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**DEVELOPMENT OF A DOPPLER
RADAR TECHNIQUE FOR THE
DETECTION OF BIRD HAZARDS TO AIRCRAFT**

JUNE 1976

FINAL REPORT: MAY 1972 - DECEMBER 1975

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19 REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
18. REPORT NUMBER AFCEC TR-76-17	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) DEVELOPMENT OF A DOPPLER RADAR TECHNIQUE FOR THE DETECTION OF BIRD HAZARDS TO AIRCRAFT.	5. TYPE OF REPORT & PERIOD COVERED Final Report. 19 May 1972 - 12 Dec 1975	
6. AUTHOR(s) John L. Green Ben B. Balsey	7. PERFORMING ORG. REPORT NUMBER	
8. CONTRACT OR GRANT NUMBER(s) AFWL 72-088	9. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 63223F, 2103, 303	
10. PERFORMING ORGANIZATION NAME AND ADDRESS US Dept of Commerce, National Oceanic and Atmos- pheric Administration, Environmental Research Lab- oratories, Aeronomy Laboratory, Boulder CO 80302	11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Civil Engineering Center Tyndall Air Force Base, Florida 32401	
12. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 12 92p.	13. REPORT DATE 12 Dec 1975	
	14. NUMBER OF PAGES 92	
	15. SECURITY CLASS. (of this report) UNCLASSIFIED	
	16. DECLASSIFICATION/DOWNGRADING SCHEDULE	
17. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited. 16 AF-2103		
18. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
19. SUPPLEMENTARY NOTES Available in DDC.		
20. KEY WORDS (Continue on reverse side if necessary and identify by block number) Doppler Radar Techniques, Bird Hazard to Aircraft, Radar Ornithology		
21. ABSTRACT (Continue on reverse side if necessary and identify by block number) The purpose of this research project was to develop a radar technique to detect the presence of flying birds potentially hazardous to aircraft near airport runways; to distinguish them from other radar targets; to estimate the size and number of birds in order to assess the hazard. The motions of a bird in flight are characterized by a distinctive velocity spectrum that can be detected by radar. These "aural signatures" were identified by Doppler technique and verified by visual sightings. This report provides a description		

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20. ABSTRACT (Concluded)

of the analysis techniques, compares range-gated to nonrange-gated systems and also conventional and Doppler radars. A discussion concerning modification of a typical system to a Doppler system is included. A method of determining the actual number of birds in the target volume is discussed. The report also includes a scene-by-scene description of a film presentation made to more fully quantify the Doppler technique.

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PREFACE

This report covers the work done under Air Force Contract AFWL 72-088 by the Aeronomy Laboratory, Environmental Research Laboratories, National Oceanic and Atmospheric Administration, Department of Commerce, Boulder, Colorado, during the period July 1972 through June 1974.

This report has been reviewed by the Information Officer (IO) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public including foreign nations.

This technical report has been reviewed and is approved for publication.

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1. INTRODUCTION

The purpose of this project was to develop a radar technique to detect the presence of birds hazardous to aircraft near airport runways, to distinguish these birds from other radar targets, and to estimate the size and number of birds in order to assess the hazard.

Collisions between aircraft and flying birds cause considerable damage to aircraft and, more importantly, cause loss of human life. Since most of these collisions occur near airports during takeoffs and landings, this hazard could be reduced by the installation at airports of a suitable "bird detection" radar system that would enable control tower personnel to establish the presence of, and to identify, large or small birds in a flight path. To maintain a small false alarm rate, this bird detection radar system should readily distinguish flying birds from other radar targets such as clear air turbulence, precipitation, swarms of insects, aircraft, and motor vehicles, or combinations of these targets. Because the collision hazard to aircraft increases with the size of the bird, this radar system should have the capability of estimating the size of the bird being detected. Also, because the probability of collision increases with the number of birds in the area, and because of the fact that a large number of small birds ingested by a jet engine can cause a sudden total loss of power, this radar system should be capable of giving an estimate of the number of birds in the flight path.

There are three characteristics of flying birds that can reasonably be measured by radar:

1. Radar cross-section
2. Mean velocity relative to the radar (i.e., radial velocity)
3. Motions of flight particular to the type of bird(s)

The radar cross-section, as used here, refers to the total effective target cross-section of a specific bird or birds and includes both body and wing areas. The mean (radial) velocity refers to the apparent velocity of the target in a direction along the radar beam. Motions of flight refers to specific motions of various parts of the bird (wings, body, tail) and their time-varying character.

The radar cross-section is typically obtained by comparing the total power scattered (or reflected) from a target with the transmitted power, taking account of other factors (antenna gain, target range, transmitted pulse widths, etc.).

The mean radial velocity is ordinarily inferred from a conventional radar by changes in position of the target on a plan position indicator (PPI) during repetitive observations. Mean radial velocity is also obtainable from the mean Doppler shift of the target by using a Doppler radar (cf. subsequent sections of this report).

The motions of a bird (or birds) in flight gives rise to a distinctive velocity spectrum that can be detected by a suitable Doppler radar (ref. 1 and 2 and also Section 4 of this report). Doppler radar, as used in this sense, refers to a special class of radars that can determine the velocity of a target from the Doppler shift of the radar return (the operation of a Doppler radar is covered in detail in Section 3 of this report). The motions of bird flight also give rise to an amplitude modulation of the radar return. This feature has been used by various workers to examine wingbeat characteristics (see, for example, ref. 3).

-
1. Green, J. L., "The Application of Doppler Radar to the Study of Flying Birds", MS Thesis, University of Colorado, Boulder, 1973.
 2. Flock, W. L. and J. L. Green, "The Detection and Identification of Birds in Flight, Using Coherent and Noncoherent Radars", Proc. IEEE, 62, 745-753, 1974.
 3. Vaughn, C. R., "Intraspecific Wingbeat Rate Variability and Species Identification Using Tracking Radar", Proc. of the Conference on the Biological Aspects of the Bird/Aircraft Collision Problem, Sidney A. Gauthreaux, Jr., Editor, Clemson Univ., Clemson, SC, Feb. 5-7, 1974.

The present study, however, has concentrated on the Doppler radar detection of the motions of bird flight, since it appears to offer a better solution to the problem: while the normal amplitude modulation data contains only information on the temporal variation of the effective target cross-section, the Doppler data also contains precise information on the radial velocity components of each segment of a specific target (i.e., the velocity spectrum).

The velocity spectrum of the radar return can be explained by the simplified model of a flying bird shown in Figure 1. This model assumes that the hypothetical bird represented in the figure has a straight wing that pivots around its point of attachment to the body. It also assumes that each element, dL , along the length of the wing is visible to the radar. If one further simplifies this model by assuming the bird is sufficiently far from the radar so that θ (the angle between the line of the wing and the direction to the radar) is independent of L , then the total (V_{dL}) and radial (V_r) velocities of an element, dL , are given by

$$V_{dL} = L(d\theta/dt) \quad (1)$$

and

$$V_r = L \sin \theta (d\theta/dt) \quad (2)$$

Furthermore, the Doppler frequency output of the radar receiver, f_d , is related to the radial velocity V_r by

$$f_d = 2V_r/\lambda \quad (3)$$

where λ is the wavelength of the radar. It follows that the frequency shift of the radar signal due to the wing motion of the model bird is

$$f_d = 2 L \sin (\theta) (d\theta/dt) \lambda^{-1} \quad (4)$$

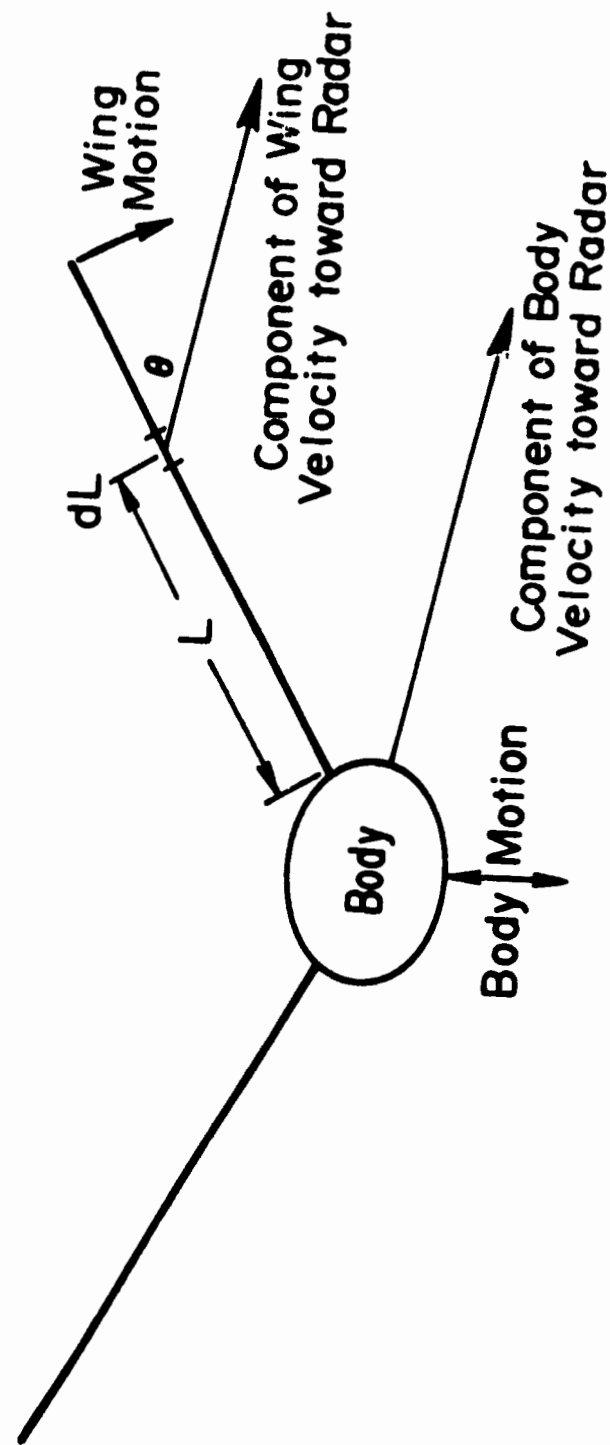


Figure 1. Simple Model of a Bird in Flight

or, in a more general functional form,

$$f_d = F(L, \sin \theta, d\theta/dt) \quad (5)$$

Since $\sin \theta$ and $d\theta/dt$ are periodic functions of the wing beat frequency of the bird, this model would predict that the resulting Doppler "signature" would vary at the wing beat frequency. The functional dependence on L indicates that each element dL would cause a different Doppler frequency at the output of the radar at a given instant of time. Thus the wing motion would appear to the radar as a distribution of frequencies or a "Doppler smear". The resulting velocity spectrum (see ref. 1) will be determined by the velocity and length of the bird wing (ref. 2) and will vary at the wing beat rate.

It is important to note that an estimate of the bird size (a feature that is important to the evaluation of the collision hazard) can be made by use of this radar spectrum. If we use the relation (ref. 4)

$$F \cdot L^{0.827} = 572 \quad (6)$$

where F = wing beat frequency and L = wing length, the wing beat rate derived from the repetition rate of the velocity spectrum can be used to estimate the size of the bird flying in the radar coverage.

The weight W of the bird can also be estimated. Figure 2 is a graph of wing beat frequency versus bird weight plotted from data for 41 species from Houghton and Blackwell (ref. 5). Also on this graph is a line representing the relation

$$F \cdot W^{0.2544} = 27.88 \quad (7)$$

4. Greenesalt, C. H., Hummingbirds, Garden City, NY, Doubleday Inc., 1960.

5. Houghton, E. W. and F. Blackwell. "Use of Bird Activity Modulation Waveforms in Radar Identification", Bird Strike Committee Europe, 7th Meeting, Frankfurt, Germany, 1974.

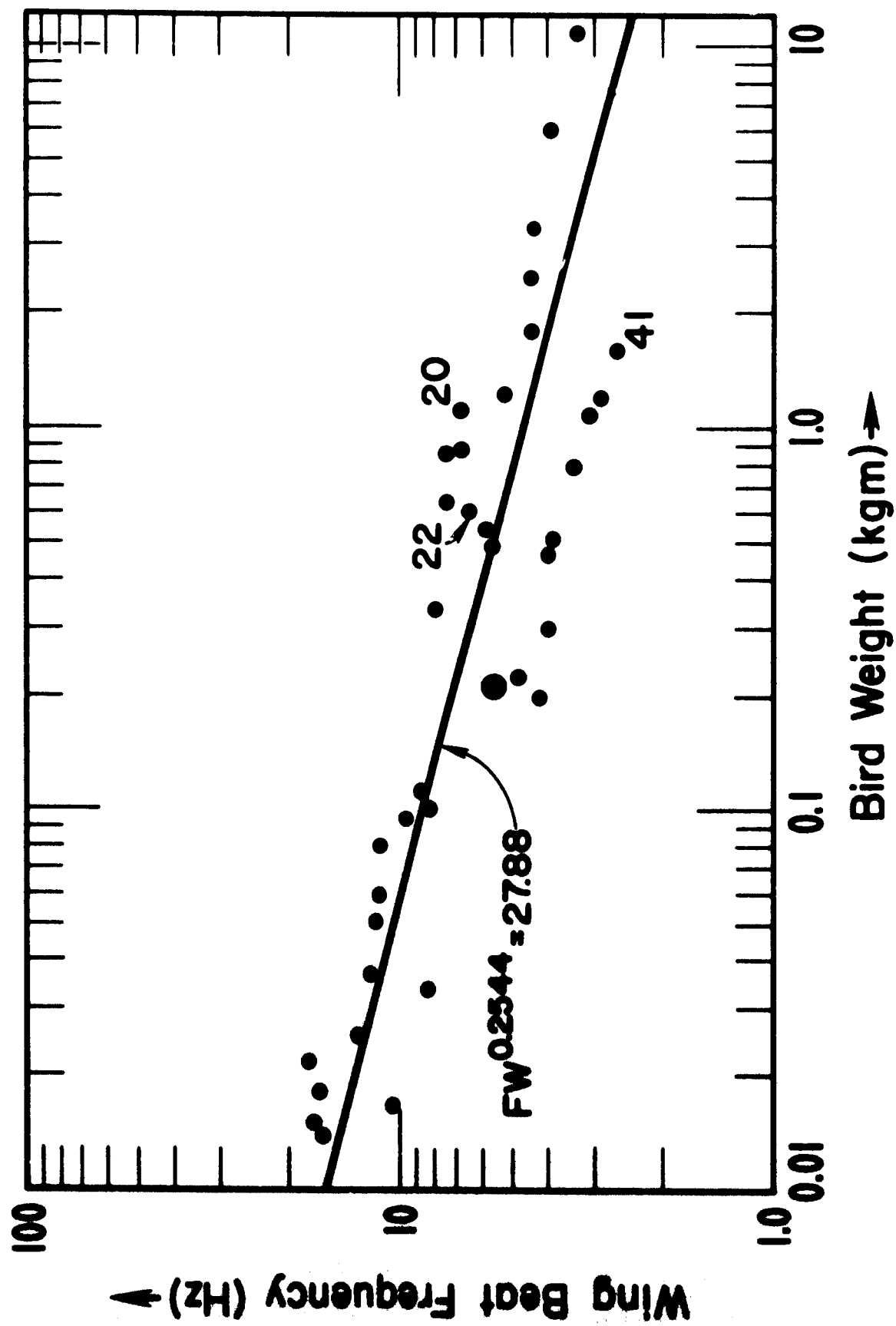


Figure 2. Bird Wing Beat Frequency Versus Weight

found empirically by the above authors where F and W refer to the wing beat frequency and the weight of the bird, respectively. It is evident from Figure 2 that, despite the scatter of the points, there is an inverse correlation between bird weight and wing beat frequency. It is also evident from Figure 2, that all species weighing more than 200 gm, which would include all species in which single individuals are hazardous, have a wing beat frequency less than or equal to 8 Hz.

An estimate of the number of birds in the radar coverage is also important in evaluating the collision hazard. Amplitude modulation analysis of radar returns from a number of birds is incapable of determining the type of bird within the beam (see Section 8 of this report) and is, therefore, incapable of establishing the number of birds within the echoing volume. Doppler analysis is significantly better in this instance, since the velocity spectrum of a number of bird returns is merely the linear superposition of the velocity spectra from all of the individual birds. Although the time varying features of the velocity spectrum are lost in the analysis of multiple targets, the shape of the velocity spectrum--a feature which is unique to the specific bird type--is retained. Knowledge of the radar cross-section of the particular bird type identified by the Doppler technique, plus information on the total echo cross-section, is sufficient to estimate the number of targets within the echoing volume.

At microwave radar frequencies, the Doppler shifts arising from the motions of flying birds lie within the range of the human ear. In our case, for $\lambda = 3.125$ cm, radial velocities will extend from 0Hz to about 4 kHz. This fortuitous feature of the microwave Doppler technique makes it convenient to examine characteristics of the "aural signature" of a variety of bird types. As will be discussed in subsequent sections, this aural analysis technique is

simple, relatively inexpensive, easy to become familiar with, and reasonably accurate. In short, we feel that the aural analysis technique is at present the most promising method for on-line identification of flying birds.

This research, then, is concerned with the development of a radar technique to detect the presence of flying birds potentially hazardous to aircraft. Subsequent sections will examine various aspects of this problem in greater detail. Section 2 will outline the basic mathematical concepts underlying the Doppler technique and will distinguish between the mathematical representations of Doppler and amplitude-modulation detection techniques. Section 3 contains a description of the radar system used in the present research effort. A description of the various analysis techniques is given in Section 4, while the observational program is covered in Section 5. Section 6 contains a scene-by-scene description of a film presentation made to more fully quantify the Doppler technique. The following section (7) compares range-gated to non-range-gated systems, while Section 8 compares conventional and Doppler radars. A discussion concerning the modification of a typical radar system to a Doppler system is given in Section 9. Section 10 describes the method of determining the actual number of birds in the target volume. The final section (Section 11) concludes with a discussion of the advantages and shortcomings of the various Doppler techniques.

2. MATHEMATICAL CONCEPTS UNDERLYING THE DOPPLER TECHNIQUE

The basic difference between Doppler radar systems and conventional radar systems lies in the capability of the Doppler radar to obtain precise information on the frequency (or frequencies) contained in the radar signal returned from an arbitrary target. The conventional radar system typically "mixes" or "beats" the transmitted frequency with a beat-frequency oscillator (BFO) to produce an intermediated frequency (IF), with no attempt to retain the Doppler frequency information contained in the incoming carrier; the resulting IF signal is detected by some simple non-linear device to extract echo-amplitude vs. range data. This is the kind of data used, for example, on normal Plan Position Indicator (PPI) radar screens and similar devices. The Doppler technique, on the other hand, retains the Doppler frequency information contained in the returned signal by mixing this signal with a precisely known frequency derived from the transmitted frequency. In the simplest case, one can visualize the process as one in which the transmitted frequency f_0 is mixed directly with the incoming frequency f_1 , where f_1 can be thought of as the transmitted frequency that has been Doppler-shifted by the motions of the target. The relationship between f_0 and f_1 is given by

$$f_1 = f_0 \pm f_d \quad (8)$$

where f_d is the Doppler shift due to the target motion (positive for an incoming target, negative for a receding target); it is directly expressible in terms of V_r , the radial velocity of the target relative to the observer, as

$$f_d = \frac{2f_0 V_r}{c} = \frac{2V_r}{\lambda} \quad (9)$$

where c is the velocity of light in the medium.

