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Remote Sensing Operational Capabilities

Final Report

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This is a final report of a project. It has been formally reviewed but has not been formally edited.

DTIC QUALITY INSPECTED 1

Space Imaging's IKONOS satellite on 14 November, 1999, collected this image of the outskirts of Duzce where damaged was incurred from a devastating earthquake that struck northwestern Turkey on 12 November. The front cover contains a processed image, while the back contains an annotated image and graphically illustrates one of the early steps in the translation of raw imagery to a useful data product.

PREFACE

This Analysis

Earth-observing satellite remote sensing systems can be powerful tools for observing economic and military activities and scientific phenomena. Because of their potential utility, these systems are also the subject of many international cooperative agreements that serve a variety of political, economic, and national security objectives. The Office of Science and Technology Policy (OSTP) requested an analysis of Earth-observing satellite capabilities within the context of current and possible future international cooperative agreements in order to better understand the applications for which both what U.S. and international systems might be used. This analysis examines issues associated with sharing the data obtained by these Earth observation systems, as well as highlighting new classes of activities that will become possible with the deployment of high resolution electro-optical and radar satellites over the next few years.

This document summarizes key points of a briefing delivered to OSTP in April of 1999. The briefing describes new applications made possible by the ubiquity of high-resolution remote sensing systems. In addition, we hope to provoke thinking about how the capabilities inherent in some of the new satellite systems might be exploited for broader public objectives.

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- Helps science and technology decisionmakers understand the likely consequences of their decisions and choose among alternative policies
- Helps improve understanding in both the public and private sectors of the ways in which science and technology can better serve national objectives.

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Bruce Don
Director
Science and Technology Policy Institute

SUMMARY

Earth-observing satellite remote sensing systems can be powerful tools for observing economic and military activities and scientific phenomena. Because of their potential utility, these systems are also the subject of many international cooperative agreements that serve a variety of political, economic, and national security objectives. The Office of Science and Technology Policy (OSTP) requested an analysis of Earth-observing satellite capabilities within the context of current and possible future international cooperative agreements. This analysis examines issues associated with sharing the data obtained by these Earth observation systems, as well as highlighting new classes of activities that will become possible with the deployment of high resolution electro-optical and radar satellites over the next few years.

There are several ways in which remote sensing satellites and their various sensors might be characterized. Some characterizations focus on the spacecraft as a single entity, emphasizing mass, power, and orbital characteristics. Other characterizations focus on the sensor suite and emphasize factors such as spatial resolution, spectral coverage, and whether the sensor is active or passive. Because this study focused on applications of data gathered from the earth observation spacecraft, we chose to look at the sensors as the primary way of categorizing the spacecraft.

We associated remote sensing systems with one of four broad categories based on the minimum ground resolved distance of the on-board sensors. The first category covers coarse resolution sensors with a ground resolved distance (GRD) (the size of the smallest distinguishable feature) of 300 meters or more. The second category contains sensors that have a GRD capability of between 300 meters and 30 meters. The third category of sensor, with GRD capability ranging

from 30m down to about 3 meters, are sensors designed for land-use observation. The final category contains high-resolution imagery systems, with a GRD typically ranging between about 1 and 2 meters.

We also associated each spacecraft with its appropriate phenomenology (electro-optical or radar), as well as with the spectral resolution of the sensors. This arrangement made it natural to consider the operational capabilities of the systems in terms of how they might be used. As the spacecraft missions change, the spacecraft ownership patterns are also changing.

One of the most interesting and potentially far-reaching trends is the concentration of high-resolution remote sensing systems in commercial or quasi-commercial hands. In looking at the ownership of the systems, it is striking that the high-resolution systems are held for the most part by either U.S. commercial or foreign commercial firms rather than by governmental agencies (note that our analysis did not include military reconnaissance satellites, only civil or commercial spacecraft). It is this change in who controls these systems, as well as the technical capabilities of the systems, that are setting the stage for a significant change in how the United States should view satellite-based remote sensing for civil and scientific applications.

Four case studies were conducted to evaluate the operational capabilities of the satellite systems. These were: an assessment of flood monitoring in Bangladesh using radar satellites; an evaluation of disaster assessment in Kobe and Mexico City using high and low-resolution electro-optical systems, as well as radar satellites; an evaluation of humanitarian operation in Burundi using high resolution electro-optical satellites; and, finally, an evaluation of natural resource management using high-resolution electro-optical systems. In each of the cases orbital and sensor characteristics were modeled, as was the possible impact of weather over target areas.

In each of the cases the satellites were evaluated in terms of their ability to deliver timely information to decision-makers. The metrics used for the evaluation focused on time elapsed from the origination of the requirement until a successful observation could be made, and the area coverage in the target area. For the natural resource management case, an additional metric was also used to evaluate the capabilities of the system. This additional metric was the ability of a given system to detect vehicles operating outside of designated boundaries.

Based on the analysis of the case studies, it appears that there are many significant capabilities becoming available with the newest crop of Earth observation satellite systems. The ultimate value of the value of these systems to the US depends, in part, on their ability to support certain useful features, including:

- Rapid revisits: in order to collect the desired information quickly, it is imperative that the satellite be capable of accessing the target area frequently.

- Flexibility and speed in tasking: the system should be capable of collecting data with a minimum of advance notification and programming required, in the event of an emergency.

- Good resolution: the system must be capable of collecting data that is adequate for the mission requirements; although these requirements will vary, it is always possible to discard unneeded data, but not to create data that are necessary but not present.

- Compatible data formats: to allow easy combination and comparison of data retrieved from different systems, systems used for these purposes should allow for easy re-processing into a standardized format that can be usefully compared with data from other systems.

Finally, there are a number of possible activities that can be undertaken by the U.S. government that might increase the utility of the new satellite systems. Some can be taken unilaterally by the federal government, such as fostering the use of emerging commercial standards and becoming a better user of remote

sensing data. Others require cooperation with other nations, such as establishing mechanisms for rapid access to commercial remote sensing data and assuring payment to vendors. Still others require cooperation with industry, such as addressing technology control issues, and the management of intellectual property rights to ensure the greatest utility from the new remote sensing systems.
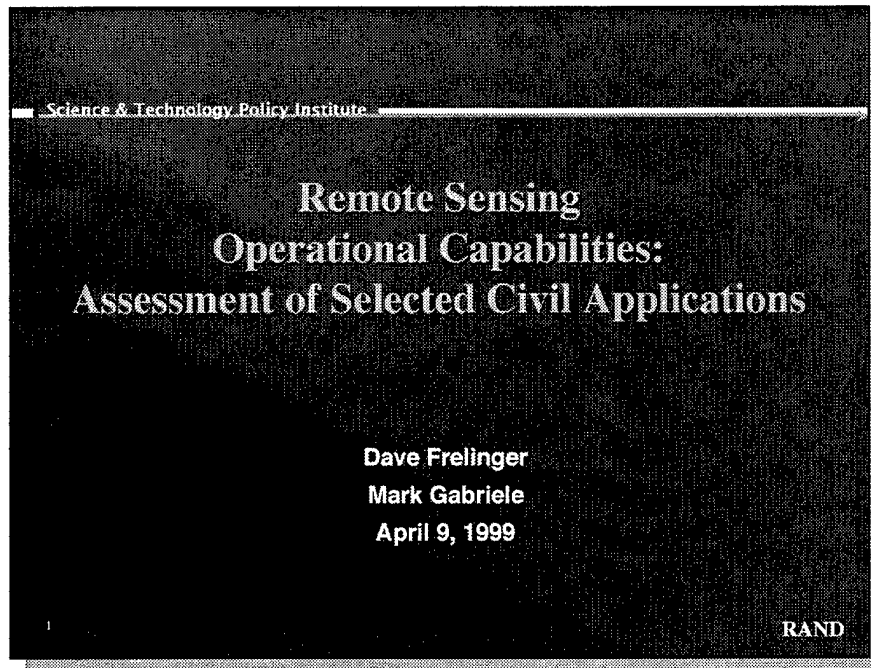
This briefing summarizes a number of significant opportunities for the use of civil sector applications of remote sensing, and highlights possible roles for the next generation of high-resolution Earth-observation satellite systems. This study was commissioned to help OSTP to better understand some of the civil applications of both American and international systems, and to help it better understand the potential benefits of using different remote sensing systems. It was presented to the Office of Science and Technology Policy, Executive Office of the President, on April 9, 1999.

Study Objectives

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- Provide OSTP with a catalog of current and planned earth observing remote sensing systems
- Facilitate an understanding of how data gathered different nation's space systems may be better combined to support scientific and policy decisions
- Flag opportunities for future agreements
- Provide insights into how changes in the remote sensing industry might impact cooperative activities

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This study was requested by the Office of Science and Technology to provide it with a better understanding of the possible impacts of currently operational Earth-sensing satellites, as well as the next generation of satellites, which will be placed into orbit over the next few years. Of particular interest was the growing role of systems belonging to other nations or non-national actors, and the possibility of new cooperative activities that might be pursued through cooperative agreements.

In order to gain a better understanding of the capabilities of the current and planned remote sensing systems, we created a database of Earth-observing satellites and focused particularly on the sensor systems cross referenced against international agreements involving that system. This database provided a snapshot of the current systems, and serves as a tutorial to those interested in earth observation systems. In addition to the database, we conducted a set of case studies to provide an understanding of how various technical characteristics of current- and next-generation remote sensing systems can be linked to application

areas with direct impact on human activities. We then further extended our work in the area by highlighting some areas where cooperation between nations might prove beneficial, and highlighted how changes in the remote sensing community might impact the form of those agreements.

Outline

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- Earth remote sensing satellites and their Characteristics
- New capabilities and employment schemes for earth remote sensing satellite systems
- Possible approaches for cooperation outside the current set of agreements

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The briefing is organized in three broad sections: first a discussion of the earth remote sensing satellite systems, second, an examination of some possible roles for those systems, and third, a discussion of opportunities for future cooperation outside of the current set of international agreements.
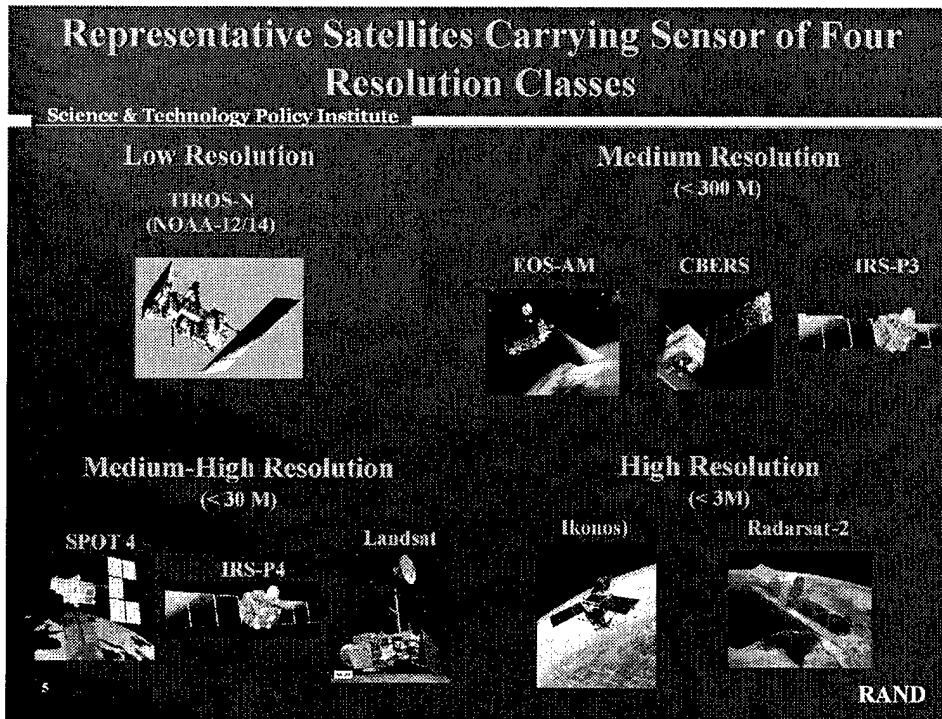
Representative Satellites Carrying Sensor of Four Resolution Classes
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Low Resolution
TIROS-N
(NOAA-12/14)

Medium Resolution
(< 300 M)
EOS-AM   CBERS   IRS-P3

Medium-High Resolution
(< 30 M)
SPOT 4   IRS-P4   Landsat

High Resolution
(< 3M)
Ikonos)   Radarsat-2

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There are several ways in which remote sensing satellites and their various sensors might be characterized. Some characterizations focus on the spacecraft as a single entity, emphasizing mass, power, and orbital characteristics. Other characterizations focus on the sensor suite and emphasize factors such as spatial resolution, spectral coverage, and whether the sensor is active or passive. Because this study focused on applications of data gathered from the earth observation spacecraft, we chose to look at the sensors as the primary way of categorizing the spacecraft.

We associated remote sensing systems with one of four categories based on the minimum ground resolved distance of the on-board sensors.

The first category covers coarse resolution sensors with a ground resolved distance (GRD) (the size of the smallest distinguishable feature) of 300 meters or more. Such sensors are typically designed to measure very large scale phenomena such as weather patterns, but can also be used to observe large scale changes on the earth's surface.

The second category contains sensors have a GRD capability of between 300 meters and 30 meters. These sensors are also designed to observe relatively large-scale phenomena. Systems such as EOS-AM (now EOS-TERRA) have very well calibrated sensors designed to monitor phenomena on a global and regional basis, and tend not to be designed to directly observe the impact of smaller scale human activities, and instead detect larger scale changes caused by humans or natural events.

