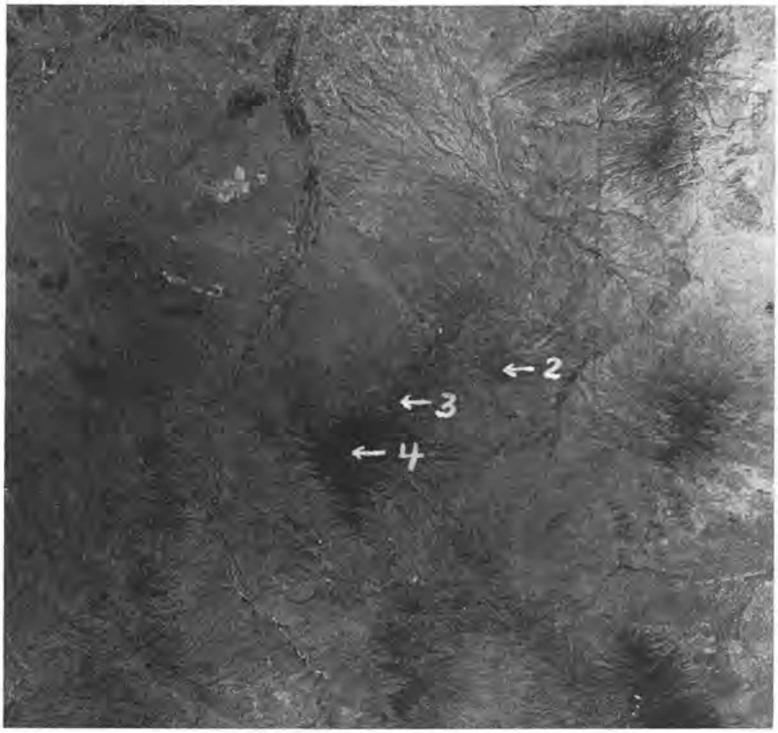

FIG. 1. Such photographs as this from space are excellent orientation aids for forest administrators and for making regional appraisals of the forest situation where the primary aim is to estimate extent of forest. In this synoptic view of several thousand square miles of Arizona, the darkest tones denote mountainous forested land. More detailed resolution of the terrain in the vicinity of the arrows at 2, 3 and 4 is evident in the following photographic illustrations. (Photograph by courtesy of NASA.)

RICHARD C. WILSON*
Forestry Remote Sensing Laboratory†
Berkeley, California

Space Photography for Forestry

Space and aerial photography may effectively complement each other.

(Abstract on next page)

SOME OF US have been privileged to observe—even to participate in—the evolution of techniques in aerial photography and photo interpretation. We have seen how they greatly reduced the burden of field work and have greatly expedited progress in forestry. We are also privileged to observe and participate in research and development of techniques for applying photography from space to jobs that need to be done in forestry—an exhilarating experience. For the many young scientists in this room, use of space photography must be a most stimulating prospect.

* Presented at the Annual Convention of the American Society of Photogrammetry, Washington, D. C., March 1966.

† Maintained by the Pacific Southwest Forest and Range Experiment Station, Forest Service, U. S. Department of Agriculture, in cooperation with the University of California and the National Aeronautics and Space Administration.

Some of you may be astronaut-scientists in the not distant future, taking pictures of the earth from orbital laboratories to help advance many scientific disciplines—forestry included. Before starting, you will want to determine the best possibilities for utilizing photography from space so that you will not waste valuable time on photography that might be done better from lower altitudes. Thus I invite you to join me in examining some photographic applications in the field of forestry to see whether some might best be done from space, and others from lower altitudes.

To establish a frame of reference, I'd like to make several premises. First, to reduce speculation, let's restrict comparisons of alternative methods to what we can expect within the next decade or so (essentially present state of the art).

Second, let's concern ourselves primarily with technical feasibilities without trying to make cost comparisons. This is not to say that cost comparisons are not needed; but experience data are not available for space photography. Cost comparisons are likely to be meaningless within the next several years when space photography will be generated as a fringe benefit—so to speak—from the general developmental program for space exploration.

