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GENESIS OF THE 1000-FOOT ARECIBO DISH

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Abstract: The giant radar/radio astronomy dish near Arecibo, Puerto Rico, was conceived by William E. Gordon in early 1958 as a back-scattering radar system to measure the density and temperature of the Earth's ionosphere up to a few thousand kilometers. Gordon calculated the required size of the antenna by using the Thomson cross-section for scattering by the electrons, and assuming that the elementary scattered waves would be incoherent. During the summer and autumn of 1958 Gordon led a study group that published a design report in December 1958. The report showed that a dish 1000 feet in diameter would be required, and described a limestone sinkhole in Puerto Rico that would make a suitable support for such a dish. Meanwhile, in November 1958, Kenneth L. Bowles performed an ionospheric radar experiment that showed that the Gordon calculation for the scattered power was roughly correct, but that the calculated spectral width was too big. The consequence of these results was that a dish substantially smaller than 1000 feet could have satisfied the original goals for the radar. However, from the spring of 1958 the value of 1000 feet had been in the minds of the study team, and a large suite of important experiments that such a dish could do had been identified. These apparently became the *raison d'être* for the project, and the possibility of shrinking the dish to accomplish only the original goals seems to have been ignored. The project was sold to a new federal funding agency, the Advanced Research Projects Agency (ARPA), which was interested, in part at least, because ballistic missiles traveled through the ionosphere and it was important to fully understand that environment. Gordon's original calculation contained a remarkably beneficial error. Without it, it is doubtful that such a large dish would have been built.

Keywords: Arecibo, space radar, plasma physics, incoherent scatter, radar astronomy, radio astronomy

1 INTRODUCTION

The giant radar/radio astronomy dish near Arecibo, Puerto Rico (Figure 1), was conceived in 1958 as a back-scattering radar system to measure the density and temperature of the ionosphere up to a few thousand kilometers above the Earth's surface. The scattered signal was calculated to be weak and a large antenna would be required to measure it; the dish would have to be around 1000 feet in diameter.

However, six months after the project began to be studied in earnest, it was shown that the characteristics of the echo are different from those assumed, and that a much smaller dish could successfully measure the signals. Nonetheless, the project continued on its original track, and the dish was built with a diameter of 1000 feet. This paper describes the project and how the much larger goals allowed by the large diameter became the *raison d'être* for the project.[1]

Figure 1: Recent view of part of the 1000-ft Arecibo dish, and the prime focus facility (courtesy: Cornell University).

Figure 2: William E. Gordon (1918–) ca 1963 (courtesy: Cornell University Archives).

The ionosphere of the Earth consists of ionized gas starting at about 60 km above the Earth; its density generally rises to a peak called the F region, typically near 300 km, and it slowly decreases above that. The electron density at the peak is around 10^6 cm^{-3} although with large variations, and the corresponding plasma frequency is about 9 MHz (the plasma frequency = $\nu_p \approx 9 \times 10^3 n_e^{1/2}$ Hz, with n_e the electron density per cm^3).

The ionosphere has been studied since the 1920s (Appleton and Barnett, 1925) with 'ionosondes', swept-frequency radars that receive echoes from successively higher layers of the ionosphere as the frequency is raised, and the local plasma frequency is reached. But when the frequency goes above the highest plasma frequency of the F region, the wave penetrates the entire ionosphere, and there are no echoes from higher levels. Rocket experiments to study the high ionosphere were being made in the 1950s (Friedman, 1959); and whistler (Helliwell and Morgan, 1959) and other experiments also gave 'top-side' information. However, these were all episodic, or otherwise limited.

The shortcomings of the traditional experiments led William E. (Bill) Gordon (Figure 2),[2] early in 1958, to investigate the possibility of seeing the weak 'incoherent scatter' from the top-side of the ionosphere. Incoherent scatter (IS) refers to the weak scattering of high-frequency radio waves by the electrons in an ionized gas, and is in distinction to the strong scattering, or reflection, seen when the wave frequency becomes equal to the plasma frequency. The term 'incoherent' implies that the elementary waves back-scattered by the electrons have no fixed phase relationship, and thus that the total scattered power is the sum of the individual powers. In fact this can be in error by up to a factor of 2 or somewhat greater, as discussed below.

Gordon (1979: 7-12; 1994: 2-5) was led to the IS problem by his prior experience with 'scatter' communications. This refers to long-distance radio propagation, around the curve of the Earth, by scattering on irregularities in the atmosphere. In 1950 Gordon wrote an important paper with Henry Booker (Booker and Gordon, 1950) that explained over-the-horizon communication by means of radio wave scattering on irregularities in the troposphere. The irregularities were described in terms of fluctuations in the dielectric constant of air, a formalism first used by Einstein (1910). Booker and Gordon (1957) then successfully investigated the possibilities of scattering in the stratosphere, which allows for communications at a greater range. Gordon (1979) continued this work by asking if the upper ionosphere could support scatter communications; this would give yet more range if it were possible. He concluded that in this case the scattered signal would be too weak to be useful in any practical system. However, it was then a straight-forward step to ask if incoherent back-scattering could be used to study the ionosphere itself. Figure 3 shows how 'forward scattering' for communications can conceptually lead to incoherent back-scattering.

