Mistakes Can Be Useful

M.H. Cohen
Caltech

Jodrell Bank, UK
1957

Arecibo, PR
1963

Perugia May 2011

“This will only take one year, and will only cost forty thousand dollars”

“If I had known how difficult this would be,
I never would have started.”

attibuted to Willis E. Lamb, speaking of the Lamb-Retherford experiments on the fine-structure of hydrogen.

Jodrell Bank Experimental Station

1941: P.M.S. Blackett and A.C.B. Lovell (Proc. Roy. Soc. A, 177, 183-186, 1941)

Radar Echoes from Cosmic Ray Trails

1941: T.L. Eckersley (correspondence with A.C.B. Lovell, Notes and Records of the Royal Society of London, 47, 119-131, 1993.)

Electron-molecule collisions will greatly reduce the echo

WW II

1945: Jodrell Bank Expt Station founded, to look for CR echoes

1946: Eckersley was correct！ Shift program to meteors.

Jodrell Bank

"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."

A.C.B. Lovell. Notes and Records of the Royal Society of London, 47, 119-131, 1993.

Arecibo Observatory

1958: W.E. Gordon (Proc. Inst. Radio Engineers, 46, 1824)

Ionosphere radar, incoherent scattering by free electrons,
Doppler broadening from electron velocities
Need diameter 305 m to measure density, temperature

1958: K.L. Bowles (Physical Rev Lett, 1, 454)

Echoes approximately the expected strength, but spectrum much narrower

1959-1961: Bowles, Fejer, Salpeter, Dougherty and Farley

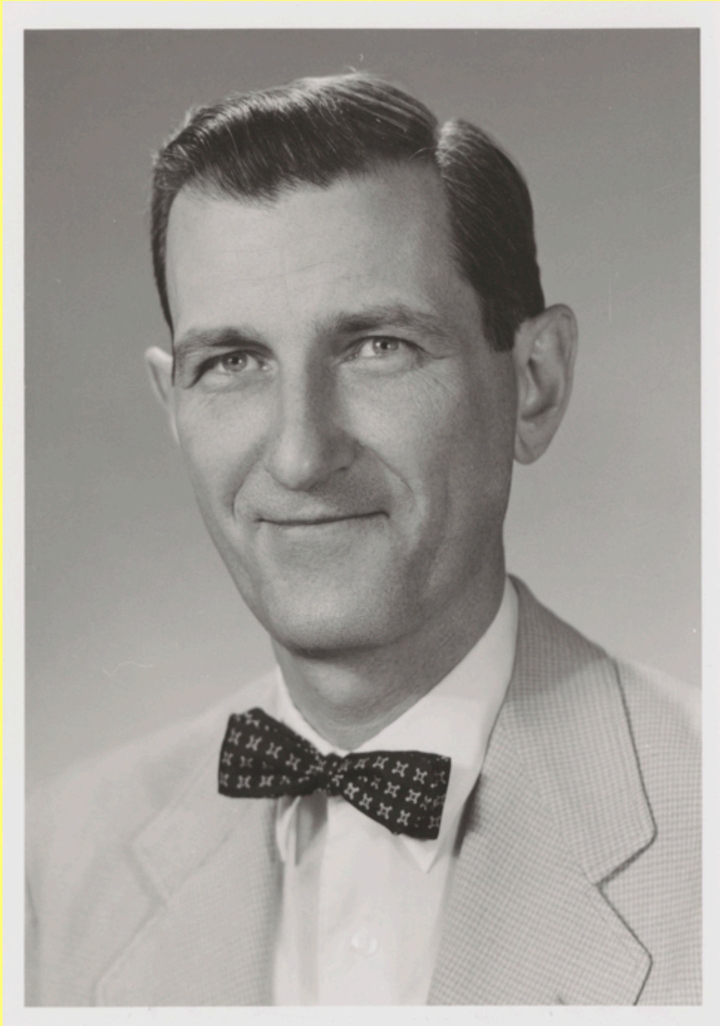
Echoes controlled by ions, at the important scale.
O^+: $(m_i/m_e)^{1/2} = 120$

1960-1963: Build 305-m dish

Arecibo

"Gordon's assumption was an extraordinarily beneficial error. Because of it, we have had the world's largest reflector for forty-five years."