Now let's look at Table 1, which tabulates ten forestry applications of photography. The columns headed "Gross," "Intermediate" and "Detailed" are arbitrary divisions of degree of required ground resolution which, as emphasized by Katz[16], is an important factor influencing interpretability of a photograph. For each division of resolution, approximate equivalents of photographic scale are listed. Thus, column two represents photography resolving gross features no smaller than 10 feet in diameter. Very roughly the equivalent range in contact-photo scale might be 1:50,000 and smaller, dependent, of course, on the quality of the photographic system. This column includes two of the four levels of ground resolution defined in the Space Handbook,[19] and columns three and four are approximate equivalents of the other two levels. Although the headings imply vertical photography, I want to emphasize that in the last column, particularly, low-altitude obliques may be substituted for verticals.

We may infer that the column headed "gross" generally represents space photography and the last two columns represent aerial photography. In support of this inference, as we read the plans by NASA[6] and consider the usefulness of space photographs to date,[8] we may expect that the great volume of space photography in the near future is likely to resolve features no smaller than 10 to 20 feet in diameter. Nevertheless, we must

ABSTRACT: *Photography from earth-orbital space platforms can provide synoptic overviews of huge forest regions superior to conventional aerial mosaics. It also can utilize short periods of good weather to image extensive forest areas. In contrast, for several decades at least, more conventional aerial photography should continue superior for identification and measurement of such details as tree size, species composition, and incidence of forest diseases, insects, and fires. The minimal parallaxes in space photography, which favor imaging forest areas accurately, are disadvantageous where tree heights must be determined, as in timber volume inventories. Ideally, space photography for over-all forest mapping may complement use of aerial photography for appraising forest details.*

RICHARD C. WILSON

TABLE 1. Resolution and approximate photo scale required for various photographic applications in forestry

Forestry Application	*Class of Resolution and Photo Scale*		
	Gross (Resol: features 10 ft. dia. or larger Scale: 1:50,000 or smaller)	*Intermediate (Resol: features 1–10 ft. dia. Scale: 1:8,000–1:50,000)*	*Detailed (Resol: features 1–12 in. dia. Scale: 1:600–1:6,000)*
Orientation Aids	X	x	x
Regional Appraisals	x	x 3d	—
Resource Management Inventories	x	X 3d	x 3d
Land Classification	x	X 3d	—
Development Surveys	—	x 3d	x 3d
Product Volume Estimates	—	—	x
Protection Plans	—	x 3d	—
Damage Detection	x	x	X 3d
Pest Control	—	x 3d	x 3d
Timber Salvage Plans	—	x 3d	—

NOTE: "3d" indicates that three-dimensional resolution through measurable parallaxes (on stereo photography from relatively low altitudes) usually is required to provide height determinations of trees, other vegetation, and microrelief. A large "X" indicates the resolution most frequently desired. Oblique photography may be substituted for stereoscopic verticals in some instances provided resolution requirements are met.

anticipate that space photography at larger scales and better resolutions will soon be available, at least in limited volume. Thus "intermediate" represents some space photography as well as the great bulk of current aerial photography.

As briefing aids for administrators of large forest regions, synoptic views from space are much superior to aerial photographic mosaics. Single synoptic photos provide overviews of huge areas. Moreover, the tones indicating gross features are consistent between adjacent photos of the same flight, as interpreters of such photography have noted.[8] In a few years, when photographs of the earth taken from space should be available at frequent intervals, consider how fortunate will be a state forester who wants a current picture of his territory.

The State Forester of Oregon, for example, might slide only four synoptic views under the glass of his desk top, arrayed so that their common corners orient on the imagery of Oregon's geographic center to give him an astronaut's view of all lands in the state. How easy it will be then for him to brief a member of the press quickly and accurately, or some other time-conscious visitor, on the hazard of a current fire to stands of sugar pine near the California line, on the progress of plantings of Douglas-fir in the old Tillamook Burn nearly two hundred miles north, or on the location of several new mills cutting larch in the Blue Mountains several hundred miles to the northeast.

Of course the state forester could get a rough substitute now for the same graphic aid by talking the Legislature into appropriating sufficient funds to compile a mosaic of Oregon's 97,000 square miles from existing aerial photographic coverage. This might require considerable talking, however, since at one of the common photographic specifications used in Oregon (1:12,000 scale, stereoscopic coverage),[13] nearly 30,000 contact prints would be required to mosaic the area covered by only one of the synoptic photos.

As I don't happen to have a synoptic view of Oregon handy, permit me, by courtesy of NASA,* to substitute one over southeastern Arizona (Figure 1).

