1-11-62

SCR-163

MASTER

Sandia Corporation

REPRINT

ATMOSPHERIC SIGNALS FROM EXPLOSIONS AND THEIR INTERPRETATION

by

J W Reed

December 9, 1959

Reprinted November 10, 1961

DISCLAIMER

A Talk Delivered at Sandia Corporation

Issued by Sandia Corporation,
a prime contractor to the
United States Atomic Energy Commission

Printed in USA. Price $0.50. Available from the Office of
Technical Services, Department of Commerce
Washington 25, D. C.

SCR-163
PHYSICS
HEALTH AND SAFETY
TID-4500 (16th Ed.)

SANDIA CORPORATION REPRINT

ATMOSPHERIC SIGNALS FROM EXPLOSIONS AND THEIR INTERPRETATION

by

J. W. Reed

December 9, 1959
Reprinted November 10, 1961

LIST OF ILLUSTRATIONS

ATMOSPHERIC SIGNALS FROM EXPLOSIONS AND THEIR INTERPRETATION

Fairly thorough theoretical calculations have been worked out on the blast waves propagated through homogeneous air at constant temperature and pressure. Analysis of blast-wave patterns from high explosives was made both before and during World War II, but only for short ranges where atmospheric inhomogeneities could be ignored. Thus, even before the Trinity test, reasonably accurate blast predictions were available. Shortly after that test, the problems created by atmospheric inhomogeneity were investigated by K. Fuchs, who made certain corrections on the calculations.

During the first atomic blasts, anomalies other than those created by atmospheric inhomogeneity claimed the interest of most of the theoreticians. For example, at Nagasaki, the hills and dales concentrated the energy of the blast and caused various anomalies in the pressure-distance curve and in the damage results. Early Nevada tests of air-burst devices at heights designed to give optimum effects radii were accompanied by a precursor wave which was propagated very rapidly in the radiation-heated surface air. Sandia Corporation has since been involved in several projects intended to document these various surface effects.

In general, these close-in anomalies overshadowed the less spectacular and less militarily significant effects of atmospheric inhomogeneity. One exception to this general rule occurred when one of the first shots in Operation Ranger in 1951 broke a number of windows in Las Vegas, 80 miles from the test site. After this incident, Dr. Cox, who was with Sandia Corporation at the time, was commissioned by the AEC to study the anomalous propagation as a result of atmospheric inhomogeneity and to predict the blast effects at off-site distances.[1] The AEC hoped it could prevent off-site damage in future continental tests. Since then, there has been only one significant recurrence of damaging pressures in Las Vegas: during the Buster-Jangle series the test people did not fully accept our predictions and some windows in Las Vegas were broken.

Figure 1 shows a number of data points and curves of reflected overpressures plotted against range for a nominal 20-kiloton surface burst. Pressures above 10 psi are perhaps more interesting, but it is below 10 psi that atmospheric inhomogeneities become effective. One curve represents the theoretical calculations made at Los Alamos in the IBM Problem M and summarized in SCTM 268-56-51 by Carter Boyles. Operation Upshot-Knothole indicated that most pressures fell below this theoretical curve, and consequently WT-782 presented a new curve as being more accurate. Later, after some of the Pacific test results were available, Military Technical Manual 23-200 (Capabilities of Atomic Weapons) recommended that an even lower curve be used in any military planning that called for pressure-distance curves. Some of the observations we have made of the effects of atmospheric inhomogeneities are also shown on this chart. The curve for Teapot Turk from WT-1155 shows the observed overpressures when a number of Civil Defense houses were damaged by 1 psi at a greater distance than had been anticipated. Plumbbob Franklin results in WT-1431 showed about 0.2 psi at a scaled 100,000 feet, but some of the gauges at this range actually measured up to 0.4 psi, and the pressures broke up a Navy airship which was moored in the area to demonstrate anti-submarine warfare techniques. Both Turk and Franklin shots were in the early morning hours at the Nevada Test Site. On the other hand, the results from Pacific Proving Ground tests show much lower pressures than were predicted on the basis of previous measurements. These lower scaled pressures were duplicated at Nevada Test Site when we shot 1-ton high explosives in the afternoon temperature gradient. There is a difference of more than a factor of two between afternoon shot pressures and early morning inversion shot pressures. An overpressure of 10 psi will cause complete damage to light structures, and even 1 psi will cause extensive damage, as was demonstrated by the Civil Defense house experiment. An overpressure of 0.25 psi will damage light aircraft and break windows. Even a minimum overpressure of 2 millibars will break very large store windows in the cities surrounding the Nevada Test Site.[2]

Figure 2 shows that temperature normally decreases with altitude up to the tropopause at about 35,000 feet (in the Pacific Ocean area it may run to 50,000 feet); above this is a shallow layer with essentially constant temperature; above this stratospheric temperature increases to above 30°C at approximately 150,000 feet in the ozonosphere. Then there is a decrease to approximately 200°K at the mesopause, before the monotonic rise of temperature with height on through the ionosphere and into the outer solar atmosphere. Since sound speed is proportional to the square root of the absolute temperature, the sound speed structure in the atmosphere follows a curve similar to the temperature curve.

General refraction conditions of the atmosphere are shown in Fig. 3. Sound waves are bent toward regions of lower sound velocity or lower temperature and bent away from regions of higher sound velocity or higher temperature. On this chart, where sound velocity decreases with altitude up to 10,000 feet, the rays are bent away from the earth; where the sound speed is constant from 10 to 20,000 feet, the rays are straight lines; and where the sound speed increases with altitude from 20 to 30,000 feet, the rays are bent back toward the earth, giving a blast wave pattern on the ground. At very short ranges, destructive shock pressures sometimes occur under an inversion which would require many times larger yields to obtain in a homogeneous atmosphere.

In the lowest layers of air, as shown in Fig. 4, where temperature varies between night and day, nighttime cooling can cause an inversion where temperature and sound speed increase with height. This graph illustrates such an inversion up to 500 feet. This situation produces a ducting, and as the sound waves hit the ground they are reflected and bounce out. The portion of the blast up to 15 degrees of elevation from the point source is propagated outward with an essentially cylindrical rather than the normal spherical divergence, and thus the pressure-distance curve is much flatter than the normal curves shown in Fig. 1.

The Teapot Turk shot of about 40 kilotons demonstrated inversion effects by giving a 0.6-psi overpressure at 13.7 miles. Normally a 152-kiloton blast would have been needed for this overpressure at that distance. Thus, the inhomogeneous atmosphere enhanced the yield by a factor of nearly four. On shot Franklin a 0.4-psi overpressure was recorded at 3.4 miles from approximately 1/7-kiloton yield. In an isothermal atmosphere, a 1.8 kilotons would have been needed for such an overpressure--13 times the actual yield.

The Army is especially concerned about the problems thus raised, because light aircraft and helicopters are vulnerable to overpressures of 0.25 to 0.5 psi. In a homogeneous atmosphere, this 0.25-psi overpressure would perhaps extend some 12 miles at most from a 20-kiloton blast, but under inversion conditions it might well extend some 25 miles. At the request of DASA and the AEC, our Blast Prediction Unit has recently conducted a series of experimental high-explosive shots under inversion conditions at the Nevada Test Site in an attempt to refine blast prediction techniques.

Though complete results have not been tabulated, some recordings of blast pressure versus altitude have been made on the two 500-foot towers constructed on Yucca Flats for this program. Some views of one tower are shown in Figs. 5, 6, and 7. Each of these towers has nine aspirated shielded thermocouples for measuring temperature, four microbarographs for blast-pressure recording and four Beckman and Whitley wind-speed and wind-direction stations.

From this study of inversions we hope to be able to define two important blast parameters which have remained rather indefinite in the past. The first is the amount of energy which remains in the blast wave as it reaches acoustic level. By definition, at acoustic level there is an adiabatic transmission and hence no further loss of energy. A great deal of the energy of close-in shock strengths is lost heating the air through which the shock wave passes. The shock wave efficiency, that is, the shock wave energy divided by the explosive energy, has still not been clearly defined, as shown in Fig. 8. The LA-1021 curves calculated in 1947 showed efficiency approaching a constant value at low overpressures. The IBM Problem M and the concomitant theoretical calculations, however, gave a different curve, and the Kirkwood-Brinkley high-explosive data give a straight line. Some of our own inversion shots in the past few years were at very low pressure levels, and a curve has been extrapolated from them. This graph is on a log-log scale, so it is obvious that there is still a great range in opinion.

The only cases where wind patterns gave good ray traces in full-scale tests (so that we were able to make a fair estimate of this efficiency from the microbarograph program) were in two Upshot-Knothole shots. From these shots we calculated an efficiency of 3 percent, that is, at acoustic level only 3 percent of the initial blast energy remained in the blast wave. We hope that with more detailed meteorological data from our towers we will be able to get more accurate ray traces and thereby refine this value even further.

The second constant that has not been satisfactorily established is the magnitude of the reflection factor when the blast wave strikes the ground. Air-to-ground density coupling calculations show that 99.7 percent of the incident energy should be reflected, but observations indicate that this is simply not the case. Only in the case of a high-altitude burst with waves striking the ground at nearly vertical incidence do we have a reflection factor so close to one. Calculations from Upshot-Knothole shots indicate a reflection factor of 94.6 percent. Some collections of inversion data studied by Dr. Cox in the past, however, have indicated reflection factors as low as 60 to 75 percent. This may seem unreasonably low, but the older concepts of inversion depths were based on measurements from rapidly rising radiosonde balloons with appreciable time-temperature lags. Our tower data indicate that these formerly calculated inversion depths were ten to twenty times too high. Thus, our ray-tracing calculations in the past have shown rays striking only 1/10 to 1/20 as frequently as they actually struck.