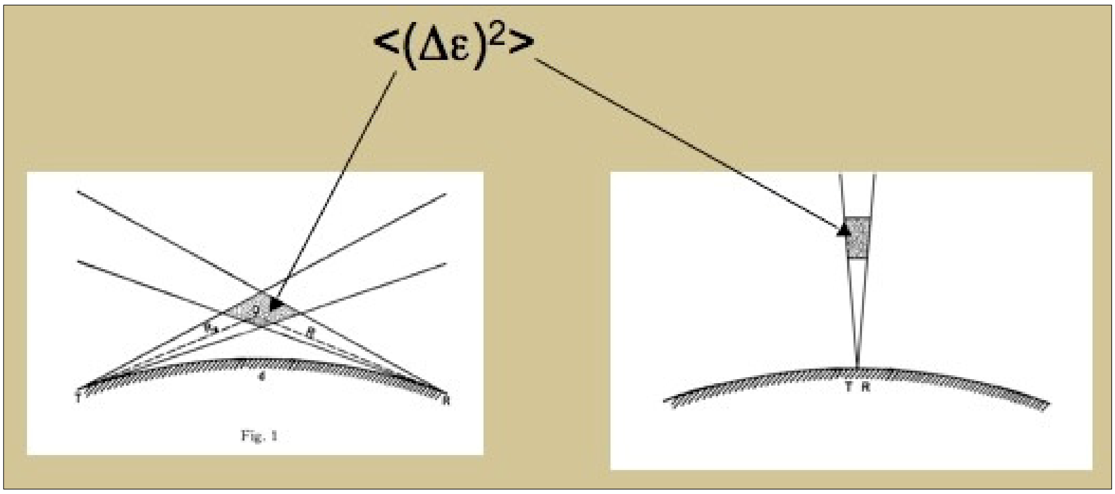

Figure 3: Simple illustration of how moving the transmitting (T) and receiving (R) antennas together takes an over-the-horizon communication system to an incoherent scatter ionosphere radar. <(Δε)^2> is the mean square fluctuation in the dielectric constant. Left panel after Booker and Gordon (1950: 407).

Modelling the ionosphere encountered a theoretical difficulty, however. Gordon had earlier used the fluctuations in dielectric constant arising from turbulence in the lower neutral atmosphere. What were the corresponding fluctuations in the ionosphere, an ionized gas? An answer to a simplified version of this question had been given by Pines and Bohm (1952), who calculated the thermal fluctuations for the fictitious case where the positive charge is smoothed out. This eliminates the electrostatic forces between electrons and ions, and the effect is to greatly reduce the fluctuations at the length scales that affect the radar backscatter. Gordon (2008) apparently did not know of the Pines and Bohm result. However, if he had used it, with the assumption that it actually did provide a good approximation to the ionosphere, then he would have found that the echoes, say at 500 km height, would be far too small to be useful. Gordon instead assumed that the echo would be due to Thomson scattering by the individual electrons, acting incoherently. With this assumption the echo would be weak, too weak for practical communications. However, with a large enough antenna, it would be adequate for backscattering experiments, to measure ionospheric electron density and temperature.

The IS idea may have been 'in the air' at the time. According to Gillmor (1986: 126), Henry Booker thought of it in the 1930s, but dismissed the idea as impractical (which it would have been, in the '30s). Kenneth Bowles (Figure 4)[3] told the author that he independently thought of the IS idea (Bowles, 2007), and his first IS paper begins as follows:

> The possibility that incoherent scattering from free electrons in the ionosphere, vibrating independently, might be observed by radar techniques has apparently been considered by many workers although seldom seriously, because of the enormous sensitivity required (Bowles, 1958: 454).

At the time there was a great deal of interest in the ionosphere, fueled by the IGY (1957-1958) and the launch of the *Sputnik* and *Explorer* satellites. More than 75 ionosondes were operating world-wide during the IGY. Rocket and propagation experiments using the satellites were part of the IGY program, and the idea of top-side sounding from a satellite was widespread. Several meetings on the topic may be noted: in October 1958 a meeting at Cornell University brought together ionospheric physicists to discuss the possibilities of satellite experiments (Forsyth, 2002; Franklin, 1993). A symposium entitled "The Upper Atmosphere Above F2-Maximum" was held in Paris, France, in May 1959 (Bowles, 1959a), and another was held at the URSI meeting in Washington, D.C. in May 1960. A good report of the state of knowledge at that time is provided by the "Summary of the Proceedings" for the URSI meeting (see Hines, 1960).

There also was military interest in the ionosphere, because satellites and missiles travel in the ionosphere and understanding the disturbances they make, and detecting them, was a high priority. In addition, the effect of high-altitude nuclear explosions on the ionosphere, and on radio propagation in the ionosphere, was of interest.

Sections 2 and 3 may be skipped by the non-technical reader. The essential result is contained in Figure 5, where the echo spectrum (i.e. the distribution in frequency of the signal that scatters from the ionosphere and returns back to the radar) is shown. The black curve shows the spectrum calculated by Gordon and used to find the required diameter of the radar dish. The top red line shows the result of a more accurate calculation. The red curve is narrower and higher than the black curve, and that means that a smaller, less-sensitive dish could have been used to accommodate the original goal, the measurement of density and temperature in the ionosphere to a height of 1000 km.

Figure 4: Kenneth L. Bowles (1929–). This photograph appeared in *Engineering: Cornell Quarterly*, 1(3): 14 (Fall 1966).

2 THE GORDON CALCULATION AND THE BOWLES CONFIRMATION

Gordon (1958b) used a beam-filled formulation of the radar equation (Battan, 1973: 31-33) to calculate the power received from a slab of the ionosphere:

$$P_r \propto P_t A\, h(\sigma n_e)/r^2 \qquad (1)$$

where P_r and P_t are the received and transmitted powers, respectively, A is the effective area of the antenna, $h = c\tau$ is the pulse length in space (c is the velocity of light and τ is the pulse width in time), σ is the scattering cross-section of an electron, n_e is the number of electrons per unit volume, and r is the height. This assumes that the electrons are randomly spaced and independent, and each undergoes Thomson scattering. The total scattered power is the sum of the elementary scatterings from all the electrons in the appropriate volume. Each elementary scattered wave has a Doppler shift given by the electron's vertical component of velocity, and the total scattered signal has a Gaussian spectrum; this also assumes that the electrons are in equilibrium at temperature T_e. The half-power width of the spectrum (in kHz) is

$$\Delta\nu = 122\,(T_e/100)^{1/2}(\nu_{MHz}/200) \qquad (2)$$

where ν_{MHz} is the radar frequency in MHz. Gordon justifies these assumptions by assuming that collisions are unimportant and that $L < s$, where L is the effective scale for backscattering ($L = \lambda/2$, where λ is the radar wavelength) and s is the mean-free-path of the electrons in their thermal motion. This formulation ignores the electrostatic effect of the ions, which produces changes in both the scattered power and spectrum in some circumstances, as discussed later.