In order to better visualize the mixing process, it is necessary to define the transmitted signal $A_0(t)$ more explicitly as a function having a finite amplitude B_0 and changing sinusoidally with time t at a rate determined by the transmitted frequency; i.e., let

$$A_0(t) = B_0 \cos(2\pi f_0 t) \quad (10)$$

Corresponding expressions for the Doppler-shifted returned wave $A_1(t)$ would then be

$$A_1(t) = B_1(t) \cos(2\pi f_1 t + \delta) = B_1(t) \cos[2\pi(f_0 \pm f_d)t + \delta] \quad (11)$$

where the new value of the amplitude $B_1(t) \ll B_0$ reflects the fact that only a small portion of the transmitted signal is returned to the observer and that this portion, moreover, can be a time varying function due to temporal variations of the target cross-section or to other effects. Also note that an arbitrary phase term δ has been included to allow for the unknown phase relationship between the transmitter and the target. This value is necessary only for mathematical completeness and will be dropped in the subsequent treatment.

In the receiving process, the transmitted and received signals are combined after appropriate amplification and filtering. The process by which the signals are combined is called "mixing" and consists of electronically multiplying the two signals together. The resulting function $A'_x(t)$ becomes:

$$A'_x(t) = kB_0B_1(t) \cos(2\pi f_0 t) \cos[2\pi(f_0 \pm f_d)t + \delta] \quad (12)$$

Here the factor k allows for relative amplitude changes in both signals that are made in order to make the processing more compatible (clearly, mixing of the two signals using the original large transmitted signal amplitude and the

extremely weak returns available at the antenna terminals would be impractical). Trigonometric identities can be used to rewrite equation (12) as

$$A'_x(t) = kB_0B_1(t) \{ \cos[2\pi(2f_0 + f_d)t + \delta] \pm \cos(2\pi f_d t + \delta) \} \quad (13)$$

There are two major features to be examined in the above equation: first of all, the first term within the brackets contains frequencies of the order of twice the transmitted frequency so that this complete term can be easily filtered out electronically; the second term, on the other hand, contains only the needed Doppler shift information plus an arbitrary phase constant. The useable "zero beat" signal can therefore be written (after dropping the phase term δ and defining $B_a(t) = kB_0B_1(t)$ as:

$$A_x(t) = B_a(t) \cos(2\pi f_d t) \quad (14a)$$

In order to also determine the sense of the frequency shift, it is necessary to generate the quadrature component of equation (14a). This is done by shifting the reference signal (in this case, $A_0(t)$) by 90° in a parallel mixing operation. The quadrature component to (14a), $A_y(t)$, is

$$A_y(t) = \pm B_a(t) \sin(2\pi f_d t) \quad (14b)$$

where the positive and negative signs refer to the relative phase change ($\pm 90^\circ$) of the quadrature channel.

Note that in the above equation both the amplitude and Doppler information have been retained. By retaining the frequency information we have established a "frequency coherent" system. The amplitude information normally used in non-Doppler analysis is contained in the $B_a(t)$ term and reflects variations of the bird's cross-section with time. This term has, at most, crude information

about the wingbeat rate. The velocity variation (Doppler) information is contained in the f_d term in accordance with equation (9). These factors are discussed in greater detail in Section 8.

In summary, in standard amplitude analysis the detected signal retains only the $B_a(t)$ component; Doppler analysis, on the other hand, makes use of both $B_a(t)$ and the f_d variations.

Strictly speaking, the above treatment is applicable only in the situation when one is operating in a bistatic mode (closely spaced, but independent, transmitter and receiver) and where the system is operated in a continuous-wave, non-pulsed mode. Pulsed systems are somewhat more complicated mathematically, in that one must also take into account the characteristics of the transmitted pulse, the sampling of the received signal at the appropriate range, as well as the transmitted pulse rate. Although these features add to the complexity of the mathematical analysis, the basic principles of the Doppler technique are the same. This more complex mathematical development has been omitted in the present treatment.

3. THE RADAR SYSTEM

To pursue this research, a low-power, X-band, pulsed-Doppler radar was installed in a van type truck for portability during the first year of operation. After the first year, the system was installed in a trailer to provide more operating space. The pertinent parameters of this radar system are listed in the table below.

Radar Parameters

Frequency	9600MHz
Wavelength	3.125 cm
Output power (peak)	1 kW
Pulse length	.6 μ s
Range resolution	90 m
Antenna beamwidth	14°
Receiver noise figure	6 db
Maximum detection range	$\approx$ 1.6 km

Equipment specifications, including manufacturer model numbers, are given in Appendix A.

3.1 The Radar System

The basic concepts for a frequency-coherent, pulsed-Doppler radar system are illustrated in the block diagram shown in Figure 3. As shown in this figure, the transmitted frequency is derived in the lower left-hand box entitled "Transmitter Driver/Pulse Generator" and is directed to the antenna via a high-power amplifier (Transmitter). The transmitted frequency is also directed to the mixer circuitry (Frequency-Coherent Demodulator) to be mixed with the

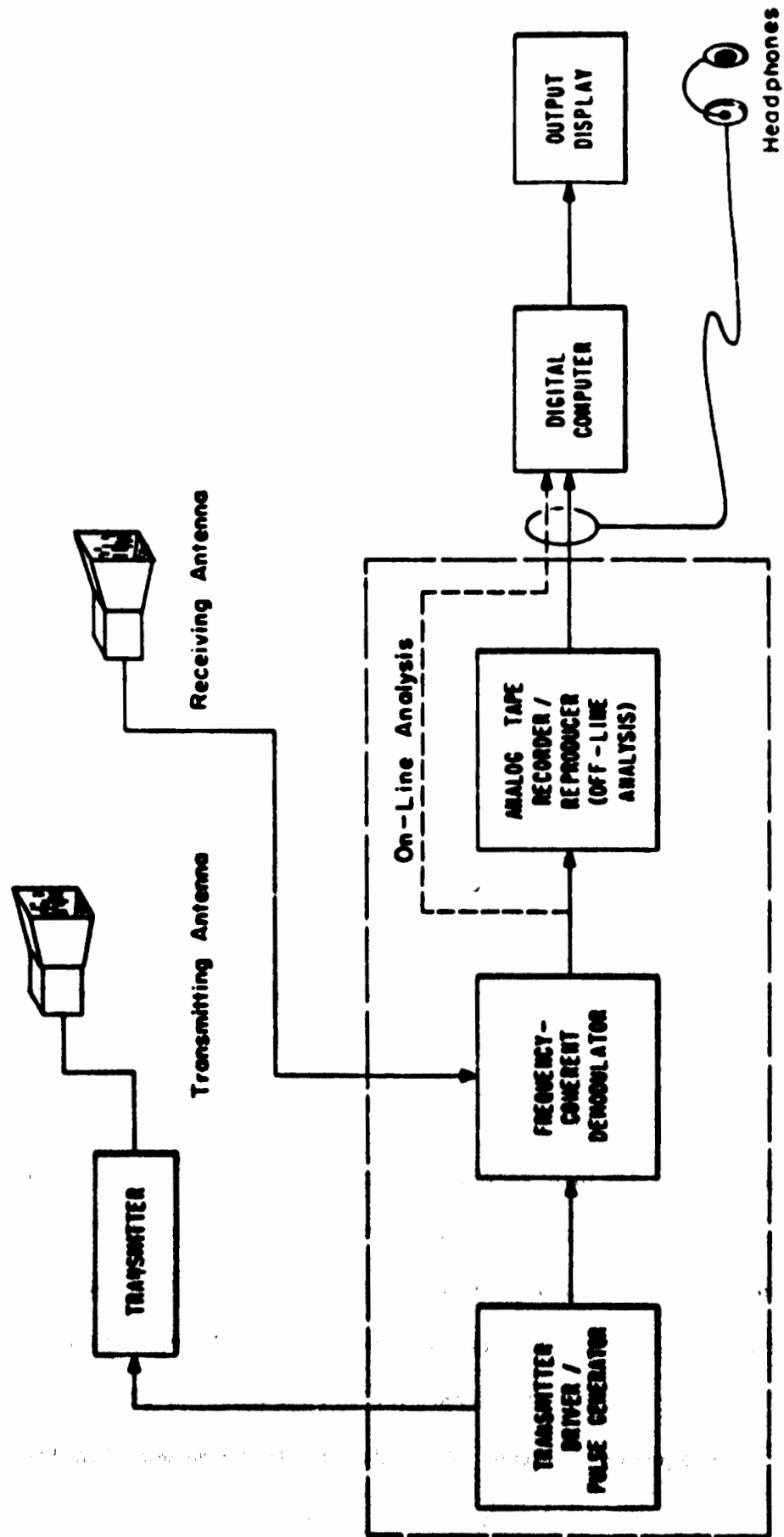


Figure 3. Block Diagram of a Frequency-Coherent Radar System

incoming signal. The other mixer input comes directly from the "Receiving Antenna". The mixer outputs (the arrow leading from the Frequency-Coherent Demodulator), after being filtered to remove the double frequency components derived from the $2f_0$ term, contain the zero-beat quadrature information described in equations (14a) and (14b). These two output signals can be treated in a variety of ways that will be discussed in subsequent sections of this report. The signals can be either analyzed directly by digital computer techniques or by other means as indicated by the dashed line path in Figure 3; it is also possible, and usually desirable, to record the analog signals directly onto magnetic tape for later analysis. Since this particular system involves a pulsed (rather than a cw) radar operation, echoes from targets at a given range arrive at the receiving antenna at a given time after the transmitter pulse has occurred. Signal returns at ranges other than the target range are unimportant and can be eliminated by "sampling" the data only at the desired range (see also Section 7). These "range-gated" samples contain all of the desired information, and it is this data which is in fact (1) recorded onto magnetic tape and/or (2) analyzed by on-line analysis techniques.

3.2 The Receiver

Schematic diagrams of the Frequency-Coherent Demodulator and Transmitter blocks are shown in Figure 4. A complete description of the various modules comprising the demodulator unit has been given in a prior publication (ref. 6), which is attached as Appendix B. Figure 4 shows that the actual mixing process involves a double conversion/mixing operation and not the simple single conversion

6. Balaley, B. B., A Portable Frequency Coherent Spectrum Analysis for Radar Applications, NOAA Technical Report, ERL 204-AL5, Boulder, CO, 1971.

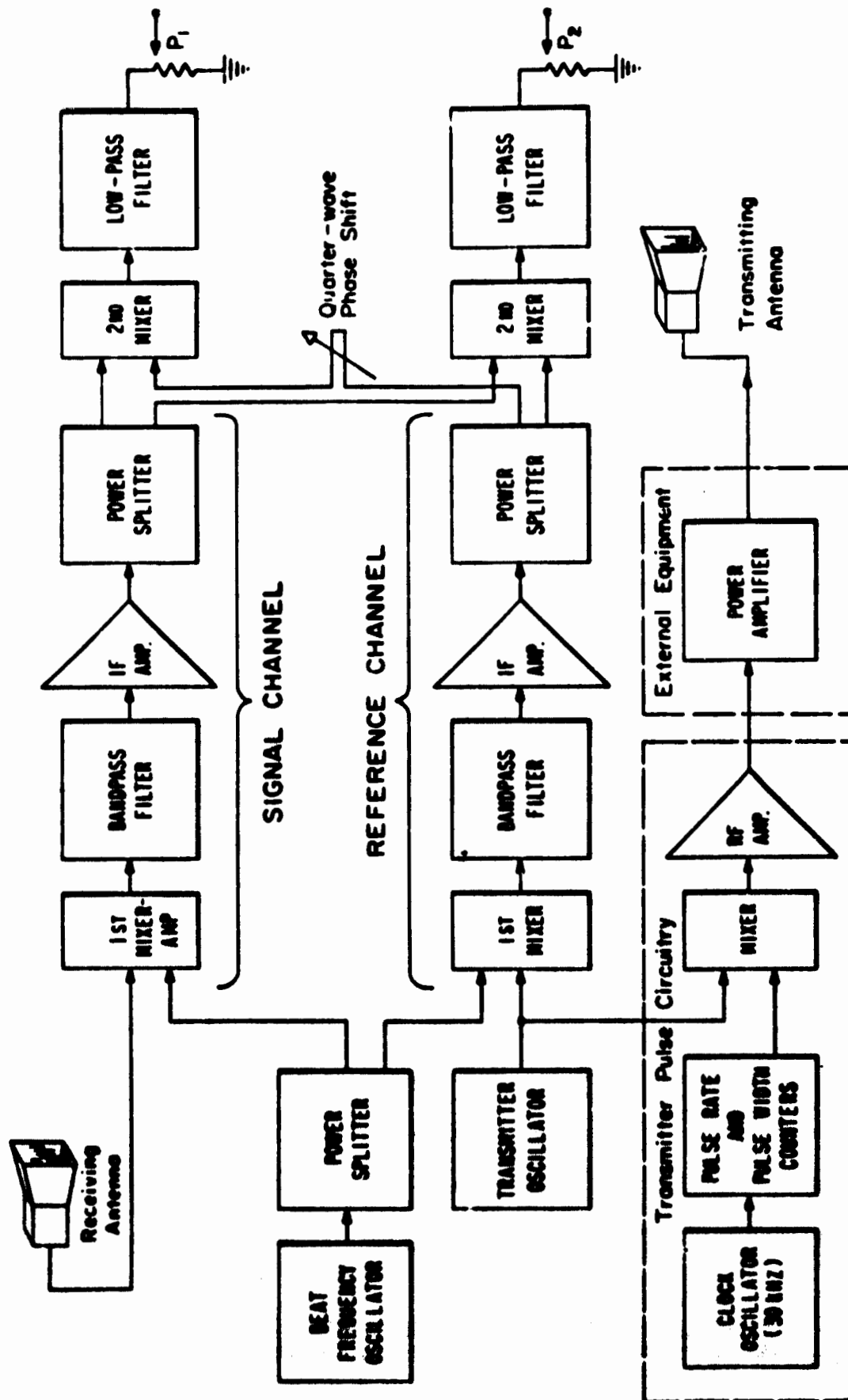


Figure 4. Receiver-Transmitter Block Diagram

concept shown schematically in Figure 3 (and discussed in Section 2). The basic reason for this is that the relatively narrow (1 MHz) bandwidths required for this type of radar analysis are not directly obtainable in a single zero-beat process at microwave frequencies; it was therefore necessary to make use of a double conversion process, reducing the signal bandwidth in the intermediate stages. This in no way affects the results described here.

For the present system, the transmitted frequency was nominally 9,600 GHz and the first conversion was accomplished by mixing both the transmitter signal (for the reference channel) and the received signal (for the signal channel) with a second microwave beat-frequency oscillator set at 9,600 GHz. The resulting 30 MHz (signal and reference) frequencies were fed through appropriate bandpass filters and intermediate frequency amplifiers. The 30 MHz reference and signal channels were then mixed together in two second-mixer circuits. Both mixer circuits were identical, except that in one of the channels there was an additional quarter wavelength section of coaxial cable inserted to change the phase of the 30 MHz signal by 90° for the quadrature requirement. Both output channels, after mixing, contain double-frequency (about 60 MHz) and zero-beat components. The unwanted double-frequency components were eliminated by the low-pass filters shown on the right-hand side of the diagram. The quadrature outputs were available as indicated as signals P1 and P2.

The receiving equipment is shown in Figure 5. The top panel contains the receiver gain control, the 30 MHz intermediate frequency amplifier, the 30 MHz reference amplifier and the coherent detector. The center panel contains the receiver output filter and the range gates. Below the center panel is the audio amplifier to be described later. The lowest panel contains the range gate generator.

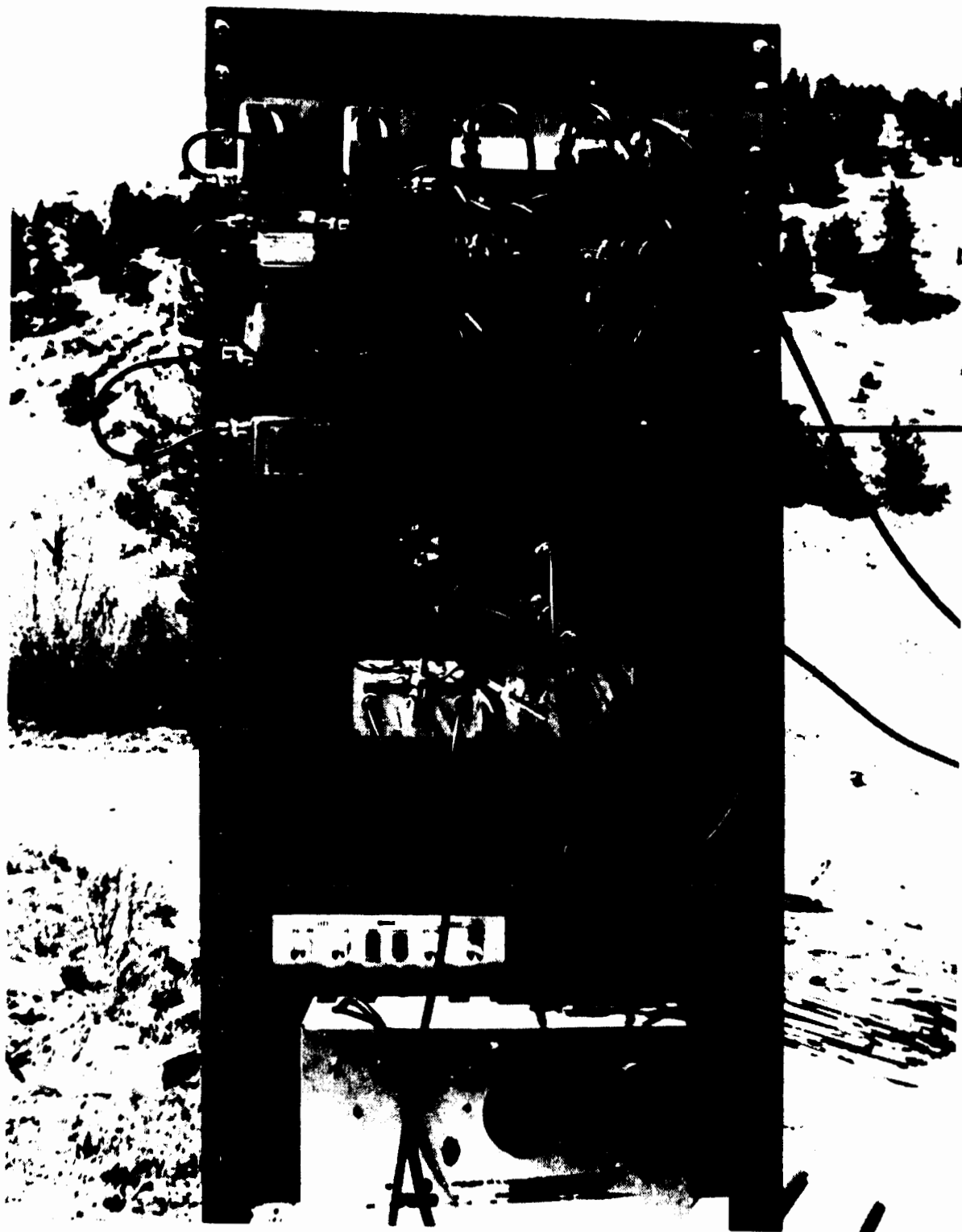


Figure 5. Coherent Receiver, Range Control and Audio Amplifier Rack

3.3 The Transmitter

The transmitter used for the majority of our studies was a reasonably portable 1 kW pulsed system. The transmitter frequency was generated by a Gunn-effect microwave oscillator operating at the approximate frequency of 9,600 GHz. The oscillator output (50 mW) was used to drive a self-contained, portable, traveling-wave-tube transmitter which required only a 110 V power source, low-level RF input, and a logic pulse (to determine both the transmitter pulse width and repetition rate. There was a maximum duty cycle requirement that limited the "on-time" of the system to 0.6 percent of the interpulse period. Since narrow pulses ($\sim 0.6 \mu\text{s}$) were used at relatively low pulse rate, this requirement offered no particular problem.

