GIS INTEGRATION FOR QUANTITATIVELY DETERMINING THE CAPABILITIES OF FIVE REMOTE SENSORS FOR RESOURCE EXPLORATION

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EXTENDED ABSTRACT:

To assist the U.S. Geological Survey in carrying out a Congressional mandate to investigate the use of side-looking airborne radar (SLAR) for resources exploration, a research program was conducted to define the contribution of SLAR imagery to structural geologic mapping and to compare this with contributions from other remote sensing systems. Imagery from two SLAR systems and from three other remote sensing systems was interpreted, and the resulting information was digitized, quantified and intercompared using a computer-assisted geographic information system (GIS). The study area covers approximately 10,000 square miles within the Naval Petroleum Reserve, Alaska, and is situated between the foothills of the Brooks Range and the North Slope.

The principal objectives of the research project were: 1) to establish quantitatively, the total information contribution of each of the five remote sensing systems to the mapping of structural geology; 2) to determine the amount of information detected in common when the sensors are used in combination; and 3) to determine the amount of unique, incremental information detected by each sensor when used in combination with others. The remote sensor imagery that was investigated included real-aperture and synthetic-aperture radar imagery, standard and digitally enhanced Landsat MSS imagery, and aerial photos.

Imagery from each of the five sensor systems was interpreted for evidence of geological structural features, which, within the confines of the study area consisted of anticlinal axes, synclinal axes, and lineaments that were interpreted to be the surface expression of underlying faults and fractures. Next, the overlays containing the interpretation results were digitized for entry into an automated geographic information system designed for the storage, retrieval, manipulation, and display of geographic-based information. Finally, manipulations were performed on the digital maps in the GIS data base to produce single- and multiple-theme structure maps, to compute statistical data enumerating the total number and length of structural features on the overlay from each sensor system, to measure the length of structures detected in common by two or more sensors, and to measure the length of structures detected uniquely by each sensor.

In respect to the total information content of each sensor, the principal results of the GIS manipulations were as follows: 1) the enhanced Landsat MSS detected 5876 km of structural information; 2) aerial photos

detected 5650 km (extrapolated from a smaller sample); 3) real-aperture SLAR detected 5589 km; 4) synthetic-aperture SLAR detected 3991 km; and 5) standard Landsat MSS detected 3697 km. In respect to information detected in common by sets of sensors, the results of the digital overlay and mensuration operations of the GIS showed that only about one-third was detected in common, and, conversely, about two-thirds of the structural geologic information was detected uniquely by one and/or the other sensor. The meaning of these results is that, in mapping geologic structure either for energy exploration or for power plant siting, it is far more important than has previously been thought to use two or more remote sensing systems and thereby to take advantage of the large amount of information uniquely detected by each.

The results of the remote sensor image interpretation were synthesized and used in the production of a map showing favorable hydrocarbon exploration targets.

1. INTRODUCTION

The House/Senate Conference Report on HR 4930 (96th Congress), Department of the Interior and Related Agencies Appropriations, 1980, states that the U.S. Geological Survey should "begin the use of side-looking airborne radar imagery for . . . geological mapping and geological resource surveys in promising areas [of the United States], particularly Alaska."

To aid the Geological Survey in this effort, Autometric, Inc. has conducted a research program to evaluate and compare the geologic information content of real- and synthetic-aperture SLAR systems and to define the contribution of SLAR and other remote sensor imagery to structural geologic mapping. In the course of this research project, imagery from five different remote sensors was interpreted, and the resulting information was quantified and intercompared using a computer-assisted geographic information system developed for the U.S. Fish and Wildlife Service.* The imagery that was examined consisted of: real-aperture SLAR (APS/94D) imagery, synthetic-aperture SLAR (GEMS-1001) imagery, standard Landsat multispectral scanner (MSS) imagery, digitally enhanced Landsat MSS imagery and color aerial photographs.

