Progress in Remote Sensing and Its Application To Highway Engineering and Research

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•CAN airborne remote sensors be used to provide information about surface conditions otherwise obtained through reconnaissance and route surveys, and information about the subsurface otherwise obtained by drilling, resistivity surveys, and refraction-seismograph surveys? The desired knowledge of surfaces includes information about general topographic, geologic, pedologic, hydrologic, vegetative, and cultural relationships; landforms and land use; geologic structure; rocks and soils and their geographic and genetic relationships; and drainage patterns and surface water conditions and their effect on the engineering problem. The relevant subsurface conditions that can only be inferred from visual observation of surface relationships include the downward extent of the rock and soil materials exposed at the surface, groundwater distribution, and the engineering properties of the materials to suitable depths.

If an aerial survey could economically furnish all of these surface and subsurface engineering data, it would be possible to prepare comprehensive engineering evaluations at all stages of a project, from first considerations for routes through subsequent phases in its evolution to post-construction activities. Such comprehensive evaluations can be made if airborne sensor data can be used to:

1. Determine land use along routes under consideration so that land values can be assigned, the effects of disrupting current land use can be assessed, and the cost of relocating existing facilities and bridging intercepted traffic routes can be calculated;
2. Determine surface geometry along proposed routes for requirements of grade, cut and fill volume, and number of culverts, bridges, and tunnels;
3. Identify rocks and soils along the route and determine their relevant engineering properties in order to compute cost of excavating, determine quantity of suitable road-building materials, and disclose natural impediments that will affect engineering costs (bearing strength of the subgrade materials, fault and fracture zones, slide zones, unusual groundwater conditions, impervious layers, etc.);
4. Determine periodically the condition of the road surface and roadway to detect changes that might affect load-carrying capacity and useful life.

Considerable skills have been developed for extracting at least some of these types of information from aerial photographs (1, 2, 3). The topographic, geologic, hydrologic, and soils maps used in highway engineering are prepared at least in part from aerial photographs. However, broad-band panchromatic aerial photographs have certain limitations. Inferences must be made about subsurface conditions, and reliability of such information depends on contextual relationships, the experience of the interpreter, and his familiarity with the area surveyed. Thus, we continue to rely heavily on drill-core data and surface geophysical surveys.

THE SENSORS AND WHAT THEY SENSE

The electromagnetic spectrum (Fig. 1) suggests numerous possibilities for obtaining the kinds of information needed. It extends through many decades of wavelength from radio waves through gamma radiation. The inventory of airborne sensors available for measuring in the various wavelength regions of the spectrum (Fig. 1) is quite impressive.

The data collected by these sensors are displayed in various forms, but the sensors may be considered in two general categories: imaging and nonimaging. Imaging

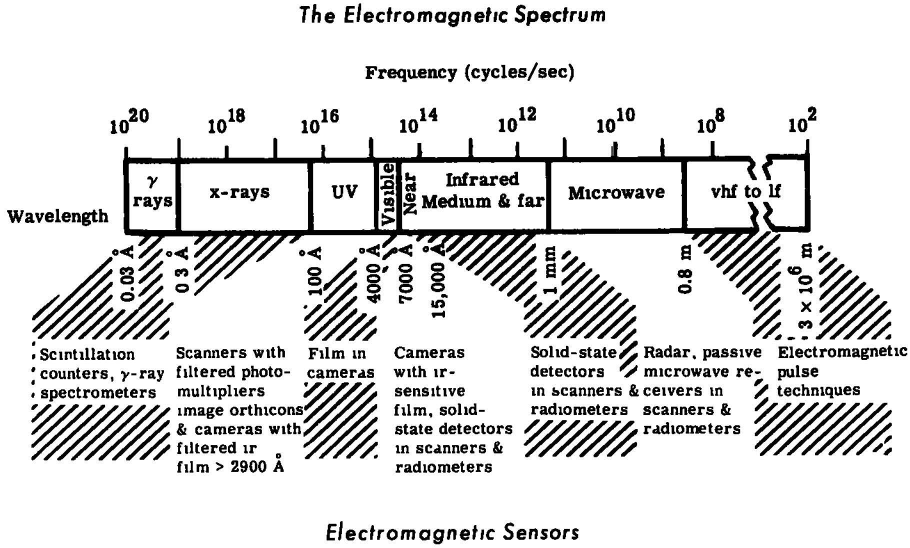


Figure 1. The electromagnetic spectrum and sensors.

sensors produce two-dimensional map-like representations of variations in the radiation within the field of view of the sensor. Cameras, optical-electromechanical scanners, passive-microwave scanners, and radar fall within this group. The data produced by these sensors are recorded (usually) on photographic film, either through direct imaging (as with the camera) or through photographing the output of a cathode ray tube (CRT) or crater lamp (as with scanners and radar). The resultant film is the medium interpreted, and from it the relevant information is extracted.

