Architecture of Future Intelligent Earth Observing Satellites (FIEOS) in 2010 and Beyond

Technical Report
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By

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EXECUTIVE SUMMARY

This paper reports the results of a project, *Architecture of a Future Intelligent Earth Observing Satellites for 2010 and Beyond*, which was funded by the National Aeronautics and Space Administration Institute of Advanced Concepts (NASA-NIAC). The period of this contract ran from June 1st 2001 – November 31st 2001. The following results are produced:

(1) A paper entitled *Architecture of Future Intelligent Earth Observing Satellites*, was published in the *ISPRS Joint Workshop on High Resolution Mapping from Space 2001*, Sept. 19-21, 2001. University of Hanover, Germany.

(2) An oral presentation entitled *Concept Design of Future Intelligent Earth Observing Satellite*, was made at the *NASA-NIAC Fellowship and Workshop*, held at the NASA Institute Advanced Concepts Headquarters on October, 30-31, 2001, in Atlanta.

(3) A paper entitled *An Advanced Concept on Future Intelligent Earth Observing Satellites*, has been prepared for presentation at the *First International Workshop on Future Intelligent Earth Observing Satellites* (FIEOS), to be held April 25-27, 2002, in Washington DC.

(4) A paper entitled *On-board Geo-Database Management System on Future Intelligent Earth Observing Satellites*, has been submitted to the *First International Workshop on Future Intelligent Earth Observing Satellites* (FIEOS), to be held April 25-27, 2002, in Washington DC.

(5) A paper entitled *Future Intelligent Earth Observing Satellites in 2010 and Beyond*, is in preparation for publication in *Photogrammetric Engineering and Remote Sensing* (PE&RS).

(6) An architecture for a future intelligent earth observing satellite system, including space segment, control segment and end-users, has been formulated, and a background analysis, including summary of current state-of-the-art of satellite development and identification of key technology issues confronting deployment of the envisioned system, has been discussed. Two aspects of the system, on-board orthorectification of satellite images and on-board geo-database management, have been considered in detail.

(7) A symposium entitled *International Symposium on Future Intelligent Earth Observing Satellites* has been organized and reported separately.

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1. INTRODUCTION

1.1 Background

Beginning with the early use of aerial photography, satellite remote sensing has been recognized as a valuable tool for viewing, analyzing, characterizing and making decisions about our environment. This is because: (1) satellite remote sensing uses sensors/detectors to acquire information about objects or phenomena from a distance, rather than *in situ* (Schowengerdt, 1997; Lillesand and Kiefer, 2000); (2) the spectral range imaged through satellite remote sensing is greater than the visible range of electromagnetic energy that our eyes only sense; (3) viewing perspectives range from regional to global scale; and (4) satellite images can form a lasting record.

To meet the needs of different users for remotely sensed data, there are many remote sensing systems (spaceborne, airborne) offering a wide range of spatial, spectral and temporal parameters. For example, some users may require frequent, repetitive coverage with relatively low spatial resolution (e.g., meteorology); others may desire the highest possible spatial resolution with repeat coverage only infrequently (e.g., mapping); while some users need both high spatial resolution and frequent coverage, plus rapid image delivery (e.g., military surveillance). With the development of information technology, user's needs have migrated from traditional image-based data to advanced image-based information/knowledge (Zhou, 2001). To meet these needs, the design of earth observing satellites faces dramatic challenges in the future. This technical report describes our vision and concept design for an emerging architecture for the *Future Intelligent Earth Observing Satellite (FIEOS)*.

1.2 History of Earth Observing Satellite Development

It is difficult to absolutely divide the history of earth observation satellite development into specific stages. However, to explain the process of satellite development, we can distinguish four general phases (Figure 1). Note that few military or meteorological satellites are considered. This is because (1) the parameters of many military satellites are classified and (2) meteorological satellites consist of a large number of satellites, which measure a wide variety of earth variables.

1.2.1 The First Generation: Early Satellites (early 1960's thru 1972)

CORONA, ARGON and LANYARD were the first three operational satellite imaging reconnaissance systems. They acquired data for detailed reconnaissance purposes and for regional mapping. They were operated in response to the uncertainties and anxieties created by the Cold War (McDonald, 1995), appearing at the beginning of the space age. The images derived from these early satellites consists of hundreds of thousands of photographs (some scanned and digitized), mostly black and white, but some in color and stereo, over large portions of the earth at resolutions of about 140 m (KH-5 camera, http://www.fas.org/spp/military/program/imint/corona.htm). The imagery, while highly instructive, was less systematic than the later Landsat data.

The primary characteristics of the observation systems in these satellites were their imaging systems, which were basically similar to aerial photogrammetric configurations (Zhou and Jezek, 2001a). For example, the ARGON 9034A mission, launched on May 16, 1962, carried a single panchromatic frame/film camera (KH-5) with a focal length of 3 inches. The overlap percentage of the neighboring photograph was 70%. The ground resolution was 140 m with a ground swath of 556 km by 556 km. Flying height was nominally 322 km with an inclination of 82.3°.

1.2.2 Second Generation: Experimentation and Initial Application (1972 thru 1986)

The Landsat 1, launched on August 7, 1972, symbolized the modern era of Earth remote sensing. For the first time it provided a consistent set of synoptic, high resolution Earth images to the world scientific community, and made it possible for the earth science community to use satellites for earth resource investigation (NASA, Landsate Satellites: Unique National Assets, at http://www.gsfc.nasa.gov/gsfc/service/gallery/fact_sheets/earthsci/landsat/landsat7.htm). The dominant characteristics of Landsat 1 were its multiple spectral scanner, which sensed four regions of the electromagnetic spectrum ranging 0.5 to 1.1 microns, a reasonably high spatial resolution (80 m), a swath width of 185 km, and repeating coverage (every 18 days). Moreover, satellite image data was delivered directly in digital form for the first time. Much of the foundation of multispectral data processing was developed in the 1970s by organizations, such as the National Aeronautics and Space Administration (NASA), the Jet Propulsion Laboratory (JPL), the U. S. Geological Survey (USGS), the Environmental Research Institute of Michigan (ERIM), and the Laboratory for Applications of Remote Sensing (LARS) at Purdue University. After 10 years, we have seen, in addition to four MSS bands, the Landsat Thematic Mapper (TM) in 1982 and 1984 with 30 m spatial resolution and 7 spectral bands, until the SPOT HRV in 1986 with 10 m resolution at panchromatic band and 30 m spatial resolution in 3 spectral bands. The characteristics in this period are:

1. Migration of satellite application from military to civil,
2. Initial use of multispectral imagery to earth resources investigation and management,
3. Stereo mapping unavailable,
4. Best ground resolution 30 m,
5. Imaging systems basically optical and passive mode, and
6. Primary systems: Dong Fang Hong (03~17, China), Meteor 1-28/29 (1977, USA), Landsat 1~5 (USA), Seasat (USA), Nimbus 7 (USA), AEM 1 (USA), Cosmos 1076, 1602, 1689 (India).

1.2.3 The Third Generation: Wide Application (1986 thru 1997)

The earth observation satellite family experienced significant development in technologies and applications during this period. The SPOT-1 satellite, launched on 22 February 1986, carrying two High Resolution Visible (HRV) sensors, was another benchmark because it was the first to use a linear array sensor with “push-broom” imaging geometry. With its 10 m panchromatic band it was the first satellite capable of stereoscopic imagery in cross-track. The ERS-1 Synthetic Aperture Radar (SAR), launched 17 July 1991 by the Europe Space Agency (ESA), is an active microwave sensor satellite with 30 m spatial resolution in imaging mode. The Japanese ERS-1, launched in February 1992, added more width to the SAR application by adding an L-band to the configuration. These active microwave sensor satellite primarily provide data useful for improving the understanding of environmental and climatic phenomena, as well as supporting a variety of operational applications, such as sea-ice charting and coastal zone studies. Briefly, the characteristics of this period are:

- The first use of linear array push-broom imaging mode in SPOT-1,
- Off-nadir viewing enables the acquisition of stereoscopic imagery for stereo mapping,
- Ground resolution of 10 m in panchromatic channel in SPOT-1,
- Deployment of active microwave sensor satellites: ERS-1 with 30 m GSD (ground sample distance) in 1991, Japanese ERS-1 with 18 m GSD in 1992, and the Canadian Radsat with 25 m GSD in 1995, and
- Development of the PFM (Plateforme Multimission) platform (used on SPOT & ERS-1).

1.2.4 The Fourth Generation: The "New" Generation of High-Resolution Satellites (1997 to "2010")

In 1995, a conference titled "*Land Earth Satellite for Decade*" was sponsored by the American Society for Photogrammetry and Remote Sensing (ASPRS) and co-sponsored by the Landsat Management Team (NASA, NOAA, and USGS), NIMA, USDA, EPA, NASA Applications and others to address the future of earth observing satellites. More than 700 experts from the satellite companies, value-added producers and end-user communities took part in the conference to discuss anticipated applications, potential problems, and common solutions (Stoney, 1996). From the conference we concluded that the ***next generation*** of high-resolution, multi(hyper)spectral satellite systems would be marketed and widely applied to a wide variety of Earth sciences. This predication has come to pass as demonstrated by the 32 satellites at ground resolution from 1 to 15 m in panchromatic, multispectral and radar formats currently programmed to be in orbit by 2005.

The specifications of these new high-resolution satellites vary widely. (See http://www.ccrs.nrcan. gc.ca/ccrs/tekrd/satsens/sats/landsate.html) The major features of interest are their spatial resolution, temporal resolution, spectral coverage, orbital altitude, revisit capability, width of swath, image size, stereo capability, imaging mode (sensors), data record, satellite owner and market requirements.

1) **Spatial resolution:** Panchromatic imagery with 1 to 3 m resolution, multispectral imagery with 4 m resolution and hyperspectral imagery with 8 m resolution.
2) **Swaths:** 4 to 40 km.
3) **Spectral coverage:** 200 channel hyperspectral imagery.
4) **Revisit:** Less than three days with the ability to turn from side-to-side on demand further decreasing the revisit interval.
5) **Delivery time from acquisition to user:** Imagery can be down-linked in real-time to ground stations located around the world.
6) **Capability of stereo:** In-tracking and cross-tracking stereoscopic capability using the linear array imaging principle. In particular, IKONOS and Quickbird satellites can offer rigid photogrammetric geometry for the high metric accuracies need by the mapping community**.**
7) **Sensor position and attitude:** GPS and digital star trackers to maintain precise camera station position and attitude.
8) **Imager type:** “Whisk-broom” and “push-broom” imaging modes.
9) **Owners**: The owners of high-resolution satellites are: Argentina, China/Brazil, Canada, France, Germany, India, Israel, Japan, Korea (South), Ukraine, the US government and US commercial companies (Figure 2).