The study area included two U.S. Geological Survey quadrangles of the 1:250,000-scale, map series: viz., the Utukok River and Lookout Ridge quadrangles in the North Slope and northern foothills of the Brooks Range. The study area lies entirely within the Naval Petroleum Reserve - Alaska, which the federal government has recently opened to exploration by private industry, with the first lease sale scheduled for later this

* This geographic information system is marketed by Autometric, Inc. under the name AUTOGIS.

year. The use of a computer-assisted geographic information system to integrate and synthesize the structural analyses of multiple remote sensor data sets should contribute significantly to the planning and execution of exploration programs in this important area.

2. OBJECTIVES

The principal objectives of the research project were:

- To establish, quantitatively, the total information contribution of each of the five remote sensing systems to the detection of structural geological features. The term "total information contribution" is defined here as the total length of structural features detected on the imagery. The sensor systems investigated were real-aperture and synthetic-aperture SLAR, standard and digitally enhanced imagery from the Landsat Multispectral Scanner, and aerial photos.

- To determine the amount of structural information detected in common by two or more sensors in combinations of imagery from the five sensor systems. For example: when SLAR and MSS imagery of the same area is interpreted, how much of the resulting geological information is detected by <u>both</u> sensors.

- To determine the amount of unique, incremental structural information detected by each sensor in combination with others. The term "unique, incremental information" is defined as the total amount of information detected by a sensor minus the amount detected by that sensor in common with other sensors. For example: when SLAR and MSS imagery of the same area are interpreted, how much of the resulting geological information is detected by <u>each</u> that was not detected by the other.

3. SCOPE AND METHODOLOGY

3.1 Description of the Study Area

The Utukok River/Lookout Ridge area lies just north of the Brooks Range between 69 and 70 degrees north latitude and 156 and 162 degrees west longitude (Figure 1). It contains approximately 26.156 square kilometers, virtually all of which lie within the Naval Petroleum Reserve, Alaska. The topography varies from the flat, low-lying land of the Alaska North Slope, in the northern half of the area, to the more elevated and rolling ridge-and-valley topography that has been developed on the folded strata in the southern half. The principal underlying rocks consist of marine and continental consolidated sediments of lower and upper Cretaceous age (Beikman, 1980). Except for willows immediately adjacent to streams, the vegetation consists of tundra grasses, mosses, and bushes (Chapman and Sable, 1960).