Nonimaging sensors produce essentially one-dimensional records of radiation received from points along the flight path of an aircraft. Gamma-ray spectrometers, infrared and microwave radiometers, laser and microwave profilers, radio-frequency sounding devices, and induction devices fall within this group. The data produced by these sensors are usually recorded on chart paper.

Imaging Sensors

If we could exploit photography thoroughly, we could probably obtain most of the information we need. Photography is so versatile that it has been called the ubiquitous component of remote sensing. Cameras can record reflected radiation in the spectral region from approximately 300 to 1100 millimicrons, encompassing the near-ultraviolet, visible, and near-infrared portions of the electromagnetic spectrum. The camera records what we are accustomed to seeing, so photographs lend themselves quite readily to interpretation. The inherent geometry of photography allows us to measure images and determine areas and volumes of the objects they represent and their relationship to each other. The resolution of detail available in photographs makes it possible to identify and delimit objects with high reliability. Further, the aerial view provides a permanent, comprehensive record of the total area of interest. Important engineering information that would be missed in ground observations may be observed in this overview.

The science of photogrammetry has progressed to an advanced degree of refinement. Accurate horizontal and vertical measurements can be obtained from photographs with a minimum of ground control. The art of interpreting photographs to obtain other engineering information has not progressed as far. The traditional panchromatic photograph contains information that is not now exploited, and techniques involving different film and filter combinations make it possible to obtain even more information. Color, black-and-white infrared, Ektachrome (color) infrared, or selective spectral filtering of panchromatic or infrared film may provide important information not obtainable with ordinary panchromatic film.

A rather new concept, multispectral or spectrozonal imaging, involves recording a scene at more than one wavelength simultaneously to record diagnostic information that is not disclosed with broad-band panchromatic or color film. Spectrozonal cameras and special optical-electromechanical scanners have been developed to exploit the concept. Various aspects of the multiband approach to solving problems have been discussed in the literature (4-11). Multispectral techniques, new film emulsions, improvements in film speed, grain size, and optical quality of cameras provide a capability for recording, in numerous ways, minute details of the surfaces within the area under investigation. These advances can greatly increase our information potential if we can couple them with significant advances in interpretation techniques.

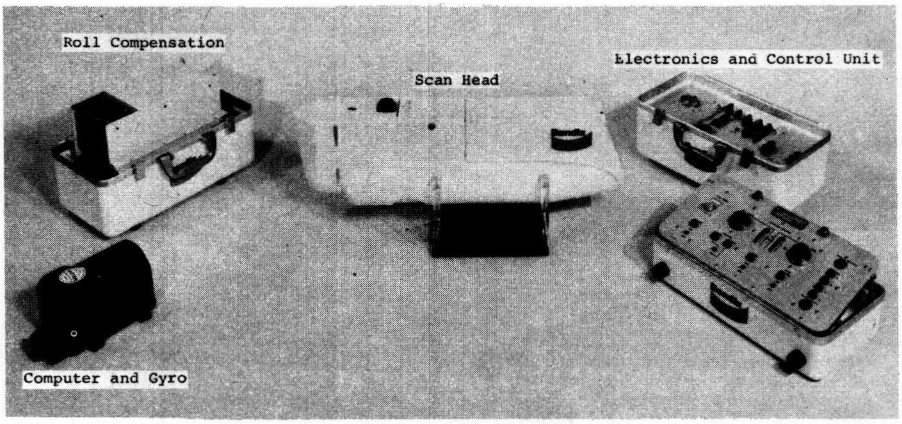
At wavelengths longer than about one micron, imaging directly on film is not possible. Imaging at these wavelengths involves detecting emitted and/or reflected infrared or microwave radiation, transducing it to an electrical signal, and using the electrical signal to modulate the intensity of a CRT or crater-lamp light source. The modulated light is used to expose film and produce a photographic rendition of the imaged scene. It represents the relative or absolute levels of infrared or microwave radiation emitted and/or reflected from the imaged scene. [Principles of infrared and microwave imaging are discussed in other works (12-18).]

The optical-electromechanical scanner evolved from a search for ways to generate infrared imagery from an airborne platform (now also used with a prism spectrometer as a multispectral scanner to generate imagery in the visible and near-ultraviolet spectral regions). Figure 2 shows an infrared scanner. It is compact and light in weight, has low power requirements, and was designed specifically for use in light aircraft. Operated as a thermal mapper (practically, within the spectral region between $\sim$3.5 μ and 14 μ), the scanner produces a record of the relative levels of thermal power emitted by the surfaces scanned. For daytime operation, if emitted thermal power is the quantity to be recorded, it is necessary to filter out the strong reflected infrared component of solar radiation that lies between the visible red and $\sim$3.5 μ.