The received power in Equation (1) must be compared to the expected noise. The noise power, N_r, in watts, can be expressed as

$$N_r = kT_{eff}B \quad (3)$$

where T_{eff} is the effective noise temperature of the receiving system, including radiation from the ground and the sky, and internal noise from the receiver itself. B is the receiver bandwidth in Hertz and k is Boltzmann's Constant.

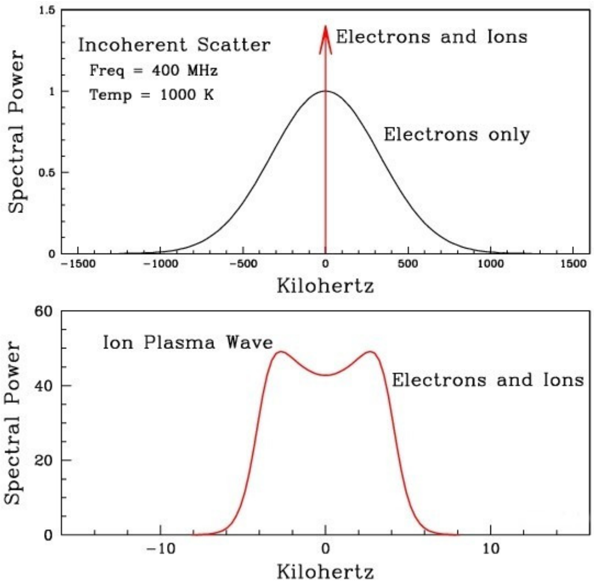

Figure 5: Spectrum of the incoherent scatter from the electrons in a plasma at a temperature of 1000K, with the incident wave at 400 MHz. Note the change in scales between the top and bottom panels. Bottom: wavelength large compared with the Debye length. The shoulders are due to heavily damped ion waves. Top: The red curve is a rescaled copy of the bottom curve. The black curve is for the case where the wavelength is small compared to the Debye length, and is the result obtained for any wavelength if the ions are simply ignored.

The ratio P_r/N_r (the signal-to-noise ratio, SNR) for a single pulse is usually well below unity, so one pulse by itself cannot be measured. But when many pulses are averaged together, the SNR is improved by the square root of the number of pulses. In his paper, Gordon assumed that 10,000 pulses would be averaged, giving an improvement of a factor of 100 in the SNR. Other factors affecting the SNR are the bandwidth, B, which Gordon chose as 100 kHz, and the pulse width, τ, which controls the vertical scale in the ionosphere that can be explored, as the height resolution is $h/2 = c\tau/2$. Gordon considered values of τ from 0.1 to 10 ms, corresponding to resolution from 15 to 1,500 km. However, τ and B are not independent, since the condition $B\tau > 1$ must hold. With $B = 10^5$ Hz, τ must be greater than 10^{-5} s, comfortably below the smallest values considered. This point will arise later, when we consider the effect of the ions, which can give spectral widths of order 1 kHz.

Gordon assumed that the transmitter and receiver both would use readily-available components, with $P_t = 10^6$ W and $T_{eff} = 600$ K at a few hundred MHz. He found that a 1000-foot dish, with 60% aperture efficiency and a feed loss of 2 db, could explore the ionosphere from 100 to 3000 km. He noted that at the lower heights a smaller antenna could be used, but the full 1000 feet is needed for experiments at 1000 km. In addition, the full-sized dish allows planetary radar measurements to be made, and also allows for sensitive radio astronomy observations.

Gordon developed these ideas early in 1958, first described them in April at the weekly seminar of the ionosphere research group in the School of Electrical Engineering at Cornell, and then presented them at a Departmental Seminar (Figure 6) on 29 May 1958 (Farley, 2007; Gordon, 1958a; 2007a; 2007b). Gordon's first paper (1958b) was received at the *Proceedings of the Institute of Radio Engineers* on 11 June 1958 and was published in November, 1958.

A former Cornell graduate student, Kenneth Bowles, heard about Gordon's work and set out to test the IS idea. Bowles was working at the National Bureau of Standards in Boulder, Colorado, and was able to adapt a new 41-MHz transmitter that was being installed at the NBS station in Long Branch, Illinois, for a test. On 21 and 22 October 1958 Bowles made vertical radar experiments that showed a weak signal consisting of excess noise at a range of about 200-400 km (Bowles, 1958). He interpreted this excess as incoherent scatter. His figures definitely show the excess noise, and the peak density region of the ionosphere, the F layer, was known to be at about 200-400 km. However, the signal appeared to have a much narrower spectrum than predicted by Gordon. At the time there probably was little doubt that he had actually seen the IS, and thus had generally confirmed Gordon's calculations. Bowles submitted a paper to *Physical Review Letters* in early November, and this was published on 15 December 1958 (Bowles, 1958).

Gordon (1994: 20-21; 2007a) relates that at an URSI meeting at Pennsylvania State University in October 1958, he received a telephone call from Bowles informing him of the 41-MHz results. Gordon then announced it at the meeting. The word probably spread quickly in the ionosphere community. The echo power was roughly as calculated for incoherent scattering, and a large ground-based radar could be used to monitor the topside of the ionosphere.

