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A field-hardened, high-resolution, broadband millimeter wave (26.5 to 40 GHz) Frequency Modulated - Continuous Wave (FM-CW) radar employing real-time data acquisition and digital signal processing (DSP) techniques has been implemented for continuously acquiring and processing data for ice thickness profiling and studying surface scattering from freshwater lake and river ice sheets. Thickness resolution is better than 3 cm ± 10%. System specifications include a 15 dBm output rf power level, a 0.066 second sweep rate and >50 dB signal-to-noise ratio (SNR). This radar is capable of operation from ground-mobile platforms and helicopters at heights of up to 7 m above ice surfaces at speeds up to 40 kph. Initial laboratory tests of the system have exhibited results that meet or exceed original design specifications.

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Implementation of a MMW FM-CW Radar System for Study of Surface Scattering from Freshwater Lake and River Ice Sheets

FINAL REPORT

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December 1991

U.S. Army Research Office

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Abstract

A field-hardened, high-resolution, broadband millimeter wave (26.5 to 40 GHz) Frequency Modulated - Continuous Wave (FM-CW) radar employing real-time data acquisition and digital signal processing (DSP) techniques has been implemented for continuously acquiring and processing data for ice thickness profiling and studying surface scattering from freshwater lake and river ice sheets. Thickness resolution is better than 3 cm ± 10%. System specifications include a 15 dBm output rf power level, a 0.066 second sweep rate and >50 dB signal-to-noise ratio (SNR). This radar is capable of operation from ground-mobile platforms and helicopters at heights of up to 7 m above ice surfaces at speeds up to 40 kph. Initial laboratory tests of the system have exhibited results that meet or exceed original design specifications.

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Introduction

An Army Research Office (ARO) grant (DAAL03-91-G-0192) enabled the implementation of a practical field-hardened mmw FM-CW radar system for the purpose of high-resolution ice thickness profiling and of studying surface scattering from freshwater lake and river ice sheets. Specifications and performance criteria formulated during the development of a prototype system (Yankielun 1991) were incorporated into the design. The following is a description of the system and a report on its implementation and operation.

System Configuration

The radar data acquisition and digital signal processing (DSP) computer system, (Fig. 1) is fully housed in a 55 cm x 60 cm x 75 cm water-resistant and shockproof case weighing less than 25 kg and powered by a 24 volt, 25 amp-hour battery providing more than 2 hours of remote field or airborne operation. Alternatively, the system can be operated from the aircraft DC power supply.

The homodyne front-end of the radar is housed in a separate waterproof aluminum enclosure containing the waveguide directional couplers and other waveguide components, HP R422C diode detector, Avantek, Inc AVD-24140, 13 dBm, 26.5 to 40 GHz YIG tuned oscillator (YTO), and Analog Modules, Inc. Model 351 low-noise voltage amplifier. Mica waveguide windows between the antenna waveguide flanges and the thru-bulkhead flanges on the front-end enclosure provide a waveguide port environmental seal. The front-end assembly can be mounted on a helicopter landing skid for airborne profiling operation. Two coaxial signal cables (for the YIG sweep ramp and radar signal out) interconnect the front-end and the computer system. Operating power (±15 Vdc) is provided via a third cable from a DC-DC converter connected to the 24 Vdc battery.

All data acquisition, monitoring, display, digital storage, and radar control are performed by seven off-the-shelf dedicated-function computer cards installed in the Industrial Computer Source, Inc. 15-slot 33-MHz 80386 DOS-based computer. Also included are an 80387 math coprocessor, a conventional 40-megabyte hard-drive and 4 megabytes of RAM. The remaining slots are available for system expansion. All system control functions are performed directly via computer keyboard input.

The SCSI card and interconnected Iomega, Inc. *Bernouli* removable platter 44-megabyte drive are for in-flight, non-volatile storage of digital data since the drive and media are less susceptible to failure in high vibration or high g-force environments. In practice, once "booted" via the conventional internal 40 megabyte hard drive, this drive is shut down with heads parked. Any subsequent acquired digital data is stored on the *Bernouli* drive.

The Metrabyte, Inc. 20-MHz, 12-bit, dual-channel digital oscilloscope card (PCIP-SCOPE) permits real-time monitoring of various system signals on the computer display without impacting on other in-progress data acquisition or processing functions. The oscilloscope display is in a "pop-up" window format that can be viewed/hidden by a "CONTROL + character" keystroke.

The Spectrum, Inc. DSP card performs dual-channel, 16-bit data acquisition to a maximum rate of 200 kHz and digital signal processing functions using the Hyperception, Inc. *Hypersignal Workstation* DSP software as a driver.

The Metrabyte, Inc. scanner (demultiplexer) board (PCIP-SCAN) is configured to provide keyboard control of the 0 to 100 dB JFW, Inc. programmable attenuator located between the front-end audio amplifier output and the DSP board data acquisition input. Access to the control and status display of the demultiplexer is functionally consistent with the "pop-up" display for the oscilloscope.

The Metrabyte, Inc. dual channel arbitrary waveform generator (PCIP-AWFG) is programmed to provide the linear ramp 0 to +10 volt sweep signal to frequency modulate the mmw YIG oscillator and a TTL-level synchronization and trigger signal signal. Access to the control and status display for the arbitrary waveform generator is functionally consistent with the "pop-up" display for the oscilloscope and the demultiplexer.

The "EL" video driver card provides an interface between the computer system and a VGA-compatible electro-luminescent orange-on-black video display. This is a lightweight, low-power, high-contrast, vibration-immune display well suited for a field operations environment.

Additionally, raw data can be acquired by a Teac, Inc. RD-104 four-channel DAT recorder for later playback and post-processing.

Fig 2 provides a summary of system implementation costs. Fig. 3 is a photograph showing all major system components including the radar front-end with dual horn antennas in a waterproof aluminium box (top), the radar data acquisition and DSP computer system in a waterproof and shockproof transportable instrument case (middle) and the DAT recorder and 24 Vdc battery box (bottom). Fig. 4 is a close-up photograph of the computer system showing the roll-out keyboard, mouse, electro-luminescent display screen, 1.4 Meg floppy disk drive and 44-Meg *Bernoulli* cartridge disk drive, and details of the computer shock-mounts. Fig. 5 is a photograph of a typical "waterfall" screen display of actual acquired and processed ice thickness measurement data. (Particulars of the display format are explained later.) Fig. 6 is a photograph of the radar front-end and antenna components. Visible in the are the dual horn antennas and waveguide bulkhead feed-thru's (top), waveguide directional couplers and isolators (middle), YTO (lower right), and audio amplifier (middle left). A 15 cm rule is shown for scale.