The spatial resolution achievable with infrared scanners is much less than with cameras, but the capability of detecting small differences in radiation temperatures is quite good (< 1 C). Differences in the apparent temperatures of objects arise from many factors, including density, thermal conductivity, heat capacity, surface roughness, composition of the material, and the placement and orientation of the radiating surface. Changing the density, moisture content, or surface characteristics of a material may give rise to detectable differences in the apparent temperature. If these temperature differences can be related to factors relevant to engineering and repeatedly and reliably identified through infrared imagery, we have a potentially useful technique. Infrared imagery has, for example, demonstrated a capability of indicating the presence of damming of groundwater along fault lines and anomalous moisture content associated with slide areas (19). Figure 3 shows an example of thermal imagery revealing material boundaries not contrasted in panchromatic photography. It also shows the general nature of the thermal imagery format.

Passive-microwave scanners are essentially scanning radiometers. The imagery records levels of microwave radiation emitted by the objects scanned. The quantity measured is the microwave component of thermal radiation. It includes radiation originating below the surface in many materials. The amount and depth or origin depends on the materials and the wavelengths recorded.* Thus, microwave temperature can more easily be related to a property of a material than surface temperature, because it is not so perturbed by prevailing meteorology. The property that most directly influences the emission of microwave radiation is the dielectric constant. Materials

*Depth of penetration $S = 1/\sqrt{\pi f \mu \gamma}$ meter (MKS units), where f = frequency (Hz), μ = permeability, and γ = conductivity.



Bendix Thermal Mapper

SPECIFICATIONS

Film Running Time—1 hour at max v/h
Liquid Nitrogen Hold Time—2 hours or more at average v/h
Instantaneous Field-of-View (Resolution)—3 milliradians
Lateral Scan Angle—120 degrees
Temperature Difference Sensitivity With Indium Antimonide Detector Filtered to 3 to 5.5 microns—0.5 C
Total Available Spectral Coverage With Indium Antimonide Detector (Manual Setting of Choice of One of 4 Filters Available in Flight)—0.7 to 5.5 microns
Maximum v/h (Aircraft Velocity in fps/Altitude in Feet)—0.275 radians/sec
Standard Detector—indium antimonide
Detector Cooling—liquid nitrogen
Power Requirements (With Roll Compensation)—10 a at 24-28 v DC
Scan Head Weight—35 lb
Weight of Control Box Electronics—22.5 lb
Recording—70 mm tri-x film
Film Capacity—100 feet

MODIFICATIONS AND ACCESSORIES AVAILABLE

Roll Compensation—compensates for aircraft roll up to ± 6 degrees (extended range available)
8 to 13 Micron Coverage by use of mercury doped germanium detector and closed cycle cryostat; 400 cps power required
Tape Recorded Output
Real Time Display
Internal Calibration Sources

Figure 2. Bendix Thermal Mapper. (Materials courtesy of Bendix Aerospace Systems Division.)

with high dielectric constant are good radiators in the microwave region, so imagery can be interpreted in terms of this property. For example, the large difference between the dielectric constants of ice and water at microwave frequencies gives rise to large differences in the apparent temperature of these two materials and consequently their image tones. Variations in the water and air content of materials cause variations in their dielectric constants; consequently differences in soil moisture and compactness may be recorded by the microwave scanner. In fact, the scanner can be calibrated to provide indications of absolute moisture content in the upper soil layer (20). Some interesting possibilities for applying this sensor can be postulated merely on the basis of its unique capabilities for discerning these variations.

Because of the dearth of existing systems and specifications, articles relating to them are scarce. Meisels (21) reveals that a system has been developed for the Coast Guard as an all-weather iceberg reconnaissance device. Communications with Space General Corporation indicate that it has developed a system for meteorological applications for the National Aeronautics and Space Administration. Specifications for this system are given in Figure 4.

Airborne mapping radar systems date back to World War II, when plan-position-indicator (PPI) systems were developed for all-weather navigation and bombing. In the 1950's the side-looking airborne radar (SLAR) systems came into being. These

