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THE NOAA SEL HF RADAR SYSTEM (IONOSPHERIC SOUNDER)

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noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / Environmental Research Laboratories

NOTICE

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The Space Environment Laboratory of the National Oceanic and Atmospheric Administration has developed a new general purpose computer based system for pulsed RF measurements of the ionosphere in the 100 kHz-30 MHz frequency range. This is a development of the earlier Dynasonde concept to permit full digital signal processing of returned echoes, a dual channel receiver to enable faster measurements of wave polarization and direction of arrival, and a considerably enhanced data processing and display capability. The system philosophy adopted is discussed and some details of the implementation and performance of the instrument are given. A number of instruments are now being produced for various institutions which will form the basis of a coordinated research program over the next ten years.

1. OBJECTIVES

The Space Environment Laboratory of the National Oceanic and Atmospheric Administration has developed a new general purpose radio frequency pulse sounding system intended for research purposes. This covers the frequency range 0.1-30 MHz and with suitable antennas is capable of making nearly all of the remote sensing measurements of the ionosphere which can be made by coherently receiving signals reflected from the ionosphere either monstatically or bistatically. This flexibility is achieved by the incorporation of a general purpose computer as the heart of the system. In this respect, the system is a logical development of the Dynasonde (Wright 1969; Wright and Pitteway 1979a,b; Wright, et al. 1979c). The primary objectives of the new development are:

1. To provide a system with the minimum of hardware-bound restraints to the characterization of signals returned from the ionosphere. This implies digital data processing techniques and requires the modes of operation to be defined and controlled almost completely by software.

2. To provide a system which is capable of self-contained real-time data analysis and display to an extent permitting the geophysical significance of the measurements or their required resolution to be used in the manual or automatic control of data acquisition.

The basic measurements to be made on signal returns are:

1. The complex (vector) numerical description of signal returns versus range and frequency, to permit the amplitude, phase, envelope group delay, $\Delta\phi/\Delta f$ group delay, and doppler spectrum to be obtained.

2. The comparison of echo data from an array of receiving antennas to permit measure of the direction of arrival, wave polarization, and other diffraction pattern information.

3. The comparison of echo data at closely-spaced times for doppler, group-rate, and other time-dependent information.

The system is also well adapted to increasing the range resolution by transforming a set of closely spaced frequency samples (Devlin, et al 1977).

Secondary objectives of the system are to function cooperatively with other sounders in a network to provide information on oblique propagation paths, to function in a spectrum surveillance mode to provide information on oblique propagation from known transmitters, and to accommodate data from other geophysical sensors.

2. SYSTEM PHILOSOPHY

One of the first decisions is the choice of the form of the transmitted signal. Ionospheric sounding systems have developed in two different directions since the early 1960's from the basic pulse sounder developed in the 1930's. In one, pulse sounding has been retained and combined with numerical data recording techniques. Signal enhancement by averaging or the use of coded pulses has been used where necessary to improve numerical accuracy and sensitivity (Bibl and Reinisch 1978). In the other direction, a completely different form of coding, FMCW, uses a linear frequency swept transmitted signal, in which the time domain dispersed signal returns are transformed to frequency dispersed returns; spectrum analysis is required to express the signal return in the ionogram form (Barry 1971). This permits the use of essentially CW transmission giving high average power without the complication of producing high peak powers. It is very effective in rejecting interference from fixed frequency communication signals. Most of the applications have used analog presentation of the output data but high quality numerical data can be obtained by Fourier Transform analysis. In general, and particularly where cross-modulation in nearby systems is a problem, FMCW produces less interference to the normal uses of the spectrum than does a pulse sounding system.

In research applications of ionospheric sounding, it is important to trade frequency resolution and time resolution, depending on the electron distribution and the dynamics of the ionosphere. Indeed, it may be desirable to interleave frequency sweeps and high time resolution sounding at a few selected frequencies. This would be much more complex to achieve with an FMCW system than with a pulse sounder. Another requirement is the sampling of multiple receiving antennas. A single channel receiver can be time shared between antennas with FMCW provided the switching rate is chosen to place the side bands generated outside the final analysis range. Multichannel receivers are more usually used. In the pulse system, any combination of sequential sampling or parallel sampling using multiple receiver channels is easy to implement. Although these problems with FMCW could be overcome and might be considered a reasonable counterbalance to the advantages, the major problem is in the increased complexity of the data processing. To obtain the simple virtual height information, if it is to be done numerically, requires one Fourier transform, and if the doppler spectrum of a time series of returns is needed, two transforms are required. This considerably increases the complexity and power needed in the data processing system and also its cost.

The foregoing factors lead to the choice of a basic pulse sounding system with software controlled options for signal enhancement using pulse-to-pulse integration and/or pulse coding. The latter can be implemented using the complementary codes which are used in pairs and, unlike Barker codes, have theoretically zero side lobes in their autocorrelation function (Golay 1961). Two receiver channels are provided so that a single phase comparison can be made between receiving antennas without any restriction on the phase rate of the process being observed, and to double the potential data acquisition rate of the system.

3. SYSTEM DESIGN

A simplified block diagram of the system is shown in Figure 1.

The main processor is a 16-bit Interdata model 7/16 with 32 K words of 1 μs core memory. Hardware multiply and divide, and hardware floating point registers are incorporated. Typical instruction execution times are 1 μs for a register to register addition, 10 μs for a fixed point 16-bit divide and 48 μs for a 32-bit floating point divide. The processor instruction set is implemented through microcode and is very comprehensive. Input/Output (I/O) communication is carried out through a separately multiplexed bus structure which permits both programmed I/O and Direct Memory Access for block data transfers. Standard peripherals are a 1600 bpi, 9-track, 35 ips tape transport for program loading and data recording, a 10 Megabyte disc memory, one half of which is a removable cartridge disc. A Tektronix graphics display console and hard copy unit form the primary operator interaction point and can in principle be located remotely from the rest of the system; a Model 33 TTY and paper tape reader/punch are used for system logging and initial bootstrap if required. An automatic bootstrap loader permits easy restart under most conditions.