Bowles did not quantify his result, and it is difficult to estimate the strength of the echoes he received from the parameters given in his first paper. We can say that there is agreement with Gordon's calculation, to within an order-of-magnitude. But Gordon also calculated the width of the spectrum of the echo, and here Bowles gives a strong hint that his measurement disagrees with the theory. He used bandwidths of 10 and 15 kHz, which for the F region should have been much smaller than the half-width of the spectrum, since the temperature of the F region is about 1500 K and the spectrum should have been at least 100 kHz wide. Bowles (1958: 455) includes this intriguing sentence: "Reception at frequencies slightly separated from the transmitted frequency indicated little thermal broadening (F-region line broadening of the order of 100 kc/sec is expected for incoherent electron scatter)." He did not take the next step and calculate a limit to the spectrum width, even though earlier in the paper he discussed different scattering regimes and how a narrow spectrum could result in some cases.

Bowles' measurements were confirmed in 1960 by Pineo, Kraft, and Briscoe (1960a; 1960b) with experiments conducted at Lincoln Laboratory in Westford, Massachusetts. Pineo et al. used an 84-foot diameter paraboloid at 440 MHz, and were able to study the ionosphere up to about 800 km. At 315 km they measured a spectrum width of 11 kHz, "... 5 to 10 per cent of that predicted by Gordon [1958] on the basis of Doppler broadening by thermal motion of free electrons." (Pineo, et al., 1960a: 1621). In fact, with a pulse width of 500 microseconds, and bandwidths as narrow as 2.3 kHz, they had values of $B\tau$ near unity, and so, as they note, their value for spectrum width is an upper limit.

E E SEMINAR

DATE: Thursday, May 29, 1958

TIME: 4:45 PM (Following tea at 4:15 pm)

PLACE: Phillips 101

SPEAKER: W. E. Gordon, Cornell University

Free electrons in an ionized medium scatter radio waves incoherently so weakly that the power scattered has previously not been seriously considered. Calculations show that this incoherent scattering, while weak, is detectable with a powerful radar. A radar with components each representing the best of the present state of the art is capable of

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

2. measuring auroral ionization

3. detecting transient streams of charged particles coming from outer space

4. exploring the existence of a ring current

The capabilities listed above depend on the incoherent scattering or radio waves by free electrons. In addition the instrument is capable of

1. obtaining radar echoes from the sun, Venus, and Mars and possible from Jupiter and Mercury, and

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

Figure 6: Announcement of the seminar by William E. Gordon on 29 May 1958 in the School of Electrical Engineering at Cornell University. This copy was provided by Mrs. Elizabeth Gordon, from material left by her late husband, Professor Ralph Bolgiano, of the School of Electrical Engineering at Cornell University.

Pineo et al. (1960b) had an independent measure of the electron density in the F region, from a nearby ionosonde, and so they could estimate the scattering cross-section of the particles. They found $\sigma_{scatt} = 5 - 8 \times 10^{-26}\text{cm}^2$, a factor 10 less than the Thomson cross-section for electrons. But their estimate of received power probably was a lower limit, again because the Bτ product was small, and thus their published value is in fair agreement with the Thomson cross-section, 6.65×10^{-25} cm^2. Pineo et al. confirmed Bowles' two results: the Thomson cross-section could be used to (roughly) predict the strength of the echo, and the spectral width of the scattered signal was much less than the value given by thermal motion of electrons.

3 ACCURATE SCATTERING CALCULATIONS

The Bowles result showed the need for a more complete theory for incoherent scatter. Some of the resulting theoretical papers started with the work by Pines and Bohm (1952), who investigated motions in an electron gas neutralized by ions spread into a uniform background, and calculated the spectrum of the fluctuations in density of the electrons. This spectrum could be used to calculate the radar echo, but first the restriction to a smooth background had to be eased. Following Pines and Bohm (1952), Bowles (1959a; 1959b) heuristically argued that the ion motions would control the electron density fluctuations. This explained the measured narrow spectrum; it was connected to the ion thermal velocity.

Bowles' discussion was qualitatively correct, but needed a rigorous basis. Four such papers appeared the following year, by Fejer (1960), Salpeter (1960a; 1960b) and Dougherty and Farley (1960). These analyses proceeded differently but all assumed that the plasma was in thermodynamic equilibrium with no magnetic field. (Salpeter allowed for different temperatures for the ions and electrons.) The common result was that the strength and spectrum of the scattered signal depends on the ratio $L/4\pi D$, where $L = \lambda/2$ is the scale for scattering and D is the Debye length, $D = (kT_e/4\pi n_e e^2)^{1/2} = 6.9(T_e/n_e)^{1/2}$, where T_e is the plasma temperature in Kelvins, and n_e the electron density in cm^{-3}. The Debye length is the 'screening distance' around an ion. At sufficiently high radio frequencies, the fluctuation scale for scattering is small and $L/4\pi D \ll 1$. This is the case that Gordon implicitly used; the electrons are independent and his calculation for the strength and spectrum of IS is correct. However, for ionosphere experiments below a few thousand kilometers the opposite is true: $L/4\pi D \gg 1$, and the scattering, crudely speaking, is mostly from electron clouds moving with the ions. The total strength of the back scattering is reduced by one half (or more, if the electron temperature is greater than the ion temperature), and the spectrum is not Gaussian but is roughly flat-topped and narrow, with the width given by the ion thermal velocity. In addition, as shown by Salpeter and by Dougherty and Farley, the spectrum contains two narrow features, the 'plasma' lines, at frequencies $\nu = \nu_o \pm \nu_p$, where ν_o is the frequency of the incident wave, and ν_p is the plasma frequency. These plasma lines subsequently have proved useful in diagnostics of laboratory plasmas, in addition to the ionosphere.

