NRL Report 6865

The Evolution of an Artificial Ionospheric Plasma Cloud as Studied by HF and VHF Radar

J. R. Davis

Radar Techniques Branch
Radar Division

and

S. R. Curley

Office of Naval Research

April 3, 1969

NAVAL RESEARCH LABORATORY
Washington, D.C.

CONTENTS

ABSTRACT

A plasma cloud was created at an altitude of 94 km over Wallops Island by exploding a canister of a cesium compound, which had been fired from a 7-in. gun. This cloud was illuminated from NRL by hf and vhf radar. The results of coherent pulse doppler analysis of the cesium cloud signature indicate that the cloud evolved in a billowy manner, with turbulent eddies of about $10^4\ m^2$ cross section appearing at several times within the nominal 70-sec duration of the signature. It was the presence of large-amplitude, specular echo components in the cloud signature that led to the suggested behavior of a cloud evolving in a billowy manner. The fact that these could be due instead to transient resonances in the plasma cloud cannot be completely discounted.

PROBLEM STATUS

This is an interim report on one phase of a continuing problem. Work is proceeding on this and other allied subjects.

AUTHORIZATION

NRL Problem R02-23
USAF MIPR FD2310-7-0016

Manuscript submitted November 29, 1968.

THE EVOLUTION OF AN ARTIFICIAL IONOSPHERIC PLASMA CLOUD AS STUDIED BY HF AND VHF RADAR

INTRODUCTION

Artificial electron-ion clouds have been of value to ionosphere physicists for many years, but it has been only recently that radio-frequency power has been available at a high enough level to probe their internal motions. Moreover, the capabilities of actually discerning and resolving the turbulences within such plasma clouds have emerged just recently, because it requires an advanced degree of coherent pulse doppler signal processing for success. Advanced ionospheric research radars are uniquely fitted by virtue of their frequency band, high power level, highly directive antennas, and sophisticated spectrum analysis facilities to investigate plasma-ionosphere interactions of all kinds. It is the purpose of this report to illustrate the application of high-resolution, coherent pulse doppler signal processing, as embodied in NRL's ionospheric research radars, to the study of high-frequency (hf) and very-high-frequency (vhf) radar signatures from an artificial ionospheric plasma cloud. The particular example which will be treated here is that of a gun-launched, cesium-seeded cloud, which was emitted from a canister of a cesium compound fired from Wallops Island.

A vertical probe was launched from Wallops Island at 1543:01 EST on April 17, 1968. At 100 sec after launch the payload, consisting of a 2-kg explosive mixture of 34% $CsNO_3$, 21% Al, 19% RDX, and 26% TNT, was detonated. Detonation occurred at 94 km altitude. The launching vehicle was a 7-in. gun operated by personnel from the Army's Ballistic Research Laboratory, Aberdeen Proving Ground, under the direction of Dr. C.H. Murphy. During this cesium cloud release, the NRL hf research radar was operated in its normal, coherent pulse doppler mode with NRL's (colocated) vhf radar slaved to the hf research radar's pulse repetition frequency (prf) and operating in a quasi-coherent mode. Data from the vhf radar were later analyzed with a digitally controlled spectrum analyzer, which is normally used with the hf research radar system.

The next section of this report contains a description of the two radar devices utilized in this combined study. The third section contains a presentation and analysis of the signatures acquired, and the last section contains a discussion of implications of the results, plus recommendations for further research of this type.

DESCRIPTION OF THE EXPERIMENT

NRL's hf research radar is located 40 miles east of Washington, D.C., on the Chesapeake Bay. At the same location is NRL's vhf research radar facility, which uses a fully steerable 150-ft paraboloidal dish antenna to radiate and receive radio-frequency energy at 139 and 435 MHz. Only the lower frequency has been utilized in the study reported here, however.

NRL's hf research radar is an advanced, coherent pulse doppler, ionospheric research device, developed by NRL in a continuous evolution that began in the mid-1950's. Over the past decade, this radar has grown and evolved in pursuit of its ionospheric research tasks, with advancements in signal-processing techniques introduced to cope with the increasing complexity of radar data from the diversity of diffuse, often fleeting targets which characterize ionospheric radar studies. Improvements in radio-frequency power transmission and in hf antenna array design have also been incorporated in the research radar during its growth. An extensive, continuing program of experimental and theoretical research in ionospheric propagation has accompanied the development of apparatus. At its present stage of evolution, NRL's hf research radar is a unique tool for investigating ionospheric perturbation phenomena of all types, with emphasis upon spectrum analysis as a principal analytical technique. Its chief distinguishing characteristic is a digitally controlled spectrum analyzer, which employs a Honeywell DDP-116 digital computer both for radar control and for signal storage. This digital control and storage function is complemented by analog filtering and display to comprise a highly efficient, hybrid signal processor and radar controller.

The antenna used for the study described in this report provided an effective gain (computed by adding 5 dB to the free-space gain at lobe peaks to account for an assumed imperfect ground plane) of approximately 10 dB relative to an isotrope in the direction of the cesium cloud. An operating frequency of 15.720 MHz was used, with a 670-μsec pluse length and a prf of 45 pps.

NRL's vhf radar facility on the Chesapeake Bay was constructed in the early 1960's for ionospheric research. Its 150-ft-diameter, fully steerable reflector may be used at frequencies between 50 and 2000 MHz. It provides a peak free-space gain of 34.6 dB at 139 MHz, in a circular beam of 3.6° half-power beamwidth. The present vhf transmitter is a relatively low-power device (3.5 kW average power), but a 50-kW (average power) transmitter is being added and will be available for future studies. This research radar has been utilized for studies of (a) ionospheric irregularities and magnetic storms by use of the Faraday effect on satellite-reflected radar signals, (b) the field alignment of meteor trail echoes, (c) absorption and scintillation effects related to ascending rocket vehicles, and (d) amplitude scintillations of satellite-transmitted signals due to sporadic-E, solar flares, and other ionospheric perturbations. It makes use of an all-digital recording system, with data analysis accomplished on NRL's CDC 3800 computer. A condition of quasi frequency coherence may be imposed on the transmitted energy, permitting the digital signal processor to be used for a limited amount of coherent integration (restricted by frequency drifts in the transmitter and receiver local oscillator).

The release point on the NASA Wallops Island Missile Range was approximately 185 km from NRL's Chesapeake Bay site, at an azimuth of 134° relative to true north, and at an elevation of about 30° above the horizon.

