Incoherent Scatter Radar:
Some Early History and Further Thoughts

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Outline

• General audience → Very little math. Aim is to paint a picture of the adventure and excitement of the genesis of ISR by some young guys (all < 40).

• The earliest years: 1958-1963
  • Gordon’s idea, Bowles’ first obs. and implications
  • Development of the proper scattering theory: the electron motions are not totally independent (but the name incoherent scatter was never changed)

• Photos of the construction of Jicamarca and Arecibo, plus some comments and stories.

• Some of the very early science done at Jicamarca
Outline (2)

• Key aspects of the radar data gathering and processing
  • Only analog techniques were available in the late 1950s
  • Proper processing to get spectral information was very difficult, except with a bi-static radar (separated transmission and reception)
  • Use (power spectrum) $\xrightarrow{\text{FT}}$ (auto-correlation function)
  • First radar controller/correlator $\rightarrow$ Peru (JRO) in 1963
  • Crucially important
• Similar device added to Arecibo in late 1960s (J. Hagen)
• Led to pulse compression and related techniques
A Personal Note

- As a grad student at Cornell, I heard the first informal talk by Bill Gordon in 1958 proposing the ISR idea.
- I worked on the plasma theory during two postdocs (Cambridge U. and Chalmers U. in Sweden)
- In 1961 I met Ken Bowles at a conference and he invited me to join him in Peru, where he was building the Jicamarca Observatory, and I thought that sounded like a fun thing to do. And it was.
- And recently I attended the 50th anniversary celebrations of both Jicamarca and Arecibo!
Background

- 1950s: Bill Gordon and Henry Booker (Bill’s advisor) worked on over-the-horizon scatter communication (military applications)
  - Troposphere: Scatter used in Vietnam later.
  - Stratosphere: longer links possible (e.g., DEW line).
  - Ionosphere? From free electrons? Gordon became interested in this possibility in the late 1950s.
From over-the-horizon propagation to ionospheric radar

Booker and Gordon 1950
Troposphere, neutral

Gordon 1958
Ionosphere, ionized
1952 Planning for IGY (International Geophysical Year) during 1957 solar maximum. Strong ionospheric component.

1957 IGY: 75 ionospheric sounders. Concern about ballistic missiles in the ionosphere
Sputnik I and II: Lots of money available

1958 Explorer I: Van Allen Belts
ARPA (Advanced Research Projects Agency—military) formed to coordinate and sponsor military programs in space; interested in promoting radar technology.
One Weekend in Dryden (small town near Cornell)

- Spring of 1958. Poor weather? So Bill pondered...
- Scatter from “free” electrons in the ionosphere? If so:
  - $\sigma_{\text{radar}}(1 \text{ electron}) = 1.0 \times 10^{-28} \text{ m}^2$ \textit{(very small!)}
  - Typical max $N_e \sim 10^{12}$ electrons/m$^3$ in the F region
  - Consider a volume of 10 cubic kilometers ($= 10^{10} \text{ m}^3$; a 1 km beam width, 10 km thick, say). If the \textit{powers}, not the voltages, add (completely independent electrons), then the cross section for all these electrons together is $10^{-28} \times 10^{12} \times 10^{10} = 10^{-6} \text{ m}^2 = (1 \text{ mm})^2$ \textit{(~ a pencil dot!)}
- A target this small, at a range of 300 km, say, would seem to be impossible to detect, but is it?
One Weekend... (2)

Gordon’s great contribution to our field was to actually do this simple calculation. He found that a tiny target of this size could be detected with a big radar, using 1958 radar technology. For his antenna he chose a 1000 foot diameter dish, a nice round number!

“If you dream, don’t be afraid to dream big!” (W.E.G., advice to grad students)
Bill Gordon c 1963
Two Important Questions:

- Is the scattering really incoherent; i.e. are the electron positions *completely* uncorrelated?
- What about the electron motions and the associated Doppler shifts?
  - How would these shifts affect any scatter communications?
  - What about the effect of bandwidth on the noise?
Is the scatter truly incoherent?