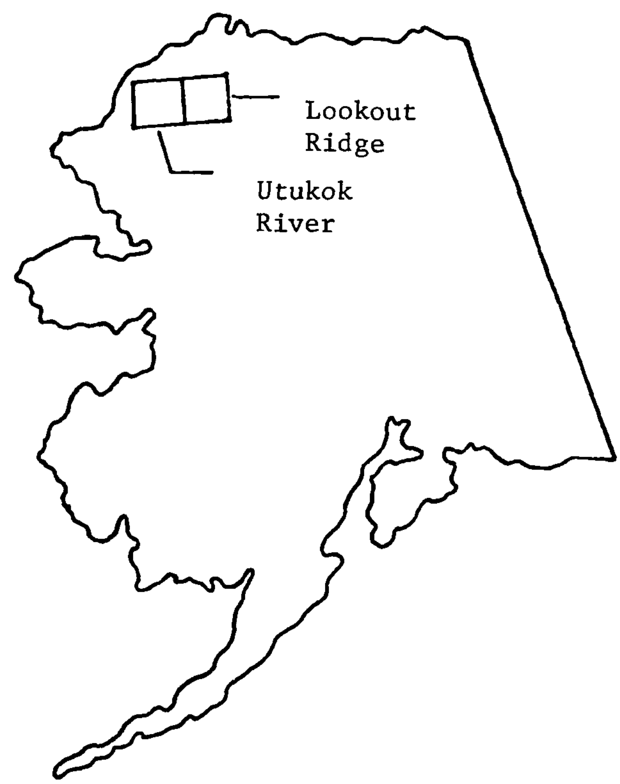

Figure 1. Location Map Showing Remote Sensor Research Area

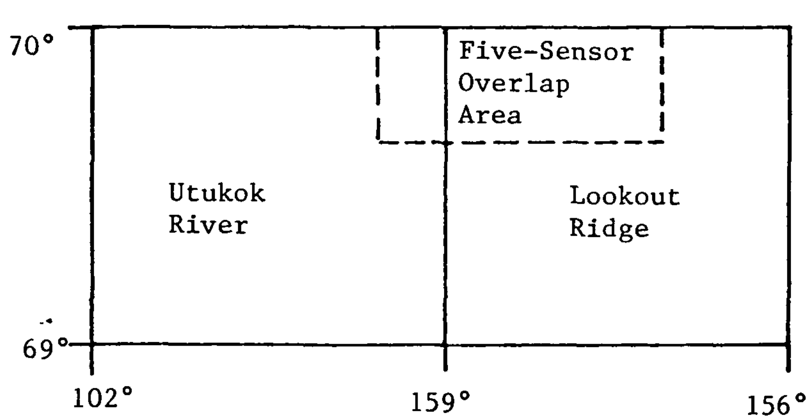

Figure 2. Location Map for Five-Sensor Overlap Area

The Utukok River/Lookout Ridge area was completely covered by the four types of SLAR and MSS imagery. Within this area, a sub-area of 8365 square kilometers was delineated for separate study. This sub-area -- called the Five-Sensor Overlap Area (Figure 2) — is the location for which aerial photographs were available in addition to the two SLAR systems and the two kinds of Landsat imagery. The most significant aspects of the study area in respect to this investigation are its vegetation (grass) and its topography (flat to rolling). In areas characterized by arboreal vegetation or by mountainous topography, the results of this kind of study would probably be very different.

3.2 Interpretation of the Remote Sensor Imagery

The geologic interpretation was limited to structural features, which, within the confines of the study area, consisted of anticlinal axes, synclinal axes, and lineaments that were considered to be the surface expression of underlying faults or fractures. The interpretation of such features is relatively straightforward as compared with features such as, for example, lithologic boundaries. In most cases, a lineament or fold axis that has been detected by one geologist will be seen by another, especially if it is pointed out to him, whereas the detection of lithologic boundaries is more difficult, more subjective, and more liable to conflicting interpretations. Therefore, since the principal purpose of the research project was to measure the amount of geological information detected on remote sensor imagery, it was decided to make the interpretation of this imagery as objective as possible by restricting it to the mapping of structural features, that is, lineaments and fold axes.

Lineaments were subdivided into two categories: "possible faults" and "probable faults". In general, "possible faults" are those lineaments characterized by alignment of geomorphologic features, hydrologic features, lithologic units, vegetation, or tone. "Probable faults" are lineaments characterized by a lateral offset of the same five types of features.

Lineaments having a trend subparallel to bedding were assumed to be the surface expression of bedding planes and were not annotated as lineaments unless other evidence was present, as when two adjacent synclines were observed without an intervening anticline.

The order in which the imagery was interpreted was: SLAR first, followed by standard Landsat MSS imagery, aerial photos, and digitally enhanced Landsat MSS imagery. This may have introduced a cumulative bias in favor of each subsequently-interpreted set of imagery, since it is probable that a cumulative geological learning process took place during the course of interpretation.

It should be noted that the SLAR data acquisition program, which produced the SLAR imagery used in this research project, was not designed as a controlled scientific experiment but as a practical test of the data products of the two SLAR systems. The SLAR data acquisition contractors were encouraged by the Geological Survey to select the mission design criteria that would, in the light of their experience, produce the best results. Thus, such design parameters as date of acquisition, flying altitude, look direction, and depression angle were not the same for both of the SLAR systems.