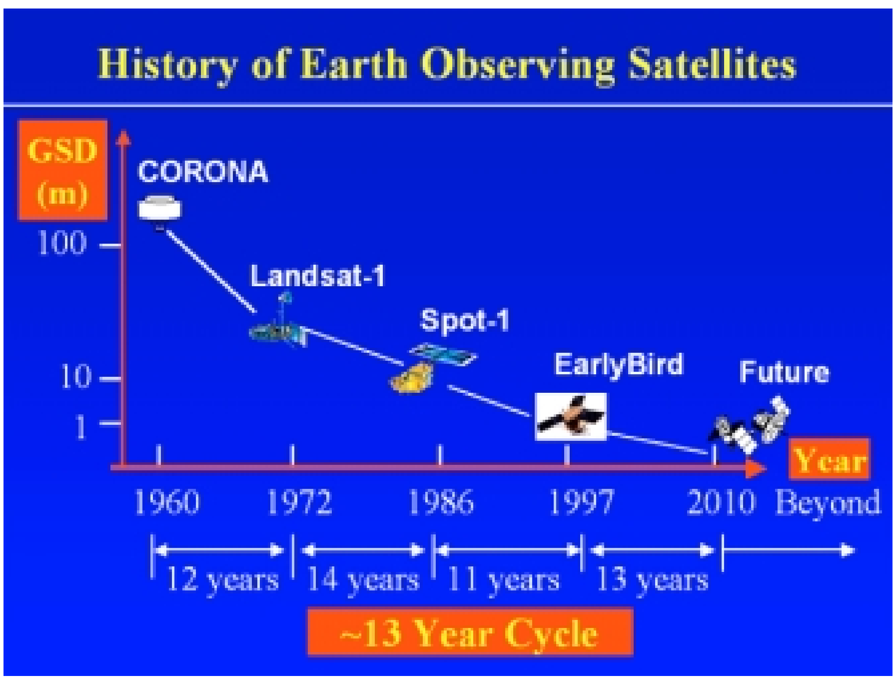
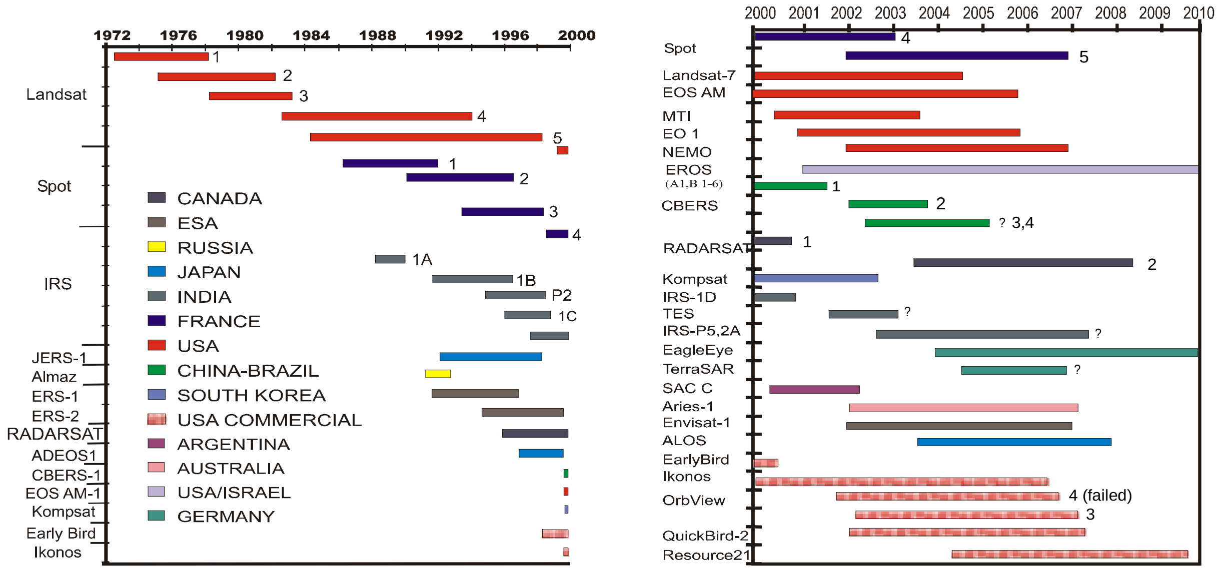


Figure 1. History of Earth observing satellite development



(a) (b)

Figure 2. Earth Observing Satellites from 1972 to 2010.

1.3 What is the *Next* "New Generation" of Earth Observing Satellites?

As shown in the analysis above, there has been a significant jump in the technology of earth observing satellites about every 13 years (Figure 1). Based on this cycle, it is estimated that the current generation of earth observing satellites will be replaced by another generation by 2010. This leads us to ask "What will characterize the NEXT generation of earth observing satellites?"

We think the Earth observation satellite has passed the threshold of maturity as a commercial space activity. The next generation of satellites will be intelligent. The intelligent system envisioned will be a space-based configuration for the dynamic and comprehensive on-board integration of earth observing sensors, data processors and communication systems. It will enable simultaneous, global measurement and timely analysis of the Earth's environment for real-time, mobile, professional and common users in the remote sensing, photogrammetry, GIS, etc., communities (Zhou, 2001). This is because user's demands in the GIS, mapping, natural resources, environmental science, Earth monitoring, etc., communities have migrated from basic imagery to temporal, site specific, update mapping products/image-based information. Data and information revisions will be requested more frequently, that is, in many ways analogous to today's weather updates. In addition, common consumers will be less concerned with the technical complexities of image processing, requiring imagery providers to use different strategies to directly provide users with value-added images (e.g., orthorectification, feature enhancement, radiometric intensification, etc.) and value-added products (e.g., orthoimage mosaics) in order to meet real-time, mobile needs. This presents new challenges for the next generation of technology development. These challenges include, for example:

(1) **Revisit cycle:** Although the revisit cycle of current satellites can be as good as 1-3 days, and IKONOS achieves near real time to users worldwide with a 5-meter mobile antenna on a trailer, the real-time data collection requirements of most users can not be met presently (e.g., emergency rescue, flood real-time monitor, military field-battle, etc.). *Intelligent satellites will require a revisit cycle with hours or decade minutes base to meet various users' needs.*

(2) **Common users:** Currently downlinked satellite "raw" data cannot directly serve common users, e.g., farmers, because they do not know how to generate orthophotos for area measurement, how to generate an elevation model or how to classify imagery according to their needs without professional training and special software. *Like today's maps, intelligent satellite images will serve a wide array of users.*

(3) **Direct downlink for users:** Traditionally, the process of providing data to a user involves: (1) transferring an original satellite signal to an intermediate frequency, (2) storing this frequency as 'raw' digital data, (3) converting the raw data to computer-readable data, and (4) archiving this data until a user orders the image. *Future intelligent satellite images will be directly downloaded with a mobile device, such as a cell phone or laptop computer.*

(4) **Simple receiver facilities:** Satellite receiving stations usually have to establish fixed facilities, such as large antennas. *Future intelligent satellite images will be downlinked by mobile devices containing small antennas.*

(5) **Easy operating receiver:** Traditionally, satellite receiving stations only carry out image receiving and archiving with little concern for how the images will be used. On the other hand, most non-professional users do not know how to order or use these images. As a result, many remote sensing images have been archived and may never be used. *Future intelligent satellite images will be down-linked and used as easily as today's TV. Users will use a remote control to select a "channel" to get the images they want.*

(6) On-board generation of value-added products: The current capability of on-board satellite data processing is still very low. Many products of satellite data are the result of post-processing, e.g., classified maps. This situation largely limits their application because common users do not typically have the software or ability to use it. *The value-added products delivered by the future intelligent satellite will be processed on-board via user commands.*

2. THE CONCEPT DESIGN OF INTELLIGENT EARTH OBSERVING SATELLITES

2.1 The Principle of Concept Design

Usually, in space system design community the principle of design has been that one begins to define and specify the satellite system, i.e., the requirements of users are not a priority (Campbell et al., 1998). In contrast, the principle of design for intelligent satellite systems is that users and their needs form the starting point. This is because more and more users want the imagery provider to provide the value added content they need, but these users are not concerned with the technical complexities of image processing. Therefore, timely, reliable and accurate information, with the capability of direct downlink of various bands of satellite data/information and operation as simple as selecting a TV channel, is highly preferred (Figure 3). Thereby, the FIEOS first will be designed conceptually without considering the complexity of technology, and then the feasibility and possibility of technologies are validated and the development phase and cost required to realize these concepts are estimated.

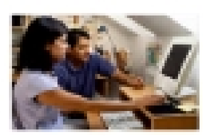
Various Users		**Illustration**
Mobile user	A real-time user, e.g., a mobile GIS user, requires a real-time downlink for geo-referenced satellite imagery with a portable receiver, small antenna and laptop computer.	
Real-time user	A mobile user, e.g., a search-and-rescue pilot, requires a real-time downlink for geo-referenced panchromatic or multispectral imagery in a helicopter.	
Lay user	A lay user, e.g., a farmer, requires geo-referenced, multispectral imagery at a frequency of 1-3 days for investigation of his harvest.	
Professional user	A professional user, e.g., a mineralogist, requires hyperspectral imagery for distinguishing different minerals.	
Professional user	A topographic cartographer, e.g., a photogrammetrist, requires panchromatic images for stereo mapping.	

Figure 3. Some examples of future direct end-users.

2.2 Architecture of Concept Design of Intelligent Earth Observing Satellite (FIEOS)

It is apparent that no single satellite can meet all of the requirements presented by users above. In addition, the past design of Earth observing satellite systems focused on placing numerous scientific instruments on relatively large and expensive space platforms (Prescott et al., 1999). This requires that the instruments, the spacecraft and the space transport system have multiple redundant components that are built with expensive failure-proof parts because of the risk of launch or in-orbit failure (Schetter et al., 2000; Campbell et al, 1999; and Zetocha, 2000). The design of the future intelligent satellite system will overcome these drawbacks by using such features as a multi-layer satellite web with high-speed data communication (cross-link, uplink and downlink) and multiple satellites with on-board data processing capability.

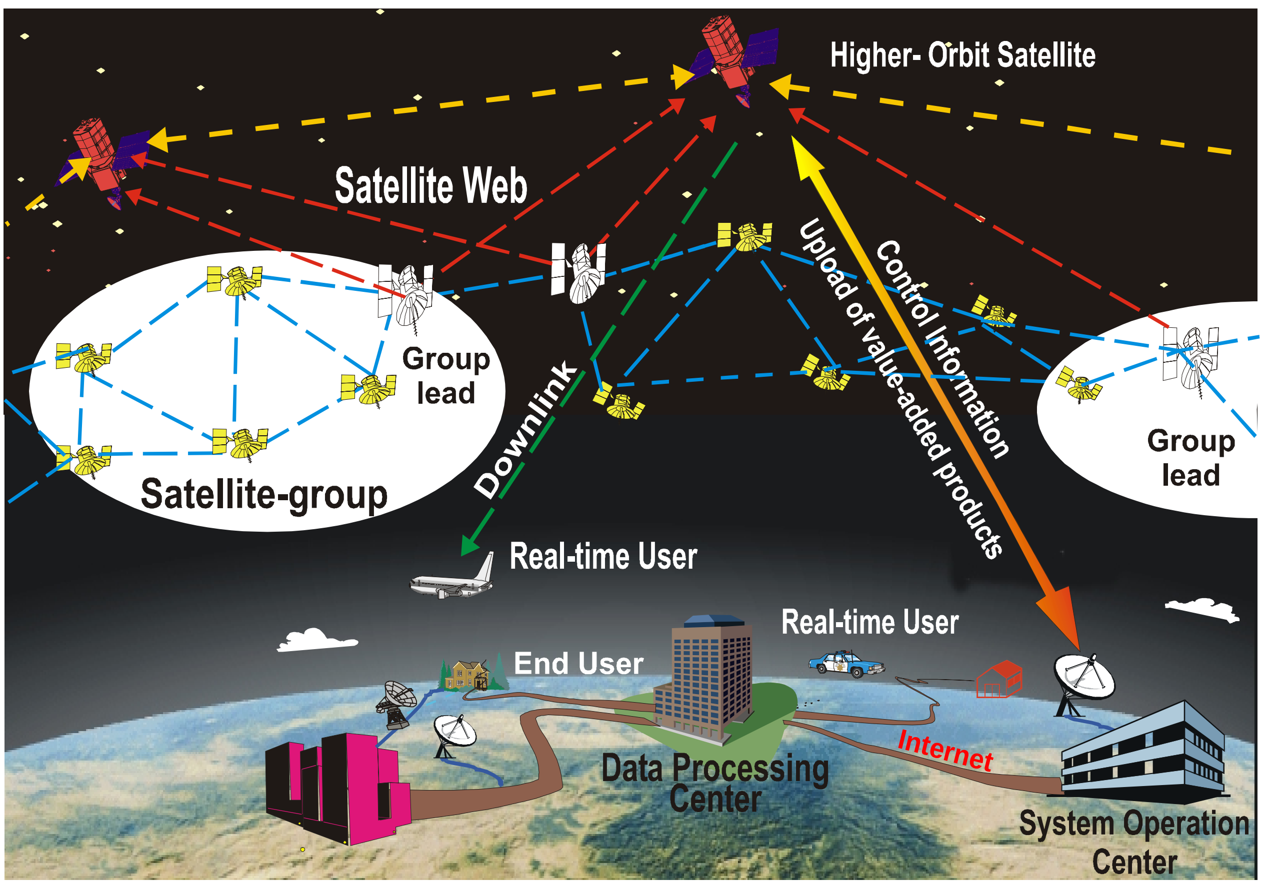


Figure 4. The architecture of a future intelligent earth observing satellite system.

2.2.1 Multi-layer satellite networks

This satellite network consists of two layers. The first layer, which consists of hundreds of earth observing satellites (EOSs) viewing the entire earth, is distributed in low orbits ranging from 300 km to beyond. Each EOS is small, lightweight and inexpensive relative to current satellites. These satellites are divided into groups called *satellite groups*. Each EOS is equipped with a different sensor for collection of different data and an on-board data processor that enables it to act autonomously, reacting to significant measurement events on and above the Earth. They collaboratively work together to conduct the range of functions currently performed by a few large satellites today. There is a lead satellite in each group, called *group-lead*; the other satellites are called *member-satellites*. The group-lead is responsible for management of the member-satellites and communication with other group-leaders in the network (constellation) in addition to communication with the geostationary satellites. This mode of operation is similar to an *intranet.* The group-lead looks like a local server, and the member-satellites look like the computer terminals. The local server (group-lead) is responsible for internet (external) communication in addition to management of the intranet (local) network. This design can reduce the communication load and ensure effectiveness of management and coverage of data collection.