The transmitting equipment used in this experiment is shown in Figure 6. Power supplies are mounted behind the top two panels. The third panel contains the two microwave oscillators and the necessary wave guide to meter and mix the transmitter and local oscillator outputs to derive the 30 MHz reference signal. Both Gunn-effect oscillators are covered with microwave absorbing material to reduce unwanted direct radiation of the microwave energy. The largest unit on this rack (Space Microwave) is the 1 kW microwave transmitter, while the two lowest panels are not pertinent.

3.4 The Antenna System

The transmitter output was fed directly into the transmitting antenna (cf. Section 3.5 for photographs of the antenna system). Satisfactory operation was achieved at radar ranges as small as 50 m by using separate transmitting and receiving antennas rather than a single antenna and a transmit-receive (TR) switch.

The selection of the antenna beamwidth was the result of a compromise. For narrower antenna beamwidths, the major advantages of greater sensitivity at

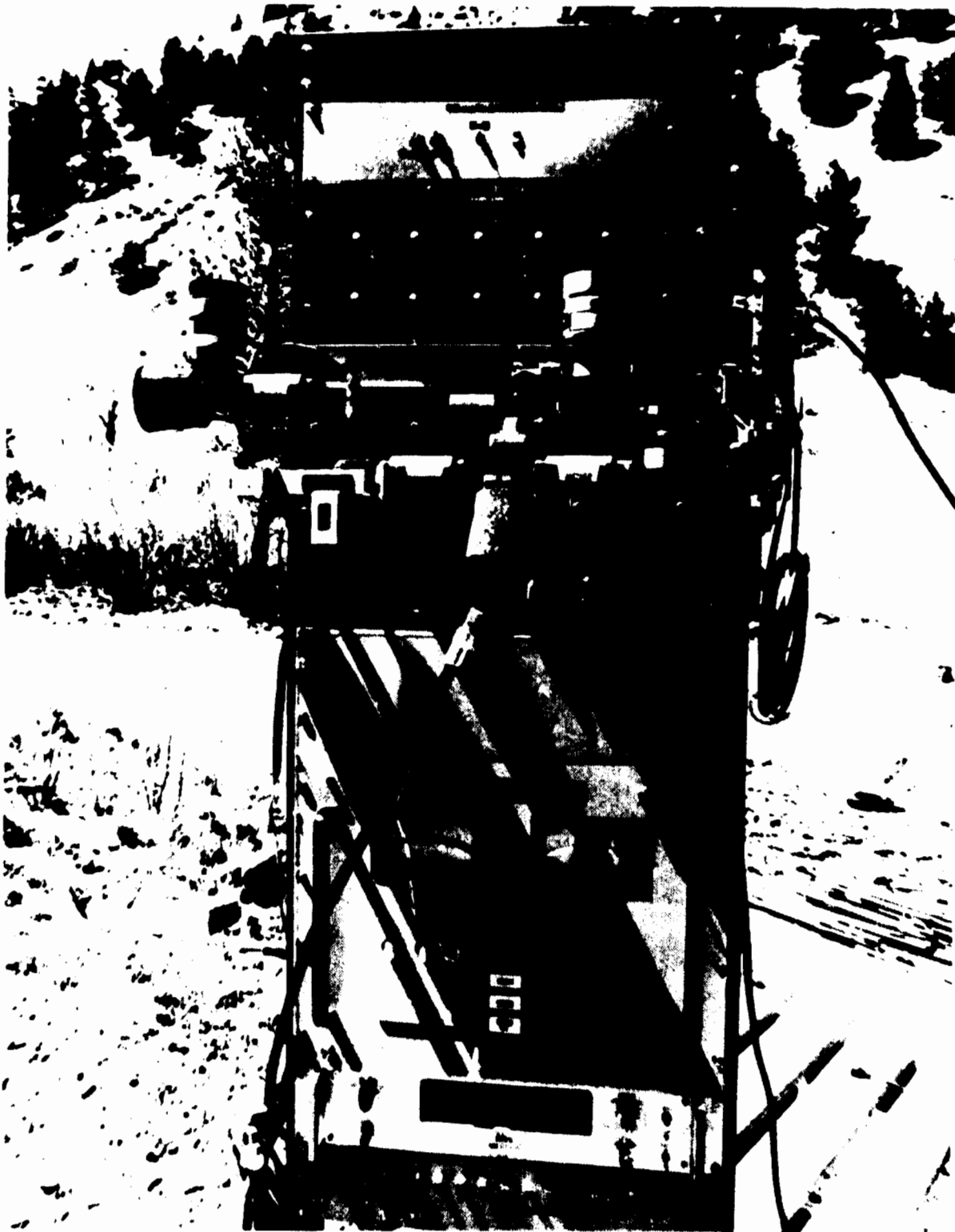


Figure 6. Coherent Reference Generator and Transmitter Rack

larger ranges and greater discrimination against background clutter were outweighed by the extreme difficulty in keeping the moving bird target in the antenna beam at close ranges. For wider antenna beamwidths, on the other hand, the ease of manual target tracking was counteracted by greatly reduced range sensitivity and enhanced background clutter.

The selected antenna system had a gain of 19 db, a physical aperture of 14 by 20 cm, and a horizontal beamwidth of 14° . For the antenna in a fixed position, a bird flying through the antenna beam at a typical velocity of 20 m/s at a range of 200 m would be within the half-power region of the antenna beam for a minimum of 2.4 seconds. In practice, the unwanted sidelobes, and hence the unwanted background clutter, were reduced by wrapping the antenna horns with microwave absorbing material.

3.5 System Operation

Under normal operating conditions, the signal output of the radar receiver was monitored in three separate ways: (1) by an oscilloscope connected to give an A-scan (echo amplitude vs. range) display, (2) by an audio system connected to one of the range-gated samples of the receiver output, and (3) from time to time by an output display of an on-line digital computer.

The A-scan display was used to determine the presence of an echo and to determine the echo range. A second trace on the oscilloscope was incorporated to show the location of the range-gate (see Section 7) and to allow for adjustment of the range delay to correspond to the target range.

The audio system (audio amplifier and speaker) allowed the range-gated Doppler returns to be studied aurally on-line. In practice, it often turned out that, if the range gate happened to be set to the range of a weak target return (i.e., a single bird at reasonably large range), the target was detectable

by ear before it could be seen on the A-scan monitor. As discussed subsequently, the passage of a flying bird through the radar beam resulted in a distinctive audio signal that "fluttered" at the wing beat frequency of the bird under observation.

The computer output display gave a cursory indication of the velocity spectrum of the target. From these data the mean velocity of the bird or birds could be obtained along with an indication of their flight characteristics.

The range-gated output of the radar receiver was also recorded on an analog tape recorder along with a voice log of the observations. Subsequent playback of these tapes enabled more detailed studies to be made back at the laboratory.

The dual (transmitting and receiving) antenna system was mounted on a tripod outside the van or trailer so that it could be aimed by one observer. The radar range control, the on-line computer, and tape recorder were operated by the second observer in the trailer. This second observer also kept the recorded voice log on the magnetic tape. The loud speaker was installed near the door of the van so that both observers could listen to the Doppler output of the radar.

During the latter part of the experimental period, a 16 mm sound-synchronized motion picture camera was mounted on the antenna tripod, between the transmitting and receiving antenna horns. In subsequent analysis, the audio Doppler output of the radar was recorded onto the sound track of the motion picture camera. The resulting sound motion picture is discussed in a later section (Section 6).

The steerable antenna mount is shown in Figures 7, 8 and 9. Facing forward, the transmitting horn antenna and its tuner are located on the left, the receiving horn antenna is located on the right, and the sound-on-film motion picture





Figure 8. Antenna and Camera Mount, Side View



Figure 9. Antenna and Cerera Mount, Back View

camera is mounted in the middle. Details of the receiving antenna, its attachment to the microwave mixer, and the placement of the side lobe shield are shown in Figure 8. The sound-on-film motion picture camera is mounted between the antennas as shown in Figure 9. Figures 10 and 11 show the equipment trailer and the deployed antenna.

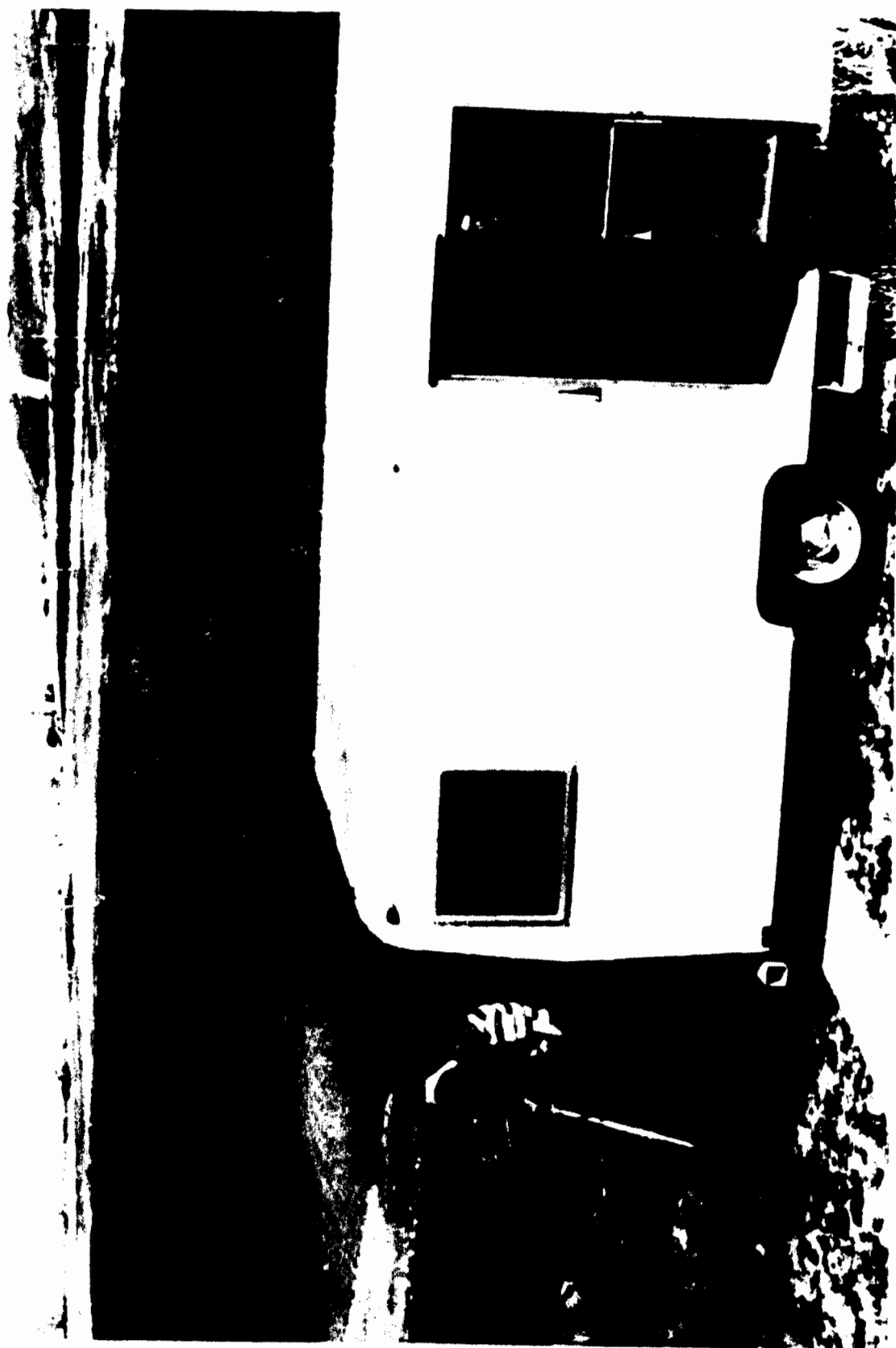


Figure 10. Equipment Trailer and Antenna Mount

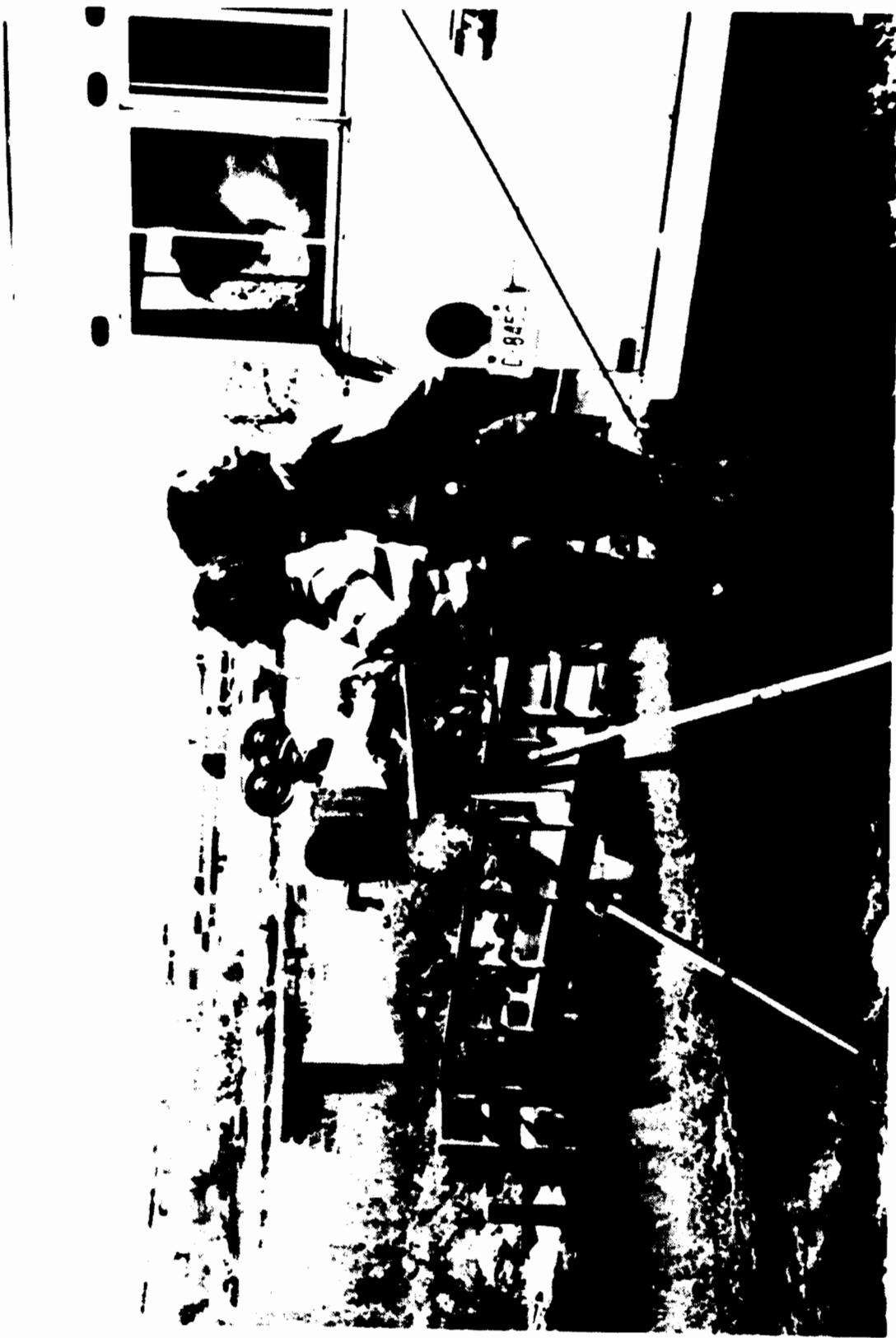


Figure 11. Antenna and Support Structure

4. ANALYSIS TECHNIQUE

There are at least five methods by which the Doppler information available at the quadrature outputs of the receiver can be analyzed. We designate these methods as (1) the sonogram, (2) the time-dependent power spectrum (3) the time-averaged power spectrum, (4) audio or aural analysis, and (5) audio-visual analysis. In the subsequent paragraphs of this section we will describe each of these techniques in turn and discuss the various advantages and disadvantages of each.

Since a large part of the following discussions will center around the power spectrum of the signal returned from the target, it is advisable at this point to define the term and to discuss how our meaning may depart somewhat from other definitions. Our definition of power spectrum is concerned with the Doppler characteristics of the returned signal. When we speak of the power spectrum, we mean the amount of echo power returned to the antenna as a function of Doppler frequency shift from the carrier frequency (f_0). For example, if our signal were returned from a simple target moving toward the radar system at a constant velocity, all of the power would be returned at a frequency greater than the transmitted frequency by an amount equal to the Doppler shift determined by equation (9); if the target were moving away from the radar at the same velocity, there would be a corresponding down-shift of the returned signal. The power spectrum, which depicts the returned energy-density as a function of frequency shift from the transmitted frequency, would show these features. There is an alternative definition of the power spectrum in terms of the typical signals obtained from conventional radar systems that involves frequency components contained in the amplitude fading component of the returned signal (i.e., the

$B_a(t)$ term in equations 14a, b). These $B_a(t)$ frequency components are due to the time variations of the echo cross section of the target and in no way reflect the Doppler displacements due to the velocity of the target. In practice, the Doppler spectrum can contain information on both the Doppler shift and the amplitude fading, although the amplitude fading is not considered significant for the present purposes. If necessary, the amplitude fading can be virtually eliminated by appropriate clipping techniques (see Section 8).