In further experimentation, we fired some high-explosive charges in the afternoon at the Nevada Site in order to simulate the anomalous effects which have been found in Pacific Proving Ground operations. In the Pacific, surface temperatures remain nearly constant day and night; sound speed therefore remains constant and temperature always decreases with altitude. A ray plot from a point source will show that it is always carried away from the ground. A blast measurement made along the ground--the way in which most data thus far collected have been measured--will show a diffraction from the sound front down to the ground. This situation will therefore give a much faster decrease in blast pressure with distance than can be expected from calculated curves for blasts in a homogeneous atmosphere. The high-explosive shots at Nevada indicated that in midday shots pressures decreased inversely with distance squared rather than in proportion to distance, as we would normally expect in a homogeneous atmosphere. We hope to be able to evaluate the diffraction coefficients which are involved in bleeding this wave down to the ground under a gradient situation.

At higher altitudes, sound speed and temperature decrease with height. Temperature decreases about 2°C per 1000 feet, and this in turn causes a decrease in sound speed of about 4 feet per second per 1000 feet. On the other hand, there are often high winds aloft which form a sound duct by overcoming the decrease of sound speed with the increase in altitude. Wind speeds in excess of about 50 knots at 20,000 feet or in excess of 75 knots at

30,000 feet will duct the sound back to the earth again. Figure 9 shows a case where a wind of 102 knots at 30,000 feet ducted the noise back to earth at about 150,000 feet or about 30 miles from the source. These are not unreasonable speeds for winds at high altitudes. In jet streams over the United States, winds frequently attain speeds of 100 knots in winter and sometimes go as high as 300 knots.

It was as a result of this phenomenon that windows were broken in Las Vegas by sound waves on the second bounce. When there is a decrease in sound velocity as height increases, capped by an increase in sound velocity with height as a result of the wind, the rays are turned over and focused by the atmosphere. Note that the lowest elevated ray lands at a distance of 180,000 feet, and successively higher elevated initial rays land at shorter distances until the minimum is reached. Angles emitted above the 20 degrees shown here land at a distance beyond the minimum. In the overpressure prediction equation, overpressure is equal to the proportionality constant times the cube root of the yield over the square root of range times the square root of $dR/d\theta$. As $dR/d\theta$ approaches zero, the equation predicts an infinite pressure at the focal point, here shown to be 30 miles from the test site, and it is still infinite at two cycles, or 60 miles away. Actually, however, this will not be true since atmospheric ripples, turbulence, and similar variations will tend to scatter the rays. Furthermore, with such tremendous concentrations of energy there will be a tendency for the energy to be diffracted away from a focus. But there is as yet no quantitative data which shows how far short of infinity these focal-point pressures might be.

In January 1960, we plan to make further measurements at the Nevada Test Site using 1-ton high-explosive shots. This time there will be a jet stream aloft, and we will have 17 microbarograph stations at 1-mile intervals down the road to Las Vegas around calculated focal points. Since we plan to have 27 shots, we will have 460 point-pressure measurements within 10 miles of calculated focal points. We expect to be able to tell from these calculations what peak pressures can occur and what pressure-distance gradients will be on the curve.

Under these conditions, blasting has been known to produce damaging pressures at great distances. On both occasions of window damage in Las Vegas from test blasts, there were high northwesterly winds aloft. Phenomena similar to this window-breaking have been reported, though perhaps they are a little more difficult to believe. In Albuquerque, in 1955, the Army detonated a 100-pound charge at Sandia Base which caused a disturbance in the northwest section of town. Although the area was 7 miles away from the blast, one woman claimed that her child was thrown out of bed. A ray-tracing calculation based on available weather data showed a focus near her neighborhood. In 1956, a sled test in Sandia Area III gave a supersonic boom which supposedly caused damage to houses near the Fair Grounds. Again, using Weather Bureau data for upper air temperatures and winds, we calculated a focus right in that neighborhood. Last year British atomic researches reported that once when they exploded 5000 pounds of high explosives, they crushed the roof of an historic church 20 miles from the blast. If these results develop from smaller explosive charges, we can imagine what might easily happen with full-scale atomic tests.

This ducting and focusing situation confronted us the last day of Operation Hardtack, Phase II--the day before the current moratorium began. Residents of Indian Springs, some 28 miles down the road from the test site, thought the AEC was ending its testing in grand style because every hour a loud rumble rolled through town. It turned out that these rumbles were coming from 1-ton high-explosive charges, which we were using to verify wind and blast predictions. The scheduled full-scale shot Adams was to give a nominal 20-kiloton yield. This would have produced as much as 0.6-psi overpressure in Indian Springs and over 3 millibars' overpressure in Las Vegas--enough to cause considerable damage. The shot therefore had to be cancelled for fear of possible off-site damage, and also because of some uncertainties in our predictions. It was at this time that the AEC requested that we begin our current research program to refine blast prediction techniques in order to be able to make more confident forecasts than in the past.

Actually, however, the best data on focusing we have obtained thus far were gathered on the day of the Adams cancellation. During one blast, 1 ton of high explosives produced a 460-microbar signal in Indian Springs. The zone of silence was within that circumference. We had another microbarograph recording of 20 microbars at 5 miles shorter range, where we could scarcely find the signal in the ambient wind noise. Thus, 5 miles further from the test site, the overpressure increased by a factor of 23.

Sound speed decreases with height up to the tropopause; there is then an increase in sound speed with height up to 150,000 feet, the peak of the ozonosphere region. Consider the scale in Fig. 9 expanded by a factor of 5, and we will have a third sound channel pattern. It will be similar to the one we just discussed, except that now the sound waves will land at five times the distance or about 150 miles. This phenomenon so far has created very little damage out at the 100- to 150-mile range, but nonetheless some interesting situations have arisen. Figure 10 illustrates the peak-to-peak pressure data recorded at St. George, Utah, 135 miles from Nevada Test Site, from all of the full-scale continental tests. Pressures are all scaled at 20 kilotons though many shots were much smaller. These pressures show a marked seasonal cycle, higher for the winter than the summer. Summer low pressures obviously result from the seasonal wind change which occurs at the ozonosphere levels of 100 to 150,000 feet. In the winter, when the wind blows from west to east, St. George is directly downwind from the Nevada Test Site. In summer it is upwind and therefore gets very low pressures. Normally one would expect pressure amplitudes to scale by the cube root of yield, but by comparing various full-scale yields with data from our 1-ton explosions, we have found that the pressure amplitudes scale best by the square root of the yield. Thus far the only explanation for this phenomenon is that because larger yields produce longer duration pulses, there is therefore more chance of constructive sound wave interference at larger yields. This constructive interference may give larger pressures which then scale as $W^{1/2}$.

In Operation Plowshare programs, we will certainly be concerned with ozonosphere propagation since we may be blasting with multimegaton yields within 200 to 300 miles of large cities. With scaling up to 2 megatons from 20 kilotons, all of the amplitudes in Fig. 10 would have to be increased by a factor of 10. The 2-millibar overpressure minimum damaging level would correspond to a 4-millibar peak-to-peak pressure, but maximum amplitudes shown would give a case of 5-millibar pressures being scaled up to 50-millibar pressures, which would be almost 1 psi at 135 miles for 2 megatons.

However, in the Plowshare program explosives will be mostly buried at depths giving optimum cratering effects. This we believe will reduce the over-all amplitudes by a factor of 10 and bring the pressure amplitude back down to 5 instead of 50 millibars. Thus, under Plowshare conditions, 2 megatons would give essentially the same type of pressure pattern as is plotted for St. George from 20 kilotons. If 20-megaton blasts were fired, amplitudes would increase by the square root of 10 or by a factor of 3, and we would have quite a few blast problems, at least downwind from any large Plowshare shots.

Until the present we have not been able to obtain weather data from ozonosphere altitudes, and we have thus been forced to predict blast effects on the basis of data obtained from 1-ton high-explosive shots, fired 1 or 2 hours before full-scale explosions. Recently, however, we have developed a capability for shooting rockets up to the ozonosphere and even higher. By ejecting reflecting chaff or balloons from these rockets, we can track the winds at these altitudes by radar. In preparation for the Plowshare program this coming March, we will experiment with some 40,000-pound explosions in cratering shots. These will be recorded on microbarographs around the St. George area. We will also make some rocket wind soundings at the Tonopah Test Range in order to obtain the upper air data necessary to calculate ray paths and make blast predictions, which we hope will then be verified by microbarograph recordings.

Wave amplitudes as small as 40 microbars are quite easily detected, provided that the surface wind speed is low enough not to interfere with sound detection equipment. If sound amplitude decreases approximately inversely with the distance, then a 1-millibar signal at St. George should still be detectable at 25 times the distance or 3000 miles. With a network of stations and with more sophisticated techniques for separating signals from noise, it should be possible to detect amplitudes even lower than this.

In the past, recordings of ozonosphere signals have been used for soundings of the upper atmosphere in much the same way that seismograph geophysical explorations are used to understand the earth underground. With two microbarograph stations we are able to establish the incidence angle of a sound ray. We know the location of our station and we can record the time of arrival of the sound ray. From the signal speed across a microbarograph pair we can calculate by Snell's law the characteristic or peak velocity of the ray at the top of its path. An empirical scheme has been developed whereby from these variables we can establish the height of the turnover point.[3] If we apply this calculation to the many signals observed at ozonosphere recording stations, we are able to get many pairs of sound velocity and height data points up through 150,000 feet. Each station will give several points through which we can draw a curve of sound velocity versus altitude. We have made such recordings in a ring of six stations around the Nevada Test Site. This gives six directed sound velocity height points at a constant height--so that six velocities can be plotted as functions of heading. These six data points will approximate a sine curve. When we fit a sine wave to the data--the mean value represents a sound speed "c"--the phase shift represents wind direction, and the half amplitude represents wind speed. This is the type of resolution we have used on all our past ozonosphere sound recordings. The wind speeds and directions we have calculated by this method agree with data established through other types of measurement of ozonosphere upper winds. On the other hand, our measurements of sound speeds and temperatures differ considerably from measurements made by other methods.

