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REMOTE-SENSING POTENTIAL IN BASIC-DATA ACQUISITION

Hydrology and Integrated Resource Surveys

Large portions of the land areas of the earth are poorly and inadequately covered by resource surveys needed to plan their development. Even areas that are highly developed are in constant need of additional basic information on the raw materials needed for economic development and on the water resources required to support the use of those raw materials. Integrated resource surveys can provide much of the information needed to plan development.

Integrated resource surveys are environmental, social, and economic assessments of the assets and liabilities of the resources of a given region which set the boundaries within which development and conservation decisions must be made. Hydrologic-data acquisition and interpretation are fundamental parts of integrated resource surveys. But the acquisition of water-resource data is a time-consuming and difficult job for any region. Moreover, the larger the region one is surveying the more difficult the task becomes.

Objectives of Hydrologic-Data Acquisition

I wish to examine here the two basic methods of hydrologic-data acquisition, their relation to integrated resource surveys, and the potential of remote sensing. Figure 1 is a flow chart of hydrologic data methods. The basic research and operational question faced in hydrology today is: How can environmental characteristics be described accurately and readily in forms suitable for analysis and prediction of cause-and-effect relations in hydrology and water-resource management? This question is answered in classical hydrology by making point measurements of hydrologic parameters in precise form at a particular site, by continuing these point measurements over long periods of time, and by synthesizing the measurements and the time series into descriptions of the environmental and water system. Modern hydrology, on the other hand, has as its goal a composite description of the hydrologic system at several points in time using a number of composite-measurement techniques of both the quality and the quantity of water. It is important to recognize at this point that the accuracy and precision needed in hydrologic measurement depend upon the scale of the problem that is being attacked.

Data acquired by classical methods are usually quite precise, while the data acquired in modern hydrology are only as precise as is needed for the problem at hand. For example, measurements made of depth to water in a desert basin should be much more precise if the scale of mapping is 1:25,000 than if it is 1:250,000. Thus one of the tenets of modern hydrology is that one must recognize the point of diminishing returns in data collection at which the time and effort that it takes to collect and interpret the data may be greater than is needed to solve the basic problem of the investigation. This is primarily true of small-scale investigations of large areas.

The Tools of Remote Sensing

A major direction of effort in attaining the objectives of modern hydrology is to use remote-sensing instruments from aircraft and spacecraft that can provide photographs, other images, and numerical data relating to the earth's terrain which have a bearing on the hydrologic environment and which can cover large areas economically in short periods of time. The sensor data can then be correlated with the available point and synthesized data to describe the environmental characteristics.

The basic developments in remote sensing evolve around an aircraft capability to collect data for large areas in short periods of time with the use of the basic sensor -- the aerial photographic

camera and film. The use of aerial photographs is of course not new in hydrology, but with the advent in the past few years of conventional and infrared color photography a new dimension has been added to the photographic capability, and the photographic sensor is now and will continue to be for some time a prime tool of the hydrologist in obtaining information about large areas. Color photographs allow color contrasts to be used for interpretation, as shown in figure 2, as well as the tone and texture criteria used for interpretation of black and white photographs.

Several factors favor a major use of aerial photographs in integrated resource surveys. The photograph is factual information and when it is presented to an interpreter, regardless of his discipline or training, he can interpret it with his problems in mind. This means then that comparable -- in fact, even the same -- data can be used by all members of an integrated resource survey team whether they are concerned with geology, hydrology, vegetation, or other facets of the environment under survey. Aerial photographs, and principally color and infrared-color aerial photographs, are also close enough to the visual experience of the interpreter that he can use them with a minimum of training and experience.

Infrared-color photography, shown in figure 3, is useful for interpretation of vegetated areas. Classification of the types of vegetation is enhanced and indications of the vigor of the plants and the salinity of the soil are given by the color.

Multispectral photography is being investigated for its usefulness in hydrology. Several black-and-white pictures are taken simultaneously through narrow-band filters and then are combined by color-printing techniques to form a composite false-color photograph. The colors of the scene and their contrasts are then interpretable. This technique allows selection of filter bands that are most applicable to the type of terrain being photographed and the printing technique that provides the highest color difference among the elements it is desired to distinguish.