M.H. Cohen, Journal of Astronomical History and Heritage, 12, 141, 2009.



William E. Gordon c 1963
1918 - 2010

Arecibo, early 1958
Where did the ideas come from?

1. Ionosphere was a hot scientific topic

    Early experiments: radio propagation, ionosondes

    Little top-side information: rockets, whistlers

    IGY 1957-1958.5 (organization started 1952)

    - 75 ionosondes around the world
        - Continuous density profiles up to F_{max}
    - Sputnik 1 October, 1957
    - Explorer 1 January, 1958
        - Van Allen belts
    - Top-side sounding from satellite (proposals)

2. Military Interest

- Ballistic Missiles
  - Ionosphere = environment of missiles
  - Lots of money
- Atmospheric nuclear tests 1945 (US) - 1980 (China)
  - Changes in ionosphere
  - Effects of nuclear explosion on radio propagation
  - Effect on missile
    - Argus
- ARPA (DARPA) founded February 1958 to sponsor and coordinate military (and civilian) research in space.

Ionosphere:

Height 100-1000 km
Density to 10^6 electrons per cm^3
Fully ionized above a few hundred km
Temperature 300K-1000K
rms electron velocity ~ 100 km per sec
thermal Doppler shift ~ 100 kHz (f = 300 MHz)

Need to measure density, temperature, composition, motions, as functions of height and time.

(Later: add heating, non-equilibrium effects)

3. Bill Gordon's Background: Over-the-Horizon Propagtion

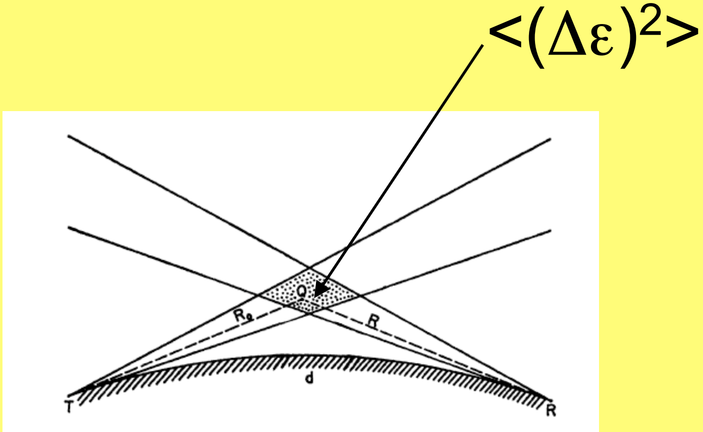


Fig. 1

Booker and Gordon 1950, Proc. IRE, 38, 401

- Troposphere, neutral
- $<(\Delta\varepsilon)^2>$ from turbulence
- Microwaves

The Bill Gordon Idea for Investigating the Topside of the Ionosphere
Early 1958

- Vertical - looking radar
- Radar frequency >> penetration frequency
- Echo from free electrons
- Small crossection, need a powerful system

The problem is the same as the troposphere scattering problem; just replace the fluctuations in dielectric constant for a neutral gas, with the appropriate formula for a plasma.

But what are the fluctuations in dielectric constant (= density) in the plasma?

Bill did not know, no one knew; the theory was only worked out two years later.

1958: What was known:
D. Pines, and D. Bohm, 1952, Phys. Rev., 85, 338.