The third category of sensor, with GRD capability ranging from 30m down to about 3 meters, are sensors designed for land-use observation. At this resolution human activities are evident, as are many man-made structures. There is difficulty in resolving small man-made objects, and it is frequently not possible to classify and identify man-made features in the image unless the GRD of the sensor approaches falls much closer to the 3-meter end of the resolution band. The terms "classify" and "identify" are used here in a specific technical sense of the words; to classify is to determine the basic nature of an object, while identification entails specifically distinguishing a particular object from other objects of the same basic type. An example would be to classify an object as a truck, while specific identification of the object may mean that the truck was determined to be a tanker truck as opposed to a flatbed truck.

The final category contains high-resolution imagery systems, ranging typically between about 1 and 2 meters. With these systems is now possible to classify and identify many man-made features, though determination of specific technical details of an object, such as distinguishing one type of vehicle from another, can still be difficult.

While a relatively crude method of distinguishing one system from one and other, the use of GRD provides a way of highlighting an important trend in remote sensing: the ability to observe smaller scale phenomena that are of interest to a new class of users. These new users include decision-makers interested in

assessing the impact of human activities on a smaller scale then was possible when using space-based remote sensing systems in the past; they may be from diverse groups, such as natural resource managers, law-enforcement, and relief organizations.

Parallel to the development of improved resolution, the field has moved towards the greater use of multi-spectral and hyper-spectral sensors. These sensors increase the amount of information gathered in a single image. The trend towards finer spectral coverage means for multispectral and hyperspectral system offers the possibility of uniquely identifying objects and phenomena based on the spectral signature of the object being observed. Additionally, greater use is being made of active imaging radar satellites, which can detect and observe both different phenomena and different aspects of areas imaged with sensors operating passively.

What is meant, effectively, by this improvement in spectral resolution is that many distinct wavelengths of light are collected and processed separately rather than all at once, much like the difference between black-and-white and color photography. Multi-spectral and hyper-spectral sensors differ only in the number of separate spectral bands collected. Multi-spectral data is typically collected in from four to several dozen bands; hyper-spectral data is typically collected in hundreds of bands. While many applications of these technologies are still in the early stages of development, the use of finer spectral resolution sensors has great long-term potential to deliver useful information to the user community. It will, however, require much time to develop databases to properly interpret data gathered from the systems.

Outline

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- **Earth remote sensing satellites and their Characteristics**
  - Resolution categories and spectral coverage
  - Who owns them
  - Which systems have international agreements associated with them
  - Problems with sharing data between systems
- **New capabilities and employment schemes for earth remote sensing satellite systems**
- **Possible approaches for cooperation outside the current set of agreements**

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The next section will examine the (current and planned) earth observation systems and discuss them in terms of:

- How they would be ranked relative to the categorization in GRD discussed earlier.

- Ownership of the system, whether government owned, or commercial.

- How they are associated with current international scientific and technical agreements to which the United States is a party.

- Some of the problems end-users may face in attempting to substitute data from one system for another.

Capabilities of Operational and Planned Systems

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Satellite name	Satellite system characteristics			
	Phenomenology	National origin	Nominal resolution	Typical image sizes
ALMAZ	SAR	Russia	5-7m 15m	30 km wide swath 150 km wide swath
ALOS-HR	Panchromatic EO	Japan	2.5m	35 km wide swath
ALOS-LR	Multispectral EO	Japan	10m	70 km wide swath
CBERS	Panchromatic EO	China /Brazil	20m	120 km wide swath
Clark	Multispectral EO	USA	3m/ 15m	30x30 km frame
EOS-AM	Multispectral EO	USA	15m	60 km wide swath
ERS-2	SAR	ESA	30m	100 km wide swath
Ikonos	Multispectral EO	USA - Comm.	1m	11 km wide swath
LandSat-7	Multispectral EO	USA	5m	60 km wide swath
Orbview	Multispectral EO	USA - Comm.	1m	8 km wide swath
Quickbird	Multispectral EO	USA - Comm.	1m	27x27 km frame
RadarSat-1	SAR	Canada	8m 30m	50 km wide swath 100 km wide swath
RadarSat-2	SAR	Canada	3m 30m	20x20 km spot 100 km wide swath
Resource-21	Multispectral EO	USA - Comm.	10m	205 km wide swath
SPOT-4	Multispectral EO	France	10m	117 km wide swath
SPOT-5	Multispectral EO	France	5m	60 km wide swath

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The above chart provides an overview of current and planned earth observation systems.[1] These systems use a variety of means to gather data about the earth such as passive electro-optical systems operating at a variety of wavelengths, as well as active radar satellites that are capable of imaging the earth's surface. Each of these types of sensors has advantages and disadvantages in terms of gathering information.

The passive visible and near visible light systems consist of both high resolution and low-to-medium resolution systems, and most operate in two different regimes. These regimes are:

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[1] The information represents information current as of April 1999. Capabilities of planned systems are subject to change. The Clark mission was included for completeness, and is intended to represent multispectral remote sensing system within current state of the art.

- Panchromatic, in which imagery from all portions of the visible and near-visible spectrum is collected and recorded as shades of gray; and

- Multispectral, in which particular wavelengths (or wavebands, or simply "bands") of light are recorded individually and can be viewed together (to produce a true-color image) or in selected combinations (to produce what is known as a false-color image).
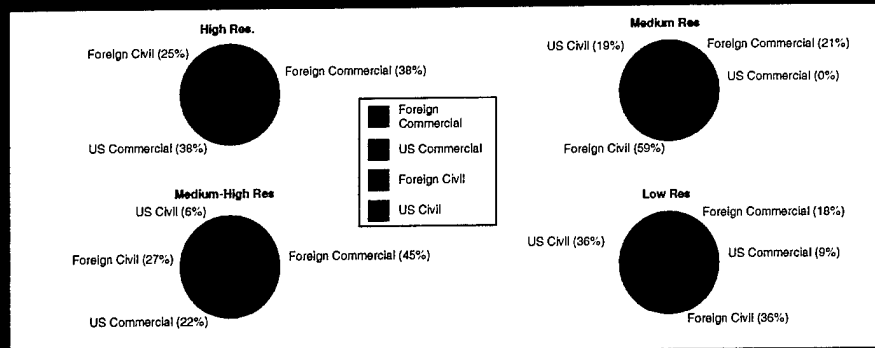
Multispectral systems vary in the number of bands they collect, and in which bands they collect. Popular bands include the blue, green, and red portions of the visible spectrum, the near-infrared, and the long-wave or thermal infrared. The near-infrared bands have a wide variety of applications; among the more common is the ability to detect certain indicators of the health of vegetation. The thermal-infrared bands detect heat differences and can be used to remotely determine the absolute temperature of a target within several degrees Celsius, or the difference in temperature between objects in a given image to an even finer granularity.

If a satellite system has the ability to image in bands outside of the visible spectrum, it is more properly called an "electro-optical" or EO systems. These systems collect data in wavelengths that are really not visible at all, but they use an electronic sensor to detect these optical signals – hence, the name "electro-optical". Some EO satellites collect both panchromatic and multispectral data; in these cases, the panchromatic imagery (which has finer resolution than the multispectral) can be merged with the multispectral to better define details. This "pan-sharpening" approaches the resolution quality of the panchromatic while offering the additional information inherent in the multispectral image. These EO systems are passive sensors; they only operate when there is sufficient light reflected by or emitted from the target for them to form an image. For all practical purposes, they do not collect imagery at night, and cannot image through cloud cover.

In contrast to the light-dependence of EO systems, synthetic aperture radar (SAR) systems have an "active" sensor. That is, they provide their own illumination, and can therefore operate at night, when a "passive" sensor that detects, for example, reflected sunlight, would not. In addition, most SAR systems operate in the microwave region of the electromagnetic spectrum (some operate at Ultra High Frequency (UHF) or Super High Frequency (SHF)). UHF, SHF, and microwaves generally have very good atmospheric penetration capability, so a SAR satellite can collect data through clouds and light rain. Finally, SAR images are created by describing a scene in terms of range and azimuth from the sensor; this gives the collected imagery the look of a "plan view" drawing, and provides very specific information about exactly where every object is positioned in relation to every other object on the ground. This is notably different than the way optical imagery works, which is that two objects that are far apart may appear close together, depending (among other things) on the angle from which we view them and whether we are able to get more than one image of the object in order to achieve a stereoscopic effect. This difference presents a significant advantage for some types of data collection operations.

A notable disadvantage of SAR systems is that the imagery provided shows only those objects that reflect the radio frequency (RF) energy back to the imaging platform; that means that objects that don't reflect RF energy, don't show up. Trucks, buildings, rock formations, etc. all tend to show up and are readily identifiable, but organic targets, such as animals or vegetation, are much less visible. The finest resolution of any of the SAR systems considered here is 3 meters; 10-30 meter resolution is more typical for this class of system. Even this lower resolution has significant utility for some operations (such as mapping of ice floes). Additionally, as a general rule for SAR and visible (or electro-optical) systems, the more coarse the resolution, the greater the area coverage capability, so a system which has low resolution will likely be capable of imaging a large area relatively quickly.

Figure categories: High Res., Medium Res., Medium-High Res, Low Res.

High Res.: Foreign Civil (25%), Foreign Commercial (38%), US Commercial (38%)

Medium-High Res: US Civil (6%), Foreign Civil (27%), Foreign Commercial (45%), US Commercial (22%)

Medium Res: US Civil (19%), Foreign Commercial (21%), US Commercial (0%), Foreign Civil (59%)

Low Res: Foreign Commercial (18%), US Commercial (9%), US Civil (36%), Foreign Civil (36%)

Legend: Foreign Commercial, US Commercial, Foreign Civil, US Civil
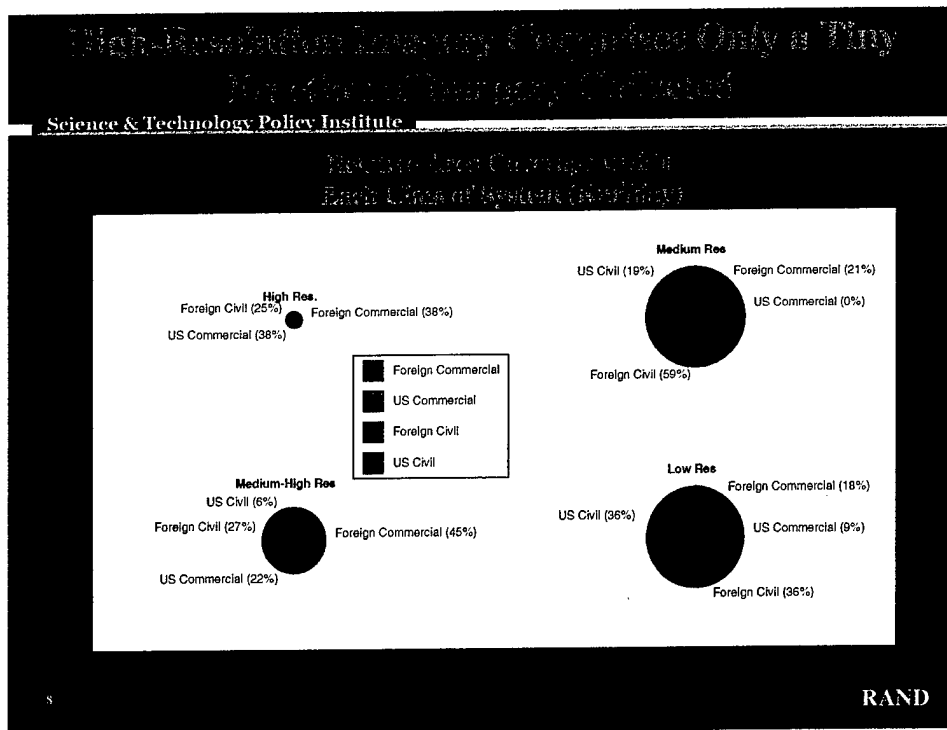
The proliferation of remote sensing systems with significantly greater capabilities brings up a number of questions regarding not only the utility of the systems but also their operational control. Specifically, who will direct the collection activities of these satellites? And will these new higher-resolution remote sensing systems demonstrate capabilities that are fundamentally different than their lower resolution predecessors?

The above chart depicts the relative contribution of coverage within each category as a function of the percentage of land imaged in each category by either US/foreign commercial, or US/foreign civil systems.[2] One of the most interesting and potentially far-reaching trends is the concentration of high-resolution remote sensing systems in commercial or quasi-commercial hands.[3] In looking at the ownership of the systems, it is

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[2] The data shown draws from a database of planned and operational remote sensing systems constructed for this analysis.

[3] For our purposes, the "foreign commercial" category includes systems like the French SPOT that act like commercial entities, even though they have significant governmental involvement.

striking that the high-resolution systems are held for the most part by either U.S. commercial or foreign commercial firms rather than by governmental agencies (note that our analysis did not include military reconnaissance satellites, only civil or commercial spacecraft). It is this change in who controls these systems, as well as the technical capabilities of the system that are setting the stage for a significant change in how the United States needs to view satellite-based remote sensing for civil and scientific applications.

High Res.
Foreign Civil (25%) Foreign Commercial (38%)
US Commercial (38%)

Foreign Commercial
US Commercial
Foreign Civil
US Civil

Medium Res
US Civil (19%) Foreign Commercial (21%)
US Commercial (0%)
Foreign Civil (59%)

Medium-High Res
US Civil (6%)
Foreign Civil (27%) Foreign Commercial (45%)
US Commercial (22%)

Low Res
Foreign Commercial (18%)
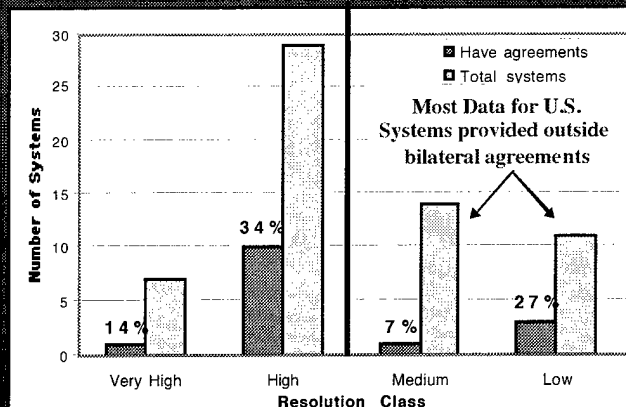US Civil (36%) US Commercial (9%)
Foreign Civil (36%)

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While looking at the percentage of ownership of various systems is useful, it is important to keep in mind that there are significant differences in the absolute coverage capability of the various systems in different resolution classes. The above figure shows the breakdown in ownership of various systems based on resolution class, and daily coverage (km^2) of the systems. The size of the circle shows the daily coverage from each class of system, while the fraction of the circle shows the percentage contribution from civil and private entities.