EXPERIMENTAL RESULTS

Figure 1 is a collection of vertical-incidence ionograms acquired from Wallops Island* during the release period. The ionosonde provided one complete scan per minute, with timing information accurate to within 1 min. The first clear evidence of the cesium cloud echo appeared in the ionogram of 2045 GMT as a diffuse trace at about 100 km virtual height extending outward in plasma frequency from the E-layer echo. Vestiges of its presence may be seen (by careful inspection) at plasma frequencies as high as 7 MHz. There is no period in which the ionograms indicate that the cloud was overly dense at frequencies above 7 MHz, however, and by 2051 GMT it seems to have dissipated completely. It should be emphasized that the relatively slow sweep rate of the ionosonde may have resulted in a failure to record short-lived electron concentrations which may have been overly dense at higher frequencies (for example, the 15.720 MHz operating frequency of the hf radar) during the ionosonde sweep's absence from its higher

*These data were provided by courtesy of Mr. E.D. Boyer and Dr. C.H. Murphy of Aberdeen Proving Ground, Md.

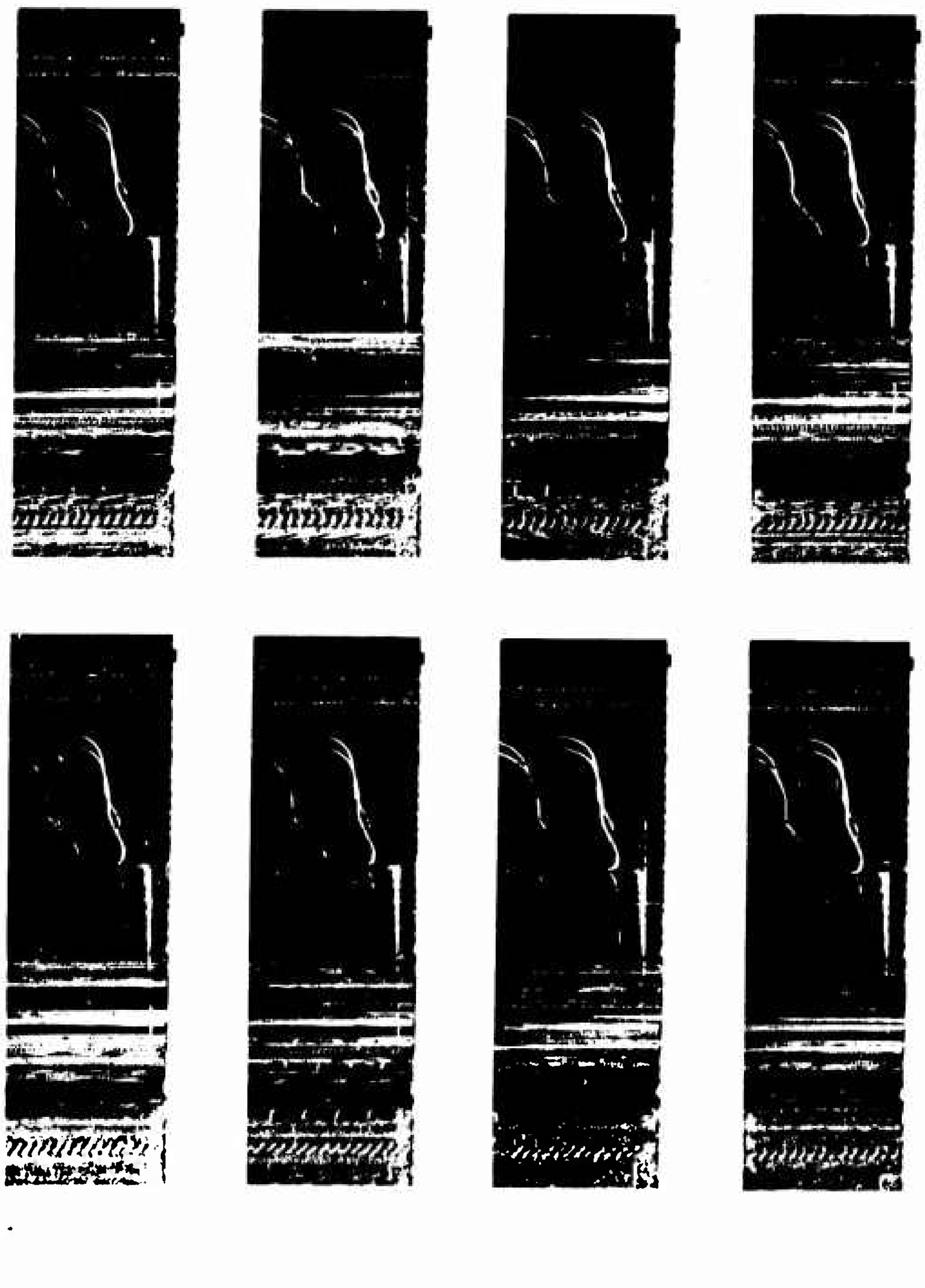

Fig. 1 - Vertical-incidence ionograms taken at Wallops Island during cesium release

frequency extreme. It also should be mentioned that the apparatus utilized for sweep-frequency sounding measurements was substantially less sensitive than the hf radar, and would not be expected to detect small, dense electron concentrations which would be detectable at higher frequencies by the more sensitive hf radar.

Figure 2 is a photograph of the signature from the cesium cloud as it appeared to the hf radar. This illustration appears in a doppler-shift-vs-time format, with the carrier frequency at the center of the vertical scale. The horizontal band of approximately 1-Hz bandwidth which appears across the entire photograph is the earth backscatter echo. Although the data in this illustration are range gated (with an effective gate width equal to the pulse width of 670 μsec, or 100 km), ground clutter from ranges extending into subsequent pulse intervals appears at the same apparent range as the cloud. Thus the clutter band, which appears here at the same apparent range (185 km) as the ion cloud, actually arises from a location one pulse interval removed (3300 + 185 km) from the cloud. Also visible in Fig. 2 are a faint horizontal line at +4 Hz, possibly due to power frequency leakage, a vertical band identified as a meteor echo, and some faint, narrow, slanted lines which are identified as nearby aircraft echoes. The doppler resolution bandwidth employed in Fig. 2 is 0.3 Hz.

The principal cesium cloud echo is identified by brackets. It begins at the release time, 2044:41 GMT, and extends for about 60 seconds before descending to noise level. Its doppler shift from the carrier frequency is approximately 4.5 Hz (to the center of its spectrum), and its spectral extent grows to as much as 5 Hz at the -20-dB points. The diffuse nature of the signature bespeaks an extensive degree of turbulence in the cloud.