The second layer is composed of geostationary satellites because not all EOSs are in view of or in communication with worldwide users. The second layer satellite network is responsible for communication with end-users (e.g., data downlink) and ground control stations, and ground data processing centers, in addition to further processing of data from group-lead satellites.

All of the satellites are networked together into an organic measurement system with high speed optical and radio frequency links. User requests are routed to specific instruments maximizing the transfer of data to archive facilities on the ground and on the satellite (Prescott et al., 1999). Thus, all group-leads must establish and maintain a high-speed data cross-link with one another in addition to uplink with one or more geostationary satellites, which in turn maintain high-speed data cross-links and down-links with end users and ground control stations and processing centers.

2.2.2 Performance of satellite constellation

The normal operating procedure is for each EOS to independently collect, analyze and interpret data using its own sensors and on-board processors. These collected data will *not* be transmitted to ground users, the ground station, or geostationary satellites unless they detect changed data. When an EOS detects an event, e.g., a forest fire, the sensing-satellite rotates its sensing system into position and alters its coverage area via adjusting its system parameters in order to bring the event into focus (Schoeberl et al., 2001). Meanwhile, the sensing-satellite informs member-satellites in its group, and the member-satellites adjust their sensors to acquire the event, resulting in a multi-angle, -sensor, -resolution and -spectral observation and analysis of the event. These data sets are merged to a geostationary satellite that assigns priority levels according to the changes detected. Following a progressive data compression, the data is then available for transmission to other geostationaries. The links between the geostationary satellites provide the worldwide real-time capability of the system. Meanwhile, the geostationary further processes the data to develop other products, e.g., predictions of fire extend after 5 days, weather influence on a fire, pollution caused by a fire, etc. These value-added products are then also transmitted to users.

If the geostationary cannot analyze and interpret the data, the "raw" data will be transmitted to the ground data processing center (GDPC). The GDPC will interpret these data according to user's needs, and then upload the processed data back to the geostationary satellites. In the constellition, all satellites can be independently controlled by either direct command from a user on the ground, or autonomously by the integrated satellite-network system itself.

The satellite transmits the image in an order of priority, the more important parts of the data first. For example, the multi-spectral imagery of a forest fire may have higher priority than the panchromatic imagery. Panchromatic imagery for 3D mapping of a landslide may have priority over the multispectral imagery. Of course, the autonomous operation of the sensors, processors and prioritization algorithms can be subject to override by system controllers or authorized users.

This concept of performance is similar to the *sensor-web* concept as envisioned by the *Earth Science Vision Initiative*, and *Earth Science Vision Enterprise Strategic Plan of NASA*. Here, we expand that concept with a detailed description of each of the FIEOS components.

2.2.3 On-board data processing

A crucial component for FIEOS is its on-board data processing capability. It should contain, for example, (1) image data processor, (2) data management processor, (3) data distributor, (4) resource management processor, (5) housekeeping functions and (6) platform/sensor control.

Image Data Processor: Each EOS should have strong capabilities for on-board image processing, especially change detection capability. This low-level of data processing should have the following capabilities:

- Image filtering, enhancement, and radiometric balance,
- Data compression,
- Radiometric and geometric on-board correction of sensor signals,
- Geometric on-board correction of systematic alignment errors,
- Geometric on-board correction of spacecraft attitude,
- A thematic on-board classifier for disaster warning and monitoring, and
- Change detection so that only specified change data are transmitted.

A higher-level data processor is required for generation of value-added products, which use robust algorithms (less human interaction). This level of processing can be cost effectively performed on the ground at present. This processor will be mounted on geostationary satellite. A typically configuration might include:

- Predication via specific model,
- Completely autonomous mission planning and schedule,
- Completely autonomous housekeeping, data management,
- Completely autonomous sensor and platform control,
- Autonomous resource management, etc.

On-board Data Management: FIEOS will have enough functions to autonomously perform all conceivable manipulations of data to meet the various user's tasks on-board, e.g., data handling, data storage, data downlink, data distribution (distributor), etc.

On-board Data Distributor: FIEOS will automatically and directly distribute data to different user upon their request without other human involvement and with minimum delay. The optimal downlink times should be uploaded in the form of a file from a ground control center or calculated on-board the geostationary satellites. The more important parts of the data are sent first, followed by the less important parts of the data.

On-board Housekeeping: FIEOS will be capable of all routine housekeeping tasks. For example, the satellites should autonomously manipulate, in the case of anomalies, failure detection, failure identification and first-level recovery actions, as well as software loading, unloading and management.

On-board Resources Management: FIEOS will be capable of autonomous management and assignment of power. Excess power and energy (above the basic spacecraft control requirements during daylight and eclipse phases (Teston et al., 1997)) will be allocated to the instruments and to the spacecraft subsystems supporting the specific operations of the instruments. The allocation will be performed on a dynamic basis, resolving task constraints and priorities. Constraints include for each activity the power and data storage area needed, the pointing requested, etc.

On-board Instrument Commanding: the typical instrument commands contain planning, scheduling, resource management, navigation, and instrument pointing, downlinks of the processed data, etc.

On-board Platform Control: FIEOS platforms will be controlled intelligently and autonomously, including the followed aspects:

- Platforms adjust their positions in space relative to the constellation of sensors in response to collaborative data gathering,
- Autonomous operation of single satellite and satellite network, and

- Decision support and planning.

On-board Mission Planning and Schedule: FIEOS will resolve the planning and scheduling of missions on-board using a combination of a constraints solver and optimizer to achieve the best possible mission data return as possible. Ideally, a completely autonomous mission planning, i.e., the schedules are programmed in on-board software, is feasible in principle. When required, the on-ground and the OBMM (on-board mission manager) mission planning tools will be used for coordinating the schedule of activities, whose resulting schedule must be confirmed on-ground prior to its execution on board.

2.2.4 End-user operation

End users expect directly down-linked satellite data (in fact, the concept of data means image-based information, rather than traditional remotely sensed data) using their own receiving equipment. The operation appears to the end-users as simple and easy as selecting a TV channel by using a remote control (Figure 5). Therefore, three basic types of antennas and receivers: (1) the hand-held antenna and receiver for real-time and mobile users, (2) the mobile antenna for mobile users and (3) the fixed antenna for popular users, professional users or satellite receiving station, are conceptually designed (Figure 6). All receivers are capable of uploading the user’s command, and mobile and hand-held receivers have GPS receivers installed, i.e., mobile user’s position in geodetic coordinate system can be real-time determined and uploaded to geostationary satellite. The on-board data distributor will retrieve an image (block) from its database according to the user’s position.

In this fashion, an ordinary user on the street is able to use a handheld wireless device to downlink/access the image map of his surroundings from a geostationary satellite or from the Internet. Homes in the future are also able to obtain atmospheric data from the satellite network for monitoring their own environments. The intelligent satellite system will enable people not only to see their environment, but also to “shape” their physical surroundings. The downlinked data that users receive is not an actual image; instead, it receives a signal, much like a TV antenna receiving a TV signal, rather than direct picture and sound. This signal must be transformed into picture and sound by TV set. Similarly, the FIEOS signal (which we call a *special signal*) is absolutely different from the signal of current earth observing satellites. Thus, FIEOS satellite signal must be transformed into an image by the users receiving equipment. Therefore, users need:

(1) User Software for Data Downlink: The *special signal* is transformed by software, which is provided by the ground control center so that real-time and common users can easily use it. For a lay user (e.g., a farmer) complicated application software is unnecessary because the user analyzes and interprets the images using their perceptual faculties. For more advanced users (e.g., a professor), advanced software will still be necessary because they use "imagery" in different ways.

(2) Accessible Frequency: Different users need different imagery, e.g., a photogrammetrist needs forward and afterward stereo panchromatic imagery for stereo mapping; a biologist needs hyperspectral imagery for flower research. Thus, different types of satellite images are assigned with different broadcast frequencies, which the ground control station provides access to for authorized users.

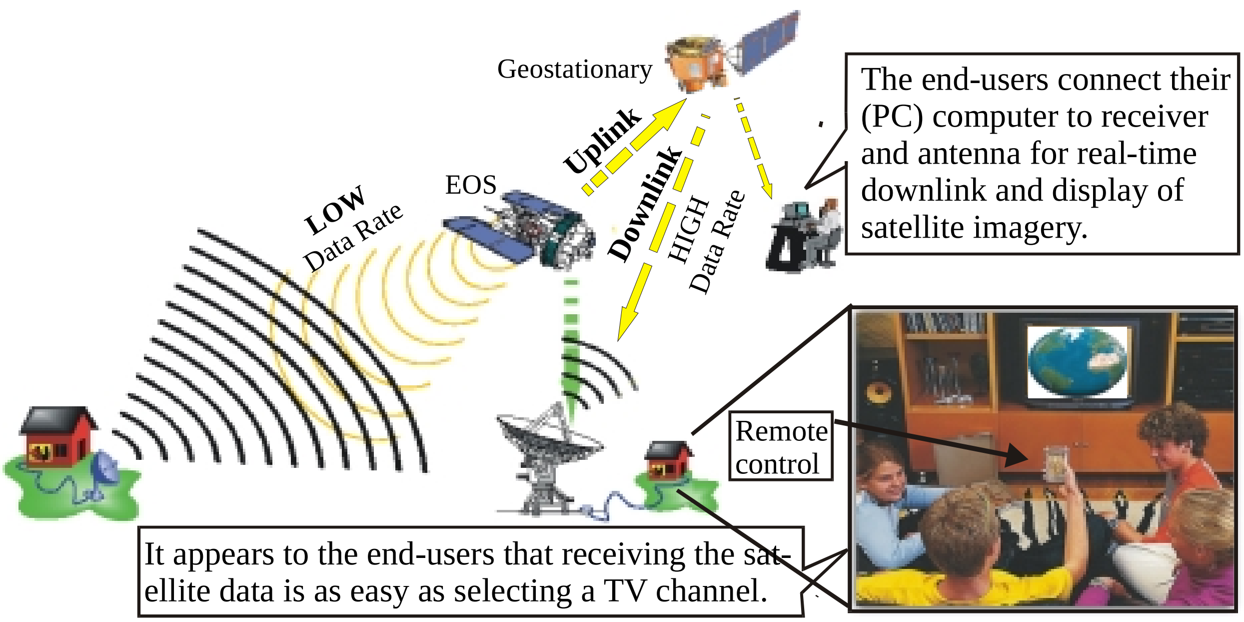


Figure 5. End-user operation like selecting a TV channel.

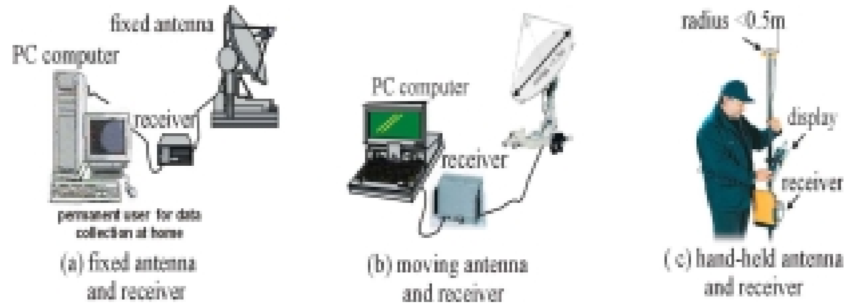


Figure 6. Concept design of antenna, receiver and end users in FIEOS.

2.2.5 Ground control station

The functions of the ground control station in FIEOS will decrease over time due to increasing satellite autonomy. In addition to some basic functions (e.g., steering and monitoring satellite transmissions continuously, prediction of satellite ephemeredes, calibrating the satellite flying parameters and navigation message periodically, evaluating the satellite's performance, monitoring the satellite's health and status, taking corrective measures in the event of detection of on-board anomaly), the characteristics of the ground control station in FIEOS are:

- Upload of value-added product data to the geostationary satellites, and
- Communicating guidance about receiving frequency, software use, display, and so on to end-users.

2.3 Characteristics of the Intelligent Earth Observing Satellite System

The design concept for FIEOS is flexible because any additional satellites can easily be inserted without risk to the infrastructure, and the instruments and platforms are organically tied together with network information technology. The constellation (multi-layer satellite network) insures that global data is collected on a frequency of decade minutes base or shorter; event-driven data are collected with multi-angle, multi-resolution, multi-bands, and users can acquire images of any part of the globe in real-time. This design concept provides a plug-and-play approach to the development of new sensors, measurement platforms and information systems, permitting smaller, lighter, standardized satellites with independent functions to be designed for shorter operational lifetimes than today's large systems so that the instrument technology in space can be kept closer to the state-of-the-art.

