

CAPABILITIES OF NEW REMOTE SENSING SATELLITES TO SUPPORT SUSTAINABLE DEVELOPMENT

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ABSTRACT

Four important types of recently-launched and new remote sensing satellites are beginning to collect worldwide datasets of panchromatic, multispectral, hyperspectral, and synthetic aperture radar (SAR) digital imagery. This imagery is collected at spatial resolutions and coverage and revisit rates useful for solving many environmental problems and achieving sustainable development. These satellites can very accurately map and measure urban and rural population and transportation patterns, industrial operations including extraction of mineral resources, natural and agricultural vegetation changes, water flow and snow and ice pack levels, erosion, boundary changes of ecosystems and coastlines, many types of pollution, and disaster impacts.

We consider the information needs for sustainable development, and compare in detail the particular performance capabilities of the new satellite systems. We focus on spatial resolution, coverage and scene revisit frequencies, and calibrated data quality, including spatial accuracy. We also discuss a number of the applications of the new datasets in terms of specific problems to be solved.

Because many of the systems compete in the commercial market, data are more available and their cost is decreasing. The increased numbers of satellites and quantities and quality of data is beginning to allow data to be coordinated and combined effectively in new ways. This allows multitemporal analyses to attain high levels of thematic accuracy and change detectability. These factors are helping to create the integrated Earth observation system essential for achieving sustainable development.

KURZFASSUNG

Vier wichtige Typen der neuesten zuletzt gestarteten Fernerkundungssatelliten sammeln globale Datensätze von digitalen panchromatischen, multispektralen, hyperspektralen und SAR-Radar (Synthetik-Apertur-Radar) Bildern. Die geometrische Auflösung und die räumliche Bedeckung des Bildmaterials, sowie die erzielten Szenenwiederholfrequenz erleichtern die Lösung vieler Umweltprobleme und das Erreichen einer nachhaltigen Weiterentwicklung. Diese Sensoren erlauben die genaue Aufnahme und Vermessung von Transportwegen, der Besiedelung von Ballungsräumen und ländlichen Gebieten, industrieller Tätigkeit einschließlich Abbau von Bodenschätzen, natürlicher und landwirtschaftlicher Vegetationswechsel, Gewässerbewegungen, Eis- und Schneehöhen, Bodenerosionen, Grenzveränderungen von Ökosystemen und Küstenlinien, vieler Arten von Umweltverschmutzung und der Auswirkungen von Naturkatastrophen.

Wir betrachten die für nachhaltige Entwicklung notwendigen Informationen und stellen die Leistungsparameter der neuen Satellitensysteme im Detail gegenüber. Wir untersuchen die geometrische Bildauflösung, die geographische Überdeckung und Szenenwiederholfrequenz der Datensätze und die Genauigkeit der Kalibration, sowie die geometrische Genauigkeit. Zudem betrachten wir einige Anwendungen der neuen Datensätze in Hinblick auf die Lösung spezieller Probleme.

Weil im freien Markt viele Anbieter konkurrieren, sind heute bei sinkenden Kosten vermehrt Daten verfügbar. Die steigende Anzahl von Satelliten sowie die Anzahl und Qualität der Daten erlauben immer neue Wege der Kombination und Koordination. So erleichtert etwa multitemporale Auswertung das Erkennen von Veränderungen bei hoher thematischer Genauigkeit. All diese Faktoren erleichtern den Aufbau von integrierten Erdbeobachtungssystemen, als wesentliche Voraussetzung zur Erreichung einer anhaltender Entwicklung.

1. INTRODUCTION

Uncontrolled exploitation of our planet's finite resources, as driven by industrial activity and population growth, would degrade our environment and reduce the quality of human life. It has become clear that to meet the growing demands of rising populations in a sustainable way, we must balance development goals and rates against the needs for long-term protection for our ecosystems and environment. Delays in determining and initiating the most effective protective actions may greatly raise the ultimate costs of repairing damage. Reliable and adequate information is needed soon to choose the best paths to preserve agricultural productivity and biodiversity, and to limit deforestation and the pollution of our air, ground, and water.

New worldwide datasets of high-resolution panchromatic, multispectral, hyperspectral, and SAR digital imagery collected by satellites should be extremely valuable in generating the information needed to help reveal and solve widespread developmental and environmental problems. Combining coverage capabilities and spatial resolutions previously unavailable to researchers and planners, the satellite sensors can very accurately map and measure urban and rural population and transportation patterns, industrial operations including extraction of mineral resources, natural and agricultural vegetation changes, water flow and snow and ice pack levels, erosion, boundary changes of ecosystems and coastlines, many types of pollution, and disaster impacts. This paper examines the nature of the problems, and approaches to their solution made possible by the new satellite capabilities.

