High-Frequency Scatter Sounding Experiments at the National Bureau of Standards

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RADIO BACKSCATTER EXPERIMENTS employing four basic types of presentation were made. The original radar-type intensity vs time recordings were followed by range-time recordings, which revealed great variability from day to day in the structure of the line showing the apparent skip-distance change for the operating frequency as time progressed. The plan-position indicator revealed many irregular phenomena and demonstrated difficulties of record interpretation. The use of the sweep-frequency technique for obtaining backscatter records out to long distances represents a new approach and effectively demonstrates that he reliability of the technique of determining skip distance by means of backscatter on a single frequency may sometimes be very poor.

It has been known for many years that when a pulsed radio transmitter operating above the critical frequency of the F2 ionosphere layer is connected to a directive antenna it is possible to receive distant echoes back from the direction of maximum gain. Most of these echoes have been shown to be propagated from distant ground regions via the various layers of the ionosphere, notably the F2 layer, as if a radar transmitter with very poor resolution were receiving echoes back from distant large areas of the earth, not directly, but by means of an ionosphere layer as a reflecting mirror. Thus it appeared that observations of the range of these echoes would be useful in determining radio-sky-wave skip distance in the direction from which they are received.

The early belief that the distant scatter source was the top of the E layer (*1*) has been largely discounted by various observers in recent years. However, use of a new technique of scatter sounding recently developed at the National Bureau of Standards indicates that the role played by scatter from the top of the distant E layer may be more important than has recently been thought. This technique, evolved after a series of backscatter experiments which began in 1946, is *sweep-frequency scatter sounding.*

Four different methods of studying backscatter echoes have been used at the National Bureau of Standards since 1946.

Intensity vs Range Photographs at a Fixed Frequency

The original backscatter experiments at the National Bureau of Standards (*2*) used equipment employing A-plan or A-scope types of cathode-ray tube

FIG. 1. Typical A-plan record of backscatter from regions to west of Sterling. Range to scattering region is shown for the instant of photographing. Transmitted pulse occurs at jog in broken rectangle at left; received echo is at right about 15 milliseconds later as shown by abscissas scale graduated in half-millisecond markers. Height of echo gives relative amplitude.

display as did early radar equipment.[1] Photographs of the display were made at intervals of about 15 minutes. Each such picture showed delay time and amplitude of the various echoes for a single operating frequency at a particular time of day, obtained by beaming the transmitting and receiving antennas in a particular direction. Figure 1 shows such a photograph. Delay time for the echo (i.e., time for a pulse of energy to leave the transmitter and return) is obtained by referring to 0.5-millisecond markers which appear along the bottom of the time base. The time of the transmitter pulse is shown by the break in the pedestal[2] at the left-hand end of the sweep. The scatter

[1] In the A-plan display the beam is made to sweep across the cathode-ray tube face in a straight line at a rapid repetitive rate in synchronism with the transmitted pulse. This pulse, known colloquially as the "main bang," is displayed as a jog in the sweep, as are the echoes. If the transmitted pulse appears at the extreme left of the sweep, the echoes will appear to the right at a distance along the sweep corresponding to the time it takes for a radio wave to reach the echoing area and return. In a simple case, if the pulse rate were 100 per second it would take 10 milliseconds (1/100 second) for the sweep to cross the tube face. Since an echo travels a given distance and returns over the same distance at a rate equal to the velocity of light the maximum range to the echoing area is determined as one half of 300 kilometers per millisecond (the velocity of light) times 10 milliseconds or 1500 kilometers. The sweep in Fig. 1 represents a 50 per second sweep rate and takes 20 milliseconds to cross the tube face. For special reasons this sweep was designed to operate at twice the pulse rate of 25 per second.