For another important application—regional appraisals of the forest situation—resolution of gross features is suitable for some phases and resolution of intermediate features suitable for others, and it should be noted that we will probably see much better photography from space than this during the near future.[6] The shot from space in Figure 1 illustrates the gross feature category. This one photograph, imaging several thousand square miles, is a useful map substitute. Even

* The photographic figures referred to in this paper are part of the series of photographs shown as slides during presentation of the paper at the 1966 joint annual meeting of ACSM and ASP.

FIG. 2.

FIG. 3.

FIG. 4.

Figures 2, 3 and 4 show three important vegetation types in the southwestern United States—desert shrubs, pinyon juniper woodland, and mixed conifer sawtimber, respectively. These views (portions of conventional aerial coverage) were taken from less than 11,000 feet over the landscape at points annotated "2," "3" and "4," respectively, in Figure 1. Such panchromatic aerial coverage, at a scale of approximately 1320 feet per inch, is the kind widely used for management inventories by forestry agencies to appraise various resources such as timber, forage, and watershed and recreation values. Usually stereoscopic coverage is needed to provide three-dimensional resolution of vegetation and microrelief. This is a particular requirement for photo interpretation of timber volumes in both management-planning inventories and regional appraisals of timberlands. (U. S. Forest Service Service Photographs.)

on this somewhat oblique view, all relief features are so flattened that by simple rectification the photo may be converted into a small-scale "map." Furthermore, on this view no images of major topographic features are hidden by images of others, as can be the situation on aerial photography of mountainous terrain.

This photo also illustrates how main vegetation features may contrast even in a small-scale view. Perhaps most striking are the contrasts between forests in the mountains (denoted by the dark tones) and the desert vegetation of sagebrush and grasslands at lower elevations (denoted by adjacent light tones). Yet we may doubt if even the keenest interpreter can determine the specific kinds of forest in this area (such as commercial pine-fir timberlands and woodlands of pinyon-juniper) from study of this imagery alone. For some of these details see Figures 2 and 3 which are portions of aerial photographs taken from about 11,000 feet over the ground at the locations indicated by "2" and "3" respectively in Figure 1.

The main purpose of a regional appraisal may be to estimate and portray the gross extent of forest for a huge area within a brief time period. Obviously a few small-scale photographs from space might constitute an expeditious answer to the problem. On the other hand some regional appraisals aim to provide more than estimates of forest area—volume of timber, for example. For volumetric estimates, space photography does not appear suitable, at least within the present state of the art. The reason is that the flattening of relief (an advantage for area estimating) works as a disadvantage for volume estimating.

To examine this problem, let's look at a reproduction of aerial photography (Figure 4) widely used both in regional appraisals and in resource management inventories.[2,5,10,13,14] This is another view from 11,000 feet over ground indicated at "4" in Figure 1. While viewing this, let's recall what image characteristics are useful for estimating timber volumes by photo interpretation. These are tree height (or stand height), tree-crown closure, and tree-crown diameter. These are the only measurable variables—with the exception of bole diameters on low-altitude obliques—that are useful in volume estimating[2,4,9,17,18]

Bear in mind that from stero pairs of such photos as this, estimates are readily made of these three variables. For determining tree heights, measurements of differential parallax are much preferred over other methods, such as measuring relief displacement or shadows on single photos.[2]

The best photography from space available in the near future will almost certainly be inferior to this single photo in one respect, not perhaps in scale or two-dimensional resolution, but in three-dimensional resolution. This photo has displacements of images which (together with shadow details) suggest differences in heights of vegetation. On the other hand, even stereoscopic pairs of space photography do not yield three-dimensional resolution except for such contrasts as between mountains and valleys, because only minimal parallaxes are recorded on the photography. You'll recall that "parallax difference" is the principal cause of the three dimensional resolution (or perception of depth) obtained by looking at one of a pair of photographs with each eye.

A brief reference to elementary photogrammetry will remind us why we can't expect measurable parallax on space photography between images of such relatively short features as vegetation. The approximate equation for determining height of object h from parallax measurements is $h = H \cdot dp/P$ where H is average flying height above the terrain, dp is differential parallax between images of top and bottom of object, and P is the absolute parallax of the base of object (in practice the base length, or distance between principal and conjugate principal point). All quantities, of course, are expressed in the same units.

The precision of differential parallax measurement (much the smallest quantity in this equation) depends not only on the instrumentation, but also on the stereoscopic acuity of the person making the measurement. Researchers say that an observer with good acuity can detect differences in angle of parallactic displacement of about 20 seconds of arc, and under ideal conditions a very few individuals may detect differences as small as four seconds.[11,15] In photogrammetry we measure parallactic displacements of images on photographs in fractions of feet, inches, or millimeters, and we generally provide for measurements in increments no smaller than about 0.00005 feet, which corresponds to the smallest increment of parallax that may be detected by a skilled observer.