Figure 11 shows the temperature structure of the upper atmosphere. In 1946, really the first period when there was any genuine need to know about the upper atmosphere, the NACA interpretation was that above 100,000 feet there was a continuous increase in temperature with height. This interpretation was based mainly on a few old sound-recording data points. By 1953, enough data had been collected from rocket firings for the Rocket Panel to establish another interpretation of the upper atmosphere. Starting with the 1953 Nevada operations, we began using acoustic sounding techniques and obtained a third temperature height curve (NTS)--one which was 50°C warmer than the Rocket Panel peak. By 1955, with more refined instrumentation, we were able to get more accurate results, and we established a new curve for springtime at the Nevada Test Site. However, in Operation Plumbbob, at the same site in summer, the average curve was about 10°C warmer.

There have been relatively few tests in the Pacific that have been recorded well enough to make such an analysis, but six shots at Bikini during the summers of the Redwing and Hardtack operations gave an average temperature curve for this area. So there has been a discrepancy concerning upper-atmosphere temperatures which did not bother anyone very much until the last year or so. A year ago, AFCRC got some results from Russian rocket measurements. Their measurement techniques were quite similar to those used to obtain the Rocket Panel data, but the Russian curve was dissimilar. In my opinion, the Russian information tended to support the high acoustic temperatures we recorded in this altitude region. The latest standard for the upper atmosphere is ARDC (1959), which suggests lower temperatures at the mesopause level and higher temperatures at the peak of the ozonosphere.

If we consider the old ARDC atmosphere to be 20 percent too low in absolute temperature all the way through the ionosphere--which is what our acoustic data would indicate--densities calculated on this basis would agree with results from density measurements determined by drag and deceleration effects on satellite orbits.[4] With the increased number of satellites in orbit, a number of density data points are now available (see Fig. 12). The acoustic density-height model is based on a 20-percent increase in absolute temperatures from the ARDC (1956) model atmosphere. Old ARDC densities were quite a bit too low. RAND Corporation rather arbitrarily attempted to fit the satellite densities with a curve, starting at 100 kilometers. On the other hand, NOL and some other measurements on the attenuation of solar X-radiation in the region from 50 to 100 kilometers have given temperatures which are even lower than the ARDC model.

The main problem in these interpretations has been to explain the upwind propagation of ozonosphere sound using the low temperatures which have been shown thus far by standard atmosphere tabulations at the 150,000-foot level. The sounds which we have recorded require that temperatures at turnover altitude be high enough to overcome the effects of wind, so they have to be considerably higher than surface temperatures. Rocket Panel and the ARDC atmospheres both show them lower or just barely equal to surface temperature at the peak.

One possible explanation for this upwind sound recording is that the signals are actually caused by a diffracted wave. That is, since the temperature is not high enough to turn it back, the wave itself is not really turned over by refraction toward the earth; rather, some of its energy is diffracted to the ground and this is what we are recording. But, if this were the case, sound amplitude would always decrease with distance, and our experience has been that, even with upwind sounds, most of the time the amplitudes at Boulder City (about 90 miles from test shots in Nevada) are greater than those at Las Vegas (in the same direction but 70 miles from the shots). This would seem to refute the diffraction argument.

Another explanation, somewhat more attractive, is that the blast wave which starts out as a shock wave--strong shocks travel supersonically--slows down to acoustic travel. Then, in the extremely low ambient pressures near the top of its path, it again becomes a shock wave, traveling supersonically, so that part of the wave is bent back over to the ground. This supersonic component can be calculated from the pressures at St. George. There we recorded a maximum peak-to-peak of 5 millibars, which would imply about 2.5 millibars' overpressure or finite amplitude effect. Since the ambient pressure at St. George was about 900 millibars, the pressure increase was about 3 parts per 1000. Calculating back by 1/R in pressure, this would become 5 parts per 1000 at the path top. The result is that sound velocity "c" would be multiplied by 1.0025 to give the shock velocity at the turnover altitude. This is only 2.5 feet per second and would explain only 10°C of this discrepancy, hardly enough to satisfy the difficulty.

The only real explanation we have for the discrepancy is simply that the Rocket Panel data is wrong, and this is not easy for a great many people to accept. We obviously need to continue experiments to determine more accurately just what upper atmosphere conditions are like.

We have made observations at Eniwetok of this reshocked wave effect. A set pattern is generally observed on Eniwetok whenever there is a multimegaton blast on Bikini. First there is a slow pressure oscillation, the gravity oscillation of the atmosphere. Then rumbles come in, the ozonosphere ducted signals. Next, there are sharp cracks and pops coming in at very steep incidence angles to the ground. They have apparently traveled up 300,000 to 500,000 feet, where they became strongly shocked and turned back to the ground. While these noises are quite loud, their actual amplitude is not usually very large, not as large as the amplitudes of the ozonosphere signals.

In Nevada tests we have also made some recordings of waves reshocked from the ionosphere. They were not reshocked much because they were recorded quite a bit later than the ozonosphere signals, but they do come in very steep and appear to have gone up to around 300,000 to 400,000 feet. We have only observed these upwind from the prevailing ozonosphere wind direction. Where we have the strongest ozonosphere signals, no ionosphere signals are recorded; with weak ozonosphere signals, we get stronger ionosphere signals. This verifies the reversal of wind direction which others have felt existed between 150,000 and 300,000 feet.

Blast propagated in the ionosphere added much to the spectacular display of Teak shot at Johnson Island last year. The huge red glowing ball, which was readily visible 800 miles away at Honolulu, threatened to engulf our observer 500 miles away at French Frigate Shoals. This was at first thought to be an electrical propagation, but through some careful blast scaling, we have been able to show that it was the shock wave compressing air to glowing temperatures while moving through the very high atmosphere near and above 1,000,000 feet.

Figure 13 is a first approximation of acoustic ray paths from Teak. Blast yield was calculated from pressures observed near ground zero at Johnston Island. With this yield and modified Sach's scaling techniques for ambient pressures and distances, we calculated overpressures and shock speeds along these ray paths. The calculated travel time along the ray striking near French Frigate Shoals differed from the recorded arrival time by only 2 percent. The same scaling laws were used to show that shock strengths along nearly the entire ray path were of the values expected 50 to 100 feet from a 1-kiloton burst at sea level. These ranges are well within the 165-foot radius of a 1-kiloton fireball. Thus, the shock was strong enough to compress the ambient air up to glowing temperatures, and the visible glowing shock front continued well beyond 500 miles.

We now believe we are able to predict the blast phenomenology of high-altitude shots by using modified Sach's scaling, just as we have done in the past for sea-level bursts. With some extrapolation to the height-of-burst versus blast-yield curve, we should be able to make order-of-magnitude predictions of blast effects from high-altitude shots up to heights of burst of 1,000,000 feet.