Infrared sensors utilizing longer wavelengths of the electromagnetic spectrum have come into play in recent years as a major development. They are capable of sensing the heat emitted from the earth's surface. The infrared sensor may be either a radiometer that measures the infrared radiation emitted from the terrain directly below an aircraft and produces a graph or a scanner that scans perpendicularly to the path of the aircraft and produces an image of the terrain. Both the radiometer and the scanner provide information interpretable in terms of the temperature of water surfaces and the approximate moisture content of the soil and rocks near the surface. Figure 4 shows the wedge of salt water in an estuary and the river water, contrasted by their temperature in infrared imagery.

Side-looking airborne-radar imagery is an excellent tool for all-weather coverage of large areas. It has proven to be of some use in the mapping of structural features and in the differentiation of some rock types. It is excellent for small-scale planimetric mapping where no better maps are available. Figure 5 shows a radar image of a synclinal fold. Radar accentuates both the topography and geologic structure where that structure has a topographic expression. Although little ground-water exploration has been done with radar imagery, it promises to be an important tool.

The availability of these sensors and techniques varies somewhat. Aerial photography of all types is readily available from commercial aerial photographic companies. Infrared radiometers and imagers are available on the open market and services for their use and interpretation are available from commercial companies. Flights of airborne-radar aircraft are not generally available yet, but imagery of some areas is available for interpretation. Other techniques being investigated at this time for their applicability to hydrologic and other problems are passive microwave radiometry, ultraviolet and visible stimulated luminescence, and absorption spectroscopy.

Remote Sensing from Earth-Orbital Satellites

I have discussed briefly the use of some of these techniques in aircraft but would like to turn now to higher altitudes to see what their applicability could be from earth-orbital satellites. Satellites are capable of covering repeatedly very large areas of the earth's surface and obtaining synoptic and repetitive data of value in hydrology and integrated resource surveys. Shown in figure 6 are some of the basic capabilities of space sensing, the results obtained, and the advantages to be gained. Remote sensors of the type previously described can be put in spacecraft, and indeed photographic cameras, television cameras, and infrared radiometers have been installed in spacecraft and data have been received.

Evaluation of these data and of the capabilities of space sensors in general defines six basic advantages of obtaining hydrologic data from space. First, the data bulk is reduced. The number of aerial photographs required to cover a given area on the earth's surface is about a thousand times the number required from space. Second, the costs of data acquisition are reduced. For example, a single complete aerial photographic coverage of the conterminous United States

would cost about \$12 million. If such photography were to be obtained from an earth-orbiting satellite, which could photograph all the land areas of the earth, the cost of photographing the United States would be about \$750,000, and because the satellite can repeat this coverage, subsequent pictures would be virtually free. Third, earth-orbital sensing facilitates inductive study. An interpreter can study pictures of a large area and select areas of maximum interest rather than build up his description of the system from small measurements. Fourth, earth-orbital sensing can provide comparable data on a global basis. This is particularly important because we are concerned with global facets of hydrology, and data should be readily comparable and factual in order to formulate and test hypotheses on the water balance of the world. Fifth, automatic data-reduction systems are applicable to the data, owing to the small data bulk and to the comparability of the data. If pattern-recognition devices or other automatic interpretive aids can be used on comparable data on a global basis, effectiveness in terms of cost and time will be increased even further. Sixth, earth-orbital data have a greater number of uses than data gathered from aircraft. The same photographs can be used by hydrologists, geologists, geographers, foresters, agriculturalists, and oceanographers; and thus the benefits from the initial collection of the data may be spread out to the large group that comprises an integrated resource survey team. This multiplicity of use applies in time as well, because the repetitive capability of satellite sensors will provide comparable data over long periods of time and thus will allow the interpreters to see changes in the environment that take place in both short and long periods of time.

The emphasis that I have placed here on the use of earth-orbital sensors by no means indicates that satellites will replace aircraft in remote sensing, but the two methods will form an excellent team. It is important to note again that the data collected in any investigation should be based upon the scale of the problem. If the area studied is very small and great precision is needed, ground methods are most applicable. If the problem is of moderate scale, aircraft methods supplemented by field checking and precise ground methods as required should be used. If very large areas are investigated, the use of data from earth-orbital satellites is indicated, supplemented by aircraft surveys and by whatever ground data are needed for correlation.

Research on the use in hydrology of remote-sensing methods going beyond conventional aerial photography began only a few years ago and is continuing at an accelerated pace. New types of sensors are becoming available, and new methods of interpreting the present sensor data are being found. Remote sensing will not be a panacea for hydrologic problems. When properly used, remote-sensing techniques will provide synoptic information that is impossible to obtain by other means, and when combined with the properly obtained ground measurements they will make hydrologic studies much more efficient and more useful parts of integrated resource surveys.

