CURRENT RESEARCH AND PROBABLE FUTURE APPLICATIONS OF SATELLITE DATA IN FORESTRY

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ABSTRACT

An important first step leading to the wise management of forest resources is that of obtaining accurate inventories of those resources at suitably frequent intervals. Remote sensing data acquired from earth-orbiting satellites is showing great promise as the means by which the desired inventories can be made, especially when such data can be supplemented with limited amounts of aerial photography and direct on-site observation.

In discussing current research relative to applications of satellite data in forestry this paper includes not only research that is now in progress but also that which has recently been completed. Findings are reported and discussed based on each of the following types of satellite data: (1) Gemini photography; (2) Apollo IX photography; (3) Skylab photography (and scanner data) as acquired through use of the Earth Resources Experimental Package; and (4) Landsat multispectral scanner data. Consideration is given to the usefulness of each of these types of satellite data for determining volume, vigor and growth rate of timber stands. Based on a review of all of these findings, the following generalizations seem warranted: (1) Because a space photograph shows a vast area in synoptic view and under essentially uniform lighting conditions, the entire boundary of land systems and associated major timber stands usually can be reliably delineated on such a photograph, even though it typically has spatial resolution that is no better than 70 to 100 meters; (2) Color infrared space photography is especially useful for defining the primary sample units of a multistage sampling scheme and for differentiating between forested and non-forested areas within such units, thereby increasing the precision and accuracy with which timber volume estimates can be made; (3) Multidate space photography (e.g., that taken in the months of June and September, respectively) when combined in a comparative analysis can provide more complete and reliable information about forest resources than can be obtained if only one date of satellite photography is used; (4) Stereoscopic study of space photography permits the photo interpreter to exploit the principal of "binocular reenforcement" and thereby to make more accurate and more detailed interpretations of forest resources; (5) The photo interpreter's skill, interest and motivation are of great importance in governing the accuracy with which he can classify forest resources from his study of space photograhy; and (6) With respect to the "human" vs. the "computer assisted" analysis of digitally-acquired remote sensing data two conclusions seem warranted (a) the human is superior to the machine for making broad delineations of forest resources, because spatial rather than spectral attributes are of primary importance in making such delineations and (b) the machine is superior to the human for recognizing subdivisions within the areas that have thus been delineated.

The remainder of the paper deals with probable future applications of satellite data in forestry. Such applications can better be speculated upon in the light of the foregoing generalizations. Foremost among these potential applications is the making of globally uniform forest resource inventories, with the aid of which such resources could be more intelligently managed on a global basis, for the benefit of all humankind.

Once an initial world wide forest inventory had been made that was, indeed, globally uniform, remote sensing scientists could look forward to the prospect of updating that inventory at suitably frequent intervals. This process, known as "monitoring", would indicate, area-by-area, the nature and extent of (a) forest depletion due either to the harvesting of timber or the depradations of fire, insects, diseases or other damaging agents and (b) forest accretion due to the reforestation or afforestation of non-timbered areas and to the net growth of timber that had occurred (throughout the undamaged parts of the forest) since the last previous forest inventory had been made. Such accurate, timely, detailed information about the world's forests would better permit foresters to determine which of their forest management activities (logging, thinning, planting, spraying, fertilizing, etc.) were proving to be most beneficial. Consequently they would be able to devise and implement more intelligent forest management measures, area-by-area, throughout the globe.

INTRODUCTION

The capability for surveying earth resources from orbiting satellites fitted with remote sensors is one of the more significant technological developments of our time. Our ability to obtain data pertaining to vast areas, from specified altitudes using narrowly prescribed sensor bandwidths and sun angles, offers a basis for inventorying, assessing, and monitoring these resources as never before possible.

The rationale for our considering the usefulness of satellite data in forestry can be expressed in a 4-part statement, as follows:

1. Whether on a regional, national or global basis, the demand for forest resources is rapidly increasing while the supply of them is dwindling.

2. This situation creates an urgent need for the wisest possible management of forest resources.

3. An important first step leading to such management is that of obtaining inventories of these resources, to specified levels of precision and accuracy, so that the resource manager can adequately plan his operations in each portion of the area for which he has management responsibility.

4. There is abundant evidence that the required inventories can best be made through the intelligent use of remote sensing data acquired from satellites, especially when such data can be supplemented with limited amounts of aerial photography and direct on-site observation.

It is in the light of this rationale that the present paper will seek, first to describe current research and then to predict future applications of satellite data in forestry.

CURRENT RESEARCH

Most of the research that presently is being conducted relative to uses of satellite data in forestry stems from a realization that each of the following kinds of information is needed relative to a forested area's timber resources: (1) The volume of timber by species, log size class, and grade within each portion of the forest; (2) The vigor or healthiness of this timber, area-by-area; (3) In those areas that are of less than maximum vigor, the nature of the causal agent or organism; (4) The rate of growth of the individual trees and timber stands, area-by-area, throughout the forest; and finally, (5) The present and probable future merchantable timber volumes, area-by-area.