2. SUSTAINABLE DEVELOPMENT

Major recent changes in technologies and cultural practices have made human interactions with our natural environment a significant issue for our times. These changes have produced (and been affected by) the great population explosion of modern times, a five-fold increase in the past 150 years, with a current growth rate of a billion people per decade. As a consequence, a population biologist has estimated that to bring the developing world up to the present living standard of Canada would require the resources of two more planet Earths (Rees, 1996).

“Sustainable development” is the idea that we must develop the benefits derivable from our environment while avoiding exhausting its key resources and degrading its quality, so as to preserve those benefits for future generations of humans. Achieving sustainable development in practice requires evaluating and controlling the human effects on our environment resulting from activities such as manufacturing, agriculture, resource extraction, and even recreation. This requires an integrated systems approach which addresses long-term environmental, economic, and social issues, and which builds consensus and partnerships among key interest groups.

Sustainable development presumes that “environmental protection and economic development are complementary rather than antagonistic processes.” (Ruckelshaus, 1989). The environment must produce sufficient food and other useful materials for humans, while supporting its other resident species and natural processes, without suffering significant harm from natural and human-made pressures. And the economy must operate and maintain its businesses, factories, and supporting infrastructure (roads, pipelines, dams, etc.), while its natural environment is preserved.

Sustainable environments and economies both must be resilient and productive. They must be resistant to excessive fluctuations in growth, compensate for harmful effects of change, and provide significant and equitable opportunities for business development and innovation. Current challenges to be met include urban sprawl, crowded streets, inner-city unemployment and redevelopment needs, overall economic development and growth, ecosystem management, agriculture, biodiversity, energy-efficient buildings, energy conservation, watershed management, and pollution prevention.

Some principles and approaches generally supported by advocates of sustainable development are the following:

- Equity: A fair division of environmental resources across the world.
- Closed process cycles: Manufacturing with minimal raw material input, returnable and recyclable packaging, and repairable or reusable parts.
- Renewable energy: Energy technology improvement and conservation.
- Proximity: Local production, near the consumer, reducing transport needs.
- Tax and pricing reforms: Accounting for environmental costs of production.

One type of major sustainable development activity today is the effort to reduce urban deterioration and its effects via renewal projects focusing on long-term economic, environmental, and social health. In Chattanooga, USA, for example, the air was

so polluted drivers used headlights during the day to cut through the smog. But in 1984, citizens and city officials worked together to plan a different future. With electric buses now providing free transportation, and a new “zero emissions” industrial park, the city has drastically reduced air pollution, attracted hundreds of millions of dollars in new investments and created 1,500 new jobs, many of them in “green” industries. And in Curitiba, Brazil, a city of two million people, a plan including modern public transport helped to curtail private-car use, reducing fuel consumption by 25 percent. Curitiba's land-use reforms and land restoration programs increased green space a hundred-fold, with over 1,000 parks, most linked by bike paths. Recycling is encouraged there through programs that exchange garbage for bus passes, food, and school books.

The worldwide distribution of development status is shown in Figure 1. If the developing countries, particularly rapidly growing India and China, develop beyond their limits as has the North, the Earth's carrying capacity will be exceeded in short order. Neither can the industrialized nations, with only 25 percent of the world's population, continue to consume 80 percent of the world's resources if the Earth is to adequately provide for future generations.

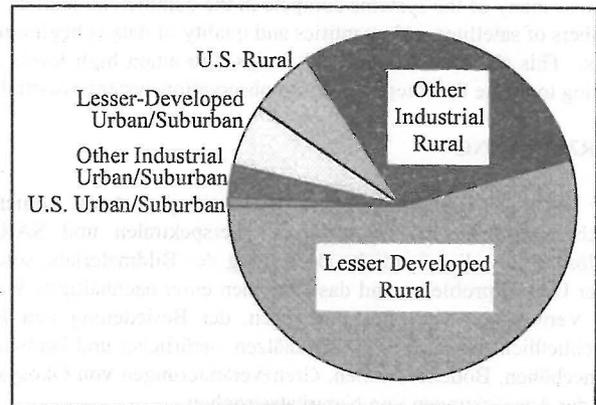


Figure 1. World Land Areas vs. Development Status

The sustainable development perspective has been challenging traditional notions of economic growth which drive most natural resource extraction policies and environmental management principles around the world. Commonly, for example, money made from a gold mine is counted as an asset, but environmental and health care costs arising from waste pollution never shows up as a debit. Instead, the money spent on mine cleanup is even counted as an additional positive contribution to a nation's economic output.