A Brief Evaluation of Remote Sensors

Water-resource data are needed both for research on the principles of occurrence, movement, and interactions of water and as a basis for planning the use and control of water. For the purpose of this report these data needs are grouped in the accompanying table in seven major categories that cover, in a general manner, all the major needs. They are matched against the remote sensors that have received the most attention by hydrologists, and a brief evaluation of each one's usefulness is given. The use of remote sensors goes hand in hand with the needs for water-resource data -- neither can reach maximum usefulness until models (conceptual, mathematical, or analog) are sufficiently developed to make proper use of the data. For example, modeling the distribution of pollutants in a tidal estuary for the purpose of predicting their concentration and distribution at any time cannot be accomplished until the analytical equations of diffusion and dispersion are fully developed and usable in actual situations in the field, not just in ideal cases. It is quite possible that remote-sensor data such as visible streamlines, in water on a photograph or the thermal contrasts on the water surface as seen in an infrared image may be usable, or indeed vital, data. There is always the possibility, however, that the data may not be usable, so that different remote-sensing techniques will have to be developed for the purpose.

Relative Value of Remote Sensors in Hydrology

The chart on the following pages includes only those sensors that have received some attention by hydrologists. A subjective ranking of the use of the sensors would place photography at the top because of the capability of hydrologists to use photography to great advantage at the present time and because of the easy interpretability and the lack of substantial data reduction needed for the use of photographs. For these reasons, top priority should be given to photographic sensors in orbiting satellites for hydrologic surveying.

Infrared sensors, because of their capability of sensing thermal features, have a large potential in hydrology, but it is secondary to the potential of photographic systems. Problems of emissivity measurement hamper the use of infrared imagery for quantitative geohydrologic use, and for the present the imagery may be most useful for semiquantitative determinations of water-surface temperature as an indication of hydrologically significant relations or processes.

Radar at present is best used for geologic purposes because, at the present state of the interpretive art, it does not provide direct hydrologic evidence. It does, however, provide much geologic information that can be interpreted in hydrologic terms.

Ultraviolet and microwave techniques have not been evaluated by hydrologists because few data are available and basic research, has not been done on the interactions of ultraviolet and microwave energy with features of hydrologic significance. From the state of the art in ultraviolet and microwave imaging, for example, it is our opinion that the resolution that could be achieved by the systems from orbital altitudes would be much too coarse for hydrologic purposes, although it may well be satisfactory for oceanographic purposes where fine resolution can be sacrificed for areal coverage.

Future Research Needed

Future applications of remote sensors in hydrology depend on two factors: (1) the capability of instruments to collect data and (2) the capability of the hydrologic community to assimilate and use the data to best advantage. Common to both these factors is the need for an accelerated basic-research program to determine the types of data that can be collected and used. A single broad example may suffice to illustrate this point.

Studies of lakes have traditionally been made of individual lakes with the objectives of either (1) describing in detail the setting and dynamics of a particular lake or (2) elucidating a scientific principle, using the lake as a testing ground. It has been enormously difficult for the limnologist to collect and use the data that have transfer value in describing a lake region or in categorizing lakes on the basis of other than geologic factors which may be hydrologically meaningless. Color photography from aircraft and spacecraft is capable of recording the shape and size of lakes and also the color of the water. Does the color of the water have a meaning in terms of the chemistry, biology, or sediment characteristics of a lake or group of lakes? If it is significant, then color photography may become a significant tool for the limnologist. In order to evaluate the use of color photography, however, it will be necessary to do research on the spectral reflectance and absorbance of lake waters and the associated hydrologic parameters. Only when such research is much farther along than at present can the limnologist interpret the color seen in photographs with confidence that he is assessing meaningful data.

Conclusion

At present remote sensors have a limited but important application in hydrology. An increase in the ability of hydrologists to interpret and use the data from well-developed sensors, coupled with an accelerated research program to assess the usefulness of more sophisticated sensors than are now employed, can provide maximum benefits from the blending of data collection and use.