SLAR imagery interpretation. Both the synthetic-aperture and real-aperture SLAR imagery were subjected to separate interpretations by two remote sensing geologists working independently of one another. The system that was followed was that geologist A interpreted the real-aperture imagery first followed by the synthetic-aperture imagery, whereas geologist B began with the imagery from the synthetic-aperture system and went on to that from the real-aperture system. When both geologists had completed their interpretations, they then placed both of their transparent overlays on the imagery and discussed each delineation that was not common to both. In by far the greater number of cases, the geologist who had not delineated the feature had simply overlooked it, but in some instances there was a good deal of discussion as to whether the feature was distinct enough or linear enough or long enough to qualify as a fault or fracture. Following these discussions, a composite overlay was synthesized which contained all the interpretations upon which both investigators had agreed. This same system was adhered to in the interpretation of all five imagery data sets.

Landsat MSS imagery interpretation. Two different types of Landsat imagery were interpreted in this project: (1) standard (unenhanced) off-the-shelf Landsat MSS products at a scale of 1:500,000, and (2) digitally enhanced (contrast enhanced and edge enhanced) Landsat MSS products at a scale of 1:250,000. Both types of Landsat products were prepared by the EROS Data Center.

Standard Landsat MSS imagery covering the Utukok River/Lookout Ridge area was interpreted. For both areas, the investigators utilized coverage that consisted of black-and-white (bands 5 and 7) and color IR imagery, all at a scale of 1:500,000. Since complete overlapping coverage was available, the interpretation was performed both stereoscopically and monoscopically. Imagery from two seasons (April and July) was interpreted in order to take advantage of the additional information that might result from different azimuths and elevations of solar illumination and from different surface coverings (snow in the April scenes and tundra vegetation of grass and moss in July). Although no measurements were made, it was apparent that much more information was derived from the April scenes, probably due to the lower sun elevation illuminating an unbroken and spectrally uniform cover of snow. The deep, uniform red reflectance of the July vegetation tended to mask the tonal variations caused by topography.

Digitally enhanced Landsat MSS products were also interpreted by the investigators. These products were prepared at the EROS Data Center using their in-house digital image processing systems and EROS Digital Image Processing (EDIPS) tapes covering the study area.

One of Autometric's remote sensing geologists traveled to the EROS Data Center to work with EROS staff members in preparing the digitally enhanced products. The most important part of the effort consisted of using the interactive digital image analysis equipment and techniques available at the EROS Data Center to prepare, review, evaluate and select the optimum contrast stretches and edge enhancements for each of the four Landsat tapes.

Upon completion of the interactive image analysis sessions, the four tapes were processed for preparation of 1:250,000-scale, black-and-white prints in bands 5 and 7. These prints were then interpreted using the same geologists and methodology as were employed in interpreting the SLAR and standard Landsat MSS imagery.

Interpretation of aerial photography. Since it was not possible, within the constraints of time and budget, to interpret large-scale aerial photographic coverage of the entire two-quadrangle area, stereoscopic aerial photos were interpreted at approximately the same level of effort as was used in the interpretation of the SLAR and Landsat imagery. This involved the stereoscopic interpretation of 87 color photos at an average scale of approximately 1:80,000. The photos (taken in June, 1971) cover the Five-Sensor Overlap Area located in the north-central portion of the Utukok/Lookout area. (See Figure 2.) Linear remnants of snow in topographic depressions were a considerable aid to the interpretations.

Interpretation of Seasat SAR. Seasat radar imagery was interpreted within the Five-Sensor Overlap Area, at a scale of 1:500,000. The photographic quality of the imagery was very poor, however, and it was felt that the information derived from it by interpretation was far less in quality than that which would have been derived from a more typical image sample and was certainly far less than that which would have been derived from a digitally processed scene. Thus, since previous experience of the investigators indicated that this particular Seasat radar imagery was not at all representative of its true performance capability, the results of the Seasat imagery interpretation have not been included in this report. This is especially regrettable, since Ford (1980) detected twice as many lineaments on Seasat SAR than on standard Landsat MSS in a study area in the Appalachians, and corroboration in the treeless environment of northern Alaska would have been most interesting.