4.1 The Sonogram Technique

This method of analysis results in a plot of the frequency-shifts (Doppler displacements) of the signal as a function of time, with the power density at any particular frequency shift being indicated by the line intensity on the plot. An example of this type of analysis is shown in Figure 12. These data were obtained from the signal returns of a single Shoveler (Anas clypeata) passing through the antenna beam. This particular sonogram contains returns from both the Shoveler and small waves on the lake (clutter). The clutter return from the lake was slightly Doppler-shifted due to wave motion and appears as a "fuzzy" wide line along the abscissa. The echo from the Shoveler, on the other hand, appears as the broad, sinuous streak with periodic "spikes" which decreases in frequency with increasing time. There are several components of this echo which are interesting and significant: the relatively wide sinuous trace is due to echoes from the body of the bird, while the sharp vertical spikes that appear at periodic intervals are due to echoes from the bird's wings. These spikes indicate a wing beat frequency of about 6.8 Hz, in agreement with the Shoveler data in Figure 2 (bird #22). Note that the positive

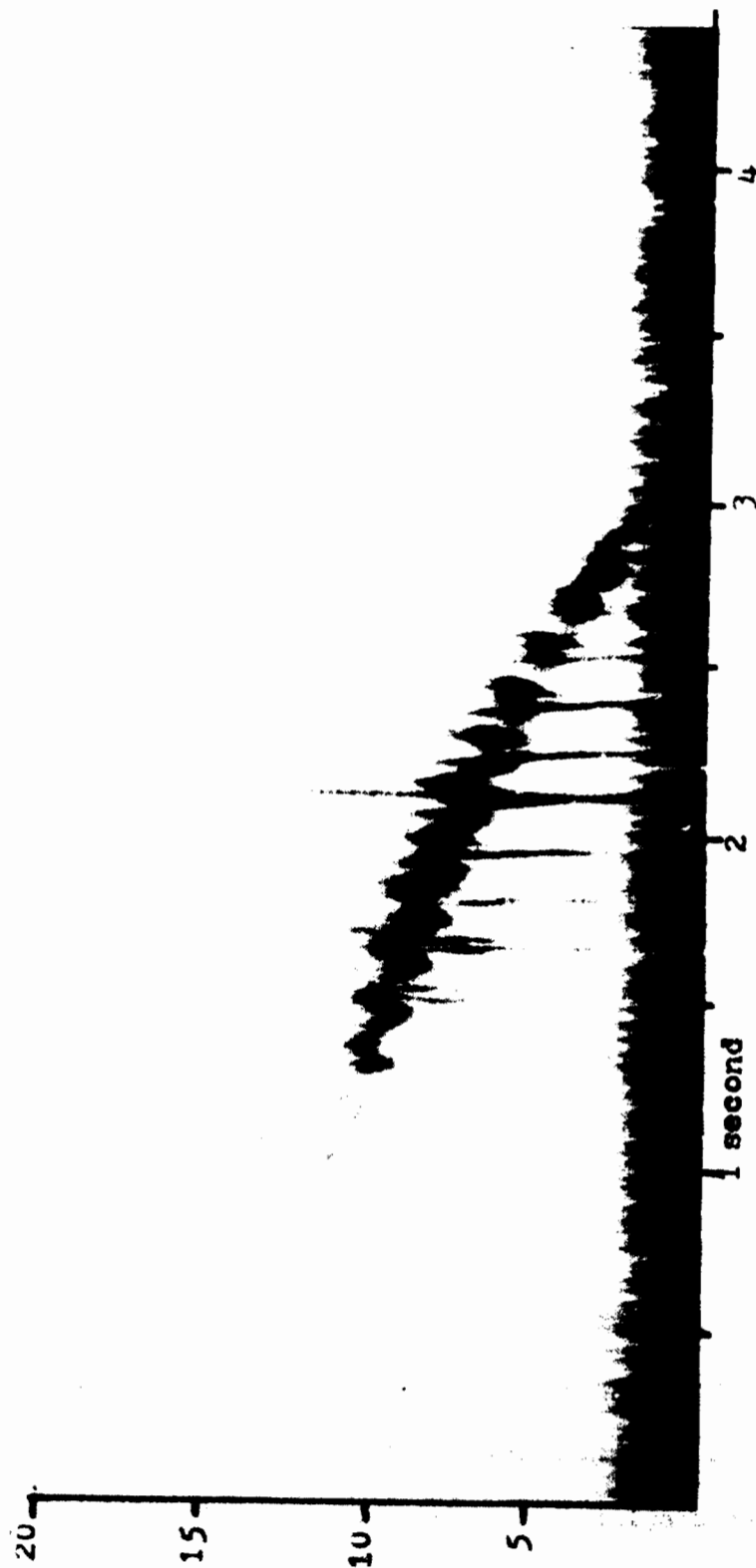


Figure 12. Sonogram of a Shoveler (Spatula clypeata)

and negative excursions relative to the mean body motion correspond to the radial motions of the wings toward and away from the radar, respectively. Note also similar but less pronounced motions of the bird's body indicated by the "wavy" character of the "body" line.

Similar data obtained for many different kinds of birds have been obtained. A sonogram of a group of Barn Swallows (Hirundo rustica) is shown in Figure 13. The most characteristic feature of this record however is the rapid and irregular frequency changes caused by the sweeping flight motions peculiar to this type of bird; the sharp spikes on the record due to the wing beats are weak but still apparent.

Figure 14 is a sonogram of an unidentified species of gull. It is notable that there are no detectable spectral components from the wings, even though the periodic body motion shows that the wings were beating. This anomaly is probably due to very shallow wingbeats, with correspondingly small velocities relative to the body--a quasi-soaring mode of flight that gulls sometimes adopt.

It is worthwhile mentioning at this point that, although the sonogram takes advantage of the frequency-coherent aspects of the radar system, no provision has been made to determine the sense of the Doppler shifted signals: both positive and negative shifts appear as positive values on the above sonograms. While this could lead to confusion in the final analysis, it is not considered particularly troublesome for the present purposes since the total mean radial velocity of the bird is greater than the maximum radial wing velocity. Moreover, this difficulty can be eliminated merely by mixing the incoming signal with a frequency somewhat displaced from the exact transmitted frequency. In this way the positive and negative component would appear on either side of the "displaced" zero-velocity echo component.

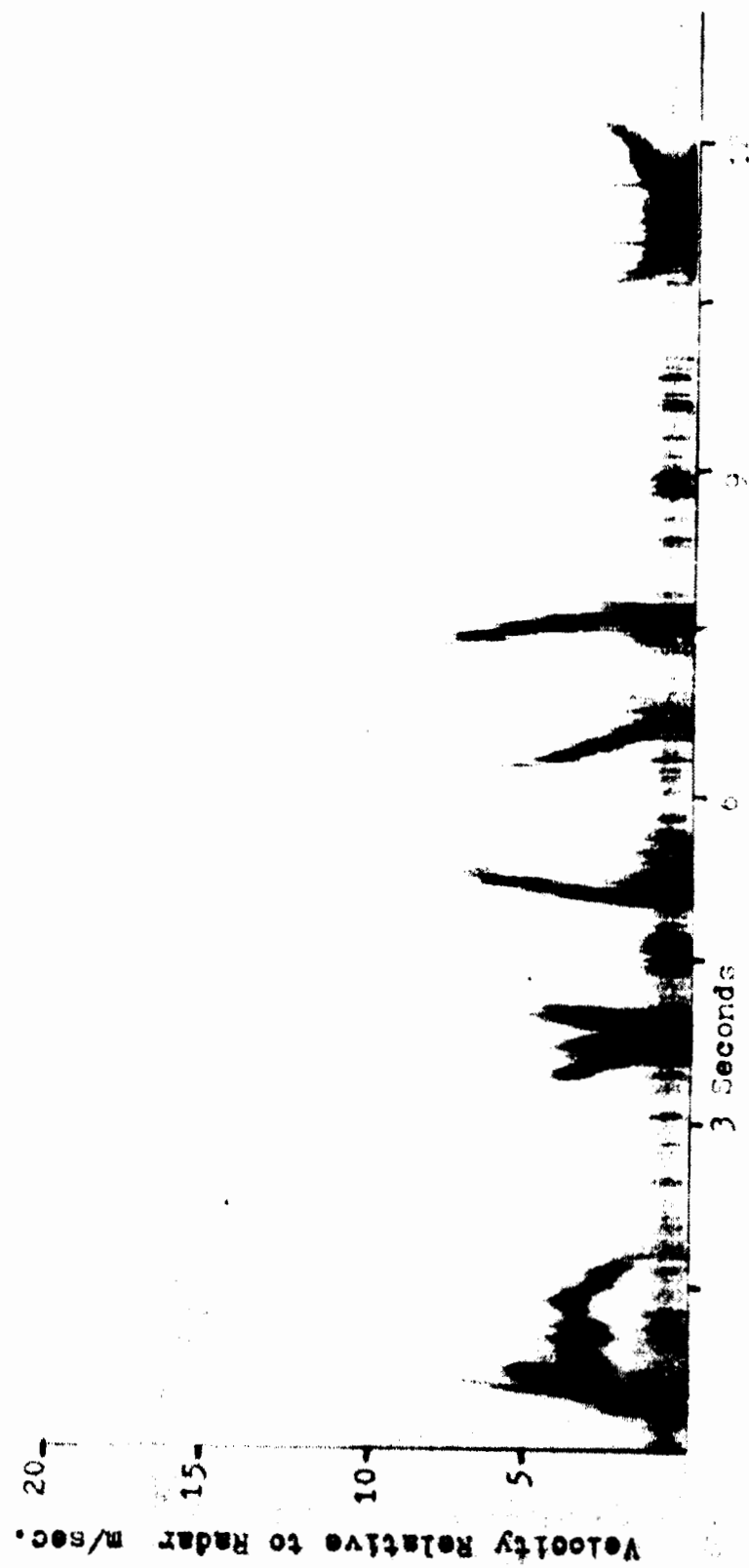


Figure 13. Sonogram of Barn Swallows (Hirundo rustica) Feeding

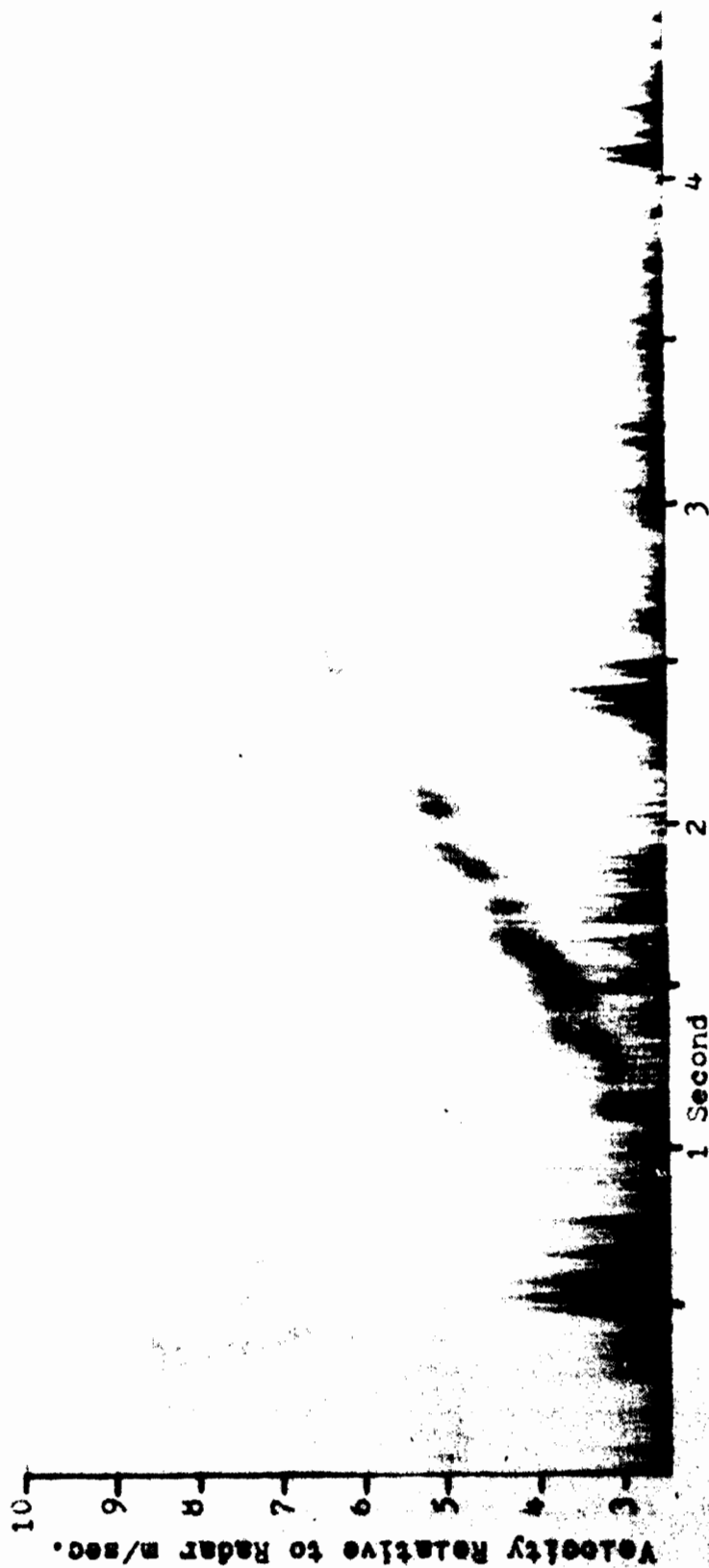


Figure 14. Sonogram of Gull Flying Away from Radar

4.2 Time-Dependent Spectral Analysis

The second method of analysis involves obtaining the actual power spectrum of the signals returned from the target. Typically, this method entails the use of a digital computer; the quadrature range-gated receiver outputs are first digitized into an arbitrary number of digital levels as a function of time, and the resulting digital information is fed directly into a digital computer programmed to perform a spectral analysis. The resulting digital output can be returned to an analog format and plotted (power spectral density vs. Doppler shift) as a curve on either the face of an oscilloscope, or alternatively, on an x-y plotter.

Since the spectral characteristics of a flying bird vary with time, a series of power spectra--obtained typically in a time short relative to the wing beat period--will show variations with time also. In order to study temporal variations of the flight characteristics, the most reasonable method of analysis is to present a series of spectra taken sequentially. This procedure is followed in the data presented in Figure 15. In this figure a series of about eighty separate spectra are shown, with the earliest spectrum appearing at the bottom of the figure. Positive Doppler shift (Hz) is shown along the abscissa. As in the sonogram examples, both positive and negative Doppler shifts are included on the same side of the abscissa (again, this problem could be rectified but is not considered important for these preliminary analyses). The complete event encompassed by the spectral set occurred in approximately $1\frac{1}{2}$ seconds as indicated by the approximate scale in the figure. This record was obtained from a single Canada Goose (Branta canadensis) flying at about a 45° angle to the radar beam. The spectral response due to the bird's body is seen at a Doppler shift of approximately 500 Hz (referring to equation (9), a 500 Hz

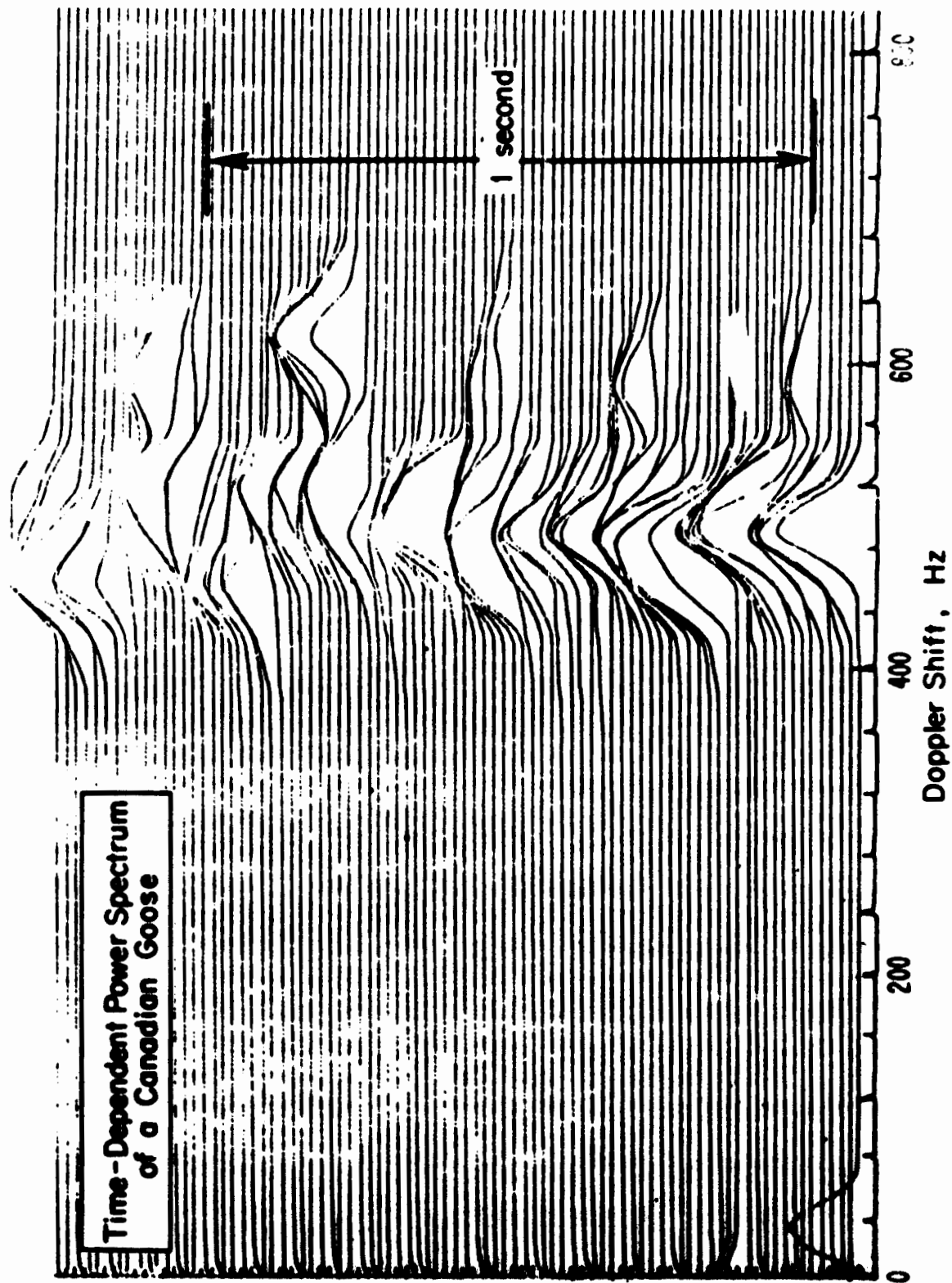


Figure 15. Time-dependent power spectrum of a Canada Goose (*Branta canadensis*)

Doppler shift corresponds to a radial velocity of about 17 m/s). The spectral response at 600 Hz with a periodic amplitude fluctuation of $\sim 5 \text{ s}^{-1}$ is due to the wing beats. The wing beat frequency of 5 s^{-1} inferred from this record is typical for a Canada Goose.

As evident in Figure 15, one obvious advantage of the power spectral analysis over the sonogram is that it is possible to determine the relative amplitudes of the various spectral responses of a given echo; the sonogram amplitudes, on the other hand, must be inferred from the qualitative process of determining the relative intensity of the darkened lines. One disadvantage of the time-dependent power spectrum method lies in the complexity of the digital circuitry necessary for the complete spectral analysis. Although this disadvantage is becoming increasingly less important as the state-of-the-art improves, it is still an important factor.

4.3 Time-Averaged Power Spectrum

Insofar as time-dependent spectral analysis can be a useful technique in the analysis of bird echoes, it is also reasonable to consider the value of the time-averaged characteristics of these same echoes. It turns out that the time-averaged spectral characteristics of bird echoes would be most useful in the instances when the echoes arise from more than a few birds of the same species (cf. Section 8). It is relatively easy to envision the complex patterns that would occur in either the sonogram analysis or the time-dependent spectral analysis mentioned in the previous sections, if there were a number of birds at the same range in the antenna beam. In the limit, one would expect a completely unintelligible set of characteristics. On the other hand, the multiplicity of signals returned from a number of separate targets is easily separable by the

time-averaged techniques. This can be illustrated by considering the time-averaged character of the set of temporal power spectra in Figure 15. The time-averaged spectrum $S(f_d)$ of these spectra would be that which would be obtained by adding all of the spectra together and dividing by N the total number of spectra:

$$S(f_d) = 1/N \sum_{j=1}^N S_j(f_d) \quad (15)$$

where the j subscript refers to the particular spectrum, $S_1(f_d)$ being the first spectrum, etc. In the present instance, it is clear that the time-averaged spectrum would contain all of the Doppler characteristics which are apparent in the individual spectra. The only missing item would be the periodicity of the wingbeat rate that would have been "averaged out" in the above process. This feature is also discussed in Section 8.