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Table 1. -- Evaluation of Remote Sensors as Hydrologic Tools (May 1967)

<u>Remote-Sensor System</u>	<u>General Comments on Potential Value and Use of Remote-Sensor System for Hydrologic Studies</u>
Panchromatic Photography	Panchromatic photography is the most widely used remote-sensing technique because of its availability and relatively low cost. Interpretive techniques are well developed and formal training in its use is available.
Multispectral Photography	Multispectral photography interpretation requires a background of spectral-signature studies of terrain and water features that have not yet been made. Data returns from multispectral systems may be so voluminous that they cannot be readily interpreted. Little work has been done on interpretation for hydrologic purposes.
Infrared Photography	Infrared photography is primarily of value in mapping drainage features and shorelines. The water is always black in a positive print. Some vegetation characteristics are discernible. Its most valuable use is as an adjunct to, but not a replacement for, standard aerial photography.
Color Photography	Color photography, in spite of its built-in spectral redundancy, promises to be a major tool of the hydrologist in many special fields and is sufficiently better for recognition of significant hydrologic features that it may replace panchromatic photography for many uses. The interpretation capability of the potential operational hydrologic users of color photography must be greatly increased.
Infrared-Color Photography	Color-infrared photography may be superior to standard color photography in some respects. It shows differences in vegetation more clearly and provides a slightly higher contrast on water surfaces. Its general superiority to standard color photography has yet to be proved but it may be highly useful and is worthy of much additional research.
Infrared Radiometry	Infrared radiometry is very useful for sequential measurements of changes in land and water surface temperatures because it is a simple measurement technique and data reduction is simpler than for infrared imagery. Radiometry is routinely used for periodic surveys of near-shore oceanic areas.
Infrared Imagery	Infrared imagery has shown its value as a tool for measuring water-surface temperature and as a means of qualitatively differentiating some terrestrial features. The lack of a simple means of determining emissivity hampers its quantitative usefulness. Analytical techniques for proper use of the reduced data need to be developed.
Radar Imagery	Radar imagery is an excellent tool for all-weather coverage of large areas. It is of moderate use in mapping structural features and of some use in differentiating some rock types. It is quite usable for small-scale planimetric mapping where no better maps are available.

Remote-Sensor SystemData Available from Remote-Sensor SystemMeasurement of Physical Characteristics of Water Surfaces

Panchromatic Photography	Much aircraft data taken for many purposes. Some special data. Some space data.	Largely unproved, with the exception of the ability to sense streamlines on water surfaces that may be indicative of movement of pollutants or other effluents. Small data use.
Multispectral Photography	Some experimental aircraft data available, primarily 9-lens photography. Much work has been done with the use of special film-filter combinations for specific purposes.	Largely unproved but may be useful in special situations. Small data use.
Infrared Photography	Much aircraft data available.	Not usable because water surfaces always appear black in infrared photography. No data use.
Color Photography	Much aircraft and Gemini Spacecraft data.	Of some value but rigorous evaluation has not been made. Small data use.
Infrared-Color Photography	Aircraft data available.	May provide a higher contrast for mapping of discontinuities on water surfaces than any other type of photography. Small data use.
Infrared Radiometry	Data available from aircraft and from Tiros and Nimbus Satellites.	Valuable for measurement of water-surface temperature but will not achieve its greatest potential until there is full development of analytical equations that express the temperature distribution within a water body as a function of the surface temperature. Moderate data use.
Infrared Imagery	Data available from aircraft and from Tiros and Nimbus Satellites.	Valuable for measurement of water-surface temperature over large areas but will not achieve its greatest potential until there is full development of analytical equations that express the temperature distribution within a water body as a function of the surface temperature. Small data use.
Radar Imagery	Aircraft data available.	Water is an excellent reflector of microwaves and, therefore, water surfaces show as a uniform black tone on radar imagery. Radar imagery, therefore, is of little value in measuring physical, chemical, or biological characteristics of water but is useful in locating and mapping areas of open water. Little data use.