Therefore let's use 0.00005 feet as a constant in the parallax equation to represent the smallest measurable parallax difference. Let's also hold the base length P constant at 0.3 foot; this approximates that frequently obtained on stereoscopic pairs of contact aerial photographs on the usual 9-×-9-inch format. This base also represents about the maximum expected within the present state of the art on space photography in which formats will probably be somewhat smaller, if anything, than those now used for aerial photography.

Using height above ground H as a variable in the equation, we can observe its effect on the smallest differential of object height detectable by measurements of stereoscopic parallax. Consider two flight altitudes that characterize some conventional aerial photography, and an altitude approximating that for which earth-orbital flights are planned in the future. As h varies directly with H, the results are predictably obvious. At 3,000 feet flight altitude, h is only 5/10 of a foot; at 30,000 feet, it is 5 feet. But at an orbital altitude of 600,000 feet (about 114 miles above the earth), h is 100 feet.

Now a measurement of object height to the closest 100 feet is of no practical use when estimating height of forest or other vegetation. Measurements within ±5 feet may be acceptable. But bear in mind that this 5 feet is the theoretical limit of accuracy assuming a flight altitude of 30,000 feet and a base length of 0.3 foot. Depending on such factors as resolution of images and complexity of vegetation, this theoretical accuracy may only be approached.

There doesn't seem to be an immediate practical way to obtain photography from space on which heights of small objects, such as those of forest stands, can be reliably estimated. We could try to increase base length P to improve accuracy of height determination, because h varies inversely with P. But does anyone now propose that base length be increased, say, to 6 feet (with proportional increase in photo format) to give us a theoretical accuracy of height measurement within 5 feet using photography taken from 114 miles above the earth? A more practical solution may be to exploit measurements of shadows for such height estimates, even though good stereoscopic images greatly facilitate scaling of shadow lengths on single photos.

Convergent photography offers a possibility for increasing the parallax base without increasing the size of the photo format. Yet this does not seem to be a resonably useful solution with the present state of the art. For example, let us consider the kind of convergent photography advocated by many photogrammetrists as useful for increasing parallax over areas of low relief. This is obtained through the use of twin cameras mounted so that their optical axes are tilted 20 degrees from the plumb line to produce 100 per cent overlap along the flight line and still maintain a favorable air base and minimum amount of obliquity. This technique would approximately double the base length P over that cited in the previous examples where vertical photography was assumed. However, this would only halve the smallest detectable differential of object height h; the technique would not constitute a significant improvement for measuring tree heights on photography from orbital altitudes.

Furthermore, we can assume that camera installations necessary to produce convergent photography would undoubtedly be given much lower priority for use in space craft for resource exploration in the near future, because so many resource disciplines have major requirments for vertical photo-

FIG. 5. Intermediate resolution of features by black and white photography taken from several thousand feet above the terrain can provide satisfactory detection of insect attacks to standing timber. Here the light-toned trees are southern pines killed by bark beetles in Mississippi. This kind of imagery is also useful for planning control of forest pests and timber salvage. (U. S. Forest Service Photograph.)

graphs for synoptic overviews and other purposes. Also, it seems that convergent photography can be considered a supplement at best to vertical photography for most forestry purposes. Particularly over regions of steep topography, and where timber stands are tall and dense, convergent views might show only portions of the forest, and the images on remaining portions of forest would be degraded through the process of transforming the convergent photographs to horizontal projections which would be necessary for forest mapping.

Before leaving this phase I want to emphasize that three-dimensional resolution is well-nigh mandatory, also, when measuring crown closure and crown diameter, the other variables besides tree height that are useful for photo interpretation of timber volumes. That is why "3d" is shown in several places in the table. It indicates that in such applications three-dimensional resolution and measurement of differential parallax is necessary. You may infer also that this means aerial photography generally is required.

The next listed application—land classification—normally requires the same kind of photography, although resolution of gross features may be satisfactory for reconnaissance purposes.

And for another application, "Development Surveys," reference to Table 1 indicated that "3d" resolution of intermediate or detailed features is also required. Either low obliques or large-scale verticals, like those in Figures 2 to 4, would be useful in planning road locations for timber sales administration, or campground or other forest recreation developments. Details on vegetation and microrelief which would not be apparent on small-scale views could best be accentuated by stereoscopic photography at large scale.