An example of this technique involving a multiple echo return is shown in the time-averaged spectrum in Figure 16. This particular spectrum was obtained by digital techniques similar to those mentioned in the previous section, with the exception that a large number of the spectra have been averaged together. The signal returns in this case were from a large number (greater than one thousand) of gulls (unidentified species) which were circling the area at a height of about 500 meters in a "vortex" configuration estimated to be 200 meters across. Although one might expect that the spectral response would be roughly symmetrical about some mean drift value, the results shown in this figure are decidedly asymmetric. The peaks of the spectral response that appear displaced to either side of zero Doppler shift (note that, in this technique, both the positive and negative shifts are distinguished) are probably due to the point in the vortex when the total cross section of the birds was a maximum.

Although very little has been done with time-averaged spectral analysis of bird echoes to date, the method has a great deal of promise for determining the

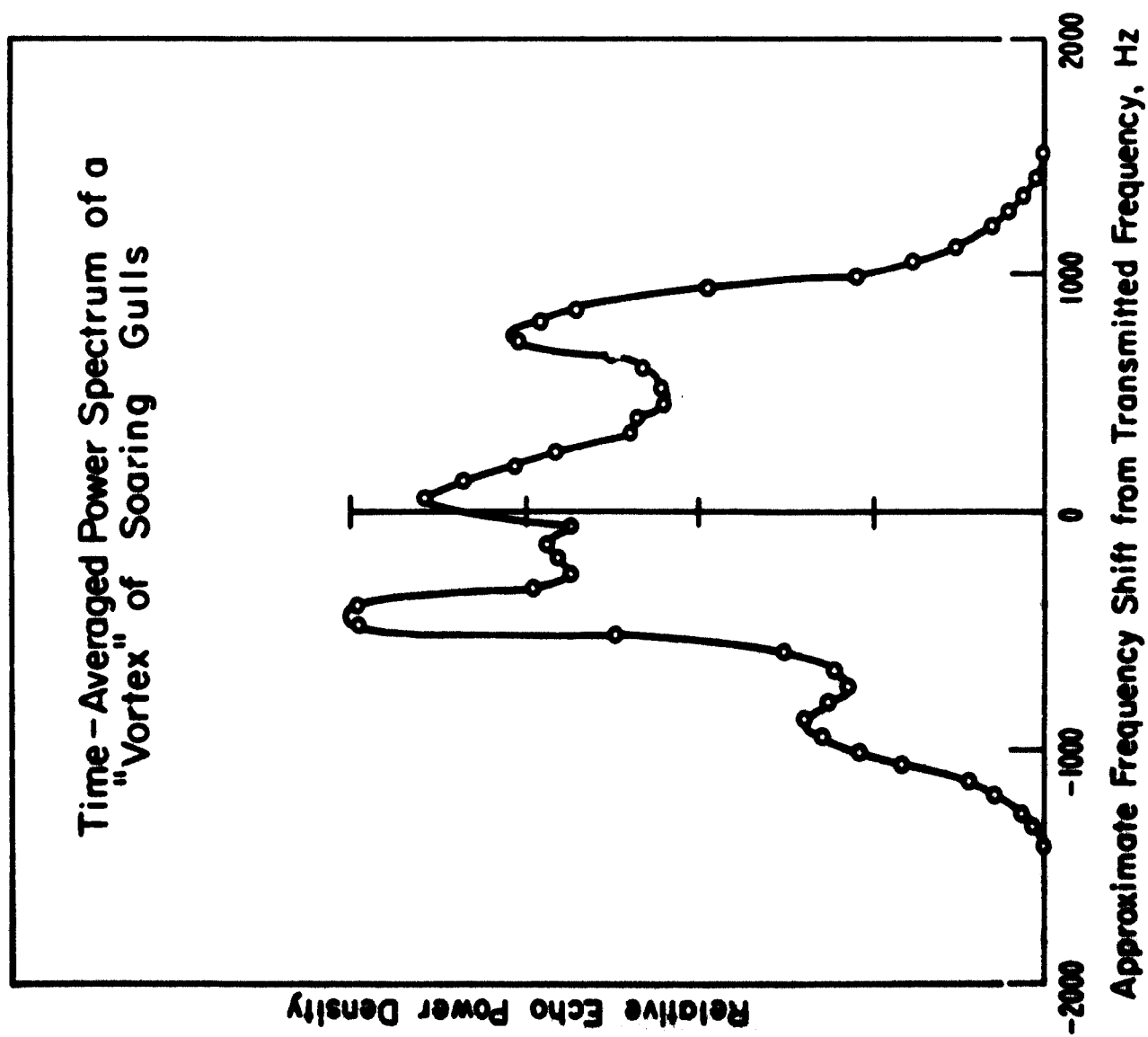


Figure 16. Time-Averaged Spectrum of a "Vortex" of Soaring Gulls

average flight characteristics of flocks of birds. As in the previous case, the equipmental requirements are somewhat complex and expensive, but should become less so with time.

4.4 The Audio Technique

As discussed in a previous section, the development of this particular technique resulted from the realization that the Doppler frequencies resulting from bird motions detected by a frequency-coherent microwave radar happen to fall in the audio range. During the course of our data gathering, we merely attached a simple "hi-fi" amplifier-speaker system to one of the signal outputs of the receiver. The resulting audio data have proved to be an invaluable aid in the analysis of our data and in the general operation of the system. It was frequently possible to immediately identify the type of bird within the radar beam long before visual contact was made. The audio "signatures" of the various bird types are quite distinct and the logarithmic response of the human ear can be used to advantage to detect relatively weak but distinguishable features that might remain undetected by other techniques.

It is unfortunate that this type of audio information is not demonstrable in this publication, since it appears to offer one of the most immediate means of on-line identification of flying birds. A reasonable demonstration of the efficacy of this technique is given however in the accompanying film. (For further details, refer to Section 8.)

4.5 The Audio-Visual Technique

Finally, we should like to mention a method which was studied during the latter part of this investigation. It consisted of coupling the audio method discussed above with a motion-picture film of the bird(s) that give rise to the

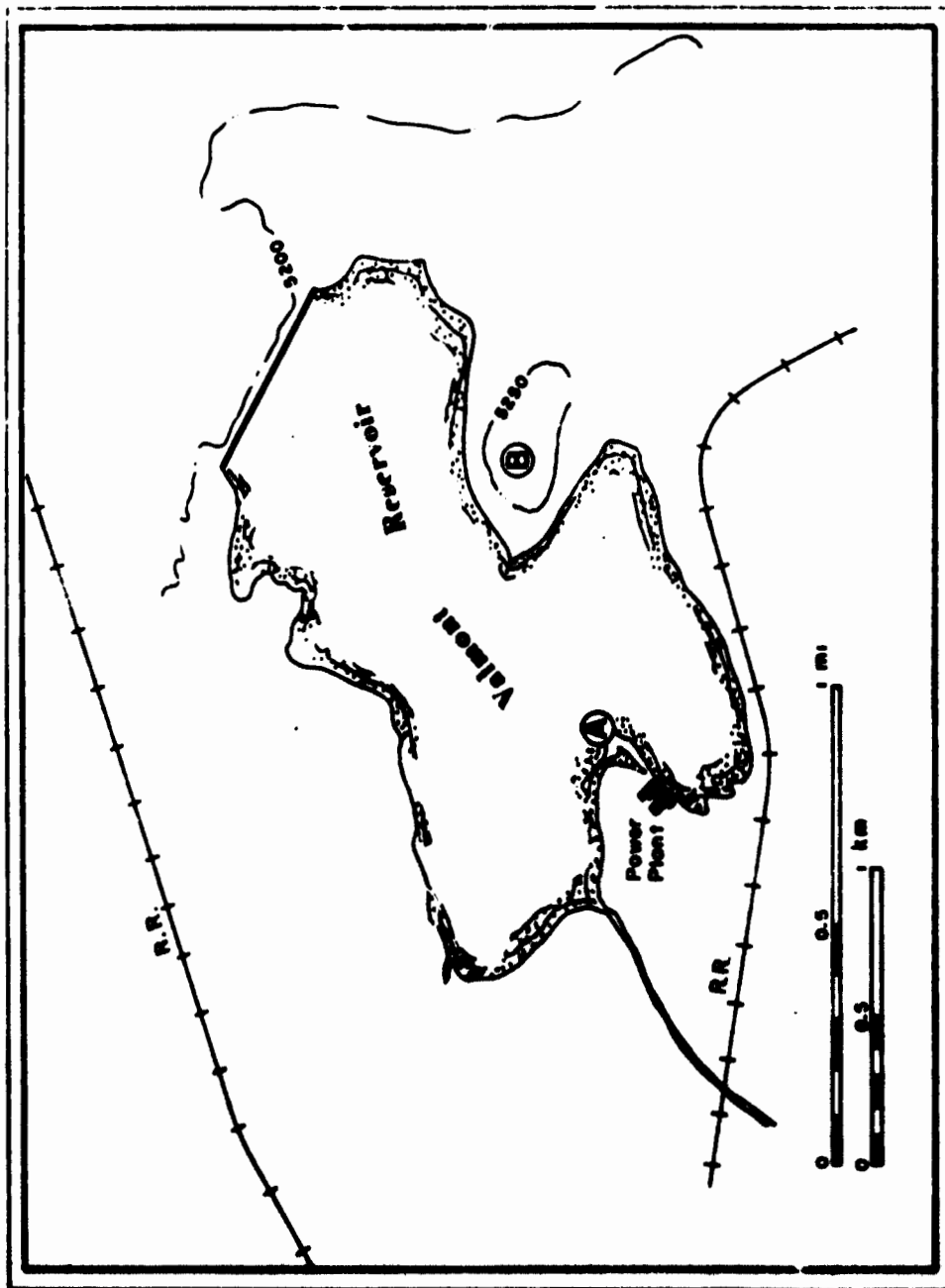
radar return. This was done by bore-sighting a motion-picture camera along the antenna axis, with the camera being operated only during the periods when there were targets within the radar coverage (refer to Figures 7-9). The audio Doppler signals were transcribed onto the film during the editing process, so that it was possible to synchronize the Doppler signals on the sound track to the wing position and motions of the target bird. A 20 minute sound film has been prepared and submitted to the sponsor of this research. One additional copy of this film is available.

5. OBSERVATIONAL PROGRAM

The first part of this observational program was conducted at Valmont Reservoir, near Boulder, Colorado. This lake, owned by the Public Service Co. of Colorado, is used to cool a steam electric power plant and is thus ice free all winter. It is leased for a wildlife refuge by the Division of Wildlife of the State of Colorado. The population of waterfowl ranges from a few hundred in summer, including about 300 resident Canada Geese, to over 20,000 in the winter, including ~10,000 Canada Geese and ~10,000 Mallards. There is also a varied population of other birds, including land birds. The radar was located on a point of land west of the lake as shown in Figure 17 (location A). Because of the exposed location it was possible to observe the bird-population activity near the lake over an azimuthal extent greater than 270° .

The first phase of the operation (observation of flying birds and development of the radar system) was conducted at this location during the period, March 23 to May 10, 1973). Although the peak of the spring migration of waterfowl had passed, a sufficient bird population was present for the purposes of this initial program. Observations were made at various times of day, the most profitable period being between late afternoon and dusk when the daily flight activity was at a peak.

The observational technique involved operating the radar and waiting for birds to fly within range. The steerable antennas were then pointed at the birds. The range delay control, mentioned in the previous section, was adjusted by listening to the audio output of the radar, since this was the most sensitive method of on-line detection. Both the antenna steering and the range control were used to track the birds in flight. It should be noted that often birds



Valmont Reservoir
105° 22' 00" - 40° 01' 30"

Figure 17. Map of Valmont Reservoir, Boulder County, Colorado

rendered invisible by local haze were detected by their audio signals and subsequently tracked as they flew into visual range. During most periods of operation, there were enough birds within range to keep the tape recorder running continuously.

The majority of bird targets recorded during this phase were Canada Geese (Branta canadensis). Canada Geese were detected out to a range of 1.6 km, the maximum position of the range control. On several occasions, during this first phase of the experimental work, these birds were observed to fly behind a small hill about 900 m east of the radar on the far side of the lake (location B, Figure 17). On another occasion, a similar flock was observed to fly behind a fuel storage tank (cf. the accompanying film explanation in Section 6 for the 317-332 second film section). On these occasions, both the visual and the radar contacts were simultaneously lost when the birds passed behind the intervening object and then regained when the birds emerged.

During this observation period, the correlation between the flapping of the bird wings and the characteristic beating sound heard at the radar output was excellent. This was true for all of the bird types observed during the program. On many occasions birds flew to the lake and then began a glide to the surface of the lake. On these occasions the characteristic sounds associated with the wing beats disappeared from the radar output as the glide began, but the steady Doppler frequency from the mean motion of the bird remained until the bird had stopped in the water. At one time a formation of approximately 300 gulls moving in a vortex of 400 m diameter was observed. This circular motion of gulls gave a very distinctive howling sound at the audible output of the radar. It was also noted that on windy days the background noise in the radar output increased due to the presence of waves on the lake, but did not seriously degrade the detectability of the birds.

During the course of this observational program, studies were made of approximately eight bird species:

Canada Goose (Branta canadensis)

Teal (Anas sp.)

Mallard (Anas platyrhynchos)

Black-billed Magpie (Pica pica)

Barn Swallow (Hirundo rustica)

Hawk (Buteo sp.)

Gull--Ring billed or Franklin's (Larus delawarensis or L. pipixcan)

Shoveler (Anas clypeata)

Recordings were also made of radar returns of other moving objects, such as automobiles, freight trains, and propeller driven aircraft, whose Doppler spectra could possibly be confused with those of flying birds. During May of 1973, an unusually large migration of Painted Lady butterflies was observed (but not recorded) on the radar. In each case the audio signature of these alternative targets was so different from those resulting from flying birds that it could easily be distinguished by an observer with only minimal indoctrination (~1 hour).

The second phase of the observational program was designed to study the relationship between the motions of flight and the resulting radar returns by making a series of audio-visual observations. Audio-visual/radar observations were made during the fall waterfowl migrations in 1973 and again during the spring migration in 1974. These observations included the species listed above, with the addition of the Great Blue Heron (Ardea herodias).

As mentioned in Section 3, these observations were made by mounting a 16 mm sound-synchronized motion picture camera on the steerable antenna tripod

so that the radar antenna system and the motion picture camera could be aimed simultaneously at flying birds. Again the radar range-gate control was adjusted by means of the audio output of the radar, and the resulting audio signals were recorded subsequently onto the motion picture sound track.

During most of the observation periods either Dr. T. E. VanZandt, of the Aeronomy Laboratory (NOAA), or Prof. W. L. Flock, of the University of Colorado, were present to identify bird species encountered by the radar. Both are very knowledgeable of the local bird species.

6. DESCRIPTION OF THE FILM PRESENTATION

As mentioned in Section 5, the latter portion of this experimental program was concerned with documenting a series of Doppler signatures using both the audio and audio-visual techniques. One documentation method consisted of recording a series of aural "events" on cassette records for sponsor demonstration purposes. These records served as interim data and will not be discussed here. The final film record, on the other hand, demonstrates both the audio and the audio-visual techniques quite effectively, and considerable effort has been expended toward making the film a major portion of our results.

The 12-minute film (with sound track) is a documentary that accomplishes the following:

- (1) The film gives a brief description of the Doppler technique. This description includes a discussion of the aural technique, a method that we feel is clearly the most useful for airport detection.
- (2) The film offers a record of the experimental set-up, including a series of shots of our standard mode of operation as mentioned in Section 5.
- (3) Documentation is presented of a variety of "bird echo events" in which the aural data is presented on the sound track along with the filmed record of the birds themselves. This presentation gives an invaluable demonstration of the correlation between the bird flight motions (wing beats, glide, mean velocity Doppler, multiple target problems, etc.) and their respective Doppler characteristics.
- (4) A comparison is presented between bird echoes and echoes from airplanes and automobiles. This comparison demonstrates the uniqueness of the bird signature and shows how easy it is to differentiate between birds and other targets.

- (5) A brief demonstration is included that shows the method of range-gate sampling to eliminate undesirable interference.

Along with pertinent introductory remarks, the film contains twelve examples of different bird signatures, two examples of airplane signatures and one example of an automobile signature. All of these data were obtained at normal film speed. Three additional examples of bird signatures with the motion slowed to one-half are also included to demonstrate how this technique can be used to study in detail the flight motions of different types of birds.

A brief description of the film sequence, along with the elapsed time to each scene, is given below.

Time (from end of captions)

Scene description

0 - 197 seconds

Introductory remarks, including a general description of the method and showing the experimental set-up, including the camera/antenna system and the trailer on location.

198 - 243 seconds

Three Canada Geese (Branta canadensis) flying around the lake. A wing beat frequency of about 4.6/sec can easily be determined from the sound track. This is in agreement with the wing beat frequency determined from the record shown in Figure 15. The cessation of the audio "beat" is apparent as the birds begin (but do not complete) a gliding approach to the lake.

244 - 276 seconds

Two Great Blue Herons (Ardea herodias) flying toward the radar. The wing beat frequency is about 2.9/sec. This is in

rough agreement with bird No. 41, in Figure 2, Ardea cinerea, the European analog of A. herodias. Note also that identification of the slow beat rate is quite easy, even though the two birds are not beating their wings synchronously.

278 - 286 seconds Four Canada Geese (Branta canadensis) on a landing approach to the lake. Note the cessation of the mean Doppler (due to the body motion) upon landing.

287 - 294 seconds One Mallard (Anas platyrhynchos) landing on the lake. Note the final "flutter" of the wings after the bird has landed, but prior to full stop.

295 - 316 seconds A large number (≈ 70) of Canada Geese (Branta canadensis) on a landing approach to the lake.

317 - 332 seconds Seven to nine Canada Geese (Branta canadensis) flying toward the radar and disappearing behind a large fuel storage tank.

333 - 374 seconds One duck (Anas sp.) flying around the lake. The wing beat frequency is about 6.1/sec. Although the species of this bird is not identified, its wing beat frequency qualifies it as hazardous to aircraft by the criterion suggested in the introduction of this report.

375 - 392 seconds One Canada Goose (Branta canadensis) flying close to the surface of the lake. The wing beat frequency is about 5.3/sec., consistent with the wing beat frequency determined in an earlier scene.

393 - 420 seconds	Seven ducks (<u>Anas sp.</u>) flying around the lake, showing how the basic wing beat characteristic is still discernible with a large number of birds.
421 - 503 seconds	Vocal description of the following half-speed film strip.
460 - 503 seconds	Half-speed record of a varying number (13-30) of Canada Geese (<u>Branta canadensis</u>) flying over the lake. The wing beat frequency is about 5/sec., again consistent with earlier scenes.
504 - 596 seconds	Half-speed record of one Great Blue Heron (<u>Ardea herodias</u>). The wing beat frequency is about 2.85/sec. This is consistent with bird No. 41 in Figure 2 and with an earlier scene.
597 - 635 seconds	Half-speed record of a single Mallard (<u>Anas platyrhynchos</u>). The wing beat frequency is 7.45/sec. This is in rough agreement with bird No. 20, Figure 2.
636 - 653 seconds	Vocal description of the following non-avian targets.
654 - 678 seconds	A single-engine aircraft flying away from the radar. Note the clear lack of any "beat" that might be confused with wing beats.
679 - 697 seconds	A second single-engine aircraft.
698 - 731 seconds	A single automobile (carryall). The record demonstrates the changing mean Doppler shift due to the radial motion of the automobile as it turns, accelerates, and decelerates.

7. COMPARISON BETWEEN A RANGE-GATED (PULSED) RADAR OPERATION AND CW (NON-PULSED) OPERATION

The two types of radar reception used in the present study may be most easily categorized as (1) non-pulsed or CW (Continuous Wave), and (2) pulsed operation. Although there are a variety of other techniques that might be used to achieve the same purposes, they are not included here.