<u>Remote-Sensor System</u>	<u>Measurement of Chemical and Biological Characteristics of Water</u>	<u>Snow Surveying and Mapping</u>
Panchromatic Photography	Useful only for assessing some vegetation types. Small data use.	Useful for mapping snow-covered areas but does not indicate depth or water content of snow. Moderate data use.
Multispectral Photography	May be valuable as a supplement to other photography but specific interpretation criteria have not been developed. Small data use.	May be useful but perhaps not superior to panchromatic photography. Small data use.
Infrared Photography	Not usable because water surfaces always appear black in infrared photography. No data use.	Not yet evaluated. Small data use.
Color Photography	Probably a high potential for use but it must be supported by basic research in the spectral response of waters of various types. Small data use.	May not be significantly better than panchromatic photography. Small data use.
Infrared-Color Photography	Probably not helpful in the detection and identification of substances in water but may be useful in mapping their distribution. Small data use.	Has been used to differentiate new snow from ice and firm. Small data use.
Infrared Radiometry	Valuable only if the chemical or biological factors have an effect on the temperature or emissivity of the water surface. Small data use.	Not evaluated for this purpose. Small data use.
Infrared Imagery	Valuable only if the chemical or biological factors have an effect on the temperature or emissivity of the water surface. Small data use.	Of some use in sea-ice mapping but has not been evaluated for use in snow surveys for water-supply forecasting. Small data use.
Radar Imagery	Water is an excellent reflector of microwaves and, therefore, water surfaces show as a uniform black tone on radar imagery. Radar imagery, therefore, is of no value in measuring physical, or chemical, or biological characteristics of water. No data use.	Has some value in mapping snow-covered areas but does not give data on the water content of snow. Small data use.

Remote-Sensor SystemMapping and Description of
Ground-Water FeaturesGlaciology

Panchromatic Photography	Highly useful for geologic mapping, drainage mapping, and identification of vegetation features associated with ground water. Large data use.	Moderate value in mapping snow and ice fields and surface structure of glaciers. Moderate data use.
Multispectral Photography	May be useful but perhaps not superior to panchromatic photography. May be useful in differentiating vegetation types as indicators of ground water. Small data use.	May be useful but probably is not superior to panchromatic photography. Small data use.
Infrared Photography	Valuable as adjunct to panchromatic photography because some rock units have different contrasts and are, therefore, more recognizable. Moderate data use.	Now being evaluated. Small data use.
Color Photography	High potential for geologic and aquifer mapping as an adjunct to the more readily available standard panchromatic photography. Small data use.	Helpful in detection and identification
Infrared-Color Photography	Probably superior to standard color photography in defining vegetation and soil characteristics. Small data use.	Has been used to differentiate new snow from ice and firn. Small data use.
Infrared Radiometry	May be helpful in measurement of soil moisture and ground-water discharge to streams but is less helpful than infrared imagery because of the small area covered and the difficulty of locating the trace of the radiometer on the ground. Small data use.	Now being evaluated for its use in measuring temperature and radiative transfer of energy from snow and ice surfaces. Small data use.
Infrared Imagery	Now being evaluated as a tool for locating points of ground-water discharge to streams. Small data use.	Helpful in mapping ice and snow temperature and state. Small data use.
Radar Imagery	Moderately valuable in mapping geologic structure and in some lithologic differentiation for ground-water exploration. Small data use.	Now being evaluated. Small data use.

<u>Remote-Sensor System</u>	<u>Geomorphology and Assessment of Changes in the Hydrologic Regimen</u>	<u>Measurement of Liquid-Vapor Transfer in the Hydrologic Cycle</u>
Panchromatic Photography	Excellent for measurement of geomorphic parameters. Small-scale photography allows synthesis of large features on a regional basis. Large data use.	Not applicable to this problem.
Multispectral Photography	Not yet evaluated for this purpose.	Not applicable to this problem.
Infrared Photography	Helpful in addition to normal aerial photography but not normally used alone. Small data use.	Not applicable to this problem.
Color Photography	Helpful in determination of types and composition of surficial deposits. Small data use.	Not applicable to this problem.
Infrared-Color Photography	May be superior to standard photography. Small data use.	Not applicable to this problem.
Infrared Radiometry	Probably not useful for this purpose. Small data use.	Helpful in determining radiative transfer of energy from water and land surfaces to the atmosphere. Small data use.
Infrared Imagery	Not yet evaluated. Small data use.	Useful in regional atmospheric physics but not used in small-scale studies. Small data use.
Radar Imagery	Now being evaluated. Small data use.	Not applicable to this problem.

Approximate amount of data use:

Small -- small number of interpreters evaluating techniques.

Moderate -- a few persons using techniques in specialized studies.

Large -- used by many hydrologists as a standard tool in hydrologic studies.

QUESTION:

HOW CAN ENVIRONMENTAL CHARACTERISTICS BE DESCRIBED ACCURATELY AND READILY IN FORMS SUITABLE FOR ANALYSIS AND PREDICTION OF CAUSE AND EFFECT RELATIONS IN HYDROLOGY AND WATER-RESOURCE MANAGEMENT ?

