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An Intelligent Earth Sensing Information System

To reduce the extremely high data rates that would be associated with future imaging systems, comprehensive on-board processing of the sensed image data would be performed.

INTRODUCTION

By the year 2000, if present trends persist, the population of the world will increase by more than 50 percent, from 4 billion to 6.35 billion.[1] Ex-

the oceans, and atmosphere. Thus, there will be ever increasing demands for effective widespread Earth resource management particularly by means of remote Earth sensing.

Most commonly remote Earth sensing involves

ABSTRACT: *An advanced concept for a user oriented remote Earth sensing system is presented. This satellite system is highly autonomous, uses a world model distributed between space and ground to avoid the present costly redundancy in imagery data transmission from space and storage on Earth, indexes the information in a complete cross-referenced form, and communicates with the user interactively in natural language. The system requires extensive use of artificial intelligence techniques for its operation. We propose that the Intelligent Earth Sensing Information System be implemented by NASA about the year 2000.*

pected consequences will be water and food shortages, widespread deforestation, soil erosion, depleted timber, mineral, and other Earth resources, altered water and air quality, extensive plant and animal extinctions, urban sprawl, and worldwide problems with pollution on the land, in

the acquisition of images or pictures. Imaging data already have high volume rates, and by the year 2000 greatly improved multispectral image sensing from Earth orbit will generate such high data rates that it will be extremely difficult and costly to continue the present practice of transmitting and

archiving all the raw data on Earth. This difficulty points out the need for comprehensive on-board satellite processing of the sensed image data.

Presently the NASA Information System handles approximately 10^{11} bits of data per day at a cost of 2×10^{-5} dollars per bit, which leads to a total cost of approximately 700 million dollars per year.[2] Delays in data flow from sensor to user of 4 to 6 weeks are typical.[3] Through the use of artificial intelligence techniques to achieve goal oriented data gathering, information extraction using a world model, and direct user interfacing, the cost of operating an Earth sensing system can be greatly reduced. Simultaneously, an enhancement of the utility of the system and benefits to the user are obtained.

In the summer of 1980, NASA in conjunction with the American Society for Engineering Education convened a technology feasibility study which was hosted by the University of Santa Clara and the Ames Research Center. The study was given the charge to investigate the use of advanced and intelligent automation in space. The Terrestrial Applications team, one team of five in the study, evolved the concept of an intelligent, autonomous Earth sensing satellite system, which was user oriented and designed to return specific information to Earth in response to user requests and needs. This paper, by the team members, summarizes this concept and methods for its implementation. Most of the details are presented in only one of the many variations and alternatives possible. The intent of this description is not to be encyclopedic about design details, but rather to illustrate the general nature of possible solutions, in sufficient detail, to convey to the reader a feeling for the system and to provide a basis for the assessment of the technological capabilities needed for the realization of such a system. Figure 1 illustrates the overall system.

SYSTEM DESCRIPTION

The system being proposed consists of cooperative autonomous satellites in low Earth orbit communicating with geostationary satellites which in turn are in communication with a ground processing facility. Among other functions, the ground facility provides a direct user interface for scheduling, acquisition, and processing of data.

The heart of this system is a World Model: a compact representation of persistent or predictable spatial and temporal characteristics of the Earth—its land, oceans, and atmosphere—together with algorithms for use of the representation. The World Model describes the topography and environment of the Earth and is used to predict features of what the satellites will observe, as well as to assist in deciding on what observations the satellites should make. The use of the World Model will eliminate the transmission of redundant data by ignoring the expected and identifying significant departures from the norm. We call these departures anomalies. The system operates autonomously without human assistance to