Figure 3 is a collection of amplitude spectra, acquired by sweeping a 0.3-Hz-resolution bandwidth filter through the cesium cloud echo at various times and by presenting signal amplitude vs doppler shift on an oscilloscope display. The photographs in Fig. 3 represent amplitude spectra at 3-sec intervals (with an effective 3-sec integration time implied by the 0.3-Hz filter bandwidth). The cesium cloud echo begins in the photograph at 2044:42, with a growing specular component at 6 Hz. It should be borne in mind that the implicit 3-sec integration time in these spectra cause all data received during a 3-sec period beginning at the nominal photograph time (i.e., from 2044:42 to 2044:45 in the first photograph) to be displayed simultaneously. This apparently discrete target persists into the third photograph, but becomes progressively more diffuse thereafter. By 2045:00, several spectral components are resolvable, suggesting that internal motion in the cloud has become quite turbulent by this time. The photographs between 2045:00 and 2045:15 display two or three narrow, high-amplitude spectral components superimposed upon the diffuse spectrum which appears in previous photographs. The maximum apparent radar cross section displayed by each of these large, narrow spectral components in this period is approximately $5 \times 10^4\ m^2$ (since this value has been calculated neglecting absorption in the lower ionosphere, and with a likely overestimate of antenna gain, it must be considered a lower bound to the actual radar cross section). It should be noted that this value reflects the integration implicit in the 0.3-Hz doppler filter bandwidth. Thus, a brief burst of signal within the 3-sec period would be averaged over the entire interval, and hence deemphasized relative to a steady, discrete signal of the same amplitude. These narrow spectral spikes persist at a lower level for 3 to 9 sec each, and the spectrum becomes diffuse once more by 2045:18. Another single, discrete spectral component grows to a peak at 2045:39 and disappears shortly thereafter. The small, diffuse echo remaining finally disappears shortly after the last photograph at 2045:51.

The presence of these short-lived, discrete signature components within an otherwise diffuse echo spectrum poses an interpretive difficulty. They might be explained alternatively by three mechansims.