Fluctuation spectrum for electrons in fully-ionized plasma with stationary (smeared-out) ions.

$$\langle \Delta n_e^2 \rangle \sim \frac{n_e}{1 + (k\,\lambda_D)^{-2}}$$

n_e = electron density
k = wavenumber ~ $1/\lambda$ ~ rf frequency
λ_D = Debye length ~ $(T/n_e)^{1/2}$

Bill Gordon did not know about the Pines & Bohm 1952 paper. He assumed that the electrons were independent, their individual echoes would be incoherent, and the total cross section would be $n_e\sigma$ where σ is the Thomson crossection.

This is the short-wavelength limit of Pines & Bohm. But for $n_e = 10^5$ cm^{-3}, T = 1000K, and f = 300 MHz, λ_D = 0.07 mm, while $\lambda \sim 1$ meter; ie the proposed ionosphere experiment is in the long-wavelength limit.

$$1 + (k\lambda_D)^{-2} \sim 5x10^4$$

and the echo is greatly reduced.

Had Bill known about Pines & Bohm (1952), and had he assumed that the smeared-out positive charge was a reasonable assumption, he would have dropped the incoherent scatter idea.

Even without the latter assumption, there would have been grave doubts about the experiment.

Fortunately, he, and the others involved at the beginning, did not know about P&B. But ARPA did become concerned as the studies progressed.

Kenneth L. Bowles
June 1966

The Narrow Spectrum

- October 1958: K.L. Bowles measures order-of-magnitude echo strength, and a narrow spectrum.
- 1959: Three papers by Bowles with more measurements and a heuristic explanation of the narrow spectrum. It is due to electrostatic effects. Each ion is surrounded by a cloud of electrons; scattering is essentially from the clouds if $\lambda >> \lambda_D$. Spectrum width is controlled by the ion velocity. But total power scattered is sum of the individual scatterings by the electrons.

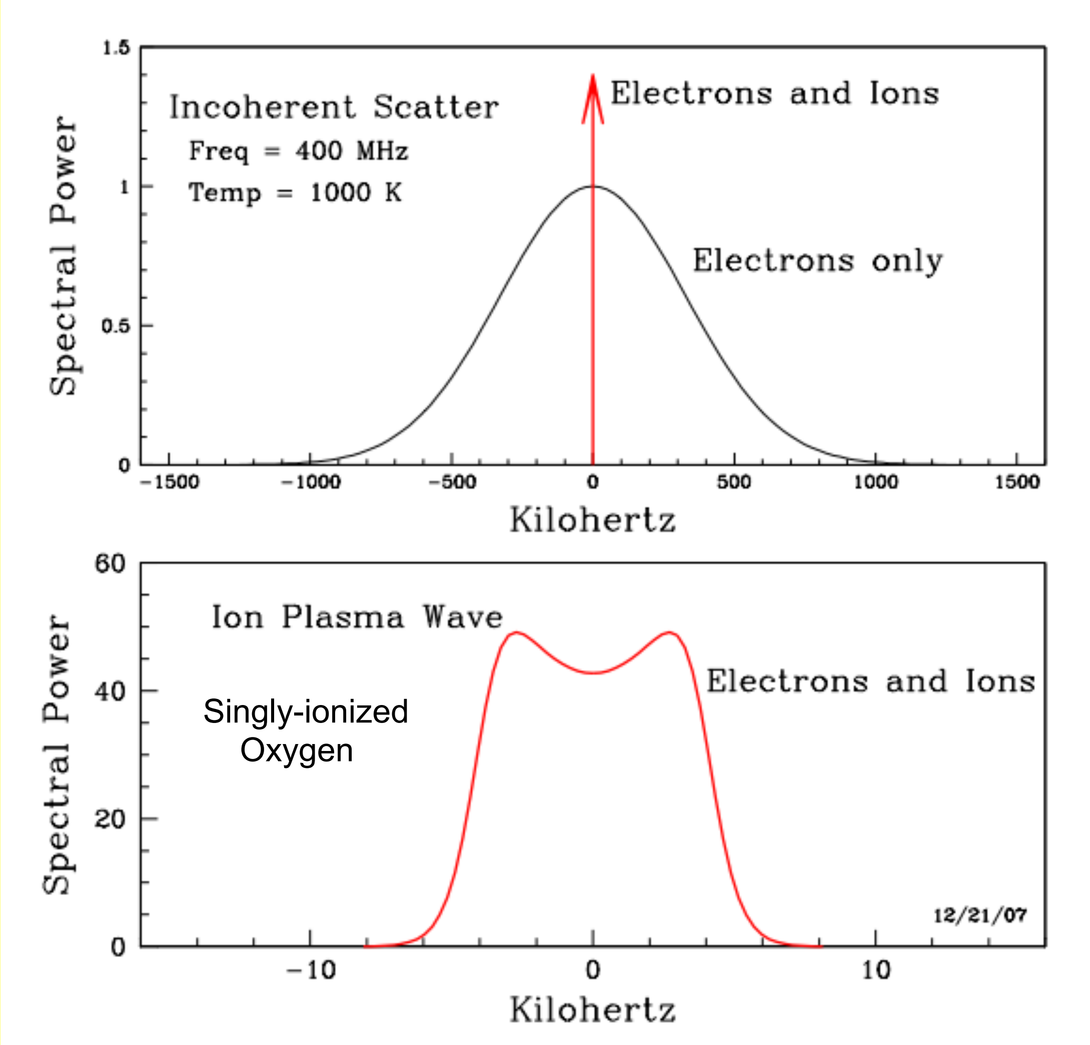
$\lambda_D = kT/(4\pi n_e e^2)$
$^{1/2}$ (Debye length)