Given such information, together with limited amounts of ancillary data, the forester can develop and implement plans for the efficient growing and harvesting of successive timber crops in perpetuity. The needed ancillary data include those relating to topography, soils, water, etc., and also to the cost-effectiveness of each of the various possible timber management alternatives including clear cutting, selective logging, and deferred cutting. Reference to these considerations, both individually and collectively will be found in the remainder of this section on current research. Furthermore, the term "current" research will be construed here to include not only research that is now in progress but also that which has recently been completed.

A. Findings from experiments based on photography taken from Gemini spacecraft. A little more than a decade ago, the first useful space photography of forested areas was acquired by the Gemini-V astronauts. Since, then, some highly meaningful research has been conducted on that photography by various forestry-oriented investigators. A major conclusion resulting from these investigations is that space photography is potentially very useful for delineating major land systems and for singling out those that are likely to contain merchantable stands of timber. The term "land system" is here used in the same sense as it was used many years ago by the originators of that term, Christiansen and Stewart (1947). In essence a land system is any sizable area throughout which the geology, soils, vegetation, and hydrologic conditions are essentially uniform. Because a space photograph shows a vast area in a single synoptic view and under essentially uniform lighting conditions, the entire boundary of each of a great many land systems usually can be reliably delineated on such a photograph, even though it typically has resolution of no better than 70 to 100 meters in terms of "ground resolvable distance".

B. Findings from experiments based on Apollo 9 photography. These experiments showed that color infrared space photography can contribute significant information in multistage timber inventory designs (Langley, 1971). Information derived from color infrared photographs taken by the Apollo 9 astronauts made it possible to separate forest from non-forest areas within primary sample units. Thus, the precision of the estimates was increased by means of stratification before the first sampling stage. The gain in precision thus obtained (when estimating the total volume of timber within the Mississippi Valley Study Area) was about 42 percent.

C. Findings from experiments based on Skylab imagery. These findings have been more extensive than with Apollo 9 or Gemini photography because of the greater number of investigators, the larger amount of data available, and better data interpretation and processing methods.

Among the types of imagery acquired by the Skylab astronauts were the following: S190A photography, taken with a 6-camera, 6 inch focal length system, each camera employing a different film-filter combination, as indicated in Table 1, and providing spatial resolution of about 50-75 meters; S190B photography, taken with a single camera having a focal length of 18 inches and employing color infrared film and a Wratten 12 filter, and providing spatial resolution of about 13-18 meters; and S192 imagery, acquired with a conical scanning system that sensed separately in 13 wavelength bands, and providing spatial resolution of about 80-140 meters. Further details with respect to the Gemini, Landsat and Skylab data will be found in Table 1.

TABLE 1

Spectral Characteristics of the Various Gemini, Landsat, and Skylab Image Types

Vehicle/System	Image Type	Wavelength, mμ
Gemini V	Ektachrome	0.4-0.7
Landsat MSS	Band 4	0.5-0.6
	Band 5	0.6-0.7
	Band 6	0.7-0.8
	Band 7	0.8-1.1
Skylab EREP S190A	A	0.5-0.6
	B	0.6-0.7
	C	0.7-0.8
	D	0.8-0.9
	E	0.4-0.7
	F	0.5-0.88
Skylab EREP S190B	HRC*	0.4-0.7
Skylab EREP S192	Band 4	0.53-0.61
	Band 5	0.59-0.67
	Band 7	0.75-0.90

*HRC = High Resolution Color Film (SO 242).

Only a synopsis of some of the more significant findings is given here. There was almost unanimous agreement, among the many investigators who made vegetation analyses from Skylab photography, that S190A color infrared photography was best overall for identifying, evaluating, and classifying vegetation resources. This was not only true in agricultural and range grass evaluations but also in forestry investigations where the identification of cover types was of primary importance. Because the infrared reflectance of vegetation is considerably higher during the spring and early summer growing seasons than in the late summer and fall seasons, these investigators found that the identification and vigor analysis of vegetation could be made more reliably during the former period. Colwell (1978) reported that stereoscopic interpretation of S190A Skylab photography yielded significant improvement in vegetation analysis. Another important finding of the Skylab investigations was that the photo interpreter's skill, interest, and motivation are of high importance for classifying forest resources accurately from space photography. Although the identification of vegetation resources was more accurate with S190A color infrared photography than with comparable regular Ektachrome color photography, there was no significant gain in precision of one type over the other when estimating timber volumes in multistage sampling designs. However, both kinds of photography yielded information which resulted in increasing the sampling precision by amounts ranging from 5 to 45 percent, depending on the interpretation method, time of year when the photography was obtained, and sampling method applied. These results can be compared with the 55 percent gain achieved by means of human interpretation methods applied to high-flight aircraft photography taken from an altitude of about 21,000 meters above the terrain.