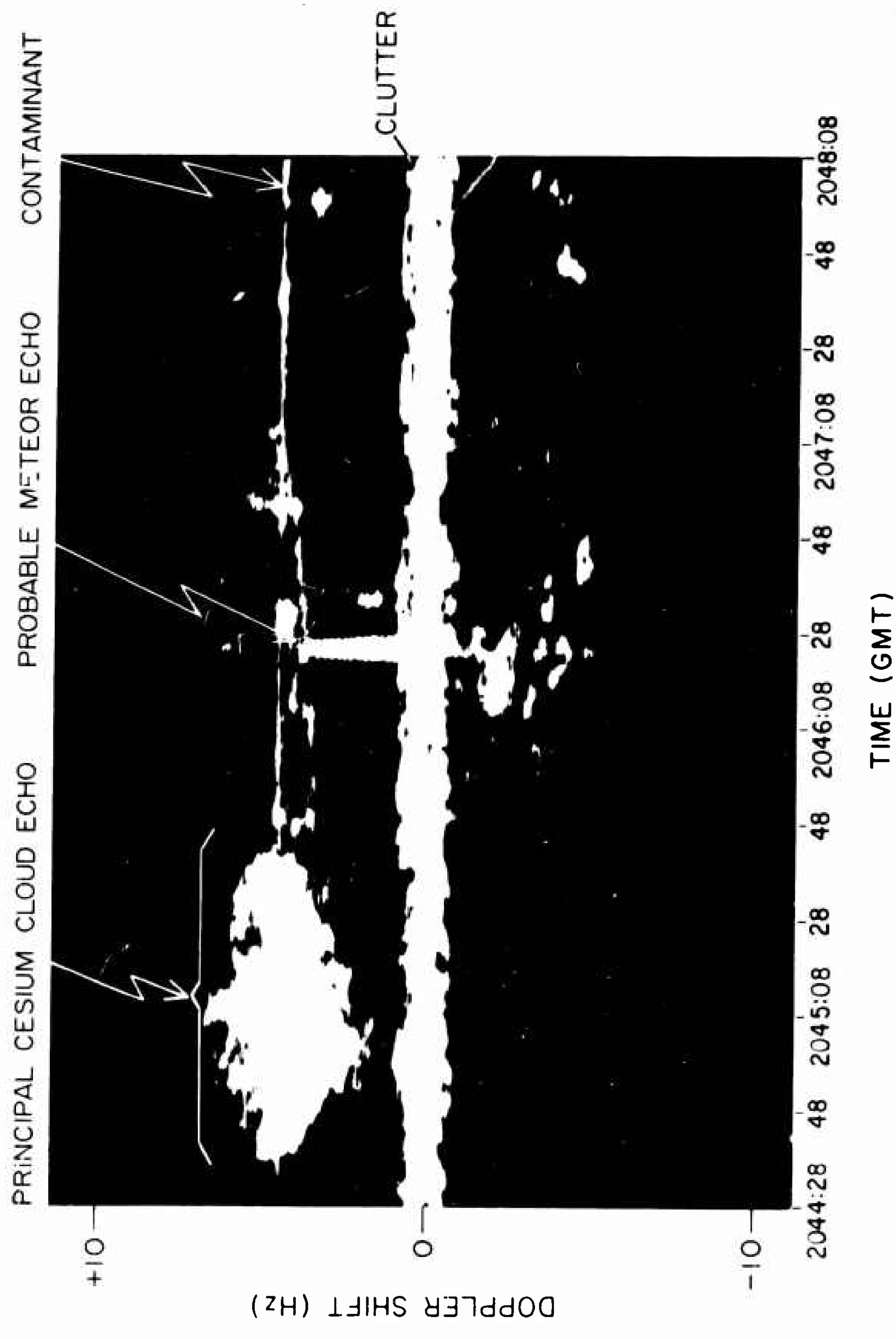

Fig. 2 - Doppler-shift vs time display of hf research radar data

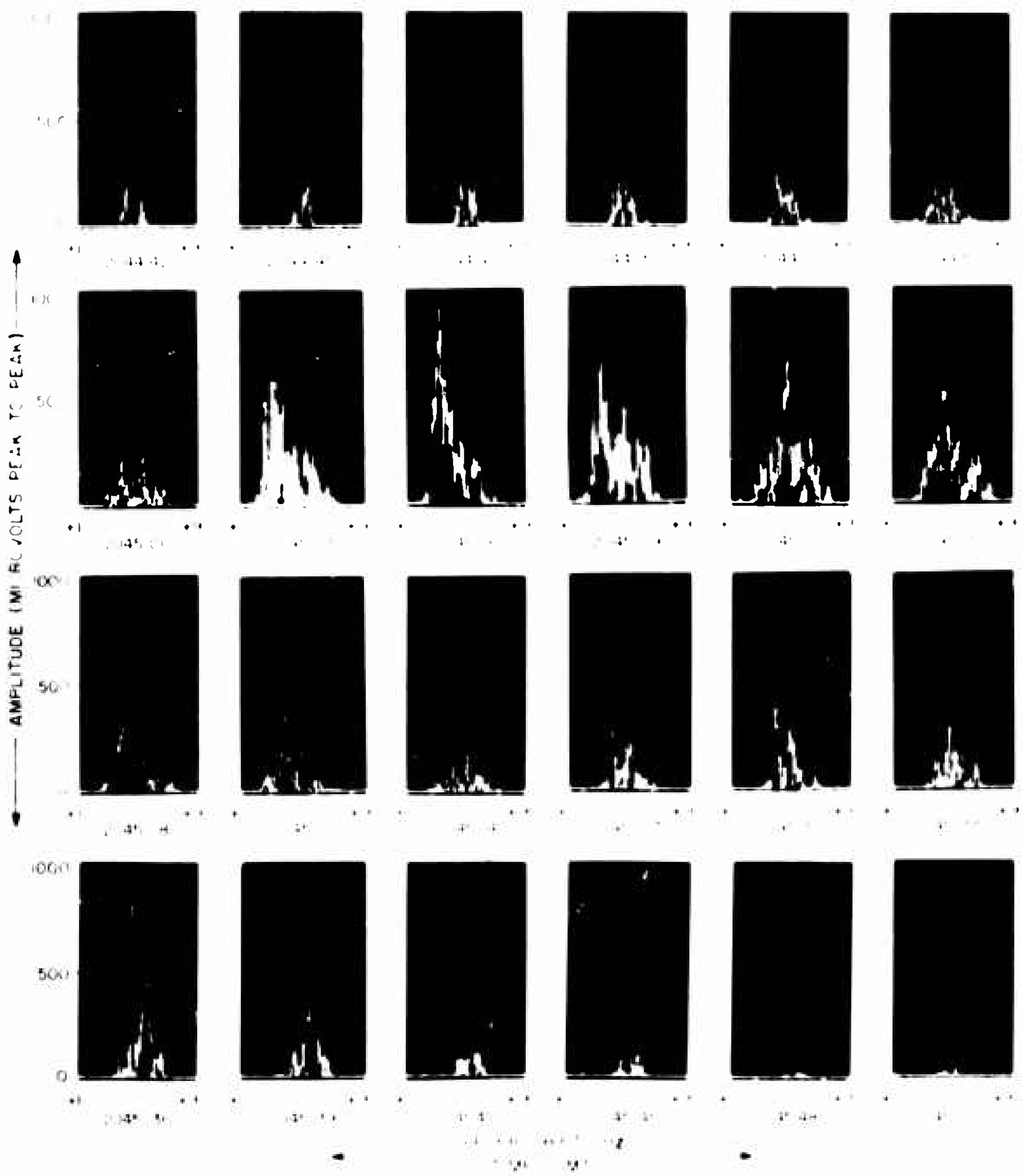

Fig. 3 - Amplitude spectra of hf research radar data from cesium cloud

1. A true specular reflector, such as the canister or the projectile body, or fragments of it, is present within the radar beam throughout the period of the cloud echo, and either rotates into and out of broadside aspect (if a single scatterer is involved) or causes an alternately constructive and destructive interference (if a collection of scatterers is involved) at various time intervals, or

2. The cloud is quite turbulent, and short-lived concentrations of electron density, or steep gradients, are formed and dissipated periodically (such as by internal turbulence or by motions induced by the environment), or

3. The cloud motion and constitution are such that short-lived plasma resonances are excited at appropriate frequency components within the illuminating hf radio waves at several times during the cloud's existence. Alternative 1 is considered to be most unlikely as an explanation of the phenomenon observed. This conclusion is based partly upon the reasoning that the canister and projectile are small radar targets at hf and would be unlikely to fragment into a resonant scattering configuration. The vhf data to be presented below also bear upon this question.

The work of Brode (1) on the spherical expansion of blast waves following a TNT detonation can be used to predict the positions of shock-wave surfaces and the contact surface between the products of explosion and the surrounding atmosphere as well as the velocities, densities, temperatures, and pressures behind these surfaces. The applicability of Brode's model to this experiment may be questioned. The ratio of the density of explosive to that of the surrounding atmosphere is a parameter of importance in Brode's development; for his work, intended to be valid at sea level, this parameter takes a value of 10^3. At the 94-km altitude of this experiment, the parameter is between 10^7 and 10^8, a seemingly large disparity. However, the results from an explosion at 108 km (2) and one at 120 km (3) show that Brode's results were reasonably applicable when the ratio was 10^8 and 10^9, indicating that this parameter is not a sensitive variable.

In Brode's model, it is assumed that all of the energy in the explosion is converted into gaseous products, whereas the actual explosion produces some solid products; it also dissipates energy in rupturing the canister and accelerating its fragments. It will be assumed here for simplicity, however, that all of the released energy, about 10^{14} ergs/kg, is coupled into the shock wave and the gaseous release products.

The evolution of the spherical blast wave in this experiment can be predicted from Brode's work, with these reservations, by considering Brode's scale radius

$$a = \left(\frac{E}{P_a}\right)^{1/3}$$

where

E = total explosive energy,

P = ambient pressure,

and the dimensionless time parameter is

$$\tau = \frac{V_a t}{a}$$

V_a = acoustic velocity in the ambient medium and

t = time after the explosion.

For the release described here, 10^{14} ergs at an estimated ambient pressure of 1.173 dynes/cm^2 (U.S. Standard Atmosphere) result in a scale radius of 400 m. Brode's dimensionless contact surface radius is

$$\lambda = \frac{r}{a}$$

where the radius of the blast-wave contact surface is r and the dimensionless time parameter is τ, achieves a value of unity at a time t = 1.5 sec after release (using V_a = 270 m/sec for an altitude of 94 km).

The positions of the shock surfaces (S^1 and S^2) and the contact surface (CS) are shown versus time in Fig. 4. The values of radius and time for this specific test are indicated on the scales. A detailed explanation of the mechansim which produces the curves in terms of r and t can be found by referring to Brode's original work (1). It was claimed by Rosenberg et al (3) that the major radar target is generally the turbulent, rapidly expanding contact surface labeled CS in Fig. 4, where it can be seen that the predicted contact-surface radius will expand to its maximum value of about 100 m in about 0.1 sec and will remain relatively constant thereafter. From postflight analysis the final vehicle velocity before detonation in this experiment was found to be 505 m/sec, with a vertical component of about 442 m/sec. Thus, during the period of expansion to 100 m radius, the cloud moved a distance of only 50 m and remained roughly spherical. Assuming as a first approximation that the radar target was a perfectly reflecting spherical cloud of 100 m radius, the radar cross section predicted from the Brode model would be

$$\sigma \approx \pi r^2 \approx 3 \times 10^4 \ m^2.$$

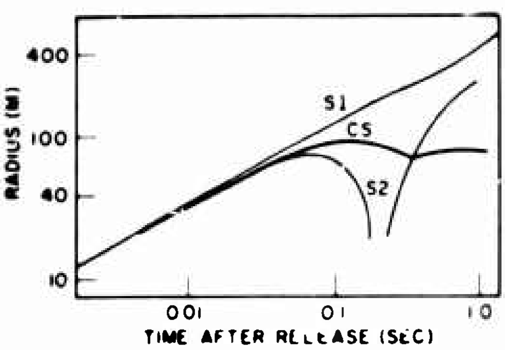

Fig. 4 - Behavior of blast-wave shock and contact surfaces as predicted from Brode model