The dramatic difference in terms of daily coverage between high resolution and lower resolution systems shows that the lower resolution systems will supply the overwhelming majority of coverage capacity (albeit at much coarser resolution and for very different purposes) even after the deployment of a number of high-resolution systems. While high-resolution systems provide an important new capability in the earth observation arena, their tightly focused observation should be considered a complement to – rather than a replacement of – the lower resolution systems that observe wide areas of the Earth's surface. This means that

while close attention should be paid to the new high-resolution systems, maintenance of cooperative agreements among operators of lower resolution systems will remain very important over time. The difference in absolute coverage is important to keep in mind.

Satellites Covered by International Agreements

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■ Have agreements
□ Total systems

Most Data for U.S. Systems provided outside bilateral agreements

Number of Systems

Very High | High | Medium | Low
Resolution Class

14% 34% 7% 27%

Only minority of satellites are the subject of international cooperative agreements
- Many agreements don't focus on payloads
- One-third at best (3m to 30m resolution class)
- No agreements covering true commercial systems

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One portion of our work on this project was the construction of a database relating sensor packages and their spacecraft with international agreements for data sharing and cooperation.[4] When we matched the various remote-sensing systems with the bilateral and multi-lateral cooperative agreements to which the U.S. is a partner, we saw that only a relatively small fraction of systems are accounted for in those agreements. While this is a somewhat surprising result, it can be better understood by considering the low- and medium-resolution systems separately from the high- and very high-resolution systems.

The reason there are relatively few agreements pertaining specifically to the low- and medium-resolution systems operated by the United States government is that in general, data from these systems is handled outside of those agreements. Ordinarily, data from these systems is provided through other mechanisms; for example, this is the case for the dissemination of most weather data, which is

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[4] The primary source for information on international agreements was Caroline Wagner, *International Agreement on Cooperation in Remote Sensing and Earth Observation*, RAND, MR-972-OSTP, 1998.

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made very widely available and can in fact be received directly from the satellite by hobbyists.

The story describing why there appear to be few international agreements for data sharing and cooperation based involving the higher resolution systems is more complex. However, many international systems are not handled within the cooperative agreement format, and instead are essentially commercial activities. This difference between how the U.S. views its civil systems and other nations view their civil systems is important. The U.S. government has made significant allowances for the sharing of data from Earth resources satellites in cooperative agreements, as well as in commercial-like arrangements, while many international actors treat consumers of data outside of their country as essentially commercial customers for that data.

What Systems Are Covered By Agreements

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- Agreements focus on state-to-state interactions and govern civil systems
  - Largest number of agreements focuses on ARGOS communications package on NOAA satellites
  - Most weather and Earth resource data shared outside of bilateral agreements (Landsat and NOAA-XX)
- Many of the new systems are not considered strictly scientific and fall mostly outside the current sets of agreements
  - New systems can support a wide variety of new missions beyond those of earlier earth observation systems
  - Getting timely access to the data is bureaucratically challenging
  - End user cost

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Given that relatively small fractions of remote sensing systems are handled under international cooperation agreements, the question arises: What is covered by those agreements?[5] Over half of the agreements in the database cover the ARGOS communication systems hosted on the NOAA weather satellites, and really don't have anything to do directly with acquisition of data directly from the satellite system itself.[6] Of the remaining agreements, the largest fractions are associated with the Landsat mission, and deal with earth resource applications. Some agreements do pertain to high-resolution sensors carried on civil spacecraft,

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[5] Note: The actual rationale for these agreements are quite varied. Some focus on scientific cooperation, other are used to advance broader political, economic, or security concerns. However, for our analysis we focused exclusively on agreements focused on Earth Observation used for scientific cooperation.

[6] The ARGOS data communications system provides an operational data collection service for several thousand data collection platforms (DCPs). Typically, these platforms are located in remote areas or aboard platforms that preclude the use of more conventional communication techniques. The space segment of this system is carried aboard a number of satellites and serves to relay data from the DCP to a central ground station located at Wallops Island, Virginia. The DCPs can be located anywhere on earth, and are most commonly used to send back data relevant to scientific research programs. The large number of international agreements involving this system is indicative of the global scope of this mission.

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but the vast majority of the capabilities in the high-resolution segment are in the hands of commercial and quasi-commercial entities, which places them outside the current set of international agreements because these agreements have been oriented toward scientific applications.

As mentioned earlier, many of the newer systems are not covered by any of the current sets of cooperative agreements in as much as they are not traditional scientific missions with an objective of making the data they collect available to the widest possible audience. The commercial nature and technological characteristics of many of these enterprises has made classic cooperative agreements difficult because of both intellectual property concerns, as well as security concerns. For instance, systems such as NEMO and Warfighter-1, are being handled under a variety of public-private partnership arrangements that allow for selective dissemination of data through commercial channels. However, because of the possible sensitivity of the data and contractual arrangements it may disseminate the data very widely. Intellectual property concerns mitigate against unrestrained government-to-government transactions that may cannibalize commercial demand for the data, and possible security restrictions limit the ability to sell data freely.

A repeated concern of many scientific and not-for-profit users of remote sensing data is that remote sensing data from commercial providers will be unaffordable. Indeed, the difference between what is paid for data sets produced by government systems and commercial systems can appear to be very large since the user of government data pays something close to marginal cost, while the user of private data pays something near average cost. In the case of a multi-hundred-million dollar spacecraft, the difference between the marginal cost and the average cost (where average cost includes the opportunity cost of the data collection opportunity amortized over the spacecraft's expected lifetime) can be tremendous. However, there are many examples in the information technology area of

educational and not-for-profit discounting schemes that appear to encourage use of a particular data source with the intention of creating a network effect that will then increase the value of the full-priced product. The mechanisms of these network effects can differ, but typically they act by creating a demand for the product among consumers who would not have had one previously. This suggests that the situation may not be as bad as many fear, and that through tiered pricing schemes geared for non-profit, government, humanitarian, or research uses, many users will pay lower prices than the nominal average cost of commercial imagery while still allowing commercial data providers to make a profit. Furthermore, market and technological changes will probably put downward price pressure on remote sensing data.

Why Is it Difficult to Share Data

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- **Sensor characteristics differ**
  - Sensitivity
  - Spectral coverage
  - Calibration
- **Sharing data is difficult**
  - Few common standards
  - Proprietary data processing systems and algorithms
  - Many corrections reveal proprietary aspects of the collection system
- **Applications demand consistency**
  - Subtle inter-scene variations can be important
  - Signal to noise can be very low for some phenomena

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Given the wide variety of space systems, and the apparent overlap in the capabilities of these systems, a quite reasonable question focuses on the ability to readily share data between systems and thereby more efficiently exploit world-wide observation capabilities, particularly for scientific applications. Unfortunately, upon closer examination it becomes apparent that there are many difficulties that mitigate against the sharing of data. These difficulties can be thought of as being associated with the sensor system, the data formats and processing systems, and the exacting nature of data requirements for many scientific applications, where small variations in data quality can lead to incorrect assessments and conclusions based on that data.

The net impact of the aforementioned difficulties in sensor technologies is that even ostensibly very similar systems (such as the multi-spectral sensors carried on the LandSat series, the French SPOT (Systeme Probatoire Observacion de la Terre) series, and the Indian IRS (Indian Remote Sensing) series) prove difficult to use interchangeably. The systems have slightly different spectral coverage, and each has different sensitivities that lead to their being used for similar yet not quite identical applications. For instance, if inter-scene differences are significant and the expected differences are small, subtle variations between the sensors can make their use very difficult.

Other sources of difficulties are associated with the different formats of the data, dependence on different proprietary software, and user familiarity with the sensor systems. Of these factors, the easiest to solve are those associated with data formats and software. For both of these, technical solutions are very possible, and indeed are beginning to be pursued. However, the issue of user familiarity with, and therefore confidence in, the system is perhaps a more difficult problem. The scientific users of data are very risk averse and are frequently not comfortable

basing their results on data obtained from unfamiliar sensor systems. The combination of their interest in measuring phenomena that are frequently subtle, combined with needs for baseline data collected over an extended period of time, makes them a set of potential users that are difficult to satisfy. A more promising set of uses for this data appears when we consider markets beyond this small but demanding set of users.

There Are Many Applications That Do Not Require the Same Data Quality as Scientific Applications

Science & Technology Policy Institute

- **Measurement of short-term events with large signal to noise**
  - Disaster assessment (earthquake, flood, storm damage)
- **Cueing for terrestrial sensors on human observers**
  - Detecting possible pollution
  - Boundary enforcement on federal lands
  - Detection of possible humanitarian disaster

GDIN discussions are a start, but there are many other possible applications

13   RAND

While it can be difficult to share data under many circumstances, there are other classes of applications where the small-scale variations and lack of extremely consistent calibration data do not impact the overall usability of the data. For instance, short-term events with very high signal to noise ratios are excellent candidates for comparative use of various sensor systems.[7] Data that might otherwise be unsuitable for many scientific applications are very useful in application domains such as disaster management, or in applications where the remote sensing system is used to cue other sensors.

The importance of standards in these applications cannot be overstated. Standardization allows for ease of data interchange and for rapid comparison of new data to existing baseline data. In time-critical applications, the use of relevant standards can provide significant enhancements to the speed with which data can be processed and interpreted. Even in applications in which there is less

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[7] By very high signal to noise we mean cases in which the inter-scene changes caused by the phenomena of interest are much larger than background changes due to other factors.

emphasis on rapid availability of data, appropriate standardization of data and data products makes it possible to make accurate and appropriate comparisons of information from multiple sources.

Some efforts are already underway to make greater use of remote sensing data in disaster assessment. The Global Disaster Information Network (GDIN) is attempting to establish new sets of standards for interchanging the data for use in disaster prevention and mediation, and as such, represents a beginning of a process to make greater use of remote sensing data.[8] There are, however, applications in many areas that are not really a focus of the GDIN that represent potential future uses of these systems. While lessons obtained through the GDIN will be helpful in the future, GDIN itself will not necessarily address all the issues necessary for broad applications of these remote sensing systems.

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[8] The actual technical data interchange standards are being developed by a host of technically focused groups such as the OPENGIS consortium.

Commercial High-Resolution Systems Represent the New Challenge for Cooperation

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- **No longer amenable to simple state-to-state agreements**
  - Many of the most "interesting" systems are not directly in the hands of any government
  - Economic incentives seem to be more important
- **Complex commercial and national security issues as both the value of the data products increase**
  - Property rights issues
  - Dual use of high-resolution data sets of sensitive areas
  - Technology transfer issues

14   RAND

The challenges of dealing with commercial remote sensing companies, and of collaboration outside of the tried and trusted regime of international cooperation focused on scientific applications are formidable. No longer can state-to-state agreements easily accommodate these systems and uses for the data. Working with the commercial world requires a clearer understanding of the incentive structures and the timelines for business decisions. While economic incentives are understood by public sector actors as driving commercial sector decision-making, the time sensitivity of those business decisions are not reflected in many interactions with the commercial sector. For instance, programmatic delays that may be inconvenient when encountered by public sector organizations can be ruinous in the private sector.

There are also complex problems that involve the intersection of national security and commercial interests. As remote sensing data begins to have greater and greater utility to applications-oriented users, it begins to have significant national security applications as well. Learning to handle the dual-use nature of this technology, as well as deciding what kinds of data and technology to protect, are

significant challenges in establishing any sort of wide-scale cooperative activities. For instance, while time-sensitive data might be easily protected for the relatively short period during which its disclosure could reveal sensitive information, protecting entire technologies that are vulnerable to a single instance of compromise is fundamentally more complex and difficult to achieve.

Outline

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- Earth remote sensing satellites and their Characteristics
- **New capabilities and employment schemes for earth remote sensing satellite systems**
  - Rapid All-weather flood assessment: Bangladesh
  - Rapid Earthquake damage assessment: Kobe / Mexico City
  - Humanitarian Operation: Burundi
  - Boundary enforcement: Yellowstone National Park
- Possible approaches for cooperation outside the current set of agreements

15   RAND

The next section will discuss how the new capabilities of the high-resolution remote sensing systems might be employed in some exemplar humanitarian operations, as well as in the case of a land-use management problem. By looking at these problems it will be possible get something of the flavor of how these different systems might be employed, and why having access to several different remote sensing systems would be advantageous.