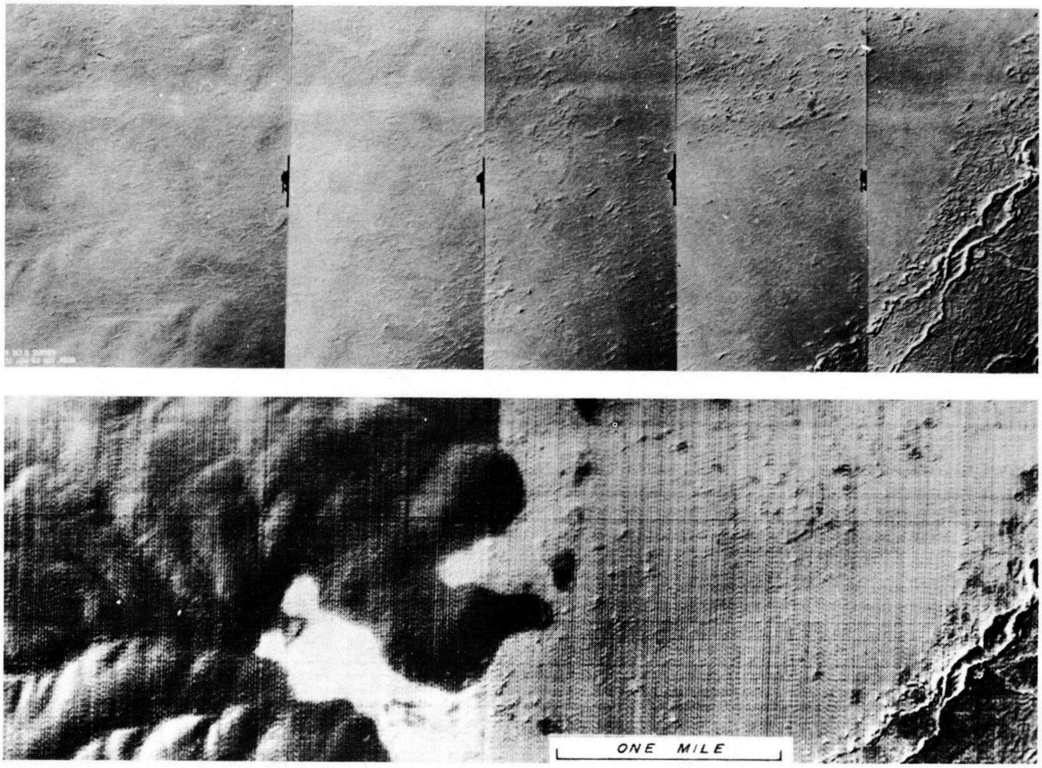


Figure 3. Snow-covered ice-bound coastline visually indistinguishable (even in stereo) in the panchromatic photography (upper) but well defined in the thermal imagery (lower). (Illustration courtesy of U. S. Army Terrestrial Sciences Center.)

have demonstrated a capability of producing imagery that contains useful and quite detailed information about the terrain and the materials that comprise it. Radar is called an active sensor because it records the reflected component of a transmitted pulse of microwave radiation. The imagery is a record of the relative strength of these sig-

LINE-SCANNING MICROWAVE RADIOMETER SPECIFICATIONS

	Original Specs	Breadboard	Aircraft
Sensitivity	$0.7^{\circ}K$	$0.7^{\circ}K$	$1.4^{\circ}K$
ΔT	$0.1^{\circ}K$	$0.1^{\circ}K$	$2.1^{\circ}K$
Scan Time	8 sec	8 sec	1 sec 2 sec
Scan	$\pm 50^{\circ}$	$\pm 50^{\circ}$	$\pm 50^{\circ}$
Beam Width	2.85°	2.85°	2.85°
Data Acq. Sys.	None Paper Printout	None Paper Printout	Real Time Map Nixie Readout Digital Tape Recording
Dynamic Range	$100^{\circ}K$ to $300^{\circ}K$	$100^{\circ}K$ to $300^{\circ}K$	$100^{\circ}K$ to $330^{\circ}K$

Figure 4. Line-scanning microwave radiometer specifications. (Courtesy of Space General Corporation.)

AN/APQ-56 RADAR SPECIFICATIONS

Operating Frequency	35 4 Gc
Beam Width	1^o
Resolution	
Azimuth	~100'
Range	~70'
Power Requirement	20 V DC + 115 V AC @ 400 cycles
Weight	~490 lb
Recording Forn.at	70 mm or 9 5" film
Coverage	~15 mi wide strip each side of aircraft or 5 mi wide strip 10-15 mi out from each side of aircraft

Figure 5. AN/APQ-56 radar specification. (Courtesy of Robert Leighty, U.S. Army Terrestrial Sciences Center.)

nals. The nature of the radar return is related to the dimensions and composition of the illuminated object's surface and its orientation relative to the SLAR system. The wavelengths employed in SLAR are around 1 cm, so many surfaces that appear rough at shorter wavelengths appear smooth at SLAR wavelengths. Furthermore, at the low angles of illumination employed in some SLAR systems, certain surfaces are nearly specular reflectors, so that little if any signal is returned.

Orientation is an important factor in determining the way that the received SLAR signal will be presented. The surfaces of interest can be illuminated from just about any conceivable angle merely by selection of flight path and altitude. This in itself is a salient feature for highlighting subtle features of preferred orientation. The low angle of SLAR illumination tends to emphasize small variations in surface relief and may disclose those not observable in other imagery, such as gullies, low fault scarps, and joint patterns. There are also reports that terrain materials can be uniquely displayed through their roughness characteristics at SLAR wavelengths (22). The SLAR imagery possesses constant scale geometry, and Simons (23) has noted that chart accuracies meeting standards governing class A maps at a scale of 1:250,000 can be achieved from it. These considerations, plus those of wide-area continuous coverage and mapping capability independent of time of day and weather, indicate that SLAR may be useful for purposes of highway engineering.