[2] In the type of loran navigating instrument adapted to this experiment the sweep is broken by a rectangular pulse known as a pedestal, generated in the instrument. It is possible to make any echo occur at a time such that it will appear on the top of the pedestal, which may then be used to trigger a fast sweep occupying a length of time equal to the length of the top of the pedestal, offering an expanded sweep for closer echo examination. In the case of Fig. 2, however, the transmitted pulse is arbitrarily positioned near the extreme left-hand edge of the pedestal, which is broken and distorted downwards by "overshoot" voltages due to the intensity of the pickup from the nearby transmitter.

signal is the rough pulse group starting about 15 milliseconds to the right of the transmitter pulse. The "range" of the scatter signal in kilometers (i.e., distance to the scatter source along the path of the signal) is obtained by multiplying the delay time in milliseconds by 150. A delay time of 15 milliseconds (range of 2250 km) and an ionospheric layer height of 300 km would correspond to a skip distance of 2120 km.[3]

Echoes often appeared on these records, however, which were difficult to interpret. Range-time graphs could be made from them to facilitate sequential examination by laboriously plotting the range of each returned pulse or pulse group as a function of time of day, but interpretation difficulties were still numerous as the intervals between plotted points were too great to yield fine detail.

Range-Time Records at a Fixed Frequency

The range-time type of recording, in which an oscilloscope beam is intensity modulated and a film is moved past a slit along which the beam is positioned in proportion to echo range (delay time), corrected some of the faults of the above plotted graphs. Detailed time variations of scatter range in a given direction on a single operating frequency could now be seen although at considerable sacrifice of intensity information. Figure 2 illustrates such a record. The abscissas are time of day and the ordinates are delay time in milliseconds.

At the left-hand edge of the record (1840 EST) there appears a band of echoes between 11 and 17 milliseconds of delay time. These echoes are undoubtedly propagated via the F2 layer because, as time passes, the delay time (skip distance) increases, corresponding to the decrease in F2 layer ionization density with the approach of nighttime conditions, until at 2020 EST the skip distance becomes too great and the echoes disappear. At 1930 another band of echoes shows up at about 7 milliseconds. As time progresses the width of this band of echoes increases but it differs greatly from the first band in that the delay time of the leading edge remains fairly constant. Behavior of this sort could not take place if these echoes were reflected by one of the normal ionospheric layers. They must therefore be reflected by sporadic-E ionization. If only one observation had been made at, say, 2000 EST, the two echo groups might have been interpreted as propagated by one-hop F2 and 2-hop F2, respectively, with considerable error in skip-distance determination.

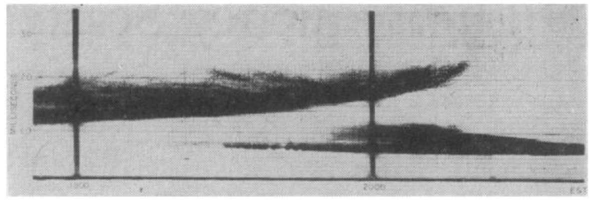

FIG. 2. Range time record of backscatter from northeast of Sterling, Va., on 13.7 Mc, October 2, 1952. This is a continuous record of the change of range to the echoing areas as time of day progresses. The straight black line at the bottom of the picture represents the transmitted pulse at zero range; the broad, heavy traces represent echoing areas at ranges corresponding to the delay times of the ordinates scale.

It was observed that the types of echoes varied greatly from one period to another. During quiet periods the echo on the range-time record was seen as a smooth, fairly thin line while during more disturbed periods it became a thicker and more wispy line (*3*). On extremely disturbed days these lines might at some times of day be replaced by streaks changing rapidly in range.

In spite of possible erroneous interpretations due to anomalous echo patterns, results of an experiment performed over a 2700-km path at 15 Mc in 1950, in which distant reception of station WWV was compared with backscatter measurements on pulse transmissions over the same path near the same frequency, indicated reliability of the scatter method of determining propagation conditions. For instance in 18 cases of observations of distant signal failure during the tests, the scatter at the correct range was visible in 17 cases and 13 of these scatter observations indicated the signal failure to within 15 minutes (*3*). This, however, was a special case of one frequency and one path.