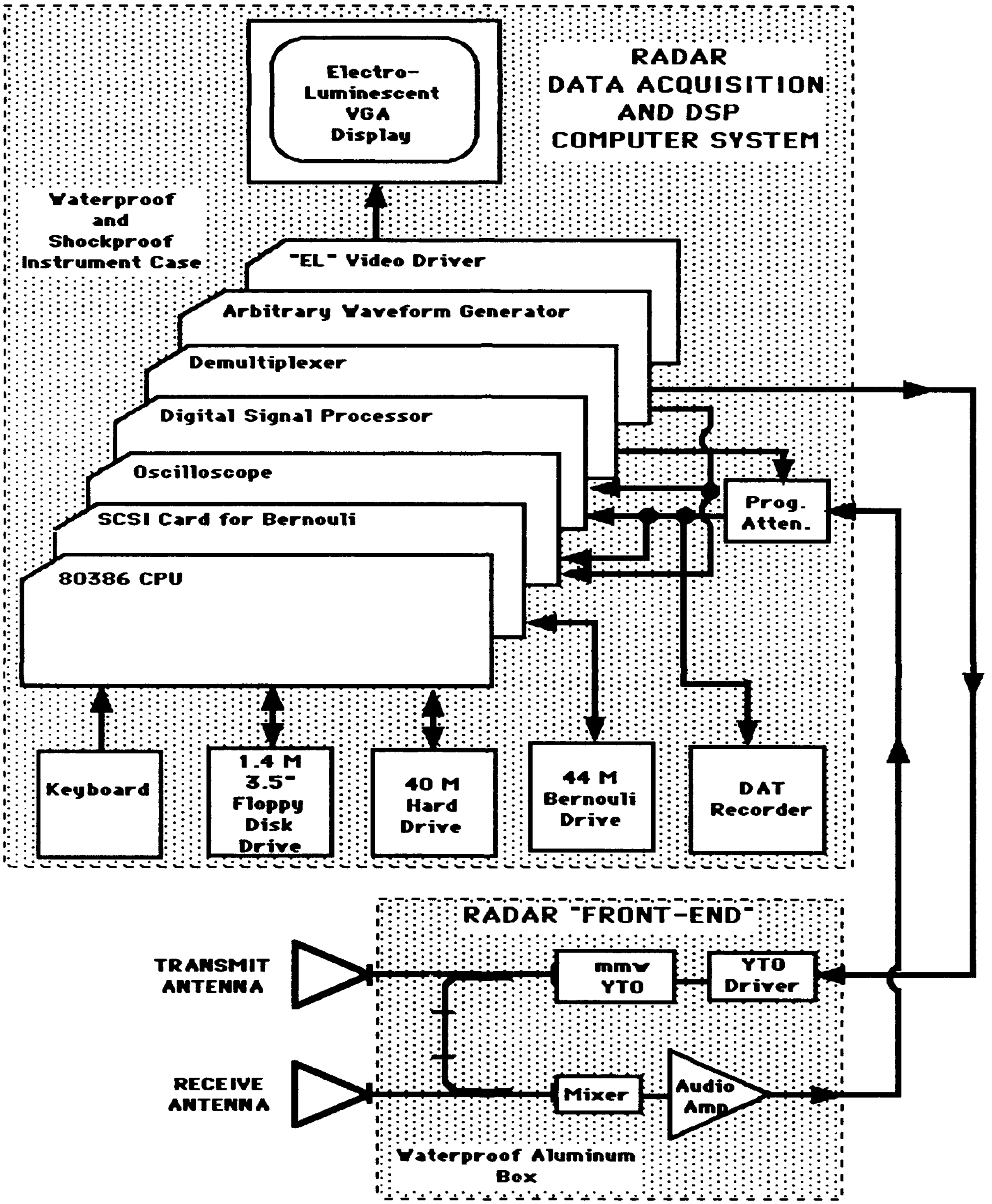

Fig.1 - ARO funded FM-CW radar system implementation

MMW Source	
Avantek,Inc. MMW YTO	$5,400
	$5,400
Radar Front-End	
Aerowave, Inc. Std. Gain Horns (2 ea.)	$800
HP R422C Crystal Detector	$800
HP R365 Waveguide Isolators (2 ea.)	$1,800
Analog Modules, Inc. Low Noise High-Gain Amplifier	$300
Miscellaneous WR-28 Waveguide	$1,000
Watertight Case and Misc. Hardware	$400
HP 752AD Directional Couplers (2 ea.)	$2,000
	$7,100
Bulk Data Storage	
TEAC, Inc. RD-101 DAT Recorder	$9,400
	$9,400
Digital Signal Processing	
Field-Hardened 386 CPU (4 MB RAM, 40 MB Hard)	$11,000
Spectrum Signal Processing, Inc TMS 320C30 DSP Coprocessor and Hypersignal, Inc DSP Software	$4,500
Iomega, Inc. 44 MB Bernouli drive	$1,500
Metrabyte, Inc Arbitrary Waveform Generator Card	$1,200
Metrabyte, Inc Dual-Channel Oscilloscope Card	$1,100
Metrabyte, Inc Scanner Card	$350
JFW, Inc. Programmable Attenuator	$250
Zero Plastics, Inc. Shock-Proof Instrument Case	$1,000
Miscellaneous Hardware, Cabling, etc.	$500
GSSI, Inc. *RADAN* Software	$2,000
	$23,400
GRAND TOTAL	**$45,300**