Figure 5 shows the theoretical spectrum of the IS echo. At top is the Gaussian used by Gordon and originally expected by Bowles; it is calculated from the Doppler shift on electrons with a Maxwell-Boltzmann distribution of velocities, and no interaction with the ions. At bottom is the spectrum obtained when the ions are included and $L/4\pi D \gg 1$. The low peaks on the spectrum are due to heavily damped ion acoustic waves. Note the different scales of both the abscissa and the ordinate on the two graphs. The ion curve (red) is shown on the top as the arrow. It is too narrow for its shape to be recognized, and is far off-scale in power. This readily illustrates that the signal is much narrower and stronger than originally assumed.

The important ion in the F region is singly-ionized oxygen, with atomic weight 16 and mass 14,500 times the mass of an electron. Its rms thermal velocity is smaller by a factor of 120, and the spectral width of the electron echo is similarly 120 times smaller than the value estimated from the electron thermal velocities.

In 1961 five papers including the magnetic field appeared: Farley et al. (1961), Salpeter (1961), Fejer (1961), Hagfors (1961) and Renau et al. (1961). These showed that the field has little effect on the scattering except near perpendicularity between the field and the incident wave vector. When close to perpendicular, the echo splits into lines separated (approximately) by multiples of the ion gyro frequency. Salpeter calculated the spectrum in considerable detail. This flurry of activity continued over the next years, especially with calculations of non-equilibrium effects. Five years later the theory appeared in a plasma physics text (Bekefi, 1966: 260ff).

4 GENERAL INTEREST IN THE HIGH IONOSPHERE (1957-1958)

The International Geophysical Year (IGY) lasted through 1957 and into mid-1958. It was timed to include the period of maximum solar activity, and studies of the ionosphere were included from the start of planning in 1953. One of the programs, for example, was the establishment of more than 75 ionosondes, to measure density and other properties of the ionosphere, up to the level of maximum electron density (IGY Observations ..., 1956). Another was the launching of a number of research rockets. In February 1959 the *Proceedings of the Institute of Radio Engineers* published a special issue on the ionosphere (Morgan, 1959) containing many articles summarizing what was then known.

On 4 October 1957, as part of the IGY, the Soviet Union launched a satellite, *Sputnik 1*, and then a month later launched *Sputnik 2*. On 31 January 1958 the US launched *Explorer 1*, which discovered the Van Allen Belts, the first major scientific discovery from a satellite. *Sputnik 1* was unexpected in the US and startled everyone (York, 1987: 100); it prompted the founding of both the Advanced Research Projects Agency (ARPA, now DARPA, the Defense Advanced Research Projects Agency) in February 1958 (*ibid*: 137) and the National Aeronautics and Space Agency (NASA) in October 1958 (*ibid*: 154). Thus, Bill Gordon's studies for an incoherent scatter radar in early 1958 grew out of an ambience of strong interest in the high ionosphere; and, as described in the Introduction, also grew out of his own earlier work on scatter propagation.

The military also was deeply interested in the ionosphere, not least because of the emerging threat of ballistic missiles. Intercontinental ballistic missiles travel in the ionosphere, and everything about this environment was of interest. In the summer of 1958 the US performed the Argus experiment, consisting of three high-altitude nuclear explosions (*Defence's Nuclear Agency* …, 2002: 143-147). Argus was prompted by some calculations by Nicholas Christofilos, a scientist at Lawrence Livermore National Laboratory. Christofilos had a strong reputation as an original thinker. Prior to the launch of *Explorer 1* and its discovery of the Van Allen Belts, Christofilos had predicted the existence of bands of particles supported by the Earth's magnetic field. He suggested that a series of nuclear bombs exploded at a high altitude would produce a band of particles that might interfere with a ballistic missile, and perhaps even disarm it (York, 1987: 128-132). In the event, Argus showed that there would be negligible interference with a missile, but that communications could be affected.

5 THE STUDY PHASE

The IS radar was enthusiastically supported at Cornell, and Bill Gordon started to sell the idea to funding agencies sometime in the spring of 1958. Gordon's contract with Office of Naval Research (ONR) for radio astronomy research provided funds at first (Gordon, 1979: 18-19), but neither the ONR nor the National Science Foundation could support a detailed study. In principle the Air Force was interested in the ionosphere; this is indicated by a *Guide for Preparation of Contract Proposals* dated August 1958, and an accompanying form letter signed by Morton Alperin, who was Director of Advanced Studies for the Air Force (Alperin, 1958). The letter states: "New knowledge of the extra-atmospheric environment is of particular interest." and "Studies concerning ion density, [and the] ... earth's magnetic field ... are important ..."

So Gordon had to circulate through the Washington agencies, until he finally got the attention of ARPA. This Agency had been founded in February 1958 to coordinate and promote research and development by the different military services, especially on projects related to missiles and space. ARPA was new, well-funded and encouraged new projects; the match between ARPA and the radar was excellent. It was a new idea, and would investigate some aspects of the ionosphere, which was ARPA's 'turf'. ARPA was an agency of the Department of Defense; but its charter also included pure civilian research on subjects related to space and other topics (York, pers. comm., 2008). Gordon's timing was excellent and he was encouraged to study the project, but many trips to Washington and other places were required before ARPA was finally convinced that the big radar would actually work (Gordon, 1994: 11-15).

A preliminary study of the radar was made during the summer and autumn of 1958, and the results were published in a report issued by the School of Electrical Engineering on 1 December 1958 (Gordon, et al., 1958). The report was addressed to the Wright Air Development Center at Wright-Patterson Air Force Base, Ohio, and presumably became the basic document describing the project when the next funding steps were undertaken.

