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Proposed Parameters for an Operational Landsat*

Sensor type, wavebands, resolution, quantizing level, sampling frequency, data rates, sensor weight, sensor power requirements, expected sensor life, satellite orbit, ground coverage, orbital position and attitude stability and determination, and data storage capability discussed.

Abstract: *Since July 1972, various members of the U. S. Geological Survey (USGS) have been evaluating the utility of Landsat data. Through professional contacts with their counterparts in foreign countries, as well as in other United States agencies, this evaluation has been conducted on a worldwide multidisciplinary basis. The results of this effort have led to the definition of a proposed operational† Landsat based on the following criteria:*

- *Continuity with respect to Landsats-1, -2, and -C;*
- *Full availability of data on a global basis; and*
- *Economic practicality.*

Unfortunately, the only Landsat-type satellites previously defined are for research purposes and are not designed to meet operational requirements. Neither the USGS nor any other Government agency now has the charter to fund for and manage an operational Landsat. Therefore, this definition of the operational satellite is restricted to technical aspects with the hope that NASA will be authorized to build such a satellite and that the management problem for operations will be resolved before launch. In any case, an operational Landsat is considered justified and badly needed by all who would monitor the Earth's surface and would strive toward better utilization and conservation of the world's natural resources and environment.

Introduction

Since July 1972, U.S. remote-sensing satellites, formerly known as Earth Resources Technology Satellites (ERTS) but now known as Landsat, have been effectively recording the Earth's surface features. Although the Landsat program is experimental, it has clearly demonstrated the operational utility of Earth sensing from space. Numerous papers (ref. 1, for example) document the utility and justification of Landsat is assumed to be an accomplished task and thus beyond the scope of this paper. Experimentation in Earth sensing must continue, but the time has come to define an operational Landsat program or at least an operational test. The problems of managing such pro-

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† Operational as used herein implies an approved program of indefinite duration with specified products and services provided.

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grams are obviously complex, but also beyond the scope of this paper. Nevertheless, an operational Landsat can and should be defined in technical terms.

It may seem presumptuous for a cartographer, or group of cartographers, to undertake the task, but the cartographers who would map this Earth have as great a stake in Landsat as any other disciplinary group. Geologists, agriculturists, foresters, and land use planners, as examples, are equally involved, but their operational use of Landsat depends in no small part on the solution of cartographic problems. These in turn depend on relative and absolute geometry as well as the information content of Landsat data. There is probably no other concerned group as demanding as cartographers and, from what we have seen to date, Landsat data when properly processed can meet its demands for the planimetric portrayal of the coarser Earth-surface features. Obviously, the definition of an operational Landsat should result from the combined effort of all who have pertinent operational requirements.

DEVELOPMENTS

During the past five years various cartographers as well as many others have been evaluating Landsat capabilities. Landsat was not defined for mapping, but it has, in fact, demonstrated many capabilities beyond those of any other known mapping system. Landsat also has distinct limitations because its resolution is at present based on a 79 m picture element* (pixel) and, as now configured, it has virtually no capability of resolving the third (relief) dimension. However, topography is static, and its mapping is basically a one-shot effort. On the other hand, the planimetric distribution of Earth surface features and cover are constantly being changed by both man and nature. Planimetric mapping becomes simplicity itself if the Earth can be viewed orthographically so that relief displacement is eliminated. Of course, the system must also resolve those features that one would map. In any case, Landsat approaches orthogonality to the point where displacement due to relief need be considered in only a few areas of the Earth.

This paper is based primarily on the following:

(1) NASA sponsored ERTS-1 (Landsat-1) Investigation 233 (by USGS), "Evaluation of ERTS Imagery for Cartographic Application." This research covered a wide variety of cartographic tasks and evaluated the work of foreign as well as domestic investigations. The final report of this investigation has been published[2].

(2) NASA Investigation 23960 (by USGS), "Evaluation of ERTS-B Imagery for Operational Cartographic Application," which is continuing the overall global cartographic investigations of Landsat.

(3) The June 1976 report of the Mapping and Cartography Subpanel of the NASA-sponsored Landsat Follow-on and Future Mission Objectives Study Group[3].

(4) Various comments, data, and reports from the governmental, academic, and industrial communities.