Fig. 2 - ARO funded FM-CW Radar System implementation costs

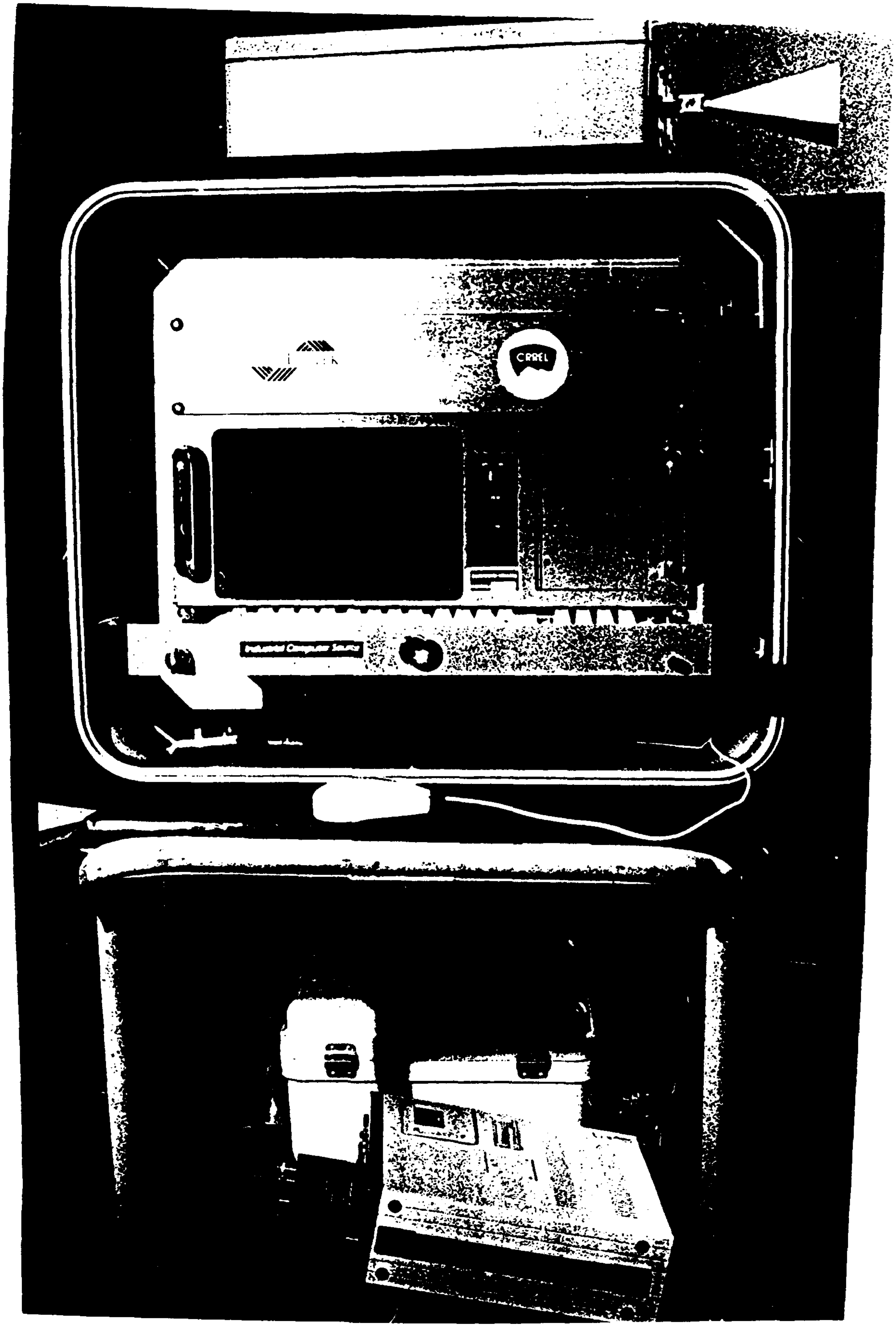

Fig. 3 - Photograph of all major system components

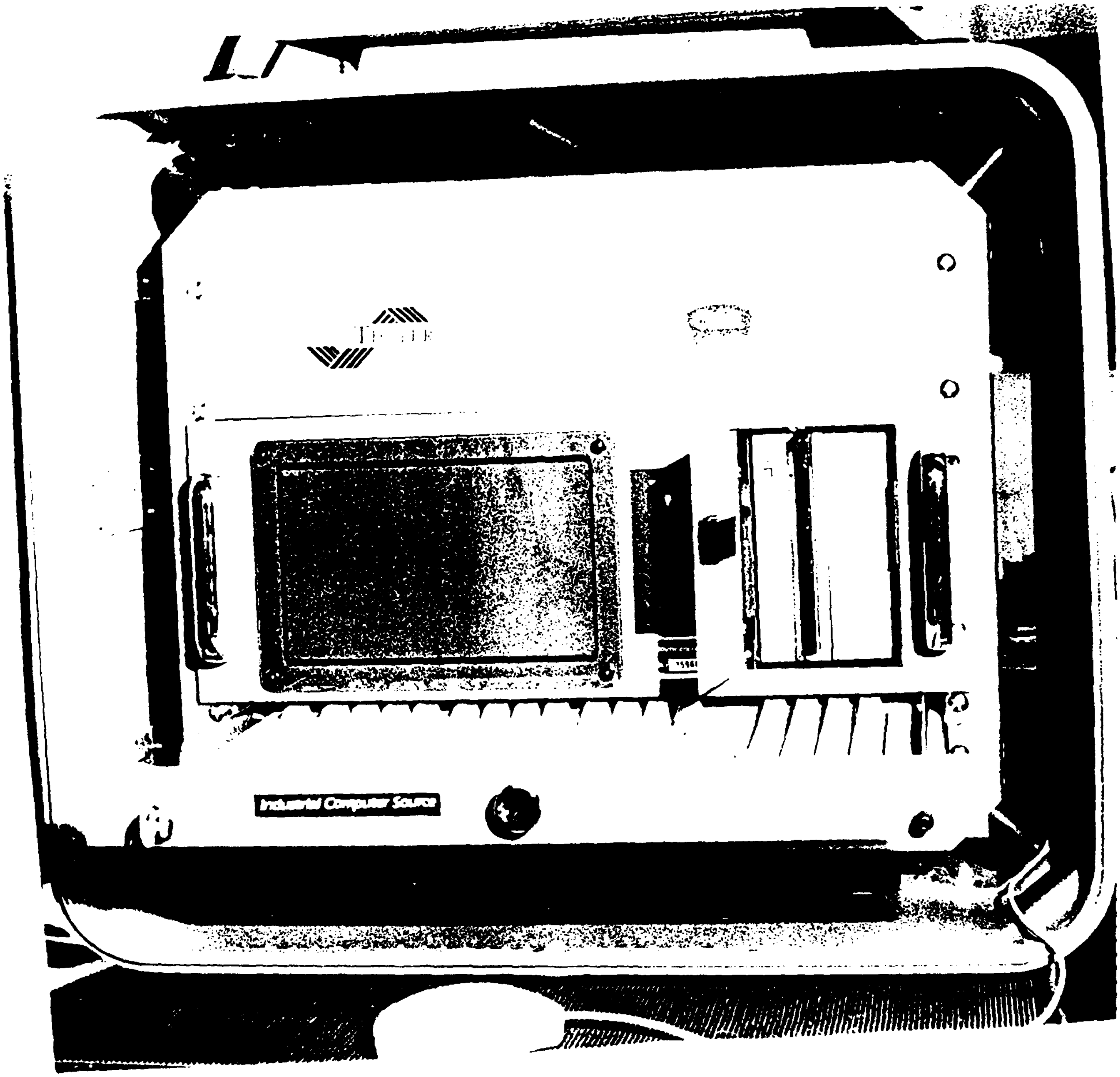

Fig. 4 - Photograph of computer system components

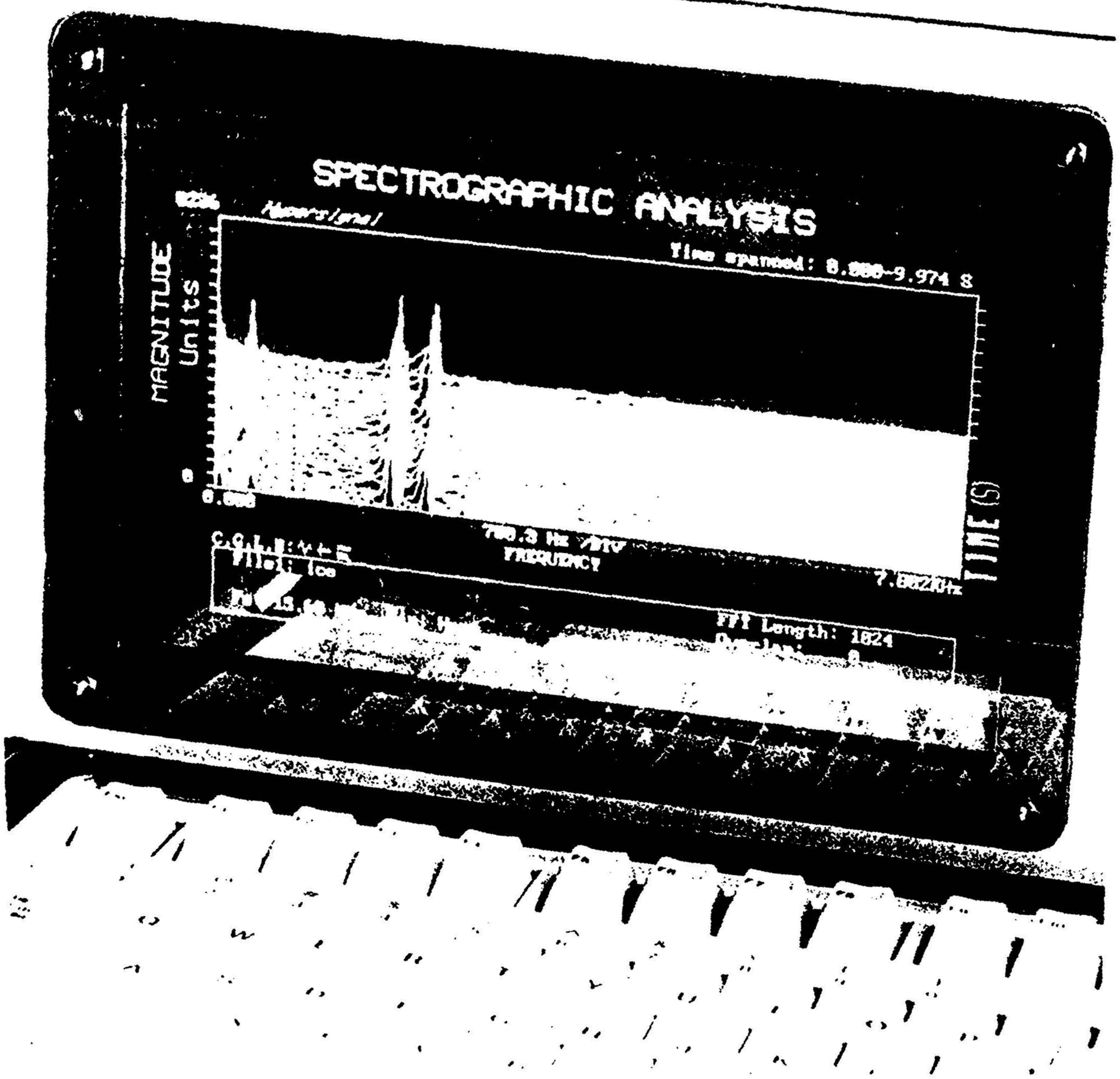

Fig. 5 - Photograph of computer screen with typical data display

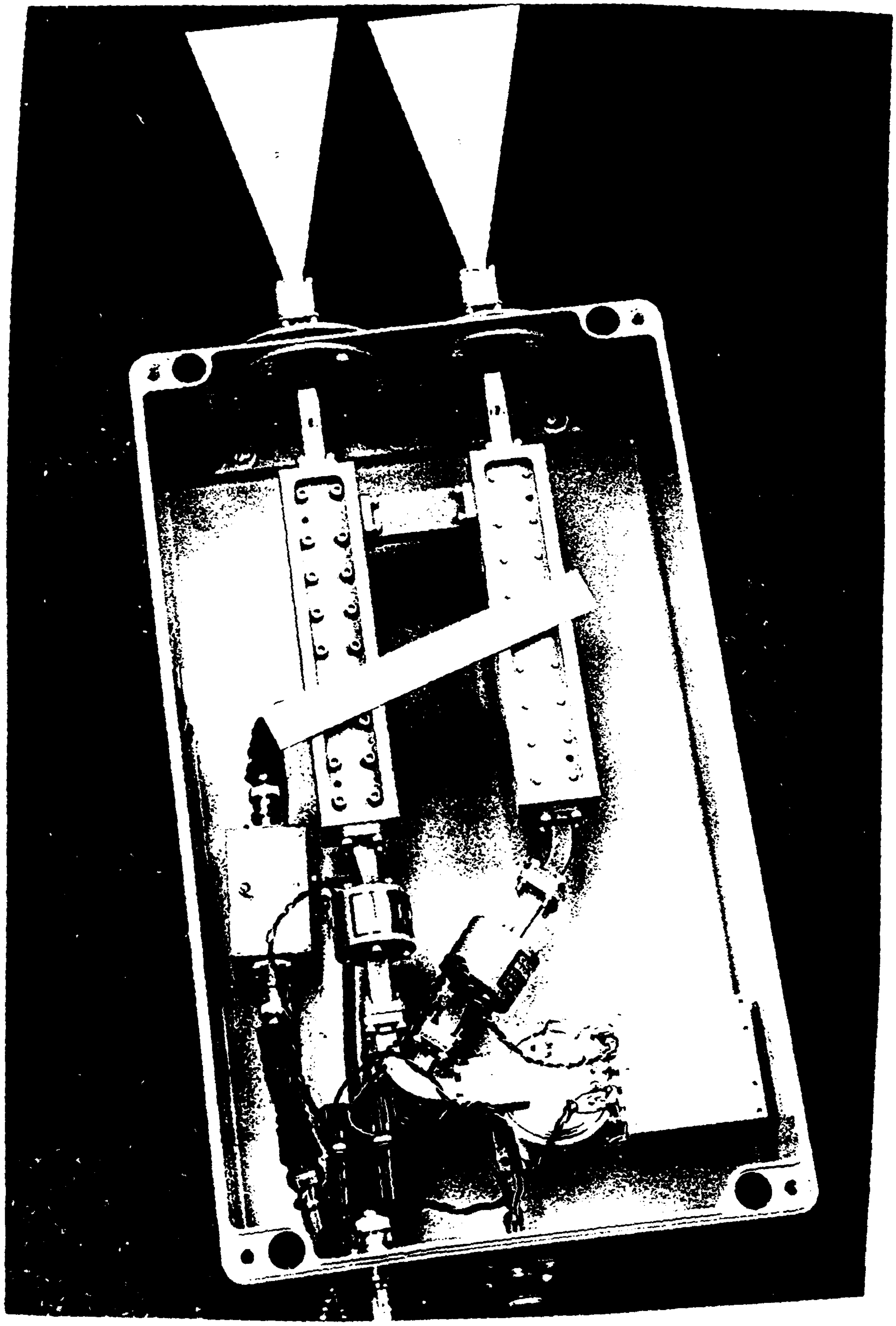

Fig. 6 - Photograph of radar front-end and antenna components

Performance Specifications

Fig. 7 summarizes the performance specifications for the MMW FM-CW radar system as implemented. Further detail can be found in Yankielun (1991).

Measurement Parameters	
Range (Height Above Surface)	3 to 10 m
Measurement Speed	> 20 km/hr
Ice Thickness	> 5 to 182 cm
Resolution	< ±10%
System Parameters	
Output Power	< 20 dBm (continuous)
Modulation Type	FM-CW
Sweep Rate	15 scans/sec (nominal)
DSP Processing Time	2 ms (1024 pt. real FFT)
Bandwidth	13.5 GHz (full K_a band)
Center Frequency	33.3 GHz
Receiver SNR	> 60 dB
Receiver Noise Figure	< 6 dB
Receiver Dynamic Range	83 dB
Receiver Performance Figure	137 dB
Receiver Noise Floor	-103 dB
Antenna Beamwidth (3 dB)	9°
Antenna Gain	> 24 dB (Tx and Rx, each)
Output Modes	
DSP Video Display	Time/Freq. Domain Displays
DAT Tape Storage	For Analysis and Archive
Removable/Fixed Disk Storage	For Analysis and Archive
Physical Parameters	
System Weight	< 90 kg
System Dimensions	< 0.25 cu. m