- Gordon thought that it was, as long as the mean free path (between collisions) of the electrons was greater than the radar wavelength, which is true in the F region and upper E region.

- But the first (1958) crude ISR bandwidth observations by Ken Bowles showed that Gordon was wrong, and kinetic plasma theory soon showed why: collective plasma effects are usually very important. The ions matter, even though they don’t scatter radar pulses.

- What matters is the *Debye length* (a few mm in the F region) compared to the radar wavelength, not the mean free path.
What about the Doppler shifts?

- The radial electron thermal velocity is
  \[ v_z(\text{rms}) = \left( \frac{K_B T_e}{m_e} \right)^{1/2} \sim 100 \text{ km/s for } T_e \sim 1000 \text{ K} \]

- This leads to a Doppler shift of
  \[ \Delta f = f_0 \left( \frac{2v_z}{c} \right) \sim 200 \text{ kHz for } f_0 = 400 \text{ MHz}, \text{ or a} \]
  Doppler bandwidth \( \sim 400 \text{ kHz} \) since \( v_z \) can be up or down

- For Bowles’ 41 MHz observations at Illinois (see next slide) this bandwidth would be \( \sim 40 \text{ kHz} \)

- For pulsed operations these values would be convolved with
  \( \sim 1/\text{pulse duration (in seconds)} \text{ Hz} \)

- The frequency spreading would make communications via incoherent scatter impractical, \textit{but probing the ionosphere would be possible}. 
Doppler shifts (2)

- Bowles’ first observations in Illinois in 1958 at 41 MHz (see later slide) showed that the bandwidth was substantially less than 30 kHz.
- Later (July & Aug., 1961) early observations at Jicamarca showed that the Doppler bandwidth for $f_0 = 50$ MHz was in fact much smaller, more than an order of magnitude smaller than Gordon’s first prediction.
- This led numerous theorists (including me) to conclude that the ions must play a key role in the scattering process. Plasma kinetic theory (which we had to learn) tells us that it is the relation between the Debye shielding distance, not the (usually much longer) mean free path, and the radar wavelength that matters. For truly incoherent scatter the radar wavelength must be less than the Debye length, which is seldom the case.
Doppler Shifts (3)

- Most of the plasma theory details were given in papers by Jules Fejer, Dougherty and Farley, Hagfors, Salpeter, Rosenbluth and Rostoker published in 1960-62, followed by many other papers. Most of these papers arrived at exactly the same results, using very different mathematics.
Now look at some of the data and papers.

- Notice the dates on some of the slides, keeping in mind that Gordon first conceived of the basic idea of ISR probing in the spring of 1958. Things moved amazingly quickly after that.
Incoherent Scattering of Radio Waves by Free Electrons with Applications to Space Exploration by Radar*

W. E. GORDON†, MEMBER, IRE

Summary—Free electrons in an ionized medium scatter radio waves weakly. Under certain conditions only incoherent scattering exists. A powerful radar can detect the incoherent backscatter from the free electrons in and above the earth's ionosphere. The received signal is spread in frequency by the Doppler shifts associated with the thermal motion of the electrons.

On the basis of incoherent backscatter by free electrons a powerful radar, but one whose components are presently within the 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; and
4) exploring the existence of a ring current.

The instrument is capable of:

1) obtaining radar echoes from the sun, Venus, and Mars and possibly from Jupiter and Mercury; and
2) receiving from certain parts of remote space hitherto-undetected sources of radiation at meter wavelengths.

* Original manuscript received by the IRE, June 11, 1958; revised manuscript received, August 25, 1958. The research reported in this paper was sponsored by Wright Air Dev. Ctr., Wright-Patterson Air Force Base, O., under Contract No. AF 33(616)-3547 with Cornell Univ.