The FIEOS will perform much of the event detection and response processing that is presently performed by ground-based systems through the use of high performance processing architectures and reconfigurable computing environments (Alkalai, 2001; Armbruster et al., 2000; Bergmann et al., 2000). The FIEOS will act autonomously in controlling instruments and spacecraft, while also responding to the commands of the user interested to measure specific events or features. So, users can select instrument parameters on demand and control on-board algorithms to preprocess the data for information extraction.

2.4 Key Technologies for Future Intelligent Earth Observing Satellites

The proposed FIEOS consisting of a multi-layer satellite-network will produce large amounts of scientific data, which creates significant challenges in the processing, transmission, storage and distribution of data and data products. Thus, FIEOS will require the fastest processors, the highest communication channel transfer rates and the largest data storage capacity, as well as real-time software systems to insure that on-board data processing and the post-processed data flows smoothly from the satellite network to the global users (Prescott et al., 1999; Schetter et al., 2000). The key technologies to realize this capability are:

- Various types of intelligent and smart sensors and detectors,
- High data rate transmission and high-speed network communication, and
- Most powerful on-board data processing capabilities.

2.4.1 Intelligent and smart sensors and detectors for data collection

Many current event detection through cost-effective image analysis on the ground, e.g., air pollution detection using hyperspectrial image analysis, will be replaced by on-board processor. Thus, the FIEOS requires various smart and efficient sensors/detectors so that sudden events on the ground can easily be detected and observed in a timely manner.

1. **Biological Sensors:** This type of sensor is mainly used for environmental science investigation, such as in terrestrial and freshwater sciences, e.g., the monitoring of toxic chemicals and pollutants both in waters and in soils.
2. **Chemical Sensors:** The chemical sensors can analyze atmospheric particles, their size and chemistry, the transport, dispersion and deposition of heavy metals, etc.
3. **Microwave Sensors:** Microwave radiometers sense far infrared radiation emitted by the earth with wavelengths in the vicinity of 1.5 cm. A microwave detector can penetrate clouds and distinguish between ground and ice or snow surfaces. (http://www.aos.wisc.edu /~hopkins/aos100/satpltfm.htm).
4. **Neural Network Sensor:** Neural network technology is advancing on several fronts. The type of sensor can simulate the human visual system, revealing the composition of information contained in a single pixel. The technique, which uses the human visual system as a model, reveals the composition of information contained in a single pixel. Thus, neural network sensors essentially increase the resolution of satellite images (http://www.globaltechnoscan.com/3may_9may/onr_visual_system.htm).
5. **Smart Dust Sensor:** These minute, inexpensive devices are self-powered and contain tiny on-board sensors and a computer on a scale of just five square millimeters (http://www.rand.org/scitech/stpi/ ourfuture/Internet/sec4_sensing.html).
6. **Computerized Sensor:** This sensor uses digital computers to control and analyze reactors and other processes (http://www.ornl.gov/ORNLReview/meas_tech/sensor.htm). The computers will be provided with direct sensing capabilities in order to interact directly with their environment.
7. **Smart Sensor:** These sensors can automatically detect a specific, sudden event, such as a forest fire, volcanic activity, an oil spill or a burning coal seam (http://www.uni-freiburg.de/fireglobe/iffn/tech/tech_9. htm).

2.4.2 High data rate transmission and high-speed network communication

In the FIEOS constellation, the satellites are in different orbits, and their relative velocities vary significantly. Hence, the establishment and maintenance of real-time network communication, including high-speed data crosslink of EOSs, uplink of user/ground control station and geostationary, downlink of user and geostationary (see Figure 2), is **NOT** a simple problem (Surka et al., 2001; Welch et al., 1999). Obviously, the technology for high-speed wireless (optical or RF) data linking to connect satellite to satellite, and satellite to ground for high data rate transmission and the network management are vital elements for this concept.

2.4.3 On-board data processing capabilities

The success of on-board data processing is crucial to realize FIEOS. On-board data processing includes, such as an image data processor, data distributor, data management processor, housekeeping, resource management, on-board command planning, platform/sensor control, etc. One of the essential capabilities provided by on-board processing is satellite autonomy (Prescott et al., 1999; Ramachendran et al., 1999). This autonomy requires the mission operations and data processing/interpretation activities to evolve from ground-based control/analysis towards on-board control/analysis. The following is only a part of on-board data processing.

1. **On-board Image Processing:** Some image processing, such as image filtering, enhancement, compression, radiometric balance, edge detection and feature extraction, could be automatically processed on-board with techniques currently available and to be developed within the next 10 years. However, higher-level intelligent image processing, like classification, spatial information extraction, change detection, image interpretation, pattern recognition and 3D reconstruction, will need several generations of development. It has been demonstrated that full-automation of image analysis and image interpretation is quite difficult, particularly in complex areas such as wetlands and urban environments. In particular for FIEOS, the important function is its change detection capability, i.e., FIEOS only transmits those data that have been changed when compared with images stored on a database system.
2. **Data Storage and Distribution:** FIEOS requires huge data storage capabilities on-board and autonomous operation of data distribution; thus, some advanced and novel data handling technologies, such as data compression, data mining, advanced database design, data and/or metadata structures, etc., will be required to support autonomous data handling (Caraveo et al., 1999).

3. **On-Board Software:** Real-time software systems for integrating all of the components of the satellite network and completing the flow of data from collection and transmission, to information extraction and distribution will be one of the key elements in FIEOS. Additionally, in order to produce the value-added data products useful to common users, the current application software, algorithm, dynamic searching, etc., will need to be improved. In order to directly downlink to common users, some advanced concepts, such as dynamic and wireless interaction technology will need to be designed for handling the huge data computational requirements of dynamic interaction.

2.5 Current Development of Satellite Technologies

Currently, several advanced satellite systems, e.g., NEMO (Naval Earth Map Observer) developed by the US Navy, PROBA (PRoject for On-Board Autonomy) developed by the European Space Agency (ESA) and COCONUDS (Co-ordinated Constellation of User Defined Satellites) developed by the European Union, are scheduled to launch. BIRD (Bispectral Infrared Detection) developed by the German Space Agency (DLR) was successfully launched on 22 October 2001. These satellites can give us some contexts about the most advanced technologies in "intelligent" satellites[1].

Naval EarthMap Observer (NEMO)

The NEMO satellite will provide unclassified, space-based hyperspectral passive imagery at moderate resolution for direct use by Naval forces and the civil sector (http://nemo.nrl.navy.mil/concept.html). The interesting characters of NEMO are (Davis et al., 2000):

1. Automated, on-board processing, analysis, and feature extraction using the Naval Research Laboratory's (NRL's) Optical Real-Time Adaptive Signature Identification System (ORASIS)
   - Real-time feature extraction and classification with greater than 10x data reduction

[1] These satellite's specification and information are from relevant website and personal communication.

- High-performance Imagery On-Board Processor provides greater than 2.5 giga FLOPS of sustained computational power
- On-board data storage (56 gigabit)

2. Real-time tactical downlink of hyperspectral products directly to the field user
   - High data rate X-Band Downlink (150 Mbps)
   - Low data rate S-Band Tactical Downlink (1 Mbps)
   - Commercial satellite bus (Space Systems Loral LS-400)
   - Preconfigured Interface (PCI) for secondary payloads/experiments

PROBA: ESA's Autonomy and Technology Demonstration Mission

Proba is an ESA mission conceived for the purpose of demonstrating new on board technologies and the opportunities and benefits of on-board autonomy, which will perform a number of mission operations functions with minimum ground involvement (Teston, et al., 1997). The basic functions of the on-board data processing are (http://telecom.esa.int/artes/artes2/fileincludes /multimedia/multi.cfm):

(1) **On-board housekeeping:**decision-making process, i.e., failure detection, failure identification and first-level recovery actions.

(2) **On-board data management:** data handling, storage and downlinks (a 1 Gbit mass memory for recording, a tuneable 2 Kbit/s to 1 Mbit/s down-link).

(3) **On-board resources usage:** power and energy usages.

(4) **On-board instrument commanding:** Planning, scheduling, resource management, navigation and instrument pointing, downlinks of the processed data.

(5) **On-board science data distribution:**Automatic direct data distribution to different users without human involvement. Minimum possible delay**.**

(6) **On-board platform control:** Platform control of the Proba is performed autonomously on-board by a high-accuracy autonomous double-head star tracker, a GPS receiver and a set of reaction wheels.

BIRD Mission (Fire Monitoring)

BIRD is a small satellite mission dedicated to hot spot detection and evaluation using an infrared detector (http://www.uni-freiburg.de/fireglobe/iffn/tech/tech_9.htm). The interesting capabilities are (Halle et al., 2000; Oertel et al., 1998):

(1) On-Board Data Processing Capabilities

- A thematic on-board classificator for disaster warning and monitoring
- Radiometric and geometric on-board correction of sensor signals
- Geometric on-board correction of systematic alignment errors
- Geometric on-board correction of spacecraft attitude

(2) On-board geocoding of thematically processed data with real-time down-link

- Immediate down-link of regional data
- Downlink of an alert message if required
- Store-and-forward, data downlink to low-cost payload ground stations

COCONUDS (Co-ordinated Constellation of User Defined Satellites)

COCONUDS explores the feasibility of developing a European co-ordinated constellation of user defined satellites to take European environmental monitoring forward into the information society (Verduijn et al., 2001). The objective of COCONUDS is to ascertain the practicality of a radically different, low-cost, distributed network approach to satellite earth observation. The interesting features are:

1. A co-ordinated constellation of 10 polar orbiting micro-satellites
2. A low-bitrate continuous data stream without on-board storage
3. Ground stations operated by end-users
4. Some point & shoot sensors for which users may uplink pointing requests

3. ON-BOARD DIRECT ORTHORECTIFICATION OF IMAGES

3.1 Introduction

One of prerequisite conditions for common users of directly down-linked satellite images is that all images should be orthorectified prior to on-board delivery. This requires the future satellite autonomously ortho-rectify various distortions. This problem has been the subject of research for more than thirty years by the photogrammetry and remote sensing communities (Albertz, 1998). Generally, the numerous techniques, which have been developed, can be categorized into the following three methods (Breuer and Albertz, 2000):

1. **Non-parametric approaches:** This method uses various mathematical models, e.g., polynomial functions, to fit the distortion of images, and then use sufficient ground control points (GCPs) to solve the models. This method does not need to consider sensor position or attitude data, but requires an adequate number of GCPs. With this method, many experiments have demonstrated that the distortion of images cannot be completely orthorectified because of the local character of image distortions (Ji et al., 2000; Zhou et al., 2001a and 2001b). Thus this method cannot meet the high-accuracy demands of orthorectification.
2. **Parametric approaches:** This method rigorously models the time-variant image capturing process using photogrammetric technique (Zhou et al., 2001a). This method allows error propagation and probably inherent disturbing effects individually because of the fact that even correlation between observations can be modeled if they are known (Breuer and Albertz, 2000). However, this method needs adequate initial auxiliary information like position and attitude of sensor, a DEM and/or a reference orthoimage (Schläpfer et al. 1998).
3. **Mixed approaches:** This method uses an integration of both the parametric and the non-parametric methods. The method, for example, first solves the position and attitude parameters of the sensor using ground control points (parametric model), and then wraps the image data to the terrain using a polynomial transformation (non-parametric model) (Breuer and Albertz, 1996).

Apparently, the first and third methods are not suitable for on-board orthorectification because they require sufficient GCPs. The second method only requires the sensor's position and attitude data in addition to a DEM. This can be easily achieved by modern navigation system (e.g., global positioning system (GPS), star tracker) and an on-board DEM data management system (further described in Chapter 4). Therefore, the problem of on-board orthorectification is transferred into how to accurately determine the position (X_s, Y_s, Z_s) and attitude (ω, φ, κ) of an image (known as the *exterior orientation parameters* in photogrammetry) at the epoch of exposure. Typically, there are two methods used:

1. **Indirect method:** This method indirectly determines the exterior orientation parameters using well-known photogrammetric aerial triangulation (AT) techniques. In this method, the six exterior orientation parameters are estimated from a number of ground control points and their corresponding image coordinates and tie points (homologous points), which connect adjacent images. Although aerial triangulation has essentially improved and expanded to so-called automated aerial triangulation (AAT) techniques in recent years (e.g., Schenk, 1997), the orientation process still suffers from a large amount of interactive editing and supervision by highly skilled technicians (Cramer et al., 2000). This is because automatically searching conjugate tie points in adjacent images and recognizing GCPs in the image plane is not reliable. However, this method has the highest accuracy (Cramer et al., 2000).
2. **Direct method:** This method directly measures the exterior orientation parameters of an imaging sensor using a navigation system (e.g., GPS and star tracker). Thus, required ground control and tie point information could be reduced significantly or eliminated. This method is called *direct geocoding* or *direct georeferencing* in photogrammetry because it does not need AT. A crucial aspect of direct georeferencing is the accuracy and reliability of directly measured orientation parameters because it significantly influences the accuracy of the orthorectification.