3.3 Digitization and Manipulation of the Interpreted Data

Upon completion of the interpretation, the overlays were digitized for entry into the geographic information system, a system designed in part by Autometric personnel and installed at the U.S. Fish and Wildlife Service facilities in Fort Collins, Colorado.

This system, marketed and installed by Autometric as the Automated Geographic Information System (AUTOGIS), is a computer software system that was specifically designed for the input, storage, retrieval, manipulation, and display of map-based geographic information. The system is scale-independent; thus, maps at any scale can be input for comparison and/or analysis. The two principal subsystems are AMS (Analytical Mapping System) and MOSS (Map Overlay and Statistical System).

The subsystem used for digitization - AMS - allows geographic information to be digitized from maps or remote sensor imagery and to be stored in a topologically valid form in a geographic data base for subsequent map generation at any scale.

The completed interpretation overlays were digitized using a standard X-Y digitizing table. Once this process had been completed, the data set was used as input into a verification process that checked the spatial consistency of the data set. Editing capabilities were then utilized as necessary to add, replace, or delete any topologically inconsistent data.

The features on the interpretation overlays are treated by AMS as a set of discrete points organized in such a way as to form line segments. Data entry and storage in AMS is organized on a "geounit" basis, which is defined simply as a "rectangular" parcel of area on the earth's surface. In this project the geounits were two 1 x 3-degree areas coincident with the standard USGS quadrangle sheets covering the project area.

Each input overlay was digitized and stored as an individual map in the geographic data base.

3.4 Map Production and Digital Manipulation

Once the interpretation overlays had been digitized and edited, the digital data were stored in the geographic data base in a form suitable for quick and efficient retrieval and analysis. The software system used for this purpose - MOSS - allows the user to perform a large number of functions related to map preparation, synthesis and analysis. The three principal sub-tasks of this effort were: (1) automated production of single- and multiple-theme structural maps at a common scale of 1:250,000; (2) the computation of statistical data concerning the total number and length of structural features shown on each map; and (3) measurements of the information detected in common by two or more sensors.

Map production. In the first sub-task, a variety of single and multiple data set maps were produced in order to assess the spatial relationships between structural features that had been delineated on different input interpretation overlays. (Fifty-one maps were produced as part of this project.) By using the computer-assisted mapping system, it was possible to compile maps at any desired scale showing any desired combination of sensors (radar plus Landsat, or radar plus Landsat plus photos, etc.) or geologic features (faults or folds, or faults plus folds).

Map preparation consisted of using a "CALCOMP" program designed to allow the user to develop any desired map from data that have been digitized previously. Factors to be considered in using the program are the type of input data, the scale of the output map, the themes to be displayed, and the line symbology and color to be used for each theme.

Measurement of total length and number of structural features. The second sub-task of the digitization and manipulation task was the computation, by MOSS, of the total number and length of each kind of geologic feature shown on each interpretation overlay. MOSS capabilities include an interactive program that allows the user to display on a CRT terminal certain characteristics of each input map. Since these data were originally entered during the digitization process, their recall and display were relatively simple and rapid. Table I is a simulation of a typical display of Landsat statistical data for the Lookout Ridge map sheet. It shows that 2431.6 kilometers of geographic features were mapped, in the categories of: probable faults (69.3 km and 26 features); possible faults (1425.6 km and 233 features); synclinal axes (489.0 km and 9 features); and anticlinal axes (447.7 km and 7 features). A "PLOT" program allows the user to produce, display, and copy a small-scale CRT version of the input map. Similar statistics were acquired for each of the overlays stored in the data base.

TABLE I
EXAMPLE OF STATISTICAL SUMMARY SHEET

Length Summary for Lookout Ridge: Standard Landsat MSS

SUBJECT	LENGTH	FREQUENCY	% TOTAL LENGTH
1. Probable Faults or Fractures	69.3 km	26	2.85
2. Possible Faults or Fractures	1425.6	233	58.63
3. Synclinal Axes	489.0	9	20.11
4. Anticlinal Axes	447.7	7	18.41
TOTAL	2431.6	275	100.00

Measurement of structural features detected in common. The third sub-task consisted of measuring the relative agreement in geologic information ("commonality") that resulted when two or more interpretation data sets from the same map sheet were combined. For example, when the "Lookout Ridge: Synthetic-Aperture SLAR" map sheet was combined with the "Lookout Ridge: Landsat" map sheet, a certain number of structures (lineaments and fold axes) were detected in common by the two sensing systems and therefore overlapped one another for some specific length. This overlap portion reflected the extent of "commonality", or agreement, between the two data sources.