These all indicate that the time has come to define the operational parameters for Landsat even though, as previously indicated, experimentation in the remote sensing of the Earth from space should continue indefinitely. Selected milestones and data about Landsat are—

- Launch of Landsat-1
  July 23, 1972
- Launch of Landsat-2
  January 22, 1975
- Total number of scenes, Multispectral Scanner (MSS) imaged as of July 23, 1976
  320,926*
- Total area of Earth imaged as of July 23, 1976 (this includes repetitive cover, clouds, and ocean areas)
  10,000,000,000 km^2†
  (4,100,000,000 mi^2)
  (3,100,000,000 nmi^2)
- Expected launch of Landsat-C
  Late 1977 or early 1978

Technical details about the satellite, orbit, sensors, and data are covered in references 4, 5, and 6.

CRITERIA FOR OPERATIONAL MODE

Landsats-1 and -2 have demonstrated a variety of applications of economic and social value, and Landsat-C promises to continue the demonstration. However, many applications will take years to fully implement, and it is suggested that an operational test of at least 10 years, based on proven Landsat parameters, is needed for full evaluation of Landsat Earth sensing. Certain

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* The area on the Earth's surface from which single (radiometric) responses are recorded is 79 by 79 meters.

* Reported by NASA Landsat Newsletter No. 11, dated October 1, 1976.

† Each scene is assumed to have a net size of 185 by 164 km.

parameters of Landsats-1 and -2 should be modified for operational use, but the changes apply to the sensing system rather than orbital parameters, which have proved to be near optimum and warrant continuation into the operational phase.

Various studies that concentrated on a particular application or geographic area, such as the United States, do not in themselves fully justify Landsat. In fact, Landsat undoubtedly has greater value outside the United States where mapping and other data bases are not as available. It is interesting to note that the most effective operational demonstrations of Landsat, such as NASA's Large Area Crop Inventory Experiment, the revision of nautical charts, and the use of imagery for oil and mineral exploration, involve foreign areas. Obviously, Landsat must be treated as a global system with data readily available to all who need it.

The final and most important single criterion for an operational mode is economic practicality. An operational Landsat should be built and flown and the data processed efficiently in order to prove or disprove economic effectiveness. The cost benefits of the system cannot be fully determined in advance, but in any case they are directly affected by Landsat costs. The benefits of Landsat include many intangible elements difficult or impossible to express as dollar values. Nevertheless, both tangible and intangible benefits must be considered in an objective evaluation of Landsat. In summary, three fundamental criteria are recognized for an operational Landsat:

- Continuity with respect to Landsats-1, -2, and -C;
- Full availability of data on a global basis; and
- Economic practicality.

Reference 8 discusses further the rationale for an operational Landsat.

Suggested Parameters

NASA and others have suggested several forms for the satellite that would follow Landsat-C, which cannot be expected to be functional much beyond 1980. Recent descriptions include the Thematic Mapper (TM),[9,10,15] but at a lower orbit altitude of 705 km. Evaluation of this system shows that such a satellite, although suitable for research, would not provide continuity or an operational test for Landsat.[3] In fact, such a satellite would not meet any of the three criteria recognized for an operational Landsat. It was this analysis that led the Landsat Follow-on Mapping and Cartography Subpanel to define a new set of parameters. Since the subpanel last met, in May 1976, many comments and suggestions have been received on the proposed parameters. However, they remain basically as outlined by the subpanel (Table 1).

Discussion of Parameters

Each listed parameter is duscussed as follows:

Sensor type. The MLA's represent new, proved technology.[11,12] However, the applications and limitations of linear array sensors are not otherwise well documented. It is anticipated that pertinent articles will be appearing soon in appropriate technical journals. Linear arrays have decided advantages over optical mechanical scanners for operational use because they have no moving parts, are lighter in weight, use less power, have higher geometric fidelity, have a longer life expectancy, and present a much simpler data handling problem. The big disadvantage of the linear array today is that, in simple form, its response is limited to the visible and near-infrared portion of the spectrum. Thus, a linear array (unless complicated by detector cooling) is not suitable for use with wavelengths longer than 1.05 μm. However, Landsats-1 and -2 are restricted to wavelengths shorter than 1.1 μm, and all of the operational uses defined to date are based on those wavelength responses. Another disadvantage of a linear array, when compared to a scanner, is the large number of detectors involved (over 6,000 at the 30 m pixel size). Each detector must be calibrated to produce a uniform response from a given scene, but since they are stable, detector calibration is basically a one-time effort and considered within the state of the art[12]. Linear arrays now offer the most promising design for an operational Landsat, and their immediate space-use development, probably by NASA, is warranted.