- routinely acquire data on-board;
- process information through comparison with the World Model;
- transmit abstracted information generally, and more detailed information if an anomaly is detected;
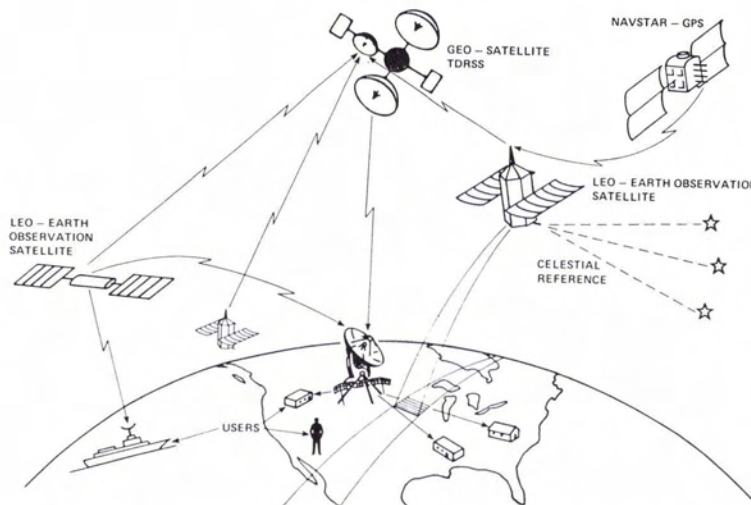- update the World Model; and
- archive information.

FIG. 1.   Intelligent Earth Sensing Information System.

A user can directly address the system interactively using natural language to

- request specific information (condition of a crop in a given area, soil moisture, pollution indexes);
- obtain cost estimates for requests;
- request algorithms for on-board processing;
- supply new algorithms (if the user is sufficiently sophisticated); and
- cancel or modify requests (according to cost, expected cloud cover, information gathered).

Processed information will be labeled on-board the satellite according to geographical location, land feature, and type of information, so that a complete set of cross-referenced information can be stored on the ground for access by users. For example, a user will be able to request the system to give pollution indexes for the previous six months for the state of New Jersey.

The World Model consists of two separate components. The first is the state component (data base), which defines the state of the world to a predetermined accuracy and completeness. The second component is the theory component, consisting of a set of interacting expert systems which allow

- abstraction of useful information (from imagery data in particular);
- achievement of large-scale data reduction by the use of feature extraction and data compression; and
- the satellites to gain experience by which to judge new knowledge.

The simplest type of data base is a terrestrial map. Given such a map, there are obvious surface features which possess a distinct boundary and homogeneous characteristics within the boundary and whose location does not vary rapidly with time. We call such features niches. That is, a niche is a feature having a high degree of spatial redundancy in its imagery as well as a high degree of temporal redundancy. More complicated data bases will incorporate contour maps, dynamic models for the oceans and atmosphere, and time dependent characteristics.

A niche possesses a high degree of spatial redundancy in its imagery. Because the niches are at least semipermanent, there is also a high degree of temporal redundancy. A large lake will remain the same lake on each satellite overpass; parts of the lake are very similar to other parts and are very distinct from the surrounding land. The large degree of redundancy allows very substantial data reduction by processing each sensor reading across the image of a single niche and extracting desired characteristics of that niche. These characteristics can then be combined across sensors to produce further data reduction. Despite the large reduction in the number of bits of data, the relevant and useful information can be retained.

To illustrate the possible data reduction we take a 10 km by 10 km square land region at a pixel resolution of 10 m. This gives an image measuring 1000 by 1000 pixels. Assume just one observation wavelength is involved, and eight bits are used for the intensity at each of the 10^6 pixels, giving an image described by 8.0×10^6 bits. We estimate from a limited examination of aerial photographs that such a region will possess on the average 30 niches. Each niche must be fully described in terms of characteristics important to that niche such as area, average sensor value, variance, higher moments, two dimensional slope in the sensor intensity, and texture. If we take 15 characteristics to describe a niche, then only 450 data pieces, at (for example) eight bits each, are needed to replace the 8,000,000 bits of the full image. A reduction of 2222:1 is immediately accomplished.

