports and many photographs of the SCR-268 based antennas and the 5-m antenna, along with photographs of Charles Seeger, William Gordon and others. It was the discovery of this binder that prompted me to research and write this paper. Finally, the suggestions by the reviewers of the paper, Marshall Cohen and James Lequeux, were greatly appreciated.

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Donald Campbell obtained his BSc and MSc degrees in Physics from the University of Sydney in 1962 and 1964, respectively. For his MSc he worked on aspects of the initial construction of the Molongo (Mill's) Cross radio telescope. In 1971 he obtained a PhD from Cornell University based on early radar interferometric mapping of the surface of Venus using the Arecibo 305-m telescope. He returned to the Cornell-managed Arecibo Observatory to continue this work making use of the high powered 13 cm radar system installed on the telescope in 1974. From 1981 to 1986 he served as Director of the Observatory before returning to Cornell University as Professor of Astronomy. He remained closely associated with the Arecibo Observatory as Associate Director from 1993 to 2004 and Director from 2008 to 2011 of its parent institution, the National Astronomy and Ionosphere Center. Campbell's research work has been in the general area of planetary studies with a concentration on the radio wavelength scattering properties of planets, planetary satellites and small bodies primarily making use of the high-powered radar systems on the Arecibo telescope. Upon his retirement from teaching in 2017 he was appointed an Emeritus Professor, but remains active in research and instrumentation projects as well as pursuing his interest in history.