CLASSICAL HYDROLOGY

SYNTHESIS FROM POINT MEASUREMENT OVER LONG PERIODS OF TIME.

POINT MEASUREMENTS GIVE QUANTITATIVE DATA AT A PARTICULAR SITE.

MODERN HYDROLOGY

COMPOSITE SYSTEM DESCRIPTION AT SEVERAL POINTS IN TIME.

COMPOSITE MEASUREMENTS, INCLUDING REMOTE SENSING TECHNIQUES, GIVE QUALITATIVE AND QUANTITATIVE DATA FOR AREAS.

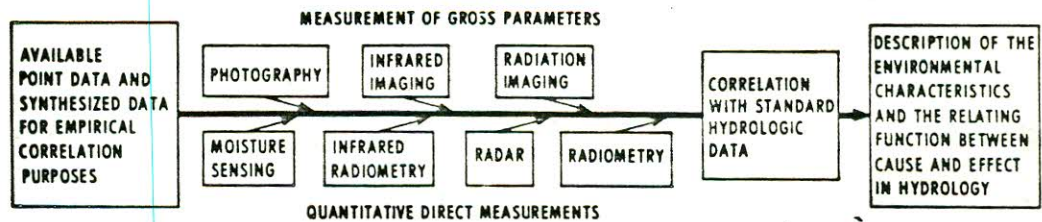
DATA ACQUIRED BY CLASSICAL METHODS**DIRECTION OF EFFORT IN ATTAINING OBJECTIVES****MAJOR OBJECTIVE OF HYDROLOGIC STUDIES**

Figure 1. -- Remote sensing provides a link between classical and modern hydrology



Figure 2. -- A synoptic Gemini photograph demonstrates the broad areal coverage obtainable with space photography (Photograph from NASA)



Figure 3. -- A black-and-white reproduction of an infrared color photograph shows the alignment of vegetation indicative of water-flow patterns in the Florida Everglades. The photograph is about 2 miles in width. (Photograph from NASA.)



Figure 4. -- Infrared imagery shows the tongue of salt water (black) in an estuary. The river water (light) is to the left. (Image from U.S. Geol. Survey)