Further reduction can be accomplished by combining the data across the, say, 20 sensor wavelengths proposed for the satellites, and across the 15 characteristics. These reduced data can be used, for example, for signature identification, identifying the state of the niche, or classifying an anomaly. The near maximum amount of data reduction occurs when the imagery is required to answer a sophisticated question posing a choice from 256 alternatives, i.e., eight bits. The 10^6 pixel elements over 20 sensors require only one eight-bit data transmission and subsequent storage, yielding a data reduction of 2.0×10^7:1. If the question only requires a "yes" or "no" answer, only one bit need be transmitted and the absolute maximum in data reduction in this simplified example is 1.6×10^8:1. Table 1 summarizes this hypothetical case.

The satellite system will be capable of discovery. Novel occurrences will be detected by the satellite system by searching for anomalous features in the imagery when compared to the World Model. Anomalies will occur as unusual values of the sensory characteristics of the niche, e.g., blight on a corn field. Prompt identification of these anomalies will allow real time management action in response to the anomalous occurrence.

The use of a World Model requires placing a simplified model in memory on-board the satellite system, in order to accomplish direct data reduction, and placing a sophisticated model on the ground. This ground model will serve as a master model of the world for use in updating, calibrating, and further processing the transmitted data. A very important feature of the World Model is that it allows full cross-indexing of world niches, sensor characteristics, and subsidiary characteristics. The ground model will constitute a full library in which, for example, a land agent can call out moisture content on all the corn acreage in Southwest Iowa.

In addition to a physical memory on-board and

TABLE 1.   DATA REDUCTION USING A WORLD MODEL IN A SIMPLIFIED EXAMPLE

To Transmit and store	Bits	Reduction
10^6 image pixels, 20 sensors, 8 bits each	1.6×10^8	$1 : 1$
30 niches, 20 sensors, 15 characteristics at 8 bits	7.2×10^4	$2,222 : 1$
256 choice answer	8	$2.0 \times 10^7 : 1$
yes or no answer	1	$1.6 \times 10^8 : 1$

on the ground, the World Model will require intelligence—expert systems which will use the memory in executing sensing, image location, and rectification, determination of satellite location, data processing, labeling, anomaly search, and decision making on-board the satellite. A set of expert systems on the ground will be needed to handle scheduling and user generated processing tasks. The ground expert systems must be capable of fairly generalized learning, such as determining time series and correlation among data and variables, and be capable of continually updating the master World Model.

Present day predictions for on-board memory in the year 2000 for Earth sensing satellites have been on the order of 10^{14} bits.[4] We wish to compare these projections with the storage capacity required by the type of abstracting and on-board processing we are advocating in this mission plan.

The bits stored on-board the satellite or satellites for use in immediate processing tasks will presumably be substantially less than the number stored on the Earth portion of the sensing system. The Earth stored World Model should be a completely updated version of the Earth model. Future feasibility experiments along with computer developments will dictate the actual number of bits required in space and on Earth. Here we simply give an estimate of the bit storage required under a particular set of plausible assumptions.

For our estimation we assume a correlation is to be performed between the incoming image of a given region and its image stored in the World Model. Significant features of the incoming image are contrasted/identified with distinguished features (niches) catalogued for the World Model region. We estimate the number of bits needed to store this information on the distinguished features to be 4.0×10^{11} bits. This figure was obtained by assuming approximately 100 bits to describe each niche, that significant identifiable land niches occur on the order of 0.3 features per square kilometer, and that 20 sensors having 15 characteristics each will be used for sensing. A more detailed description is given by Fay *et al.*[6]

ON-BOARD PROCESSING

The observing satellite will receive the schedule for its next pass from the uplink and perform the required processing according to this instruction set. Overall Earth cloud cover and weather conditions will be obtained from one of the geostationary satellites of the system and navigational data will be obtained from a global positioning system assumed to be in place. The satellite will adjust (if required) its attitude, turn sensors on or off or modify their resolution, and take both active and passive observations of the Earth. The data can then be processed by comparing them to the predicted observables as derived from the World Model, and any anomalies can be noted. If anomalies are present, they are identified, if possible, and then cataloged and appropriate action is taken. If anomalies are present and cannot be identified by the system with a high degree of confidence, the anomaly is placed on file for transmission to a human for analysis and action. All sensor data collected are abstracted and summarized by feature and placed in the abstracted observation file for archiving and World Model updating. Any user-requested processing is then performed and a user file is established. This is shown schematically in Figure 2.