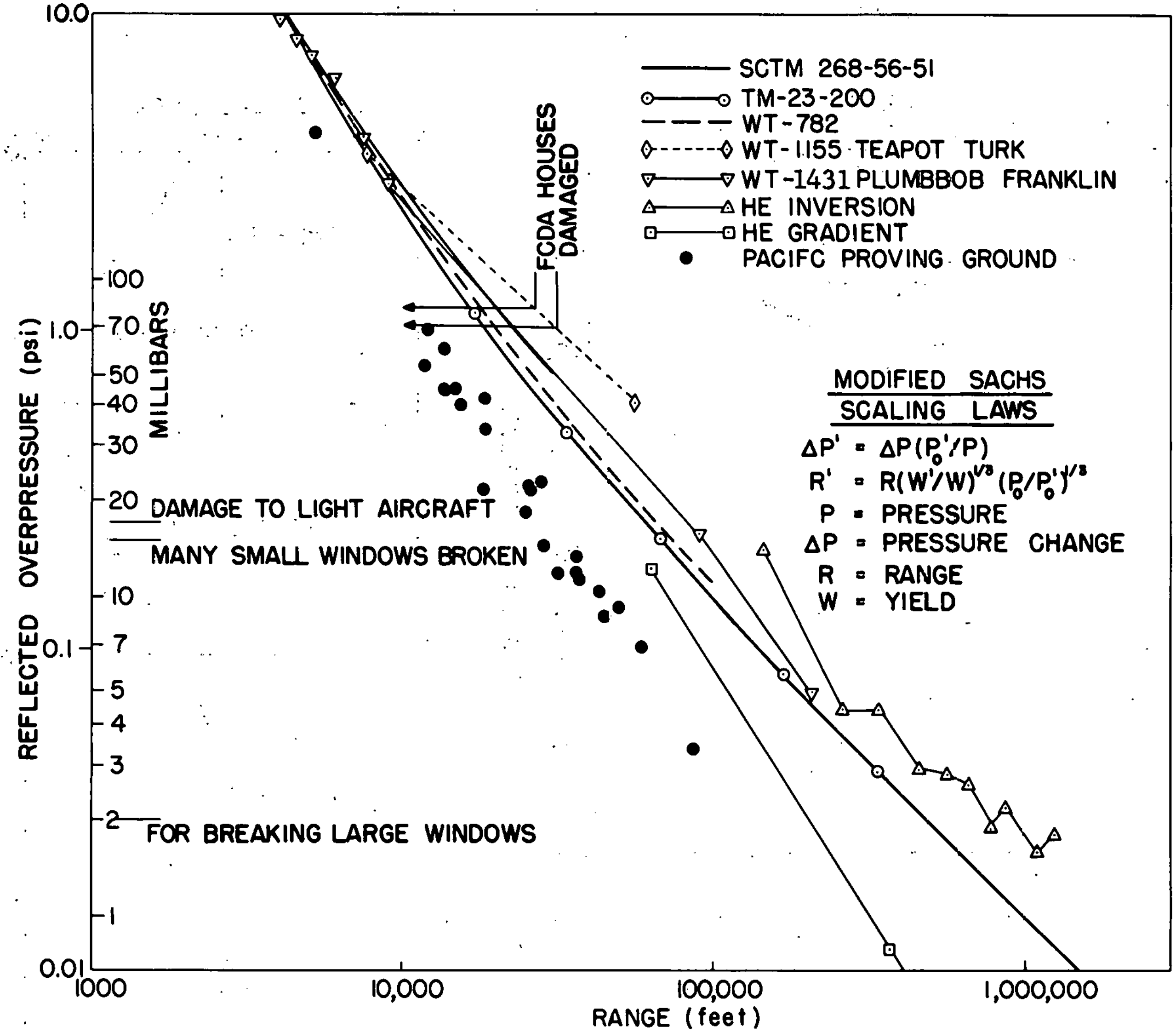


Fig. 1 -- Ground-reflected overpressure, 20-kt surface burst, sea level

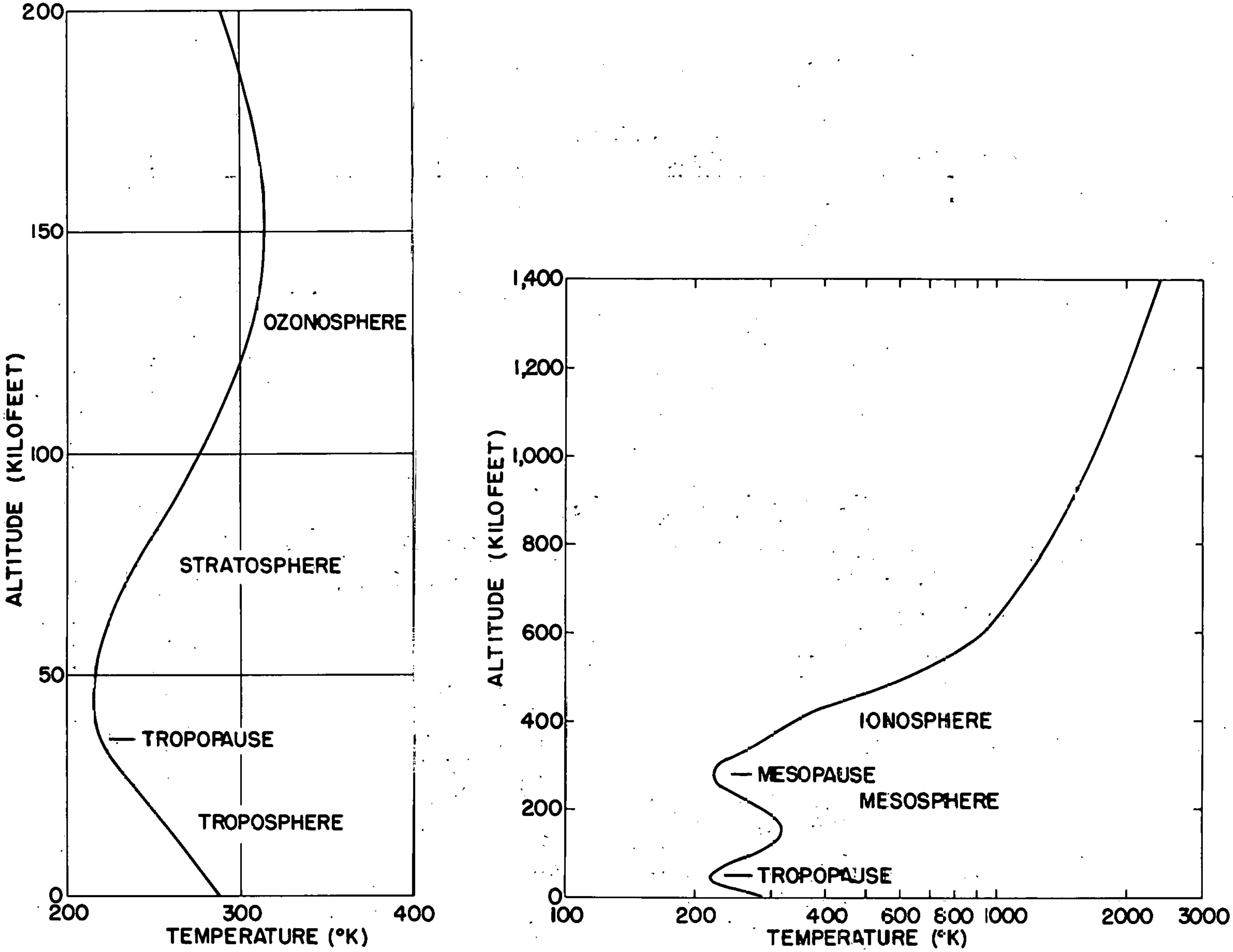


Fig. 2 -- Recommended atmospheric temperature model