In one timber inventory experiment using S190A color infrared photography of forested areas at approximately 40 degrees north latitude the volume estimates obtained by using composites from both June and September photo dates gave higher precision than could be obtained from any single-date S190A photo products.

One of the chief tests conducted with Skylab S190A photography was that of determining the effectiveness of various human interpretation methods for providing information of use in multistage forest sampling models. In such models, measurements made at adjacent stages of the design are tied together by statistical correlations that ultimately relate remote sensor data to resource measurements obtained on the ground in sample areas. To cite three examples: (1) in variable probability sampling, the model provides predictions which are used to determine unequal probabilities for drawing a sample in the next stage; (2) in regression sampling, the model is used to adjust extensive but relatively inexpensive measurements made at the aerial stage with fewer but more accurate and more costly measurements made on the ground; and (3) in stratified sampling, it is used to define strata in which independent ground sampling will take place.

Certainly the sampling method used is an important factor with regard to the overall level of precision and accuracy obtained in a sample survey. But the interpretation model is of crucial importance since it governs the transfer of information from the image into the sampling design, and thus makes or breaks the quality of the survey assuming the transient data are adequate.

Colwell (1978b) observed that photo interpretation entails two kinds of operations: (1) observing such photo-image characteristics as size, shape, shadow, tone, texture, and location, and (2) judging the significance of the features, based in large measure on their interrelationships or "association." He further noted that while a machine may have the capability to do the former, rarely is it capable of doing the latter sufficiently well. On the other hand, while a human being excels at judging associations, he may not be able to do a consistent job of interpreting features such as tone and texture from large amounts of image data, as he may soon be overcome by boredom and fatigue.

In view of these considerations, most of the Skylab human image interpretation efforts were concentrated on relatively simple interpretive models appropriate to the S190A, S190B photography. Vegetation boundaries could be seen on all of the S190 photography but were better seen on S190B than S190A. Even so, the interpretation process was sometimes difficult since it required a substantial amount of subjective judgment.

In order to augment purely human interpretation techniques in judging the adequacy of Skylab photography in inventorying timber resources, Langley and van Roessel (1976) performed some experiments wherein S190A and B photography and S192 scanner imagery were subjected to a simple multispectral additive viewer and a density slicer. The purpose of these experiments was to determine, in a cursory way, the possibility for achieving gains in sampling precision by virtue of obtaining better quality interpretive data related to forest variables. In Table 2, we have summarized the most significant results of their S190 and high-flight aerial image interpretation trials as they relate to timber volume estimation in Trinity County, California employing one-square-mile primary sampling units. The most important results from the sampling standpoint are the relative gains that could be achieved using three different sampling methods: (1) stratified, (2) probability porportional to size (pps), and (3) regression. The gains listed in the table are in relation to what would be achieved under simple random sampling. The reason for this comparison is that under simple random sampling, primary

TABLE 2

Selected Statistics from the Space and Aerial Image Interpretation Trials Employing One-Square-Mile Sample Units and Comparison of Alternative Sampling Methods*

Image Type	Month of Aquisition	Image Scale	Inter. Method	Sample Size	Proportion of variability explained by the model (r^2)	Average % Gain in Sampling Precision Compared to Simple Random		
						Stratified	pps.	Regression
S-190A B&W IR	June	1/500,000	VP-8	34	.14	9.5	4.9	14.0
S-190A Color IR	June	1/500,000	Human	114	.38	23.4	30.5	38.4
S-190A Color	June	1/125,000	"	170	.24	15.0	21.3	24.4
S-190A Color IR	June	1/125,000	"	184	.25	17.3	22.8	25.3
S-190A Color	Sept.	1/125,000	"	184	.38	28.1	32.1	38.8
S-190A Color IR	Sept.	1/125,000	"	185	.36	25.2	31.9	36.2
S-190A Color IR	June/Sept. Composite	1/125,000	"	140	.43	35.1	39.5	43.3
S-190B Color	Sept.	1/125,000	"	186	.37	27.8	35.6	37.3
High-Flight Aerial Color IR	June	1/125,000	"	40	.55	43.4	49.9	55.1
Average Gain (Human Interpretation of Space imagery)						24.6	30.5	34.8
Standard Deviation						6.8	6.5	7.1

*Extracted from Langley and van Roessel (1976).

sample units would be drawn without benefit of any prior information concerning the resource base, in other words, without taking advantage of the interpretive data available from the aircraft or space imagery. All of the three plans listed do take advantage of the image data but in different ways. Therefore, any one of these methods may be most appropriate in specific situations. Interactions among sample units, the interaction between the remotely-sensed and ground-acquired data, the sample size, and even the experience of the interpreter in the local area can affect the best selection of sampling method. Nevertheless, it can be seen from the table that all three of the sample methods shown do take advantage of all kinds of imagery in increasing the precision of a forest inventory for a given sample size.