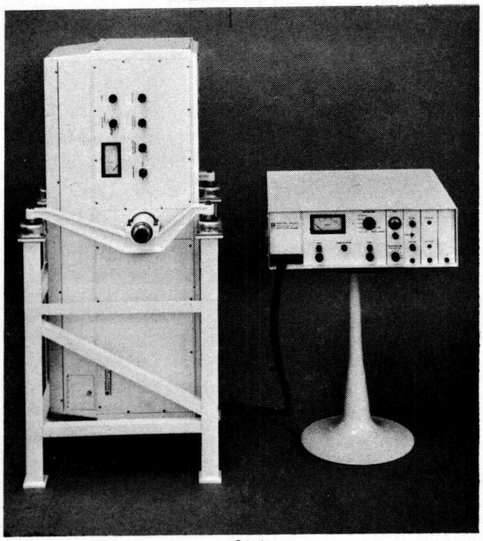
Specifications for most SLAR systems are classified. One, the militarily obsolete AN/APQ-56, likened by Simons (23) to the pinhole-camera state of photographic development, has been declassified. Specifications for it are given in Figure 5. The AN/APQ-97, currently in use for projects such as the NASA Earth Resources Aircraft Program, can be used for nonclassified purposes although some specifications remain classified.

Nonimaging Sensors

Passive-microwave radiometers, radio-frequency sounding devices, gamma-ray spectrometers, and electromagnetic induction devices are some of the nonimaging sensors currently under development that show promise for providing useful highway engineering information. They may be able to provide some of the information that is at present, routinely obtained with seismic or resistivity surveys or by drilling. They are not now routinely employed for highway engineering tasks although such applications are being investigated.

A number of frequencies in the millimeter-wave and microwave regions of the spectrum are being investigated to determine their usefulness in providing information about subsurface conditions in soils. In 1962, Vivian (24, 25) discussed the use of microwave radiometer techniques in analyzing terrain. He stressed the fact that inability to interpret the data rather than inadequate equipment is the big problem standing in the way of widespread use in geophysical applications. In another discussion, Hodgin (26) treated the subject theoretically, concerning himself with its applicability to studies of layered soils and soil moisture. Since 1965 a considerable amount of field testing has been done by Space General Corporation with ground-based, passive-microwave radiometers operating at selected frequencies between 13 and 94 Hz (27, 28). Most of these tests have involved in situ measurements of soil and snow to determine the microwave characteristics of these materials under various conditions of moisture

GEODOLITE 3A PRECISION ALTIMETER



(a)

GEODOLITE 3A PRECISION ALTIMETER

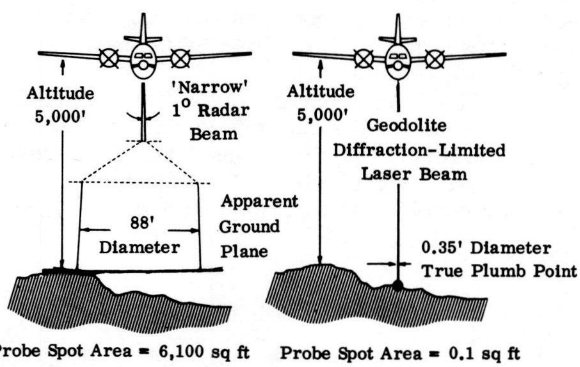
Specifications

Transmitter Beam Width	Less than 10^{-4} radians
Analog Voltage Output	0 to +10.00 volts
Full Scale Range Steps	Choice of 10, 100, 1000, 10,000 and 100,000 feet
Resolution and Accuracy	Better than 1 in 10^4
Range	Greater than 15,000 feet in full sun. Greater than 25,000 feet at night.
Response Time	1, 2, 5, 10, 20, 50, and 100 millisecs.
Mounting	Vibration-isolating vertical mounting frame.
Dimensions and Weights	Telescope Assembly with Mount: 46 x 14 x 10 inches 110 pounds Control Unit: 17 x 16 x 5¼ inches 40 pounds
Input Power	115 ±10 volts, 50 to 400 hertz
Price	**Geodolite 3A** . . . . **$79,000** (Recorder not included)

Prices and other data are subject to change; consult Spectra-Physics Sales Office for further details.

(b)

"NARROW BEAM", 1° APR vs GEODOLITE LASER PROFILER



(c)

Figure 6. Geodolite 3A precision altimeter (a), specifications (b), and comparison with radar altimeter (c). (Materials courtesy of SpectraPhysics.)

content, layering, density, and surface roughness. One of the important findings of these tests is that there is a direct relationship between apparent temperature and soil moisture at the wavelengths used. The equipment used in conducting these ground-based tests can be adapted for airborne operations.