Low altitude obliques are ideal for making estimates of volume of timber products at concentration points, such as log decks and ponds. Current levels of log inventories might easily be determined by flying periodic coverage of oblique photography, merely counting logs, and multiplying the count by average board-foot volume factors. These factors might be determined infrequently by a limited random sampling of log decks or ponds.[2]

For detecting incidence of destructive agents, resolution of rather small features through low-altitude photography often is required.[1,3] The oblique in Figure 5, for example, provides satisfactory contrast in shades of gray between beetle-killed and live trees in stands of loblolly pine. Where species composition of the forest is varied, stereoscopic photography may be required for determining which species of tree is damaged, as an essential item for the identification of the specific destructive agent so that proper control measures may be applied. Imagery is needed showing characteristic shapes of branches and subtle hues or tones of foliage, etc.[3,9,12] (see Figure 6). To justify the use of such large-scale photography may require a carefully designed correlated double sample: one sample a very limited number of ground plots; the other a larger number of photo plots which might be confined within systematic strips of photography over only a fraction of the area of interest.[2,7,20]

On the other hand, even small-scale photography may be used to detect heavy incidence of a destructive agent. The distant view in Figure 7, for example, imaged smoke columns which pinpointed forest fires in an inaccessible area. As some current space photography is better quality than that souvenir photo of World War II, we may assume that even small-scale photos from space can be very useful for early detection of such forest hazards.

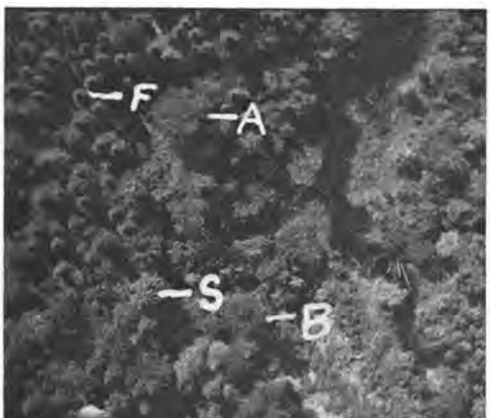

FIG. 6. Large-scale photography may be necessary as an aid to determining agents causing damage to the forest, and thus to orient measures for control. This is usually the situation where tree species composition is variable. In this illustration differences in shapes of tree crowns and branching patterns are clues to identification of species, including the following annotations: S-spruce, F-fir, B-birch and A-aspen. In the originals of the flight strip from which this reproduction was taken characteristic "signatures" of species are evident. Those originals exhibit detailed 3rd-dimensional resolution of tree images and varying hues of foliage since they comprise stereoscopic coverage in color film at a scale of approximately 100 ft. per inch. (U. S. Forest Service Photograph.)

FIG. 7. A distant view of the headwaters of the Yangtze River in China imaging the location of several forest fires (at arrows) demonstrates that gross resolution of features is satisfactory for detecting damage to forests when the incidence is heavy. This souvenir frame of trimetrogon coverage, taken several decades ago, is poorer in quality than some current photography from space. This suggests that even small-scale photography from earth-orbital laboratories will be very useful for early detection of fires in inaccessible wildlands. (World War II Photograph by courtesy of 14th USAAF)

CONCLUSIONS

In briefly mentioning some broad fields of forestry application of photography, I have pointed out that space photography might be applied most appropriately to a couple of applications, and aerial photography applied most appropriately to several others. Both kinds of photography have some advantages and disadvantages.

Time does not permit discussion of all these advantages and disadvantages. Certainly we can see both opportunities and difficulties in space photography if we consider the potential of the orbital photographic laboratories that have been proposed to fly in the next few years. For example, while such laboratories are functioning, cameramen may take advantage of suitable photographic weather. Because of the multi-purpose responsibilities of such laboratories to a large number of scientific disciplines (geography, geology, agriculture, forestry, etc.), who will get prime camera time?

I would emphasize that photography from space should be definitely superior for very generalized regional appraisals and maps of the forest situation, and as briefing aids to the administrator of large forest regions. In particular, space photography is an excellent medium for periodic reconnaissance of underdeveloped regions to chart trends of gross changes in forests and other land uses due to man's activities or to destructive natural agents. Mosaics of conventional aerial photography are not satisfactory substitutes for synoptic views from space. Because synoptic views should be useful to many disciplines, we may anticipate their production with increasing frequency. The current state of the art in space science does not offer a satisfactory substitute for aerial photography in such applications as timber volume inventories, detailed land classification surveys, and appraising impacts of such forest-destroying agents as fire, insects, and disease. Even at large scales, space photography yields much smaller parallax differences than aerial photography, and thus cannot provide the three-dimensional resolution needed for estimating heights of trees, other vegetation, and microrelief.