Many efforts to achieve the highest-accuracy determination of attitude and position of spacecraft have been made. Briefly, spacecraft attitude determination is generally based on the use of attitude sensors such as sun sensors, earth sensors, star sensors, inertial sensors, magnetometers and multi-antenna GPS systems (Lu, 1995; Bae et al., 2001; Moreau et al., 2000). Current state-of-the-art commercial star sensors typically attain an accuracy of 0.02 to 0.05 degrees (Wang et al., 2001), though accuracies up to 10 arcseconds have been reported (Clark et al., 2000; Bisnath et al., 2001). For example, a low earth observing satellite with 350 km flying height would yield about a 35 m error (one direction generates 20.4 m error) (Figure 7). This accuracy cannot meet the orthorectification requirement of the envisioned future intelligent satellites. Use of GPS positioning data for orbit determination of spacecraft has been investigated for well over a decade. Presently, near-real-time processing of GPS tracking data can routinely provide low-earth orbit determination accuracy at the level of 5 cm (Bertiger et al., 1999; Rim et al., 2001). Such processing systems can be fully automated. Recent results from the Jet Propulsion Laboratory (JPL), where ongoing daily processing of low earth GPS tracking data has been undertaken for several years, has demonstrated that orbit determination accuracies of less than 10 cm are feasible. Furthermore, it is anticipated that orbit determinations in the sub-centimeter range will be feasible in the near future (Bertiger et al, 1999).

GPS offers high absolute accuracy of orbit position, while attitude sensors provide relatively low accuracy. Validation of an on-board orthorectification system via integration with a navigation system (GPS and star tracker) and an on-board geo-database management system is discussed in this chapter. The architecture of this concept is:

(1) An on-board DEM database management system to manage DEM data and an on-board geo-database manager to manage spatial objects (spatial data and attribute data). The two databases are connected by a unique identifier and support the satellite image processor. A detailed description is discussed in Chapter 4.
(2) An on-board navigation systems (GPS or star tracker) to provide orientation data (position and attitude), which are taken as an approximation and then refined by (satellite) image-based processing, which is supported by an existing on-board database.
(3) Once the orientation parameters are determined, the parameteric method for orthorectification is used (DEM data are available in an on-board DEM database).

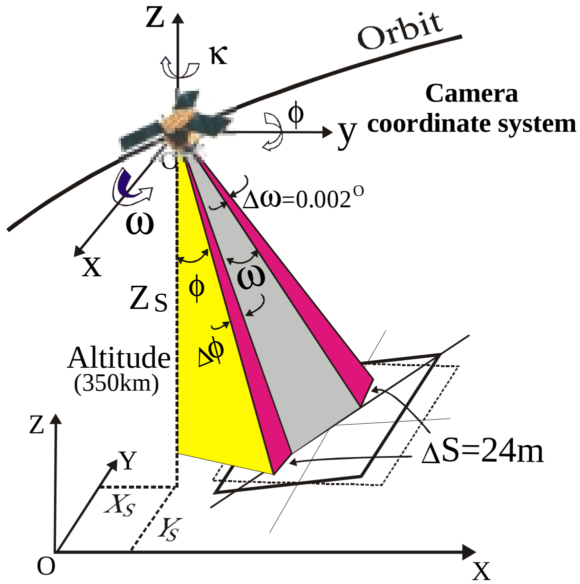


Figure 7. The error of navigation causes the error of orthoimage.

3.2 Concept Design of On-board Data Collection

In order to better describe the on-board orthorectification, an imaging system for collection of ground surface data is conceptually designed (Figure 8). The architecture of this type of imaging system has the following characteristics:

(1) Satellite would collect panchromatic, multispectral imagery (e.g., 8 channels), and hyperspectral imagery (e.g., 200-300 channels) with meter-level resolution.

(2) The imaging mode applies the push-broom principle. Several hundred CCD line detectors are mounted in parallel at the focal plane of a lens, which is orthogonal to the direction of flight. Multiple superimposed image strips are acquired almost simultaneously by the forward motion of the aircraft over the terrain. Mass Memory System should be over 1000 Giga Bytes.

(3) Two of the CCD lines are arranged at specific viewing angles to provide stereo imaging and stereo photometric capability (Figure 8). The rest of the CCD lines are covered with different filters for the acquisition of multispectral and hyperspectral images. Each CCD line sensor captures a band image.

(4) The entire satellite should be able to pivot in orbit to collect cross-track images at designed distance on either side of the ground track. Depending on the satellite's orbital

altitude, ground resolution, and other factors. Imagery will maintain at least a meter-level ground sample distance (GSD) with specific swath width.

(5) The system is designed to carry GPS antennas and multiple digital star trackers to maintain precise camera station position and attitude. A rigid satellite platform is required to reduce motion vibration of the platform and to contribute to the integrity of the line-of-sight determination.

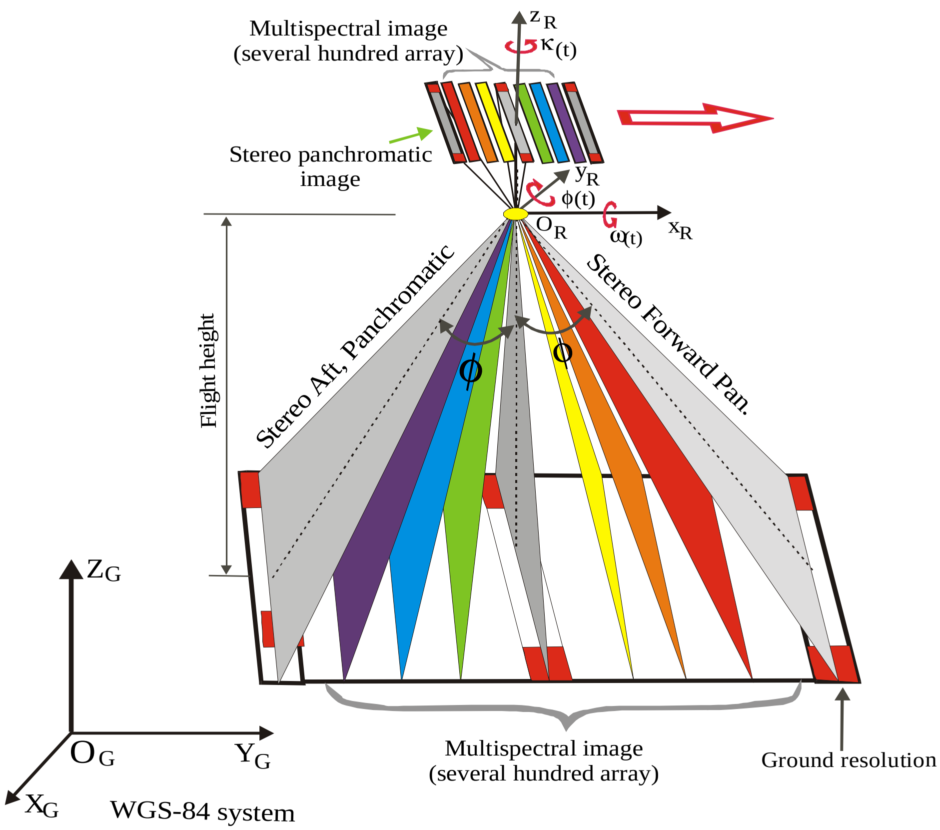


Figure 8. The architecture of a type of imaging system for collection of ground surface data.

3.3 On-board Orthorectification Model

The reliable orthorectification model should allow for high quality radiometric and geometric correction. The radiometric correction however will not be discussed in here but should be considered as an integral part of data preprocessing in the future. To get a precise geometric correction based on the imaging geometry of Figure 8, a rigorous mathematical model is developed as follows (Zhou and Li, 2000).

3.3.1 Interior orientation (and parameters)

Interior orientation transforms screen coordinates (i and j in Figure 9) into image coordinates (x and y in Figure 9), and corrects lens distortion (symmetric and tangential) and CCD array curvature distortion. The interior orientation parameters are usually measured via laboratory (in-lab) calibration, which is assumed to be known for the bundle adjustment process, or self-calibration (in-flight), which is solved in a bundle adjustment process. (The calibrated parameters from the two approaches are different.) (Zhou et al., 1998)

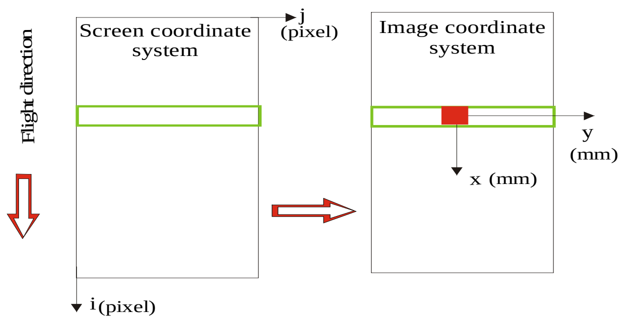


Figure 9. Screen and image coordinate system

3.3.2 Collinearity equations

For any image point within a CCD array, its image coordinates are (x, y, z). The corresponding ground point coordinates are (X_G, Y_G, Z_G). The coordinates of the exposure center of the array in the ground coordinate system at the imaging epoch t are (X_s(t), Y_s(t), Z_s(t)). The collinearity condition states that all these three points must be on the same line:

$$x_R = f\frac{r_{11}(X_G - X_S(t)) + r_{12}(Y_G - Y_S(t)) + r_{13}(Z_G - Z_S(t))}{r_{31}(X_G - X_S(t)) + r_{32}(Y_G - Y_S(t)) + r_{33}(Z_G - Z_S(t))}$$

$$y_R = f\frac{r_{21}(X_G - X_S(t)) + r_{22}(Y_G - Y_S(t)) + r_{23}(Z_G - Z_S(t))}{r_{31}(X_G - X_S(t)) + r_{32}(Y_G - Y_S(t)) + r_{33}(Z_G - Z_S(t))} \quad (1)$$

where R_G^R is a rotation matrix from the ground coordinate system to the image coordinate system and is defined by

$$R_G^R = \begin{pmatrix} \cos\varphi\cos k & \cos\omega\sin k + \sin\omega\sin\varphi\cos k & \sin\omega\sin k - \cos\omega\sin\varphi\cos k \\ -\cos\varphi\sin k & \cos\omega\cos k - \sin\omega\sin\varphi\sin k & \sin\omega\cos k + \cos\omega\sin\varphi\sin k \\ \sin\varphi & -\sin\omega\cos\varphi & \cos\omega\cos\varphi \end{pmatrix} \quad (2)$$

The rotation angles $\varphi(t)$, $\omega(t)$ and $k(t)$ are defined for each CCD array at the epoch t. Depending on types of observations, coordinates and parameters may be treated as knowns and unknowns differently in various situations.

Considering the large influence of the Earth's curvature distortion over a full-scene of satellite image, the geocentric coordinate system is established as a basis. The adjustment is then carried out in that coordinate system. Thus the model will be associated with the following coordinate system transformations (refer to Figure 10):

(1) Image plane coordinate system $(o-u,v)$: a right-hand coordinate system with the principal points in the imagery as the origin, the flight direction is taken as the u axis.

(2) Camera coordinate system $(O-U,V,W)$: the lens center of camera is set as the origin O, the W axis crosses the lens center of camera orthogonal to the image plane, and the U,V axes are parallel the u,v axes in the image plane.

(3) Geocentric coordinate system: the XcYc-plane describes the plane of the equator, and XcZc-plane transects the zero meridian, usually the Greenwich meridian. A point has the geocentric coordinates Xc, Yc, Zc based on the defined reference ellipsoid of WGS-84.

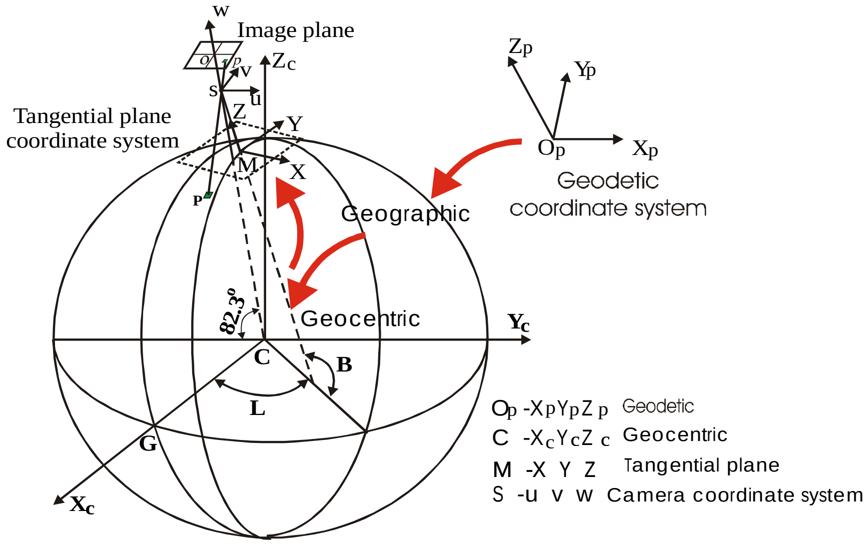


Figure 10. The coordinate system of orthorectification.