Figure 5 is a group of plots of apparent radar cross section vs time after release. The large dots, which appear on Fig. 5 at 3-sec intervals, were calculated from amplitude spectra similar to Fig. 3, with a 0.3-Hz-resolution bandwidth. These data were acquired by summing the squared amplitudes within the several nominal 0.3-Hz-bandwidth, contiguous filter positions occupied by each amplitude spectrum display. The solid line in Fig. 5 is fitted roughly to these measured data to give them continuity. The dashed line in Fig. 5 represents a possible growth and decay profile for a plasma cloud whose reflecting boundary might, in the early stages of its development, be determined by the contact surface of a spherical high-explosive discharge as described by Brode. The later stages of cloud growth, and its decay, are arbitrarily matched to the measured data; the decay rate probably indicates the effects of recombination and attachment. Although, from the Brode model, the contact surface remains fairly constant at its maximum radius for a long period of time, the radar cross section depends on the electron density contained within the contact surface. At 94 km altitude, recombination and attachment are important mechanisms and tend to reduce the cross section quickly.

The curve segment indicated by x's has been calculated by removing the contributions of three of the largest discrete spectral components discussed above, assuming that they represent echoes not associated with the overall cloud boundary. It can be seen that this expedient permits the experimental data to fit the smooth growth and decay profile, particularly after 30 or 40 sec. Indeed, the removal of the single discrete spectral component which appears between 2045:30 and 2045:42 in Fig. 3 (roughly between 50 and 62 sec in Fig. 5) places the x'ed curve quite close to the dashed one. The earlier period between 2045:00 and 2045:15 in Fig. 3 permits no such simple component removal, because there appear to be several contributing discrete components. Removal of the two largest ones reduces the measured data to the small x'ed peak in Fig. 5 between 20 and 35 sec.

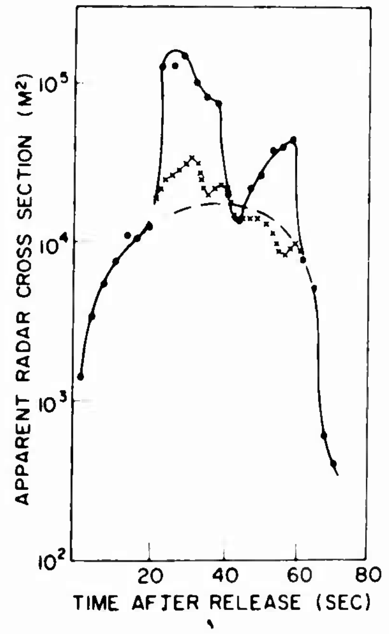

Fig. 5 - Plots of apparent radar cross section vs time after release for hf radar data

The quasi-stable cross-sectional value of $1.7 \times 10^4\ m^2$ indicated by the dashed curve in Fig. 5 agrees quite well with the predicted value of $3 \times 10^4\ m^2$. The x'ed curve peak value of $3.5 \times 10^4\ m^2$ agrees even more closely with the prediction. This value also is in good agreement with the results of previous experiments (4). It should be noted, however, that the growth rate to full expansion indicated by Fig. 5 has a time constant that is closer to 10 sec than the 0.1-sec figure obtained by scaling Brode's results. This result departs significantly from both optical and radio-frequency data acquired at somewhat higher altitudes (3), which agreed closely with Brode's work. However, it is clear from Fig. 3 that the purely specular phase of the cloud echo's development (that is, the period in which its doppler spectrum consists of a single, relatively narrowband component) cannot have continued for more than 4 sec (the time between the burst and the end of the data represented by the first photograph in Fig. 3). It is likely that the greater importance of turbulent diffusion at this lower altitude in governing the plasma cloud's evolution obscured whatever demarcation might otherwise be made between the nearly instantaneous blast-wave expansion and the more gradual turbulent diffusion which succeeds it. The 60-sec duration of the target detected by the NRL radar is consistent with other measurements made during similar circumstances (4).

With the background of the spectral data presented in Fig. 3, and the behavior of the radar cross section illustrated in Fig. 5, a preliminary assessment of likely sources for the short-lived, discrete spectral components discussed above is appropriate. Studies of rocket-emitted chemical "smoke" trails (5,6) show the very strongly turbulent nature of fluid motion in the lower E layer. Indeed, photographs of chemiluminescent clouds within this region show that they display a striking billowy character, not dissimilar to the upper portions of cumulus clouds. It is tempting to associate these large, discrete components with the formation of large, globular billows, which result from turbulent diffusion in the expanding plasma cloud. An interpretation of this type requires that the plasma cloud be visualized as an initially spherical bubble, which develops a limited number of ruptures within its lifetime. These ruptures permit large, globular bubblets to form on the cloud surface, which grow rapidly to dimensions of the size of their parent, and then become underdense and hence undetectable to a radar observer. This description is speculative at present, but it should be noted that the dimensions of globules observed in chemical trail releases (5,6) are not inconsistent with the radar cross sections measured in this experiment.

The remaining possibility, that is, the notion that the large, specular-echo components were actually manifestations of plasma resonances in the cesium cloud, connot be substantiated without further effort. A limited amount of theoretical work (7) supports the idea that such resonances are likely characteristics of ionospheric irregularities, but no explicit experimental data exist to verify this idea. It should be mentioned that atmospheric turbulence, the very phenomenon which characterizes the globular, billowy cloud evolution suggested above, is intimately involved in the processes that permit plasma resonances to develop.

Figure 6 is a pair of doppler-shift-vs-time displays of the vhf radar information acquired in two adjacent range gates during the cesium-cloud release. The upper display, at closer range, shows by the narrow, vertical stripe appearing adjacent to its left-hand edge (an artificially introduced time strobe) the time of firing of the 7-in. gun. The bright, blobby trace which begins almost immediately and zigzags up and down rapidly across the display is the early portion of the shell trajectory before the release of the ion cloud. It should be noted that the vertical scale on Fig. 6 is labeled relative doppler shift. Because the vhf transmitter and receiver local oscillator's frequencies were not locked to the hf radar signal processor's internal clock, the data in Fig. 6 do not represent absolute doppler shift relative to the vhf transmitter frequency. Indeed, the vhf radar oscillators do not remain stable over periods of several seconds, and thus the data in Fig. 6 have superimposed upon them the drift of the vhf frequency sources. The wobbly line that appears across the upper third of both photographs is leakage from the vhf transmitter oscillators and illustrates graphically the reason for describing this radar's operation as quasi-coherent.