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Proceedings of the IRE, Nov 1958: Gordon’s first paper on ISR (published 6 months after the May ‘58 Cornell seminar)

1960 – 1963: AIO Construction

Inauguration in Nov 1963: William Gordon – Director
Bowles’ First Observations of ISR

• Ken Bowles, a former grad student at Cornell (3 or 4 years ahead of me), had been thinking about scattering also, and he heard about Gordon’s work in the summer of 1958.

• He was working for CRPL (now NOAA) in Boulder and had access to a powerful 41 MHz transmitter in Illinois.

• He contacted an Ithaca tree surgeon (!) who quickly drove out to Illinois and built a 1024-dipole array antenna for this transmitter in a few weeks!
Bowles’ 1024-dipole array in Illinois in 1958

Individual dipoles, part of 4-acre array antenna at Long Branch, Ill. This antenna, consisting of 1,024 dipoles, will be used to study the physics of the upper reaches of the ionosphere.
Bowles’ paper on first observations of incoherent scatter at 41 MHz

The 4 sec “integration” (averaging) was done photographically!

- There was an URSI meeting at Penn State on the day that Gordon presented his Proc. IRE paper (that would be published a few weeks later) at an afternoon session.

- He began by saying, “I’m going to describe a new way of probing the ionosphere, and then I’m going to tell you about a telephone conversation that I just had” (with Ken Bowles, about Ken’s first observations of IS that very same morning!).
1958 Illinois 41 MHz radar obs. by Bowles that showed that the received signal spectrum was narrower than Gordon’s first prediction.

9 kHz filter centered on $f_0$

Filter shifted up 15 kHz

Filter shifted down 15 kHz

The obs. (small) BW is a convolution of the 120 μs pulse BW (~8 kHz) and the plasma Doppler BW, and so the latter must be far less than Gordon predicted.

[From Bowles, J.Res.NBS, 65D, 1961]
Further Confirmation in 1960

- This experiment was done with an 84-foot dish.

Fig. 5. Frequency spectrum of ionospheric backscatter observed at 440 Mc/s from a height of about 315 km between 1423 and 1515 hr EST, April 22, 1960. Antenna elevation = 45°; antenna azimuth = 281°.
1959 power measurement by Bowles with the Illinois 41 MHz radar

Figure 3. A'scope photograph using the "integrator" display. 1135 LT, 27 February, 1959

(mercury jet charges separate capacitor for each range gate)
Early (Aug. 1961) observations from Jicamarca, using only part of the main antenna and less than the full transmitter.

The primitive data analysis was done by hand with a ruler and probably a slide rule (!) for the $r^2$ factor.

Normalized with ionosonde data.

[From Bowles et al. J.Res.NBS, 66D, 1962]
Bowles’ first measurement of the (narrow) spectrum of the scattered signal showed that the simple Gordon theory was wrong, and the obvious conclusion was that the slow ions were somehow involved, even though it was the fast electrons doing the scattering. Why were no large Doppler shifts observed?

Bowles made some suggestions, but what was needed was a proper kinetic theory, but in the 1950s there was not much published plasma theory!

Those of us who were interested in the problem barged in, using whatever mathematics we were familiar with (e.g., nuclear physics, electrical engineering, ...)

Kinetic Plasma Theory
In 1959 I was a post-doc at Cambridge University and shared an office in the Cavendish Lab with a senior English grad student, John Dougherty.

I mentioned the IS problem to John and he got interested too, and so we decided to see what we could do.

We asked around the lab for ideas, and a visitor mentioned a couple of 1950s papers by Callen and Welton that had generalized Nyquist’s classic 1928 noise theorem paper and showed how it could be applied to many problems.

With my engineering physics background, this seemed like an appealing approach.
Kinetic Theory (3)

- *Nyquist thought experiment*: apply a fictitious sinusoidal force to the charged particles and calculate what happens, including all the thermal motion effects, so that the particles see Doppler shifted forces.