3.3.3 Navigation data as exterior orientation parameters

The satellites can provide positions (X_s, Y_s, Z_s) and attitudes (ω, ϕ, κ) of the CCD arrays by carrying GPS receivers and star trackers. Since the navigation data have lower data collection rates, they are not acquired for every image line. Those lines with the navigation data are called *Orientation Lines* (OLs). Exterior orientation parameters of OLs are introduced at certain time intervals. Navigation data at OLs can be used as their approximate exterior orientation parameters. Previous investigations based on simulated orbit data showed that a 3rd order polynomial function can exactly approximate exterior orientation parameter changes (Wu, 1986). Exterior orientation parameters of lines between OLs are computed by a polynomial interpolation:

$$\zeta(t) = \sum_{0}^{3} f_i t^i \tag{3}$$

where $\zeta(t)$ represent exterior orientation parameters, t denotes exposure epoch, $f_i(i=0 \sim 3)$ denotes the coefficient of the polynomial. The parameter t may be time beginning at a certain epoch or image line number from a certain orbit position. The unknown coefficients in Equation (3) can be determined either independently or in a bundle adjustment.

3.3.4 Distortion correction

In addition to the distortion correction of camera lens described in the interior orientation, the other distortions contain:

(1) **Earth's curvature:** (extremely) high latitude or large coverage of the image causes the Earth's curvature distortions. This type of distortion can be corrected by the use of the geocentric coordinate system that we established in section 3.3.2 (Zhou et al., 2001b).

(2) **Relief displacement:** the difference of elevation, especially in areas of high mountains, causes big relief displacements. This type of distortion can be corrected by a collinarity equation and known DEM data (Zhou et al., 2001a and 2001b). Our model has considered this correction.

(3) **Atmospheric refraction**, this distortion can be rectified by the model (Mikhail et al., 2001, Wolf et al., 2000).

3.3.5 On-board orthorectification

After the orientation parameters of images are determined, each image scene can be orthorectified. The procedures contain (1) the determination of the size of the orthorectified image; (2) the transformation of pixel locations from the original image to the resulting (rectified) image; and (3) resampling of the original image pixels into the rectified image for assignment of gray values.

Determination of orthorectified image size: The orthorectification process registers the original image into some chosen map-based coordinate system, and invariably the size of the original image is changed. To properly set up the storage space requirements when programming, the size of the resulting image footprint (upper left, lower left, upper right and lower right) has to be determined in advance. These procedures are as follows:

- *Determination of the 4 corner coordinates:* For a GSD, $\Delta_{Xsample}$ and $\Delta_{Ysample}$ along x and y direction in the original satellite image, assume that the planimetric coordinates of any GCP are (X_{GCP}, Y_{GCP}), whose corresponding location in the image plane is (row_{GCP}, col_{GCP}). The coordinates of the 4 corner points can then be described (see Figure 11):

Corner 1:
$$X_1 = X_{GCP} - col_{GCP} \cdot \Delta_{Xsample}$$
$$Y_1 = Y_{GCP} - row_{GCP} \cdot \Delta_{Ysample}$$

Corner 2:
$$X_2 = X_{GCP} + (col_{size} - col_{GCP}) \cdot \Delta_{Xsample}$$
$$Y_2 = Y_{GCP} - row_{GCP} \cdot \Delta_{Ysample}$$

Corner 3:
$$X_3 = X_{GCP} - col_{GCP} \cdot \Delta_{Xsample}$$
$$Y_3 = Y_{GCP} + (row_{size} - row_{GCP}) \cdot \Delta_{Ysample}$$

Corner 4:
$$X_4 = X_{GCP} + (col_{size} - col_{GCP}) \cdot \Delta_{Xsample}$$
$$Y_4 = Y_{GCP} + (row_{size} - row_{GCP}) \cdot \Delta_{Ysample}$$

- Determination of the minimum and maximum coordinates for the 4 corners is found by:

$$X_{min} = \min(X_1, X_3), \quad X_{max} = \max(X_2, X_4)$$

$$Y_{min} = \min(Y_3, Y_4), \quad Y_{max} = \max(Y_1, Y_2)$$

- Determination of the size of the resulting image is by:

$$\mathrm{N} = \mathrm{Col} = \frac{X_{max} - X_{min}}{\Delta X}, \quad \mathrm{M} = \mathrm{Row} = \frac{Y_{max} - Y_{min}}{\Delta Y}$$

where ΔX and ΔY are the GSD that the end-users specify for the orthorectified (resultant) image.

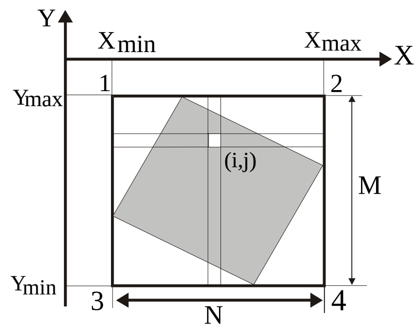


Figure 11. The design of the size of rectified image.

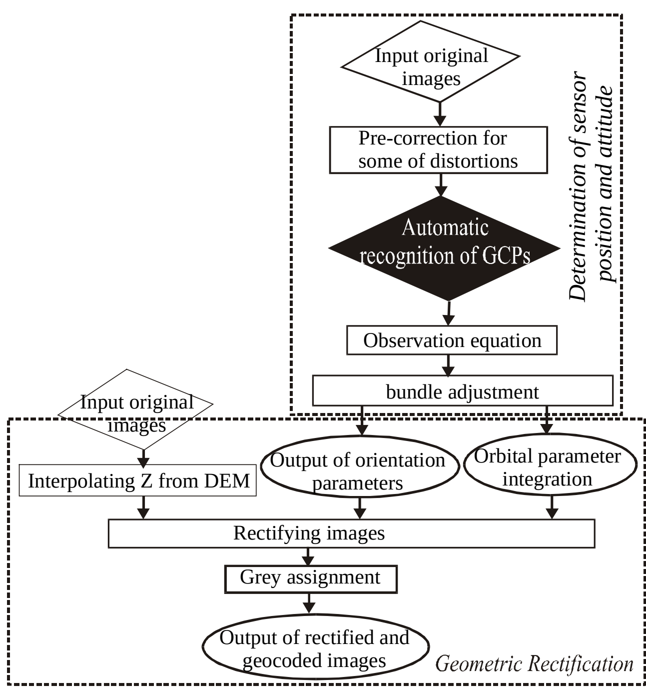


Figure 12. Flowchart of geometric rectification process.

Orthorectification: The orthorectification process includes (1) calculation of the geographic coordinates of individual pixels, (2) the resampling of the original image and (3) registration into a map-based coordinate system. A detailed description for this process can be found in Zhou et al. (2001b).

The above procedure is then repeated for each pixel to be rectified. The processing procedure from the determination of the sensor's exterior orientation parameters to the transformation of the original imagery to the orthorectified product is illustrated in Figure 12.

3.4 On-Board "GCP" Recognition

Because of the low accuracy and reliability of navigation information, a few GCPs in each scene are necessary for high-accuracy orthorectification. However, it is difficult to obtain the traditional photogrammetric target points everywhere in the world. Therefore, some feature points, like building corners or road intersections, can be used. An algorithm, which uses neural network technologies to recognize the "GCPs," is conceptually designed. In this method, an on-board geo-database including spatial data and DEM (elevation, slope and aspect) provides excellent training data sets for neural network computation (Figure 13). The intrinsic advantages of the neural network recognition approach are (1) no need for a priori knowledge of the data set's statistical distribution, (2) parallel computation potentials, (3) high adaptability, and (4) great error tolerance.

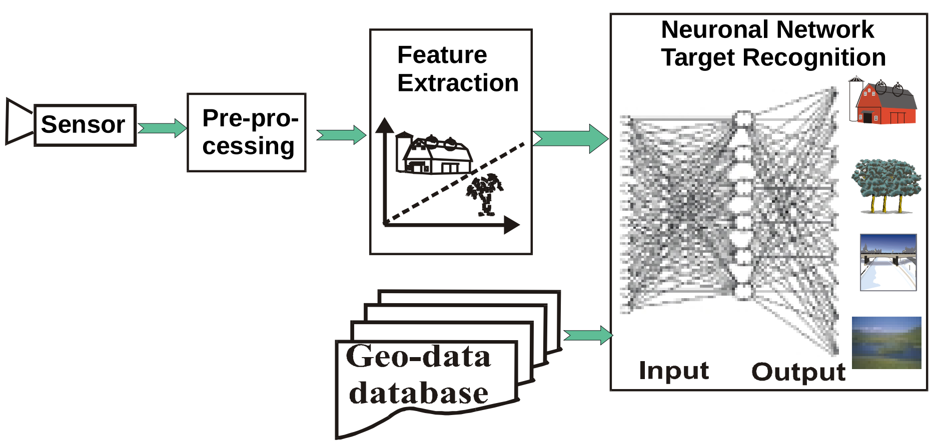


Figure 13. On-board feature recognition based on geo-database management system.

3.5 Key Technologies of On-board Orthorectification

One of the key technologies for on-board geometric orthorectification is obtaining a few "GCPs" in each scene through on-board data processing. Because current technologies cannot provide high-accuracy navigation data on-board (Altmayer et al., 1998; Gill et al., 2001), recognition of GCPs on-board via the support of a geo-database is conceptually designed, from which a model of an on-board orthorectification procedure is developed. Future development and investigation will be required to create an on-board system of orthorectification.

4. ON-BOARD GEO-DATA MANAGEMENT SYSTEM

4.1 Introduction

Enabling end-users to directly downlink satellite imagery, for which they specify an area of interest (AOI) (e.g., location and extent), using a simple receiving unit, such as a laptop computer and a mobile antenna, even, a cellular phone, one of the key challenging technologies is how the on-board data distributor autonomously retrieves the imagery according to user's command. Additionally, once the on-board data distributor finds the imagery specified by users in the image database, how does the on-board data distributor simultaneously retrieve other data sets, such as, temperature, moisture or geographic attribute data (e.g., street name), from other databases, which will be simultaneously downloaded to end-users directly? The solution to these problems may require a whole new concept in design of on-board data management. We here present a concept design of an on-board integrated management system for the management of image database, geographic spatial database (geo-database) and digital elevation model (DEM). The geo-database management system includes data organization, data structure, data model, query, etc. The purpose of the on-board geo-database management system is to provide the end-user with attribute information. The purpose of the DEM database management system is to directly provide the end-users with elevation information. The integrated data will give the user better visualization and understanding of the situation surrounding him/her. The basic idea of this concept design is (also illustrated in Figure 14):

(1) The satellite (network) sensors collect the Earth surface data/images. An on-board image data processor processes the image data and generates geocoded images, then archives the geocoded images in an on-board image database in real-time. As mentioned before, only changed data is archived according to the concept design of the future intelligent earth observing satellite (Zhou and Kauffmann, 2002).

(2) The on-board geo-database, called the *virtual sensor*, stores existing global geo-data including attribute data and spatial data. These data are effectively organized by data structure and data mode and are easily and quickly are accessed (retrieve and query) (Xie et al., 2000).

(3) End-users uplink/upload the request for an image downlink to the geostationary satellites. The on-board data management system in the geostationary satellites searches for the requested image data from the image database via geodetic coordinates sent by ground user. Meanwhile, the on-board data management system simultaneously searches for corresponding geo-data (attribute and spatial data) from the geo-database and elevation data from the DEM database.

(4) Satellite image data is taken as a backdrop, and geo-data and DEM are superimposed on the backdrop. After these data sets are integrated and are compressed by an on-board data processor, they are directly downloaded to end-users. The downloaded satellite image looks like a geographic image map, we call *geo-imagemap* (see Figure 14).