Wavebands. Landsat has demonstrated three fundamental wavelengths for operational Earth sensing:

(1) In the green region the MSS band 4 (0.5 to 0.6 μm) has clearly demonstrated a water-penetration capability that promises to aid accurate mapping of the shallow seas of the Earth, which today are largely unmapped. By slightly lowering the waveband into the blue-green (0.47 to 0.57 μm) the capability can be further enhanced. Band 4 also provides a strong indication of water quality insofar as suspended solids and certain other

TABLE 1. PARAMETERS FOR AN OPERATIONAL LANDSAT

• Sensor type	Multispectral Linear Arrays (MLA)
• Wavebands (three)	
1. Blue-green (water penetration)	0.47 to 0.57* μm
2. Green-red (boundary delineation)	0.57 to 0.70* μm
3. Near infrared (water, vegetation, and cultural delineation)	0.76 to 1.05* μm
• Resolution in terms of picture element (pixel) dimension	
1. Band 1 (blue-green)	60 to 90* m (similar to Landsat-1, -2, and -C)
2. Band 2 (green-red)	30 to 40* m
3. Band 3 (near infrared)	60 to 90* m (similar to Landsats-1, -2, and -C)
• Quantizing level (radiometric sensitivity)	64 to 256 levels* (6 to 8 bits)
• Sampling frequency	1.4 times per pixel (same as Landsats-1, -2, and-C)
• Data rate	Approx. 15 megabits per second (Mb/s; capability of Landsat reception stations)
• Sensor weight (est.)	40 kg
• Sensor power req. (est.)	40 W
• Expected sensor life	6 to 10 years
• Satellite orbit	Circular Sun-synchronous at 919 km (same as Landsats-1, -2, and -C)
• Ground coverage and frequency of coverage	185 km swath and 18 day frequency of coverage (same as Landsats-1, -2, and -C)
• Orbital position and attitude stability and determination—improved over Landsats-1, -2, and -C—perhaps by a magnitude	
• Data storage capability—equal to or better than Landsats-1, -2, and -C	

* Parameters subject to adjustment based on engineering tests for final design.

pollutants are concerned and aids in the discrimination of dormant vegetation.

(2) In the upper portion of the visible spectrum, MSS band 5 (0.6 to 0.7 μm) now delineates most spectral differences, except for vegetation, found on land areas. Thus, it is the fundamental band for indicating boundaries between both natural and manmade features. A slight expansion of this band into the green-red (0.57 to 0.70 μm) will further expand this capability.

(3) MSS bands 6 (0.7 to 0.8 μm) and 7 (0.8 to 1.1 μm) have demonstrated the operational value of the near infrared for vegetation, open-water (shoreline), and cultural delineation. However, the two bands are highly redundant, and one band (0.76 to 1.05 μm) can meet most operational requirements for the near infrared. The approximate upper limit for a linear array of detectors, unless they are cooled, is 1.05 μm.

Resolution in terms of picture element (pixel) dimension. A broad range of resolutions is needed for various Earth-sensing operations. However, Landsat has a fixed attitude and field-of-view and is designed to cover the entire Earth (or at least major portions of it) rather than selected areas of limited size. Every bit of information must be recorded and to some extent transmitted and processed. Thus, the resolution of the system determines the cost of construction, launch, and satellite operation together with data transmission, reception, and processing. Resolution is an exponential function in that doubling it (halving the pixel dimension) quadruples the data flow and costs.