In evaluating the economic benefit of Skylab S190 imagery when used in this manner, one must consider the cost of obtaining and interpreting the imagery in relation to the cost savings achieved by virtue of the reduction in the required sample size. Since other data types are sometimes available, (e.g., aerial photography) the feasibility of implementing a satellite remote sensor program must depend heavily on the multidisciplinary aspects of the program, the size of the area covered, the consistency of the data, and the frequency of coverage. It might be appropriately noted here that, in the forest inventory business, there is always a shortage of good quality imagery covering the right area at the right time. Amelioration of this problem alone would go a long way in advancing the art of resource information management and consequently of forest management.

There are several other significant results that can be observed in Table 2:

1. The results from the "VP-8 Image Analyzer" experiments were disappointing. Although some gain was achieved, considerably

more effort would be needed to develop this type of instrument into a viable competitor in forest survey work of the type investigated here.

2. The S190A products obtained in September yielded significantly higher gains than the products obtained in early June. This was because of a greater spectral difference between commercial conifers (evergreen) and noncommercial broadleafs, brush, and grass in September compared to June.
3. The color composite incorporating June and September S190A imagery yielded the highest gains of any of the space acquired data tried. It was concluded, therefore, that temporal variations were important in forest resource analysis (i.e., two timely coverages are significantly better than one).
4. There was no significant difference between the gains achieved with S190B imagery and with S190A imagery.
5. There was no significant difference in the interpretability of S190 A color versus S190A color infrared photography in this particular situation.
6. The gains in sampling precision were significantly better with the high-flight aerial imagery than with any of the space acquired data. This is even more significant when we consider that the June S190A imagery, when the aircraft data was acquired, gave poorer results than the September

> S190A products. Therefore, the capability to resolve trees yields significantly better results and is more important than seasonal variations when inventorying timber volume.

Langley and van Roessel concluded that a combination of two factors largely accounted for the similarity in the results of the S190A and S190B image interpretations: (1) significant vegetation type boundaries could be delineated on all the space imagery used and (2) individual trees were discernible on none of them. Because of the latter, important data concerning the density of commercial species, bole sizes, and tree heights cannot be ascertained. Therefore, the conclusion must be drawn that the Skylab S190 data is of significant but limited usefulness in forest inventories using human interpretation methods.

One general conclusion is that the number of primary sample units required to achieve a given level of variance can be reduced by 24 percent to 43 percent by introducing Skylab type information into the sampling design. This general conclusion was indicated in the Apollo 9 experiment, the authors' LANDSAT investigation, and re-verified in their Skylab investigation. To achieve further gains from space systems, and to obtain a capability for forest stand mapping for management purposes, it would be necessary to increase the resolution to a point where trees are discernible. At that point, a new plateau in capability would be reached.

D. Findings from research based on Landsat data. Because of their repetitive coverage and uniformity of data with regard to sensors and constant time over any given latitude, the LANDSAT vehicles have provided more research opportunities than any other remote sensing medium. Data from these satellites have been acquired continuously since the launch of ERTS-1 (later called Landsat-1) in July of 1972.

The advantages of LANDSAT data over other remote sensing media are well known and documented. Some of the more important features from the standpoint of inventorying and assessing forest resources can be summarized as follows:

1. multispectral capability
2. multi-temporal coverage
3. repetative observation points
4. sun synchronous
5. narrow angular field for uniform lighting
6. computer compatible products
7. systematic coverage
8. potential minimum delay in acquiring data.

The LANDSAT investigations which have been conducted so far addressing forest inventory problems have focused on two main subjects: (1) the classification and mapping of forest species types or, more generally, forest cover types, and (2) the contribution of LANDSAT data to increasing the precision of timber inventories for a given total cost.

The results of the LANDSAT investigations oriented toward forest type identification have shown classification accuracies ranging between 48 percent and 64 percent. These figures are based on pixel-by-pixel supervised classification of multispectral scanner data only, using computer methods. Two other investigators, working separately in forests of the western United States, have included topographic data in with the MSS data with startling increases in the accuracy of forest type classification by means of computer methods.

Logan (1978) reports forest classification accuracies as high as 83 percent in the mountains of northwestern California and Hoffer (1978) reports similar results in the Rocky Mountains of southern Colorado. In Logan's study, elevation was the most important topographic variable, contributing 18 percent to the classification accuracy, while aspect (i.e., direction of slope) contributed seven percent. The authors of the present paper believe that if topographic data are to be used in forest type classification models over large areas, then latitude and climatic factors should also be included. It is a well known fact that the most valuable commerical tree species grow at increasingly higher elevations when traversing the globe from northern latitudes toward the equator. Therefore, unless a rather complex correction is made, topographic information, by itself, must be of only limited significance when used with MSS data in classifying forest types.