Antenna Dimensions	< 0.03 cu. m
Antenna Attitude	Normal To Surface
Minimum Operating Temperature	< 0°C
Humidity Range	5% to 95% Non-Condensing
Altitude (Maximum)	4600 m

Fig. 7 - MMW FM-CW radar specification summary

Demonstration of Operation

Initial system tests conducted indoors using large slabs of marble and granite indicate that the system is operational and that design specifications have been met or exceeded. Outdoor operational testing will commence with the formation of natural local freshwater ice sufficiently thick ($\approx$10 cm) to safely support the system and an operator. Additionally, the arrival of a dual polarity DC-DC converter, necessary to battery-power the YTO, will provide full system mobility.

Fig. 8 shows a typical single-trace formatted of the real-time processed radar data from a 5 cm thick natural marble slab. The thickness of the slab is determined by determining the frequencies of the two major spectral peaks and the application of the following:

$$\text{Thickness (m)} = \frac{(F_{r2} - F_{r1})(t_{swp})\,c}{2(BW)(n)}$$

where

F_{r1} = Difference frequency due to first interface reflection (Hz),

F_{r2} = Difference frequency due to second interface reflection (Hz),

t_{swp} = FM-CW radar sweep time (sec)

c = Velocity of light in vacuum = 3×10^8 m/sec,

BW = Bandwidth of FM-CW radar system (GHz)

and

n = Index of refraction of medium.

Similarly, Fig. 9 illustrates a typical single-trace formatted display of the real-time processed radar data from a 7.5 cm thick granite slab. Note that while the granite slab is 2.5 cm thicker than the marble slab the spectral peaks for granite appear closer together. This is due to the lower index of refraction for granite (approx. 2.3) than for marble (approx. 2.9). Fig. 10 again shows real-time data from the granite slab, but in waterfall format, that is, several sequential scans (a user-defined number) are displayed and scrolled up the screen as a new scan is added at the bottom. This format permits subtle scan-to-scan variations to be easily observed.

Post-processing of data using the capabilities of this system permits additional analysis and display formats. Fig. 11 shows a spectrogram of data that was recorded on magnetic tape during an actual airborne ice thickness profiling exercise and later processed and displayed using the DSP capability of the system. *Radan* software (Geophysical Survey Systems, Inc., North Salem, NH) permits further post-processing capabilities including stacking, horizontal and vertical filtering of the data. Fig. 12 illustrates a *Radan* "wiggle" formatted display and Fig. 13 shows a "line-scan" formatted display, both of data that was recorded on magnetic tape during an actual airborne ice thickness profiling exercise and later processed and displayed.