At present, Landsat operates on a nominal data rate of 15 Mb/s, and Landsat receiving stations, built and under construction, are designed for that data rate. For a global, operational Landsat, the 15 Mb/s rate is considered reasonable for the first such satellite. Based on this rate and indicated uses, the resolution in terms of frequencies or picture element (pixel) dimension at ground scale have been developed as follows:

(1) Band 1 (blue-green)—60 to 90 m. Although higher resolution would be useful for selected areas, this pixel size has proved adequate for the general portrayal of shoal water, differences in water quality, and vegetation status.

(2) Band 2 (green-red)—30 to 40 m. Because this is the band that best defines the smaller land features, it has been selected as the one of high resolution. The rationale is the same as that used for color television and high-resolution color photography in which one band has a resolution at least double that of the others. This approach assumes that band 2 will define spatial boundaries and that the other two bands can, in effect, be raised to the higher resolution by assuming that the spatial boundary defined by band 2 exists for all three bands. The human eye apparently does this automatically, and in the digital domain the computer can do the same thing. This assumes that the areas concerned are at least several pixels in extent so

that the computer can find the suitable signal in defining the higher resolution boundary within the lower resolution waveband response. For features (areas) too small to provide a meaningful signal in the lower resolution wavebands, higher resolution portrayal will be completely dependent on the response obtained in the higher resolution waveband. It is true that not all spatial boundaries are defined by the green-red band, but those few that are not, such as differences in stress in crops, do not constitute major defined operational applications. Field boundaries that normally define different crops, or at least different planting times, will in general be defined by the green-red band. The 30 to 40 m range has been established by several studies[13,14] and there is no current serious effort to define a Landsat-type satellite with a pixel smaller than 30 m. The 40 m size is cited here because there are relatively small differences in usability between the 30 and 40 m pixel sizes. There are processing advantages in having the low-resolution pixel size a simple multiple of the high-resolution, such as 70 m for the low and 35 m for the high or 90 m for the low and 30 m for the high. This multispatial approach is considered essential to provide increased resolution and at the same time maintain a reasonable data rate and meet the established criterion of economic practicality.

(3) Band 3 (near infrared)—60 to 90 m. For certain important operational applications related to vegetation, water, geologic, and cultural patterns, such resolution is inadequate by itself. However, because band 2 will define most boundaries at higher resolution, the spatial response obtained in this band can be raised to the higher resolution. Thus, there is justification to keep the pixel size of this band in the 60 to 90 m range.

Quantizing level. This parameter defines the radiometric sensitivity of the transmitted signal. On Landsat-1 and -2 bands, MSS signals are quantized into 64 levels (6 bits). There is evidence that 128 levels (7 bits) or even 256 levels (8 bits) might be justified, but these must be weighted against the additional data rate, particularly with respect to transmission. Seven bits require a 17 percent and 8 bits a 33 percent data rate increase per pixel as compared with 6 bits.

Sampling frequency. In a scanner or linear array, sampling frequency establishes the resolution along the axis of principal motion (transverse sweep for a scanner, forward motion for a linear array). Sampling should occur at least once per resolution cell (pixel), but there are factors, such as the spread function (analogous to image smear), which make it desirable to increase the frequency to 1.4 times per pixel. In any case, the resulting resolution in the two cardinal directions should be of the same general order.

Data rates. As previously discussed under spatial frequency, 15 Mb/s is considered optimum for the first operational Landsat. This rate assumes the same transmission, reception, and processing capabilities as for Landsats-1, -2, and -C. The TM, proposed by NASA for Landsat-D, involves more than 100 Mb/s.

Sensor weight—40 Kg. Solid state linear arrays are both small and lightweight. With them, the principal weight is the optics, which must provide suitable resolution across the linear arrays. The field-of-view of the optics is less than 12°, and the linear array is expected to be no more than 10 cm long. Suitable optics of the weight indicated are considered within the state of the art. In comparison, the MSS weighs 65 kg and the TM 150 kg.

Sensor power requirements. Solid-state linear arrays need less power than other comparable sensors. Whereas 40 W is estimated for the MLA, the MSS needs 80 W and the TM 250 W.

Expected sensor life. Tests to date indicate practically no deterioration with time in the detectors of linear arrays[11,12]. Since no moving parts are involved, a longer lifetime can be expected for a linear array than for a scanner. A conservative estimate for the MLA is 6 to 10 years whereas the MSS and the TM are rated at 2 to 4 years.