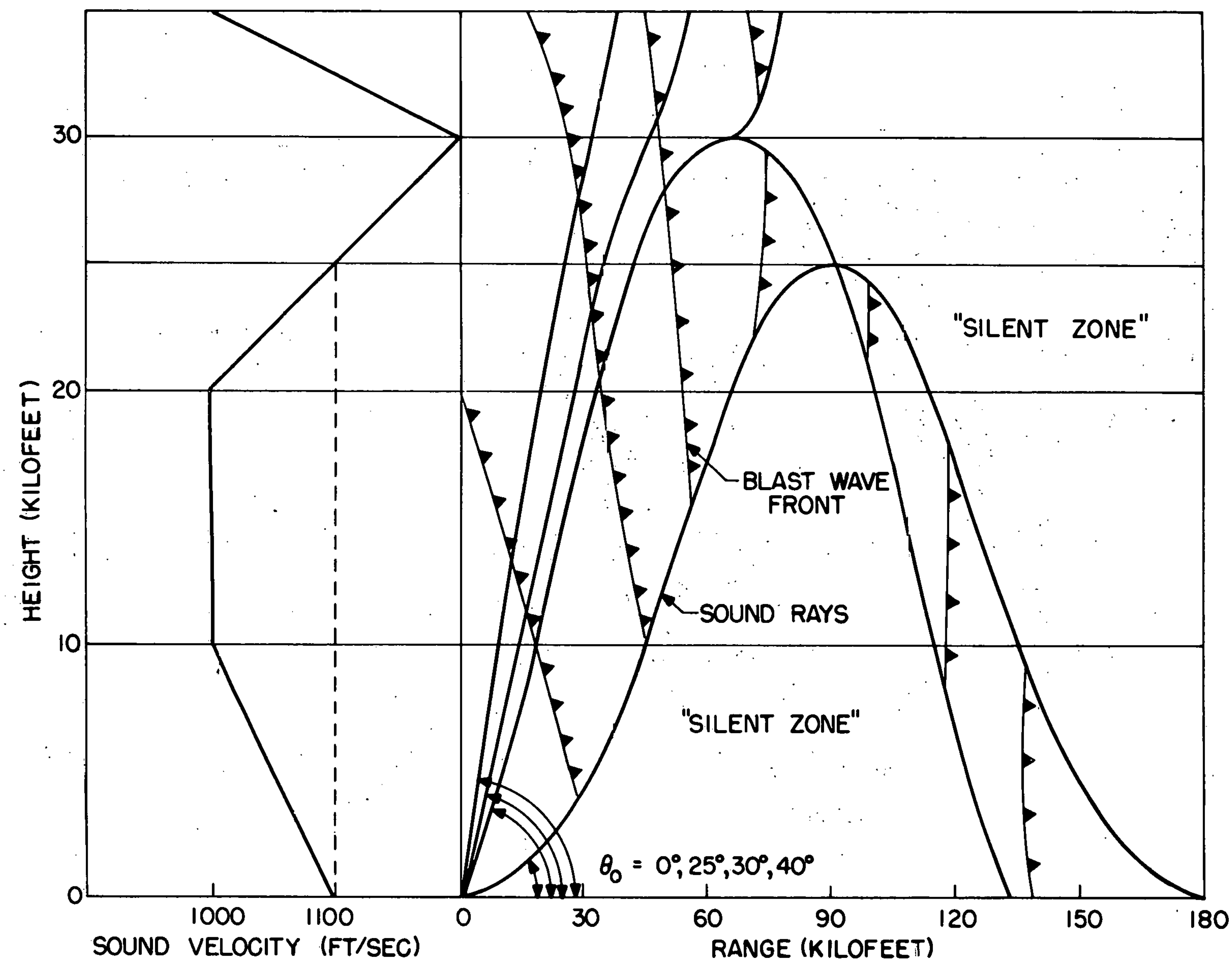


Fig. 3 -- Atmospheric sound paths

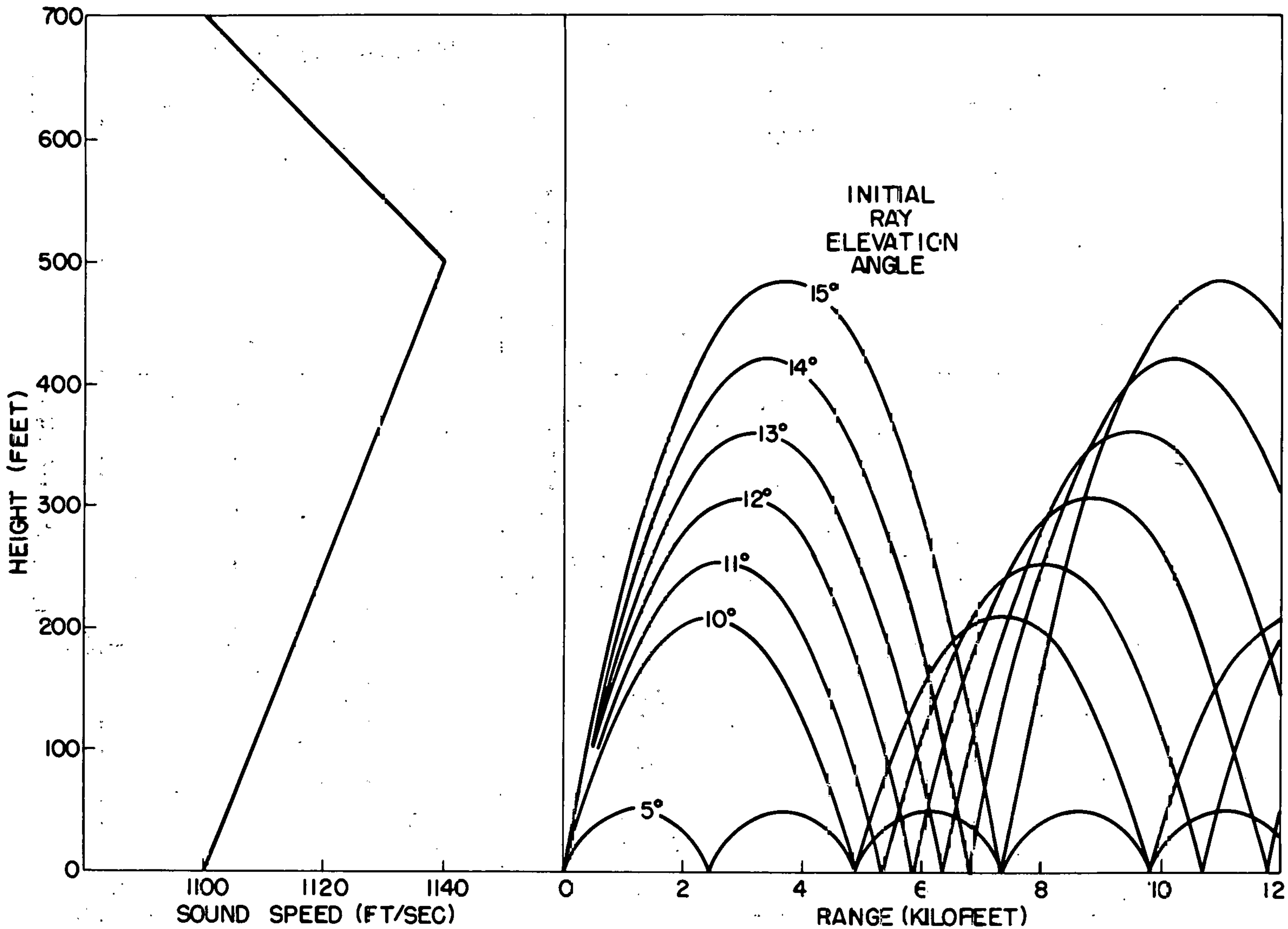


Fig. 4 -- Inversion duct sound rays