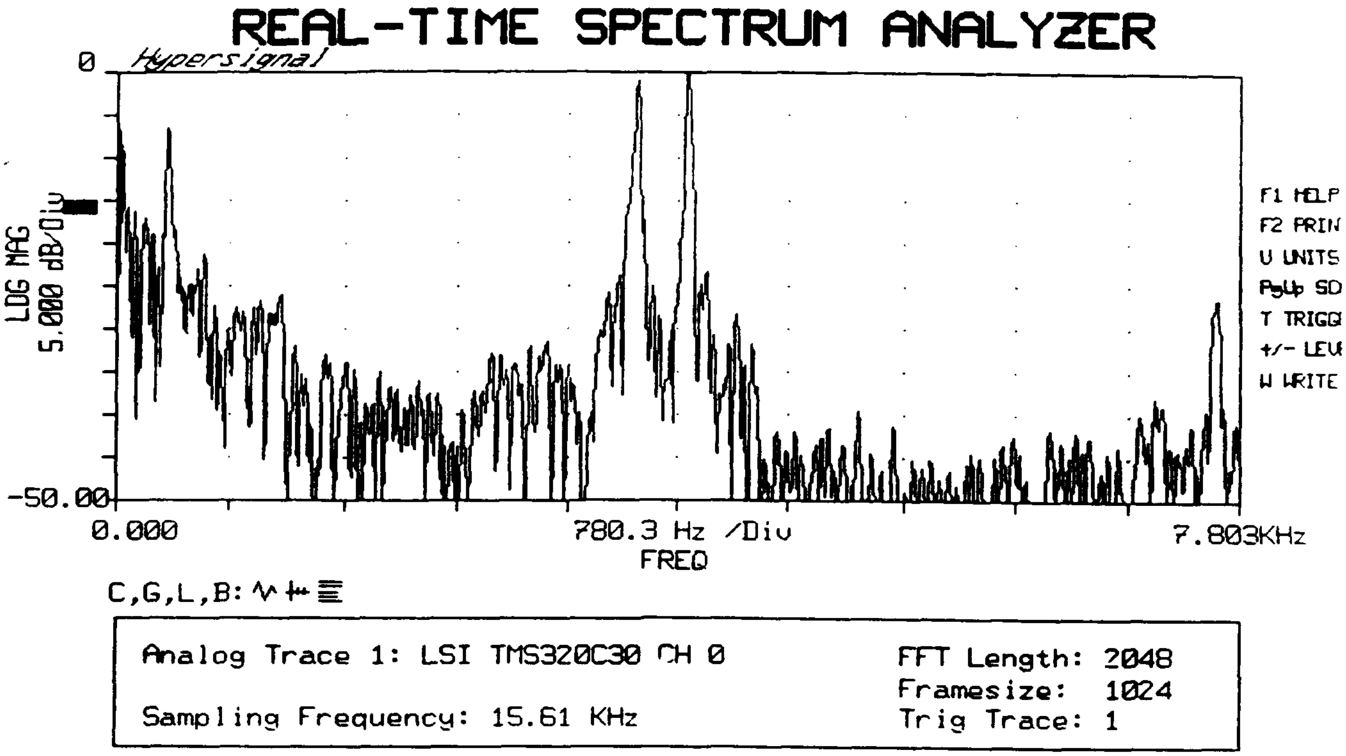

Fig. 8 - Single trace formatted reflections from a 5 cm thick marble slab

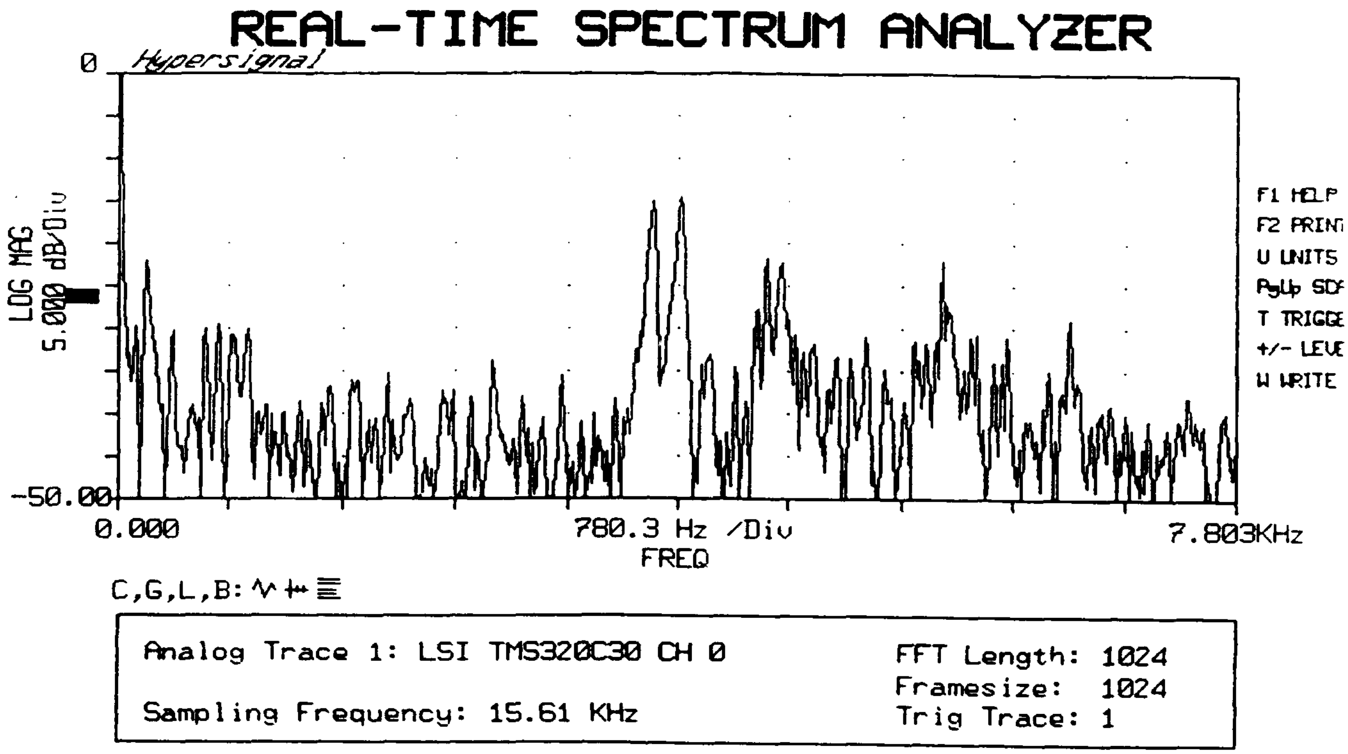

Fig. 9 - Single trace formatted reflections from a 7.5 cm thick granite slab

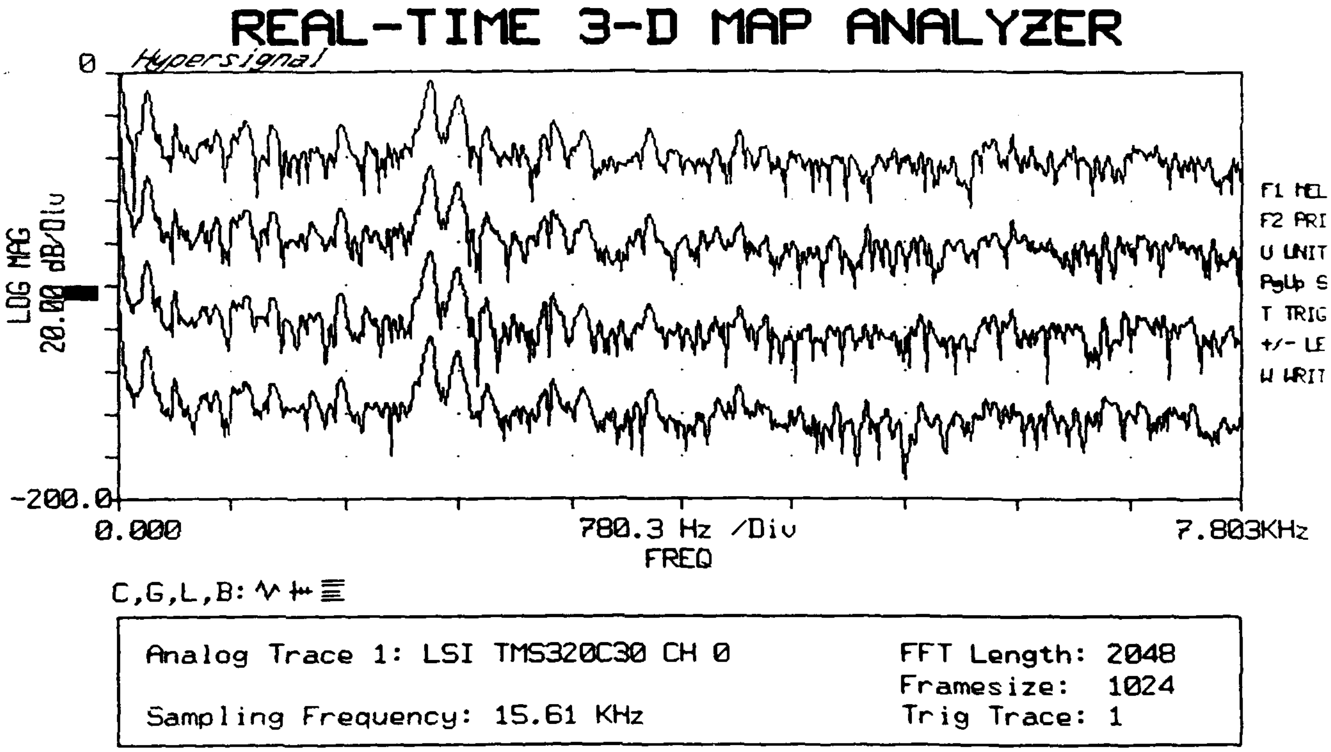

Fig. 10 - Waterfall formatted reflections from a 7.5 cm thick granite slab

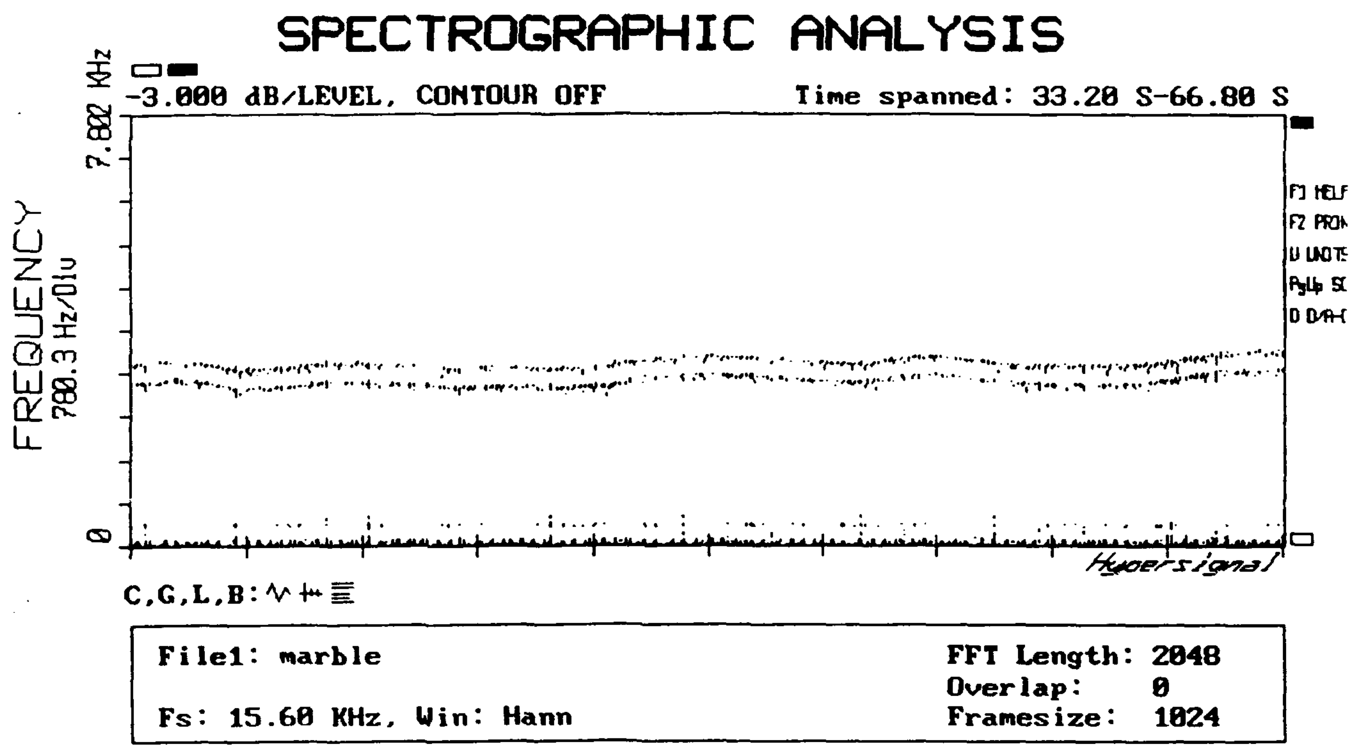

Fig. 11 - Spectrographic formatted post processed airborne lake ice profile data

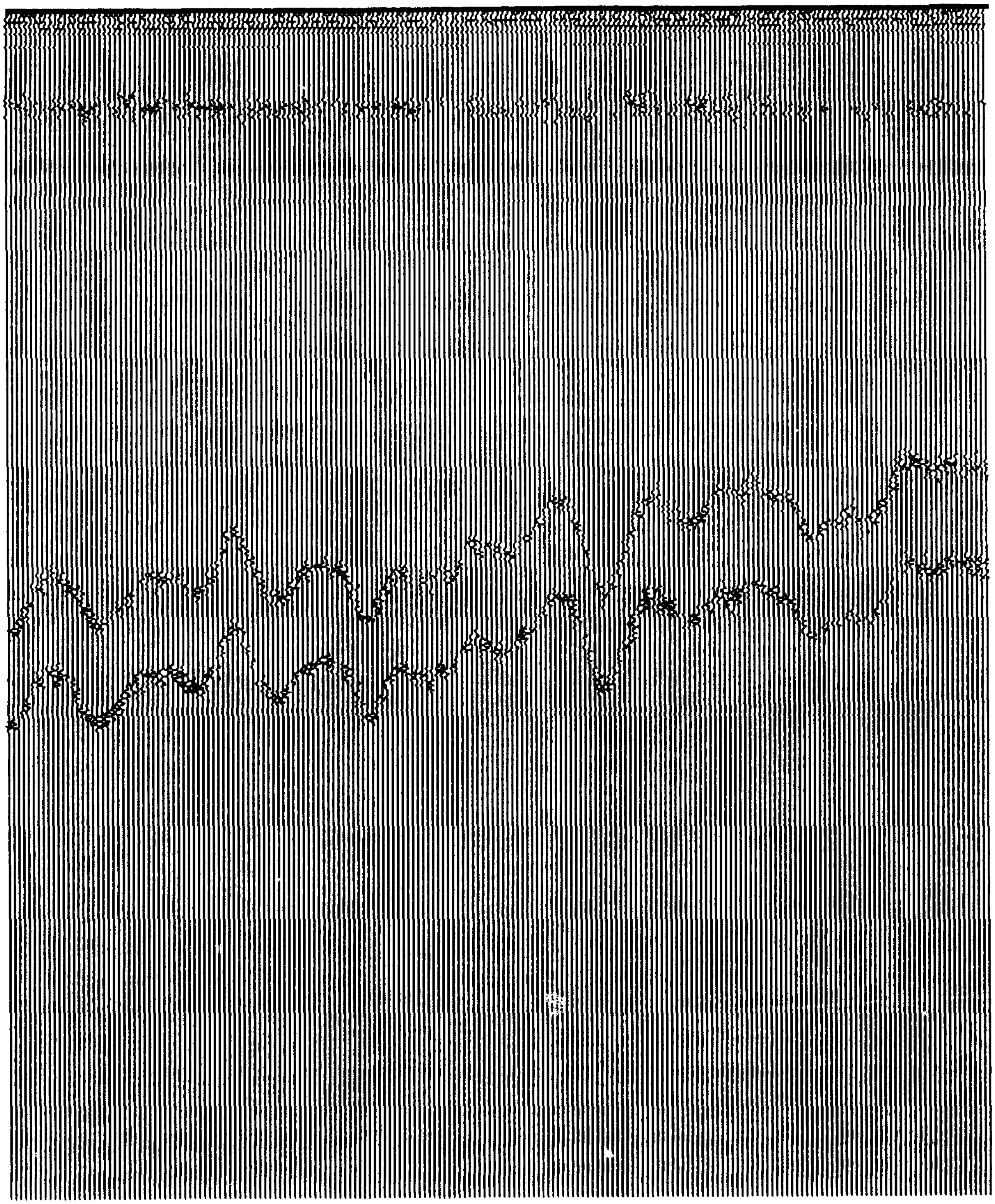