Employing New Capabilities in Four Case Studies

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We examined five specific scenarios, exercising various satellite remote sensing capabilities
- **Bangladesh**
  - SAR only
- **Kobe / Mexico City**
  - High- and low- resolution electro-optical and SAR
- **Burundi**
  - High-resolution electro-optical
- **Yellowstone National Park**
  - High-resolution electro-optical

16   RAND

Given the characteristics of the satellites, we now consider each of these cases in the context of what information the remote sensing systems can contribute about each situation. It is important to note at the outset that the following quantitative analyses described below are based on available information about the systems considered, and actual performance of many of these systems in these roles remain to be demonstrated. Where information was unavailable, a set of standard assumptions was applied uniformly, so that the results should be consistent with the actual behavior of the systems.
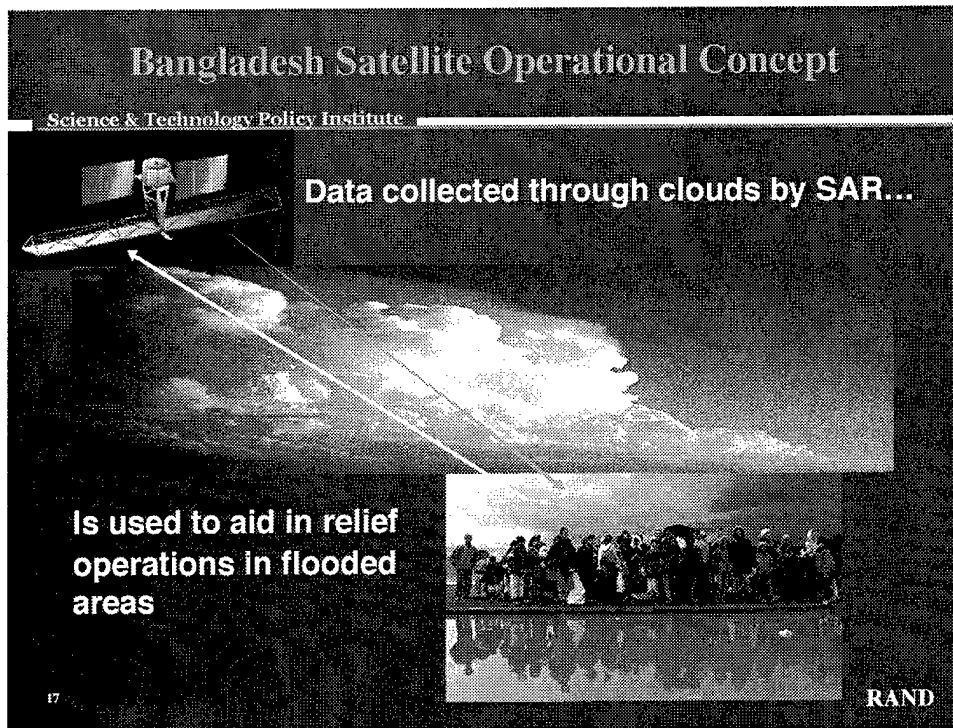
Bangladesh is subject to serious flooding each year during the monsoon season. In this case, a reasonable goal of satellite remote sensing capability is to collect imagery of the affected areas of Bangladesh, in order to determine the extent of the flooding. Communication is so poor in many of these areas that it would be of assistance just to know what areas are and are not covered by water, as a simple way of determining where rescue operations should be deployed. Of course, the flooding occurs at the time of year that the nation is most likely to be covered by clouds, so electro-optical imaging sensors have little chance of being effective. However, a SAR sensor could probably penetrate the clouds and precipitation and collect imagery of broad areas, and would allow the identification of those areas covered with water.[9] Because a SAR intrinsically provides an image that can be

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[9] As an aside, water reflects the RF energy from the SAR very well, but does not tend to reflect it back at the satellite; instead, it reflects the energy away. This leads to the appearance of a "hole" in the image, which is readily interpretable to an analyst as pool of still water.

said to resemble a "plan view" or a map, once the image is registered with the ground, the extent of flooding can be determined with great precision (30 meters is certainly sufficiently fine resolution to establish general maps of flooded areas and determine those areas which are worst affected).

Bangladesh Satellite Operations

Science & Technology Policy Institute

Problem: Low-lying areas in Bangladesh subject to frequent flooding

- **Want to know where to target relief efforts**
  - Need to map currently flooded areas through cloud cover: use Synthetic Aperture Radar (SAR) systems
- **Four systems considered**
  - European Remote Sensing Satellite (ESA)
  - RadarSat-1 and RadarSat-2 (Canada)
  - Almaz (Russian)
- **Area coverage and revisit rates most important in this case**

18   RAND

The four SAR satellites evaluated for possible use in this disaster-relief role in Bangladesh were the Russian Almaz (which translates into "diamond"), the European Space Agency ERS-2, and the Canadian systems, RadarSat-1 and RadarSat-2. As of this writing, only two of the four are on-orbit and operational; those are RadarSat-1 and ERS-2. Almaz is scheduled (based on reports published in 1995) to be nearly ready for launch as of this writing, but financial turmoil within Russia has caused the launch to be delayed; detailed information is unavailable, but launch will probably occur within the next few years. RadarSat-2, which is still in the design stage, is also slated for launch in the next few years. As is evidenced by the graph shown on chart 21, there are three systems that are clearly comparable: RadarSats-1 and –2, and the Almaz satellite. ERS-2 will typically revisit the target every 6.5 days, which puts it squarely in position as the least capable of these four systems for short lead time, large area coverage SAR collection. In contrast with RadarSat-1, the ERS-2 SAR has a maximum gap 3.5
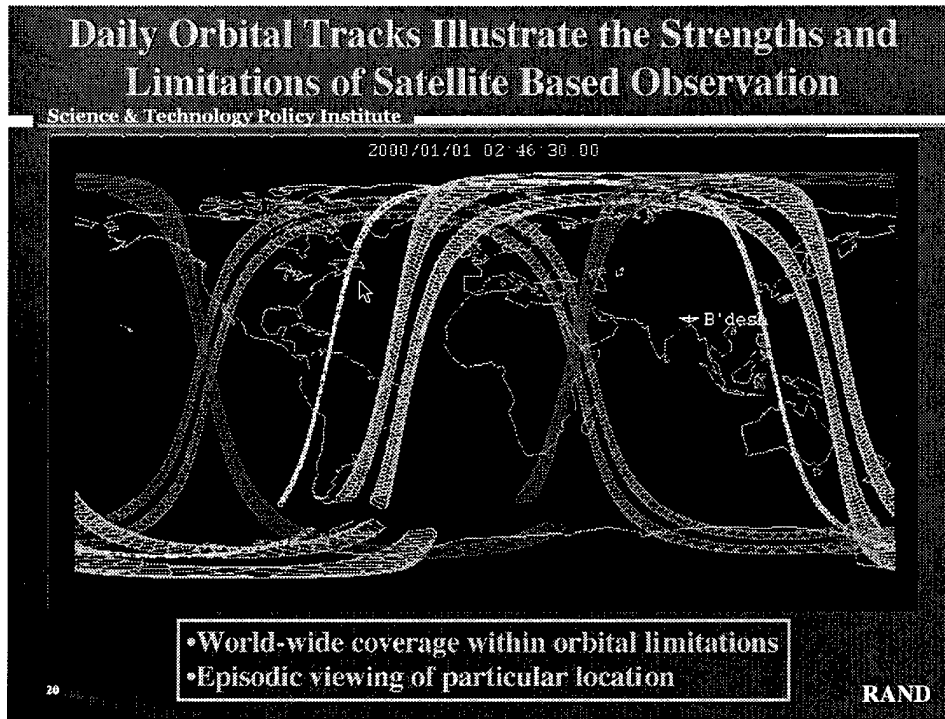
times as long, and may go for almost 20 days between imaging passes for this target. Of the two future satellites, Almaz has a mean revisit time that is almost as low as that of RadarSat-2, and offers finer resolution (15m as opposed to the 30m of the other satellites). For the purposes of wide-area flood assessment, it is unlikely that the finer resolution provided by the Almaz system would be of much greater utility than the 30-meter data of the other systems. This higher resolution would not detract from the value of the imagery, and it would likely serve as at least a marginal aid in the interpretability of the data.

Resolution is also a factor in the collection of the data. For each of these systems, the resolution (referred to for SAR systems as the impulse response or IPR) is selectable. While 30m is the finest resolution offered by ERS, all of the other satellites can do better. Almaz and RadarSat-1 provide resolution in the range of 5-8 meters in their finest-resolution modes, and RadarSat-2 is being designed to provide a maximum of 3m resolution in its finest-resolution mode. In each case, as the resolution becomes finer, the area of the image collected tends to decrease dramatically, since the amount of data collected increases with better resolution (to be precise, it increases as the square of the resolution). The goal of the problem is to be able to collect imagery of as great a percentage of the Bangladeshi landmass as possible in a short time, to best assess flooding. Because the area of Bangladesh is approximately 144,000 square kilometers (55,600 square miles), it appears evident from the graph shown on chart 21 that nearly the entire area of Bangladesh can be imaged in little more than one pass by any of the systems except ERS, which will require 3 passes to complete the job. Unfortunately, the problem is not quite that simple. Part of the difficulty involves the shape of Bangladesh, and how that shape compares to the imaging swath of the satellite; another part depends on system-specific characteristics of the SAR system itself (which deal with technical aspects of the SAR data and how it is collected and processed). It is likely that the imagery will not be collected as rapidly as is depicted on chart 21, and so it is important to consider how rapidly

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the satellite can revisit the area. Although in an actual crisis, data from multiple satellites could be collected and used together in order to increase the revisit rate, there is no data available regarding the exact timing of the satellite orbits with respect to each other, and those calculations cannot be completed without that information. Optimal timing of satellite orbits to decrease revisit times would be an appropriate goal for any cooperative-use satellite agreement. There is also a natural history to any flooding process, and observations of the area over time are essential to determine that history and how the flooding has, and is likely to, proceed.

Daily Orbital Tracks Illustrate the Strengths and Limitations of Satellite Based Observation
Science & Technology Policy Institute

2000/01/01 02 46 30 00

+ B'des

•World-wide coverage within orbital limitations
•Episodic viewing of particular location

RAND

An important requirement for each of the cases considered here is the timeliness of imagery collection. The ability to collect the imagery given only a short lead time is a component of each of these problems. It is therefore important to carefully consider how long it will take before imagery of relevance to the case in question can be obtained.

It is a truism of satellite imaging systems that, once a satellite is on orbit and operational, it tends to be very reliable over its lifetime, and will provide predictable coverage over locations on the Earth's surface..[10]   Unfortunately, this predictability can work against satellites in certain cases. It may not be possible for a satellite to collect imagery on very short notice, because the desired satellites' orbit may not bring it to its target for some time. This could theoretically be remedied (within limits) by maneuvering the satellite. However,

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[10] While many public-sector supported space imaging missions have been very reliable once they have reached orbit and have become operational, but it is unclear of privately funded space missions operating on far tighter budgets will have the same experience.

this maneuvering, which changes the satellite's orbit, is almost entirely out of the question, because it consumes fuel, and because the supply of fuel carried is necessarily limited. Further, none of the satellites considered here is designed to be refueled once it is launched. Thus, all fuel on a satellite is a precious commodity and most maneuvering is limited to that necessary to counteract drag or stabilize the satellite. Simply put, once a satellite is launched into a given orbit, it stays there, guided by Kepler's laws.

This is a very real consideration for satellite designers, and it affects the designs of the orbits used by the systems, as well as the designs of the systems themselves. For example, electro-optical satellites most commonly use a type of orbit called "sun-synchronous". These are orbits that pass over the equator each day at the same "sun time" – that is, the sun is in the same place in the sky relative to the satellite as it makes each pass. This causes the length of the shadows in the image to be the same from day to day, which is a boon to imagery interpreters trying to compare images over time. It also makes it possible to collect stereo pairs of images over a span of days (in order to capture a very similar image, but create a parallax effect to allow the analyst's eyes to see the image in stereo), which allows for a perception of height information by the imagery interpreter.

In contrast, because of the difference in phenomenology, SAR satellites need not be constrained by many of the concerns that affect EO satellites. They are not really capable of collecting imagery in stereo pairs; the information recorded by the SAR is in terms of range and azimuth to the objects imaged, which differs from the manner in which we perceive depth. In addition, because the angle of the sun with respect to the ground does not materially affect the quality of a SAR image, SAR satellite orbits need not be particularly cognizant of the need to maintain sun-synchrony. However, many SAR satellites are sun-synchronous anyway, either because the spacecraft carries other payloads that are more sensitive to the orientation of the sun, or because of the convenience of having easily predictable repeating coverage most of the time.

Predictability is another factor in favor of sun-synchronous orbits. The procession of the orbit is matched to that of the sidereal day, so it is a relatively simple matter to understand and predict the coverage periodicity of the satellite, given information relating to the sensor field of view. The ready predictability of the ground track of the satellites allows for easier planning of periodic revisits; for example, a given area can be imaged every third day with the intention of creating a library of images of a given target. Such a library of imagery can be reviewed at length in order to support further analysis of the natural history of an event (such as a flood).
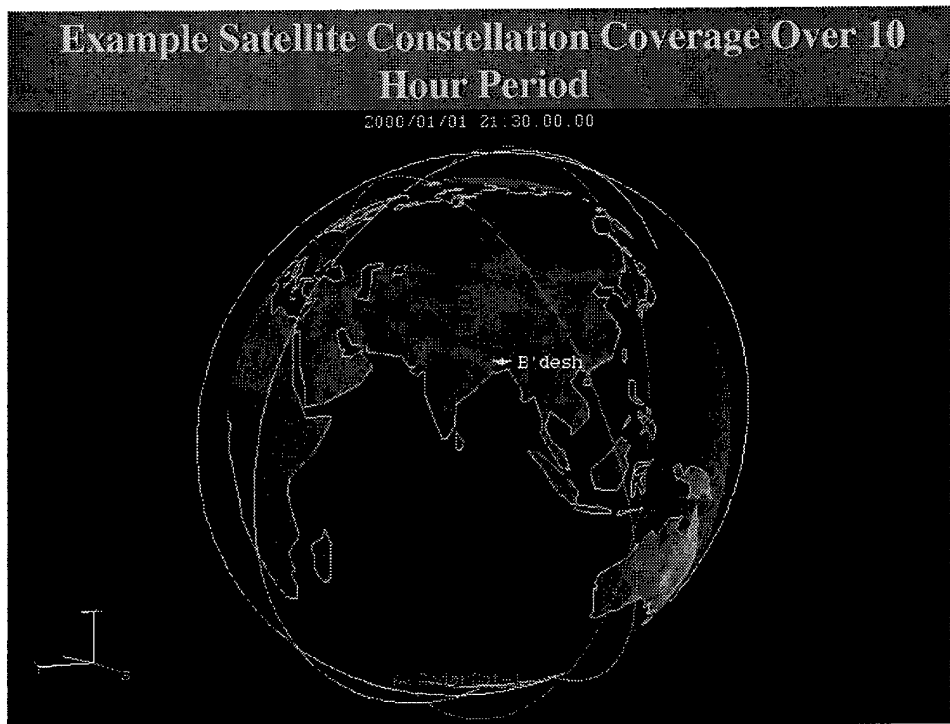
Example Satellite Constellation Coverage Over 10 Hour Period

2000/01/01 21:30.00.00

B'desh

The above slide illustrates a single frame from a movie generated to illustrate the orbits of several radar satellites. We simulated the orbits of the radar satellites over an extended period of time in order to assess the operational impact of sensor characteristics, as well as orbital parameters on their ability to support a disaster assessment mission in Bangladesh. The satellites' specific capabilities were taken into consideration so that a target could only be imaged when it was within the field of view of the particular sensor carried by that satellite. Because timeliness of the imaging operation is a primary measure of merit for these systems, the focus of the calculations related to the periodicity of satellite revisits over a six month period for SAR. The results of those calculations are shown below.