- You then have a complex conductivity (or equivalent dielectric constant) that you plug into the theorem. The theorem does all the thermodynamics for you!

- You can tweak the Nyquist theory so that it yields the spontaneous *mean squared electron density fluctuations that cause the radar scatter and control its power spectrum* rather than the spontaneous currents or voltages that arise in a circuit.
Kinetic Theory (4)

- Fortunately Cambridge had a computer and a programmer that could calculate the required complex numerical integrals. The result is a double humped spectrum (not a Gaussian) with Doppler shifts characteristic of the ion velocities. The spectrum can also be thought of as resulting from heavily damped up- and down-going ion-acoustic waves.

- The theory can also be approached from a “dressed particle” point of view. Moving ions attract a cloud of electrons and push away other ions. The neutralizing cloud has a radius of about a Debye length, or the Debye shielding radius. For slow moving ions the cloud contains about half an electron and a deficiency of about half an ion.
Kinetic Theory (5)

- For faster ions the neutralizing cloud contains more electrons and a smaller deficiency of ions (that can’t move out of the way fast enough).
- In contrast, the (almost) free electrons move too fast to attract an ion cloud; they are shielded almost entirely by repelling nearby electrons.
- So for radar scattering purposes, an ion+cloud has a scattering cross section somewhat smaller (depending on its speed) than a free electron, and an electron+deficiency cloud has a cross section of nearly zero!
- This picture is too simplified to account for plasma lines, which involve a sharp resonance, but both theories can explain them.
Kinetic Theory (6)

- Only if $\lambda_{\text{radar}} / 4\pi << \lambda_{\text{Debye}}$ does the Gordon theory (truly incoherent scatter) apply. This inequality is seldom valid in the ionosphere, where the Debye length ($=v_{\text{thermal}}/\omega_p$) is usually of order mm or cm. Only for low electron densities, high temperatures, and short radar wave lengths are the electron positions truly independent.

- If $T_e = T_i$ (not always true) the total scattering cross section is one half the value predicted by Gordon, but of course the power spectrum is much narrower, making the signal easier to detect.

- It is important to emphasize that the theory predicts only the statistical properties of the signal, not the signal itself. There is no useful information in a single echo.
Free electrons

Slightly correlated electrons and ions

Original Gordon theory (controlled by electron velocities). Only if $\lambda_{\text{radar}}/4\pi<<\lambda_{\text{Debye}}$

Modern plasma theory [narrower by $\sim (m_e/m_i)^{1/2}$]

For $T_e=T_i$ and single ion species
Implications for Plasma Theory

- The complete success of linear kinetic plasma theory in explaining all ISR spectral observations to date provides what is probably by far the best quantitative and detailed test of the kinetic theory.

- To show this, however, we first had to figure out how to accurately measure the spectrum and the power.
Measuring the Power Spectrum

• The spectral shape of the echoes depends on the temperatures, ion composition, drift velocities, and other parameters of the ionosphere, so it is important to measure this power spectrum in detail. *This is not easy to do!*

• It is easy to measure the Doppler shift of a radar echo from a single “hard” target, but what about a diffuse distributed target with a broad range of velocities? *Not* so easy.

• We have to deal with the problems of range and/or frequency *aliasing* if we use a *pulsed radar* (the usual case) and/or spectral convolutions if we use short pulses.
Measurements (2)

- To avoid range aliasing we want a large separation between pulses (long interpulse period, or IPP), but to avoid frequency aliasing, the sampling theorem tells us that we want rapid sampling of a particular volume (short IPP).
- If we can’t cope with both problems at once we have an overspread target. *The ionosphere is such a target!*
- So what do we do? We are saved by two facts: (1) the power spectrum is the Fourier transform of the auto-correlation function (ACF), and (2) the echoes from two disjoint volumes of plasma are statistically independent.
- But first we look at the simple case of a bi-static radar.
Monostatic vs. Bi-static Radars

Short pulses distort analog power spectrum

Usually transmit CW (single frequency). Used by a French group in the early 1960s. Gives nice power spectra, but only for one altitude at a time.