Three Theoretical Papers in 1960

1. Fejer, J.A. "Scattering of Radio Waves by an Ionized Gas in Thermal Equilibrium", Can. J. Phys., 38, 1114, 1960.
2. Salpeter, E.E. "Electron Density Fluctuations in a Plasma", Phys. Rev., 120, 1528, 1960.
3. Dougherty, J.P. and Farley, D.T. "A Theory of Incoherent Scattering of Radio Waves by a Plasma", Proc. Roy. Soc. A, 259, 79, 1960.

Result:

Spectrum has a flat-topped shape with width set by ion thermal motions, also two narrow weak lines offset by the plasma frequency.



Spectral Power
1.5
1
0.5
0
Incoherent Scatter
Freq = 400 MHz
Temp = 1000 K
Electrons and Ions
Electrons only
−1500
−1000
−500
0
500
1000
1500
Kilohertz
Spectral Power
60
40
20
0
Ion Plasma Wave
Singly-ionized
Oxygen
Electrons and Ions
12/21/07
−10
0
10
Kilohertz

Detailed Confirmation

- Pineo et al, 1960 “Some Characteristics of Ionospheric Backscatter Observed at 440 Mc/s”, Journal of Geophysical Research, 65, 2629-2633.
- This experiment was done with an 84-foot dish.

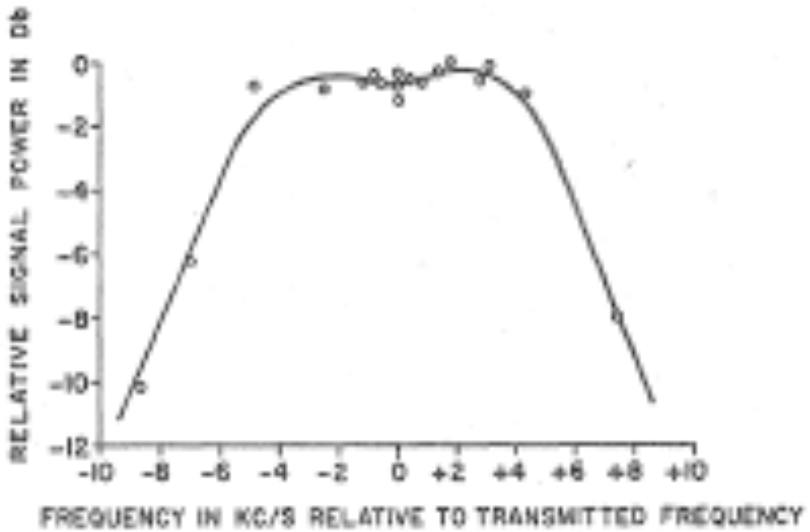


Fig. 5. Frequency spectrum of ionospheric backscatter observed at 440 Mc/s from a height of about 315 km between 1423 and 1515 hr EST, April 22, 1960. Antenna elevation = 45°; antenna azimuth = 281°.