Sounding possibilities using pulsed-radar techniques have been discussed by Cook (29) and were said to be potentially useful in such areas as measuring the thickness of fresh-water ice, determining the depth of the permafrost layer or to the water table, locating caves in limestone country, and possibly finding shear zones. Monopulse radar techniques have been applied successfully to measuring the thickness of lake ice and snow (30). They have not yet been successfully applied to sounding sea ice or other layered materials with complex dielectric constants that introduce attenuation, so it remains to be seen whether monopulse radar can provide answers to sounding problems more generally related to highway engineering.

The Army Engineer Waterways Experiment Station has initiated considerable research in the use of radar techniques for making terrain trafficability investigations. A theoretical study, for example, indicated that monochromatic pulsed-radar systems operating in the very high frequency (VHF) band are not suitable for measuring subsurface soil conditions, but that swept-frequency techniques might be (31). Laboratory testing has confirmed that monochromatic pulsed-radar sensors cannot disclose whether interfaces exist or how deep they are, but can provide information about the water content in deep homogeneous soils (32). These laboratory experiments also corroborated the predictions that swept-frequency techniques can provide information about the depth to subsurface interfaces.

In 1964, radio-frequency sounding devices operating in the VHF band (30 MHz and 35 MHz) were used to sound through 4600 feet of ice on the Greenland icecap and produced a continuous record along the line of surface traverse (33). The equipment has been refined for airborne use by a team from the Scott Polar Research Institute. In 1967 this system was flown over the Antarctic icecap. Continuous profiling of the top and bottom surface of the ice was achieved through ice up to 12,000 feet thick.

Gamma-ray spectrometers are being investigated to determine their utility in soil trafficability studies (34). Barringer (35) has stated that an airborne gamma-ray spectrometer has demonstrated the ability to provide criteria for identifying bedrock even when bedrock is covered with ground moraine.

Another system that has demonstrated a capability of obtaining data about the subsurface from the air is called INPUT—an acronym for induced pulse transient (35, 36, 37). INPUT was designed primarily as an airborne sensor for detecting conducting ore bodies. It also has demonstrated a capability for detecting gravel aquifers buried in glacial clays. Further development and employment of this system may turn up other uses potentially valuable in highway engineering.

Finally, lasers show potential application to highway engineering. They will find many uses in the areas of optical ranging and profiling. One instrument, called an airborne laser terrain profiler, has already been developed by Spectra Physics and Aero Services Corporation (38). Some of the specifications are given in Figure 6. Because the laser light spot illuminates such a small area, it can give a much higher resolution of terrain profile than the longer wavelength radar profilers can, especially in rugged country. The small areas of illumination coupled with the high information rate of the equipment make it suitable for measuring surface roughness on the order of inches.

ARE AIRBORNE SENSORS ECONOMICAL?

Economical employment of sensors must be considered. Is there a decided savings in time, money, or intangibles by using the various sensors, particularly the airborne ones? At present we can only point to the case of aerial photography because, to our knowledge, no figures exist for the other sensors. As an adjunct to preparing this paper we queried a number of state highway departments regarding savings that they realized by using remote sensing techniques, and the significant ways in which the sensors figured in a calculable or noncalculable saving. Our inquiries were very graciously acknowledged by the highway departments of Alabama, Idaho, Louisiana, Michigan, Montana, New York, North Carolina, Pennsylvania, Virginia, and Wisconsin, which represent a good cross section of terrain conditions and engineering problems. It is interesting that savings estimated as high as 75 percent were reported for cases where aerial photographic surveys were used for developing plans for highway construction. Savings estimated at 50 percent of the cost of a ground survey were reported for aerial photographic surveys conducted in areas of extremely rugged terrain or high cultural development; the savings became less and finally became losses for surveys in flat terrain with little cultural development. It is significant that most of the reported savings involved the photogrammetric rather than the interpretive attributes of aerial photographs. Uses for which noncalculable savings were mentioned included materials investigations, studies of landslide areas, condemnation cases, land appraisals, and preliminary surveys for design and preparation of construction plans.

Results of the inquiry reveal two facts. First, when aerial photographic surveys are used in highway engineering, savings result. That was the consensus. Some respondents seem to have a better feeling for the dollar value than others, and some reported more ways in which they could use aerial photographs and save money than others did. The second fact is that none reported using airborne sensors other than cameras. This illustrates that there is a lot of growth potential for the field of electromagnetic sensing applied to highway research and engineering.

WHERE DO WE GO?

The uses of aerial photography in engineering applications are well documented and the economics of their employment are well established. New developments in photographic spectral techniques and uses for color, Ektachrome infrared, and other special-emulsion films are exciting. The job of determining their utility in engineering applications is challenging.