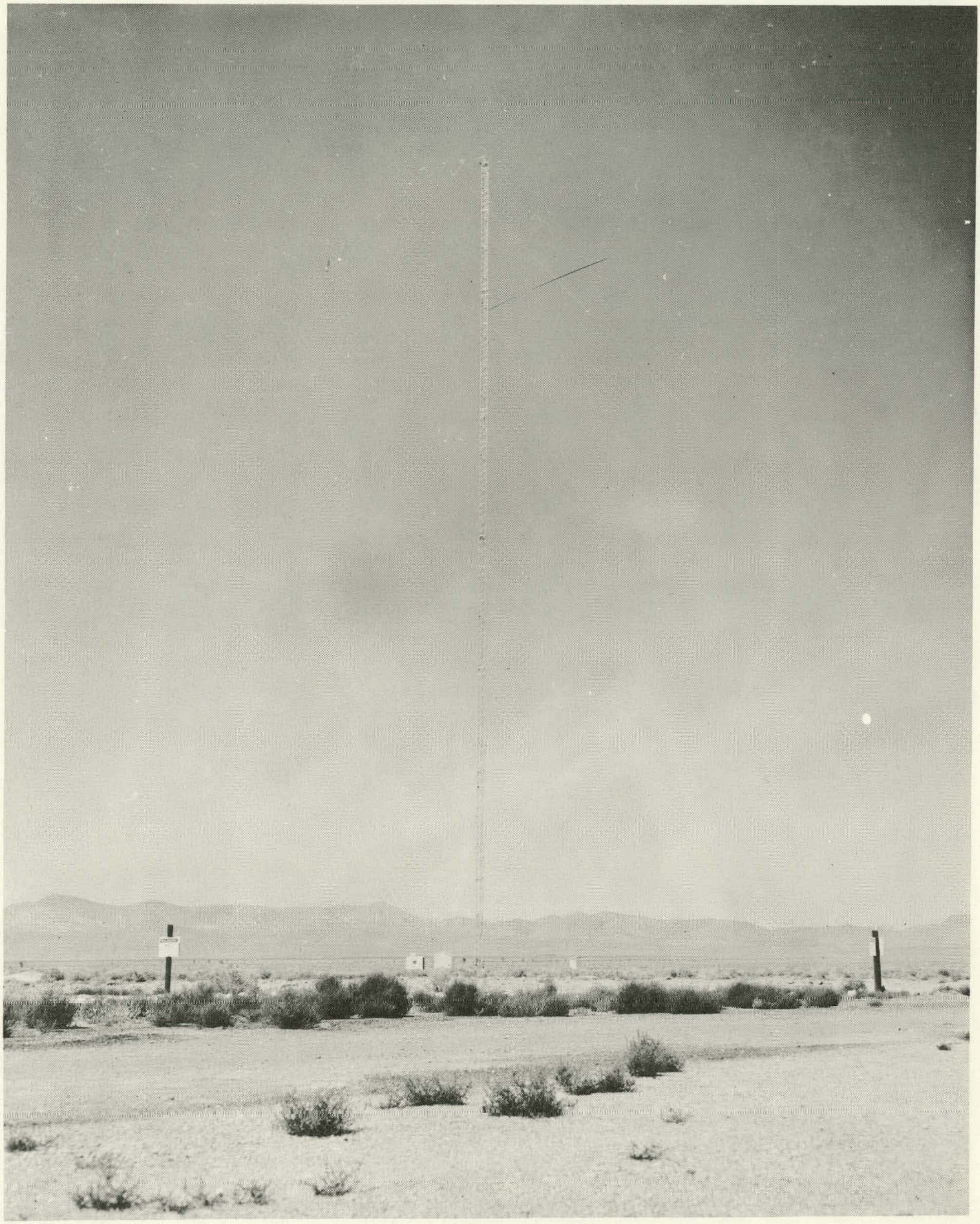


Fig. 5 -- Meteorological observation tower at Yucca Flats

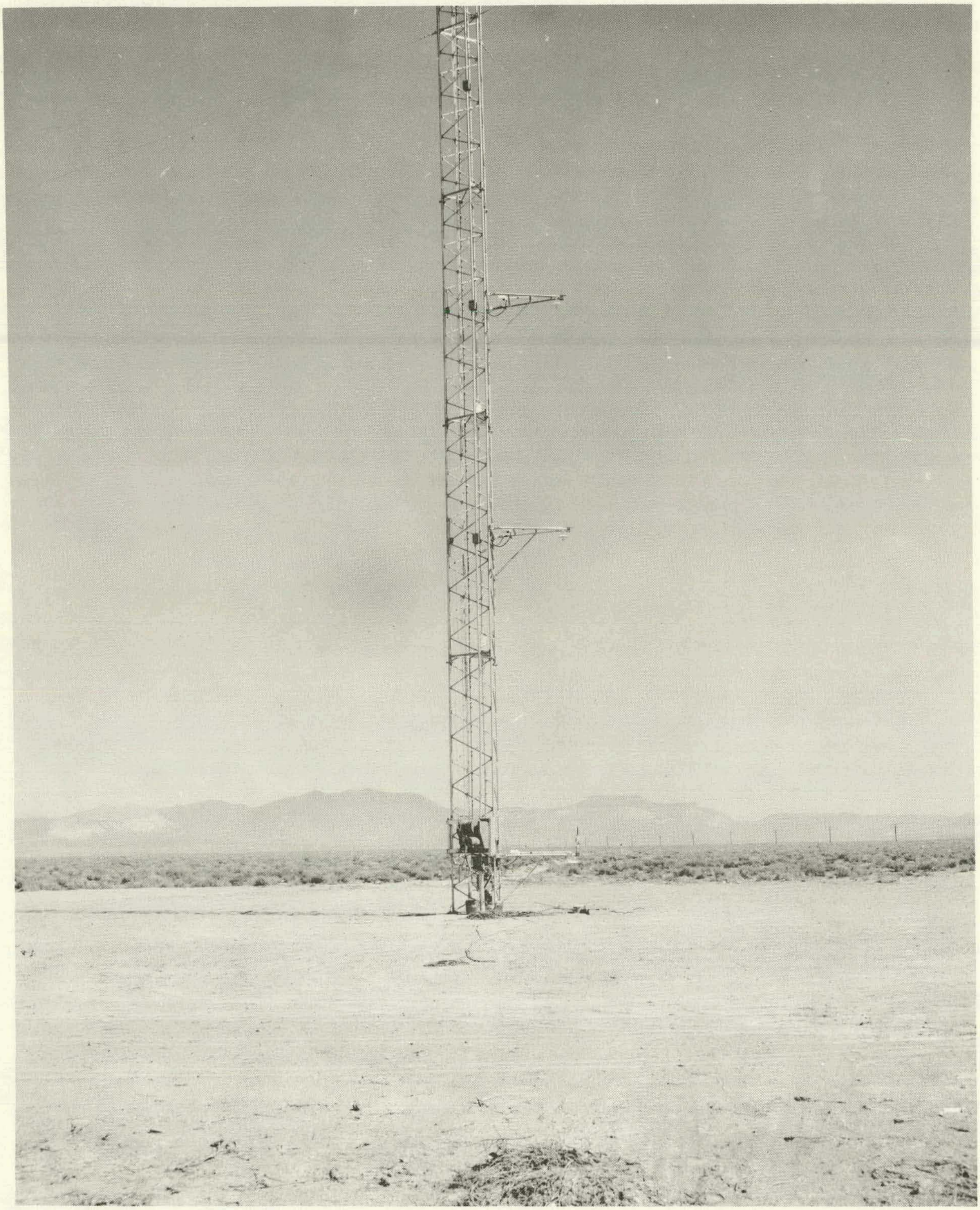


Fig. 6 -- Meteorological observation tower at Yucca Flats