Exclusive focus on economic measures of well-being has led to many such practices harmful to overall quality of life. In fact, the results of a recent survey by the Merck Family Fund indicated that as we gain in material consumption, beyond a certain point we lose in satisfaction:

Compared to My Parents at My Age:	
• I have more possessions:	72 percent
• I am more financially secure:	66 percent
• I am more successful in my career:	58 percent
• I am happier:	49 percent

There is a growing understanding that as more of the world's forests are felled, as we feel less safe and happy in our cities, as the gap between rich and poor continues to widen, we have serious problems to solve. Environmentalism, social justice, or economic growth each pursued separately cannot leave our children a world that is better, or even as good as now. Without social, economic, and environmental justice, there is no true sustainability: if one community becomes sustainable at the expense of another, is the biosphere as a whole better off? As Mark Dowie said, "Unless a significant number of humans stand actively against all degradations, wherever they occur, global sustainability simply won't happen."

3. PROBLEM

Achieving sustainable development requires the availability of many types of information. Sound decisions on development must be based on the best scientific evidence. Sustainability indicators have to be identified and measured to support effective environmental and natural resource management, and to monitor and assess environmental hazards and disasters as well as longer-term environmental and socio-economic changes.

Countries at all development levels have a great common interest in acquiring the information needed to achieve sustainability. As long ago as 1962, Vikram A. Sarabhai of the India Space Program already stated, "There are some who question the relevance of space activities in a developing nation. To us, there is no ambiguity of purpose. We must be second to none in the applications of advanced technologies to the real problems of man and society." Among the many space technologies with great potential to influence our future is the collection of high-resolution, high-accuracy remote sensing imagery of the Earth gathered using satellite sensors. Useful satellite remote sensing measurement of sustainability indicators should support:

- Research, understanding, and transmission of knowledge about ecosystems and ecological and economic trends
- Protection and restoration of plants, animals, soil, water, and natural processes
- Economic development which is lasting and ecologically sensitive
- Establishment of policies based on local experience and needs, to guide local and national government regulations, and regional and international agreements and treaties.

4. APPROACH

Measurements of multiple sustainability indicators help a community or nation determine its status and preferred path. Satellite remote sensing information useful in these measurements includes past and present land and water cover and usage classifications at local, regional and global scales, as well as change detection and monitoring of environmental "hotspots", threats to biodiversity, and processes affecting global change. Three-dimensional spatial information is of also of value, in hydrological and geological investigations, and in more accurately locating features and phenomena.

Some features important to monitor are: marine resources, rivers, lakes, irrigation systems, and other hydrologic features, as well as snow and ice; geological features including soil types; farms, rangeland, forests, mines, and other natural resource sites; main roads, railroads, pipelines, power lines, and airfields; and cities and human settlements and other enterprises. Examples of indicators to be derived might be: flood volumes, land development activity, crop yields, animal and vegetation invasions and stresses, air clarity, area affected by off-road vehicles, and extent of deforestation and resultant fragmentation of ecosystems.

Once indicators are measured, the next steps in applying the information to sustainable development in an area are to:

- Identify the elements needing improvement, or which might constitute threats
- Evaluate their relative importance
- Identify their root causes
- Find practical ways to improve the situation

5. SATELLITE RESOURCES

The major new remote sensing satellite capabilities include high spatial resolution, wide coverage and frequent scene revisits, and, in some of the systems, improved data quality resulting from advanced calibration technologies. We compare in detail the performance capabilities in each of these areas.

5.1 Design Types

The new types of remote sensing satellites discussed here fall into four main design and performance classes:

- high resolution optical imagers, typically at most 3 m in panchromatic (pan) band ground sample distance (GSD), swath width generally below 40 km, high metric accuracy, and up to four multispectral bands in the visible-and-near-infrared (VNIR, 0.4-0.9 μm) spectrum
- wide-coverage optical imagers with about 5 - 8 m pan band GSD, VNIR bands, 70 - 120 km swaths, and sometimes short-wave infrared (SWIR)
- hyperspectral satellites, currently in an experimental stage, with up to hundreds of narrow (~10 nm) spectral bands from visible to mid-wave IR (MWIR), and GSD > 20 m
- synthetic aperture radars (SARs); some of these are also combined with optical imagers on one satellite. SARs can often determine surface characteristics complementary to those sensed by light waves, such as surface slope and roughness, water content, and organic overburden.

Table 2 (much of the data is from Kramer, 1996) list the characteristics of the newer systems originating from all sources except the military and intelligence domains, where data is rarely made available to civilians. Besides the listed systems, which are either already up or relatively likely to achieve operational status soon, additional optical imaging systems with about 2-meter panchromatic GSD may well be launched, such as Israel's EROS, Russia's SPIN-2 and DD-5, and Orbimage's Orbview 3.