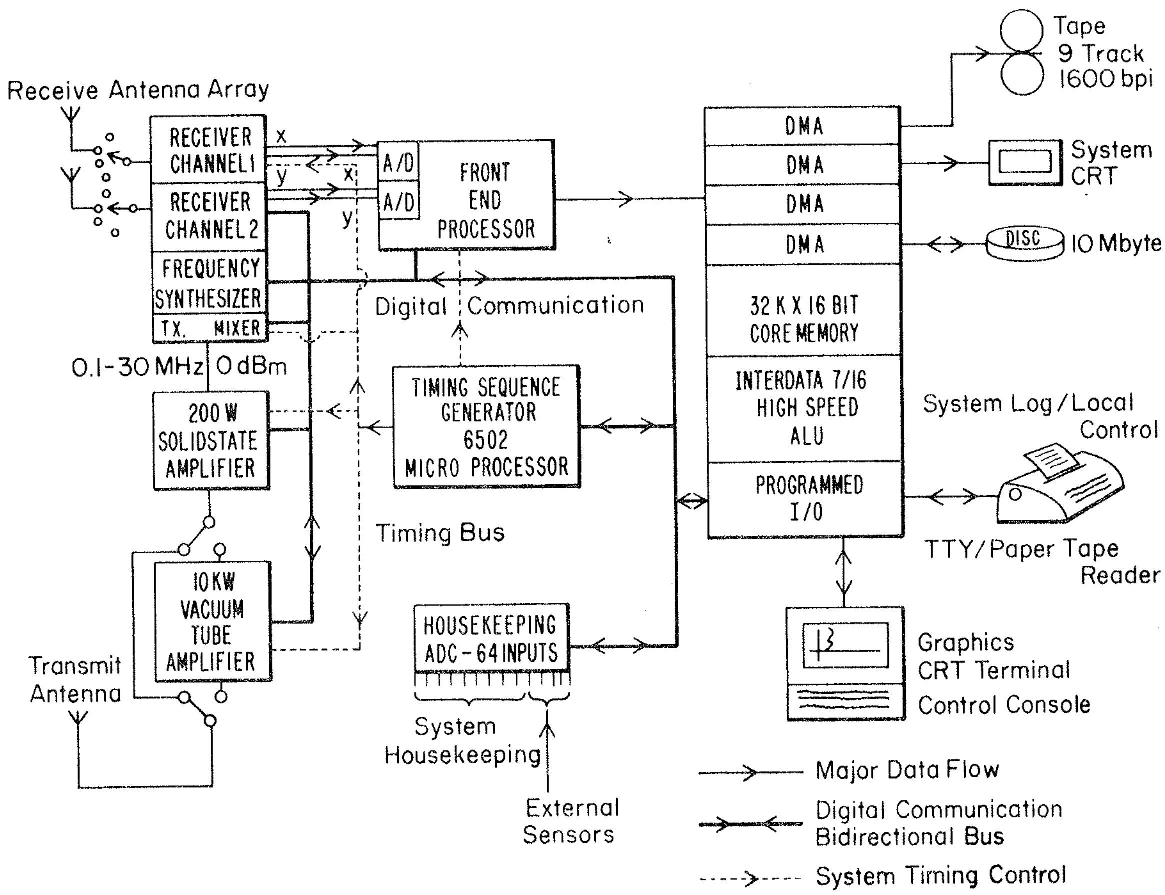


Figure 1. SEL Ionospheric Sounder, general block diagram.

Special purpose peripherals are the interfaces to the two other processors described below and to the local system graphics display.

A separate 15 cm XY CRT display with 1024 x 1024 addressable points is intended as the primary local operator graphics display and for local photographic data recording. Point addressing, vector, and alphanumeric modes are provided. The display is refreshed by direct memory access to the Interdata computer core memory making possible rapid changes in the display for time sequence presentation of the data. The display formats are entirely determined by software and are not predetermined by hardware. The capability also exists for light pen interaction with the data displayed. In addition, the CRT can also be used in standard XY and YT modes to display system timing lines and signal returns in an A-scan mode.

It is not practical to carry out all of the programmable functions needed to meet the system objectives directly with one central processor, particularly since it is desired to have software for general purpose interaction, data processing, and program development coexist with the sounder operating software. The two most time-consuming and routine functions are the generation of the precise timing sequences needed to initiate a transmitted pulse and in the processing of the returning echo data. In the latter operation, a large amount of data must be processed at comparatively high speed to perform initial signal processing, which is needed to reduce the volume of data before it is passed to the main processor. One approach to this problem would have been to build special purpose digital and analog interfaces directly controlled by the main processor. This would have restricted the modes of operation of the system to those which had been foreseen as needed in the original design. The alternative which we have adopted, and which has been made practical by the advances in microprocessor technology, is to use a distributed processing system in which the timing functions and the "front end" signal processing are handled by separate program-controlled processors. These are slaves to the main processor in that they rely entirely on it for nonvolatile program storage and user interaction. Programs for both are loaded from the Interdata 7/16 via a general purpose 8-bit digital I/O bus which is used to communicate with the system for control and status monitoring purposes.

The Timing Sequence Generator (TSG) uses a 6502 8-bit microprocessor. This executes a program which provides control interaction with the other parts of the system and exercises eight general purpose timing lines allocated to various control functions such as transmitter keying and receiver data acquisition gating. The timing is controlled by a sequential state look-up table which contains the states required and the time intervals between them. The time intervals are restricted to integer multiples of 10 μs with a minimum of 30 μs between state changes. This is not generally restrictive considering the bandwidth of the RF system. Timing coherence is ensured by reclocking the microprocessor outputs with the system 100 kHz clock, although the microprocessor clock is itself locked to the system clock. Up to eight separate timing sequences or "scenarios" are stored in the microprocessor program and can be called by a control word from the Interdata. Two are used in system "no op" modes and the remaining six are available as mode selections. If necessary more could be made available by reloading the microprocessor memory from the Interdata.