Plan Position Indicator (PPI) Representation

The idea of using a radar-type plan position indicator for skip distance indication was first conceived by Dr. Newbern Smith of the National Bureau of Standards in 1945 (*4*) and independently in 1947 by Dr. J. T. deBettencourt (*5*), then at Raytheon Manufacturing Company. Each record obtained by this method is a plan view of the echo ranges in all azimuths for a single operating frequency at a particular time of day. The first experiment of this type was done for the U. S. Air Force by Raytheon, and the same experiment was performed independently by Villard and Peterson in the winter of 1951–52 (*5, 6*). Meanwhile work progressed on equipment of this type at the National Bureau of Standards, and it was first put into operation in the spring of 1952.

The Bureau's transmitter usually operates at 400-kw peak pulse output, although it is capable of a megawatt on short runs. The pulse width used is 40 to 50 microseconds. The rotating antenna is a double Yagi with vertical elements, and the receiver is a communications receiver adapted to pulse work. The antenna

[3] In simple one-hop transmission if scatter is from the distant ground, the range is proportional to the length of an equivalent triangular path from the transmitting point on the earth's surface to a midpoint in the ionosphere and down to earth at a distant point. The distance along the earth's surface between the two points is naturally less than this echo range and for a given range, is less the higher the height of the reflecting region. It can be shown that for this simple case the distance determined by the leading edge of the echo is approximately the "skip distance" for the radio wave at the particular frequency used, i.e., to a first approximation a radio signal on this frequency cannot be detected at a shorter distance in the direction of the scatter source from the transmitter. The skip distance can be determined from the range by a geometric calculation but it is simpler to use graphs or nomographs prepared for the purpose.

rotates once per minute and a photograph of the resulting ppi representation is made. Use of a motion picture camera enables sequential study of the results. The high power and relatively narrow pulse width of this equipment affords better range-resolution of the scatter echoes than can be obtained with low-power equipment emitting long pulses.

One of the significant, though puzzling, characteristics of the echoes observed with this ppi equipment is that, as the antenna rotates, the range of the echoes seldom varies smoothly. The range, and therefore the apparent skip distance, sometimes jumps by discrete amounts of as much as 10 milliseconds as the azimuth changes. Also, at times, there are substantial azimuth intervals in which no echo is recorded at any range, without any indication of a transition between the echoes on either side. Figure 3 is a photograph of the ppi face at Sterling, Virginia, on December 28, 1952, at 1120 EST at 13.7 Mc. The rings are range markers at intervals of one millisecond. Toward the north (top of illustration) the range of the echoes is about 19 milliseconds (A), and remains fairly constant at first as the azimuth is changed clockwise, but in the northeast it moves in very rapidly to 12 milliseconds (B) and then more gradually to about 9 or 10 milliseconds in the easterly direction (C). Echoes at such ranges are difficult to interpret since they could contain ground-scatter echoes propagated by E, F1 or F2 layer. Beginning at the east and continuing around to the west (D) a heavy trace is generated with leading edge between 8 and 9 milliseconds. The shorter traces at 7 or 8 milliseconds toward the south (E) are no doubt ground scatter propagated by sporadic-E ionization. The strong echoes taper off just north of west (F), while another group at around 19 or 20 milliseconds, which first appeared just south of west (G), prevails with small irregular jumps all the way around to north.

Some of the irregular jumps may be due to focusing and defocusing effects of irregularities in the F2 region (*7*) or to varying amounts of defocusing caused by the changing intensity of sporadic-E ionization below the F2 layer (*8*). In fact, partial or complete shielding of the F2 layer by the E layer below it could cause gaps in the F2-layer echo range plot.

The high resolution of the system makes the fine structure of the echoes visible. The alternate black and white lines seen in any one photograph represent maximum and minimum amplitudes whose positions are relatively independent of the characteristics of the receiving system except that in the illustration some enhancement of the weaker echoes occurs at the range markers because of equipment characteristics. They are seen to shift as much as one or two milliseconds in position between one minute's sweep and the next. A wave interference phenomenon is evident here, the changes which take place being due to changes in the reflecting areas of the ionosphere as its irregularities change in position or shape.

