95% confidence. From the tables we find $d_{0.05} = 0.1 = 1.36/(n)^{1/2}$, and $n = 185$ samples.

If, as just stated, we are particularly concerned about large or small values of x, then a result due to Rényi[10] is to be preferred to the Kolmogorov statistic. Rényi determined the distribution of a proportional statistic:

$$\sup_x \left| \frac{S_n(x) - F(x)}{F(x)} \right|$$

His result leads to a confidence band of the form:

$$S_n(x)/(1 + y/n^{1/2}) < F(x) < S_n(x)/(1 - y/n^{1/2})$$

However, there are certain subtleties involved with Rényi's statistic, and the interested reader should see Spear[11] or, for detailed theory, Rényi.[10] Both papers contain tables of the asymptotic distribution of the statistic which are valid for $n > 50$. If large x is of particular concern, the variable chosen for study should be $z = 1/x, x \neq 0$.

Example

A problem was to size the propellant supply tank for a gas generation system which is to be used in a positive expulsion system for a liquid rocket engine. The solution rested primarily on an adequate description of the heat transfer taking place from the hot gas to the surrounding components. Seven first-order, nonlinear differential equations were developed to simulate the heat transfer occurring in the system and to predict the gas required for a given expulsion schedule. The principal uncertainties concerned the probable values of three heat-transfer coefficients, h_i. Previous experience had shown that an experimental investigation aimed at estimating these values was very expensive and unwarranted unless the tankage configuration was absolutely fixed. Therefore the design engineers, relying on previous experience and intuition, found it possible to formulate upper and lower bounds for each h_i and agreed to experiment with the Monte Carlo approach.

The simulation equations were set up such that the main engine propellant was expelled in a set time interval at an essentially constant flow rate. These data then specified the pressure/volume requirements of the gas as a function of time, etc. The routine for calculating the total propellant requirement (the model and associated logic) was then incorporated in the random sampling program shown in Fig. 1. The project engineer asked for an estimate of the total propellant volume that would be adequate for 95% of the cases that might arise under the assumptions concerning the h_i with 95% probability. Using the tolerance statistics just discussed with $m = r + s = 0 + 1 = 1$, fifty-eight samples are required to achieve 95% coverage at the 95% tolerance level. Figure 2 shows the sample distribution function resulting from the experiment. The value of u_{58} is 4.15 lb. Hence, by designing the system to carry 4.15 lb of gas generator propellant the probability is 0.95 (with 95% tolerance) that there will be enough propellant to deal with the demand if the assumptions concerning the h_i are valid. Figure 2 also shows the width of the 90% confidence limits, $2\,d_\alpha$, on the distribution function which result from the Kolmogorov statistic for 58 samples.

The most interesting result was that the total propellant required was rather insensitive to the h_i values. This fact was of much greater interest to the design engineers than the statistical results. However, renewed interest in the statistical method arose when it was decided to consider a size index for the gas generator itself, specifically maximum flow rate, which shows greater variation in Fig. 2. This result indicated that considerable uncertainty existed concerning the dynamic requirements placed on the generator.

In the case of two correlated variables of interest, like maximum flow rate and total propellant, multivariable tolerance level results[6] can be applied, but they are beyond the scope of the present discussions.

Conclusions

An example has demonstrated the simplicity of the application of Monte Carlo methods when the variables of interest can be studied using distribution-free techniques. The three statistical methods discussed herein are but a few of a large number which can be used to advantage in the same context.

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Comparison of Basic Modes for Imaging the Earth

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In September 1969, President Nixon in an address to the United Nations General Assembly stated, "I feel it is only right that we should share both the adventures and the benefits of space. As an example of our plans, we have determined to take action with regard to earth resources satellites, as this program proceeds and fulfills its promise." Making this a reality is going to require several complex experiments before an operational system is properly defined.

The Department of the Interior has developed the Earth Resources Observation Satellite (EROS) program so that Earth-sensing systems can be put to practical use. The department further recognizes that surveying the Earth's resources requires remote sensing from spacecraft for the global synoptic approach and from aircraft for localized use. NASA has designated the Earth Resources Technology Satellite (ERTS) as a series of space flights to meet the needs of Interior and other departments, such as Agriculture and Commerce.