The general arrangement of the Front End Processor (FEP) is shown in Figure 2. The structure is designed to permit "pipelined" flow of data from the receiver through the processor and into the main CPU. Two sets of input memories are alternately loaded with data from the ADC's and operated on by the FEP following each transmitted pulse. Similarly, one output memory is being loaded by the FEP CPU while the other is transferred to the Interdata. The FEP is implemented with Schottky LSI 4-bit slice ALU's and control building blocks. The CPU is 24 bits wide to permit fixed point manipulation of the products of the input 12-bit numbers. As the programs are expected to be largely repetitive and of

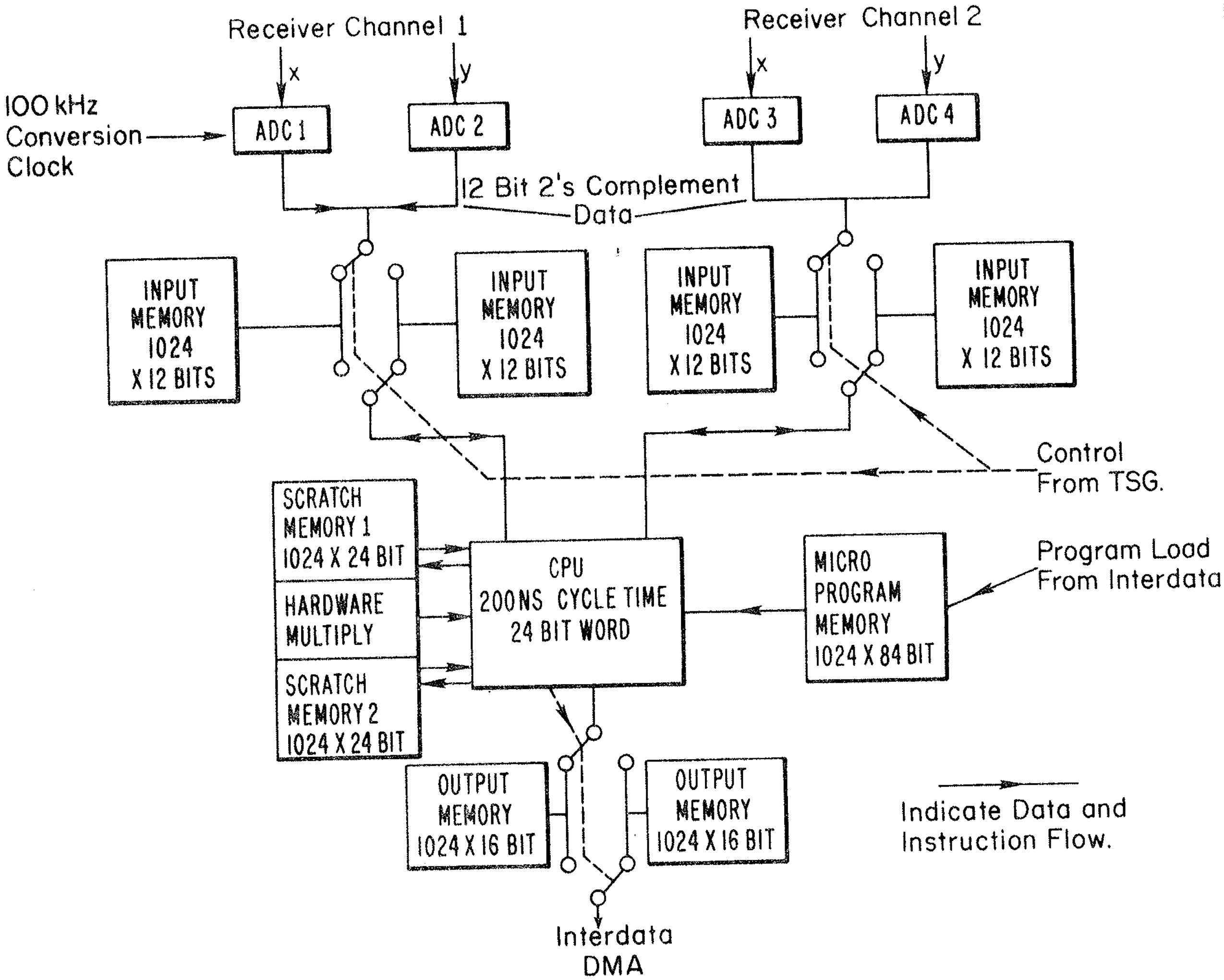


Figure 2. Front End Processor, simplified block diagram.

the continuous loop variety, no macro code interpretation is provided, and the program is executed directly from an 84-bit wide microprogram memory which is loaded from the Interdata. This program memory cannot be modified by the FEP CPU itself. Working memory space is provided by the two scratch memories, each 1024 x 24 bits wide. These memories are addressed in parallel and the required output (or that of a high speed hardware multiplier which multiplies the contents of the addressed memory locations) are selected by a program controlled multiplexer. Sixteen internal general purpose registers are also available within the bit slice ALU for temporary storage. Whenever possible within the FEP, the data flow is pipelined so that operations can be carried out concurrently and at maximum speed. The execution time for one microcoded instruction is one 200 ns clock cycle. This includes all simple fetch, add and subtract, logical compare, and write operations, which for favorable source and destination locations, may be executed concurrently in one clock cycle. The output of the 12-bit x 12-bit multiplier is available in two clock cycles. With the system transmitting 50 pulses per second, 20 ms is available for processing the data from both receiver channels permitting a maximum of about 10^5 microcode steps (50 per data sample in the normal mode). The size of the output memory presupposes reduction in data volume by at least a factor of 2 in the processing. Data from a single receiver channel can be passed to the output directly for system test or for special operating modes. An elementary microcode assembler program has been developed which will be resident in the Interdata.

Figure 3 shows the basic arrangement of the RF system used for the generation of, the transmitted signals and the coherent reception of echoes. A symmetrical up- and down-conversion scheme is employed with two oscillators. The first oscillator, a general purpose synthesizer, generates a frequency between 40.1 and 70 MHz and up-converts the receiver band of 0.1-30 MHz to a 40 MHz IF. The second oscillator, a fixed-frequency 40 MHz crystal oscillator, is down-converted by the same synthesizer output to form the transmitted frequency. Keying and filtering of the transmitted signal is performed at the fixed 40 MHz frequency. The 40 MHz oscillator then provides the reference for coherent quadrature detection of the received signals. The frequency of operation is selected by the Interdata computer which controls the synthesizer.