Sweep beam to change altitude (tedious)
Double Pulse Technique

At Jicamarca the two pulses can have orthogonal polarizations, eliminating the radar clutter (the gray diamonds).

This technique gives good resolution in both altitude and time lag (for the ACF).

Sampling at all altitudes gives one lag of the ACF at all altitudes. Then vary the lag cyclicly to build up the full ACF at all altitudes.
Extend to 4 pulses (6 different lags)

With 4 pulses you can measure 6 different lags at once and so build up the ACF more quickly. The added clutter may not matter if S/N is small.
Use Cyclic or Random Codes

Changing $a_0 - a_3$ randomly or cyclicly in a particular way will eliminate all but the black diamonds.
Pulse Compression: 5 baud Barker Code

A properly “matched” filter will compress the 5-baud pulse to 1 baud length, with 5 times the signal/noise.
Early Digital Devices at Jicamarca

- **The correlator**: built in the Boulder labs using discrete transistors, with many counters, gates, flip-flops, etc. Programs were hard-wired using a 2 x 1024 hole patch panel and up to 1024 wires (or more in a pinch). It arrived at JRO in early or mid 1963. This device was crucial, and surprisingly powerful and versatile.

- **A Packard-Bell PB 250 computer** (mid or late 1963) with an acoustic delay line memory (16 x 256 words!)
The Correlator

- Two separate radar controllers could generate and process lagged samples for ACFs.
- The separate controllers could generate different polarizations, for example.
- Complex cross correlations as well as ACFs could be generated.
- Absolute values (for power measurements) could be accumulated.
- Digital thumb wheels could easily change the measurement timing.
- Each program “step” could do an unlimited number of things, so a lot could be done with the 2 x 8 available steps.
The correlator (made with discrete transistors!) ~ 1963

Basic clock rate was 30 kHz
(33 μs intervals, or 5 km range)
Plug board for the correlator:
2 x 1024 holes,
~ 1963

Some programs used all the holes! Tedious to debug!
The PB-250 Computer: paper tape reader, acoustic delay line memory (16 x 256 words = 12 kilobytes!)
~ 1963    Cost was ~ $30K or so? (In 1963 $!)

Interesting story about Ken Bowles fixing/improving this computer in the first week, before the PB technician arrived to “install” it!
The PB 250

- Efficient programming was very tedious and difficult since commands had to be in the right position on the acoustic delay line of the memory. Debugging could be very frustrating!
- The delay lines often had to be “tuned” due to changes in temperature (and the acoustic velocity)!
- Multiplications took a time that depended on the number of digits.
- The programs were loaded via paper (or mylar) tapes.
- Despite its limitations, the PB250 provided a huge leap forward towards the era of modern data processing.
Some early science at Jicamarca

- 1962: Echoes from Venus at 50 MHz
- 1962: “Starfish” high altitude nuclear bomb test
- 1965: High altitude electron densities
- 1966: **Total** solar eclipse over Jicamarca
- 1967: Observations of the proton gyro-frequency
1962 Venus echoes from Jicamarca