If you don't recall any other part of my comments, I trust you may remember these points: synoptic photography from space offers foresters new dimensions of application; but to realize the depth perception essential for administrative and management information, foresters must continue to use aerial photography. As a corollary, these two kinds of photography may complement each other to increase the scope and effectiveness of forestry applications.

References

1. Aldrich, R. C., Bailey, W. F., and Heller, R. C. "Large-scale 70-mm Color Photography Techniques and Equipment and their Application to a Forest Sampling Problem." PHOTOGRAMMETRIC ENGINEERING. 25(5): 747–754. 1959.
2. American Society of Photogrammetry. MANUAL OF PHOTO INTERPRETATION. Chapter 7, Photo Interpretation in Forestry. George Banta Publishing Company, Menasha, Wisconsin. 1960.
3. Avery, Gene. "Helicopter Stereo-photography of Forest Plots." PHOTOGRAMMETRIC ENGINEERING. 24(4): 617–625. 1958.
4. Avery, Gene and Meyer, Merle P., "Volume Tables for Aerial Timber Estimating in Northern Minnesota." U. S. Forest Serv. Lake States Forest Exp. Sta., St. Paul, Minnesota. Station Paper No. 78. 1959.
5. Avery, Gene and Meyer, Merle P., "Contracting for Forest Aerial Photography in the United States." U. S. Forest Serv. Lake States Forest Exp. Sta., St. Paul, Minnesota. 1962.
6. Badgley, Peter C. "The Application of Remote Sensors in Planetary Exploration." Proceedings of the Third Symposium on Remote Sensing of Environment, Infrared Physics Laboratory, University of Michigan. pp. 9–28. 1964.
7. Bickford, C. A. "The Sampling Design Used in the Forest Survey of the Northeast." *Journal of Forestry*. 50: 290–292. 1952.
8. Bird, J. B. and Morrison, A. "Space Photography and Its Geographical Applications." Geographical Review. 54(4): 464–486. Oct. 1964.
9. Colwell, Robert N. "Aerial Photography—A Valuable Sensor for the Scientist." *American Scientist*. 52(1). March 1964.
10. Colwell, R. N. and Marcus, L. F. "Determining the Specifications for Special Purpose Photography." PHOTOGRAMMETRIC ENGINEERING. 27(4): 618–626. 1961.
11. French, J. W. "Stereoscopy Re-stated." Trans. Optical Society. 24(4) London. 1922–23.
12. Heller, R. C., Doverspike, G. E. and Aldrich, R. C. "Identification of Tree Species on Large-scale Panchromatic and Color Aerial Photographs." U. S. Dept. Agr. Handb. 261. July 1964.
13. International Union of Forest Research Organizations. Aerial Photographs in Forest Inventories, Applications and Research Studies. Munich. 1963.
14. Jensen, Herbert A. and Colwell, Robert N. "Panchromatic Versus Infrared Minus-Blue Aerial Photography for Forestry Purposes in California." *Photogrammetric Engineering*. 15(2): 201–223. 1949.
15. Judge, Arthur W. Stereoscopic Photography. Chapman and Hall Ltd. London. 3rd Edition, 1950.
16. Katz, A. H. "Observation Satellites: Problems and Prospects," *Astronautics*. April 1960.
17. Moessner, Karl E. "Aerial Volume Tables for Ponderosa Pine Type in the Rocky Mountains." U. S. Forest Serv. Intermountain Forest and Range Exp. Sta., Ogden, Utah. Research Note No. 76. 1960.
18. Pope, Robert B. "Aerial Photo Volume Tables for Douglas-fir in the Pacific Northwest." U. S. Forest Serv. Pacific Northwest Forest and Range Exp. Sta., Portland, Oregon. Research Note 214. 1961.
19. Select Committee on Astronautics and Space Exploration. Space Handbook: Astronautics and its Applications. U. S. Gov. Printing Off. Washington, D. C. 1959.
20. Wilson, R. C. "Surveys Particularly Applicable to Extensive Forest Areas." Fifth World Forestry Congress, Proc. The National Publishing Co., Washington, D. C. 1962.