The CW operating mode, in which the transmitted frequency is emitted continuously and the receiver is constantly in operation, is by nature a bistatic mode involving separate transmitting and receiving antennas. The transmitting and receiving antenna systems are located so as to minimize direct coupling. This typically involves isolation, both by physical separation and by the placement of RF-absorbent material to minimize coupling from the transmitting antenna along a direct path to the receiving antenna. Even though the direct coupling is rendered negligible, there are a number of problems inherently associated with a CW mode of operation. The major problems are (1) lack of range resolution, and (2) contamination of the true target returns by background echoes. The first of these problems could be solved partially by separating the transmitting and receiving antennas by a distance more or less comparable to the distance of the expected echoing region and by using relatively narrow-beamwidth antennas. This solution, unfortunately, precludes using the CW radar in a practical search mode (i.e., for a PPI presentation). The second problem is also a major one, in that there is virtually no way to eliminate the strong, undesirable returns from targets at near ranges. These returns will typically suppress all but the strongest of bird targets, rendering the overall system ineffective.

One obvious solution to both the above problems is to use a pulsed radar system with a reasonably narrow beam. For pulsed operation, the targets occur

at some time delay ($\approx 5-20 \mu s$) after the transmitted pulse. The unwanted targets occur at a specific delay, typically different than that of the desired target. By proper sampling of the receiver output at the delay of the echo, it is possible to eliminate essentially all of the unwanted returns from the analysis.

Sampling of the receiver output (points P_1 and/or P_2 in Figure 4) is accomplished by analog Sample and Hold circuitry as indicated in Figure 18. As shown in the figure, the sample delay (center trace in the diagram) is set to examine the range delay of the desired target (upper trace). The analog output (bottom trace) measures the amplitude of the echo at that point and the variation of the output amplitude from pulse to pulse yields the desired Doppler frequency data. Provided that the rate of sampling (as determined by the transmitted pulse rate) is faster than twice the maximum expected Doppler frequency, then the sampled output shown on the lower trace of Figure 18 contains all of the Doppler frequency information arising from the target motions.

Improvement of the overall system sensitivity by sampling is difficult to quantify since the potential interfering signals can occur at any range, including the range of the target. On a qualitative basis, however, it is possible to anticipate an overwhelming improvement in comparison with the CW case where the bird echo is superimposed upon strong interfering ground "clutter". If the target range is different than that of the echo, then the sampled (pulsed radar) system will eliminate essentially all of the interfering signal. A strong interfering signal, at the same range, on the other hand, would clearly not be eliminated by sampling.

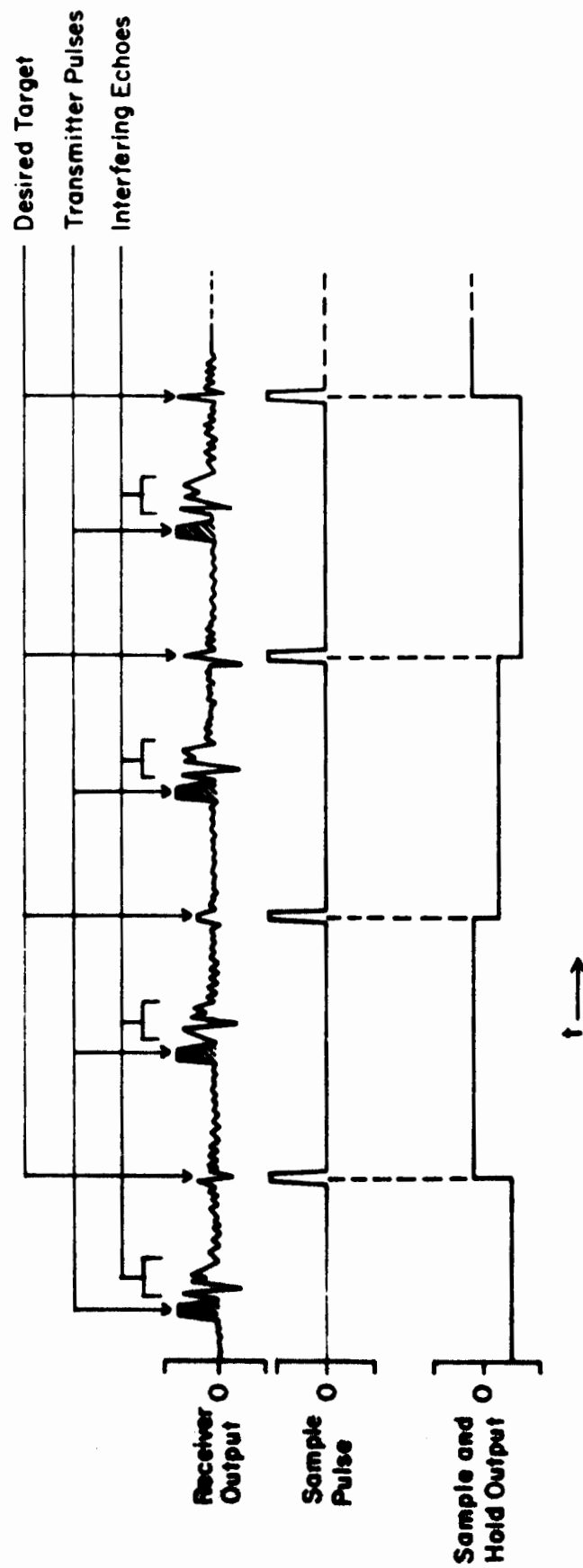


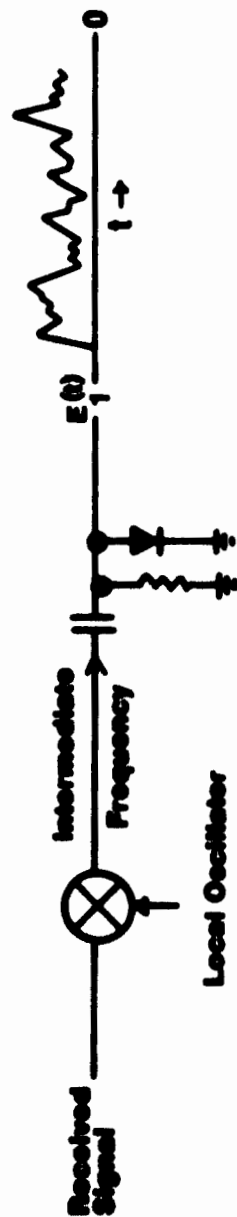
Figure 16. Discrimination Between Targets by Use of a Range Gate

8. A COMPARISON BETWEEN CONVENTIONAL RADAR SYSTEMS AND DOPPLER RADAR SYSTEMS FOR THE DETECTION AND IDENTIFICATION OF FLYING BIRDS

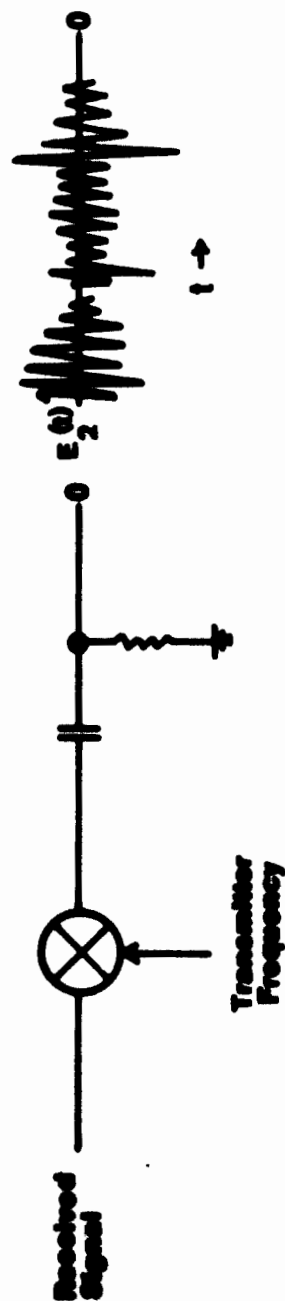
At various points within this report we have alluded to the advantages of a Doppler radar system relative to a conventional radar for the detection and identification of flying birds. In the following paragraphs we will compare the two systems and will discuss the specific advantages and disadvantages of each. Let us first restrict the discussion by considering only pulsed radar systems with non-rotating antennas. Furthermore, we require that the transmitted pulse consist of a burst of RF energy at some single, nominal, transmitted frequency. In making this second restriction, we eliminate from consideration the pulse-coded and frequency-chirped modulation schemes which, although they hold many inherent advantages over the present method, are too complex for consideration here.

Thus we will consider a conventional pulsed radar such as would normally be employed in airport situations, that--for the sake of simplicity--has an antenna fixed to a single azimuth and elevation angle. This system will be compared with a similar Doppler radar system. The only difference between the two is that the Doppler radar is a frequency-coherent system while the conventional system is not. In other words, the conventional radar detection scheme "throws away" the frequency-coherence information by using standard amplitude-modulation detection techniques; the Doppler radar retains this information by mixing the incoming signal with the transmitted frequency.

Consider the schematic representation shown in Figure 19, that represents the principles involved in the two techniques. The upper schematic shows that standard amplitude-modulation (AM) detection technique retains only the envelope



AM Detection



Doppler Demodulation

Figure 19. Standard Amplitude Detection Circuitry (Upper Schematic) vs Doppler Demodulation Circuitry (Lower Schematic)

of the received signal, since the Doppler shift information has been lost due to (1) the mixing of the incoming signal with a non-synchronous frequency at the mixer stage, and (2) the filtering of the detected signal to eliminate the "unwanted" higher frequency components. Either of these factors is sufficient to preclude determination of the Doppler frequency content of the signal. The lower diagram, on the other hand, shows how the Doppler "demodulation" procedure retains both the amplitude and Doppler shift information contained in the incoming signal (note that the double frequency components are assumed to have been filtered out here). Note, also, that the AM detected envelope $E_1(t)$ is immediately obtainable from the demodulated return $E_2(t)$, but that the reverse is impossible. Thus, the Doppler demodulated signal contains not only the envelope of the returned signal, but also information on the instantaneous target velocity determinable from the Doppler shift data.

The above comparison is also inherent in the mathematical treatment given in Section 2. Note that the amplitude variations are described by variations given by the first term $B_a(t)$ in equations 14a and 14b. In fact, the envelope of the received signal is given by

$$E_1(t) = \sqrt{A_x^2(t) + A_y^2(t)} = B_a(t) \quad (16)$$

which contains only the amplitude variations discussed above.

Consider now the situation in which a single bird is in the beam of either system and flying in a direction perpendicular to the radar k vector (i.e., across the antenna beam). Recall that the AM detection scheme responds only to variations in the total effective cross-section of the bird (if we assume that the destructive interference effects arising from multiple reflections from different parts of the bird's body are minimal). Thus, the signal amplitude

variations are produced by the variations of the bird's cross-sectional area that are in turn caused by time variations of the projected cross-section of the wing. This can be made more apparent by imagining the projected sidewise cross-section of the laterally extended wing (minimum cross-section) relative to the vertically extended wing (maximum cross-section) for the model shown in Figure 1.

Thus for conventional AM detected radar systems, temporal variations of the projected bird's cross-section will yield temporal variations of the signal strength. Insofar as these cross-sectional variations arise from the wing projections, the temporal signal strength variations will contain information on the wing beat rate. This is the type of data (i.e., the $E_1(t)$ variations in Figure 19 currently being examined by other investigators to extract wing beat rate (ref. 7).

A Doppler radar system operating in the same configuration could produce the same type of data described in the previous paragraph. It will, however, also produce data on the integrated velocity spectrum due to reflections from every portion of the bird target. Furthermore, standard techniques can be used to eliminate the effects due to the cross-sectional variations, leaving only the pure Doppler variations (e.g., a conventional clipper-amplifier circuitry can eliminate essentially all but the frequency variations of $E_2(t)$ in Figure 19). This means, for example, that only the periodic wing/body motions will be present in the data, and no other effects need be considered (imagine, in contrast, the potential problems for the AM detection technique if the destructive interference effects mentioned above are not negligible).

7. See, for example, a series of pertinent papers in Proc. of the Conference on the Biological Aspects of the Bird/Aircraft Collision Problem, Sidney A. Gauthreaux, Jr., Editor, Clemson Univ., Clemson, SC, Feb. 5-7, 1974.

Another way of looking at the relative differences between the two techniques is by considering the frequency content of the data output from each system. The AM-detected signals contain frequencies in the vicinity of the wing beat frequency, i.e., in the range 2-20 Hz. The frequency content of these signals, as mentioned above, can also contain components arising from effects other than the normal wing beat (e.g., destructive interference effects that will also vary with time). Furthermore, these frequencies are essentially subaudible, and at best reflect only the mean wing beat rate. The Doppler data, on the other hand, contains the complete "signature" of the velocity pattern of the entire bird target. The mean target velocity typically produces Doppler frequencies of a few hundred Hz; the complex frequency shifts due to the wing and body motions are distributed around this mean target motion and vary periodically in concert with the wing beat pattern. These variations differ strongly for different types of birds, as indicated in the accompanying sound-motion picture.

Because the Doppler signature contains much more information than the AM signature, the identification of bird types from the Doppler signature is much more precise than from the AM signature. From the AM signature, at best only the wing-beat frequency can be determined, so that birds with the same frequency but quite different flight characteristics cannot be distinguished. With the Doppler signature, birds with the same wing beat frequency, but in different genera, families, etc., can usually be distinguished by their specific flight characteristics. This has been demonstrated in the experiments described herein. Furthermore, after only a few minutes of observation of various bird types, the "novice" operator can easily and immediately distinguish between a variety of birds in the antenna beam. This has, on occasion, been clearly demonstrated by a novice operator detecting and naming the type of bird in the antenna beam, even before the bird is located visually.

Consider now a comparison of the two techniques in the situation where a number of identical bird targets occur within the echoing volume. For the AM-detected signal, there is virtually no expectation of ascertaining the type (and therefore the number) of birds in the beam. This problem arises because of the fact that the sum of a series of non-constant amplitude, non-synchronous, quasi-periodic, amplitude-detected returns arising from multiple bird targets will contain insignificant information on the wingbeat rate. For the Doppler demodulated signal, the picture is much more promising. On the practical side, aural analysis of the audio output of the Doppler system shows that even when there are many (i.e., greater than ten) birds in a flock, the human ear can easily determine the type of bird. Our results show that a flock of Canada Geese can be differentiated from a flock of Mallards within a few seconds. This capability is the result of the ability of the ear-mind system to do an excellent qualitative spectral analysis of the audio signal. Since the velocity spectrum of the Doppler-demodulated signal from a group of bird targets is merely the sum of the velocity spectra of all the individual targets, the composite return retains the time-averaged characteristics of each velocity spectrum (cf. the section on time-averaged spectral analysis in Section 4). Moreover, the spatially averaged signal arising from the multiple but finite targets in the echoing volume will contain time-varying signals that enable the easy identification of large numbers of birds. On the theoretical side, the true characteristic spectral signature of a particular type is obtained, in fact, by considering an infinite number of birds observed within the antenna beam for an infinite amount of time. Thus the efficacy of time-averaged spectral signature increases rather than decreases with increasing target numbers. This fact should be contrasted with the AM techniques, where the increased number of targets results in a decrease of information content.

9. MODIFICATION OF TYPICAL RADAR SYSTEM FOR DOPPLER OPERATION

The mathematics underlying the frequency-coherent (Doppler) technique have been outlined in a previous section (Section 2). The basic problem to be discussed in this section concerns the modification of existing radar systems to a Doppler capability. The discussion must of necessity be general in nature, owing to the wide variety of systems in use. Nevertheless, the general concepts outlined below are valid and necessary for the successful modification of any radar system to a frequency coherent system.

The basic requirement for frequency coherence is a knowledge of the exact relationship between the transmitted and received signal. Rewriting Eq. (8) yields

$$\pm f_d = f_1 - f_0 \quad (17)$$

In order to retain information of the Doppler frequency variation f_d , it is essential to have information on the exact relationship between the transmitted frequency f_0 and the received frequency f_1 .

Precise knowledge of the transmitted frequency at some time after the transmitted pulse has occurred requires that the transmitted frequency (1) be stable to within a fraction of the expected Doppler frequency variation over the time period between the transmitted pulse and the echo return, and (2) be relatively pure and constant during the transmitted pulse period. Although these two requirements are related, they put different requirements on the type of microwave oscillator that can be used in a frequency-coherent system.

Consider the first requirement: the frequency stability of a given oscillator depends upon a number of factors including temperature, long-term drift, voltage variations and load impedance. It is difficult to completely differentiate

between these factors, and, indeed, it is not really necessary for the present purposes. The first requirement merely establishes the maximum allowable frequency variation in the time period between the transmitted pulse and the received signal. No specification is required, for example, for long term stability: the oscillator frequency can vary at random, within the basic bandwidth restrictions of the receiver, provided that the first requirement is met. As an example, consider a typical microwave transmitting frequency of, say, 9 GHz. A typical Doppler shift expected for a bird flying toward the radar is about 2 kHz, corresponding to a radial velocity of about 30 m/s (cf. Eq. (9)). We must require that the oscillator frequency variation be much less than this, say 10 Hz, over the time period between the transmitted pulse and the echo return. Otherwise, a comparison of the transmitter frequency at the time the echo occurs will show an incorrect value of f_d . Assuming the target is at about 1.5 km range, this time period is 10 μ sec. Therefore, the required oscillator frequency variation, δf_{osc} , should be better than

$$\delta f_{osc} = 10 \text{ Hz} / 10^{-5} \text{ s} = 10^6 \text{ Hz/sec} \quad (18)$$

Equivalently, the required oscillator stability should be better than .01%.

With regard to the second oscillator requirement, while the purity of the oscillator frequency during transmitted pulse is not a critical requirement for some typical microwave oscillators, it essentially precludes the use of the magnetron for frequency-coherent applications. Although the magnetron has proven to be extremely useful in conventional radar systems, the frequency variations during a single pulse period, resulting from the pulsed-cavity oscillation mode, far exceed the frequency tolerances required for a frequency-coherent system.

The system used in this study incorporated Gunn-effect microwave oscillators having frequency stability tolerances within requirement (1). These oscillators were operated continuously (being well shielded from the rest of the system) and thus the spectral purity during the transmitted pulse (requirement (2)) was not a problem.

Now, let us assume that the transmitted and received signals are available simultaneously, and that the transmitter and beat-frequency oscillators meet the above requirements. A subsequent requirement is that the frequency-coherent system be capable of determining the frequency differences between these two signals. This capability is not one typically contained in conventional AM-detected radar systems and must therefore be added. If one refers to Figure 4, this requirement involves mixing both the transmitter frequency (reference channel) and the received frequency (signal channel) with a common beat-frequency oscillator. For the system used in our tests, the beat frequency oscillator was a second Gunn-effect microwave oscillator tuned to a frequency 30 MHz away from the transmitter oscillator. The bandpass filtering and 30 MHz intermediate-frequency (IF) amplification could utilize the existing radar receiver, although a type of modular system similar to that described in Appendix B is recommended. This would allow, for example, simultaneous operation of the radar in question as a conventional radar and as a frequency-coherent Doppler system: conventional receivers would provide the standard AM-detected output to conventional observing equipment, such as PPI oscilloscopes and A-scan devices, while the coherently-demodulated signals could be connected directly to both on-line analysis devices as well as to an audio detection system.