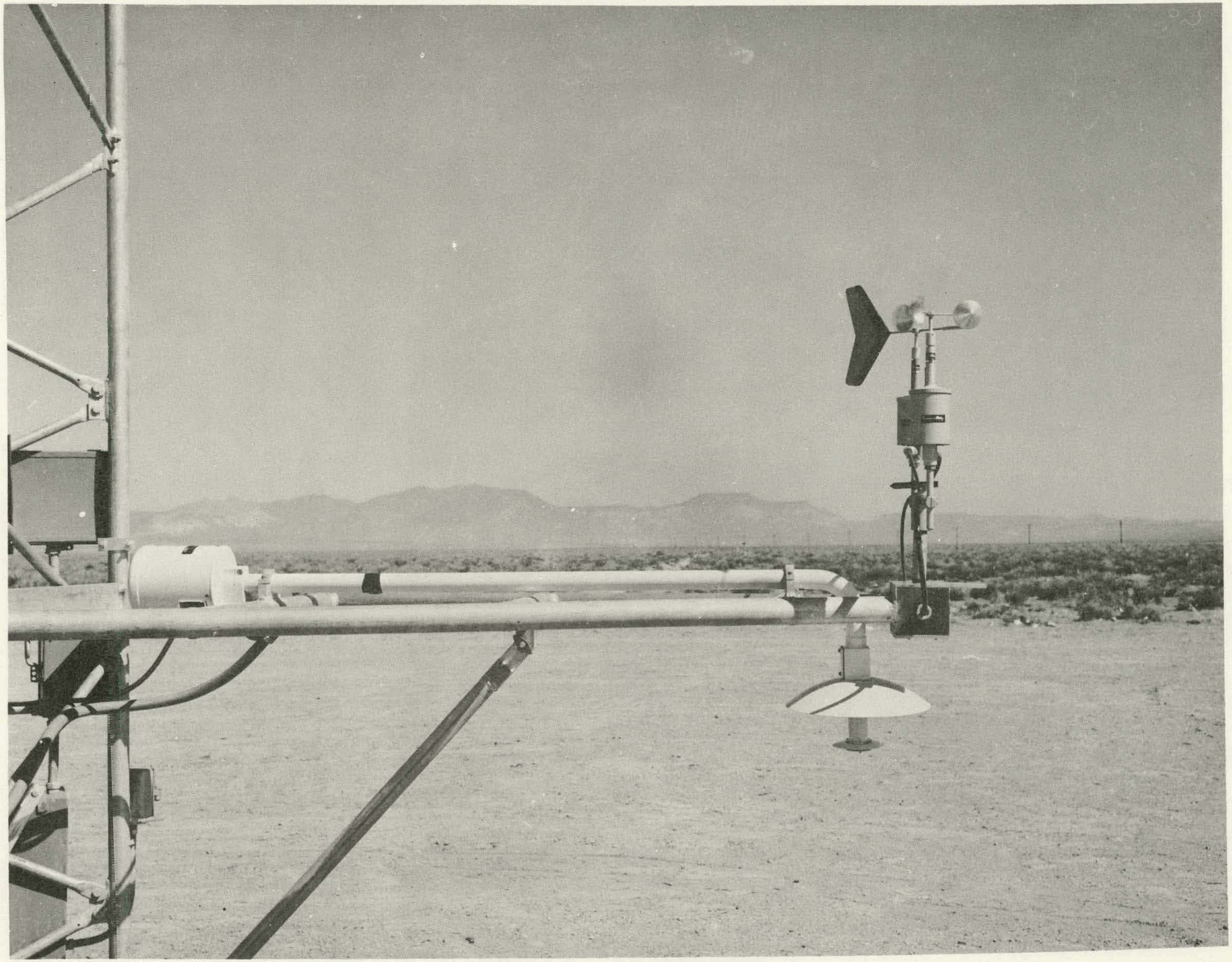


Fig. 7 -- Wind and temperature sensor

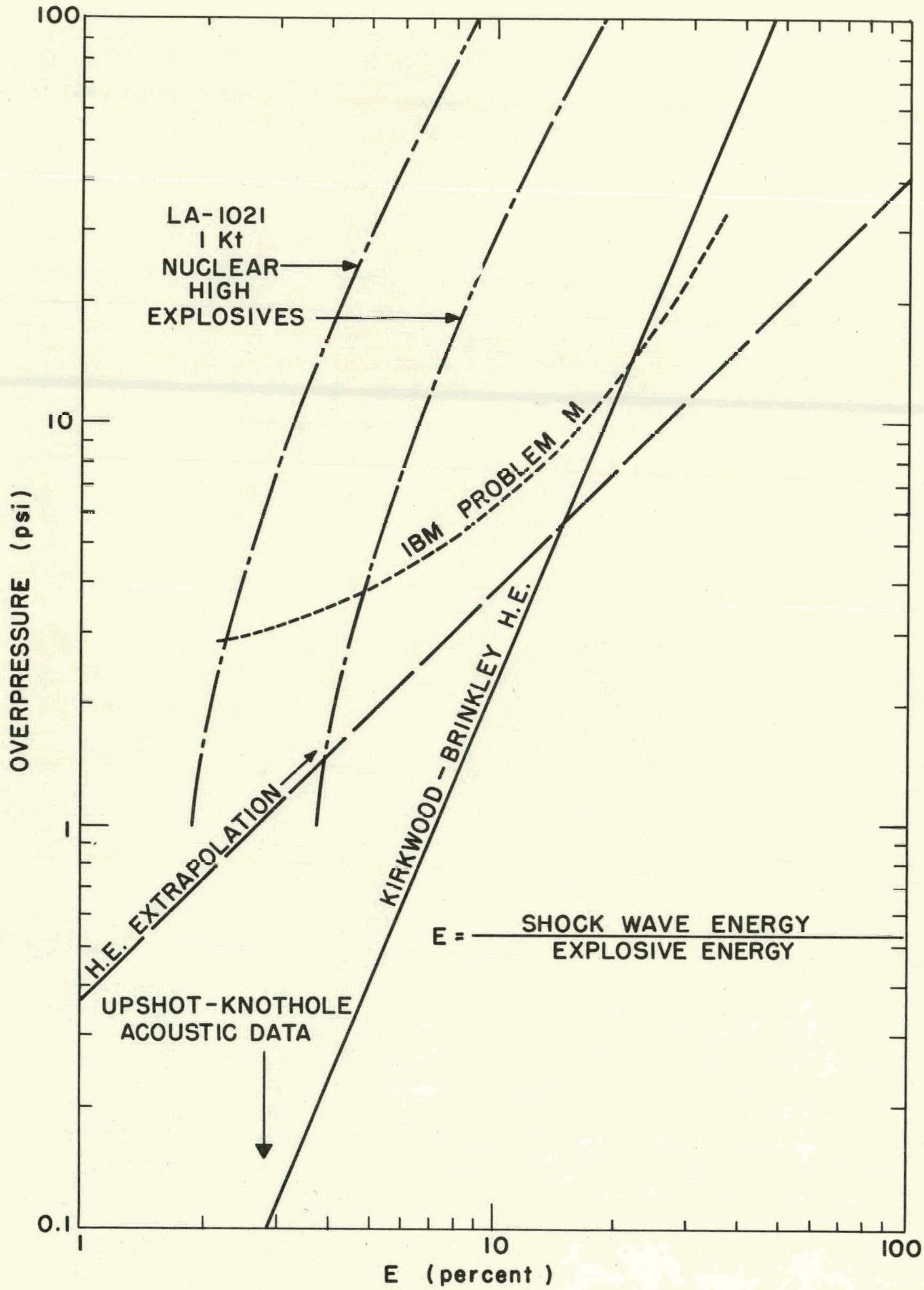
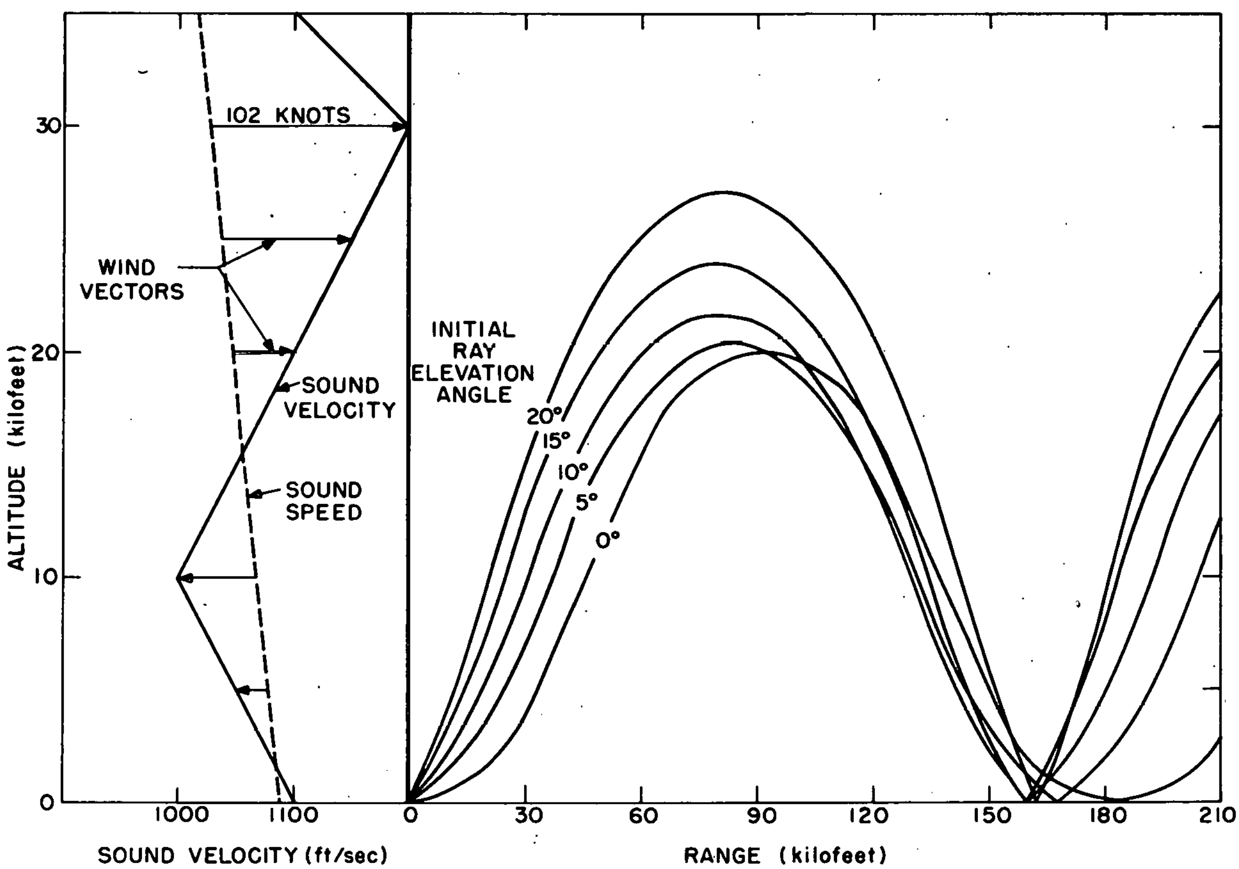
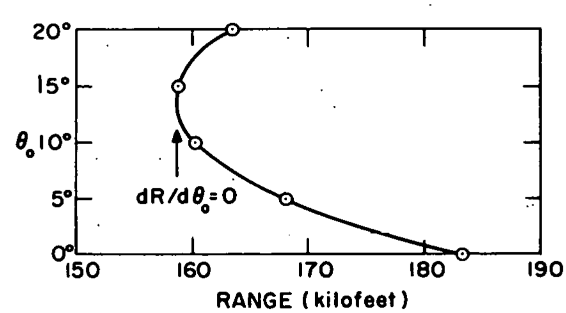