The lower photograph in Fig. 6 contains radar signal information from the latter part of the shell's trajectory and from the release. The signal level introduced into the signal processor was raised for this photograph to permit the brief, diffuse echo associated with the release to be seen. The two inverted-W traces in the lower left-hand corner, as well as the wobbly line extending across the width of this photograph, are all associated with vhf oscillator frequency leakage and should be ignored. A few zigzag traversals of the 2.0 to 22.2-Hz available doppler bandwidth indicate the last portion of the shell trajectory, and the release occurs at the left-hand edge of the last bright vertical band. An extremely high-amplitude, short-duration echo follows immediately, displaying for the 3-sec integration time of this photograph a spectral bandwidth in excess of the 20.2-Hz available. This initial return dissipates rapidly, leaving a diffuse, decaying return that appears to persist for 15 sec or so longer before becoming obscured by noise. This later effect also has components throughout the 20.2-Hz available doppler bandwidth, although they seem to become compressed toward (relative) zero toward the end of the interval. That some components in this decaying or dissipating echo occur as vertical bands on Fig. 6 suggests that several short-duration scatterers or scattering concentrations are involved. A careful comparison of the times at which these vertical bands occur with the hf spectral data in Fig. 3 indicates that they take place during the same period(2045:00 to 2045:12) as the large, specular echoes in the hf data. The vhf signal is nearly at noise level during this period, and so only an estimate of its effective radar cross section can be made: it is estimated that the brief, vertical bands in Fig. 6 represent a vhf radar cross section less than 0.1 m^2.

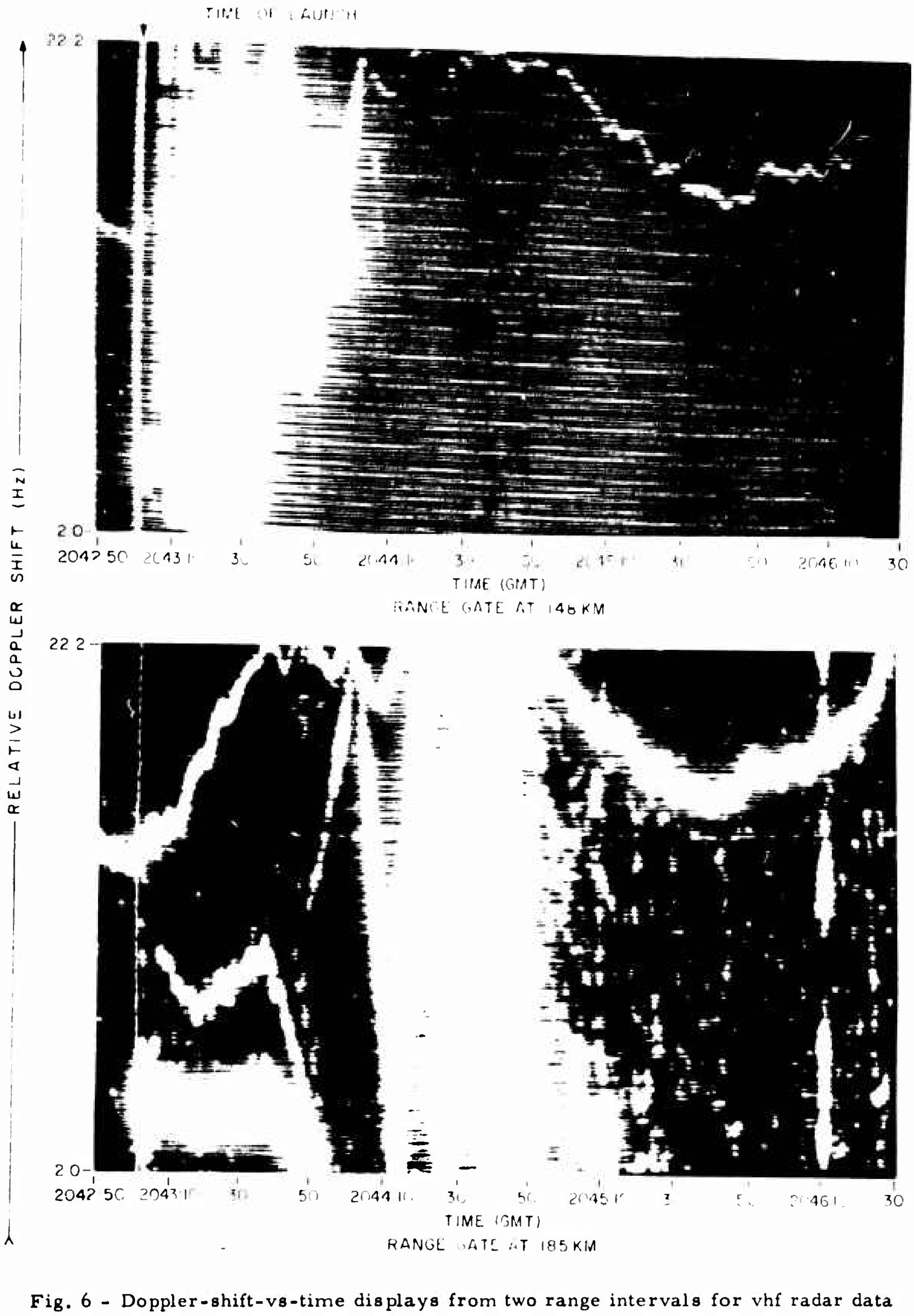

Fig. 6 - Doppler-shift-vs-time displays from two range intervals for vhf radar data

Figure 7 is a collection of amplitude spectra taken with 0.3-Hz-resolution bandwidth at 3-sec intervals through the vhf cesium cloud signature. Amplitude appears vertically as an arbitrary linear scale, and relative doppler shift appears horizontally in hertzes. The first photograph, at 2044:37, illustrates the quiescent, prerelease condition. A series of smooth undulations at the left side of the photograph represents the echo from the rising canister. The wobbly line that appeared in Fig. 6 across nearly the whole display is momentarily off-scale in this photograph. The second photograph, taken at 2044:40, contains the beginning of the large, diffuse signature associated with the release. Once again, implicit integration of 3 sec causes the data represented in each photograph to extend for 3 sec, centered on the nominal time labeled on the photograph. This initial signature has a magnitude in excess of 100 m^2 radar cross section at vhf and persists until 2044:46, at which point its spectrum appears to be largely concentrated to within a single 3-Hz band. The subsequent photograph, at 2044:49, shows only a small spectral peak at the far right, associated here with transmitter frequency leakage. In the next photograph (also at 2044:49), the sensitivity level has been raised by 12 dB to permit a residue of the diffuse release signature to be discerned. In this and following photographs, a substantial noise contamination exists, and the vhf oscillator frequency leakage dominates the right-hand edge of the spectrum display. The next subject of interest involves the series of photographs from 2045:01 to 2045:13, in which may be seen the contribution from the brief, discrete components described as vertical bands in Fig. 6. Two distinct contributions exist: the initial spectral peak, most evident in the photograph at 2045:01, displays a bandwidth of about 1 Hz. This component gradually declines in amplitude, and a new one, apparently lower in relative doppler shift, occupies a 1-Hz bandwidth in the photograph at 2045:13. Both contributions are relatively narrow in spectral dispersion, and compare roughly to the bandwidth of the corresponding spectral peaks in Fig. 3. By 2045:16, there remains only a vestige of the ion cloud echo, with the ever-present transmitter frequency leakage as the dominant feature of the spectrum.