An important feature of the system is the choice of output signal representation. Most previous ionospheric sounding systems have used logarithmicly compressed amplitude representation with zero crossing phase or logarithmic quadrature components. The use of a logarithmic scale is inconvenient for many kinds of digital signal processing. For instance, if a Fourier transform of the received signal is desired, it has been necessary to exponentiate the logarithmic function, which is likely to be inaccurate if the function was generated by analog means in the first place. The justification for this choice of signal representation has been that it is otherwise difficult or impossible to cover the dynamic range of the received signals in any other manner. However, recent developments in solid state technology have made available stable, wide-band linear amplifiers with extremely wide dynamic ranges, typically > 140 dB in a 30 kHz noise bandwidth. By combining these with passive filters and a well-designed mixer and quadrature component detector, it is possible to build a linear receiver that is basically limited only by the choice of digital quantization and the DC stability of the detector. We have chosen this route. By using 12-bit 2's complement binary encoding of the quadrature components, we have < 60 dB dynamic range between quantization noise and saturation, giving a 30-40 dB operating range allowing for reasonable numerical accuracy at the lower end and some margin against overload at the upper end. The position of this range is adjusted to prevailing signal levels between pulses by means of stepped attenuators which are under the control of the Interdata computer. DC offsets are removed by an autocalibration program. Provision has also been made for range dependent gain switching should it be required.

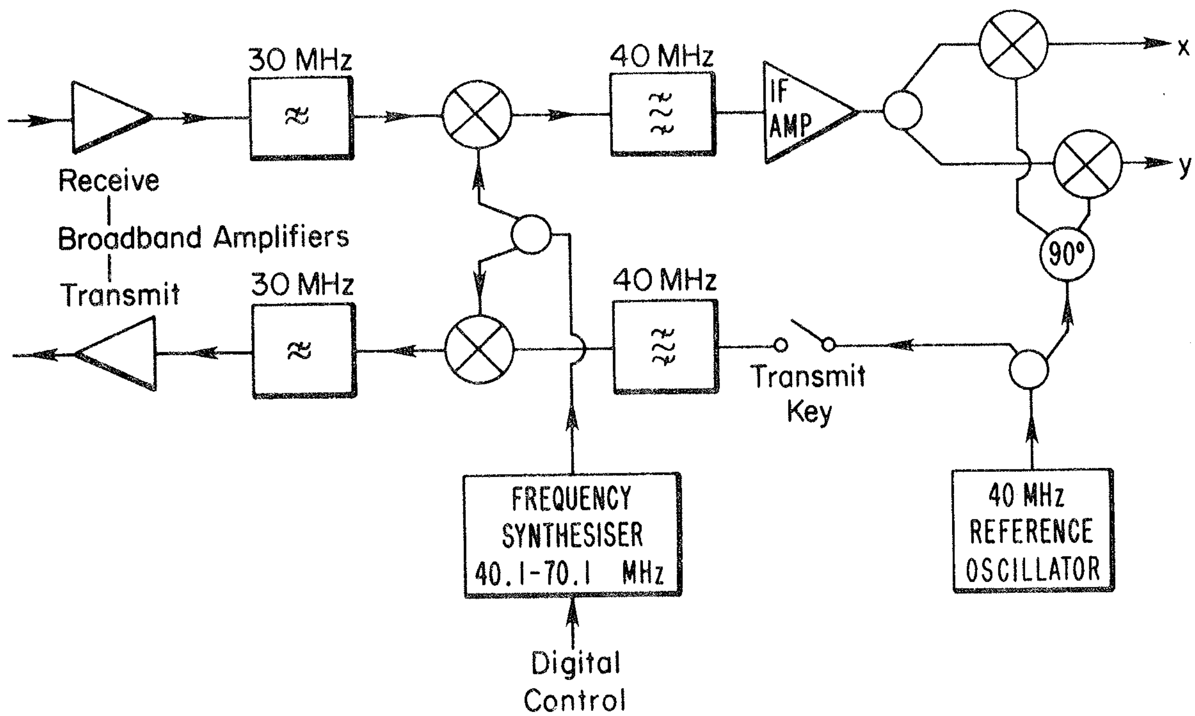


Figure 3. RF system, simplified block diagram.

A more detailed block diagram of the RF system is shown in Figure 4. The bandwidth of the system is similar to that of previous ionosphere pulse sounders. Maximally flat time delay crystal filters are used, two in each channel of the receiver and one following the transmitter keying circuit. Each filter has a 4-pole response and a 3 dB BW of 30 kHz. This gives an overall 3 dB bandwidth of 22 kHz in the receiver and a matched response to a 60 μs transmitted pulse. The impulse response is Gaussian in form. Provision is made for phase reversal switching in the receiver input multiplexer and for quadrature phase modulation in the transmitted pulse. The sampling rate of the ADC's in the Front End Processor has been chosen to be 100 kHz giving a folding frequency of 50 kHz. At this frequency offset, the receiver IF gain is 56 dB down from the response at the center frequency. The input memory for each receiver channel holds 512 XY pairs corresponding to a total acquired virtual height range of ≈ 776 km.

Great care has been taken to preserve a high degree of linearity at the input of the receiver to reduce intermodulation of received signals and minimize the need for preselection filters. A high level mixer is used, driven by a fast square wave with 1 nanosecond rise and fall time transitions to provide highly linear switching. The 1 dB desensitization point at the main receiver input (excluding the antenna preamplifier) is +15 dBm and the third order intercept +26 dBm with 0 dB RF attenuation.