Obviously, the integration of satellite raster image data with the already existing geo-data is one of the important challenges, along with on-board image processing, on-board image geocoding, image database management, a spatial data structure/model, fast query, and an integrated management system for the management of image, geo-data and DEM databases. In the traditional GIS (geographic information system) community, the integration of satellite images and GIS has been accomplished by one of three basic methods (Ehlers et al, 1989; Abdelrahim et al., 2000): (1) *Separated but Parallel Integration*, which means that the image processing system and GIS system are separate. This is the oldest integration scheme and is mainly used for exchanging data between systems; (2) *Seamless Integration*, which means the GIS and image analysis systems are stored in the same computer and the functions of both systems are simultaneously accessed through a common interface. This type of integration still needs to exchange data between the two systems; and (3) *Total Integration*, which means the remote sensing data and geo-data support each other for analysis and processing, and make full use of the GIS and image analysis functionality simultaneously with no need for data conversion between the systems.

Most commercial GIS or image processing software packages currently support only the first two levels. Only a few GIS systems have the third type of integration functionality (Abdelrahim, 2000). However, all the integration schemes are for a single image or for management of two data sets in a workspace (Gong, 2000). For FIEOS, the on-board autonomous geo-database management system (OAGMS) not only manages the huge image data sets associated with the geo-data and DEM, but also seamlessly links them together. For example, either vector geo-data or raster satellite imagery can be used to query the real world. Compared to current GIS system, the characteristics of OAGMS are:

(1) OAGMS manages three sub-databases (DEM, Image-database, and Geo-database), which are connected by a unique identifier. All data sources are seamlessly linked together.

(2) OAGMS does not require more powerful spatial data analysis capabilities compared to current GIS spatial analysis (e.g., transportation, hydrology, etc.). However, on-board fast query is absolutely necessary because of high-speed motion of the satellites.

(3) The interactive medium with users is wireless communication rather than a cursor and screen.

As we can see, the proposed design is based on the idea of using satellite imagery, supported by a geo-database associated with attributes and a DEM database as the data sources to describe the real world of the area of interest. The query results will be directly downlinked to users in the form of geo-imagemap. Thus, the new data model concept for management of the huge data sets is designed so that the raster satellite imagery and geo-database can be better queried, visualized and flexibly handled.

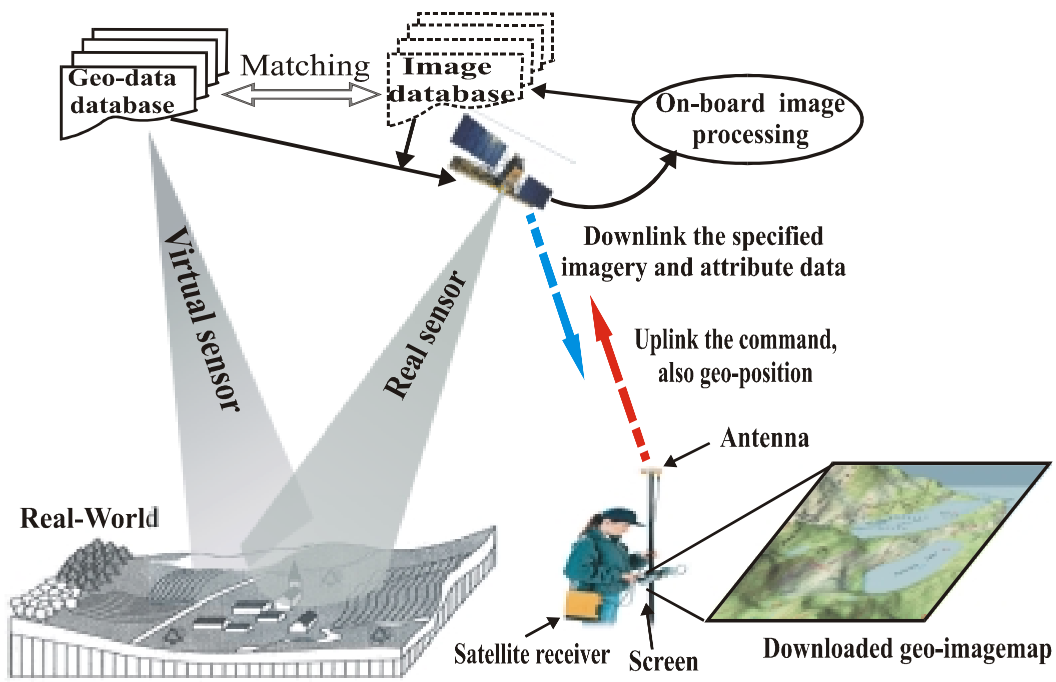


Figure 14. Concept design of on-board geo-data management system.

4.2 Data Types and Data Model

In the on-board data management system, there will be three types of data sets: (1) satellite image (orthoimage) data, which are from on-board satellite sensor; (2) geo-data sets, which describe the spatial objects, like buildings, roads and rivers; and (3) DTM, which directly provides the elevation information to users.

<u>DTM Data</u>

DTM provides the elevation information for end-users by superimposing it onto imagery. Traditionally, there are three basic types of data structure for description of DTM: (1) a regular raster data structure, (2) triangular irregular network (TIN) and (3) hybrid. Each structureits advantages and disadvantages. In general, the grid structure is easy to handle, operate and store, but it cannot effectively represent complex terrain, e.g., a cliff. The TIN structure consists of an array of triangular areas. The points of each triangle are selected in an important position such that they can effectively represent the terrain. Thus, the area of the triangles varies. Usually, the smaller the triangles, the more complex the terrain. The advantage of this structure is that it can effectively represent the terrain in more detail, e.g., a cliff, using fewer points. Moreover, the calculation of slope and aspect of terrain is easy. The disadvantage is that it requires considerably larger storage capacity than the grid structure. In order to save storage space, the DTM in the OAGMS is represented in raster form, whose cell size, row, column, map project type, accuracy, etc., are recorded in an integrated management system (see Section 4.3).

<u>Satellite Image Data</u>

The original satellite images from the on-board satellite sensor are co-registered to the ground coordinate system using on-board image processor with specified algorithms. For example, an algorithm for orthorectification was described in chapter 3. All image data are stored in an image database, and are queried via an image identifier (ID). According to the concept design of

FIEOS, only changed data will be transmitted. Therefore, only the changed area/image in the image database is updated.

Spatial Objects

The geo-spatial data object is the abstract of an entity in the real world. The spatial object has two obvious features: (1) geometric characters, which indicate their size, shape and position, and (2) physical characters, which indicate their nature, such as a river, house or road. Spatial objects in the real world are thought of as occurring as easily identifiable types: points, lines, area and complexes (see Figure 15).

- **Point Object:** Its space is zero-dimensional; thus, it has a position but no spatial extension. Three types of point objects are (1) a single coordinate point without direction (used to represent the point location, such as control points and wells); (2) a single coordinate point with direction (used to represent point location and its direction such as bridges, when a bridge is represented with a point and its direction); and (3) a point cluster (group of coordinate points).
- **Line Object:** Its space is one-dimensional or two and a half dimensional (e.g., a power line); thus, only its length is measurable. For example, a linear path consists of any number of connected arcs where none branch.
- **Area Object:** which means its space is two-dimensional. Thus the area and perimeters are measurable, e.g., a polygon or multiple-holes polygon with no overlay.
- **Complex Object:** a compound object consisting of at least one other object.

These defined primary geographic entities are taken as basic classes, and other geographic entities are derived from these primary geographic entities. For example, line and area types of an object probably consist of several arcs, and each arc has two terminal points. Collectively, these four objects can represent most of the tangible natural and human phenomena that we encounter on a daily basis. This data model not only inherits primary operators but defines its own special operators. Thus, a spatial object can be extracted into one of the object types according to its attributes (see Figure 16).

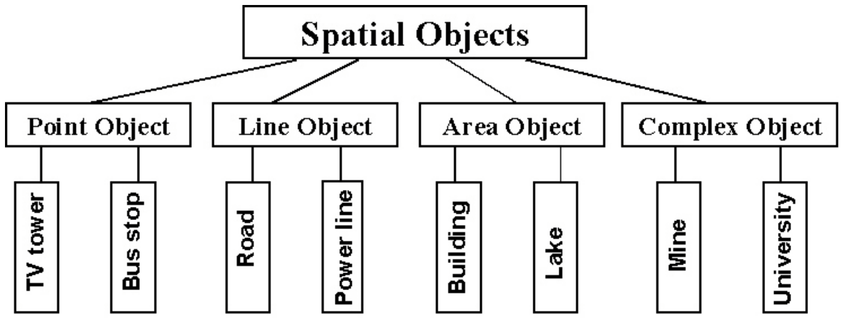


Figure 15. The spatial data types in proposed on-board geo-database management system.

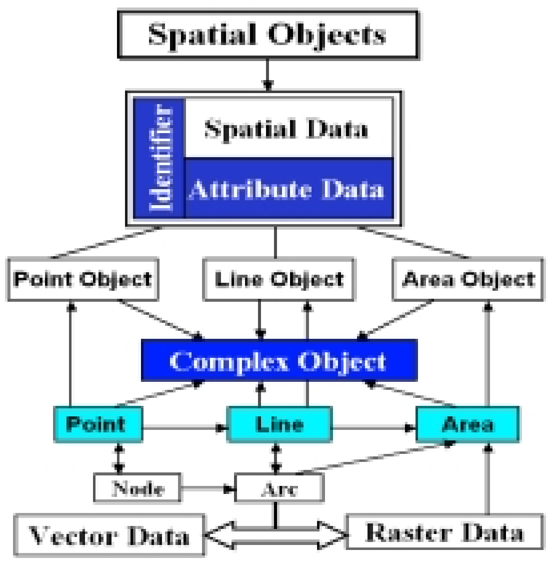


Figure 16. Spatial data model proposed.

4.3 Implementation of the On-board Geo-data Database Management System

4.3.1 Three separate database management systems

Image Database Management System

In the image database each scene is stored as a unit. Due to the huge data volume of each scene, it is difficult to meet the demands of real-time query. Thereby, each scene is divided into different blocks, and each block is stored as a sub-unit with a specific name. Each block is easily indexed by a unique identifier, which is represented by a type of code, such as geodetic coordinates in UTM (Universal Transverse Mercator). Once the image management system accepts a command for query, a pointer will index block (image) ID and immediately access the block data directly according to the spatial position (latitude and longitude). After the image of the AOI specified by ground user is retrieved, the on-board image processor will automatically re-sample it to the resolution that fits both the extent of the image and the size of the ground users screen. Thus, downloaded data will be displayed in a different display scale on the users screen size. This type of data management not only saves the on-board storage space, but also increases the search speed without degrading the accuracy of the image.

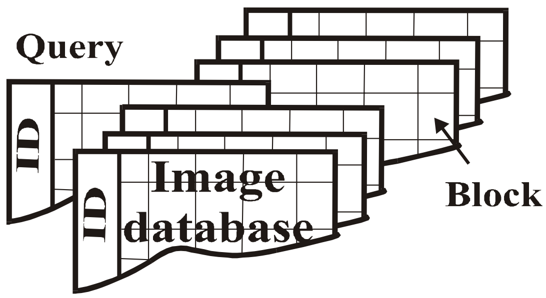


Figure 17. Image database management.

DEM Database Management System

As mentioned early, the purpose of the global DEM database is to directly provide elevation information for users without any processing on ground. The global DEM data in the DEM database is divided into different block, whose size is fit to the image block. The data structure and model are similar to the image database. The DEM block is indexed according to a type of code, which is a unique identifier we call the *DEM identifier*. In addition, the DEM data processor will automatically generate DEM pyramid data, which fit the image size specified by users. Thus, we can view either the whole area at small-scale or the local area at large-scale.

Geo-Database Management System

The data model shown in Figure 16 is a relational model, which can be implemented by relational database technology. In this model, we have spatial data and attribute data. For the spatial data, each type of object is defined as a table. For example, a tree is defined as a point type table. For the table of point type, we further define the point identification (PID), point attribute identification (PAID) and point name (PN). The PID is for identification of the type of point object. The PAID is for linkage to attribute data. Different point objects have different attribute data. For example, a tree and a well have different attribute values. The PN is for identification of a geometric point.

Similarly, for line objects, we also define the line identification (LID), line attribute identification (LAID) and line name (LN). Different line objects have different attribute tables, but the LAID will always directly link to the attribute data table. The area objects have a similar structure. For example, different areas have a different area identification (AID) and attributes. An area attribute identification (AAID) is designed for linkage of attribute table and spatial.

As we have seen, the attribute data and spatial data must be connected by a unique identification. In current GIS systems, the connectivity between attribute data and geometric data is accomplished by either organizing attribute data and spatial data in the same record, or separating them and specifying a link. The former connection is rigid, causes large redundancy and restricts data sharing. Our scheme is to directly employ the spatial data (geodetic coordinate) as a unique identifier (index) to connect the attribute and spatial data. This is because the ground users directly use a geodetic coordinate to query their image AOI. For example, if a spatial object type is a type of point object, we may put spatial data and attribute data together because the coordinates of this point can directly be considered as two attribute items, and can be put together with other attribute values. If the spatial object types are a line or area type of object, the coordinates are taken as attribute items for the coordinates of an individual point describing the line or area. In this case, a unique identical code (identifier), which corresponds to each type of object (PID, LID and AID) has to be created as previously described. The connectivity between attribute data and graphic data can be carried out by unique identifiers (Figure 18).