Satellite orbit. Landsats-1, -2, and -C follow a nominal circular Sun-synchronous orbit of 919 km altitude. The advantages of this orbit have been described and have been compared to the 705-km orbit defined by NASA for Landsat-D.[7] For an operational Landsat, the 919-km orbit appears ideal. Comparative disadvantages of the 705-km orbit, based on the same 185 km width of coverage, are summarized as follows:

(1) Disrupts continuity of Landsats-1, -2, and -C.
(2) Reduces orthogonality by up to 27%.
(3) Increases shadow-effect differences by up to 70%.
(4) Increases relief displacement by up to 32%.
(5) Increases atmospheric noise by a small (0.4%) amount.
(6) Decreases the area of direct data reception for a ground station by about 25% (reception radius by 13%)

Ground coverage and frequency of coverage. Landsats-1, -2, and -C all utilize a swath width of 185 km (100 nmi). This parameter, coupled with the orbit, provides for complete Earth coverage (potentially) every 18 days except for the small (8° radius) circle around each pole. There is no known reason for changing the swath width for the operational mode. If frequency of coverage must be increased (say to nine days), a second satellite is called for.

Orbital position and attitude stability and determination. At present, Landsat orbital positions, based on (NASA provided) two-day predictions are rated as having a 3σ (99 percent probability) error of 179 m in the combined x, y position (equivalent to longitude and latitude). However, solar (Sunspot) activity is due to reach a maximum in 1980, at which time the two-day prediction is expected to degrade to a 3σ of 378 m, after which it will improve. Such positioning is sufficient for Landsats-1, -2, and -C because attitude uncertainties have considerably larger effects. For an operational Landsat there is no reason why positions cannot be determined to much higher accuracy inasmuch as geodetic satellites can now be fixed within a few meters. However, there is no point in utilizing an expensive positioning system if attitude uncertainties negate the accuracy of the Earth scene. Orbital positioning should be engineered to complement attitude determination, which is the more critical factor. Landsats-1, -2, and -C have maximum attitude deviations of 0.4° in pitch and roll and 0.6° in yaw.[4] Attitude determination in pitch and roll is to 0.07° (rms) and in yaw to perhaps 0.1°. These represent uncertainties that are too large for independent mapping. For example, the combined pitch and roll uncertainty may reach 0.1°, or 1.6 km on the Earth's surface. The mapping capability of Landsat depends directly on attitude stability and determination, and any reduction in the quoted deviations will enhance this application. It is understood that positional and attitude systems now being developed by NASA are a magnitude or so better than those presently employed on Landsat and should be applied to the operational version. The reduction of moving parts, by replacing existing scanners with linear arrays, greatly facilitates the development of a more stable satellite.

Data storage capability. On-board data storage by tape recorders has been one of the weak spots in Landsat-1 and -2 performance. However, a fundamental criterion for an operational Landsat is "full availability of data on a global basis." To meet this criterion, on-board data storage equivalent to or better than that on Landsats-1 and -2 must be provided unless the installation of additional ground receiving stations or the development of the communication satellite systems negates the need for on-board data storage.

CONCLUSIONS AND RECOMMENDATIONS

As previously indicated, the management problems of an operational Landsat are beyond the scope of this paper. It is hoped, however, that NASA will be authorized to design and build such a satellite with the understanding that its operation will be taken over by an appropriate agency once it is successfully in orbit. Because three or four years are involved, it is assumed that the management problems can be resolved before launch. Continuity of the Landsat program is an essential criterion, and the current management of Landsat is adequate until operational responsibilities are assigned. In any case, an operational Landsat should be initiated without delay. Landsat-D as currently conceived is strictly an experimental satellite that meets none of the three defined criteria for operations. Surely those who believe in Landsat and want to see it applied operationally can agree on the basic parameters. This paper will have served its purpose if those who would apply Landsat examine the proposed parameters, provide appropriate comments or recommended changes, and support the definition and construction of an operational Landsat.

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Erratum

In the "Report of the Photogrammetric Surveys Division" on page 926 of the July Yearbook issue of *Photogrammetric Engineering and Remote Sensing*, 17 lines of text were misplaced. Lines one through 17 in the second column should follow line 17 in the first column.