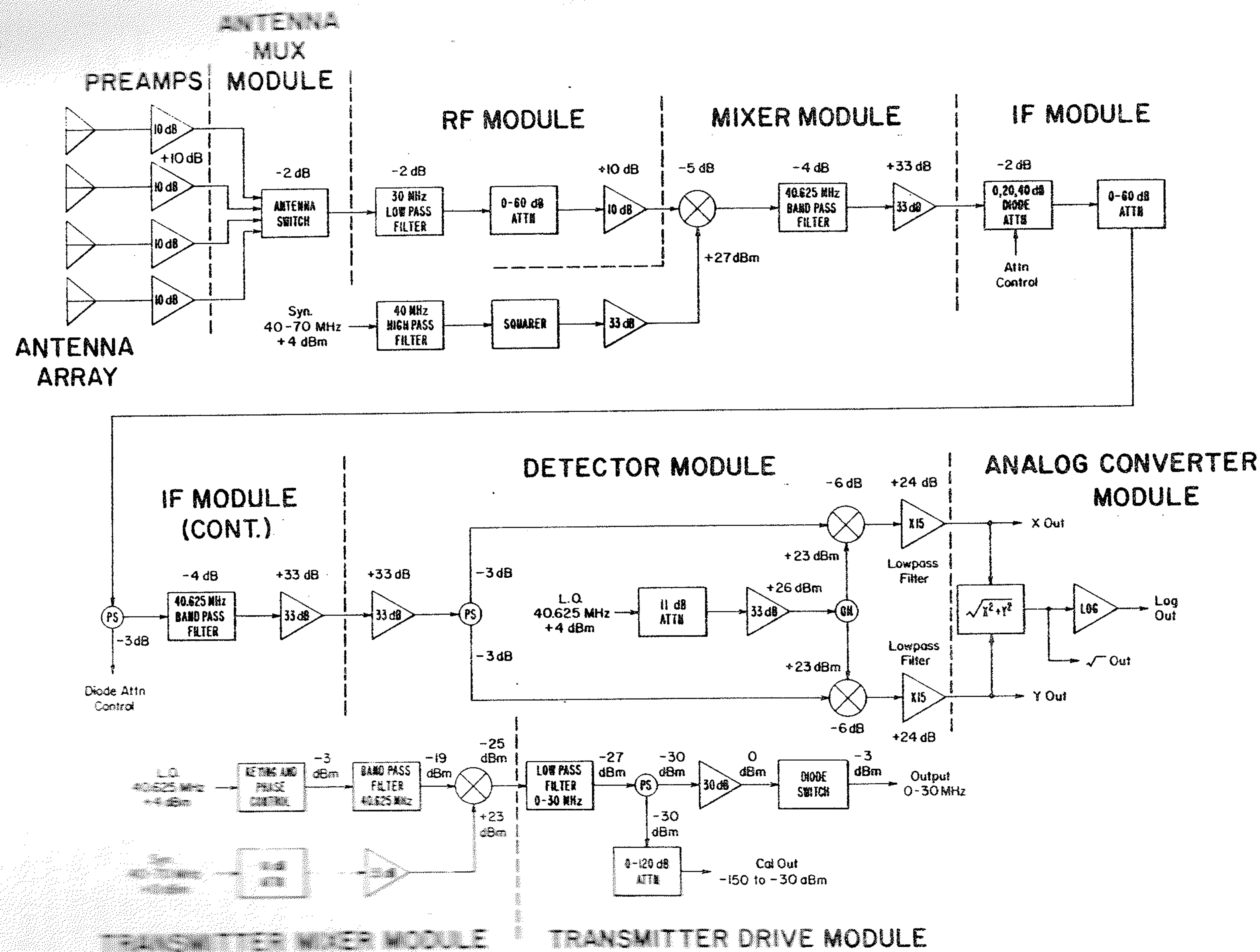


Figure 4. RF system, detailed block diagram.

This performance is limited, particularly at low frequencies, by the diode switches in the antenna multiplexer. The receiver gain varies less than ± 2 dB from 0.2-29 MHz and the tangential sensitivity is $\leqslant 1\ \mu V$. Operating experience indicates that preselection filters are not required for operation in typical site conditions.

The low level transmitter drive output is amplified first by a solid state class A amplifier to the 200 W level. This can be used directly or can be used to drive a pulsed class A wide band vacuum tube amplifier with a 10 kW output. The transmitter outputs are nominally 50 Ω unbalanced. Wide band unbalance-to-balance transformers are used to drive typical sounding antennas.

A feature of the system is the provision for generating a low level replica of the transmitter pulse. This can be inserted at an arbitrary range under control of the Timing Sequence Generator and is coupled to the receiving antennas to serve as an overall calibration of the group and phase delays of the receiver channels and a means of self checking the entire system without making unnecessary transmissions.

An auxiliary component of the system is the housekeeping ADC. This is a multiplexed Analog-to-Digital Converter with 64 inputs. It is controlled by the Interdata through the digital I/O bus. The output is a 12-bits 2's complement binary number representing a ± 10 V input range. This unit is intended to provide general supervisory voltage, current, and temperature monitoring which is recorded along with the data from the sounder. It is also connected to the analog outputs of the receiver and can be used to provide data in the spectrum surveillance mode and also for AGC feedback when the system is used as a general purpose receiver. The ADC may also be used with additional programming to acquire data from other sensors such as riometers or magnetometers.

4. SYSTEM STATUS AND OPERATION

Software has been written to operate the system as a basic vertical pulse sounder with both flexible sweep modes and "Kinesonde" operation at up to 10 operator selected fixed frequencies. Four pulses are transmitted per frequency, 2 at f and 2 at f + Δf. Δf is usually 8 kHz which is a suitable value for determination of the group path delay. Four antennas are sampled, two at a time with the two receivers. A simple FEP program generates a 64-point running mean of the amplitude to remove slowly changing interference signals and looks for new data which exceeds a threshold of n times this running mean. Data which meet this criterion are classified as a suspected echo and the quadrature component data block is passed to the Interdata. Data above threshold are excluded from the mean calculation. n is normally chosen as 2.5 or 3. The effect of this procedure is similar to that of a fixed threshold operating on a logarithmically compressed signal after high pass filtering and results in a minimum signal-to-noise ratio depending on the value of n selected. In the