At least two studies have addressed the question of utilizing LANDSAT data to increase the precision of estimating timber volumes and other related parameters in multistage sampling designs. The earlier of the two studies (Langley and van Roessel, 1975) investigated the increase in sampling precision (i.e., reduction in variance) when estimating timber volumes in the mountainous terrain of Trinity County, Northern California. The study concentrated on the potential gains from LANDSAT MSS data when used at the first stage in multistage sampling designs. Four kinds of multistage models were compared: (1) stratified, (2) regression, (3) ratio, and (4) probability proportional to size (P.P.S.) sampling. The computer models used for assigning preliminary timber volumes to primary sample units were based on unsupervised classification techniques which utilized 2x2, 4x4, and 8x8 clusters of MSS pixels. The Hadamard transform was used to evaluate the contrast inherent in each cluster of pixels as well as the average level of reflectance in each spectral band. The most important single variable encountered for assigning timber volumes to primary sample units that were one square mile in size, was the normalized difference between the cluster reflectance averages of MSS bands 5 and 7.

Generally, the gains in precision achieved at the first stage by Langley and van Roessel ranged between 20 and 50 percent depending on the sampling model used.

During the past three years remote sensing scientists from the Department of Forestry and Conservation, of the University of California, have been helping wildland fuel specialists to develop plans for reducing the very serious fire hazards that exist in California's wildland areas. The primary objective of wildland fuel management there is to break up the many large homogeneous fields of brush into smaller brush-grassland mosaics. In this situation, not only are fire hazards reduced, but the "edge effect" around each brushfield is increased so as to provide more shelter and forage to wildlife and domestic animals. In addition, soil stability improves if stands of grass can replace the decadent brush. Such remote sensing-derived information is particularly valuable in developing plans for wildland fuel management because it can be acquired efficiently for extensive, inaccessible areas. To date, the fuel types present in a 476,000 acre (193,000 hectare) study area have been mapped at an average cost of approximately one cent per acre through the use of computer assisted analysis of digital data obtained from the Landsat satellite. Based on this and other remote sensing-derived information, augmented by ancillary data such as topographic maps and soils maps, fuel management plans are being developed and put into operation on the ground. These actions include construction of fuel breaks, prescribed burning of 200 to 400 acre (80 to 160 hectare) blocks of brushland, planting grass seed, and the annual burning of strips throughout the standing brush in order to develop an uneven aged brushland mosaic. Because of the remote sensing-derived information, many man-hours of field work that otherwise would be required already have been avoided.

A rather extensive study concerning the application of Landsat data to operational forest inventories in the United States has recently been completed by the Department of Natural Resources, State of Washington (Harding and Scott, 1978). The findings from this study indicate that machine classification of Landsat data could be utilized cost effectively in forest surveys covering a minimum of one to two million acres (400,000 to 800,000 hectares). In the State of Washington, however, there are problems in identifying accurately on Landsat data the boundaries of many small ownerships containing forest land. The investigators also encountered difficulties in separating tree covered sub-urban areas from forest land.

Another finding of the DNR investigation relates to the number of computer classes that should be identified for stratifying forest areas into meaningful classes. The investigators at DNR concluded that the Landsat classification should be oriented toward identifying an average number of 35 meaningful multispectral classes. However, these 35 groups should then be grouped into about nine classes that are more meaningful stratifications for forest sampling purposes. This coincides generally with the present authors' experience with forest classifications made on aerial photographs. A meaningful forest photo interpretation key for medium scale aerial photography will usually produce between 30 and 40 distinct classes for use in predicting the contents of individual forest stands as to their volume and numbers of trees by species, size and density classes. For sampling purposes, however, the classes should be collapsed into less than ten strata for the most efficient allocation of a limited number of field plots to each stratum.

Another significant observation made by the DNR investigators was the importance of providing adequate training to individuals working on the Landsat classification process in local areas. They concluded that resource specialists would need several years of experience with a particular resource, a good background in photo interpretation and field measurements, and a personal knowledge of the geographic area being studied. A final conclusion of the Washington study was that there is a high degree of potential usefulness of Landsat imagery in detecting temporal changes in the extent and character of forest cover types.

E. Findings of investigations based on Side-Looking Airborne Radar (SLAR) Imagery. It is well known that the acquiring of remote sensing data by means of conventional cameras or multispectral scanners that are mounted in aircraft or spacecraft is seriously hampered by continual adverse weather conditions. Consequently it has been suggested by many individuals that these problems might be ameliorated by the use of side looking airborne radar (SLAR) imagery because this medium takes advantage of a part of the electromagnetic spectrum that readily penetrates clouds. It was suggested that such imagery might be useful for making forest inventories, for example, particularly in the tropical regions of the earth.