The report was issued only a month after Bowles' demonstration of the narrow nature of the echo spectrum, and before his paper appeared in *Physical Review Letters*. Nearly all the work in the report must have been done with the wide spectrum in mind. There is no reference to Bowles' work in the report, and the funding agencies may not have known about it when they received the report. However, the agencies, where many atmospheric scientists worked, would have learned about Bowles' work soon afterwards.

The primary criterion for the radar was to obtain a useful echo from 1000 electrons cm^{-3} at a height of 1000 km in one second, with a height resolution of 150 km, using readily available components (Gordon, et al., 1958: 2). This leads to an antenna diameter of about 1000 feet. There is some, but not much, arbitrariness in the numbers and hence in the required dish diameter. Based on what was known of the ionosphere at that time, the diameter could not be substantially smaller than 1000 feet without seriously weakening the radar as a scientific instrument.

From the first discussion of a powerful radar in a 1000-foot dish, it was obvious that important scientific programs in addition to the ionosphere could be undertaken. Surfaces of the Moon and planets could be studied (Cohen, 1959), and it was clear that the planets out to Jupiter could be detected with the radar. The inferior conjunction of Venus with the Earth provided an excellent potential target, and the conjunction of 2 May 1961 was picked as a date for completion of the radar (Gordon, et al., 1958: 21). In fact that date was missed by several years.

The Sun provided another possible target, although it was not known if any echoes could be detected from its plasma atmosphere. At that time there was general interest in the topic of solar echoes (Coles, 2004), with the first positive result coming in 1959, at 25 MHz (Eshleman et al., 1960). The solar radio astronomy program at Cornell provided additional interest, including theoretical studies of the possibility of enhanced echos from magnetized regions of the Sun, or from shock waves (Cohen, 1960; Petrosian, 1963). All this led to the first requirement on motion of the radar beam: it had to be at least ±2° from the zenith, to allow for the round-trip travel time between the Earth and the Sun (Gordon, et al., 1958: 5). Radio astronomy possibilities with the dish were less specific than for Solar System radar, but confirmation and extensions of the surveys made in England and Australia were recognized as useful observations, and if the dish surface were accurate enough, studies at the 21-cm line of atomic hydrogen had great potential value. A later report, *Scientific Experiments for the Arecibo Radio Observatory* (1960: 28), also discussed the study of missile wakes, which was an important topic for ARPA.

5.1 Picking the Site

From the beginning it was clear that the radar should be in the tropics, so that the Sun, Moon and planets would go overhead. However, at the urging of the Air Force, some attention was also given to sites in Texas and northern New York, where infrastructure was already in place. In the latter cases the axis would be tilted so that the beam itself would go out close to the Earth's equator. However, the Texas and New York sites were not competitive in cost with the site ultimately chosen, and the New York site also had weather problems (Mason and McGuire, 1958: 26, 34).

A site search was made by the firm of Donald J. Belcher Associates, which was led by Donald Belcher, a Professor of Civil Engineering at Cornell University and a specialist in aerial photographic interpretation (Donald J. Belcher ..., 1958). The choice quickly narrowed to karst regions, limestone areas where underground caves had collapsed, leaving large depressions, or 'sinkholes', in the ground. If the sinkhole roughly fitted the desired shape, the excavation cost could be greatly reduced. For geographic and political reasons Puerto Rico was the region of choice, and three good possibilities were found. These sites were presented to a meeting at Cornell on 12 August 1958, only about six months after Gordon first conceived of the radar. At that meeting two sites were selected for detailed field studies. The optimum site was in the northwest part of the island, in the town of San Sebastian, about 60 miles from San Juan.

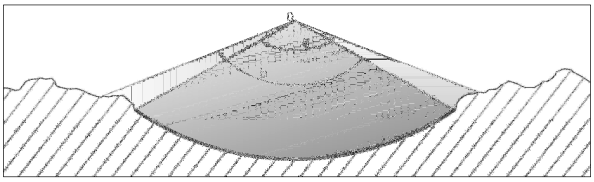

Figure 7: Schematic diagram of the 1000-foot spherical reflector. The primary feed is at point O, the paraxial focus located half-way from the vertex to the center of curvature. The transmitted energy goes out from the feed into the cone of opening angle a. When the feed is aimed off axis, into the angle b, some of the transmitted power is wasted on the ground. This off-axis vignetting, or reduction in the size of the effective aperture, exists for reception also.

Later in 1958, before a specific design was started, a decision was made to find a larger bowl, one that could hold a 1500 foot dish. This diameter was connected with the idea of using a spherical, rather than paraboloidal, dish, so that the beam could be swung off the vertical. With a 1000-foot dish the primary beam starts to hit the ground as it is swung off the vertical, as shown in Figure 7. This leads to a reduction of sensitivity. But if the dish is 1500 feet in diameter, while the primary beam illuminates only 1000 feet, there is no 'vignetting' until the swing reaches 20°, the desired maximum (Gordon, 1959). In a report submitted to the Wright-Patterson Air Force Base in mid-1959, Gordon (1959: 1-2) says "... we propose ... a total size (diameter) of the aperture of 1000 feet ... but located at a site where a future increase in reflector size can be accommodated." Donald J. Belcher Associates returned to the study of Puerto Rican karst topography and found one acceptable site, south of the city of Arecibo, where the observatory was later built (Donald J Belcher ..., 1959). ARPA did not approve the suggestion that the dish should be 1500 feet in diameter (Gordon, 2007a), and the dish as built at 1000 feet has been the largest such structure in the world for forty-six years. However, it will some day be eclipsed by a new structure in China, where radio astronomers have started to build the FAST project, a 500-meter (1640 feet) dish, in a limestone sinkhole (Nan, 2006; Hvistendahl, M., 2009).