Developments in the other sensor technologies also show great promise, especially those sensors that can provide information about the subsurface. Before we can realize the full capability of the sensors, and particularly appropos the nonphotographic sensors, we must learn much more about the in situ characteristics of the materials of primary interest so that we can confidently interpret the sensor data.

Each research problem or engineering application should be considered separately in light of existing sensor technology and our knowledge of the way that the object, the condition, or the phenomenon under consideration manifests itself spatially and spectrally. It is only through this approach that a systematic analysis of the applicability of the sensors will evolve. Generalizations about capability are of little value in the solution of specific problems. It is essential that specific highway research and engineering problems be made known to those doing research in sensor technology and basic spectral phenomena so that progress can be made.

In the near future it should be possible to exploit economically the special problem-solving potential of some of the sensors discussed in this paper. It may turn out that economics will be the catalyst that accelerates the use of remote sensors in highway research and engineering. As one of our reporting highway departments pointed out, it is becoming increasingly difficult to find people to perform ground surveys and the cost of ground methods is steadily increasing.

ACKNOWLEDGMENT

This paper was prepared in part through funds made available by the Office of Naval Research.

REFERENCES

1. Photogrammetry and Aerial Surveys. HRB Spec. Rept. 82, 1964.
2. Manual of Photographic Interpretation. American Society of Photogrammetry, 1960.
3. Lueder, D. R. Aerial Photographic Interpretation. McGraw-Hill Book Company, 1960.
4. Colwell, R. N. Some Practical Applications of Multiband Spectral Reconnaissance. American Scientist, Vol. 49, No. 1, p. 9-36, 1961.
5. Colwell, R. N. Platforms for Testing Multi-Sensor Equipment. Proc. Second Symposium on Remote Sensing of Environment, Report No. 4864-3-X, Inst. of Science and Tech., Univ. of Michigan, p. 7-49, 1963.
6. Colwell, R. N. Uses and Limitations of Multispectral Remote Sensing. Proc. Fourth Symposium on Remote Sensing of Environment, Report No. 4864-11-X, Inst. of Science and Tech., Univ. of Michigan, p. 71-100, 1966.

7. Holter, M. R., and Legault, R. R. The Motivation for Multispectral Sensing. Proc. Third Symposium on Remote Sensing of Environment, Report No. 4864-9-X, Inst. of Science and Tech., Univ. of Michigan, p. 71-77, 1965.
8. Legault, R. R., and Polcyn, F. C. Investigations of Multispectral Image Interpretation. Proc. Third Symposium on Remote Sensing of Environment, Report No. 4864-9-X, Inst. of Science and Tech., Univ. of Michigan, p. 813-821, 1965.
9. Molineux, C. E. Air Force Remote Sensing Program. Proc. First Symposium on Remote Sensing of Environment, Report No. 4864-1-X, Inst. of Science and Tech., Univ. of Michigan, p. 93-98, 1962.
10. Molineux, C. E. Aerial Reconnaissance of Surface Features With the Multiband Spectral System. Proc. Third Symposium on Remote Sensing of Environment, Report No. 4864-9-X, Inst. of Science and Tech., Univ. of Michigan, p. 399-421, 1965.
11. Lowe, D. S., and Braithwaite, J. G. N. A Spectrum Matching Technique for Enhancing Image Contrast. Applied Optics, Vol. 5, No. 6, p. 893-897, 1966.
12. Proc. IRE. Inst. of Radio Engineers, New York, Vol. 47, No. 9, p. 1413-1700, 1959.
13. Morgan, J. O. Infrared Technology. Proc. First Symposium on Remote Sensing of Environment, Report No. 4864-1-X, Inst. of Science and Tech., Univ. of Michigan, p. 45-59, 1962.
14. King, J., Limperis, T., Morgan, J., Polcyn, F., and Wolfe, W. Infrared. International Science and Technology, No. 16, p. 26-37, April 1963.
15. Wolfe, William L. (ed.) Handbook of Military Infrared Technology. Office of Naval Research, Dept. of the Navy, 906 pp., GPO, 1965.
16. Study of Thermal Microwave and Radar Reconnaissance and Applications. Final Report ASTIA 250 363, Ohio State Univ., July 1, 1960.
17. Berkowitz, R. S. Modern Radar, Analysis Evaluation and System Design. John Wiley and Sons, New York, 1965.
18. Weiss, H. G. Modern Radar. International Science and Technology, No. 13, p. 75-84, Jan. 1963.
19. Sabins, Floyd F. Jr. Infrared Imagery and Geologic Aspects. Photogrammetric Engineering, Vol. 33, No. 7, p. 743-750, 1967.
20. Kennedy, J. M., and Edgerton, A. T. Microwave Radiometric Sensing of Soils and Sediments. Paper presented at American Geophysical Union, 48th Annual Meeting, 14 pp., 1967.
21. Meisels, M. Microwave Radiometry Gains Systems Interest. Microwaves, Vol. 4, No. 7, 1965.
22. Rydstrom, H. O. Interpreting Local Geology From Radar Imagery. Proc. Fourth Symposium on Remote Sensing of Environment, Report No. 4864-11-X, Inst. of Science and Tech., Univ. of Michigan, p. 193-201, 1966.
23. Simons, J. H. Some Applications of Side-Looking Radar. Proc. Third Symposium on Remote Sensing of Environment, Report No. 4864-9-X, Inst. of Science and Tech., Univ. of Michigan, p. 563-571, 1965.
24. Vivian, W. Passive Microwave Technology and Remote Sensing. Proc. First Symposium on Remote Sensing of Environment, Report No. 4864-1-X, Inst. of Science and Tech., Univ. of Michigan, p. 35-42, 1962.
25. Vivian, W. Application of Passive Microwave Techniques in Terrain Analysis. Proc. Second Symposium on Remote Sensing of Environment. Report No. 4864-3-X, Inst. of Science and Tech., Univ. of Michigan, p. 119-125, 1963.
26. Hodgin, D. M. The Characteristics of Microwave Radiometry in Remote Sensing of Environment. Proc. Second Symposium on Remote Sensing of Environment, Report No. 4864-3-X, Inst. of Science and Tech., Univ. of Michigan, p. 127-137, 1963.
27. Conway, H. W., and Sakamoto, R. T. Microwave Radiometer Measurements Program. Proc. Third Symposium on Remote Sensing of Environment, Report No. 4864-9-X, Inst. of Science and Tech., Univ. of Michigan, p. 339-356, 1965.