Most of the cases discussed in this paper will occur at random intervals with respect to the position of the satellites' orbital phase (e.g., there is no telling when an earthquake will strike). Further, these random intervals will be uniformly distributed; so, the expected value of the revisit time is that the event will occur
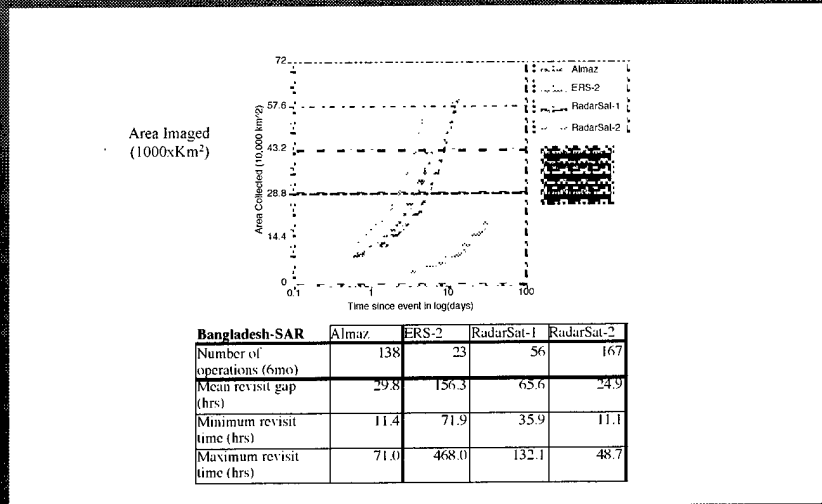
halfway between two consecutive satellite coverage passes. Because of this, the mean time to collect an image of a target after the event occurs will be half of the mean value of the time between two passes over the target. These times are expressed in terms of "days to image a target" in the tables that will be shown on the following slides.

It is also important to consider that data from systems that are similar in gross characteristics (e.g., similar resolution) is not necessarily equivalent in terms of data quality or interpretability under any given set of circumstances. So, for example, one SAR satellite capable of delivering ten-meter resolution may provide imagery with more noise than another ten-meter SAR system; thus, there may be a noticeable difference in quality between the two systems that may affect the interpretability of the data. Such differences in interpretability may have substantial effects under some conditions; however, it is very difficult to assess those differences, particularly given that criteria such as processing noise tolerances in the systems are not widely available data. In order to make accurate decisions regarding these systems and their specific capabilities, much more detailed technical analysis of the specifications for the system and its processing elements would be required.

Given all of these characteristics of the satellites, we now consider each of the cases mentioned previously in the context of what the remote sensing systems can contribute to provide information about each situation. It is important to note at the outset that the quantitative analyses described below are based on available information about the systems considered. Where information was unavailable, a set of standard assumptions was applied uniformly, so that the results should be consistent with the actual behavior of the systems.

Area Imaged (1000xKm²)

Area Collected [10,000 km²]

Time since event in log(days)

Legend: Almaz, ERS-2, RadarSat-1, RadarSat-2

Bangladesh-SAR	Almaz	ERS-2	RadarSat-1	RadarSat-2
Number of operations (6mo)	138	23	56	167
Mean revisit gap (hrs)	29.8	156.3	65.6	24.9
Minimum revisit time (hrs)	11.4	71.9	35.9	11.1
Maximum revisit time (hrs)	71.0	468.0	132.1	48.7

RAND

The above chart combines a graph and a table to compare the coverage generated by several different radar satellites. The graph uses a logarithmic scale along the X-axis to more readily fit the time scale of the different systems into the same frame while allowing the differences among the Almaz and two RadarSats to stand out. The log scale of days counts days in decimal fractions from .1 day (2.4 hours) to 100 days.

The characteristics of the systems, as described in the table, support and expound upon the primary result shown in graph: Radarsat-2 is the most capable system, followed closely by Almaz. RadarSat-1 is the most capable of the currently available systems, and ERS-2 is the least able to provide timely imagery in support of a contingency such as the hypothetical Bangladesh flooding considered here. In this case, the calculus of satellite system selection in easy to perform; the results consist of a series of dominant choices. RadarSat-2 is preferred over Almaz, which is preferred over RadarSat-1, which is preferred over ERS-2. This is true in every dimension considered above; maximum and average revisit times
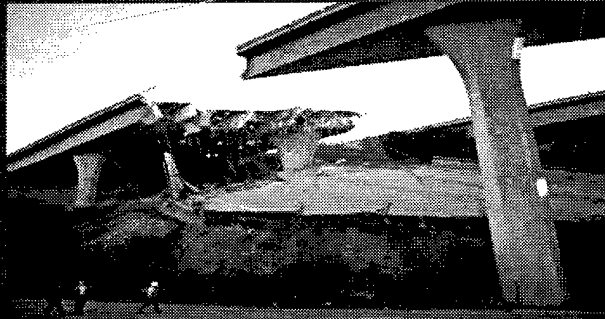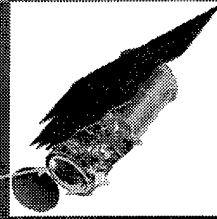
are all shortest for RadarSat-2 and grow steadily longer, up to the performance of
ERS-2.

Earthquake Damage Assessment Operations

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High or medium-res systems can
detect specific property damage
SAR can pinpoint areas of
greatest ground movement

22   RAND

The other use of satellite imagery is to try to determine patterns of movement of
the ground itself in and around the city. Specifically, it is important to ascertain
the points at which the earthquake caused the most ground movement (as this will
generally be an indicator of greater concentrations of more severe damage), as
well as helping to show the underlying fault structures in the area. This can be
accomplished by electro-optical systems and SAR systems; particularly valuable
information about ground movements can be extracted from SAR data by a
technique called Interferometric SAR (IFSAR), which is discussed below.

Kobe/Mexico City Satellite Operations

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Problem: Earthquakes / Volcanic activity
- **Want to know location and extent of damage**
  - Want: area coverage for gross damage assessment, high-resolution for delivering assistance, IFSAR for ground motion assessment
- **Sixteen systems considered:**
  - Four SAR, four high-resolution EO, plus:
  - ALOS-LR (Japan)
  - SPOT-4 and SPOT-5 (France, commercial)
  - CBERS (China/Brazil)
 - EOS-AM, Landsat-7, Resource-21, Clark (USA)
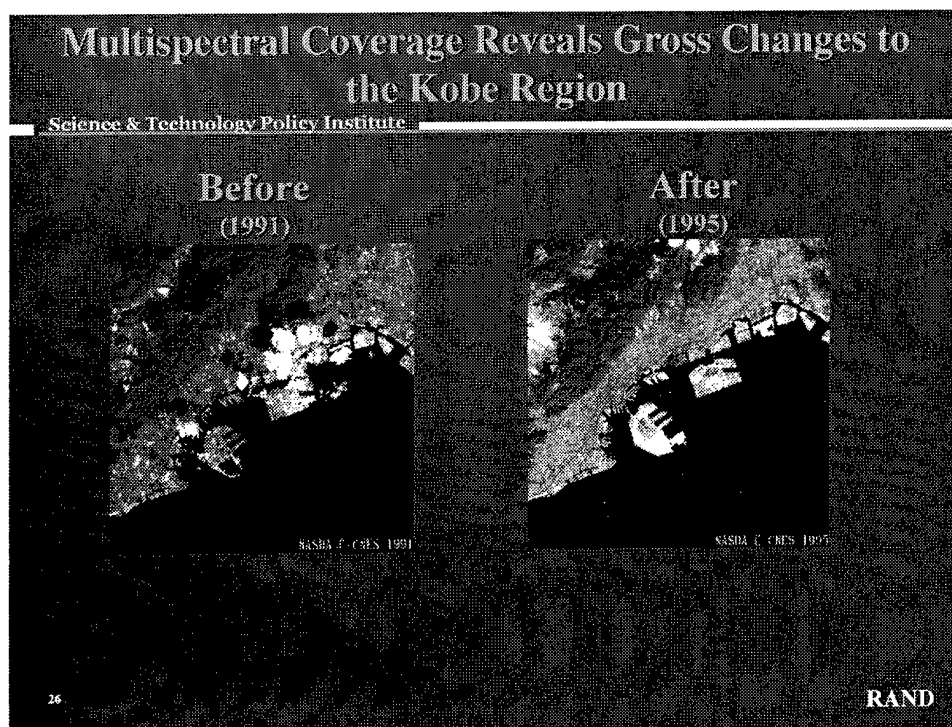
23

RAND

Kobe, Japan, and Mexico City, Mexico, are both very large urban centers that are unfortunately located on or near geological fault lines and are subject to major seismic disturbances. In the event of a major earthquake, either city may be cut off from most forms of communication or transit. Conducting a damage assessment and allocating resources for emergency assistance is therefore complicated by the fact that it may be difficult to determine where rescue resources should be dispatched in order to optimize their effectiveness without the benefit of a "God's-eye" view. In the case of seismic activity, satellites can serve two distinct (but related) purposes: identification and location of areas that have suffered heavy damage and detection of patterns of ground movement caused by the earthquake. Below, we consider the use of three types of satellites for data collection in these situations: high- and low-resolution EO satellites, and SAR satellite systems.
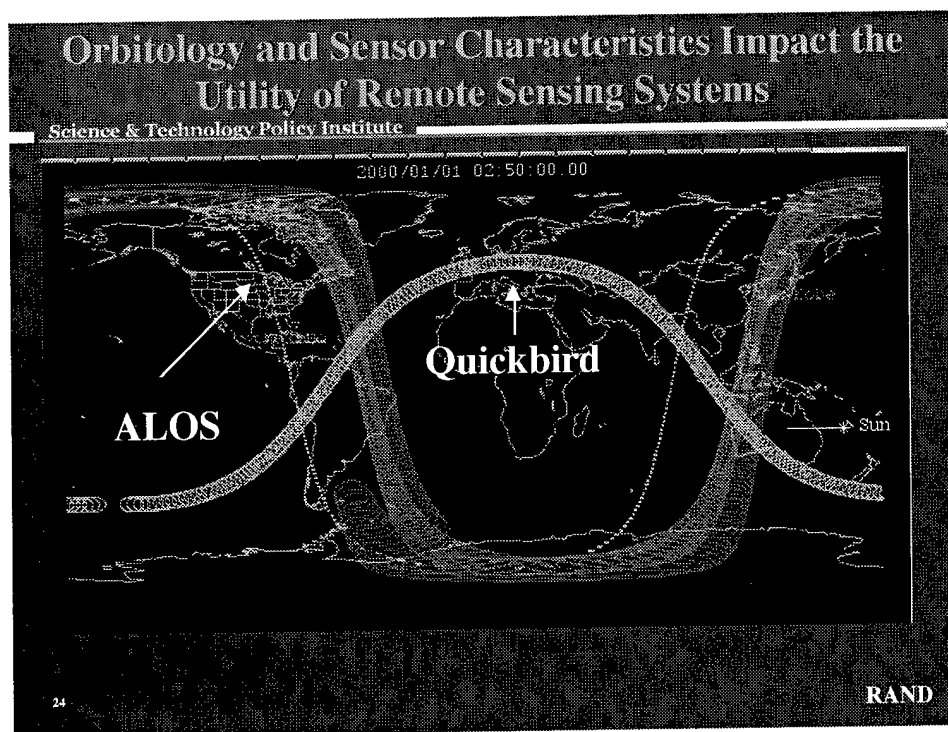
This figure illustrates the potential viewable region below the electro-optical satellites considered for this mission. Note the small viewing area for the ALOS satellite is a function of a design limitation limiting it to a small pointing angle.
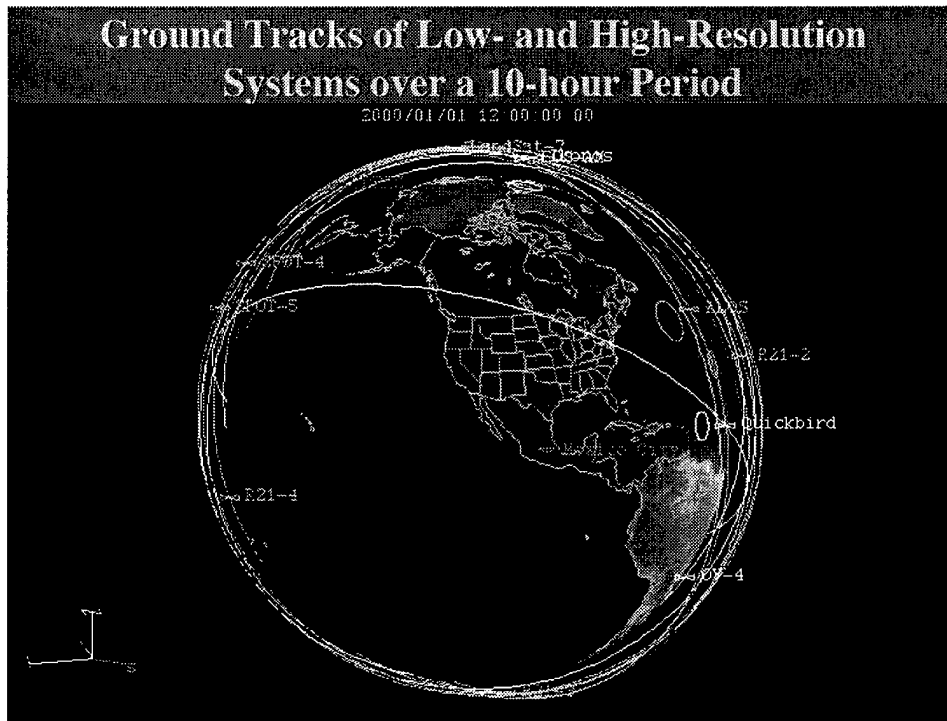
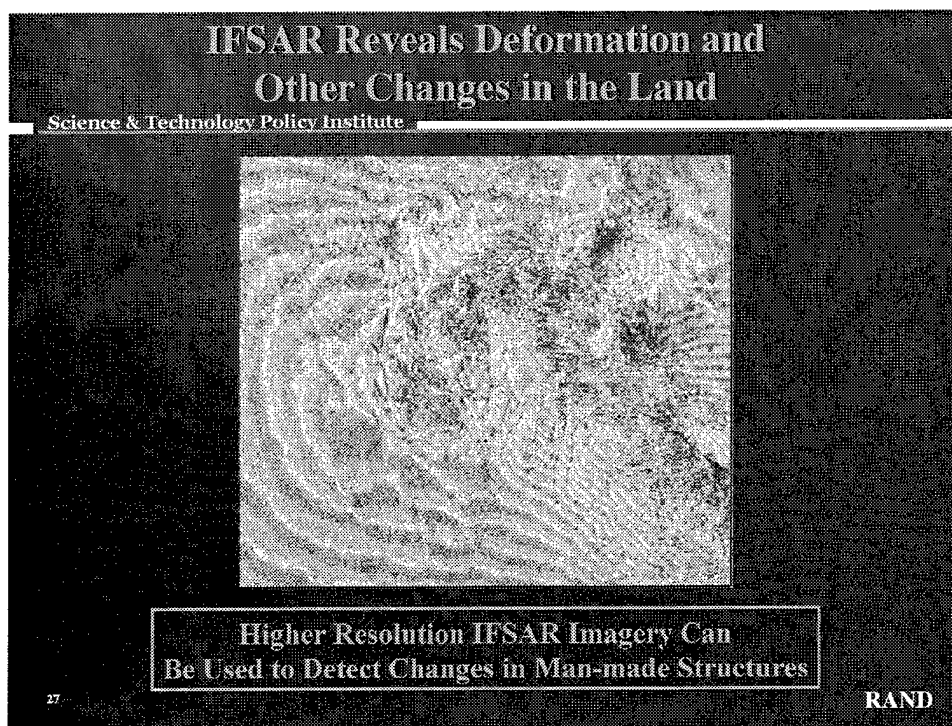Ground Tracks of Low- and High-Resolution Systems over a 10-hour Period