Certainly, the most extensive opportunities to date for evaluating the present and future applications of SLAR data exist in Brazil as a result of Project RADAM (acronym for "Radar Amazon"). It is not within the purvue of this paper to include the detailed results of studies conducted in Brazil, as these are well covered in other papers presented at this symposium. Instead, we will cite the general results from two prior studies that were made elsewhere; the first by Daus and Lauer (1971) conducted in the mixed conifer region of the northern extreme of the Sierra Nevada Mountains in California and the second by Smit (1975) conducted in the tropical rain forests of the Columbian Amazon, sometimes referred to as the "green hell".

Daus and Lauer sought the answers to three main questions: (1) to what extent do slope, aspect, and vegetation/terrain type relate to interpretation results; (2) can meaningful evaluations be made of important vegetation resources, e.g., vegetation type, stand density, stand height, and stand volume; and (3) what is the overall usefulness of the SLAR imagery in the temperate forests of Northern California. Although their studies were limited, of necessity, to imagery taken in one flight direction, at one time, in one wavelength band and with one polarization arrangement, they were able to arrive at several important conclusions, including the following:

1. The two primary characteristics of the SLAR imagery that are useful in analyzing the wildland vegetation resources were image tone and texture.
2. In the wildland area studied, vegetation was the main factor governing the texture of the SLAR imagery and the combination of slope and aspect was the main factor governing tone.
3. A skilled interpreter could delineate differences in major vegetation cover types in certain portions of the SLAR imagery, especially in areas of flat or nearly flat terrain.
4. A skilled interpreter rarely could identify the major vegetation cover types seen on the SLAR imagery -- unless a limited amount of supplemental data was made available to him.
5. In areas which were nearly flat and level, timber stands consistently were differentiated from everything else on the SLAR imagery because of their relatively coarse texture.

6. Slight differences in topographic relief or changes in slant range often caused two nearly identical timber stands to appear quite different on the SLAR imagery.

7. Given adequate supplemental data, a skilled interpreter could effectively apply the concept of "convergence of evidence" while mapping forest types on this type of SLAR imagery.

8. It was not possible to derive detailed measurements about the timber resource directly from the AN/APQ-97 SLAR imagery used in this study, because it exhibited resolution of only about 50 feet, in terms of GRD (ground resolvable distance).

9. Although in this case the utility of this type of SLAR imagery for quantifying specific forest resources was severely limited, in many instances its use in a wildland inventory procedure would be invaluable since the SLAR imagery often can provide highly accurate information regarding geologic and geographic configurations, and can be obtained under inclement weather conditions.

It is apparent from the results of this study that vegetation <u>typing</u> could not be accurately done on this imagery in an area of rugged terrain. Likewise, it was not possible to obtain more detailed information about the vegetation resources of the wildland area studied (height, density, species, etc.), since the major vegetation types could not be identified. However, this does not mean that SLAR imagery of this quality is useless. It was discovered that an interpreter could effectively <u>delineate</u> a variety of tonal and textural anomalies on the SLAR imagery, and he could also consistently identify (1) bodies of water, (2) drainage networks, (3) aspect and relative steepness of slope, and (4) watershed boundaries. In addition, in relatively flat areas, delineated boundaries seen on the SLAR imagery often related to changes in vegetation type. The cover types on each side of the boundary could rarely be identified on the SLAR imagery alone, but stratifications indicating differences in vegetation type and condition were made. Consequently, basic map information such as this, showing unidentified homogeneous terrain features could be coupled with a minimum amount of supplemental data derived from another source (e.g., Landsat), and preliminary maps indicating the extent and distribution of resources could be compiled for areas of low relief.

The findings by Smit (1975) on the usefulness of SLAR for forest type mapping in the Columbian Amazon can be stated as follows:

1. On SLAR images, tree species cannot be identified. In his study, all information as to the presence of palms, the dominance of a species in swamp forest, and species composition in dry land forest had to be based on supplementary data from air reconnaissance surveys and/or field inventory data.

2. SLAR images give a good impression of the physiographic conditions of the terrain and, as a result, swamp forest can be differentiated from dry land forest on flat terrain in the hill zone, even where tone and texture are exactly the same on the radar imagery. However, the differentiation between swamp forest and forest on temporarily inundated terrain, in the flood plain zone, was more complicated requiring ancillary data from air photos, visual aerial reconnaissance, or ground observation. This conclusion also applied to the identification of other upland forest types. Smit suggests that the

association that often exists between species types and physiographic indicators should be explored more fully in order to achieve a more general forest type classification scheme in the Columbian Amazon region.