Owner/ Operator	Canada (CSA/CCRS)	India (ISRO)	Japan (NASDA)	USA (NASA)	EarthWatch		Space Im. EOSAT	USA (NASA)	Russia (NPO-M)	France (CNES)
Satellite and Sensor	RadarSat	IRS-1C & 1D PAN & LISS-III	ALOS AVNIR-2 & VSAR	Clark Imager	Early Bird	Quick Bird	IKONOS 1 & 2	Lewis-type replacement	ALMAZ 1B	Spot 5
Launch,	1995	1995,1997	2002	1998	Dec., 1997	1999	Mar. & Dec.,1998	2000 ?	1998	2002
Status	Up	Up								
Revisit Time	6 days at Equator; for Canada= 4 d	24 days; at reduced resol., 5 d	45 days; at reduced resol., 3 d	20 days; at reduced resol., 5 d	20 days; at reduced resol., 5 d	≥5 d avg. w/sun, for 1 m GSD	4 d @ 1 m; 2 d @ 1.5 m GSD	5 d	1-3 days	26 days
Orbit Altitude	793-821 km	C:801-833, D:736-825	700 km	496 km	470 km	600 km	681-708km	523 km	400 km	832 km
Inclination Equat. Crossing	98.6 deg 6:00 p.m.	98.7 deg 10:30 a.m.	98 deg ?	97.3 deg 11:25a.m.	97.3 deg 10:30 a.m.	52.0 deg varies	98.2 deg ≈10:30 am	97.45 deg ≈ 10:30 a.m.	73.0 deg varies	98.7 deg 10:30a.m.
Pan Band Nadir GSD Swath Width	N/A	0.5 - 75µm 5.8 m 70.5 km	0.52 - 0.77 2.5 m 35 km	0.45 - 0.8 3 m 11 km spot	0.45 - 0.8 3 m 11km spot	0.45 - 0.9 0.82 m 22 km	0.45 - 0.9 0.82 m 11 km	0.48 - 0.75 5 m 12.9 km	0.58 - 0.8 2.5 m 80 km	0.51-0.73 5 m 2 x 60 km
Blue Band Nadir GSD Swath Width	N/A	N/A	0.42 - 0.5 10 m 70 km	N/A	(in green)	0.45 - 0.52 3.28 m 27 km	0.45 - 0.52 3.27 m 11 km	24- 5nm bds. 30 m 7.7 km	N/A	yes
Green Band Nadir GSD Swath Width	N/A	0.52 - 0.59 23.5 m 142 km	0.52 - 0.60 10 m 70 km	0.50 - 0.59 15 m 55km spot	0.45 - 0.59 15 m 55km spot	0.52 - 0.60 3.28 m 22 km	0.52 - 0.60 3.27 m 11 km	16-5nm bds. 30 m 7.7 km	0.5 - 0.6 4 m 80 km	0.50-0.59 10 m 2 x 60km
Red Band Nadir GSD Swath Width	N/A	0.62 - 0.68 23.5 m 142 km	0.61 - 0.69 10 m 70 km	0.61 - 0.68 15 m 55km spot	0.61 - 0.68 15 m 55km spot	0.63 - 0.69 3.28 m 22 km	0.63 - 0.69 3.27 m 11 km	32-5nm bds. 30 m 7.7 km	0.6 - 0.7 4 m 80 km	0.61-0.68 10 m 2 x 60 km
Near-IR Nadir GSD Swath Width	N/A	0.77 - .86 23.5 m 142 km	0.76 - 0.89 10 m 70 km	0.79 - 0.89 15 m 55km spot	0.79 - 0.89 15 m 55km spot	0.76 - 0.90 3.28 m 22 km	0.76 - 0.90 3.27 m 11 km	56-5nm bds. 30 m 7.7 km	0.7 - 0.8 4 m 24-300km	0.79-0.89 10m 2 x 60 km
SW/Mid-IR Nadir GSD Swath Width	N/A	1.55 - 1.75 70.8 m 142 km	N/A	N/A	N/A	N/A	N/A	256 bands 30 m 7.7 km	N/A	1.58 1.75 20 m 2 x 60 km
Microwave GSD Swath Width	5.3 GHz 9 - 100 m 35-510km	N/A	L-band 10 - 100 m 70 km	N/A	N/A	N/A	N/A	N/A	0.43, 3.13, 8.6 GHz 5 - 40 m 20-170km	N/A
Downlink	105 Mb/s	125 Mb/s	>240Mb/s	25 Mb/s	23 Mb/s	300 Mb/s	320 Mb/s	2 Mb/s	245 Mb/s	150 Mb/s
Launcher	Delta II	Molniya	H II	LMLV 1	START-1	Cosmos	LMLV 2	LMLV 1	Proton	Ariane

Table 2. Existing and Expected New Remote Sensing Satellite Systems

To provide remote sensing information useful for sustainable development, feature discrimination and change detection are vital functions, often performed more effectively with higher resolution and with multispectral sensors. The ability to collect at particular lines-of-sight, sun angles, and seasons of the year can also enhance those functions.

The most advanced of the newer satellites have packaged large aperture telescopes into a compact and lightweight structure which includes sophisticated electronics for data compression and communication, GPS receivers and star trackers for accurate mapping capabilities, and extremely stable attitude control systems to produce images which are sharp and free of distortion.