The EROS program recognizes that any one satellite system may not fully meet the operational needs and has in fact defined four basic modes for remote sensing of the Earth and its resources, as follows: 1) airborne, generally film return, 2) space, data transmission, global, 3) space, film return, global, and 4) space, data transmission, geosynchronous.

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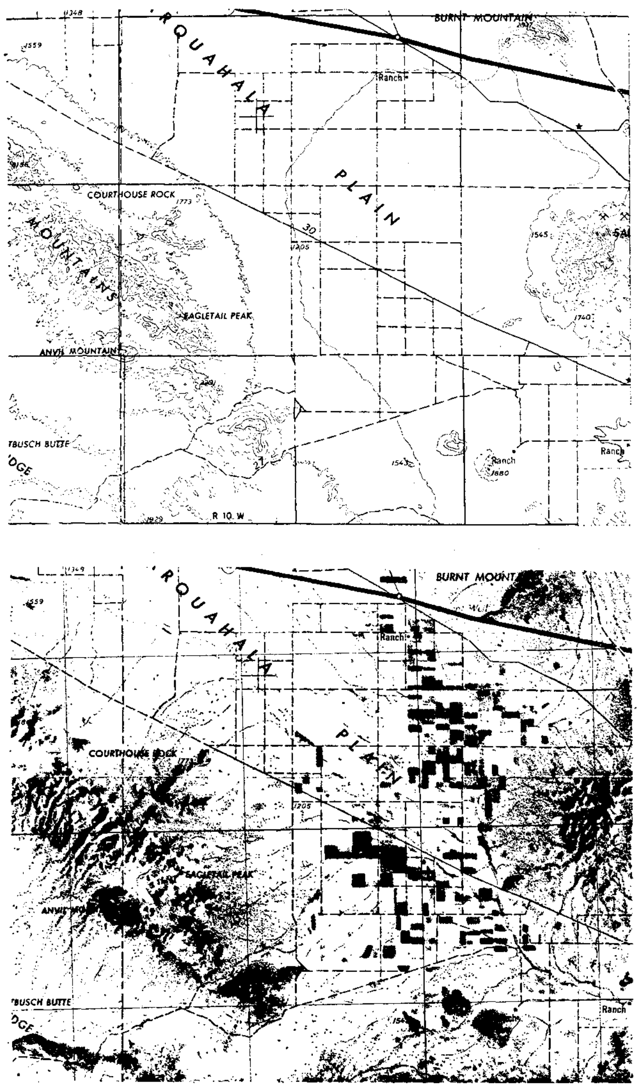

Fig. 1 Use of space photographs as a base for a standard map at 1:250,000 scale. On top is a standard line map, on the bottom, basically the same map with space imagery superimposed.

In addition to these four basic modes, there are numerous variations, including elliptical orbits which can concentrate on a given area or set of areas. There are also combinations of modes; in fact, there are already indications that no one single mode could possibly answer the varied requirements related to Earth resources.

NASA and the Department of the Interior are collaborating on a research project aimed at comparing the basic modes and eventually coming up with relative cost/benefits for various applications. The first phase of this research should be completed in about 6 months. In the meantime, all who have an interest in remote sensing should study their specific requirements and relate them to the four modes. The results of these studies could help NASA and Interior in their basic study. This paper will discuss only the more obvious characteristics of each mode without attempting any over-all comparison.

Parameters

The design of any operational system of Earth observations requires consideration of all components of the system. However, this Note is limited to the data-gathering aspects. If we stick to the remote-sensing aspect of Earth-observation systems, the following parameters and factors can be used for comparing the four modes; there is nothing final about this list, and no priority among the items is intended: 1) spatial resolution, 2) spectral discrimination, 3) photometric fidelity, 4) geometry: fidelity; geometric relationship of scene to imagery, 5) processing time (time from exposure to user), 6) opportunities for observation: frequency; ability to obtain data at various time intervals; ability to overcome visibility problems; ability to image unpredictable phenomena, 7) area coverage and ability to vary such coverage, 8) reliability, 9) compatability with data-handling requirements, including capability of selective imaging, and 10) relative cost per unit of data, resolution† cell, or other common base.