The above slide illustrates a single frame from a movie generated to illustrate the orbits of several electro-optical satellites. We simulated the orbits of the EO satellites over an extended period of time in order to assess the operational impact of sensor characteristics, as well as orbital parameters on their ability to support disaster assessment missions. The satellites' specific capabilities were taken into consideration, so that a target could only be imaged when it was within the field of view of the particular sensor package carried by that satellite. Because timeliness of the imaging operation is a primary measure of merit for these systems, the focus of the calculations related to the periodicity of satellite revisits over a one year period for EO satellites, for each of the targets. The results of those calculations are shown below.

Multispectral Coverage Reveals Gross Changes to the Kobe Region

Science & Technology Policy Institute

Before (1991)   After (1995)

The first of the two distinct purposes to which satellite imagery might be put –

damage assessment and location using satellite-derived imagery – has been

conducted to a limited extent in the past, notably in the case of the Kobe

earthquake of 1995. The images in this chart are actual SPOT imagery of the

Kobe area before and after the earthquake. These images are relatively low

resolution (20 meter) "false color" images, but were still useful in making some

determinations about earthquake effects. As higher resolution imagery becomes

more commonly available, there will be more complete libraries of imagery to

provide a "pre-event" database for comparison to imagery collected in the

aftermath of a disaster. In these figures, it is difficult to distinguish fine detail of

the imagery, but certain elements stand out. Notice the clouds present in the

"after" image, and the coloration changes in some areas (owing to the scale of the

reproductions, it is nearly impossible to pick out finer details on these images).

Even with imagery of this low resolution, it is possible to identify features that are

grossly displaced; for example, the appearance of a discontinuity in a formerly unbroken multi-lane highway is a relatively clear sign of a road collapse (the scale of reproduction here makes detail at that level undetectable, but it is a detectable feature in these images at larger scale). The time span elapsed between the "before" and "after" periods (nearly four years) does make change detection somewhat more ambiguous; ideally, routine data collection would provide for more current baseline data. Even given the age and resolution of these data, valuable information regarding damage extent and localization could be obtained through careful analysis.

Both low-resolution (seen here) and high-resolution EO satellites can help in earthquake damage assessment operations. High-resolution EO systems can provide information of sufficient detail that an analyst can rely upon to detect and identify many badly damaged structures. Low- or medium-resolution EO systems can provide information allowing for detection and identification of major damage to large structures. All of the EO systems, particularly the lower-resolution systems, lend themselves to use for change-detection purposes. These are applications in which imagery collected prior to the event is compared by computer with imagery collected after the event, and changes between the two frames are highlighted. Lower resolution satellites tend to provide an advantage here because they tend to collect larger areas at a given time, and it is therefore easier to build up a library of current imagery to compare with the post-event imagery.

IFSAR Reveals Deformation and
Other Changes in the Land

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Higher Resolution IFSAR Imagery Can
Be Used to Detect Changes in Man-made Structures

27   RAND

The other use of satellite imagery is to try to determine patterns of movement of the ground itself in and around the city. Specifically, it is important to ascertain the points at which the earthquake caused the most ground movement (as this will generally be an indicator of greater concentrations of more severe damage), as well as helping to show the underlying fault structures in the area such as shown above.[11]

Even the lower-resolution SAR imagery can be useful because of a characteristic peculiar to the phenomenology of synthetic aperture radar. SAR, like most radar systems, works by sending out a modulated radio signal and then recovering information from the signal when it is reflected back off of the target. These modulated radio signals emitted by the radar are called "chirps". In a SAR, system, the chirp returns can be recorded for later processing; this recording
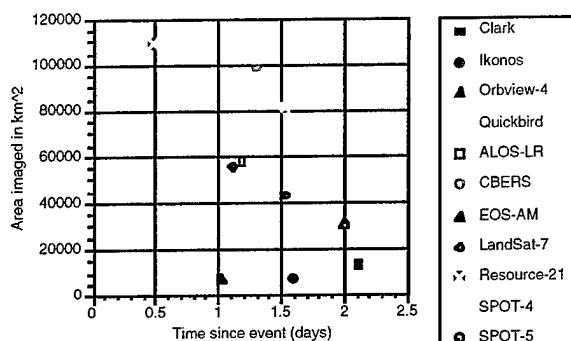
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[11] See Price, Evelyn J. and Sandwell, David T. (1998). "Small-Scale Deformations Associated with the 1992 Landers, California Earthquake Mapped By Synthetic Aperture

includes the data describing the phase of the chirp as it bounces off the target and returns to the radar antenna. This phase data from a SAR image can be compared to the data from another SAR image of the same target, through the use of a procedure known as interferometric SAR or IFSAR . By the use of interferometric SAR techniques, changes that are much smaller than the nominal resolution of the SAR can be readily detected by finding those areas in which the phases of the returns have changed relative to each other. In the image displayed as chart 27, an example of interferometric SAR processing can be seen. This image was constructed from data collected by the ERS satellite, and the contours indicate displacements of the earth as a result of the Landers, California, earthquake of 1992. The contour lines indicate areas in which a shift in the ground caused the returned radar signal to move out of phase with respect to the signal collected prior to the event. Thus IFSAR requires a set of "before and after" images be collected, as well. The size of the change that can be detected through the use of IFSAR techniques is generally dependent upon very specific characteristics of the SAR systems. While those details were unavailable to the study team during the course of this analysis it is typical to detect changes that are a relatively small fraction (perhaps 20% or less) of the size of the nominal resolution (the impulse response) of the SAR system. As the capability of generally available computer processors continues to increase, the ability to perform IFSAR processing will become more accessible and should soon be able to support policymakers in determining the areas of greatest displacement within a relevant timeframe.

Radar Interferometry Phase Gradients," Journal of Geophysical Research, 103(11), pp 27001-27016.

Science & Technology Policy Institute

	Clark
	Ikonos
	Orbview-4
	Quickbird
	ALOS-LR
	CBERS
	EOS-AM
	LandSat-7
	Resource-21
	SPOT-4
	SPOT-5

Area imaged in km^2 (vertical axis: 0 to 120000)
Time since event (days) (horizontal axis: 0 to 2.5)

28   RAND

These charts show our calculations of estimates for coverage and revisit of
Mexico City.[12] The first graph shows the speed of area collection as a function of
time lapsed after an event for each of the satellites considered.[13] In each case, the
area covered by the satellite is shown on the vertical axis. Notice that even the
satellite with the least area coverage capability of the systems shown (Ikonos or
Orbview-4; ALOS-HR was deleted from the graphs because it skewed the time
axis so far to the right) is capable of collecting several thousand square kilometers
of imagery on its first pass over the afflicted area. This is true for the Kobe
scenario and for the Mexico City scenario. The resolution of the systems as a
function of revisit rate is shown on the second of the two figures in each pair.
Generally, there does not appear to be a great distinction between the lower- and
higher-resolution satellites in terms of resolution as a function of revisit rate.

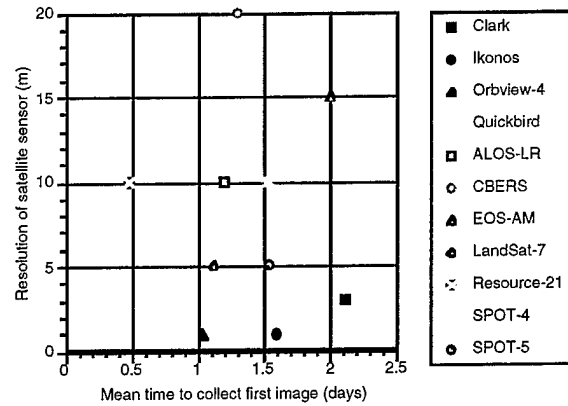[12] For Kobe, the revisits are slightly more frequent.

[13] Though cancelled for programmatic reasons, the Clark mission was retained in this
analysis to represent the capabilities of a relatively low-cost and high resolution multi-
spectral system.

The general appearance of the graphs does not change much from between those for Kobe and those for Mexico City. The greatest difference, and most important for illustrative purposes, is the change in the scale of the X-axis, which marks the expected value of the time from the occurrence of the event to the first collection opportunity. For each system considered, the expected time to image Kobe is less than the expected time to image Mexico City. In some cases, the two times differ by more than 6 hours. As a result, the X-axis on the Mexico City graph is shifted slightly to the left relative to the Kobe graph. This difference is due to the fact that the orbits of nearly all of the satellites considered take them near the poles on each orbit, while the earth turns beneath them. The imaging swath of the satellite is the same size (assuming a circular orbit, which is true in most cases) at all points along the orbit, so objects near the pole could be imaged by the satellite on each orbit, while those near the equator are moving much more rapidly through the spacecraft's field of regard. Another way to consider this is that to circumnavigate the earth along the 80 degree latitude line (near the pole) is a much shorter journey than a circumnavigation around the equator.

The smallest difference in expected time to image between Kobe and Mexico City is that of the Resource-21 satellite system. This is because Resource-21 intends to orbit four satellites whose orbits are staged to provide coverage of all areas of the earth on a daily basis.
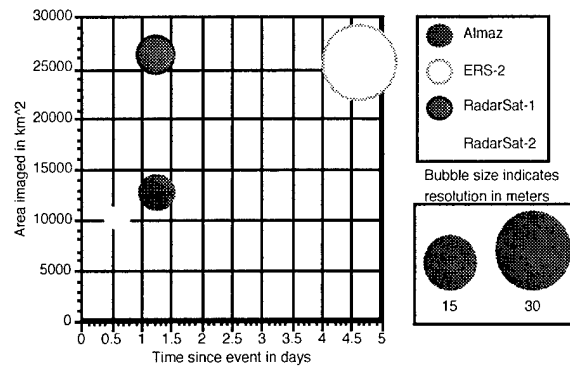
The resolution of the systems as a function of revisit rate is shown on above. Generally, there does not appear to be a great distinction between the lower- and higher-resolution satellites in terms of resolution as a function of revisit rate.
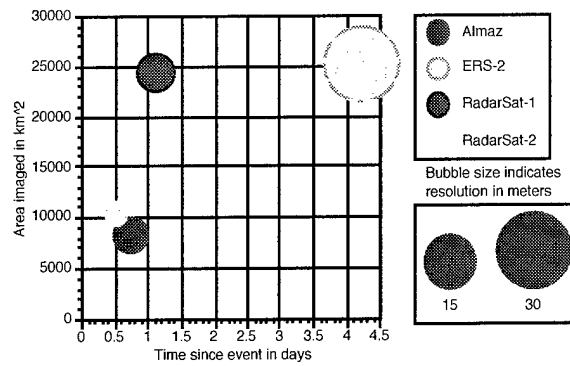
A similar picture holds true for the SAR satellites, whose characteristics are diagrammed above for Mexico City.