One difficulty with the ppi system is that it conveys *too much* information at any one time even when photographs are individually studied. To overcome this difficulty W. L. Hartsfield of the National Bureau of Standards has devised a scheme of projecting a ppi motion picture on a surface containing a slit with a translucent surface. This slit can be set at any azimuth and, to the lens of a range-time recording camera, appears just like the face of an oscilloscope tube reproducing echoes at a fixed azimuth in a range-time recording system. Thus the ppi photographs become the potential source of range-time recordings over any desired azimuth. It is merely necessary to photograph the slit on the moving film of a range-time camera.

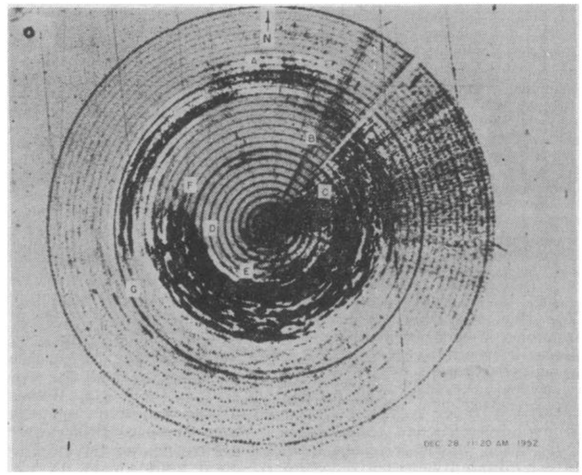

FIG. 3. Ppi recording of backscatter echoes illustrating discontinuities in echo ranges, and fading pattern. (Rings are range markers in steps of one millisecond delay time. Echoes are dark traces; ripple texture is due to instantaneous fading pattern of signal at different ranges. Fan-like traces in northeast and north are due to station interference; blank sector results from photographing; wavy lines of dots are caused by power-line interference.)

In common with all scatter-sounding systems employing the usual directive antennas with beam widths of the order of 20 or 30 degrees, the ppi system suffers from the difficulty that if such an antenna is pointed in a given direction and the range to the scatter in an adjacent direction is shorter, there is often enough energy from these shorter-distance echoes to falsify the range for the azimuth being recorded (*9*).

Also as was noted for range-time records, there exists the possibility of false mode interpretation and consequent erroneous skip distance determination. For instance, echoes with delays of the order of 10 milliseconds may be propagated by the F2 layer or the F1 layer or the E layer. A mistake in assuming F2-layer propagation at that delay when sporadic-E ionization is really responsible, would be followed by an erroneous virtual height assumption, giving a calculated skip distance about 7.5 per cent too short and any forecast of failure time of point-to-point transmission at the same frequency would probably be completely in error.

Studies are now being conducted at the National

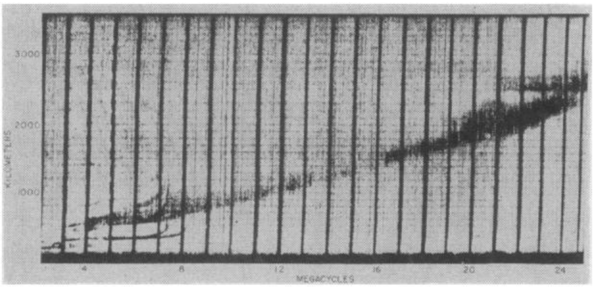

FIG. 4. Typical sweep-frequency record made at Sterling, Va., Dec. 15, 1952, at 1258 EST, showing regular vertical-incidence echoes and backscatter echoes. Waves returning directly from the ionosphere give the thin trace observable at about 250-km range in the lower left-hand part of the picture. These traces turn upward at 7.3 and 8.0 km. Waves returning after striking the ground and bouncing off the ionosphere a second time create a trace at twice this range. This trace, however is obscured by diffuse echoes developing into a plume-like trace receding to about 3000 km at 25 Mc. These echoes are backscatter echoes.