By subtracting the commonality length from the total length of geologic structures on each data set, it was possible to determine the length of uniquely detected data in each data set. That is, as defined here, "unique data" equals "total data" minus "common data".

4. RESULTS

In the following sections, the information content of the sensors is discussed in terms of total contribution, common contribution, and unique contribution.

4.1 Total Information Contribution of Each Sensor

Table II shows the total length of structures detected by each sensor in each of the four categories of structural geological information. The overall sensor performance, as shown by the table is: enhanced Landsat MSS detected 5876 km of structural information; real-aperture SLAR detected 5589 km; synthetic-aperture SLAR detected 3991 km; and standard Landsat MSS detected 3697 km. (If the total length of structural elements detected by aerial photos in the 8365-square-km Five Sensor Overlap Area be extrapolated over the entire 26,156-square-km Utukok/Lookout Area, it totals 5650 km, which would rank aerial photos between enhanced Landsat and real-aperture SLAR.)

Table III emphasizes the relative total information contribution of the sensors by comparing them with one another. Thus, if the enhanced Landsat is rated 100%, the contribution of the real-aperture system is 95% as much, the contribution of the synthetic-aperture is 68%, and the standard Landsat contribution is 63%. (Using the total extrapolated from the Five-Sensor Overlap Area, the contribution of aerial photos is 96% that of enhanced Landsat.)

A word of explanation should be given here concerning the great disparity in the performances of the real-aperture and synthetic-aperture SLAR systems. The real-aperture system has a resolution of 50 x 150 meters, while the resolution of the synthetic-aperture system is 10 x 12 meters, yet the real-aperture system contributed 40 percent more information. (Using the same SLAR systems in a geomorphological study conducted on the Alaska Peninsula, Cannon (1981) found that the real-aperture system contributed 25% more landform information -- 263 versus 210 landform units -- than did the synthetic-aperture radar.) The explanation for the superior performance of the lower-resolution system appears to be that, in the flat and rolling terrain of the Utukok-Lookout study area, the synthetic-aperture system with the large depression angle used (30° inboard and 11° outboard) produced a nearly shadowless image that contained less geologic information than the imagery produced by the real-aperture system with its depression angles of 21° inboard and 8° outboard. (The function of shadowing on SLAR imagery is twofold: large shadows obscure information, while smaller shadows enhance it.) It is necessary, therefore, to design the acquisition mission so that optimum shadowing is

TABLE II
TOTAL INFORMATION CONTRIBUTION

		Structural Element by Length (km)				
AREA	SENSOR	Probable Fault or Fracture	Possible Fault or Fracture	Synclinal Axis	Anticlinal Axis	TOTALS
Utukok River/ Lookout Ridge	Synthetic Aperture SLAR	18	2660	623	690	3991
	Real Aperture SLAR	159	3063	1088	1279	5589
	Standard Landsat MSS	77	1923	814	883	3697
	Enhanced Landsat MSS	167	3984	822	903	5876
Five-Sensor Overlap Area	Synthetic Aperture SLAR	8	1239	24	63	1334
	Real Aperture SLAR	3	1238	278	298	1817
	Standard Landsat MSS	5	958	188	175	1326
	Enhanced Landsat MSS	60	1556	126	204	1946
	Aerial Photos	0	1670	76	61	1807

achieved.

Of the relative sensor performance in the Five-Sensor Overlap Area, shown at the bottom of Table III, it can be seen that enhanced Landsat again contributed the most information, based on total length, but is approximately equal to the real aperture system and aerial photos. It is also interesting to observe that, in this case, standard Landsat is approximately equal in geologic information content to the synthetic aperture system.