In Figure 3 we see a drawing of a typical satellite of the type we have been discussing. The progress in satellite design over the past 40 years has taken us from satellites with one-kilometer resolution to such new, efficient imaging systems with resolution better than one meter. Of note in the drawing is the mechanical compactness, contributing rigidity for image sharpness, and low inertia for increased pointing maneuverability.

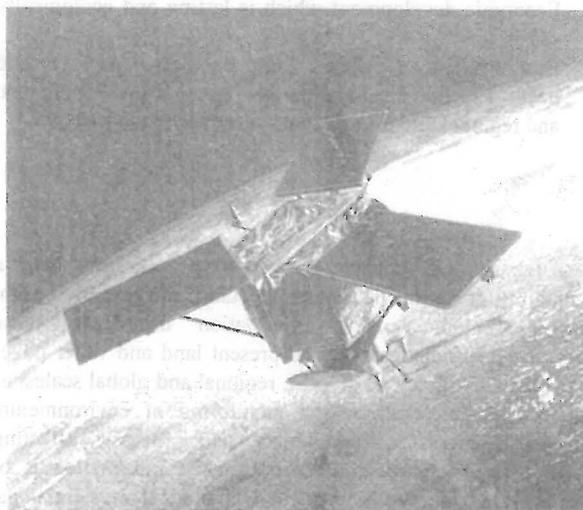


Figure 3. Space Imaging EOSAT's IKONOS satellite.

5.2 Swath, Orbit and Constellation, Access and Revisit

The goal of frequent coverage at high resolution has led to increased numbers of satellites and quantities of data. High spatial resolution constrains swath widths and area coverage rates, due to the effects on system cost of the enormous data collection rates involved, as well as to the difficulty in obtaining radio frequency bandwidth allocations adequate for data transmission to ground stations. However, the availability of many satellites collecting data will give overall area coverage and revisit rates able to fill in many gaps and solve many problems. Individual systems with at least two pointable satellites, such as IRS and IKONOS, can offer revisits almost daily in most locations, and the combination of the many systems will raise access rates far higher still.

Timing of observations needed for solution of particular problems also limits the effective access rates. For example, optical sensors best see down to the ground (in many places) between late fall and early spring, when deciduous trees are bare. But radar, in certain radio frequency bands, can penetrate foliage to gather information on the underlying terrain in any season. Although their resolution is substantially below that of the most capable visible-wavelength systems, the radar systems are the only ones that can also image at night or through clouds, which (together with the foliage penetration) substantially improves their revisit capabilities.

5.3 Resolution

The importance of resolution scale cannot be overemphasized (Hassan and Hutchinson, 1992). Direct inspection reveals more details in a higher-resolution image. Most of the highest-resolution imagery is collected in panchromatic visible-wavelength bands, but some multispectral products and radar imagery are also quite high in resolution.

High resolution is now possible because of new sensor designs achieving large aperture with low mass, joined by extremely stable satellite attitude control. One-meter panchromatic resolution will soon be attainable for every location on nearly all clear days. Besides its obvious potential for identification of important features and phenomena, the resulting high resolution can also be used to improve the calibration of lower-resolution imagery from other systems which have much wider coverage areas for identifying and characterizing regional land-cover and land-use properties and changes.

Higher resolution also improves radiometric accuracy crucial for measurement of temporal differences, since different land features are viewed in separate pixels with uncontaminated signatures. One-meter resolution can make it possible to determine the presence of disease in a single tree, or the type of roof on an individual house. Sun-synchronous satellites also aid in consistent and reliable interpretation, collecting data with relatively constant shadows during each season.

The need for both high resolution and wide coverage is leading to increased numbers of satellites on orbit and to advanced near-lossless data compression techniques. Cooperative efforts in providing ground test sites for calibrating and validating sensor measurements, together with agreements on standards and evaluation criteria, are beginning to allow data from different satellites to be compared reliably, and then

coordinated and combined effectively (sensor fusion) a powerful technique for producing the most useful datasets.

5.4 Accuracy, Image Quality, and Calibration

Geometric and radiometric calibrations permit accurate scene feature mapping and classification. With in-flight calibration using star trackers and GPS receivers on board, some satellite systems can yield imagery product spatial accuracies better than 10 meters without use of ground control data. Same-pass optical stereo imaging can also generate terrain models with vertical accuracies as good as 3 meters. Such terrain maps of high spatial accuracy constructed from optical stereo or radar are important for two reasons. First, they can be used directly to monitor certain environmental processes and changes, as in hydrological applications such as predicting water runoff amounts and changes. Second, detailed positional and terrain knowledge will help orthorectify high resolution imagery data, improving spatial registration of GIS layers from different datasets so multitemporal analyses reach high levels of thematic accuracy and change detectability.