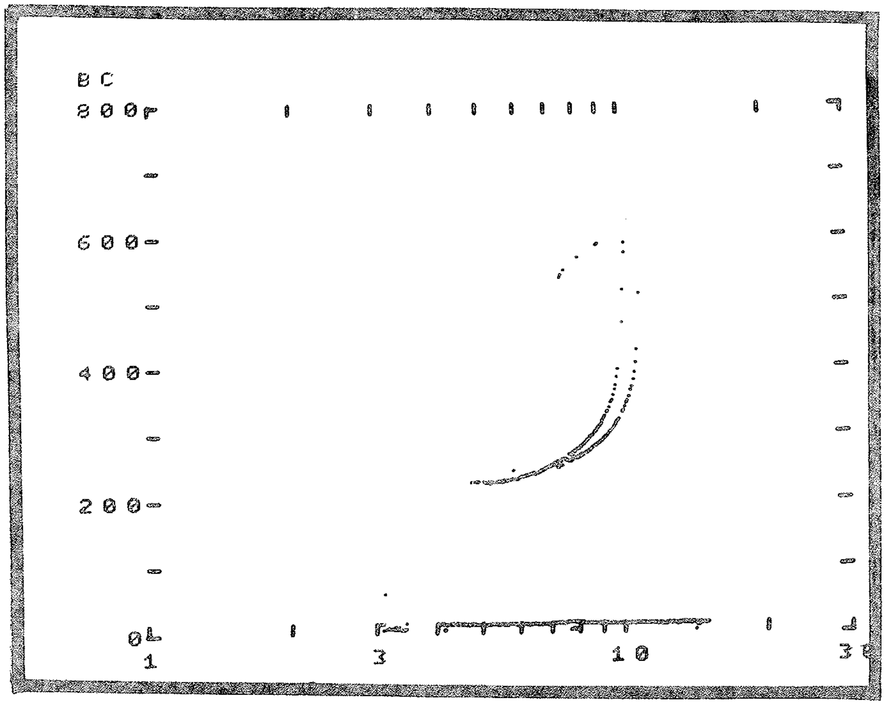
Interdata, each data block is examined for the position of the peak sample point. Data are accepted as valid only at ranges where m out of 8 (usually 8 out of 8) peak ranges fall within the range $\pm$ 20 μs. Data accepted by this test are characterized by an XY value obtained by averaging the highest three samples and with an envelope delay by carrying out a parabolic fit to the highest five samples. The complete XYh'(f) data set is recorded on tape and also on the disc. All values of h'(f) are averaged as an input to an ionogram display on the system CRT. The historical data on the disc may be recalled to the display at will.

This very elementary utilization of the hardware has worked well. Figure 5 shows two samples of ionograms made using a simple wide band dipole transmitting antenna of the type usually used for vertical FMCW sounding and 150 W peak RF pulse power from the solid state amplifier. The average power under these conditions is ≈ 0.5 W and about 10 seconds is needed for the sweep. The low frequency cutoff of the antenna is ≈ 3 MHz. Figure 6 shows examples taken at the same power level using an apex-down log periodic transmitting antenna with a lower frequency limit of 1 MHz. Figure 7 shows two examples taken with the latter antenna. One was made with 150 W and the other with 10 kW peak RF power. The lower continuous line in Figures 5 and 6 is the artifically introduced calibration pulse. Some breakthrough of the transmitted pulse also occurs at zero range. Figures 5 and 6 also have a negative offset of the height scale of 39 km which was not set into the plotting program at the time these examples were taken, and frequency deletions were made at 2.5, 5, and 10 MHz and for the 1.8 and 3.8 MHz amateur bands. In general, very few interference-generated points are evident. The effect of interference is generally to suppress data rather than to introduce false data, as was the intent of the FEP program.

Figure 8 shows the presentation adopted for data display to the operation of Kinesonde mode data. In Kinesonde mode, the system is programmed to sound repetitively on a small set of frequencies selected by the operator. Each horizontal bar in the display represents the origin for an XY plot of the locus of the signal phasor received at the particular frequency. Figure 9 shows an operator display which depicts the apparent source of each echo on a "SKYMAP" in which the local zenith is at the center of the display. In all these displays, the operator can opt to show only the ordinary wave polarized echoes or the extraordinary or both together.

5. FUTURE PROGRAM

Six systems are being built, five of which are now complete. These will form the basis of a loosely coordinated international research program, primarily directed at the problems of magnetospheric-ionospheric interaction in the Arctic and Antarctic ionospheres. Table 1 shows the distribution of these systems. Very much software development remains to be done to exploit even a part of the possibilities of the system. We hope that the



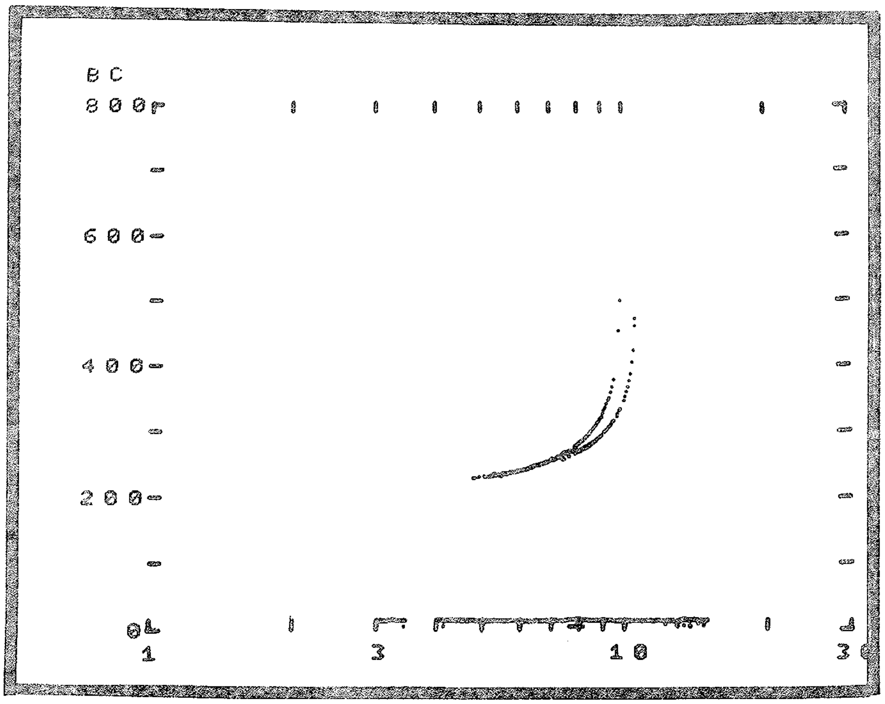
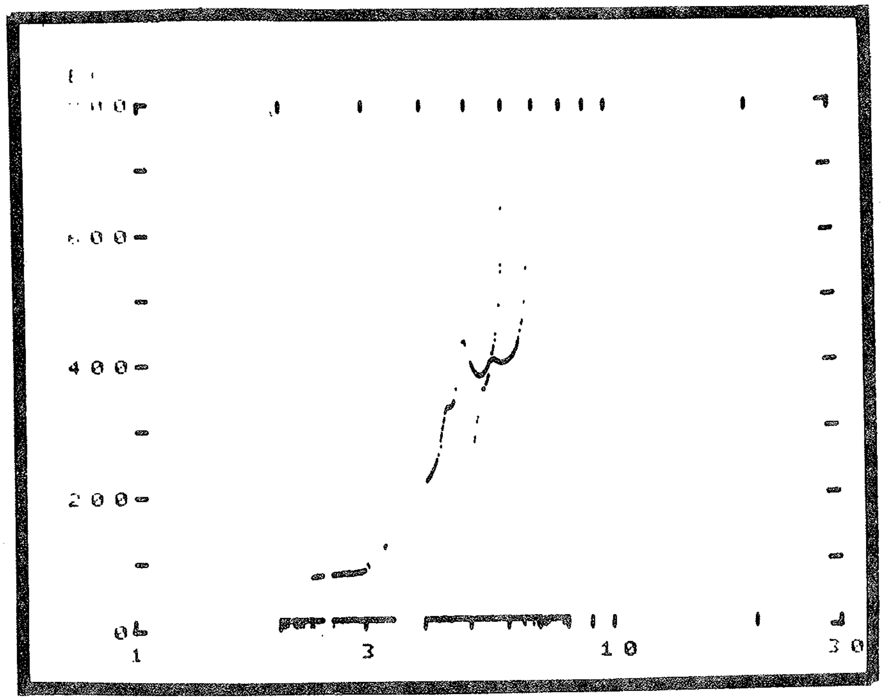