Fig. 8 -- Shock wave energy





$$\text{OVERPRESSURE} = \frac{(\text{CONSTANT})(\text{YIELD})^{1/3}}{(\text{RANGE})^{1/2}\ (dR/d\theta)^{1/2}}$$

Fig. 9 -- Sound duct focus

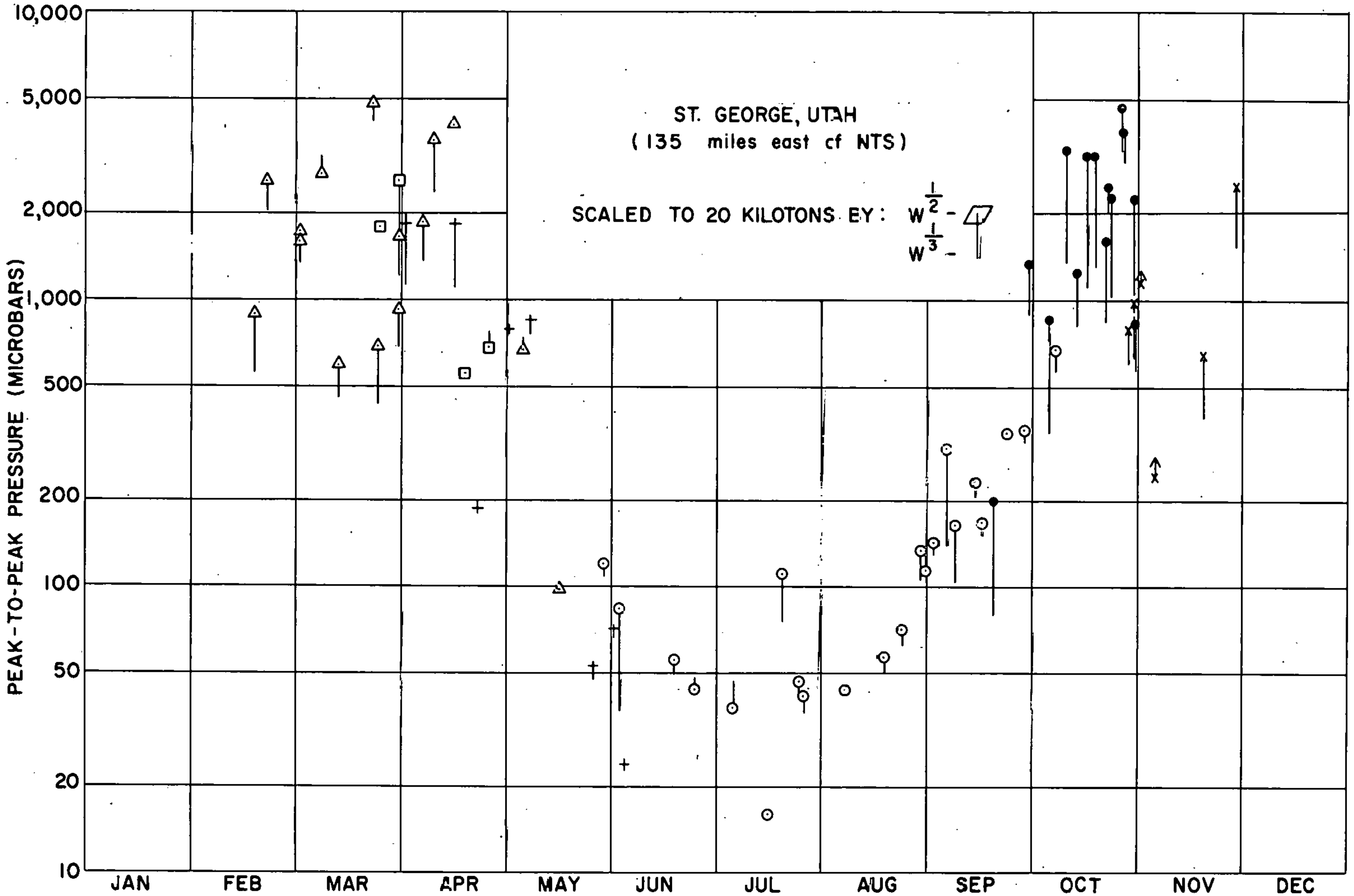


Fig. 10 -- Annual march of ozonosphere blast pressure amplitudes

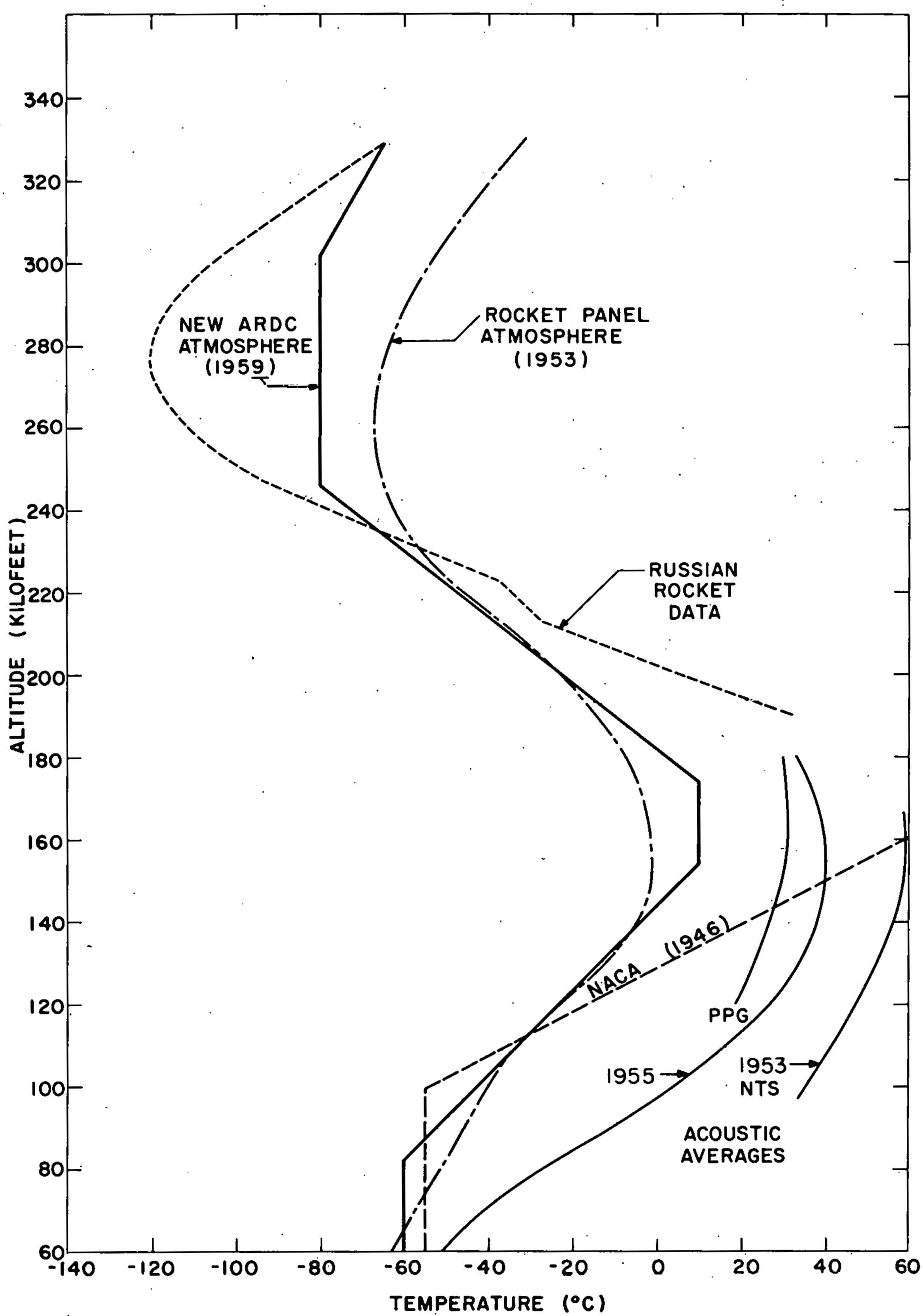


Fig. 11 -- Upper air data comparisons

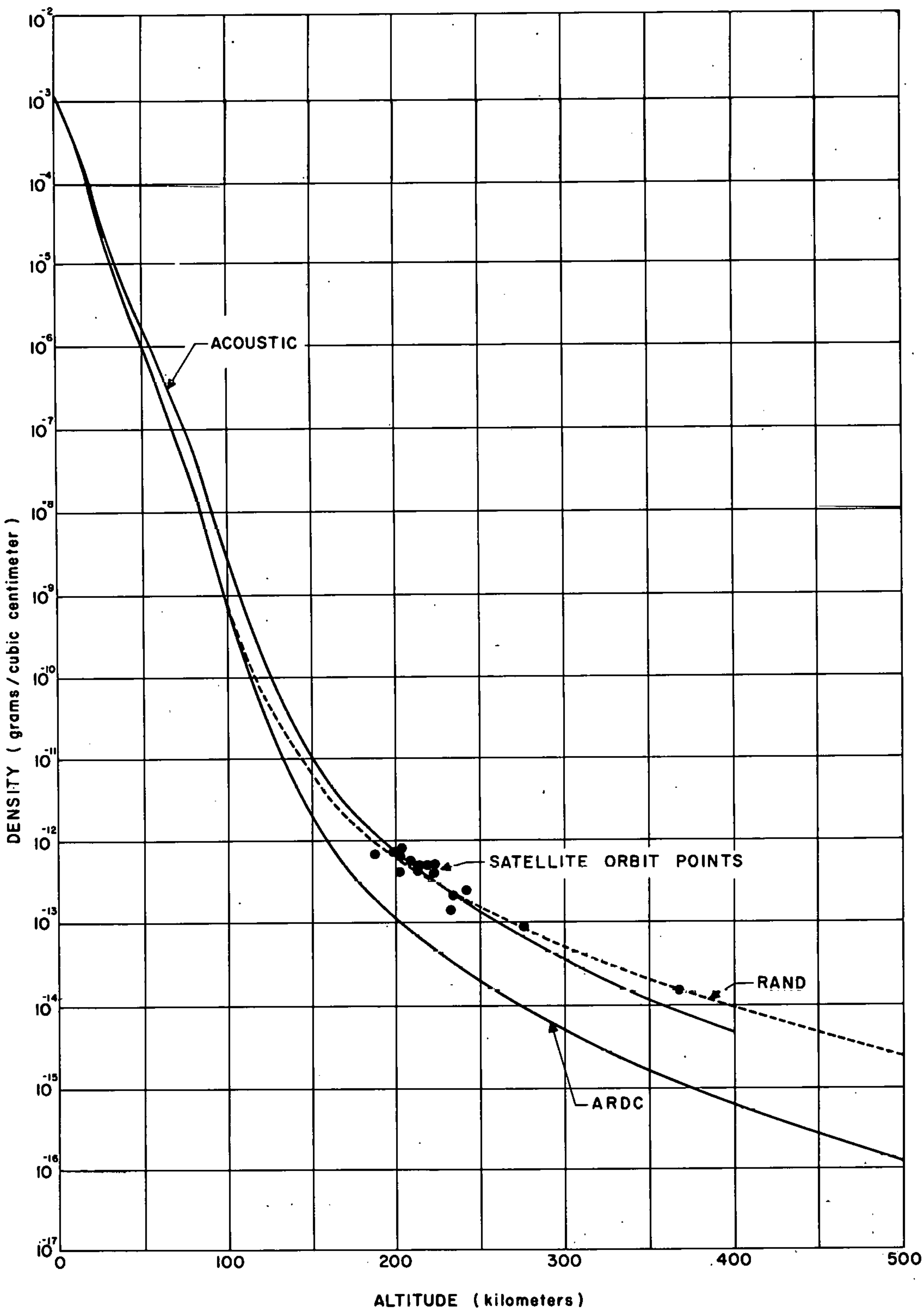


Fig. 12 -- Atmospheric densities to 500 kilometers

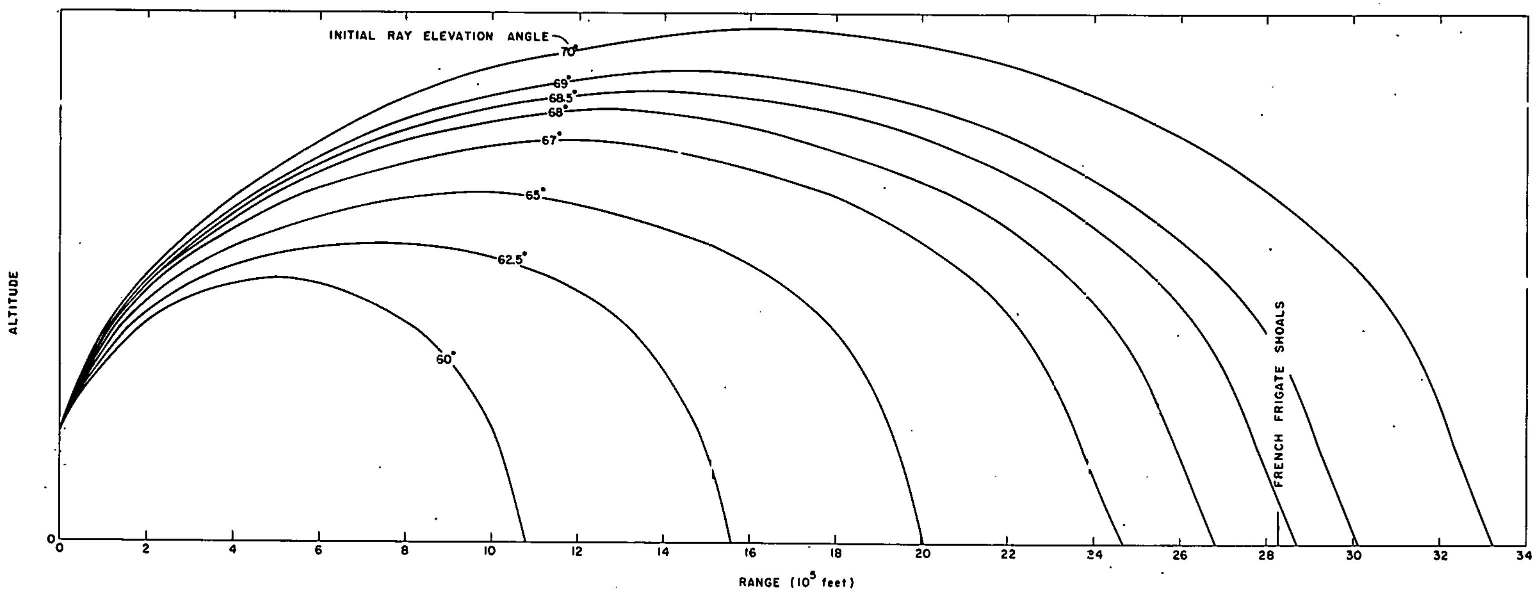


Fig. 13 -- Teak acoustic ray paths

LIST OF REFERENCES

1. Cox, E. F., Plagge, H. J., and Reed, J. W., "Meteorology Directs Where Blast Will Strike," Bulletin of the American Meteorological Society, Vol. 35, No. 3, March 1954.

2. Cox, E. F., "Sound Propagation in Air," Handbook der Physik, Vol. 48, Chapter 22, Springer-Verlag, Berlin, 1957.

3. Reed, J. W., "Ozonosphere Observations from Propagation of Atomic Blast Waves," SCTM 86-55(51), Sandia Corporation, June 1, 1955.

4. Reed, J. W., "A Note on Satellite Density Observation," Bulletin American Meteorological Society, Vol. 40, No. 6, June 1959.