For the intelligent satellite system we propose, the sophisticated image sensing devices which it will have in orbit place strong demands for rapid and economical processing of the image data. One of the primary functions/services of the system being designed herein is to perform rapid and massive data reduction on-board the satellites. The desired capabilities of such an intelligent satellite are given in Figure 3.

The bit rate generated by one optical or IR sensor is 8 × orbital velocity × swath width/ (resolution distance)², for an eight-bit pixel. As an example of the data rate generated, we assume that each satellite will contain three steerable platforms of 20 sensors each and that two platforms have a high resolution of 5 m over a 110-km swath while the remaining platform has low resolution of 15 m over a 350-km swath. The total bit rate generated at a 7-km/sec orbital speed is 11.5×10^9 bits/ sec. Of the remaining sensors, a synthetic aperture radar will produce the maximum data rate by far. A present day SAR apparatus generates data at 0.65 × 10^9 bits/sec.[5] Representative Doppler Lidar, Doppler Radar, and Laser Altimeters generate data at the rates of several kilobits/sec, while radar al-
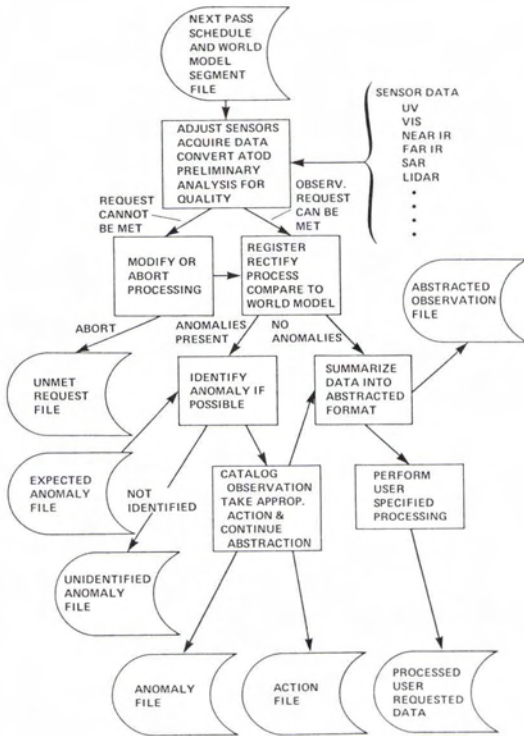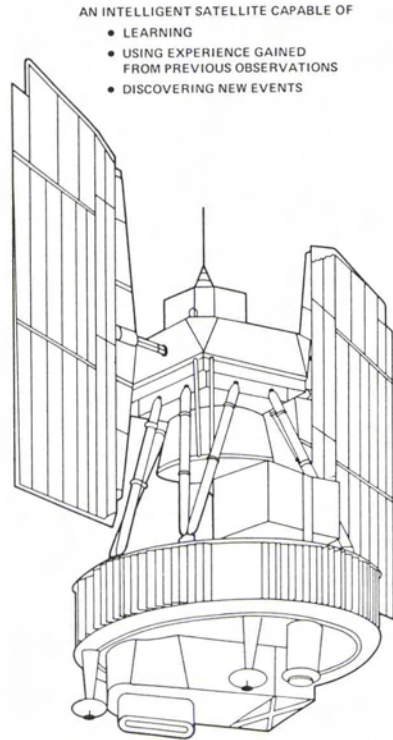
FIG. 2.   On-board processing.

FIG. 3.   Satellite characteristics.

timeters generate data at the rate of several tens of kilobits/sec. On-board computing capability requirements thus must be sufficient to handle data rates near 12×10^9 bits/sec.