4.2 Common Information Contribution of Each Sensor

Note that Table II addresses the total length of structural elements contributed by each individual sensor, without regard to overlaps

TABLE III
RELATIVE INFORMATION CONTRIBUTION

AREA	SENSOR	Total Length of Structural Elements (km)	Relative Performance
	Enhanced Landsat	5876	-
Utukok River/	Real Aperture SIAR	5589	95% of Enhanced Landsat
Lookout Ridge	Synthetic Aperture SIAR	3991	68% of Enhanced Landsat
	Standard Landsat MSS	3697	63% of Enhanced Landsat
	Enhanced Landsat MSS	1946	-
	Real Aperture SIAR	1817	93% of Enhanced Landsat
Five-Sensor	Aerial Photos	1807	93% of Enhanced Landsat
Area	Synthetic Aperture	1334	69% of Enhanced Landsat
	Standard Landsat MSS	1326	68% of Enhanced Landsat

(commonalities) in sensor contributions. The table does not show the five sensors, nor does it show the length of features uniquely detected by each sensor. This is an important consideration, for the following reason: it was seen that, in the Five-Sensor Overlap Area, the information contributed by aerial photos and real-aperture SLAR was approximately equal, for all practical purposes. Hypothetically, if the photos and the SLAR both detected the same structural geological features, there would be little reason for acquiring SLAR in areas in which aerial photos currently exist. The extent to which SLAR is required in structural geologic mapping depends on the amount of unique information it contributes.

Figures 3 and 4 show the length and percent of overlapping structural elements (features detected in common by two or more sensor systems) when data sets are compared by digital manipulation.

This set of results is very significant, showing, as it does, that when two remote sensors acquire data over a common area, only from 20 percent (aerial photos and real-aperture SLAR) to 38 percent (enhanced Landsat MSS and synthetic-aperture SLAR) is detected in common by both sensors.

A corollary to the finding that so little (about one-third) information is detected in common is the fact that a large amount (about two-thirds) of remote sensor information is detected uniquely by each sensor.

4.3 Unique Information Contribution of Each Sensor

As mentioned earlier, the unique information contribution of each sensor is defined as its total information contribution minus the

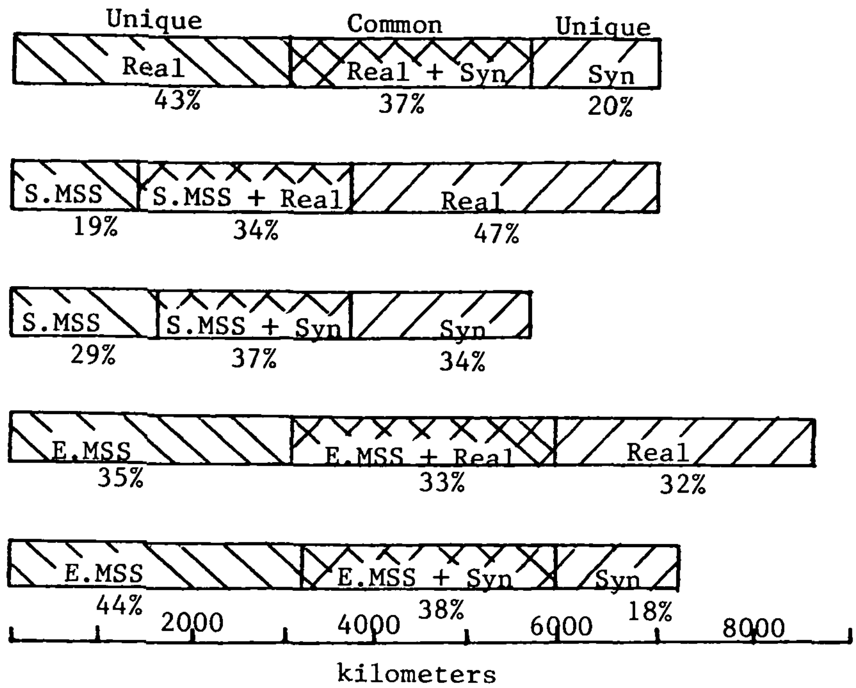

Figure 3. Percent of Common and Unique Information Contributions Utukok/Lookout Area