For Kobe, the radar satellite revisit time is slightly better than that for Mexico City. However, the differences are relatively small.

Burundi Satellite Operational Concept

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High-resolution systems are used to detect signs of distress or unrest and alert UNHCR or other cognizant authority

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RAND

Burundi is a nation whose population, composed primarily of ethic Hutus and traditionally ruled by members of the minority Tutsi tribe, has been frequently in a state of unrest, with one side or the other committing or attempting to commit atrocities such as genocide against the other. This is of great concern to the global humanitarian community. Organizations such as UNHCR would like to be able to keep abreast of significant relocations or movements of people in the countryside, with the intention of directing resources to quell disturbances before they become full-blown disasters. Unfortunately, the poor communication infrastructure in the area makes it difficult for news of threats to specific communities to reach the outside world, where some action might be taken to assist or to provide support for refugees.

Burundi Satellite Operations

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Problem: Tribal unrest leading to massacres in isolated villages
- Want to know where and when these incidents arise
  - Need to collect readily releasable high-resolution imagery of the suspected trouble spots: use electro-optical (EO) systems
- Four systems considered
  - ALOS-HR (Japan)
  - Ikonos, Orbview-4, and Quickbird (US Commercial)
- Timeliness a primary concern in this case

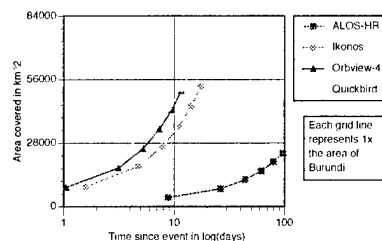33   RAND

In this case, satellites that provide low-resolution imagery – either SAR or EO imaging systems – will be of little use. What is needed is to be able to collect high-resolution imagery of villages and be able to determine if they are still occupied and whether they are intact or have been destroyed. Four high-resolution visible-light imaging satellites were considered for this operation; each of these would be capable of returning information that would be useful to an organization wishing to determine the occupancy of a village, or whether that village had been destroyed. In this case, the four systems are ALOS, a Japanese system containing a high-resolution and lower-resolution sensor (thus, the designator –HR for the higher-resolution sensor), and three commercial systems built by US-based companies. These companies are Space Imaging (the Ikonos satellite), OrbImage, a subsidiary of Orbital Sciences Corporation (OrbView-4), and EarthWatch (Quickbird). ALOS-HR is capable of 2.5-meter resolution, while the three commercial systems advertise themselves as being capable of 1-meter resolution or slightly better (e.g., .9 m at nadir).

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Burundi Satellite Operations Illustrate the Impact of Picking particular Satellites

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64000

56000

28000

0

Area covered in km^2

Time since event in log(days)

1   10   100

- ALOS-HR
- Ikonos
- Orbview-4
- Quickbird

Each grid line represents 1x the area of Burundi

				Quickbird
Number of operations (12mo)	17	115	173	142
Mean revisit gap (hrs)	423.1	76.1	50.6	61.6
Maximum revisit time (hrs)	1569.2	119.6	72.0	82.9
Mean time to image (days)	8.81	1.58	1.05	1.28

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RAND

It is clear from this chart that the ALOS satellite requires, on average, a much longer time to collect imagery than any of the others (a mean expected time of first collection in response to crisis tasking of nearly nine days). All of the other systems have an expected value of less than two days to collect imagery of the target. This discrepancy is due to a design characteristic of the ALOS-HR sensor; it is not capable of being pointed at any angle more acute than 1.5 degrees off of the satellite's nadir. This feature renders the ALOS-HR sensor much less useful for the collection of any urgently required data.

In contrast, the Quickbird orbit is designed not for sun-synchrony, but to maximize the number of revisits to the bulk of the world's populated areas. This feature has the effect of causing slightly less-frequent revisits at equatorial latitudes, but it does increase the revisit rate for targets in mid-latitudes. Even in this case, in which the target area lies in the equatorial region, the only system with a shorter average interval between collection opportunities is Orbview-4,

which uses a different approach to minimize revisit times. The Ikonos sensor, which has a field of regard similar to that of the Quickbird sensor, has average revisits of just over three days, while the Quickbird sensor can, on average, collect imagery of Burundi about every 2.5 days. This difference in timeliness illustrates the advantage afforded by Quickbird's orbit with respect to hastening the revisit cycle. The alternative approach to minimizing revisit time is that taken by the Orbview-4 satellite. This system, which affords the shortest revisit time of any considered in this case, is capable of collecting imagery further away from its nadir than any of the other three systems. Orbview-4 can collect imagery at up to 50 degrees off-nadir, in contrast to the 30 degrees off-angle allowed by Ikonos and Quickbird, or the 1.5 degree range of ALOS-HR.

Any of the three commercial systems will be able to provide imagery of nearly the entire nation of Burundi within a span of 10 days from the initial decision to begin collecting. Any collection with these systems is, of course, subject to the constraints of weather (cloud cover, fog, etc.). This class of potential difficulty associated with this phenomenology (visible light imaging) should be considered in view of the advantages of the use of visible light imaging; for example, flames and smoke will be visible on an EO image that would not appear on a SAR image, for example.

The first imagery can be collected by all of the commercial systems within the first two days, on average, after a decision is made to begin imaging the area, e.g. in the event of a conflict. On their first pass, these systems will each collect several thousand square kilometers of high-resolution imagery, which can be processed within a few hours and provided to imagery analysts, humanitarian relief agencies, military or police forces, etc.[14] The ability to disseminate information that literally illustrates the conditions on the ground (what is referred

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[14] Turn-around times are claimed by the majority of commercial remote sensing companies. As of the date of this analysis these capabilities have not been fully demonstrated.

to as "ground truth" in the remote sensing community) within such a short timeframe could potentially influence actors on all sides of such a conflict. Within several more days, additional imagery may be collected, as shown by the data presented in the table. Periodic re-inspections of problem areas can be conducted at random and with no notification to parties on any side of the conflict; this knowledge can help to reinforce any peace agreement or settlement that may be arranged.
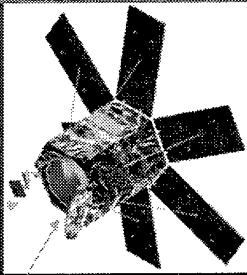
In all, the likelihood of deriving utility from high-resolution EO systems for the purpose of humanitarian operations in Burundi appears high, provided that the information can be collected in a timely fashion. The three commercial systems will offer this capability; the ALOS-HR payload will be only marginally useful for this purpose because of the length of time it requires to collect the imagery (nearly ten times longer than the others). This is the case even if we neglect to consider the lower quality of the imagery provided by ALOS-HR's 2.5-meter resolution sensor (the commercial systems offer six times more detail in their imagery).
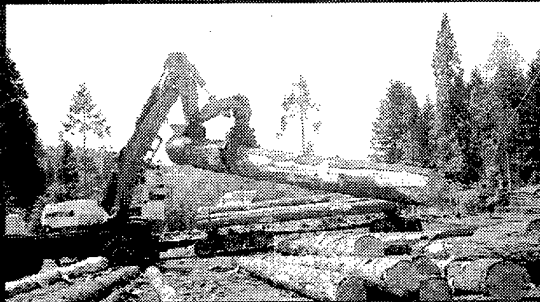
Eco-Enforcement Operations

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Different tools for different jobs
• High-res to detect illegal logging
• Lower-res MSI to track effluent streams to their sources

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The objective of our analysis of Yellowstone was to consider the effectiveness of satellite imagery for certain law enforcement / natural resource management purposes. The scenario was to attempt to detect an illegal commercial logging activity somewhere within the boundaries of Yellowstone National Park. In this case, we assumed that the loggers used a commercial logging truck, and that they would be operating during the summer months (when weather in Yellowstone is more amenable for logging operations, and cloud cover is less prevalent to permit imaging operations). In this concept of operations the satellite remote sensing system serves a cueing function for more either ground teams, or airborne assets that could actually be used for enforcement activities.

Yellowstone Satellite Operations

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Problem: Detection of Illegal Logging Operations

- **Want to know where to direct law enforcement**
  - Need to image Yellowstone National Park area and detect logging operations in progress
  - Indicators will include logging trucks and ground cover changes
- **Four systems considered**
  - Three US commercial high-res systems plus Clark
  - False alarm rates at lower resolution transform the problem to one of change detection
- **Area coverage and resolution most important in this case**

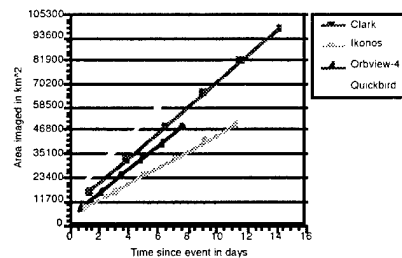36   RAND

In this instance, we considered several different high-resolution EO satellites, with the explicit goal of maximizing the probability that an imagery analyst would be able to detect ongoing logging operations over the span of the month of July. We based our analysis on the satellites' capabilities and on historical data for cloud coverage over the park area for that month. In this case, several variables entered the equation; since the goal was to identify a logging truck so that enforcement action could be taken, it is important that the only things identified as unauthorized logging trucks are, in fact, unauthorized logging trucks (this is called the "false alarm" problem). Data provided by the National Imagery and Mapping Agency indicate that for a trained imagery analyst looking at imagery of this type to spot a target of similar dimensions, the probability of detection is approximately 50%. Thus, the search for unauthorized logging leads to a generalizable algorithm that can be used to consider the use of EO satellites when searching for many different types of activities (e.g., strip mining, narcotics processing facilities, dumping of hazardous wastes).

The satellite systems chosen for this exercise were the highest-resolution systems, excluding the ALOS-HR payload, which has a very low revisit rate that makes it impractical to use for spot-check operations of this type. The remaining systems consist of the three commercial satellites considered earlier, and the Clark spacecraft (a now defunct NASA program). Clark was interesting in that it was to collect 3-meter panchromatic imagery and 15-meter hyperspectral imagery, which would allow an imagery analyst to determine a great deal of information about conditions on the ground that would otherwise be impossible to ascertain. Primarily, hyperspectral imagery enables the identification of materials based on the chemical composition of their reflective surfaces. This capability can allow an analyst to tell the difference between, for example, a large bush and a truck painted green, although given the resolution of the imaging system, they both may appear as a green blob to the naked eye. This capacity to gather remarkable detail from an image collected from space helps to offset the lower resolution of the imagery collected by Clark. Still, owing to the lower resolution of Clark (one-ninth that of the other systems), the probability of successful detection was reduced from the nominal 50% for the other systems down to 25%.

Several Commercial Systems provide Adequate Area Coverage and Revisit Times

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Area imaged in km^2: 105300, 93600, 81900, 70200, 58500, 46800, 35100, 23400, 11700, 0

Time since event in days: 0, 2, 4, 6, 8, 10, 12, 14, 16

Legend: Clark, Ikonos, Orbview-4, Quickbird

| Yellowstone-HR EO	Clark	Ikonos	Orbview-4	Quickbird
Number of operations (12mo)	132	169	253	303
Mean revisit gap (hrs)	62.0	49.3	33.3	26.2
Maximum revisit time (hrs)	96.1	72.1	48.5	608.4
Mean time to image (days)	1.29	1.03	0.69	0.55

37   RAND

The graph in the figure above shows the area coverage rate of the satellite systems against the area of Yellowstone National Park (the grid lines indicate 1x the approximate park area). In this scenario, as the imagery is collected, it will be evaluated by imagery analysts looking for logging trucks in areas of the park where they are not permitted. It is presumed that the logging trucks operate with other vehicles, and that on average, an imagery analyst will be able to detect an illegal logging camp with this configuration of equipment roughly 50% of the time with the 1-meter satellites, and 25% with the Clark satellite (as described previously).
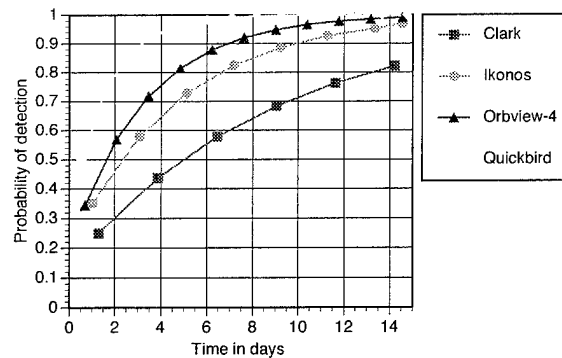
The probability of detection of the hypothetical illegal logging operations over time is shown above. The systems are presumed to be used over a 2-week period during the month of July. From the time the decision is made to begin collecting imagery for this purpose, the systems begin to collect as much imagery as possible when they are in view of Yellowstone. The imagery collection was conditioned upon the known probability of cloud-free skies and the systems' known revisit rates and average data collection capabilities. Obviously, Quickbird is capable of collecting more imagery more quickly, and that factor makes it the most likely system to be able to detect the illegal logging activities in the shortest span of time. The Orbview-4 system, due to its more frequent revisits, will be able to collect more data over the two-week period than Ikonos, which leads to its higher probability of success in detecting the target activity. Clark, with its lower probability of detection, finishes the two weeks of collection with a probability of detection of just over 80%, while all of the other systems have probabilities of detection over time running up to 98% or more.