28. Kennedy, J. M., Edgerton, A. T., Sakamoto, R. T., and Mandl, R. M. Passive Microwave Measurements of Snow and Soils. Vols. I and II, Report No. SGC-829-4, Space General Corporation, 1966.

29. Cook, J. C. Monocycle Radar Pulses as Environmental Probes. Proc. Second Symposium on Remote Sensing of Environment, Report No. 4864-3-X, Inst. of Science and Tech., Univ. of Michigan, p. 223-231, 1963.

30. Meyer, M. A. Remote Sensing of Ice and Snow Thickness. Proc. Fourth Symposium on Remote Sensing of Environment, Report No. 4864-11-X, Inst. of Science and Tech., Univ. of Michigan, p. 183-192, 1966.

31. Nikodem, H. J. Effects of Soil Layering on the Use of VHF Radio Waves for Remote Terrain Analysis. Proc. Fourth Symposium on Remote Sensing of Environment, Report No. 4864-11-X, Inst. of Science and Tech., Univ. of Michigan, p. 691-703, 1966.

32. Lundien, J. R. Terrain Analysis by Electromagnetic Means, Report 2: Radar Responses to Laboratory Prepared Soil Samples. U. S. Army Material Command, Vicksburg, Miss., 1966.

33. Rinker, J. N., Evans, S., and DeQ. Robin, G. Radio Ice-Sounding Techniques. Proc. Fourth Symposium on Remote Sensing of Environment., Report No. 4864-11-X, Inst. of Science and Tech., Univ. of Michigan, p. 793-800, 1966.

34. Williamson, A. N. Laboratory Investigations of the Gamma-Ray Spectral Region for Remote Determination of Soil Trafficability Conditions. Proc. Fourth Symposium on Remote Sensing of Environment, Report No. 4864-11-X, Inst. of Science and Tech., Univ. of Michigan, p. 623-633, 1966.

35. Barringer, A. R. The Use of Multi-Parameter Remote Sensors as an Important New Tool for Mineral and Water Resource Evaluation. Proc. Fourth Symposium on Remote Sensing of Environment, Report No. 4864-11-X, Inst. of Science and Tech., Univ. of Michigan, p. 313-325, 1966.

36. Barringer, A. R. The Use of Audio and Radio Frequency Pulses for Terrain Sensing. Proc. Second Symposium on Remote Sensing of Environment, Report No. 4864-3-X, Inst. of Science and Tech., Univ. of Michigan, p. 201-214, 1963.

37. Geleynse, M., and Barringer, A. R. Recent Progress in Remote Sensing With Audio and Radio Frequency Pulses. Proc. Third Symposium on Remote Sensing of Environment, Report No. 4864-9-X, Inst. of Science and Tech., Univ. of Michigan, p. 469-494, 1965.

38. Rempel, R. C., and Parker, A. K. An Information Note on an Airborne Laser Terrain Profiler for Micro-Relief Studies. Proc. Third Symposium on Remote Sensing of Environment, Report No. 4864-9-X, Inst. of Science and Tech., Univ. of Michigan, p. 321-337, 1965.