Table I. Jicamarca radar parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter</td>
<td></td>
</tr>
<tr>
<td>Peak power</td>
<td>$4 \times 10^4$ W</td>
</tr>
<tr>
<td>Frequency</td>
<td>49.92 Mc/sec</td>
</tr>
<tr>
<td>Pulse-repetition frequency</td>
<td>20 cps</td>
</tr>
<tr>
<td>Pulse length (as used for Venus experiment)</td>
<td>3 msec and 500 $\mu$msec interlaced with gap at 1-sec intervals</td>
</tr>
<tr>
<td>Antenna</td>
<td></td>
</tr>
<tr>
<td>Area</td>
<td>84 000 m$^2$</td>
</tr>
<tr>
<td>Gain over isotropic radiator appropriate to this experiment (see text)</td>
<td>40 dB</td>
</tr>
<tr>
<td>Receiver</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>49.92 Mc/sec minus predicted Doppler</td>
</tr>
<tr>
<td>Noise figure</td>
<td>1.5</td>
</tr>
<tr>
<td>Sky-brightness temperature at time of experiment</td>
<td>$\sim$6000$^\circ$K</td>
</tr>
<tr>
<td>Predetection bandwidths</td>
<td>300 cps</td>
</tr>
<tr>
<td>Frequency stability</td>
<td>3 kc/sec</td>
</tr>
<tr>
<td>Timing accuracy (range gates and tape recorder)</td>
<td>2 parts in $10^9$</td>
</tr>
<tr>
<td></td>
<td>parts in $10^8$</td>
</tr>
</tbody>
</table>

1. Integrator readout, 3-msec echo. Integration time 12.5 sec, range boxes spaced 500 $\mu$msec apart.

Fig. 2. Integrator readout, 0.5-msec echo. Integration time 1 min, range boxes spaced 100 $\mu$msec.

1962 Starfish High Altitude Nuclear Bomb Test

[Ochs et al., JGR, 1964]
Fig. 5. Total synchrotron radiation received at Jicamarca at 50 Mc/s for the first 50 minutes following the explosion (solid curve). $\Delta T_A$ is the increase in antenna temperature over the normal background value, and $t$ is the time measured from the time of explosion. The dashed curve is the theoretically expected variation of $\Delta T_A$ with $t$, assuming the trapped electrons to have the energy distribution shown as the solid curve in Figure 6.
High altitude profiles in 1965

CEDAR Workshop – June 2012 – Santa Fe, NM
Electron densities to high altitudes

[JRO report]
The **Solar Eclipse** of 1966 over Jicamarca

- A *total solar eclipse* was predicted to pass directly over Jicamarca in the early morning of November 12, 1966.
- Everyone who worked at Jicamarca was told to arrive very early just in case something went wrong.
- *Little did we know!*
- An hour or two before the eclipse was due to start, a *major fire broke out* in a tunnel with many power cables.
Eclipse (2)

- Fortunately, the Peruvian electrician who had installed most of the cables in the tunnel remembered which was which in spite of all the smoke, and the fire was soon put out.
- We started our observations almost on time at 6 a.m.!
Electron densities and temperatures during the eclipse
The Ion Gyro-resonance

- One of the original reasons for building Jicamarca on the magnetic equator was to measure the ion gyro-period. The idea was that if you pointed the radar perp. to B there would be a peak in the ACF at the gyro-period, as the ion+cloud returned to the “same place,” at least in the F region, where $\nu_i << \Omega_i$.

- But this didn’t work. Even though the O$^+$ ions did not make a Coulomb “collision” in one gyro-period, they did deviate more than $\lambda_{\text{radar}}/4\pi$ from their unperturbed orbit, and that was enough to destroy the resonance.

- But that did not happen for H$^+$ ions, and we successfully observed the proton gyro-resonance, with results that agreed very well with a calculation in Rod Woodman’s PhD thesis of 1967!

- *Compare with modern theory of Kudeki and Milla?*
The proton gyro-frequency

Woodman theory, 1967

Fig. 3. A comparison between theory (Ref. 17) and a typical experimental curve taken from Fig. 2.
Some Early Jicamarca Photos
Jicamarca site from the air – 1959?
Early road to Jicamarca
Sacio farm, Cajamarquilla ruins
Site looking east, before construction
Jicamarca site survey, 1959
The Main Dipole Array