5.2 From Paraboloid to Sphere

As originally conceived, the dish was to be a paraboloid with a vertical axis, an aperture 1000 feet in diameter, and the feed at the focal point, 500 feet above the vertex (Gordon, et al., 1958). The feed is supported on a vertical tower and moves on a horizontal structure about 7 meters in radius, so that the beam can swing up to 2° off the vertical. This gives enough motion to follow the Sun during the round-trip flight of the radio waves, during a solar radar experiment. The beam degrades as the feed is moved off-axis, and the degradation gets worse as the frequency is raised. At 400 MHz, the highest frequency considered, the loss in sensitivity is 7 db more than it is at 200 MHz (Gordon et al., 1958). This reduction in sensitivity is lessened if the focus is moved higher, but that increases the height of the tower, leading to an increase in cost. The compromise between cost and performance was complex and involved many variables. The vertical paraboloid was analogous to the 218-foot dish constructed at Jodrell Bank, England, in 1946-1947. This had a tiltable tower mounted at the vertex, and at 160 MHz the beam swing could be as much as 15° (Hanbury-Brown and Lovell, 1958: 192).

Many programs in addition to ionosphere experiments were considered as soon as the dish diameter was calculated as 1000 feet. The inner planets and the Sun were obvious radar targets, and could be studied with a beam swing of 2°. But much more could be done if the swing could be increased. The planet Jupiter, for example, at closest approach, requires about 15°. Note from Figure 6 that Jupiter was considered as a possible target from essentially the beginning of the project. With a 15° swing, observations of more than half of the northern sky could be made, and, importantly, selected targets could be tracked for more than an hour. Further, the ionosphere work could be enhanced, for example by changing the angle to the magnetic field, and by tracking traveling waves.

Gordon learned at ARPA that the Air Force Cambridge Research Laboratories (AFCRL) had been working on spherical reflectors for a decade. All lines through the center of a sphere are equivalent, meaning that a spherical-section antenna fixed to the ground could still look in all directions equally well, except for the 'spillover' or 'vignetting' that occurs when the main beam is moved off-axis and the primary beam is partly aimed at the ground (Figure 7). Gordon credits Ward Low at the Institute for Defense Analyses (IDA) and ARPA for his knowledge and help with spherical dishes, and for connecting him with AFCRL (Butrica, 1996: 89; Gordon, 1979: 26; 1994: 13).

ARPA and AFCRL both were enthusiastic about the large spherical dish. A study published in August 1959 (Gordon, 1959) produced the final shape for the dish: radius 870 feet, aperture diameter 1000 feet, and a maximum off-axis beam swing of 20°. A short 7-page proposal to Air Force Cambridge Research Center dated 30 October 1959 (*Proposal* …, 1959) described the system and its capabilities in broad terms and proposed "... to design build and operate the radar in Puerto Rico." Funding to start this work was obtained in November 1959. A further proposal dated 30 April 1960 (*Proposal* …, 1960) to provide money for construction was approved in June 1960. Excavation at the Arecibo site started in September 1960. A good description of the project and the construction phase can be found in the Final Construction Report to the Air Force Cambridge Research Laboratories dated 30 November 1963 (*Construction* ..., 1963).

The Arecibo Ionospheric Observatory (its then-name) was dedicated in November 1963 (Figure 8). The interval from conception of the project to completion was less than 6 years—a remarkable achievement. There is an extraordinary contrast between the speed of the Arecibo project and the painfully slow pace of a large science project today. A great deal of the speed can be credited to ARPA and the Cold War rivalry, but the dedication and enthusiasm of Bill Gordon and his team were central.

6 CODA

As described in Section 2, the dish was over-designed by a large factor for its original task, which was the measurement of ionospheric electron density and temperature up to a few thousand kilometers. This came about because Gordon used an incorrect assumption for the density fluctuations in the plasma, and this led to the 1000 feet diameter of the dish. People then began thinking about a 1000-foot reflector, and the remarkable power of that swamped the original task when the error was discovered less than a year later. Apparently, neither the designers nor the funding agency looked back. No discussion on this point is in any of the Cornell reports available to me. The reports published in 1958 and 1959 do not make reference to Bowles' 1958 paper, although the result was known to the Cornell people and must have been known at ARPA. The entire program remained focussed on the 1000-foot dish, with all the enhanced possibilities that entailed. It appears that ARPA, whose interest centered on studying missile wakes, found the 1000-foot dish interesting and worth funding, whereas a 100-foot dish was not interesting (York, 2008).

Gordon's assumption was an extraordinarily beneficial error. Because of it, we have had the world's largest reflector for forty-five years. It is interesting that a somewhat analogous situation developed in England at The Jodrell Bank Experimental Station (now the Jodrell Bank Observatory). In 1941 P.M.S. Blackett and A.C.B. Lovell (1941) published an article on radio echoes from cosmic ray (CR) air showers, and showed that they should be readily detectable. Two months later, however, T.L. Eckersley wrote to Blackett pointing out that collisions of the electrons with air molecules might greatly reduce the echo strength (Lovell, 1993: 124). This letter was forgotten during the War but surfaced again in 1945, and Lovell returned to the CR echo problem. By early 1946 it was clear that Eckersley was right: collisions were important and the echoes would be seen only if the CR spectrum extended to very high energies, and a very large antenna was used. But by this time the Jodrell Bank Experimental Station had been set up, to do CR experiments based on the 1941 article. That work shifted to studying meteors, but the realization that a large dish would be needed to see the CR echoes helped to support later decisions to build first the stationary 218-foot paraboloid, and then the moveable 250-foot dish. Lovell (1993: 119) states

> Evidently if we had been able to give attention to Eckersley's letter in 1941, the incentive for the proposed post-war research would have vanished and Jodrell Bank would not exist today.