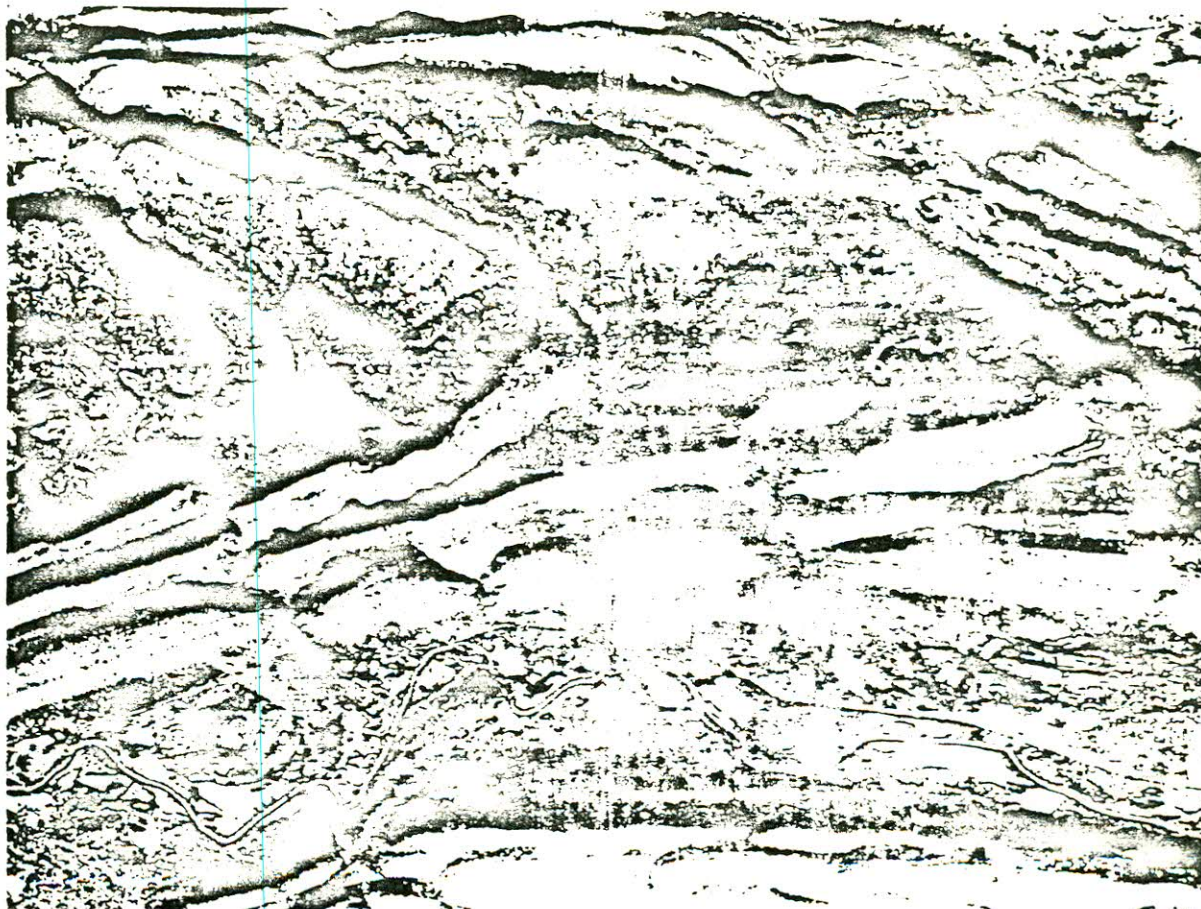


Figure 5. -- A side-looking airborne radar image shows a sincline. The structure and topography are accentuated in the radar reflection image. (Image from NASA)

EARTH ORBITAL SENSING...

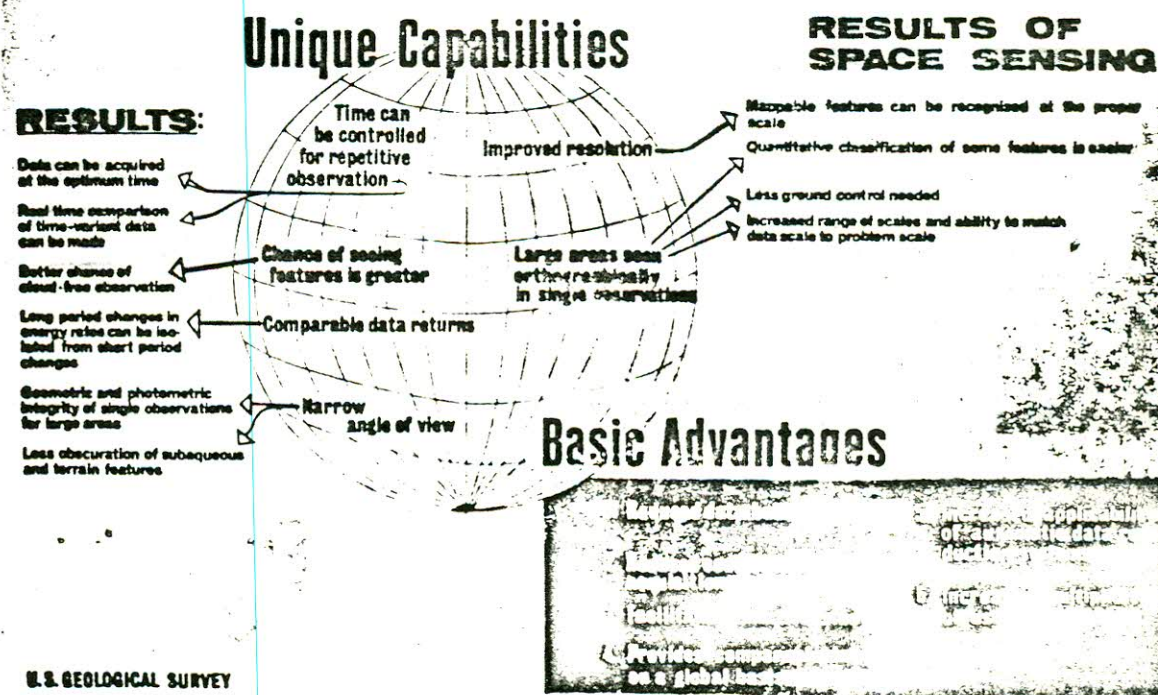


Figure 6. -- Six basic advantages of earth orbital sensing result from the unique capabilities of remote sensors in satellites.