Airborne Mode

Among the parameters listed, several favor this mode. Studies[1] have indicated that space imaging systems can be justified only when sizeable areas are involved. Space systems are required for global coverage; however, the use of aircraft for such supplementary use as large-scale sampling is necessary. For active sensing, such as side-looking RADAR for which penetration of cloud cover is the principal objective and the beam angle to the ground is critical, aircraft may prove superior to space systems regardless of the area involved.

Data-Transmission Mode (ERTS A and B)

The NASA-designated flights of ERTS A and B exemplify the data-transmission space mode from moderate (300–900 km) altitude. The satellites are sun synchronous and designed to fly a year with a set of frame imagers and a scanner—both in multispectral mode. Optical resolution equivalence is expected to be about 100 m.

This system can survey all but the poles of the Earth at a given time of day once every 18 days. Since the Earth is about one-half cloud covered at any one time, there is a 50% probability of seeing any random area on the earth once every 18 days.‡ Of course, this probability varies greatly with the seasons and specific areas of the globe.[2] Even if a given area is seen only once every month or so, the potential for repetitive coverage on a global basis adds a new dimension to remote sensing. The benefits of repetitive coverage have been well established by the weather satellites, but to date no sensor has been flown in spacecraft which images the Earth's surface with meaningful resolution and transmits the data to the ground in near real time.

The large amount of data that such a system can produce creates a data-handling problem in itself, and the rate of data acquisition will have to be carefully controlled. By making experimental flights, as defined for ERTS A and B, the full value and limitations of this mode can be determined. It is doubtful if the users can all be identified until the imagery has been examined by agencies and individuals in a wide variety of pursuits. However, there is ample evidence that ERTS A and B imagery will be put to many practical uses.

Film-Return Mode (ERTS C and D)

Earth-sensing flights in the film-return mode have been designated for NASA flights ERTS C and D. These flights, in contrast to those in the data-transmission mode, last only a few weeks and do not attempt to provide near-real-time information. Proposals for this mode involve mapping cameras of 12-in. and 6-in. focal length resolving the Earth to about 15 m and 40 m respectively. If flown during the optimum season, perhaps 90% of the United States plus sizeable foreign areas could be covered by a single flight. The photographs from this mode have very high geometric fidelity and are therefore ideally suited for topographic and precise planimetric mapping. New maps can be compiled from such photographs which can be used as an effective map base.

† Resolution as used herein is based on the optical line pair spacing criteria.

‡ The 50% probability is based on the Equator. Probability does increase with latitude due to increased sidelap.

Figure 1 shows a section of a standard 1:250,000-scale line map with and without superimposed space photoimagery. Superimposing a space photograph on an existing map is a relatively simple cartographic procedure, but look at the difference it makes in the map. The photographic base on this map consists of two exposures taken on Apollo 9 with a camera of slightly over 3-in. focal length. ERTS C and D, if flown with a 12-in. camera as favored by the Department of the Interior, would provide photographs which could be used for new map compilation and as a photobase for a wide variety of standard and nonstandard maps. Because of their high resolution and geometric fidelity, the photographs can also provide a base for calibration and correlation of ERTS A and B imagery and thus materially enhance the value of these flights. The extent to which such applications can be made can only be determined by acquiring the photographs and imagery and experimenting with them.

So far, photographs of suitable quality have not been obtained by the data-transmission mode for mapping and other uses in which geometry is important. But the aircraft-mode also produces photographs, so why go to space? The economy of the space mode is one of the reasons. The time and cost of map production vary directly with the number of photographs involved—and space systems can reduce the number of stereopairs of photographs (and control points) needed to cover a given area by a factor of at least 100. Thus there is a good case for a film-return satellite as defined for ERTS C and D.

Geosynchronous Mode

This last mode is the least known, least understood, and by far the most expensive per flight. There is, however, some technical literature on the mode.[3] At first glance the geosynchronous mode looks like a rather poor one for earth observations since it involves putting a telescope 20,000 miles away from the Earth. But let's look a bit further.