Image quality of optical observations through the Earth's atmosphere is greatly enhanced by increased sensor dynamic range, which maintains good image contrast by allowing effective subtraction of haze and scattered light. The IKONOS and QuickBird systems are to achieve high dynamic range by using 11-bit digitization. Another requirement for preserving image contrast and signal-to-noise ratio is to avoid image smear: highly stable sensor attitude control systems are needed to achieve this.

Radiometric accuracy is critical, both for good quality images free of streaks or bands, and for measuring subtle spectral signature differences. Absolute radiometric accuracy, needed for reliable temporal comparisons, requires a stable calibration source. The best systems regularly monitor sensor responsivity with respect to the sun, which is stable to 0.4%; this allows colors and multispectral indices to be determined with errors well below 10 %.

Radiometrically accurate data also improves the performance of the many algorithms needed for land-cover and land-use analyses. Atmospheric correction of optical satellite data further raises classification accuracy, and can be made more effective by taking advantage of new and better algorithms, as well as by correlation with data from some of the highly calibrated sensors available on the U.S. Earth Observing System (EOS) AM-1 platform. Corrected data also permits combination of different data types, such as optical and microwave, into band-ratio products yielding increased classification accuracies.

5.5 Processing and Distribution

Satellite imagery collected worldwide will be processed into highly useful information via new and more efficient analytical techniques made possible by advances in computer hardware (e.g., ever-growing processor speeds and storage capacities) and software (Geographic Information Systems [GIS] and related products). Data will be distributed ever more rapidly via digital communications technologies, such as the Internet and World-Wide Web. The data will be coordinated and analyzed by many agencies at local to worldwide levels. The

synergy of these technologies with the new remote sensing satellites will yield vital resource management and environmental monitoring capabilities.

Availability of and experience in using the resulting datasets will make it possible to identify further applications for sustainable development, reduce uncertainties in classification and change detection, and solve database and information distribution problems inherent in dealing with the extensive data quantity expected. The large amount of high-quality data will be of great use in deriving accurate quantitative spatial and spectral characteristics of features in specific environments, and in enabling construction of comprehensive atlases vital to operation of local, national, and international environmental monitoring systems.

5.6 System and Data Costs

For practical use of the satellites, no factors are more important than system reliability and low data cost. Because many of the systems compete in the commercial market, these factors have been paramount considerations in their development, designed in from the start. Efficient availability of the data from archives also contributes to decreased product cost. The new satellite imaging systems will in most cases offer be more cost-effective than aerial systems because they provide wide-area coverage, digitally processed data, and "off-the-shelf" pricing, as opposed to custom collection pricing.

Although capabilities and limitations and their significance vary with the satellite system, the scene location, and the environmental application, we need to be able to calculate costs per unit area. For commercial systems there will be an uncertainty range contingent upon the levels of demand (including product size, data urgency, and multiple sales of the same data), supply (availability from archives or from competing suppliers), and processing needed to generate a particular value-added product. For example, 5-m GSD optical image digital products now available cost approximately from \$0.40/km² to \$4/km². Current SAR image prices from RADARSAT in its Fine Resolution mode (pixels about 9 m) are below \$2/km². Higher-resolution products will be more costly. The price varies approximately in proportion to the number of pixels of data; for 1-m GSD products we can therefore expect prices about in the range from \$10/km² to \$100/km². However, all these prices are expected to decrease considerably as archives become populated and competition increases.

5.7 Summary of Satellite Data Impacts

Because the new satellites enable us to monitor our surroundings in great detail, they will increase our knowledge of environmental effects previously ignored, exaggerated, or inaccurately reported. The new datasets will therefore alter research approaches, which makes it even more important for researchers to know what the satellites can and cannot do. Understanding the satellite capabilities and the indicators important to measure for sustainable development lets us optimize the efficiency of research plans, collect and apply the data most appropriate to each problem, achieve reliable research results, and recommend realistic solutions derived from comprehensive knowledge of the situations. With this understanding we can also initiate the collection and

production of those specific datasets most helpful in achieving sustainable development.

To summarize their advanced capabilities, the new remote sensing satellites for environmental monitoring will provide:

- Large total area coverage rates by greatly increased number of satellites, with frequent revisits possible
- Much higher spatial resolution than previously available satellite data
- Accurate 3-D spatial grid to serve as coordinate system
- High dynamic range and radiometric accuracy for precise classification
- Hyperspectral (high spectral resolution) capability (experimental stage)
- Observations of areas under cloud cover via use of SAR

6. SELECTED APPLICATIONS

6.1 Classification and Monitoring

The different types of satellites have countless applications. At higher spatial and spectral resolutions new types of results are achievable and new types of features are visible. From radiometrically and geometrically accurate data, multispectral algorithms can provide NDVI (normalized difference vegetation index), turbidity index, principal components analysis, and pan-sharpened (high resolution color) products. SAR products provide such capabilities as monitoring areas previously hidden from view by clouds, determining coastal changes and habitat suitability, mapping forest and land cover, and evaluating rice growing status.