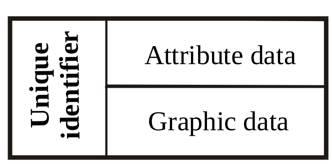


Figure 18. The connective principle between attribute data and graphic data.

4.3.2 Integrated management system for three sub-systems

Three types of data are stored in three separate databases. An integrated management system is designed to manage and process the three sub-systems and queried data sets. A dynamic linking pointer (DLP), e.g., geodetic coordinate, is designed for connection of three databases. With DLP, the query can simultaneously be carried out in each of the image, geo-data and DEM databases. The integrated management system also is responsible for superimposition, scale, compression, coordinate transformation and transmission to on-board data distributor (Figure 19).

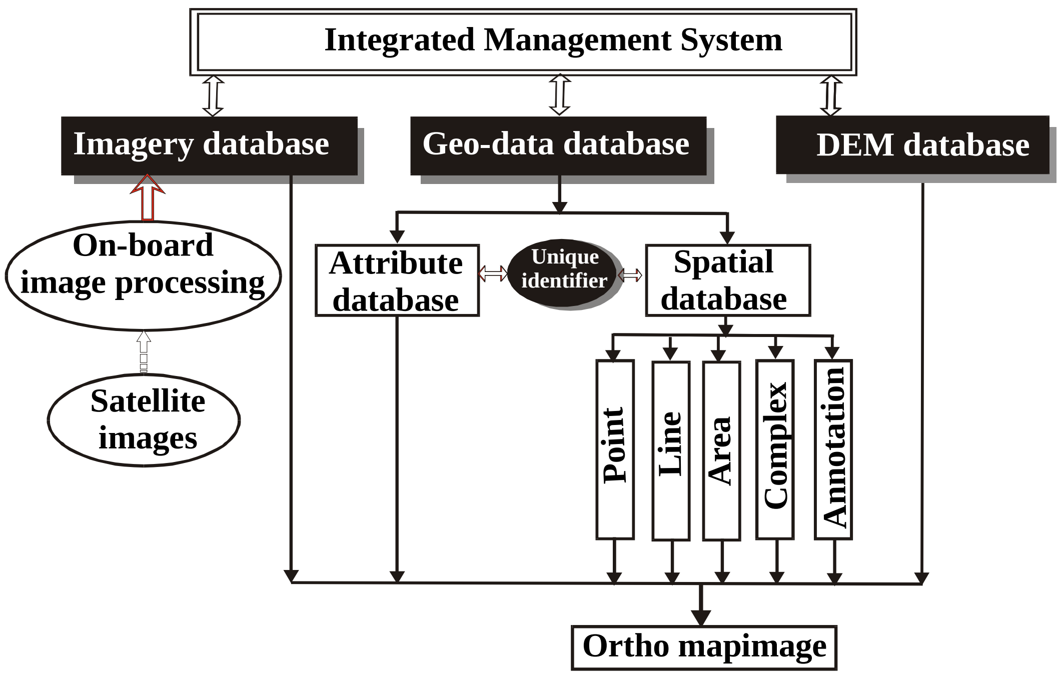


Figure 19. Integrated management system.

4.3.3 Query operation

When an end-user on the ground uploads his/her command for local imagery, the geodetic coordinates of the end-user and extent of AOI imagery are simultaneously uploaded to the on-board integrated database management system. A corresponding ID is created for retrieving imagery from the image database, geo-data from the geo-database, and DEM from the DEM database. After the three data sets are retrieved from the separate databases, they are merged into the integrated management system where superimposition, coordinate transformation to fit screen size (like Geo-tiff format), data compression, etc., takes place. The data sets are finally transmitted to an on-board data distributor.

Each end-user receiver on the ground includes a GPS receiver that can provide the user's position (latitude and longitude) in a geodetic coordinate system in real-time. Different receiver's parameters, e.g., size of screen, display speed, display resolution, etc., are stored on-board. The user's satellite receiver is also coded for on-board recognition of receiver types. As long as the on-board data management system recognizes the receiver's ID, it can immediately know the receiver's parameters. Thus, as soon as a user opens his/her receiver and uplinks to satellite for request of downlinking AOI image, his/her position (latitude, longitude), receiver's parameters, etc., will immediately be known to the on-board satellite autonomous management system. End-users also can download imagery of any AOI (for example, someone in Norfolk can obtain image data of New York City). Similarly, the on-board management system will search for AOI imagery based on specified coordinates and retrieve all available information based on these coordinates. The system then identifies the attribute data related to that query, defines its occupation areas, identifies the screen pixels that belong to these features and highlights them. If nothing is found, the integrated management system will immediately inform all subsystems to stop search and send the feedback to ground users.

Finally, the end-user should get an "image" in which the satellite imagery is supported as a reference layer in querying the real world by user. The existing geographic data (attribute data and DEM) will be superimposed on the imagery. The purpose of superimposition is for better visual analysis and understanding of the situation.

4.4 Key Technologies of On-Board Geo-Database Management System

The proposed concept uses the image as a reference layer in which the geo-data and DEM data are superimposed for analyzing and querying the real world. This type of product (geo-image map) contains more information than traditional satellite imagery (Mckeown, 1987). Users can better orient themselves with a geo-image map, especially if they are not familiar with the area under consideration. Furthermore, using satellite imagery as a backdrop beneath the map layers will increase the visual interpretation of an event. Realization of this function will encounter the following challenges:

(1) Retrieving the raster images, DEM and attributes as well as returning them to a user faces speed problems. More advanced query technologies, which considers *"on-the-fly"* query, need to be investigated.

(2) As the complexity increases, more data, especially attribute data, will be involved. It will be time consuming to query them one at a time. In order to reduce the downloaded data volume, the on-board decision-making processor should determine which data are most important and necessary to a particular user.

(3) As mentioned, the orthoimages are used as a geographic reference layers. The images may be differentially rectified, partially rectified or un-rectified because of on-board autonomous processing. When attribute data are superimposed on these images, the error of superimposition should be investigated.

(4) Inappropriate linkages of DEM, images and geo-data may produce slower performance, confusion and inaccurate results in downloaded imagery. If the linkage between the raster image and the geo-data is established through ground features, feature recognition is a big problem. If linkage is established via feature (geodetic) coordinates as we propose, some factors, such as scale, projection and coordinate system, should be unified.

In summary, the proposed OAGMS provides an approach for on-board integration of satellite data with corresponding geo-data (spatial and attribute data) and DEM data. The approach is based on the idea of using satellite imagery as a reference layer. Users can directly retrieve spatial information and perform spatial query via uplink of their commands to FIEOS. The geo-data is used for support of image processing, image interpretation and feature extraction. Thus the OAGMS is complete and seamless in connectivity of satellite data and geo-data. We expect this architecture of OAGMS can generate an entering point in future on-board geo-data management of the intelligent earth observing system.

5. FINANCIAL, POLITICAL, SOCIAL AND INSTITUTIONAL ISSUES

5.1 Cost and Budget Source Analysis

One may speculate that the more realistic issue is whether sufficient capital will remain available to develop and launch the systems, especially for the multi-satellite networked systems. A large outlay of capital is needed for the development to be completed before private enterprises can begin to realize a revenue stream. It is quite conceivable that these ventures will lead to significant advances in science and technology (Fritz, 1996). Possible budget sources are government agencies, private sector capital, and end-user investment. A recognized fact is that, in the rush to utilize outer space, governments have always given the highest priority for funding imagery collection systems and have allocated very limited resources for development of efficient imagery exploitation systems.

5.2 Development Phase/Time

The complexity of the on-board Earth observation satellite technology suggests that it will be necessary to split development of the intelligent earth observing satellite system into different components. The development time/phase for the intelligent satellites really depends on the development of real-time information technology (Prescott et al., 1999). On the other hand, since space activities are connected with a number of scientific and technological disciplines and are subject to a rapid change, it is important to ensure the efficient use of research results of other disciplines. Currently available and emerging technologies suggest that it is possible to realize *basic "intelligent"* data processing on-board (data processors). The development of *high "intelligent"* on-board data processing will require several generations to mature because image processing and computer vision research has demonstrated that full-automation of image processing (e.g., change detection) and fully automatic generation of value-added production (e.g., classification) is quite difficult. These issues will be investigated in more detail in phase II.

6. CONCLUSION

This report provides a high-level entry point for the design and architectures of an envisioned future intelligent earth observing satellite system. The proposed system is a space-based architecture for the dynamic and comprehensive on-board integration of Earth observing sensors, data processors and communication systems. It is intended to enable simultaneous, global measurements and timely analyses of the Earth's environment for a variety of users. The architecture and implementation strategies suggest a seamless integration of diverse components into a smart, adaptable and robust Earth observation satellite system. We have concentrated on validation of the on-board orthoimage generation and on-board geo-database management.

The design concept envisions a system that uses instruments requiring technologies capable of providing earth science measurements to a degree of precision and span of coverage not currently available. Common users would directly access data in a manner similar to selecting a TV channel. The imagery viewed would most likely be obtained directly from the satellite system. Real-time information systems are key to solving the challenges associated with this architecture. Realization of such a technologically complex system will require the contributions of scientists and engineers from many disciplines. Hopefully, this revolutionary concept will dramatically impact how NASA develops and conducts missions in the next ten years and beyond.

As the spatial information sciences mature, it is time to 'simplify' our technologies so that more users can directly obtain information from satellites. The future is promising for the photogrammetry/remote sensing/GIS communities. A thorough feasibility study addressing the key technologies of each of the components, the necessity, possibilities, benefits and issues, and exploration of specific funding opportunities for implementation will be performed in Phase II.

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The First International Symposium

On

Future Intelligent Earth Observing Satellites (FIEOS)

Progress Report
(June 1st 2001 – December 31st 2001)

Submitted to

National Aeronautics and Space Administration Institute of Advanced Concepts (NASA-NIAC)

By

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December 2001

The first Workshop (Symposium) on *Future Intelligent Earth Observing Satellites* has been organized. Since June 2001 until present, the symposium has produced the following significant progress:

The First Announcement and Call for Papers for the International Symposium on Future Intelligent Earth Observing Satellite has been completed. We have co-organized this conference with Dr. Kafatos at George Mason University, an imminent authority in Earth Observing science. Status of preparations so far are:

- **The Conference Date and Place:** The international symposium is schudled on April 25-27 Hilton Hotel Embassy Row in Washington DC.
- **Conference Themes**: Five themes, which are closely related to the topic of a future intelligent earth observing satellite system, have been selected. The themes are: Earth Observing Strategic Directions

  On-board Data Processing Schemes for General Users

  New Satellite Concepts and Smart Sensors

  Ground Station Networks and High-Speed Data Flows

  New Applications and End–User Requirements

- **Poster:** Design of a conference poster has been completed and is available at website http://www.fieos.gmu.edu
- **Steering Committee Members**: 30+ international experts have been selected and confirmed. See webpage for list of members.
- **Keynote speaker:** A keynote speaker (Congressman Davis) has been selected. Invitation and acceptance pending.
- **Additional speakers**: Experts from NASA-HQ will been identified and invited as guest speakers.
- **Journal Articles**: ASPRS has agreed to publish a special issue in their refereed journal to consist of 8-12 high-quality papers selected from the workshop.
- **Media:** We intend to invite a reporter from the Washington Post to cover this International symposium.

The Current Progress

- **Number of Received Abstracts:** We have received 55 abstracts covering 15 countries. 18 steering committee member are scheduled to attend this symposium. A delegation with 15 persons from National Aeronautics and Aerospace Bureau of China will attend this symposium. It is estimated the over 100 attendee will participant this symposium.
- **New FIEOS:** We have had such a positive response from international colleagues and the interest in this topic has grown so large that we have been invited to merge our FIEOS symposium with the 15th William T. Pecora Memorial Remote Sensing Symposium/Land Satellite Information IV Conference and the ISPRS Commission I (Platforms, Sensors and Imagery) Symposium in Denver Colorado scheduled from November 10-15, 2002. The web site describing this conference is found at: http://www.asprs.org/Pecora-ISPRS-2002/
- **The Second FIEOS Symposium:** Dr. Stanley Morain, a Chair of Commission I of International Society of Photogrammetry and Remote Sensing (ISPRS) is inviting us to co-organize the second International Symposium of FIEOS (FIEOS-II) in 2004 to be hosted in Istanbul. We will plan to organize the second FIEOS.