The geosynchronous satellite continuously hovers over the same area of the Earth. Thus time becomes an important and unique asset of the mode. A sensor in this mode can be pointed at anything within its view (a sizeable portion of the Earth) at any time, subject only to conditions of visibility. What if we want to look at a serious environmental problem such as a pollution source or a natural disaster? Or what if we want to monitor a specified area on a daily or even weekly basis? A large covey of dedicated aircraft might do it, but neither of the other space modes, unless used in large numbers, could meet the requirement.

Another big problem in any Earth-observation program is selectivity. Most imaging systems tend to acquire much more data than actually needed or utilized; however, it all has to be processed, which makes the data-handling problem so critical. A geosynchronous satellite can monitor the Earth at low resolution and at a low data rate until visibility or specific requirements warrant the high-resolution mode. This is exemplified by the Soumi spin-scan camera on the Advanced Technology Satellite (ATS) which is monitoring the earth today at low resolution. The high-resolution mode involves a very high data rate, but it can be restricted to specified areas or conditions, and thus the over-all data bulk can be controlled. It is true that other combinations, such as the ESSA weather satellite and ERTS, also provide some selectivity.

How high a resolution can we expect from such a system? This depends principally on the size of the primary optical collector used. Today reflectors of 1-m diam are being built for NASA's Orbiting Astronomical Observator (OAO). With optimum visibility such an optical collector, if diffraction limited, would resolve a high-contrast object of 20 m. From a practical standpoint, the resolution would probably be closer to 50 m for the average ground scene. The optical industry indicates that diffraction-limited optical reflectors of 1-m diam can be built and put into space today and that much larger ones are technically feasible. In a few years, resolution of about 5 to 10 m could probably be attained, if we are willing to pay the price.

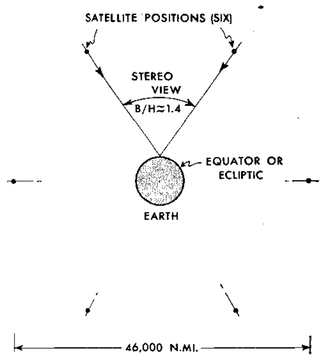

Fig. 2 A six-satellite geostationary system.

But how do we cover the Earth with a satellite that is earth stationary? Obviously we do not. A number of satellites are required for a global-monitoring system. A satellite system which would cover all but the polar areas is diagramed in Fig. 2. One important aspect of such a system is that two satellites could image the same area and thus produce stereoimagery with a relatively high degree of positional accuracy. Thus, such a system has potential for geodetic and cartographic applications as well as for other applications more directly associated with Earth resources.

Summary

This is neither the time nor the place to say which of the four basic modes of imaging the Earth is best or which should be given priority. If we recognize that each mode has unique advantages, then each one should be fully evaluated before deciding on an operational system. Studies, which are currently being made, will help define potential and comparative value of the modes, but this is not enough. Each of the four modes warrants an operational test, and this can be done only by actual flights. The airborne mode has been given many tests, but the three space modes deserve flights dedicated to Earth-resource surveys. If we are going to look at the Earth, let's go about it in a logical and orderly manner. This involves the following three actions: 1) Flying ERTS A and/or B as soon as possible to demonstrate the data-transmission mode. 2) Flying ERTS C and/or D, preferably during the flights of ERTS A and/or B, to demonstrate the film-return mode and to complement ERTS A and B. 3) Flying a geostationary satellite with a high-resolution tracking telescope as soon as a meaningful system can be defined and built.

What about cost? The simplest space flight costs several million dollars, and the geostationary experiment is at least an order of magnitude more expensive than the other two modes on a flight basis. Even so, we are talking about relatively low-cost systems in relation to the space program as a whole.

Cost effectiveness rather than cost is the real issue. What will Earth-sensing systems do to improve the quality of life in the United States and throughout the world? Objective studies on this subject indicate that the benefits will be real and that they will greatly exceed the program cost. Here is a space program that promises to be a really sound investment for the future.

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