Such products will add capability to map precisely and track plant diseases and deforestation in critical sites, precisely measure small tributaries and wetlands to evaluate water resources and to monitor and analyze very sensitive ecosystems, keep track of growth at urban boundaries, and help solve many other problems. A study in India showed that a ground water resource location efficiency of 45% increased to 92% when augmented by satellite imagery.

Knowledge of terrain elevations at the very detailed level of the IKONOS Model dataset, with the grid of elevation data latticed at spacings 30 meters and smaller, is a highly important element of analyses relevant to monitoring environmental processes and changes. It can improve spatial registration with respect to different datasets, increasing thematic accuracy and change detectability. When combined with multispectral imagery and GIS representations, terrain data is important for analysis of geological forms, snowpack and melt levels, water flows, and flood and drought forecasting critical to vegetation, erosion, and many natural and industrial processes. Via statistical techniques, the new satellite data can be used to improve the accuracies of regional and global estimates of many land-cover features, by performing spot checks against ground truth, and then serving as a phenomenology calibration source serving more accurate discrimination of land-cover types and land-use patterns when data from systems with lower resolution is analyzed.

Methods such as the unsupervised clustering algorithm can classify regions within specified band-ratio thresholds. After clustering is performed, interactive interpretation procedures can map forest, agriculture or pasture, abandoned areas, etc. Image data and ground truth can refine and evaluate algorithms to correct landcover reflectance signatures for effects of topography, water vapor and aerosols, and seasonal differences. Comparisons across site boundaries will make use of expected continuities to increase overall thematic accuracy. Such techniques improve the accuracy of sampling and counts of deforestation occurrences, of evaluations of morphology (shape and dimension), and of identification and classification.

A very important application of high-resolution, frequent-revisit observations is the monitoring of environmental or biodiversity "hotspot" indicators in critical areas. It is important to characterize the areas well enough to be able to identify the locations which should be studied further with particular remote sensing instruments, how often the observations should be made, and which algorithms will be most useful in deriving conclusions significant enough to optimize environmental strategies and decisions.

Problems with public health are some of the most obvious indicators of a lack of sustainability. The new satellites can collect data relevant to monitoring and controlling vector-borne human diseases such as malaria, by helping to identify and characterize man-made structures, standing water, and vegetation types. This permits more accurate estimation of spatial and temporal distributions of disease risk.

Monitoring can also be of great use in controlling tropical deforestation. More than 10 percent of the Amazon jungle has already been destroyed, and data from satellites currently on orbit show that burnings in 1997 exceed those in 1996 by 28 percent. Brazil's regulations require Amazon landowners to preserve 80 percent of their land, and environmental inspectors fine those who burn or log illegally, but for every person fined for destroying the rain forest, hundreds are never caught. Only about 300 inspectors monitor the vast Amazon region. "They're outnumbered," says Philip Fearnside of the Institute for Amazon Research. "Just a handful of inspectors can't possibly control an area that's 5 million square kilometers." The potential contribution of the new remote sensing satellites is quite evident.

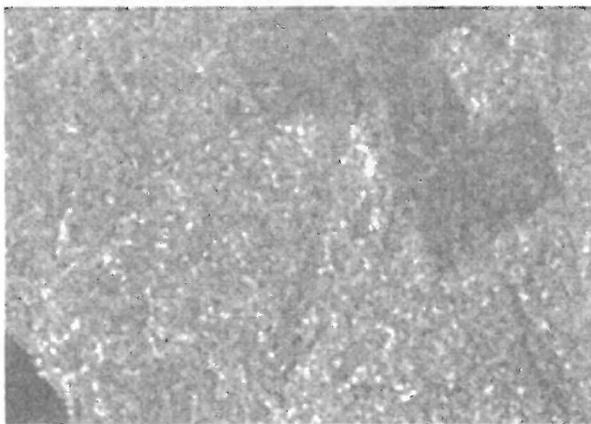


Figure 4. Indonesia forest clear-cut: RADARSAT image.

Where smoke or clouds often interfere with image collection, satellite SAR capabilities are especially effective for monitoring deforestation, as shown in Figure 4.

6.2 Agricultural Development

Spatially-accurate satellite imagery will serve to create digital base maps, for ground-truth collection field maps, and for foundation base maps upon which crop conditions, soil moisture, elevation data and other field information gathered are layered for integrated analysis and decision making. Derived primarily from the high-resolution panchromatic images, these base maps will show the locations of field boundaries, fences, roads, drainage ditches, irrigation equipment and other features as small as one meter in diameter.