The compressed spectral extent of the small, later, vhf echo components, together with the comparable spectral extent of the larger hf echo components to which they correspond, suggests on first appraisal that they represent moving, or expanding, transient concentrations of electrons. Their larger apparent size at hf, when considered together with their similar spectral appearance at both frequencies, suggests that somewhere within the electron cloud there exist large, rapidly moving boundaries with a plasma frequency of 15.7 MHz, and much smaller, more slowly moving boundaries with a plasma frequency of 138 MHz. Thus an intuitive picture may be drawn of expanding, turbulent bubbles whose relatively low-density outer edges are advancing rapidly, while their relatively high-density inner regions are expanding much more slowly. The existence of discrete echo components at vhf at the same time as the large, discrete components at hf supports the notion that the scatterer is in each case a fleeting concentration of electron density. This suggestion fits closely into the speculative picture of a rapidly evolving, billowy cloud structure, which was sketched briefly above.

However, the very size of the hf radar cross sections displayed by these discrete components, together with the agreement between measured hf radar data and predictions based upon a Brode model, when these components are removed, prohibits the authors from concluding that this picture of an expanding ensemble of several turbulent plasma bubbles can by itself explain the experimental results. The notion, that brief bursts of resonant interaction within the plasma cloud can arise from electromagnetic waves incident on the cloud boundary and then permit large-amplitude reflections to propagate to the radar site, cannot be discarded. Indeed, the occurrence of concurrent bursts at vhf and hf can be interpreted as manifestations of resonant behavior within the cloud resulting in the reception of oscillation products at both hf and vhf, with some nonlinear process within the cloud to relate the two.