Bureau of Standards on several months' ppi films to see if disturbance forecasting or tracking, originally proposed by NBS workers (*3*), is feasible. Other objectives of the work are to evaluate the ppi as a skip-distance indicator and to increase the knowledge of ionospheric phenomena in general.

Sweep-Frequency Backscatter Records

The sweep-frequency technique represents the latest approach by the Bureau to the study of backscatter. Occasional records of backscatter out to great distances were obtained as early as July 1951 using a standard NBS Model C3 ionosphere recorder modified for a 12-minute sweep and operating with a rhombic antenna beamed to the west. Results in this work were considered marginal, however, because of insufficient signal-to-noise ratio, until improvements in the recorder made it possible to obtain usable records on a fairly continuous basis during the winter.

In the range-time type of recording at a fixed frequency and azimuth, echo identification can sometimes be accomplished only by observing the change of the record with time of day, as ionization conditions change. However, in the sweep-frequency type, the change of frequency during a single sweep, by continuously changing the ratio of the operating frequency to the critical frequency of a given layer, accomplishes the same thing in the course of a single sweep. Thus it is possible to see the scatter "grow" out of the traces of the regular vertical incidence reflections and each mode of scatter propagation develop as the frequency increases.

A test originally described by Dieminger (*10, 11*), and later by Peterson (*12*), for establishing whether backscatter propagated by a given layer was from the ground, was tried on a large number of sweeps, verifying that at least just beyond the critical frequency of the F2 layer the scatter was from the ground.

A simple sweep-frequency scatter record appears as shown in Fig. 4, the ordinates being virtual height or slant range in km, and the abscissas frequency. The ordinates are marked every 100 km and the abscissas in megacycles, running from 3 at the left to 25 at the right. The thin solid curves at the left of the picture are the well-known virtual-height versus frequency curves for the ionosphere overhead. The F2-layer ordinary-wave critical frequency is about 7.3 Mc. The second trace above the bottom of the graph, similar in shape to the first, but diffuse on top, is the second (2-hop) reflection. The weak and more diffuse looking echoes which start out along an imaginary straight line from the origin (off the diagram) running tangent to the bottom of the second-multiple F2 trace are the ground scatter echoes reflected by the F2 layer. These run all the way out to 24.8 Mc where the slant range is 2400 km. The F2-layer skip distance for any frequency is obtained from the slant range by using curves of tabulated values of slant range vs skip distance for various virtual heights of the reflecting layer. In this case for an F2-layer virtual height of 300 km the skip distance would be 2260 km.

Attention is called to the group of echoes starting at about 21 Mc, behind the line of the regular F2-propagated echoes. These echoes appear at about the same distance on a great many records. Their slant range is fairly constant and their calculated distance agrees with the distance to the Rocky Mountains from the transmitter site at Sterling. It may be possible to use the variations in their apparent range as an indicator of ionospheric conditions.

On some records it is possible to distinguish ground scatter propagated via the F1 layer and the E layer as well as by the F2 layer.

Because of the sweep-frequency feature it was possible to check the reliability of backscatter echoes for skip-distance determination a great many times in one day, since a distance could be selected which would be the skip distance for some frequency in the recorder sweep at any time during the day. The path chosen for the test was the 1150-km path from Sterling, Virginia, to a point near St. Louis, Missouri, since this had been the path for two-way pulse experiments with the same equipment. The St. Louis equipment had been dismantled but satisfactory use was made of the vertical-incidence ionosphere recorder situated at the midpoint of the path near Batavia, Ohio. Previous experiments had shown that the Batavia data could give the maximum usable frequency (i.e., skip-distance frequency, abbreviated as MUF) for the St. Louis path with reasonable accuracy (*13*). Also during part of the experiment, transmissions from station WWV located near Washington, D. C., were recorded at St. Louis and afforded a very satisfactory check of MUF.