High-resolution multispectral space imagery will be successful at identifying field variations in many leafy crops, detecting such anomalies as insect infestation, disease, nutrient stress, and irrigation malfunctions, in areas as small as a square meter, weeks before the condition is visible to the naked eye. It will be of great value in extending practice of precision agriculture techniques, which reduce waste and pollution by precisely applying fertilizer, pesticide, or water in doses that vary every few meters in the field according to immediate requirements. A growing number of farmers have Global Positioning System (GPS) receivers that can lead them to a precise spot in their field if they are given a problem area's accurate location. The satellite imagery should have relative spatial accuracy to within a few meters, matching the capabilities of variable-rate delivery technology. Space Imaging EOSAT, for instance, will offer imagery that provides accuracies of ± 1.5 m.

Farmers need crop condition information in near-real time because they have to isolate and mitigate the problem before it spreads to the entire field or causes permanent damage. For some crops, images are needed often twice a week during the peak growth period. Farmers need delivery of insect infestation and disease information within 48 hours for high-value vegetable crops, and within a week for cereal crops. The key to precision agriculture is an imaging and delivery system that makes the crop information available within hours of its collection, at cost low enough to maintain profit margins. Agriculture experts estimate that, for many crops, the cost of processed satellite image information must stay below \$1 per acre (\$250/km²) to be economically useful.

Space Imaging EOSAT is developing a system to process and deliver information using accurate high-resolution imagery for base mapping of fields, deriving crop information from archived satellite and aerial images, growth records, meteorological data, elevation maps, and other data. The system can process imagery for delivery of crop information within 24 to 48 hours, on CD, the Internet and in other electronic and hardcopy formats. The information can be used to guide variable rate applicators to maximize field potential, stabilize crop quality, reduce costs and protect the environment.

6.3 Urban Planning and Development

Significant advances in the scope and comprehensiveness of urban planning, which address the wide range of impacts of populations on the existing immediate and nearby environments are made possible by use of the large coverage



Figure 5. Japan urban/forest boundary: from IRS 1-C.

and rapid update frequencies of the new satellite imagery collections. Just a small fraction of the single-scene coverage possible with satellites like IRS 1-C is shown in Figure 5. We will need to conduct many studies to improve our knowledge of the impacts of past development, as viewed from such encompassing perspectives, in order for the proper lessons to be applied to new projects.

7. PROSPECTS AND CONCLUSIONS

Data continuity is needed for long-term analyses and monitoring to support sustainable development. This continuity is ensured by the plans of the commercial remote sensing companies and of government bureaus (such as the Indian National Remote Sensing Agency) for upgrading, launching, and maintaining new satellites on orbit. The demands of commercial customers for frequent updates and timely data will result in imagery collection which is ideal for multitemporal analysis tasks.

The existence of well-calibrated, low-cost data in compatible formats from satellite sensors of the optical panchromatic, multispectral, and hyperspectral types, and from SAR satellites, will make sensor fusion possible, and eventually produce an integrated Earth observation system of great use in producing the full range of remote sensing information needed for sustainability.

Speaking at the 51st United Nations General Assembly on "International Cooperation in the Peaceful Uses of Outer Space" at the Special Political and Decolonization Committee, A.C. Jose, MP and member of the Indian delegation, said that space technology has demonstrated its immense potential to contribute to the solutions of several problems of global significance including protection of the Earth's environment and achievement of sustainable development. He said economic and social development of the countries could be achieved only by a strong commitment to promoting international cooperation at a global level and making constant efforts to renew it. Jose said sharing of space resources and the evolution of cooperative global systems relevant for the economic and social development are examples of roles played by

international bodies like COPUOS, the Committee on Peaceful Uses of Outer Space.

Jose said the main thrust of the Indian space program is to develop space technology for peaceful applications, particularly for rapid socio-economic development in India. The IRS series of satellites have been used for monitoring crops, predicting their yields, mapping forests, managing lands and water resources, environmental protection, marine fishery development, and geological mapping. Jose said that these are critical inputs to provide food security, and he added that they improve productivity of natural resources on a sustainable basis. Other Indian satellites are aimed to gather and provide data on atmospheric constituents critical to environmental monitoring, including ozone and greenhouse gases.

The rapid increase in satellite remote sensing resources and capabilities will greatly benefit the achievement of sustainable development, an idea inspiring more and more individuals, groups, communities, states, government agencies, and international bodies. This satellite technology will contribute information which can help optimize:

- Integrated plans to maintain environmental, social, and economic health
- Measurement of indicators tracking environmental, economic, social well-being, and quality-of-life targets
- Informed participation by affected parties, to reach consensus on actions.

The new remote sensing satellites, greatly enhanced in both performance and numbers, have a vital role to play in the applying the power of technology to solve problems due in considerable part to the misuse of technology. Each type of these satellites will, with its own particular advantages, augment our information and understanding so as to contribute to the best decisions for our planet and ourselves, and for future human generations.

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