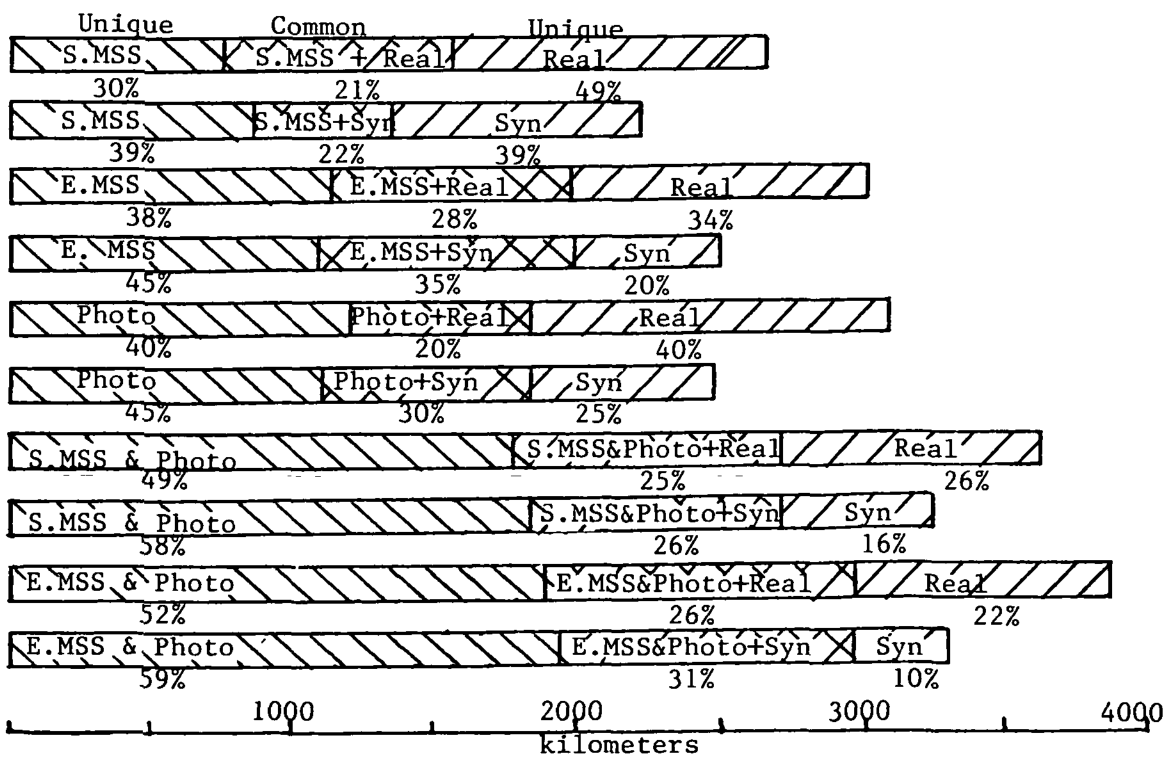

Figure 4. Percent of Common and Unique Information Contributions Five-Sensor Overlap Area

information contribution it has in common with another (or other) sensor(s). The most important finding of the investigation is the unexpectedly large amount of information contributed uniquely by each remote sensor. The application of this knowledge is obvious in such energy-related fields as resource exploration and nuclear power plant siting, where geologic structure is frequently the most important single factor to be considered. By pointing out the amount of incremental information that can be expected from the acquisition and interpretation of additional imagery, a basis is provided for more accurate cost-benefit analyses.

Figures 3 and 4 show the length and percent of the unique incremental structural information that was obtained when remote sensor data sets were used in combination.

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