Figure 5. Ionograms made using a simple wide band dipole transmitting antenna.



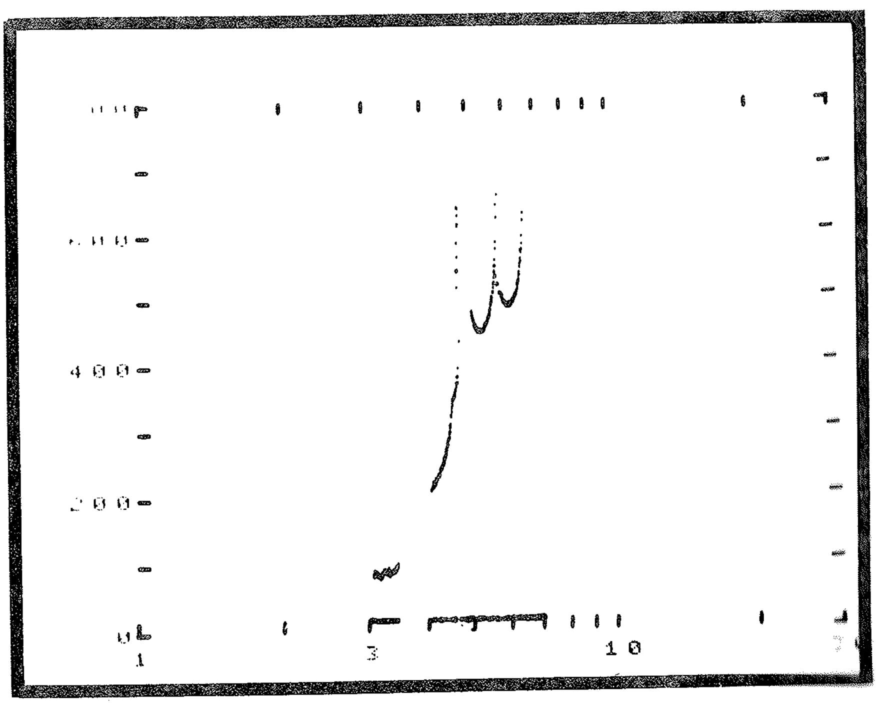


Figure 6. Ionograms made using an apex-down log periodic transmitting antenna.