Basically, then, the radar in question must (1) either contain, or be modified to contain, a stable oscillator as described above, and (2) have, as

a peripheral device, some form of the frequency-coherent demodulation scheme described herein. Other than the above requirements, very little modification is anticipated. One possible exception is the modification of the existing antenna system, although, at first glance, existing systems would seem to be perfectly adequate. It may turn out that specific circumstances will require different antenna configurations, although this feature will depend upon a variety of yet-to-be determined variables.

10. ESTIMATING THE NUMBER OF BIRDS IN THE TARGET VOLUME WITH DOPPLER TECHNIQUE

In order to determine the number of birds within a target volume, it is necessary to know first the effective radar cross-section of the target bird, and second the total power returned from all of the birds within the target volume. Knowledge of these two factors is sufficient in general to obtain an estimate of the number of birds within the volume.

The expected scattered power P_r from a single bird target of cross-section σ_b at a range R from a transmitter transmitting a power P_t depends on the antenna area A and the antenna gain G , in a manner described by the radar equation:

$$\frac{P_r}{P_t} = \frac{GA \sigma_b}{16 \pi^2 R^4} \quad (19)$$

All of these factors are determinable in principle, including the value of σ_b , which can be determined by prior experimentation for the given transmitted frequency and the kind of bird in question.

Define the total power returned from a target volume containing more than one bird as P_{Total} so that the total effective cross-section σ_{Total} is, from equation 19:

$$\sigma_{Total} = \frac{16 \pi^2 R^4 P_r}{GA P_{Total}} \quad (20)$$

Furthermore, we may define a factor α , such that

$$\sigma_{Total} = \alpha \sigma_b \quad (21)$$

If we now assume that the type of bird in the target volume has been identified (either by the on-line aural method or by on-line spectral analysis) and the total echo power P_{Total} has been established (this can be done by

calibrating the average echo signal level $B_a(t)$ as a function of range), then the number of birds in the target volume can be estimated by the value of α in (21). Thus, $\alpha \sim 5$ would indicate 5 birds, $\alpha \approx 20$, 20 birds, etc. The only assumption here is that each bird acts as an individual scattering source so that collective effects are not considered.

The accuracy of a determination of the total bird number depends primarily on the ability to determine α . This in turn depends on the accuracy of knowing σ_b , which for example, can vary as a function of the bird's flight vector relative to the radar. Errors in the determination of values for P_t , G , A , and $B_a(t)$ also must be evaluated.

11. CONCLUSIONS

In the previous sections of this report, we have demonstrated various techniques for analysing the output of a frequency-coherent microwave radar system in order to determine the "Doppler Signature" of flying birds. It appears that each of the techniques described above has features that are desirable for particular aspects of the problem of flying bird detection. With regard to the individual spectral techniques, the sonogram analysis is perhaps the least complex and least expensive method that leaves the experimenter with a tangible, permanent record; the major drawbacks to this method appear to be the difficulty in determining quantitative data from the records and the inability of the method to examine echo returns from more than a very few birds within the echoing volume. On the other hand, the time-dependent spectral technique, which produces a series of power spectra over a short period of time as in Figure 15, allows for a quantitative analysis of the echo intensity but still suffers from the problem of analyzing multiple target returns. It is also more complex and requires more sophisticated equipment. The third method (time-averaged spectral analysis) holds a great deal of promise in the analysis of simultaneous echoes from a large number of birds. This technique has similar drawbacks to the time-dependent spectral technique as far as complexity is concerned, and it suffers as well from the fact the wingbeat frequency is averaged.

There is another problem common to all of the spectral analysis techniques discussed herein. This problem is that, while they have great potential for the study of birds, in order to use them as a real-time warning system for an airport they require complicated computer pattern recognition programming.

It appears, as a result of these studies, that the most feasible method of detecting flying birds for purposes of airport safety involves the use of an X-band (3 cm) Doppler radar with an on-line aural analysis system. The aural analysis, where the Doppler output of the radar is presented to the observer by means of earphones or a loudspeaker, has proven to be a practical method of detecting flying birds, of distinguishing the bird targets from other targets, and identifying the type of bird. An operator can quickly acquire the ability to detect the presence of birds within the radar beam. With the present system, an observer, analogous to a sonar operator, using a radar similar to the one used in these studies, can readily detect the presence of large birds flying within a few kilometers of the end of an airport runway. Detection at much larger ranges would be possible if more powerful transmitters were employed. Furthermore, it is possible for the observer to distinguish between a number of types of birds by means of this audible presentation of the radar output.

The observer can sense at least three important characteristics of bird flight that are related to airport safety: the gross motions of flight, the type of bird, and the presence of flocks. The gross motions of flight, such as diving, swooping, gliding, and circling are denoted by changing tones that can be associated with velocities. For example, the Doppler output from many circling gulls shown in Figure 16, gave a "howling" sound in the loud speaker, while the Doppler output from the quasi-gliding gull, shown in Figure 14, gave a slightly wavering tone that changed pitch with time. The type of bird is inferred from the Doppler signature, particularly the wing beat frequency. Because the bird weight correlates inversely with wing beat frequency (see Figure 2 and Eq. (7)), generally the lower the wing beat frequency, the heavier the bird, and therefore, the greater the collision hazard. The presence of multiple birds is made obvious to the observer by the confusion of wing beats in the audible output of the radar.

Soaring or gliding birds cannot, of course, be as quickly distinguished from non-avian targets and they are more difficult to identify as to type. Nevertheless, since the gross motions of bird flight are different from the motions of non-avian targets, and since these larger motions and the slight wing motions differ from type to type, with longer observation, soaring birds can usually be detected and identified as to type.

The aural analysis technique is recommended because it is both simple and effective. Of all of the analysis methods discussed above, it requires the least time delay between the acquisition of the radar information and its evaluation. It has the added advantage of leaving the eyes of the operator free for other tasks.

We envision a typical warning system as an addendum to a conventional airport radar system. Normal operation would consist of scanning the area around the airport with a conventional radar. If the conventional radar shows evidence of anomalous echo activity along or near a flight path, then the operator could switch the system to the "Doppler Mode" (or, alternately, use a separate Doppler radar) and examine the aural characteristics of the anomalous echoes using the on-line audio system. Subsequent identification of these echoes as flying birds, along with a reasonable identification of the type of birds, could be used in conjunction with the estimated signal strength to establish the number of targets, and thereby the danger to an approaching aircraft.

There are, of course, other possible operating modes. It may also be feasible, for example, to have an unattended radar directed to examine the region around the approach path with only crude range resolution. The presence of any echo within the subject volume (with Doppler shifts lower than that of an approaching aircraft or with a periodic "wing beat" frequency) could be used to flash a warning to the tower operator, who could then merely connect the Doppler audio system and ascertain the potential strike hazard to approaching aircraft.

APPENDIX A
EQUIPMENT LIST

Item		Manufacturer and Model	Manufacturer's Address
Amplifier (Audio)	1 each	Herald, AM-51A	Chicago, Ill.
Antenna, horn	2 each	FXR, X638A	Woodside, New York
Computer, digital	1 each	Data General, NOVA 800	Southboro, Mass.
Demodulator/Receiver	1 each	Constructed In-House (See Appendix B)	
Mixer/RF Amplifier	1 each	RHG/MPO.2CRFI	94 Milbar Blvd. Farmingdale, N.Y.
Oscillator, Transmitter	1 each	Varian, VSX 9001GX	611 Hansen Way Palo Alto, Calif.
Oscillator, BFO	1 each	Varian, VSX 9001GX	" "
Recorder, Analog	1 each	Sangamo, 3500	Springfield, Ill.
Sonograph	1 each	Raytheon Corp.	
Transmitter	1 each	Space Microwave Laboratory	775 Montecity Center Santa Rosa, Calif.
Camera	1 each	Beaulieu, R76	Paris, France

APPENDIX B

A PORTABLE, FREQUENCY-COHERENT SPECTRUM ANALYZER FOR RADAR APPLICATIONS

(NOAA Technical Report ERL 204-AL 5)

Ben B. Balsley

This report describes a portable device that can be connected to a conventional pulsed-radar system to obtain frequency-coherent radar returns. The device has been designed to record the analog, frequency-coherent radar returns onto magnetic tape for subsequent spectral analysis. Although the design criteria have been chosen for VHF radar investigation of the earth's ionosphere, the system is easily adaptable to other types of investigation wherever the spectral analysis of radar returns is desirable.

Key Words: frequency coherent detector,
ionosphere, spectral analysis,
spectrum analyzer.

1. INTRODUCTION

The technique of spectral analysis is becoming increasingly useful in a variety of scientific and engineering applications. This is partly due to the development of faster, smaller, and more sophisticated computers and partly due to recently developed fast computer algorithms. The combination of these factors often makes it possible to perform a fairly detailed "on-line" analysis. One example -- the one that this report is concerned with -- is the spectral analysis of VHF radar echoes scattered from electron density irregularities in the earth's ionosphere. These spectra have proved very useful for examining the character of ionization drifts and for studying ionospheric plasma instabilities.

To obtain meaningful spectra from the radar returns, it is necessary to control the frequency, the sampling rate (PRF), and the pulse width of the ionospheric radar system consistent

with the phenomenon being investigated. In addition, the frequency of the returning signals must be referenced to the transmitted frequency to detect slight (~ 1 part in 10^6) frequency differences (Doppler shifts) arising from the scattering process. Finally, the received radar signal must be treated so that the "receiver" output is compatible with the computer input requirements.

This report describes a device that is designed to perform the above functions. This device contains the necessary features to control the radar transmitter frequency, pulse rate, and pulse width. The incoming signal is "zero-beat" with the transmitted frequency, so that both the amplitude fluctuations and Doppler shift information caused by the scattering processes are retained. The output is fed directly to the (digitizer) input terminals of a digital computer to obtain the power spectrum of the sampled return.

The present design incorporates concepts that have been developed over the past few years at the Jicamarca Radar Observatory (near Lima, Peru). It also takes advantage of the technological advancements made in the interim and contains modular, solid-state circuitry that was not previously available.

This particular system has been designed to be portable. (The complete system, excluding the high-power transmitter and the antennas, weighs less than 200 pounds.) Its usefulness is thereby extended because it is possible to obtain radar-echo spectra of ionospheric irregularities at remote field sites. Since the operating frequency is determined by two plug-in oscillators (one to set the transmitter frequency and the other to mix with the incoming signal to obtain the 30 MHz intermediate frequency), it is a simple matter to adapt the system to operate over a wide range of frequencies.

2. GENERAL SYSTEM OUTLINE

The block diagram in figure 1 depicts a complete system to obtain radar-echo spectra from ionospheric irregularities. Examination of figure 1 shows that the transmitting frequency, pulse rate, and pulse width are generated within the logic block entitled *transmitter driver/pulse generator*. The resulting low power (~ 20 mW) rf (radio frequency) pulse is used to drive an external *transmitter*, whose output is fed directly into the *transmitting antenna*. Echo returns from this transmission are brought in via the *receiving antenna* to the *frequency-coherent demodulator*, where the received signal is "zero beat" with the transmitting frequency (from the *transmitter driver/pulse generator*). The demodulator output contains information on the amplitude fluctuations and the Doppler frequency variations arising from the ionospheric scattering process. This output is either fed to the *analog tape recorder/*

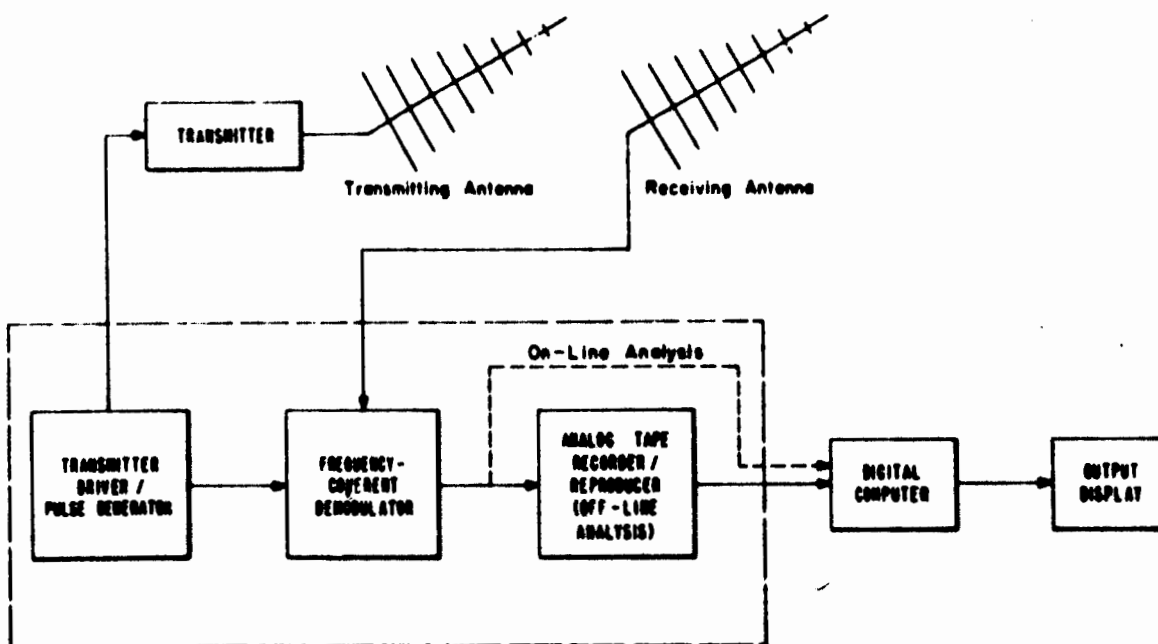


Figure 1. Block Diagram of a System To Obtain Frequency-Coherent Radar Returns for On-Line (or Off-Line) Spectral Analysis

reproducer for later (off-line) analysis, or fed directly to the *digital computer* for on-line treatment. The *output display* presents the computed spectrum in a useful format.

In the system shown in figure 1, the utility of the analog tape unit is really twofold. It can be used to analyze the recorded data at some later time and also used to "simultaneously" analyze the recorded signal at many different radar ranges by replaying the same strip of magnetic tape. This latter feature is quite useful, since simultaneous spectral analyses without a tape unit can only be accomplished with a large computer.

This report is concerned primarily with the description of that part of the system enclosed within the dashed lines in figure 1. The additional equipment requirements are outlined briefly in section 3.4.

3. SYSTEM SUB-UNIT DESCRIPTION

3.1 Frequency-Coherent Demodulator

Figure 2, excluding the dashed-line areas and the antenna symbols, is a detailed block diagram of the frequency-coherent demodulator. Front and rear view pictures of this unit (including the transmitter driver/pulse generator described in sec. 3.2) are shown in figures 3 and 4, respectively. The numbers in these figures refer to the specific sub-units and pertinent connectors listed in appendix A. Where applicable, sub-unit descriptions, including manufacturer and model numbers, are given in appendix B.

As shown in figure 2 (refer to figs. 3 and 4 for numbered references), the incoming signal appears at the input (No. 3) of the *first rf amplifier* stage. This signal is amplified (*first and second rf amplifiers* (No. 1 and No. 4) and then adjusted to an optimum level by a *step attenuator* (No. 6). The

amplified signal is then mixed (*first mixer* (No. 21)) with the *beat frequency oscillator* (No. 22) (BFO) whose frequency is 30 MHz above the transmitted frequency. Following along the upper path (signal channel), the mixer output is amplified (*IF amplifier* (No. 8)), after being filtered by a 30 MHz *band-pass filter* (No. 10), and is passed through a *power splitter* (No. 12). The purpose of the power splitting is to provide equal and isolated signals to one port of each of the two *second mixers* (No. 15 and No. 25). The signal that appears at the remaining port of the two second mixers is termed the "reference signal" and is derived from the difference between the BFO and the transmitter oscillator frequency. The reference signal is treated in the lower path (reference channel) in the same manner as the received signal is treated in the signal channel; i.e., the reference is derived in a first mixer (No. 38) and is subsequently filtered (No. 36),

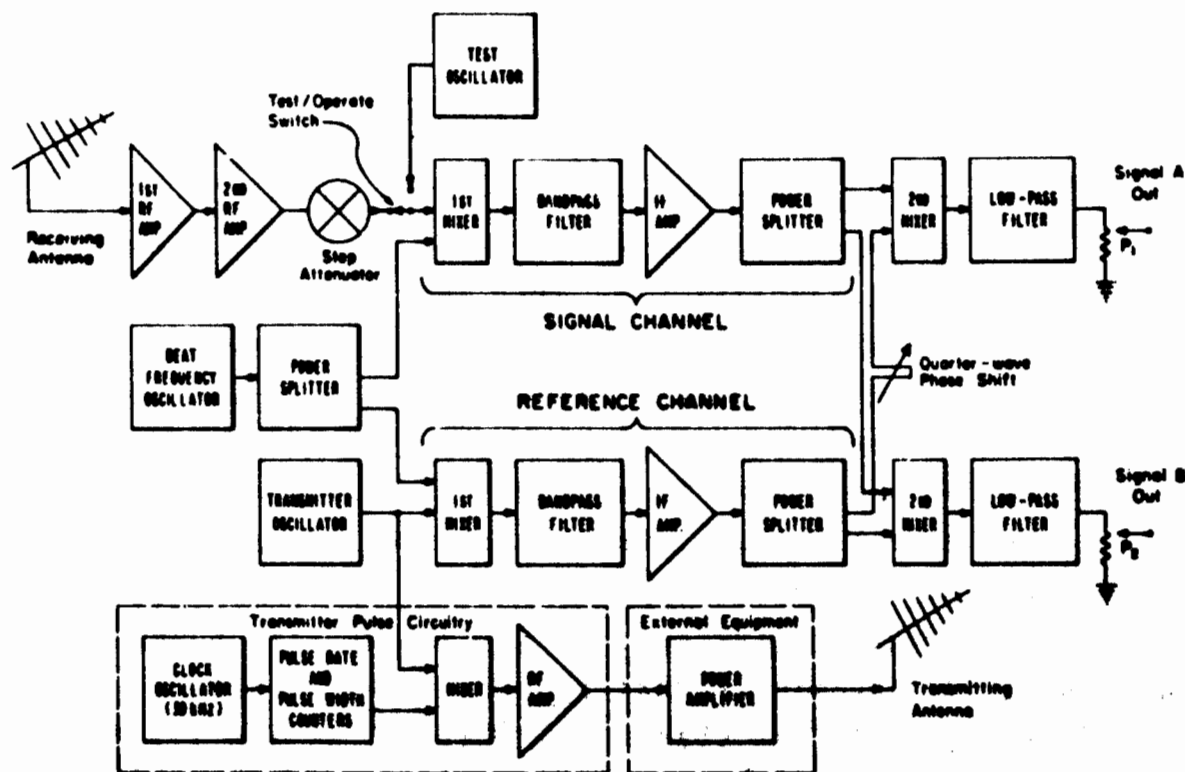


Figure 2. Block Diagram of the Frequency-Coherent Demodulator and Associated Units

amplified (No. 35), and split (No. 23) into two separate, equal, and isolated paths.

The input signals to the two second mixers are identical, except that the reference signals that appear at the two separate ports are in phase quadrature (i.e., one is shifted by 90° relative to the other). This is accomplished by inserting an additional quarter-wavelength of cable (approximately 1.7 m of cable at 30 MHz). This cable section is contained in the small metal box (No. 32) seen in the lower center of figure 3. The second mixer outputs are passed through *low-pass filters* (No. 13 and No. 28) and then to the level-adjust potentiometers (P1 (No. 17) and P2 (No. 30)). The two signal outputs (*Signal A out* (No. 14) and *signal B out* (No. 31)) differ from each other only in that they are in phase quadrature. In the computer analysis this (quadrature) relationship is necessary to establish the sign of the Doppler shift information contained in the zero-beat signal.