The satellites' different capabilities (varying shadow angles for Quickbird, hyperspectral capabilities for Clark) will contribute to or detract from the interpretability and false-alarm rates for each of the systems. The hyperspectral capability of Clark will most likely serve to reduce its false-alarm rate dramatically. The Quickbird's varying shadows may make change detection more difficult (increasing the difficulty of spotting the target) or it may allow the detection of a target that is partially shaded by obstructions (by looking for the target from different angles). It will be difficult to make these determinations until actual data is collected and interpreted with the specific intent of detecting and identifying these types of targets. Further policy work in this area is therefore needed before the systems are employed to perform a significant role in law enforcement.[15]

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[15] There are significant issues associated with the use of space based remote sensing systems, just as there are with airborne remote sensing systems that already have been the subject of case law. Currently case law in this are is somewhat mixed, some sensors are considered non-intrusive and acceptable, others are considered excessively intrusive and can not be used without warrant since they infringe with various Constitutional protections for U.S. citizens. While it seems likely that the particular application outlined in this section would be acceptable, such activities would require careful review before being undertaken.

Necessary Elements for Successful Employment of Remote Sensing Systems

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- **Timely access to suitable collection systems**
  - Tasking authority, initial time to visit, and revisit rate
  - Spectral coverage
  - Ground resolution
- **Sufficient ground processing capability**
  - Initial preparation of raw data
  - Feature extraction and automated processing
  - Conversion of the data to suitable product
  - Compatible data formats

Lack of user trust and understanding of the data products are serious obstacles

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The cases that we have considered here serve to point out several general points in addition to the specific details stemming from the analyses. Because of the leadership role of the US in the global humanitarian community, and because of the depth of US interests abroad, our ability to quickly and efficiently understand and respond to natural and man-made disasters is of great importance to us as a nation and to people worldwide. Satellites that allow rapid collection of data that can inform and support a US response to these types of crises are therefore valuable to the US and should be treated as such. The value of these systems to the US depends, in part, on their ability to support certain useful features, including:

- Rapid revisits: in order to collect the desired information quickly, it is imperative that the satellite be capable of accessing the target area frequently.

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- Flexibility and speed in tasking: the system should be capable of collecting data with a minimum of advance notification and programming required, in the event of an emergency.

- Good resolution: the system must be capable of collecting data that is adequate for the mission requirements; although these requirements will vary, it is always possible to discard unneeded data, but not to create data that are necessary but not present.

- Compatible data formats: to allow easy combination and comparison of data retrieved from different systems, systems used for these purposes should allow for easy re-processing into a standardized format that can be usefully compared with data from other systems.

In selecting candidate systems for these types of contingency operations, it is important to think in terms of the marginal benefits of one system over the other, where the system is likely to be employed, and what those benefits are worth in different intended applications (e.g., is it useful to have revisits n hours more quickly, on average? What is the value of that capability? How valuable is better resolution for an intended application? Are 15m much different for the purpose than 10m? Than 20m?) Once the benefits have been determined for one application, other applications should be considered, and a final determination of the costs vs. capabilities and benefits of each system on an overall basis can be determined.

The need for choosing where and when to focus agreements is based on the costs associated with technically building infrastructures to work with a wide variety of systems, building sufficient expertise to be an effective user of the system, possible fees for establishing rapid tasking priorities with commercial providers, and negotiation costs. This is not to suggest that agreements should not be pursued with the widest range of providers, rather it means that if a choose is to

be made between one provider and another then it is important to focus on those that initially provide the greatest capabilities at the time of the agreement.

In the cases described above, for example, there were several obvious conclusions. For operations involving SAR imaging over each of the three targets (Bangladesh, Kobe, and Mexico City), the results indicate very consistently that the ERS system is the least able to respond quickly to an emergent tasking requirement, though it has a tremendous advantage in that it actually is an operational system and can produce data today. In contrast, the proposed Canadian Radarsat-2 will be able to provide higher-resolution imagery in a small fraction of the time. This should not come as a surprise given the technology difference between the two systems (ERS is an older SAR that has been on-orbit for several years, while RadarSat-2 is still under development, with launch planned for early in the next century).

When considering high-resolution EO imaging operations, a somewhat less clear picture emerges. None of the high-resolution satellites included here is actually on-orbit as of this writing, but all have substantial differences in their design criteria. The ALOS satellite has a high-resolution imager and a low resolution imager; only the low-resolution imager can be pointed more than 2 degrees away from the satellite nadir. Thus, for the collection of high resolution imagery, ALOS is not an expedient platform, and the mean time to collect of from 8-12+ days (depending upon the target) indicates that fact. The Quickbird satellite, with its lower-inclination orbit, provides rapid revisits, but the best (shortest) revisit time is actually provided by the Orbview-4 satellite, which has a capability to collect imagery as much as 50 degrees away from its nadir. In attempting to consider between these two systems which one would be more efficient, other factors, such as the area imaged by the satellite, the constant vs. changing sun angles, potential international cooperation aspects, etc., should sway the decision. Among the low-resolution EO systems, there is one clear standout: Resource-21, with its four-satellite constellation, offers the ability to image any of the targets

every day. The other systems are generally undistinguished with the exception of EOS-AM, which collects less frequently than the other systems, and CBERS, which collects frequently enough but has the lowest-quality imagery of any of the systems cited here (20m panchromatic pixels). Even the "least frequent" revisits, those of EOS-AM, are not terribly long intervals; only about 4 days, with a 2 day expected value for an initial visit.

Given the promise of a large constellation of remote sensing systems on orbit, the likelihood is that some system will be positioned to collect imagery of the target within a short timeframe. The challenge, then, is to ensure that data-sharing agreements are in place with an appropriate set of system operators to keep this timeframe within some acceptable range. In order to accomplish that goal, it is imperative to identify the systems and understand the specific orbital ephemeris data that describe the exact positioning of the satellites with relation to each other. Once these data are known, it is a simple matter to construct comprehensive satellite coverage models that will describe coverage capabilities for any point on Earth.

Outline

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- Earth remote sensing satellites and their Characteristics
- New capabilities and employment schemes for earth remote sensing satellite systems
- **Possible approaches for cooperation outside the current set of agreements**
  - U.S. Government actions
  - Government to government actions
  - Industry focused activities

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Because of the study's emphasis on providing a broad assessment of operational capabilities of remote sensing systems, it was not possible to draw strong conclusions in regards to recommended action. The following section will discuss a possible framework for cooperation outside the current array of agreements, and consider activities that could be pursued by the U.S. government alone, in concert with other national governments, or that would be led by industry. Such approaches, as well as the ramification of particular action are suitable topics for further examination. We conclude with several recommendations for policy actions that might be taken to encourage efficient use of these systems as they become more available.

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Exemplar U.S. Government Actions

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- Exploit the expertise in government agencies to such as NASA, NOAA, NIMA, and USGS to help other agencies use remote sensing data
- Focus agencies on the characteristics of the data necessary to support government actions rather then on the collection system itself
- Preferentially adopt industry standards for GIS and remote sensing data used by the government
- Participate actively in standards setting bodies to reflect desired of of public good users
    - OPENGIS, Digital Earth, etc

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The government can take some actions based on its own initiative that will have the net effect of helping make the government a better customer for the data, and to allow it to take the lead in increasing public sector use of these new capabilities. Government leadership might be particularly beneficial in a variety of intergovernmental activities designed to transfer knowledge of how to use remote sensing data. Take for example the expertise embodied by organizations such as NASA, NOAA, NIMA, and the USGS. All of these organizations have a significant capacity to: 1) provide expertise to other agencies about what they would need to do to effectively exploit remote sensing data, and 2) help organizations identify the best choices for data derived from remote sensing systems. Indeed, deciding what to do first may be of the greatest importance for many agencies since the tolerance for failed programs is very low today, and the resources necessary for converting to new data sources will be limited.

There is perhaps another, even more important, activity that can be undertaken on the part of the government. This is to have its various agencies focus on the key

characteristics of the data they wish to have collected, rather then focus on the modality of the collection. This approach means that agencies should examine their data requirements with an eye towards what is needed to do the job and toward building a system that will prove to be superior in the long run. This in turn means examining not only the data acquisition system, but also the underlying analytic models and regulatory requirements current data collection methods support. With a clear idea of what the characteristics of the necessary data are, it is possible to consider using data provided by a wide assortment of remote sensing systems. For instance, if high-precision maps of ground cover are required, whether that information is obtained from remote sensing systems or direct observation should be irrelevant should the minimum set of standards necessary for that application be satisfied. The focus on the application rather than the modality of measurement is useful for the industry as well, since it forces the consumers to consider what they really want and thus allows industry to provide products that best suit those preferences.

The adoption of key standards and the purchase of products based on those standards are also very important. The FGDC and OpenGIS consortia are working to advance standards in the United States, and are working with the ISO to create international standards for meta-data and interchange. However, without both the determination to replace customized solutions with standardized products, and the resources for that transition, the impact of efforts in these areas will be muted. Early and wide-scale adoption of these standards for significant activities inside the government means that a significant demand will be created for products and create a standardized set of tools appropriate for both public sector and private needs.

Exemplar Issues Requiring Government to Government Cooperation

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- Establishing prearranged tasking, purchase, and data-sharing agreements using home nations as conduits for requests
- Examine funding alternatives for obtaining data
- Reconciling intellectual property rights issues for data gathered by U.S. and foreign companies
- Address technology transfer issues implied by access to relatively raw data

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There are other classes of activities that require government to government interactions. For instance, the significant contribution of international space systems to world-wide observation capabilities suggests a need for arrangements that speed access to data while at the same time respecting domestic political concerns of both the United States and the country in which the foreign remote sensing system is based. Because of domestic political concerns related to harming domestic providers of comparable services, there may be significant difficulties associated with establishing standing orders for data collected by foreign commercial systems when firms based in the respective nation might suffer as a consequence. One way to address these concerns is for the governments involved to approach the problem as a sort of mutual aid arrangement. In this way, each host government could maintain a set of contracts with its own nation's remote sensing companies, and arrange licenses to allow redistribution of the data purchased within limited circles or for clearly specified

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purposes. This approach would help the U.S. to avoid subsidizing foreign systems directly, and could be implemented on a reciprocal basis with other nations operating their own remote sensing systems.

In order for a reciprocal approach to work efficiently, the use of interoperable standards for both the data and meta-data would be very desirable. The efforts directed at building the standards for the domestic use of remote sensing data would be helpful in creating the basic building blocks that could form the core of standards for the industry as a whole.

Intellectual property rights are of significant importance to many remote sensing information providers. One of their greatest concerns is that they will be denied revue stemming from the sale of products derived from their remote sensing data. Without agreements and procedures to assure the safety of proprietary data, agreements for the broad use of commercial remote sensing data are likely to fail because of a fear of data bleeding over to lucrative commercial markets. There is great concern about this topic among many U.S. information providers, and indeed on the part of providers in many other countries as well. However, the vulnerability of firms differs significantly depending on where they plan to extract their greatest economic returns. Companies obtaining the bulk of their revenue from value added resellers and derivative products may be less impacted then those attempting to make their money of the raw imagery data products.

The issue of technology transfer also requires attention. Currently there is a great deal of disagreement on the appropriate level of control of remote sensing technology (and data sets) given foreign capabilities, connectivity and efficacy of controlling it. The main problem here is that there is little agreement among many of the actors involved as to exactly what constitutes the appropriate degree

of control on the technology and data.[16] On one hand some see the significant overlap of capabilities between national security and commercial applications when operating at a higher resolutions, as well as finer spectral coverage in the hyperspectral applications, as justifying attempts to tightly control the technology because of its immediate potential for misuse. Others view that overlap and development of alternative centers of technologies abroad as a signal for decontrol of the technology. From a practical stand-point this means that any attempt that triggers technology control concerns will require effective state-to-state interactions to help make sure that this issue does not interfere during crisis situations when the time-sensitive data is of greatest utility.

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[16] In general more liberal technology control regimes are favored by those attempting to gain advantage in the area, while more restrictive regimes are favored by those who believe that they hold any sort of unilateral advantage.

Industry Focused Initiatives

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- Industry has to examine a variety of business models for information from remote sensing systems
  - Current aerospace-like system has government sharing risk
- Needs to focus on long-term building of demand for their products
  - Exploit the breathing space created by large NIMA data purchases
- Capitalize on new focus on multi-scale phenomena to build connection into scientific and applications community

43   RAND

Industry can take a number of steps on its own to promote cooperation. For instance, it can continue to examine a variety of business models to better promote end-uses of remote sensing data. In place of the dominant model based on the aerospace industry, multi-source information companies (which incidentally collect remote sensing data) would provide a different emphasis for a company and different possibilities for pricing based on alternative sources of cash. There are possibilities of focusing on a long-term business development via large bridging activities such as governmental data purchases for NIMA or for scientific agencies like NASA. The latter offers the possibility of building demand through scientific interest in multi-scale phenomena that might be observed from the new high-resolution systems.

To summarize the primary policy-related findings of this study:

- Government should carefully assess its data requirements and priorities and be a wise consumer; toward this end,

- The expertise of those government organizations with significant expertise in the use of remote sensing data(e.g., NIMA, NOAA, USGS), should be employed wherever possible to assist other government users in incorporating remote sensing data in their organizations in the most efficient way.

- The use of standards for data products and metadata are important facilitating factors for government user organizations. Government and industry should work together to adopt and participate in relevant standards processes.

- While international cooperation is important, it is imperative to consider the intellectual property issues that arise when working with different data providers and users across international borders.

- The participation of industry in developing the market for commercial remote sensing data is vital to the establishment of a robust market; in the short term, the patronage of US government organizations can provide a stream of income that will allow for the development of this broader patronage.

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