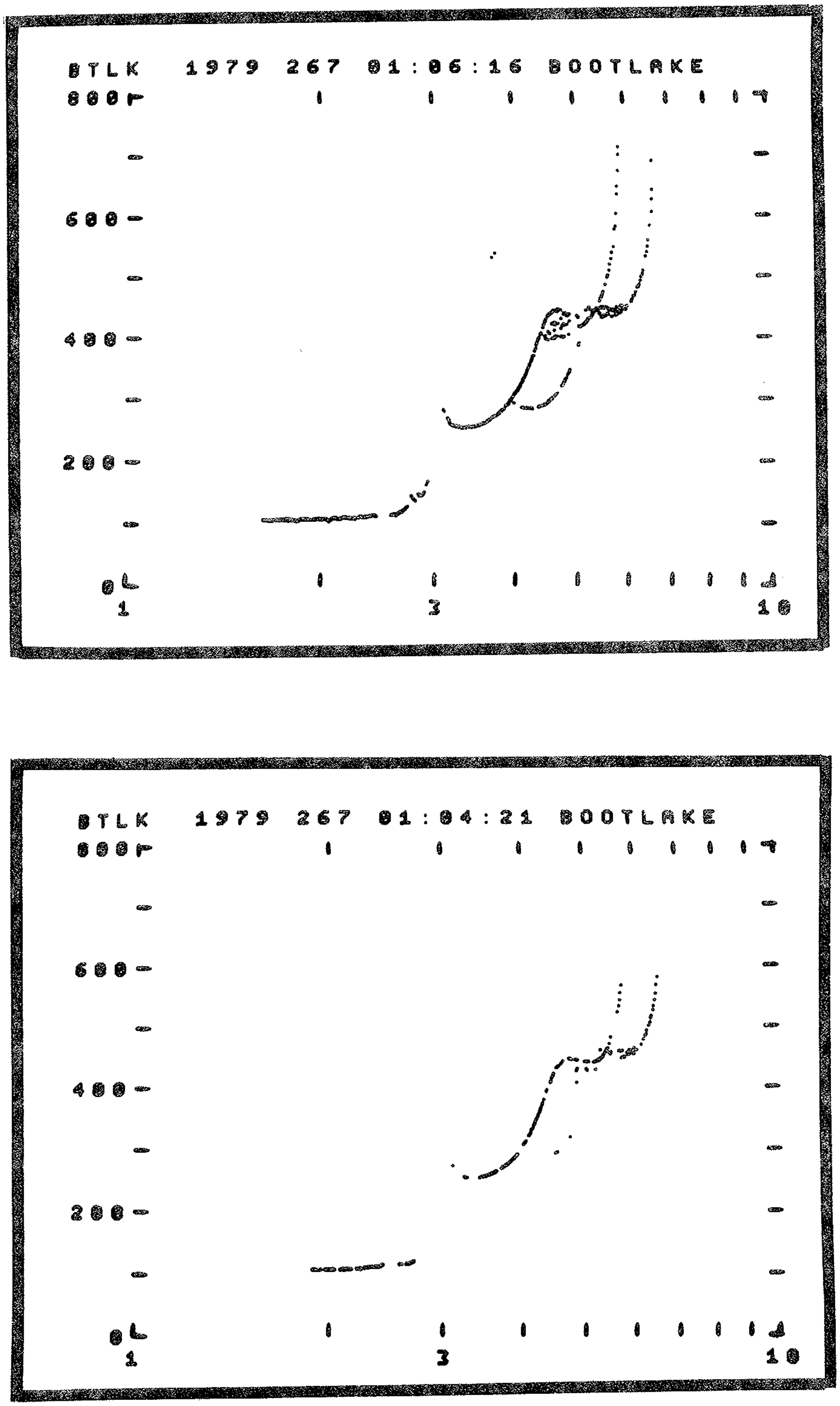


Figure 7. Ionograms made at 10 kW (top) and 150 W (bottom).

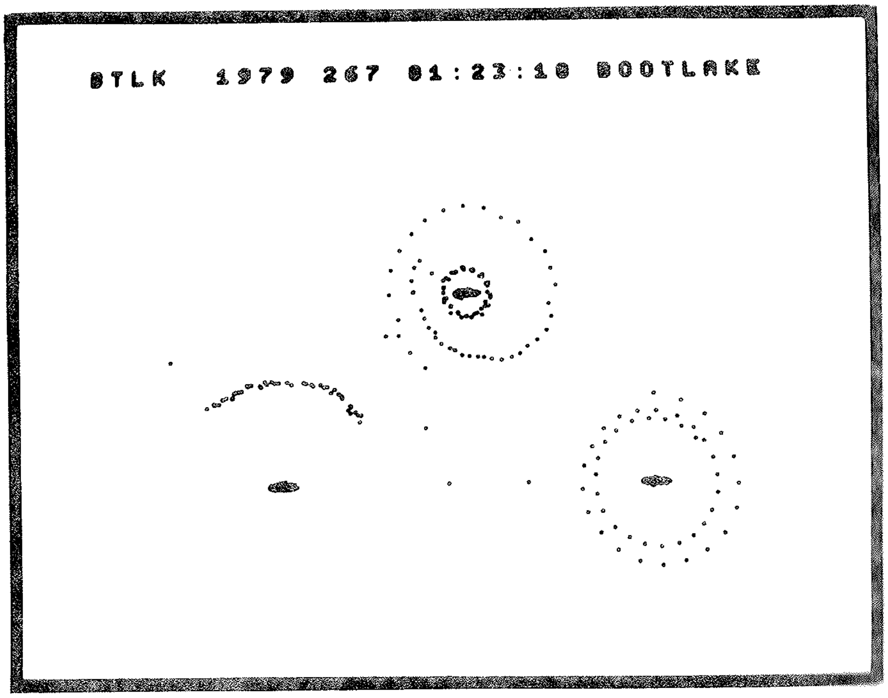


Figure 8. Kinesonde mode display.

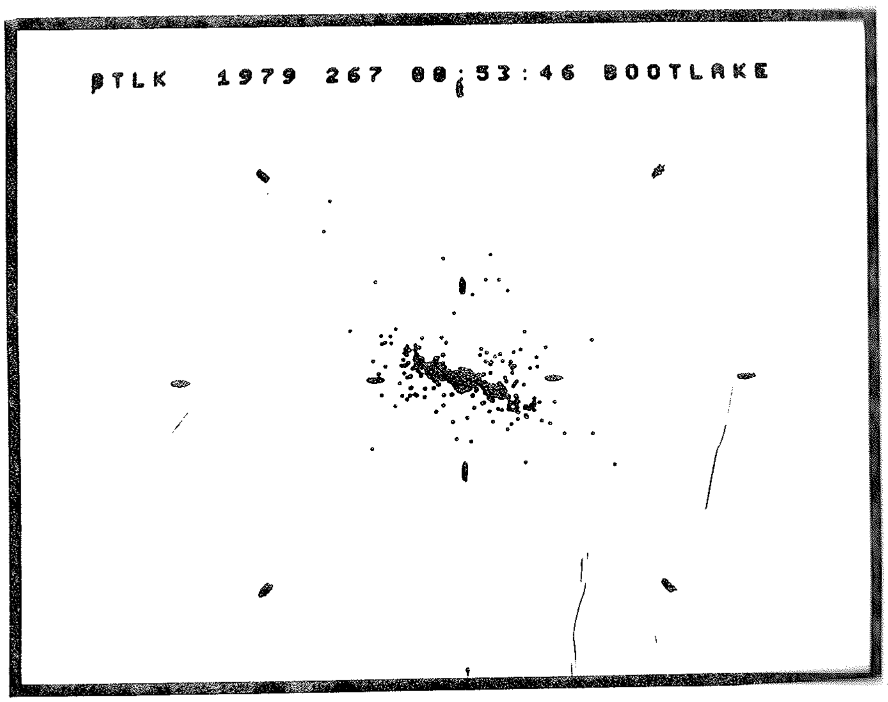


Figure 9. SKYMAP mode display.

pool of software will be augmented by contributions from all the major research groups involved. There are no plans at present for any further systems to be assembled or deployed in any general routine manner.

6. ACKNOWLEDGEMENTS

The development of the system described in this paper took the skills of a large group of programmers and engineers. Included were D. Hilliard, J. Jones, L. Jacobson, D. Mackison, L. Matheson, P. Orswell, J. Taylor, D. Walden, J. Winkelman, and R. Zwick*. The support and encouragement of Dr. D. J. Williams, Director of SEL, is also gratefully acknowledged.

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*Mr. Zwick has now returned to the Max-Planck Institute for Aeronomy, Katlenburg-Lindau, West Germany

TABLE 1

RADAR NUMBER	1980	1981	1982	1983	1984
1. NSF/IMS	Fairbanks		Roberval		Greenland
2. MPI	Lindau	EISCAT →			→
3. WSMR	White Sands Missile Range	→			→
4. NOAA/SEL	Boulder — Northern Canada	Boulder	(Various Field Trips)		→
5. British Antarctic Survey	England	Halley Bay, Antarctica	→		→
6. Utah State University	Utah — Roberval		Siple Station, Antarctica		→

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