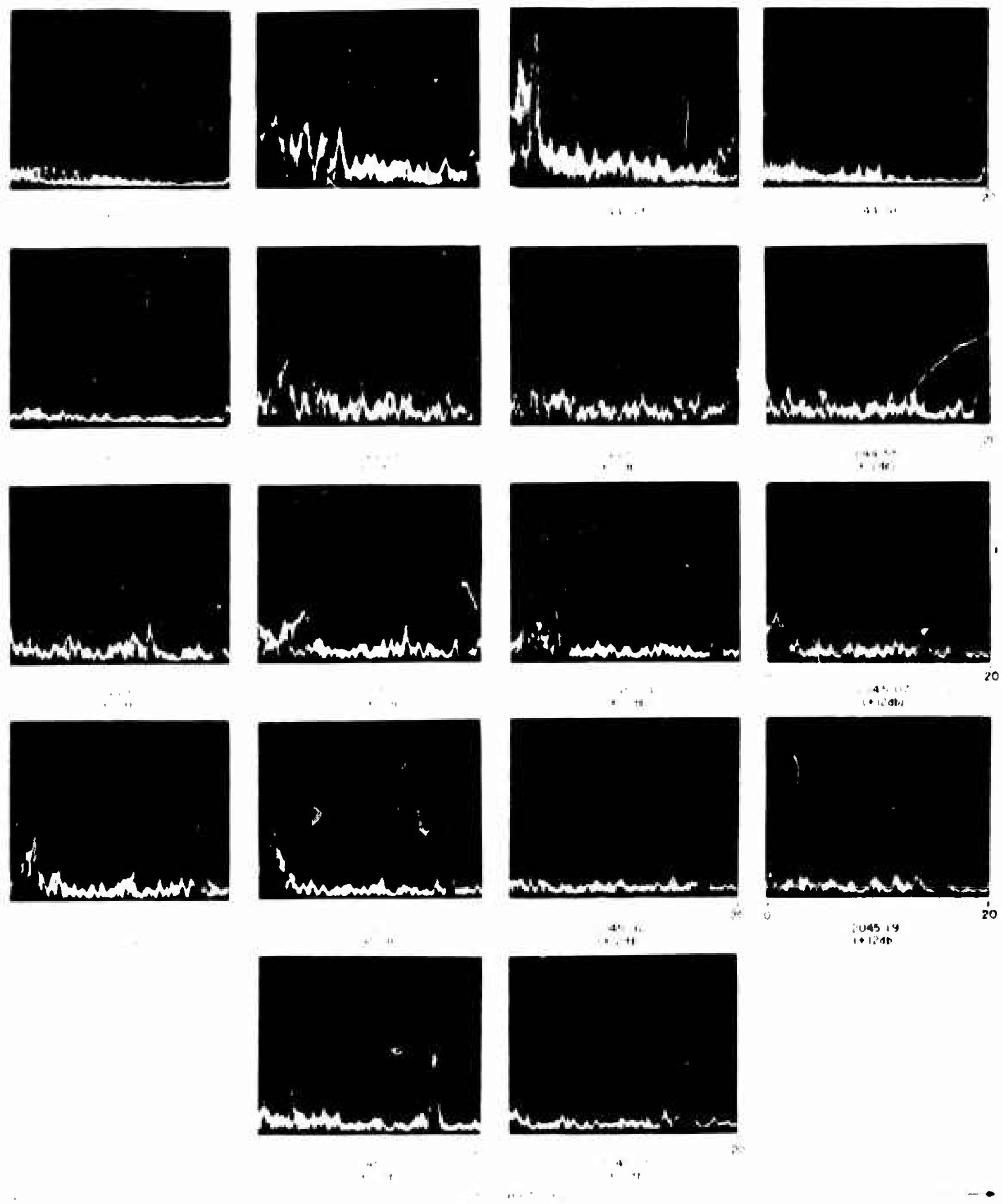

Fig. 7 - Amplitude spectra of vhf radar data from cesium cloud

IMPLICATIONS OF THIS EXPERIMENT AND RECOMMENDATIONS FOR FUTURE INVESTIGATIONS

The most clearly apparent result of this study has been to demonstrate the unique characteristics of advanced research radars for detailed examination of the entire dynamic behavior of ionospheric plasma clouds. This initial investigation has stressed the spectral resolution, which is the forte of doppler radar, and the application of this spectral resolution to studying internal motions in a plasma cloud. It is anticipated that the accumulation of similar data for future cloud releases will ultimately permit a description of the turbulent motions or plasma resonances that manifest themselves in the diffuse, rapidly changing doppler spectra observed. It should also be emphasized that these techniques are equally applicable to the study of turbulences, wind motions, and instabilities in the unperturbed ionosphere as well. The same effects, be they shearing winds or plasma oscillations, which cause such familiar phenomena as sporadic-E, spread-F, and traveling irregularities, may be responsible for much of the apparent turbulence in an artificial plasma cloud. The availability of vhf and uhf radar, whose data may also be subjected to detailed spectral inspection, permits turbulent phenomena to be investigated over a range of scale sizes from meter through decameter wavelengths. However, spectral sensitivity provides but one dimension of the overall radar resolution cell, and while doppler radar provides spectral resolution, there remains a wealth of information to be acquired by adding the spatial dimension to this resolution cell. Highly directive antennas permit angular resolution to be achieved, and NRL's research radars possess this quality. Short pulses provide depth or range resolution, and to a certain extent advanced hf research radars embody this feature as well. However, it is only in the meter-wavelength region and at shorter wavelengths that fractional-steradian beamwidths and microsecond pulse lengths are available to actually map the detailed spatial structure of an evolving plasma cloud, and it is chiefly for their superiority in spatial resolution that the vhf and uhf radars are valued; this capability can be more thoroughly exploited in future studies.

In summary, it is believed that the inclusion of the meter- to decameter-wavelength region, in a coordinated investigation of artificial as well as natural ionospheric plasma phenomena, provides an opportunity to construct a spectral/spatial resolution cell small enough to discern and resolve the internal dynamics of plasma clouds in the ionosphere. It is emphasized that the most sophisticated available spectrum-analysis techniques must be employed in this effort, and that narrow-beamwidth, short-pulse vhf and uhf radars must be utilized as well. Coordination among these radars in studying artificial and naturally occurring ionospheric perturbation phenomena should permit a determination both of processes peculiar to artificial plasma clouds in the ionosphere and of natural processes that manifest themselves upon both artificial and naturally occurring ionospheric perturbations.

It may be added that insofar as certain aspects of high-altitude nuclear explosion effects upon radar performance may be investigated in the study of chemical plasma clouds with hf and vhf radars, studies of the type described here provide the highest likelihood of success.

For the fullest possible exploitation of available radar techniques in ionospheric plasma studies of the types discussed here, a large number of plasma cloud releases will be required. The full spectrum of ionospheric processes can be studied only if releases are performed under many conditions of solar illumination, at many geographical locations, and under various meteorological conditions. Both diurnal and seasonal variations must be considered. In addition to these general requirements, however, there are certain specific investigations which should be conducted to study particular ionospheric processes. For example, in seeking evidence of wind-shear effects in ionospheric-layer structure, it is recommended that a series of releases be conducted with the intent of depositing a plasma source in a region of high shear. A preliminary, trail-type release of some luminous substance could be made to indicate high-shear regions, which then could be inoculated by a cloud- or burst-type plasma release as a source of electrons. The radars would then study the temporal behavior of the resulting plasma cloud. Alternatively, a trail-type release of ionizable material such as cesium could be deposited by a vehicle traversing a region in which strong shearing motion is suspected, and the resulting plasma trail could be illuminated by radar to discern concentrations of electron density along the trail. Coordinated forward- and backscatter radar studies could be made, with the use of stations beyond the plasma cloud to measure signal strengths. A sophisticated variation of this type of operation would involve the use of a rocket- or satellite-borne station placed above the cloud. This station would not only permit absorption measurements through the cloud, but would permit electron-density measurements to be made by the measurement of polarization rotation and differential doppler. The available phase-coherent hf, vhf, and uhf radar devices are obvious candidates for such an operation.

A further variation of the bistatic technique could employ a vehicle which actually traverses the plasma cloud. This vehicle could not only provide a reflecting surface for radar measurements and a platform for beacons and/or receiving apparatus, but could also carry independent instrumentation to measure electron density and the direction of flow of electron current in the plasma cloud.

ACKNOWLEDGMENT

The authors are pleased to acknowledge the contributions of Messrs. A.M. Knopp and M.W. Lehman of the Search Radar Branch, NRL, in acquiring the vhf radar data for this study.

REFERENCES

1. Brode, H.L., "Blast Wave from a Spherical Charge," Phys. Fluids 2:217 (1959)

2. Rosenberg, N.W., "Ionospheric Temperatures Obtained from Photography of Shock Waves," J. Geophys. Res. 69:2323 (1964)

3. Rosenberg, N.W., Conley, T.D., Curley, S.R., and Lorentzer, A.H., "Studies of Detonations at Ionospheric Altitudes Under Project Red Lamp," AFCRL Technical Report, AFCRL-65-356, May 1965

4. Rosenberg, N.W., and Golomb, D., "Propagation by High Altitude Chemical Plasma Release," in Rosenberg, N.W. (ed.) Project Firefly 1961-1962. AFCRL Technical Report AFCRL-64-364, May 1964

5. Blamount, J.E., and de Jager, C., "Upper Atomospheric Turbulence Near the 100 km Level," Ann. Geophys. 17:134 (1961)

6. Blamont, J.E., "Turbulence in Atmospheric Motions Between 90 and 130 km of Altitude," Planetary and Space Sci. 10:89 (1963)

7. Herlofson, N., "Plasma Resonance in Ionospheric Irregularities," Arkiv Fysik 3:247 (1951)

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Research Laboratory Washington, D.C. 20390	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

THE EVOLUTION OF AN ARTIFICIAL IONOSPHERIC PLASMA CLOUD AS STUDIED BY HF AND VHF RADAR

4. DESCRIPTIVE NOTES (Type of report and inclusive dates) An interim report on one phase of a problem; work is continuing on this and on other aspects of the problem.

5. AUTHOR(S) (First name, middle initial, last name)

J.R. Davis and S.R. Curley

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
April 3, 1969	20	7

8a. CONTRACT OR GRANT NO. NRL Problem R02-23 b. PROJECT NO. USAF MIPR FD2310-7-0016 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 6865 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Department of the Air Force, Washington, D.C. 20330

13. ABSTRACT

A plasma cloud was created at an altitude of 94 km over Wallops Island by exploding a canister of a cesium compound, which had been fired from a 7-in. gun. This cloud was illuminated from NRL by hf and vhf radar. The results of coherent pulse doppler analysis of the cesium cloud signature indicate that the cloud evolved in a billowy manner, with turbulent eddies of about 10^4 m^2 cross section appearing at several times within the nominal 70-sec duration of the signature. It was the presence of large-amplitude, specular echo components in the cloud signature that led to the suggested behavior of a cloud evolving in a billowy manner. The fact that these could be due instead to transient resonances in the plasma cloud cannot be completely discounted.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Ionospheric physics						
Plasma - ionospheric interaction						
Coherent pulse doppler analysis						
Ionospheric research radar						
Plasma cloud signature						