SATELLITE REQUIREMENTS

A summary of required measurement rates has been given by Nagler and Sherry for a wide range of environmental and resource assessments.[5] The required frequency of observation is generally lowest for Earth based features, higher for ocean observation, and highest for atmospheric-weather assessments, with considerable overlap in the requirements. Table 2 summarizes our interpretation of reasonable frequencies of Earth observation and attendant observation swath width.

It appears reasonable to have a set of sun-synchronous satellites operating continuously so that each Earth point will be covered at the equator every two days by at least one satellite of the set. Sun synchrony will produce similar sun angle conditions for an observed land point for a particular satellite. This standardizes image interpretation for that satellite at that point. An altitude near present day Landsat orbital altitudes (920 km nominal) will produce a long lived satellite. If the altitutde is adjusted to yield 14⅛ orbits per day, the orbit of a particular satellite will repeat every eight days and four such satellites will cover the Earth with the desired two-day period at the equator. The swath width required of a satellite for eight-day coverage at 14⅛ orbits per day is about 350 km. In order to take account of partial cloud cover, we propose six satellites in sun-synchronous orbits. If the satellites are placed substantially uniformly about the Earth's circumference, the local viewing time for each satellite will be about two hours apart. It may be desirable to bunch the satellites somewhat if there are reasons to pick a particular local viewing time. Polar conditions can be monitored by a seventh polar satellite, which can also act as a spare satellite if one of the sun-synchronous satellites is disabled.

In order to efficiently communicate between the Earth and space portions of the system, a minimum of two geostationary satellites will be required. These satellites will also be used to monitor global conditions, particularly global

TABLE 2.   POSTULATED OBSERVATION FREQUENCY AND SWATH WIDTH

	Observation Frequency	Largest Swath Width
Earth	0.5/day	350 km
Ocean	3/day	700 km
Atmosphere	12/day	1400 km

cloud cover. The global cloud cover information will be used to prepare each satellite for the tasks which it can most usefully perform during its upcoming orbit by identifying areas covered by clouds, enabling modifications in sensors and processing to optimize the information obtained from the observations.

The sensor requirements are dictated by the Earth environment which must be scanned to fulfill the terrestrial resource mission. In order to fully utilize the satellite's abilities and operating time, we demand useful sensing during the daylight pass of an orbit, during the nighttime pass, and during cloud cover.

For daylight sensing we suggest two ultraviolet bands, five visible bands, and three near IR bands as giving a sufficiently broad color space of ten dimensions to allow for very widespread signature analysis of important Earth features such as crops, rivers, lakes, clouds, forests, snow, and so on.

Four wide band far-IR sensors would allow accurate temperature and signature definition of nighttime features, although not to the same precision and resolution as daytime sensing.

All-weather capability requires active microwave scanning of the Earth. The Synthetic Aperture Radar (SAR, SIR-A, operating at 1-10 GHz)[5,7] is capable of substantially all-weather observation at good resolution. The SAR system would also augment the nighttime passive measurement in the far IR.

Altitude information will be useful for monitoring Earth resources, for example, crop height, reservoir levels, and mountain snow cover. Such height can be recorded from differential altitude measurements at a boundary, for example, by altitude differencing between a crop top and nearby level ground. We thus specify a differential altitude measurement system such as possibly using a rapid Q-switched LIDAR. Absolute altitude measurements can be obtained by LIDAR or with a microwave altimeter. Finally, we require Doppler sensor capability for directly determining such things as cloud and river velocity.

There will undoubtedly be requirements for additional specialized optical, IR, and microwave sensor bands to detect important surface and atmospheric components such as ozone, CO_2, and H_2O.[8] We have arbitrarily allocated six specialized sensor bands to these uses, which brings the complement of passive image sensors to 20.

SUMMARY

We have presented in outline the concept of an ambitious Earth resource monitoring system directed toward future needs. We propose the extensive use of artificial intelligence techniques within an autonomous satellite system to acquire and interpret data required by future users at as low a cost as feasible. Comments on the concept are solicited with the expectation that discussion will begin on the usefulness of and problems involved in the system suggested. In this way we hope to facilitate the move from concept to reality.

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