Figure 8: Aerial photograph showing the newly-completed Arecibo Ionospheric Observatory and the surrounding karst terrain (courtesy: Cornell University).

The Arecibo system has made remarkable advances in radar and radio astronomy, as well as in atmospheric and ionospheric physics. An important early result was the surprising determination that the rotation period of Mercury is 59 ± 5 days, two-thirds of the orbital period (Pettengill and Dyce, 1965). Another important result was the 1974 discovery of a pulsar that orbited another neutron star (Hulse and Taylor, 1974). Long-term monitoring of this binary system showed that gravitational radiation caused the pulsar's orbit to change in a manner consistent with Einstein's General Theory of Relativity. Hulse and Taylor were awarded the 1993 Nobel Prize in Physics for this discovery.

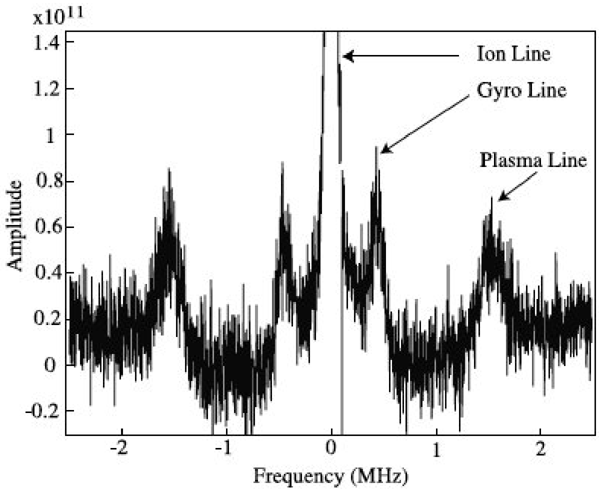

Figure 9: Spectrum of ionosphere echo obtained at sunrise at Arecibo on 15 August 2004. The central high peak corresponds to the red curve in Figure 5. The close-in peaks are offset, approximately, by the electron gyro frequency times the cosine of the angle between the wave vector and the magnetic field; and the outer peaks are offset, approximately, by the electron plasma frequency. With information like this, the strength of the field and the electron density can be tracked with height (after Aponte et al., 2007: Figure 3).

The Arecibo radar has also done far more in ionospheric research than could have been planned in 1958. As an example, Figure 9 shows a recent IS spectrum with three lines, each connected to a type of wave in the magnetized plasma (after Aponte, et al., 2007). The ion line corresponds to the red curve in Figure 5, and arises from scattering on ion acoustic waves. The gyro and plasma lines correspond to the lower and upper hybrid resonances (Stix, 1962: 32). These lines offer powerful diagnostics of the plasma and its magnetic field. The great sensitivity of the 1000-foot dish makes measurements like this possible. As the largest dish in the world, with ever-increasing versatility, the Arecibo radio telescope has the potential to continue to make fundamental discoveries for years to come.

7 NOTES

1. Research for this paper began in the early 2000s, when the author realized that he had forgotten some of the details of his own involvement in the Arecibo project some forty-five years earlier. Rereading the early papers then led to the question implied in the first paragraph of the Introduction: "Why, after Bowles' measurements, did the dish continue to be 1000 feet in diameter?" This paper is an attempt to answer this question. Useful histories of the Arecibo Observatory have been written by Butrica (1996) and by Altschuler (2002). Butrica describes the origins of the radar and its relationship with other planetary radar systems at Lincoln Laboratory and the Jet Propulsion Laboratory; he also discusses the politics and early funding problems associated with the Observatory. Altschuler (2002) gives a brief history of the Observatory, including its origins, construction, and the upgrades, the first in 1974 to raise the operating frequency, and the second in 1997 to greatly increase the bandwidth and versatility of the system for radio astronomy.
2. William E. Gordon was born in Patterson, New Jersey, on 8 January 1918. He went to Montclair State Teachers College and received a B.A. degree in mathematics in 1939. During World War II he trained as a meteorologist at New York University, and spent much of the wartime studying the atmospheric refraction of radio waves. After the war he did atmospheric research at the University of Texas and in 1947 went to Cornell University, where he worked with Henry Booker on the mechanism of long-distance radio propagation (Booker and Gordon, 1950). He received a Ph.D. degree in 1953, and was a member of the Electrical Engineering faculty at Cornell from 1953 to 1965. In 1958 he conceived of the incoherent scatter radar technique for studying the ionosphere. He developed the Arecibo Observatory, and was its Director from 1960 to 1965. In 1965 he moved to Rice University as Dean of Science and Engineering, and in later years was Provost and Acting President. He retired from Rice in 1986 and currently lives in Ithaca, New York. Professor Gordon has received many honors and awards, and was active in many scientific and engineering societies (including a term as Foreign Secretary of the National Academy of Sciences).
3. Kenneth L. Bowles was born in Bronxville, N.Y., on 20 February 1929. He attended Cornell University, receiving a B.S. degree in Engineering Physics in 1951 and a Ph.D. in 1955 in Electrical Engineering, working with Henry Booker on radar studies of the Aurora Borealis. In July 1955 he joined the National Bureau of Standards where, in 1958, he successfully adapted a NBS transmitter to make the first measurements of ionosphere scatter echoes (Bowles, 1958). In 1960 he founded the Jicarmaca Radar Observatory, an equatorial ionospheric scatter radar near Lima, Peru, and was its Director from 1960 to 1964. In 1965 he joined the new Department of Applied Electrophysics at the University of California, San Diego (UCSD). His career-long interest in computing eventually resulted in widespread use of the programming language Pascal on personal computers. Professor Bowles retired in 1995 and currently lives in Del Mar, California. He has become an expert on California wildflowers and their identification with computers.

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