Fig. 12 - Radan post-processed, wiggle-formatted airborne lake ice profile data

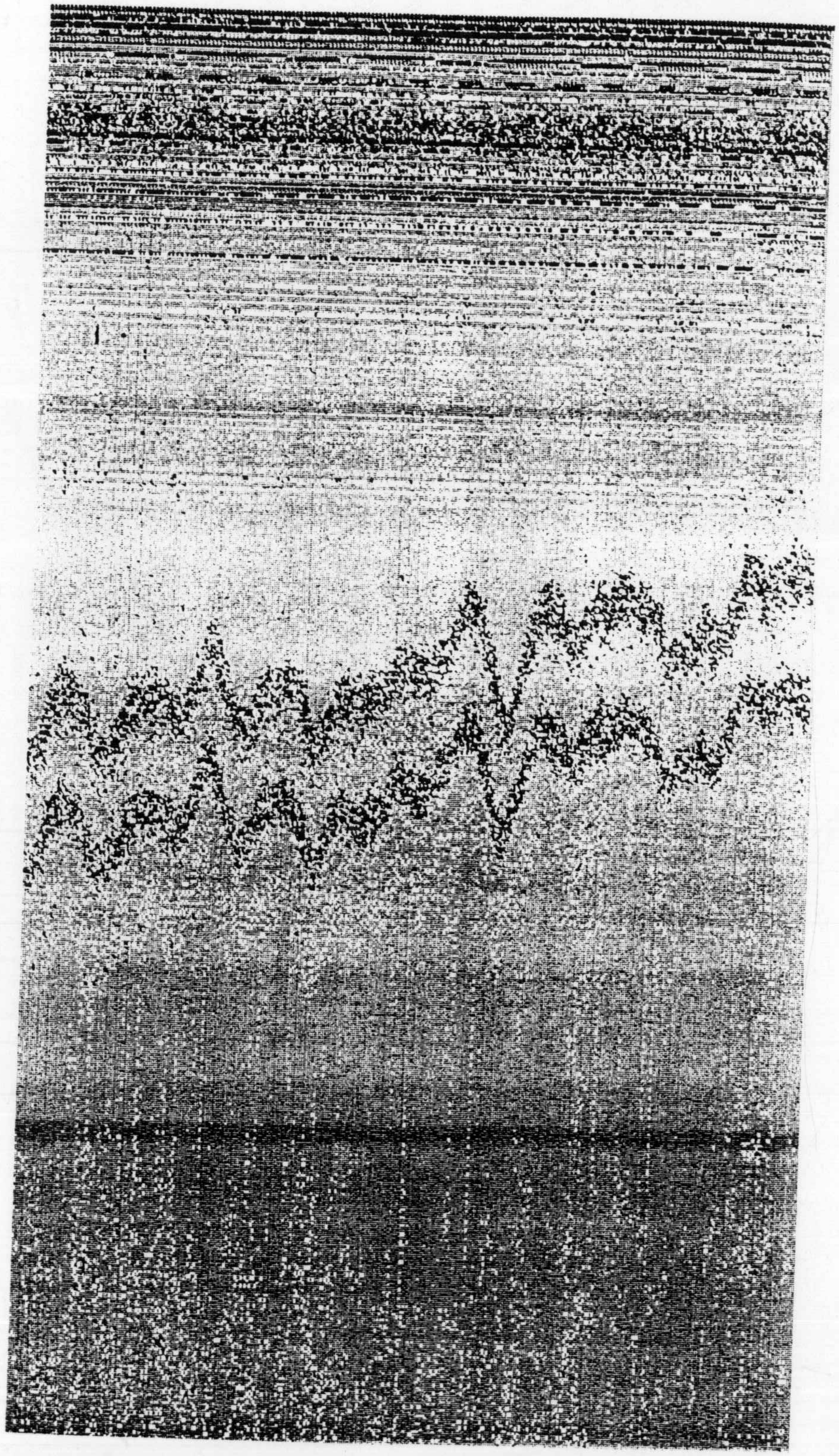

Fig. 13 - Radan post-processed, line scan-formatted airborne lake ice profile data

List of Publications and Technical Reports

A doctoral dissertation "An Airborne Millimeter-Wave FM-CW Radar for Thickness Profiling of Freshwater Ice", was written simultaneously with the design and implementation of the MMW FM-CW radar system by Norbert E. Yankielun at Thayer School of Engineering, Dartmouth College, Hanover, NH, in November 1991.

Advanced Degrees Earned

As a result of this research, Norbert E. Yankielun earned the Doctor of Engineering (D. E.) degree at the Thayer School of Engineering of Dartmouth College in Hanover, NH in November of 1991.

Bibliography

N. E. Yankielun, "An Airborne Millimeter-Wave FM-CW Radar for Thickness Profiling of Freshwater Ice", Doctoral Dissertation, Thayer School of Engineering, Dartmouth College, Hanover, NH, November, 1991.