18,432 dipole (9,216 crossed pairs)
64 separate modules
Steered by manually (!) changing cable lengths for each module
Start of construction
One test line of dipoles
Partly finished, 1961
Some details, 1961
Last ("gold") dipole, 1962
Showing the connections
Coaxial-colinear (COCO) connection scheme
The “switch yard”
Jicamarca ~ 1962
The Jicamarca Transmitter
80 ton transformer crossing the Rimac river
Some capacitors!
Spark here must dump entire Capacitor bank in < 1 ms
Note the dry river beds, marked by plants that survive on one drink every several years.
Big boulders are moved by “huaycos”
Commuting was a little difficult sometimes!
A later year, another huayco. This bridge survived, barely.
Some young guys at that same bridge (late 1970s?)
The Jicamarca well (1960 or 61). 100 meters deep!
(Two stories re drilling the hole, guards, thieves.)
Note the protective dam and the antenna arrays outside the protection.
The protection was needed!
1st Int’l Symposium on Equatorial Aeronomy
Huaychulo, Peru (altitude ~ 11,000 ft), 1962

Can you find Sidney Chapman, Ken Bowles, Don Farley, Ron Woodman?
Some Early Arecibo Photos
Ben Nichols, Bill Sears, Bill Gordon, Tom Gold, Henry Booker
Puerto Rico
Eye on the Universe

Note the “karst” geography with many natural sinkholes
November 1959 – Contract signed between Cornell and AFCRL / ARPA
October 29, 1962
Total of 9,000 cubic yards of concrete
First upgrade: New surface with 38,778 solid panels
Second upgrade:
Gregorian feed, extra screen
Enterprise!
The Ground Screen
Arecibo by Night
007 and friend

Goldeneye
AO has many “contacts”
Why is this dish 1000 feet in diameter?
Why 1000-foot diameter?

- The early (1958, 1959) observations by Ken Bowles showed that the signal bandwidth was much narrower than that predicted by Gordon, and theoretical work soon showed why this was so (the effect of the ions).
- This means that the receiver bandwidths could be narrowed, admitting less noise and improving the radar sensitivity considerably.
- In spite of this, there was never any discussion (at least not in the written records) of reducing the size of the Arecibo dish to save money! The original mistake turned out to be very fortuitous.
Why 1000 feet (2)?

- All the interested parties (including the military) realized that there were lots of other interesting things that could be done with a huge, reasonably steerable dish, and they were unwilling to give up this option.

- *If you dream, don’t be afraid to dream big!* (W.E.G.)
Looking to the Future

- For Jicamarca
  - More elaborate interferometry using antenna modules
  - Continued use of JULIA mode (low power, remote operation)
  - Electronic beam steering (hours → seconds or even ms)
  - Add an EM wave heating facility?
  - And more—JRO is very versatile.

- For Arecibo
  - New heating facility
  - Enhanced efforts re near Earth dangerous asteroids?
  - More efforts re the plasma physics of gyro-lines and related topics?
Future (2)

- **New ISRs**
  - Relocate one or more AMISRs. E.g., Ethiopia?
  - Add a full AMISR to Jicamarca?
  - Add a 50 MHz array to Ethiopia? And smaller radars to study plasma instabilities.
  - Various other options for the AMISRs

- **New scientists:** legacy of students trained at Jicamarca and Arecibo, especially from Latin America
Conclusions

- An amazing amount of good science, both experimental and theoretical, was done very rapidly in the first decade (1960s) of research on (almost) incoherent scatter, using very primitive (by modern standards) data processing tools.

- Two small groups of young, U.S., gringo engineers had fun solving an impressive string of problems.

- Their pioneering work led to the network of ISRs now operating—with more to come.

- Good science is still being done and will continue to be done.
Questions?
Arecibo Dish, overhead structure, and shadow
Starfish (3)

Fig. 6. The normalized electron energy distribution. The solid curve is derived from the observations of $\Delta T_4$ versus $t$ shown in Figure 5. The dashed curve is the fission spectrum, $\exp(-0.575E - 0.055E^2)$, where $E$ is the energy in Mev. Multiplying $N$ by the factor $2 \times 10^4$ gives an estimate of the total number of trapped electrons per Mev energy range.