FUTURE APPLICATIONS

As a first step in considering the potential future applications of satellite data in forestry, let us first describe briefly the space vehicles and sensors that are likely to be available in the future for collecting the satellite data. In so doing, let us limit ourselves to capabilities that are likely to be realized within the next 5 to 10 years. Let us also recognize that plans for these vehicles and sensor systems frequently can change. Therefore, allowance should be made for possible disparities between the descriptions which follow and those which may be provided by other participants at this symposium.

1. LANDSAT-D

A 1981 launch of this vehicle has been approved. According to present plans, LANDSAT-D will be sun-synchronous at an altitude of 705 km and will have two primary sensors--the conventional MSS (Multispectral Scanner) and a high data-rate sensor known as the "thematic mapper." The thematic mapper will have a total of 7 bands, including one in the 2.0 to 2.5 micron region. Most of these 7 bands are expected to provide a spatial resolution of approximately 30 meters. Since the data acquisition and transmission rates will be approximately 150 Megabits per second (10 times greater than that of LANDSATS-1 and -2), foreign countries that have already built receiving stations for LANDSAT-type data may not be able to receive LANDSAT-D data unless they make modifications costing about $15 million per receiver.

In addition, because of the higher resolution, the cost of producing a frame of imagery reportedly will be about 100 times greater than from LANDSAT-1 or -2. Also, because of this higher resolution, only 50 scenes per day will be acquired from LANDSAT-D whereas 180 to 200 per day are routinely acquired from LANDSATS-1 and -2.

2. LANDSAT-E

A 1983 launch date is planned for this vehicle. Both the vehicle and its sensors probably will be identical to LANDSAT-D in most respects. It is anticipated that Space Shuttle (as described in the next section) will be used both to launch LANDSAT-E and to recover LANDSAT-D. It is hoped that throughout the 1980's LANDSATS-D and -E can be used alternately. As each is retrieved, it will be refurbished and made ready for reuse.

3. Space Shuttle

This vehicle will have a vertical takeoff and a wheels-down glide to a conventional landing. Most Space Shuttle missions will be of seven-days duration and will carry a seven-man crew (pilot, co-pilot, and five observers). Initially all launches will be from Cape Kennedy in Florida. On the Space Shuttle vehicle, the two solid fuel tanks are to fire first. Once expended, they are to be jettisoned, parachuted into the ocean, and recovered.

The large external fuel tank of Space Shuttle will supply enough liquid fuel to take the Space Shuttle vehicle the rest of the way into orbit; then this tank will be jettisoned after which it will burn up in the atmosphere. Most Space Shuttles will have a built-in "cherry picker" for use in deploying and retrieving smaller spacecraft. Of the first five Space Shuttle vehicles that are being built, each is expected to be good for about 50 to 100 missions.

Each Space Shuttle vehicle will be able to operate in either of two modes: (a) The conventional sortie mode. In this mode the 5 meter x 16 meter cargo bay will contain several pressurized compartments in each of which various experiments (remote sensing and otherwise) can be conducted in a "shirt-sleeve" environment. All compartments will remain rigidly in place throughout the mission. (b) The "Buddy-Sat" mode. When this mode is to be used the Space Shuttle "mother ship", upon reaching earth orbit, will deploy a tethered smaller vehicle which will have its own attitude control, e.g., to facilitate picture taking by astronauts. They will use either a large format camera or a "stereo-sat" system. The first "useful" Space Shuttle mission is scheduled for the 1979-1980 time frame with an orbital inclination of about 35°. Later missions from Cape Kennedy will permit orbital inclination as high as 55°. By 1983 Space Shuttle missions are scheduled to be flown from Vandenberg Air Force Base in California with polar or near-polar orbits.

4. The Multi-Mission Modular Spacecraft (MMMS)

This vehicle is intended to be a versatile, low-cost manned spacecraft which can be used for any of several highly specific remote sensing missions. It can be inserted into various orbits, including a geosynchronous one above the equator at an altitude of about 23,000 miles. Launch date for the first MMMS has not yet been announced.

5. The Tracking and Data Relay Satellite System (TDRSS)

Two of these satellites are to be launched in geosynchronous orbit soon. One of these will hover above the equator at 41°W and the other at 171°W. They will be able to receive and relay data from as many as 20 satellites simultaneously, and at a data rate of up to 50 Kilobits per second per satellite. A remote sensing satellite, if operating at an altitude of greater than 112 km., reportedly can be accessed at all times from one or the other of these two TDRSS satellites. There will be no tape recorders aboard the TDRSS, i.e., it will rely upon an instantaneous relay capability.

6. SEASAT

Future SEASAT vehicles, like the one which acquired useful satellite data in 1978 (before becoming malfunctional), will have a 794 km. orbit with a 108^o inclination. They will have an L-band synthetic aperture radar with 25 meter resolution, primarily to study sea-ice, but also useful for the imaging of cloud-infested forest areas, such as the Amazon Basin.