Note that both the amplitude and phase information contained in the incoming radar signal have been retained. By proper analysis of these output signals, it is possible -- within reasonable limits -- to differentiate between these two types of information. This is a necessary requirement for a system designed to investigate the character of the ionospheric echoes.

The *test oscillator* (No. 41) is a voltage controlled crystal oscillator, whose frequency is variable by approximately ± 1000 Hz around the transmitted frequency. The frequency control is a potentiometer (No. 42) located on the front panel. The test oscillator is used to adjust the signal levels and the orthogonality of the signal A and signal B outputs. This is done by setting the test oscillator frequency to be approximately 100 Hz from the transmitter oscillator frequency, so that a 100 Hz sinusoidal wave appears

at the signal A and signal B outputs. Amplitude differences in these two signals can be minimized by potentiometers P1 and P2. The phase relation between them can be determined with a standard phasemeter, or by a similar device.

3.2 Transmitter Driver/Pulse-Generator

The transmitter driver/pulse-generator logic flow diagram is pictured in the lower left (dashed-line area) section of figure 2. The clock oscillator and the pulse counters are located in the enclosed sub-chassis (No. 7) in the upper-central portion of figures 3 and 4; the mixer and rf amplifier are located in the enclosed box (No. 27) at the center of the unit in figure 4.

The transmitter pulse rate (PRF) is generated from an internal 30 kHz clock oscillator. This is accomplished by dividing down the clock frequency with a preset counter that has been set to divide by a factor, m , to produce logic pulses at a rate

$$\text{PRF} = 30 \text{ kHz}/m \quad \text{pulses/sec,} \quad (1)$$

where the value of m is determined by the operator and is set by a decimal-coded thumbwheel switch (the first three sections of the thumbwheel switch (No. 7) in fig. 3).

The transmitter pulse width is generated by using the pulse train in (1) to start a second thumbwheel-controllable preset counter, which then counts a number, n , of internal clock pulses. The width control switch is the fourth thumbwheel switch seen in No. 7 of figure 3. The resulting output pulses are designed to begin at the beginning of each pulse in (1) and continue until the completion of the n^{th} clock pulse. Since the basic clock period is $33 \frac{1}{3} \mu\text{sec}$ (corresponding to a radar range of 5 km), the pulse width is incrementally variable in steps of $33 \frac{1}{3} \mu\text{sec}$:

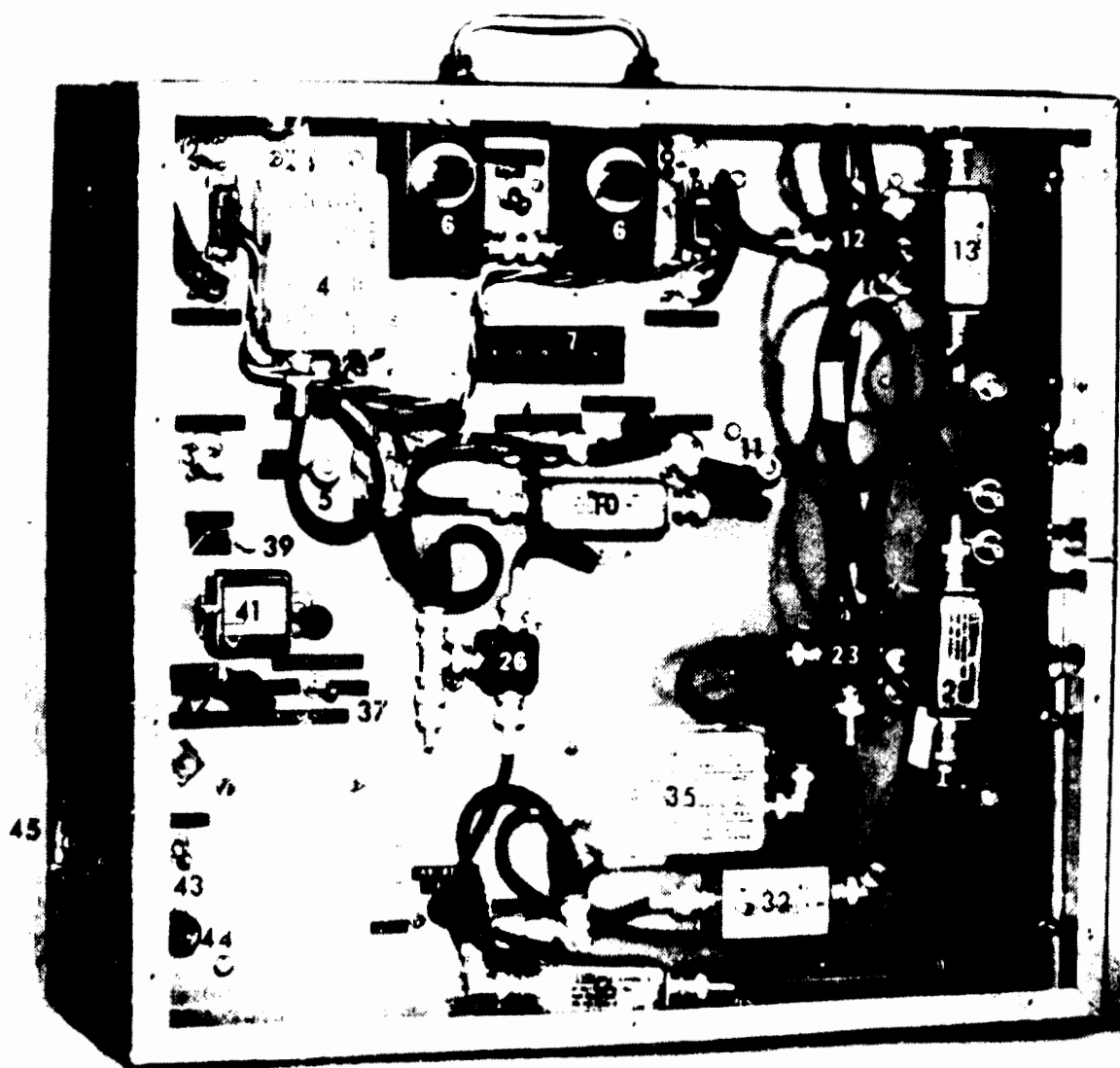


Figure 3. Front View of the Portable System Excluding the Tape Recorder/Reproducer

$$\text{pulse width} = (33 \frac{1}{3})n \quad \mu\text{sec} \quad (2)$$

Hence, both the pulse rate and the pulse width are controllable by thumbwheel switches and can be set as desired for a particular experiment. The ranges of m and n are

$$2 \leq m \leq 999 \quad (3)$$

and $1 \leq n \leq 9$, (4)

so that the PRF lies in the range

$30 \leq \text{PRF} \leq 15,000 \text{ pulses/sec}$, (5)

and the pulse width limits are

$33 \frac{1}{3} \leq \text{pulse width} \leq 300 \text{ } \mu\text{sec}$. (6)

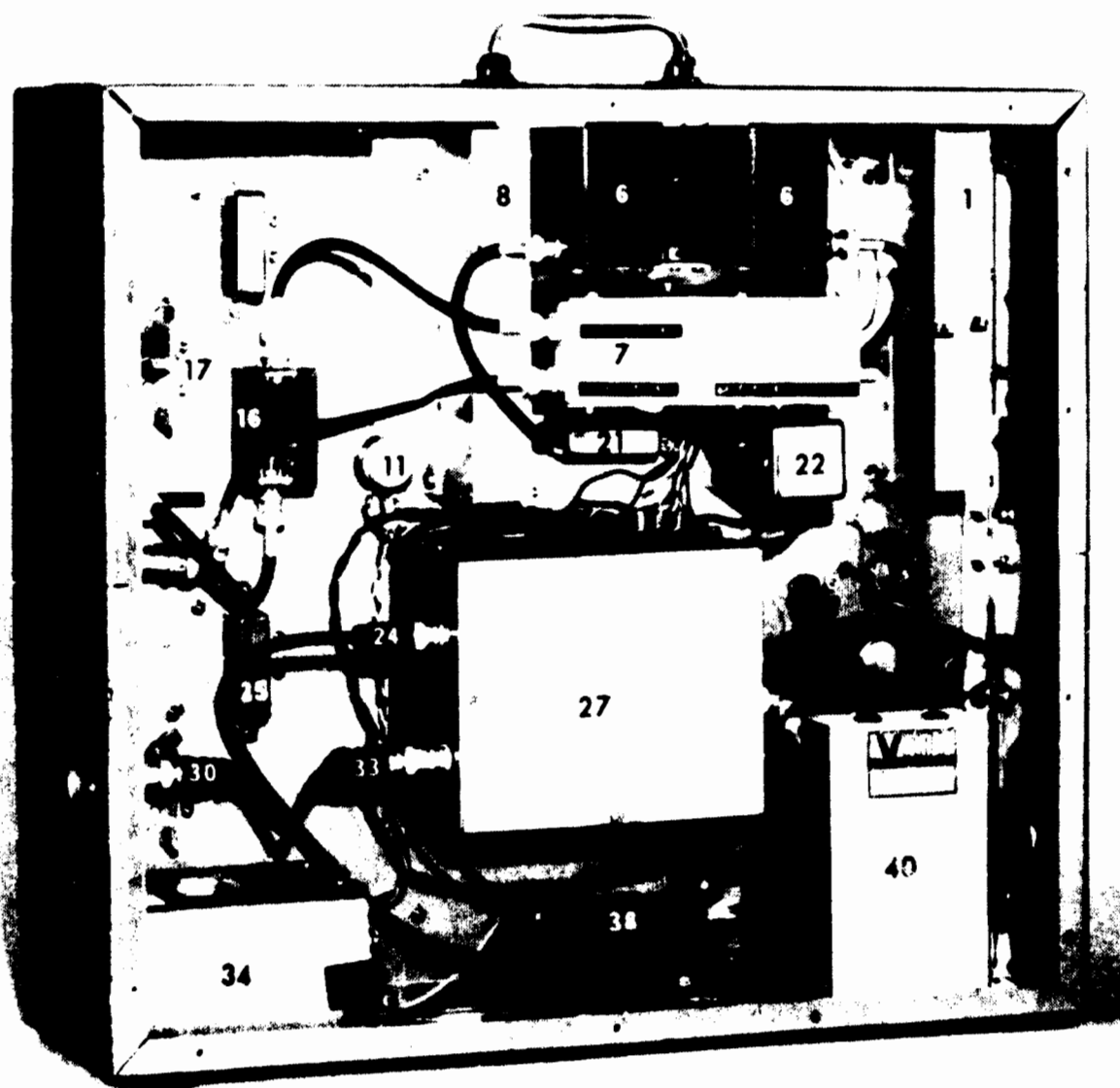


Figure 4. Rear View of the Portable System Excluding the Tape Recorder/Reproducer

The limitations imposed by (5) and (6) are not excessive, since typically (at an operating frequency of 50 MHz) the desired pulse width is about $66 \frac{2}{3}$ μ sec ($n=2$) and the PRF is in the vicinity of 300 pulses/sec ($m=100$).

The low-level rf transmitter pulse is generated by gating the rf signal from the transmitter oscillator with the output pulse of the pulse width counter. This is accomplished in the *mixer circuit* as indicated in figure 2. The *rf amplifier*, which follows the mixer, raises the power level to approximately 20 dBm. The amplified rf pulse output (No. 33 in fig. 4) is then used to drive the *rf power amplifier* (i.e., the final stages of a VHF transmitter) shown in the *external equipment* section and denoted by dashed lines in the lower right section of figure 2.

3.3 Magnetic Tape Recorder/Reproducer

The Sangamo Model 3562 recorder/reproducer used in this system is a portable, seven-channel unit, whose pertinent specifications appear in table 1. Three channels are required to record the necessary data. These consist of two signal channels (to record the signal A and signal B outputs) and one channel to record the 0-12 V logic pulse (No. 19 in fig. 3) from which the transmitter pulse is derived. Under some circumstances, it is also desirable to record (on a fourth channel) the 30 kHz clock frequency (No. 18 in fig. 3) for accurate range determination. The two signal channels are recorded in the FM record mode (cf table 1), since the required frequency response is from dc to 40 kHz. The pulse channels are recorded in the direct record mode, since the low frequency response is not needed, and the higher frequency response of the direct mode is desirable to reproduce the fast pulse rise times.

Table 1. General Specifications of the Sangamo 3562 Tape Recorder/Reproducer

	Operating Mode	
	Direct	FM
Freq. Response	30 Hz-300 kHz @60 IPS	0-40 kHz @60 IPS
Input Level	0.1 V rms (minimum)	60 mV rms (minimum)
Output Level	1 V rms	+ 1.4 V peak
Tape Specifications		
Tape Reel Size	up to 16 inches	
Tape Width	1/2 inch	
Tape Speeds	7 1/2, 15, 30, 60 IPS	
Weight	130 lbs.	

An additional advantage of this recorder is that it is capable of bi-directional operation. This means that it is possible to record the three channels in a forward direction and then, at tape-end, to continue to record on an alternate set of three channels in the reverse direction. This effectively doubles the record time per tape reel.

3.4 External Equipment

To have a complete system to obtain VHF radar-echo spectra from ionospheric irregularities, it is necessary to supplement the equipment already described with the additional equipment listed and described below.

- (1) *High-power VHF transmitter.* The final stage(s) of a transmitter at the designated frequency is required to boost the 20 dBm rf pulse, generated by the transmitter driver/pulse-generator sub-system, to a usable peak pulse power (10-100 kW nominal).

- (2) *Transmit-receive antenna system.* This could be one antenna system for both transmission and reception containing the necessary TR-ATR circuitry (to short the receiver input terminal during transmitter pulse periods and to "disconnect" the transmitter during the receiver "listening" periods). Alternatively, two separate systems could be used, thus eliminating the need for such protective circuitry. The antenna patterns must be commensurate with the experiment under consideration, but, in general, they should be reasonably directive (beamwidth 30°) and preferably steerable.
- (3) *Digital computer.* A digital computer is needed to perform the spectral analysis of the received signal. Since the output of the system within the dashed line in figure 1 consists of an analog, time varying signal (signal strength vs. radar range) it is necessary that the computer sub-system contain appropriate sampling and digitizing circuitry.
- (4) *Computer output device.* This unit is required to display the resulting spectra in a useful form. It could be, for example, a standard tabular computer output format, an x-y plotter, or a CRT graphic display unit.

4. ACKNOWLEDGMENTS

It is a pleasure to acknowledge the help of O. A. Mills during the construction phase of this project, and W. L. Ecklund, who aided in the initial experimental checkout of the system.

5. Parts List for Units

Number *	Item
1	First rf amplifier
2	Detector output of first rf amplifier (not normally used)
3	Signal input, first rf amplifier
4	Second rf amplifier
5	Bias adjust, first rf amplifier
6	Step attenuators (one set)
7	Clock-oscillator/pulse-generator subchassis
8	IF amplifier (signal channel)
9	Detector output of IF amplifier (not normally used)
10	Bandpass filter (signal channel)
11	Bias adjust, IF amplifier
12	Power splitter (signal channel)
13	Low pass filter (signal A)
14	Signal A output
15	Second mixer (signal A)
16	Decoupler (clock record output)
17	Signal level adjust, P1
18	Clock record output
19	Gate record output
20	Transmitter pulse switch
21	First mixer (signal channel)
22	Beat frequency oscillator (BFO)
23	Power splitter (reference channel)
24	Transmitter (logic) pulse input to mixer
25	Second mixer (signal B)
26	Power splitter (beat frequency oscillator)
27	Shielded enclosure for transmitter oscillator, mixer, and rf amplifier
28	Low pass filter (signal B)
29	RF pulse output (to external transmitter)
30	Signal level adjust, P2
31	Signal B output
32	One-quarter wavelength of RG 58 c/u cable
33	RF pulse output

*Numbers of units match those in figures 3 and 4.

Number	Item
34	Power supply (LEL)
35	IF amplifier (reference channel)
36	Bandpass filter (reference channel)
37	Test oscillator switch
38	First mixer (reference channel)
39	Test oscillator output
40	Power supply (C-cor)
41	Test oscillator
42	Test oscillator frequency adjust
43	Power switch
44	Fuse
45	Power receptacle

6. Manufacturer Model Number and General Description of Units

Part	Quantity	Manufacturer and Model	Description
Amplifier, rf (receiver)*	1	LEL ITM-2-49.920-10-50	Solid state amplifier: $f_c = 49.920$ MHz, BW=12 MHz, gain (adjustable) = 95 dB max, noise figure = 2.1 dB, $Z_{in} = Z_{out} = 50 \Omega$
Amplifier, rf (transmitter)	1	Constructed in-house	Single stage, tuned, transistor amplifier: $f = 49.920$ MHz, BW > 5 MHz, $C_{gain} = 25$ dB, $P_o = 20$ dBm, $Z_{in} = Z_o = 50 \Omega$
Amplifier, IF (signal)	1	LEL ITM-2-30-10-50	Solid state amplifier: $f = 30$ MHz, BW=11 MHz, gain (adjustable) = 95 dB max, noise figure = 2.4 dB, $Z_{in} = Z_{out} = 50 \Omega$
Amplifier, IF (receiver)	2	CCOR # 3528	Pass band 100 Hz to 100 MHz, gain 20 dB, $P_o = 12$ dBm, $Z_{in} = Z_{out} = 50 \Omega$
Attenuator, step	1 pair	Hewlett-Packard 355C/D	Step attenuator set to vary attenuation between 0-132 dB in 1 dB steps; $Z_{in} = Z_o = 50 \Omega$
Counter, pulse rate	1	Constructed in-house	See text
Counter, pulse width	1	Constructed in-house	See text
Filter, bandpass	2	McCoy # 209B4	$f_o = 30$ MHz, bandwidth (3dB) = 100 kHz, $Z_{in} = Z_{out} = 50 \Omega$, insertion loss < 3 dB
Filter, low pass	2	McCoy # 209B5	Cutoff frequency (3 dB down) = 45 kHz (60 dB down @ 200 kHz), $Z_{in} = Z_{out} = 50 \Omega$, insertion loss < 3 dB
Mixer	5	Relcom M1	Double balance mixer, conversion loss ≈ 7 dB, isolation ≈ 45 dB
Oscillator, beat	1	Accutronics CLT01M	Crystal-controlled oscillator, $f_o = 70.920$ MHz, $P_o = 0$ dBm, $Z_o = 50 \Omega$
Oscillator, clock	1	Bliley CM0-26	Crystal-controlled oscillator, $f_o = 30$ MHz $\pm 0.1\%$
Oscillator, test	1	Vectron Co. 233V	Voltage-controlled oscillator, $f_c = 49.920$ MHz, $P_o = 6$ dBm, $Z_o = 50 \Omega$, frequency deviation = ± 100 Hz
Oscillator, trans-	1	Accutronics RL 101M	Crystal-controlled oscillator, $f_o = 49.920$ MHz, $P_o = 0$ dBm, $Z_o = 50 \Omega$
Phase shifter	1	Constructed in-house	One-quarter wave of coaxial cable @ $F = 30$ MHz, with additional RC vernier adjustment (see text)
Power splitter	3	Dynagraphic #200	Two-way power divider, isolation = 30 dB, insertion loss = 0.3 dB

* Actual total rf amplification consists of LEL amplifier followed by a CCOR No. 2528 (see specifications listed under IF amplifier for a total rf gain of 115 dB [adjustable]).

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TAC/DEEV	1	USAF Rgn Civ Engrg (San Francisco)	1
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