Comparisons of skip distance deduced from sweep-frequency backscatter and from the midpoint data were made for a period when the ionosphere was relatively calm and there was little sporadic-E ionization. Comparisons were also made for another period when the ionization values were fluctuating greatly throughout the day and much sporadic-E ionization prevailed. In the former case agreement between the values of

MUF obtained by the two methods was very close—within 5 or 6 per cent in most cases. In the latter case agreement was extremely poor. Values of MUF obtained by the scatter technique were always higher by varying amounts, sometimes of the order of 50 per cent. The scatter records, too, were vastly different from those made on calm days. Instead of being straight and thin they were relatively crooked and broad, often exhibiting at least two branches, and their configuration changed from one sweep to the next. Oddly enough, however, the skip-distance comparison for most of these records gave results which would be consistent with reflection from the top of the distant E layer although the traces at nearly vertical incidence from which the echoes emerged as the frequency increased appeared to be reflections from the ground.

Some of the poor results and branched traces for the disturbed day may have been due to the breadth of the antenna beam and the turbulence of the ionosphere. On a disturbed day there would undoubtedly be many regions off the beam, especially to the south, with higher ionization density than that for the path midpoint at any one moment; some of these regions would be capable of propagating ground scatter in sufficient intensity to appear as echoes of lesser delay times than the great-circle echoes. The possible use of sweep-frequency backscatter to study, track and forecast radio disturbances is indicated here (*3, 6*).

The equipment, with the relatively small rhombic antenna which was used, proved to be inadequate for nighttime operation when the skip distance at the lower high frequencies was long, requiring a very large rhombic antenna, radiating at low angles.

Future plans call for backscatter experiments over the path from Sterling, Virginia, to Boulder, Colorado, in conjunction with a two-way pulse propagation experiment. Since Boulder is at the edge of the Rocky Mountains it should be of value to see how variations in the range of the fixed echoes compare with variations in two-way signal transit time and backscatter delay time.

Results of all experiments to date corroborate the author's views expressed in an earlier report (*3*) that there will be times when skip distance determination by backscatter delay will be difficult or impossible, and it now appears that such circumstances may be rather frequent. Two things are certain. One is that skip-distance determination by scatter techniques can be done only by a skilled person familiar with the regular behavior of the ionosphere in the region. The other is that a great deal of further experimentation will be needed under a variety of circumstances before the value of the technique is finally assessed.

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Introducing a New Editor of the A.A.A.S. Journals

For some months the editorial direction of SCIENCE and THE SCIENTIFIC MONTHLY has unavoidably been of a temporary character. The Acting Chairman of the Editorial Board is therefore glad to be able to announce the new and permanent appointment of Dr. Duane Roller as Editor of both journals and Chairman of the Editorial Board.

Dr. Roller received the Ph.D. degree in experimental physics from the California Institute of Technology in 1928. He has taught physics at the University of Oklahoma, Hunter College, and Wabash College, and has been visiting lecturer at Harvard University and at the Case Institute of Technology. During World War II he served with the Armor and Ordnance Divisions of the National Defense Research Committee. Dr. Roller founded and for 15 years was editor of *American Journal of Physics*, He is a co-author, with Millikan and Watson, of the textbook, *Mechanics, Molecular Physics, Heat and Sound*, is co-translator and editor of Vols. 2 and 3 of Cranz's *Lehrbuch der Ballistik*, and is the author of three monographs and numerous articles.

Duane Roller's interests extend into the areas of the history, methodology, and language of science. In 1946 he received the Oersted medal for outstanding contributions to college and university physics teaching, in 1949 was President of the American Association of Physics Teachers, and in 1952 was awarded an honorary degree by Hamline University for his contributions to physics as a part of liberal arts education. He has held fellowships of the General Education Board and the Ford Foundation. Currently he is a member of the Governing Board of the American Institute of Physics and of the Board of Trustees of Science Service. Since July, 1952, he has been Assistant Director of the Hughes Aircraft Research and Development Laboratories.

These broad interests and wide experience eminently qualify Duane Roller for his new task as Editor. Under his leadership SCIENCE and THE SCIENTIFIC MONTHLY should attain new distinctions in scientific reporting and in keeping a widening audience aware not only of the achievements of science, but of its nature, methods, and spirit. BENTLEY GLASS