7. A Geo-Exploration Satellite

Plans for this vehicle and its sensor system are not yet completed, but the following attributes are desired of the sensor system listed in order of decreasing priority: (a) 10 to 30 meter resolution, (b) stereo coverage, (c) two additional spectral bands, centered at 1.6 and 2.2 microns, respectively, (d) also, perhaps both X-band and L-band radar devices, and (e) a laser-stimulated fluorescence measuring device.

8. Spacelab

This is a European-sponsored spacecraft similar to Space Shuttle. On reaching the desired orbit, Spacelab would deploy its sensors and leave them unattended for one to two years. One of Spacelab's cameras would provide approximately 20 meter resolution (AWAR) and would cover an area of 190 km. x 190 km. per frame.

9. Stationary Earth Observation Satellite (SEOS)

The camera lens for this vehicle's primary sensor would be 1.8 meters in diameter and would provide 50 meter resolution even from the required orbital altitude of 23,000 miles. A lower resolution sensor system would select areas meriting detailed study; the high resolution camera would then be directed at the selected areas. Because of its high orbital altitude SEOS would require the use of a "trans-stage" booster that has not yet been built. Even so, the plan is to launch SEOS in the mid-1980's.

10. Specifications for an Additional Sensor that is Being Constructed (The "Linear Array")

One version of this sensor would have a total of 1872 separate sensing cells comprising the single linear array. Sensing would be done by all cells simultaneously; hence, the term "push-broom" to distinguish the linear array from a "line-scanner" which uses a rotating mirror. To obtain stereoscopic imagery, two linear arrays providing a stereo angle of 45 to 60 degrees would be used simultaneously in the same spacecraft. From its planned use at an orbital altitude of 577 km., the linear array would cover a swath only 31 km. wide, but at high resolution (each pixel would be a rectangle with dimensions of 16.6 x 19.3 meters). To acquire multiband imagery the linear array would need to have a data rate of 8.8 Megabits per second unless "on-board data compression" such as band-ratioing could be used.

In speculating on the probable future applications of satellite data in forestry, we would do well to keep in mind (1) the probable future capabilities (as just described) for acquiring remote sensing data from satellites, and (2) the generalizations on the usefulness of satellite data in forest inventories as cited earlier in this paper. Foremost among these potential applications, as will presently be discussed, is the making of globally uniform forest resource inventories, with the aid of which such resources could be more intelligently managed on a global basis, for the benefit of all humankind.

It has been pointed out in this paper and elsewhere in the reference material that satellite data, though significant, are limited in application because of their low resolution compared to other media, such as medium to large scale aerial photography. However, by utilizing the information obtained from satellites, sampling techniques employing data acquired from aircraft and/or on the ground can be implemented to obtain estimates of the exact amounts of forest resources present in particular areas. These exact estimates can be obtained by tree species, size, and quality classes area-by-area by varying the sampling intensity in each stage of the design as is appropriate to satisfying the particular requirements for information. When taking this multistage approach to forest inventories, it happens that nearly all the information available from the imagery at each sampling stage can be effectively utilized to maximize the sampling efficiency for an entire survey. Furthermore, valid estimates of detailed information about the resource base that are applicable to the entire area of interest can be obtained easily and systematically. This is true even though the details are not directly discernible in satellite data.

By means of the multistage sampling approach to forest inventories employing satellite data, resource information systems could be developed wherein current estimates of the world's supply would always be available when needed. When more precise data were needed in local areas, new samples would be selected utilizing the current information in the system. Then, aircraft and ground teams, manned by professionals from the countries involved, would be dispatched to the selected areas for further data collection from which the final analyses would be made.

By taking the multistage approach, local teams would have the opportunity to participate in global surveys driven by satellite systems at levels of sophistication that suit their particular manpower and equipment station. They could obtain subsamples using single film cameras or multi-channel scanners. Furthermore, they could handle their own data processing for the space, aerial, and ground stages of the surveys. By these means, the final estimates concerning the quantity, quality, and distribution of earth resources would remain under the jurisdiction of each country, even though they would be reported to the global system under a uniform set of standards and definitions.

Once an initial world-wide forest inventory had been made that was, indeed, globally uniform, remote sensing scientists could look forward to the prospect of updating that inventory at suitable frequent intervals. This process, known as "monitoring", would indicate, are-by-area, the nature and extent of (a) forest depletion due either to the harvesting of timber or the depradations of fire, insects, diseases or other damaging agents, and (b) forest accretion due to the reforestation or afforestation of non-timbered areas and to the net growth of timber that had occurred (throughout the undamaged parts of the forest) since the last previous forest inventory had been made. Such accurate, timely, detailed information about the world's forests would better permit foresters to determine which of their forest management activities (logging, thinning, planting, spraying, fertilizing, etc.) were proving to be most beneficial. Consequently they would be able to devise and implement more intelligent forest management measures, area-by-area, throughout the globe.

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