Gordon’s original calculation showed the need for a dish with a diameter of 1000 feet. Eight months later, Bowles’ experiment showed (roughly) that a 100-foot dish could measure the ionospheric density and temperature, the quantities Gordon originally was interested in. Yet, one year later, Cornell signed a contract with AFCRL to design and build a 1000-foot dish.

Why did ARPA (AFCRL) go for the 1000-foot dish,
when a far cheaper 100-footer would have done the primary job?

Conclusions

Gordon did not know about the Pines and Bohm 1952 paper, and used the natural assumption that the electron echoes were incoherent. This led to a 1000-foot dish, which immediately led to the recognition of exciting, valuable experiments in the fields of ionospheric physics, planetary radar, and radio astronomy. At the same time, ARPA was established to coordinate and fund projects that might have military relevance, especially for aerospace or ballistic missiles. The timing was perfect. The possibility of performing the original task with a 100-foot dish was ignored, and the 1000-footer was funded and built.

The fact that Bill did not know about Pines and Bohm was extraordinarily beneficial. If he had, it is hardly likely that a very large dish would have been built at that time.

But

Some mistakes are not beneficial.

Tacoma Narrows

7 November 1940

The End

From over-the-horizon propagtion to ionospheric radar

$<(\Delta\varepsilon)^2>$

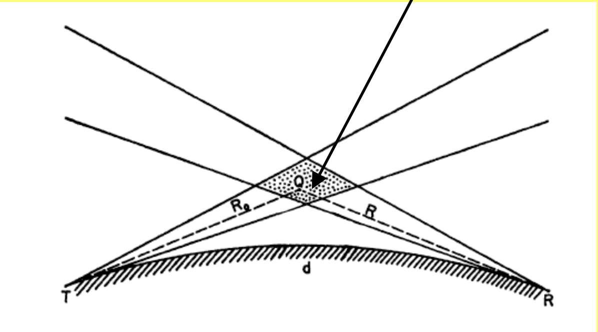
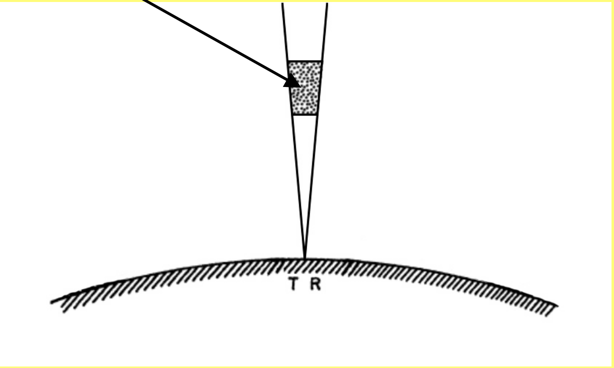


Fig. 1



Booker and Gordon 1950

Troposphere, neutral

Gordon 1958

Ionosphere, ionized

Speculations

What if Bill had known about Pines and Bohm? His studies, given the intense interest in the ionosphere at that time, might well have prompted the theoretical studies that produced the correct spectrum in 1960. In addition, they almost surely would have prompted Bowles or Pineo, or someone else with an 85-foot dish, to make an experimental test of the echo. In either case the intensity and spectrum of the echo would have become known in a few years and the possibilities for ion spectroscopy, non-linear heating, studies of the magnetic field and other phenomena, would be seen.

Perhaps these, and the many planetary and radio astronomy experiments, would have generated a proposal for a 1000-foot dish in any event, in say 10 years.