LEGAL CHALLENGES AND MARKET REWARDS TO THE USE AND ACCEPTANCE OF REMOTE SENSING AND DIGITAL INFORMATION AS EVIDENCE

KENNETH J. MARKOWITZ*

We need to see the future more clearly if we are to stay within ecosystem limits. Our new ability to uncover facts brings with it new opportunities and challenges for evidence, particularly in the area of environmental compliance. Satellites and other remote sensing technologies are revolutionizing our ability to visualize and simulate the potential consequences of our environmental and resource management decisions. These advances are enabling scientists, governments and industry to peer into the remotest corners of the globe, with a perception far beyond human senses. Our challenge is to determine the most efficient way to establish technologies and processes that will enable us to better manage critical ecosystems through the integration of digital earth system science, including remote sensing data, into legal systems at all levels of resource management.

Professor Durwood Zaelke[1]

I. INTRODUCTION

Emerging technologies are revolutionizing the collection, organization, application, storage, and distribution of earth science information and enabling more cost-effective decision-making and better environmental protection. Satellite remote sensing and digital systems, including geographic information systems (GIS), provide powerful

* Esq. President of EarthPace LLC. Director of Law and Technology Program, Center for International Environmental Law (CIEL).

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1. Durwood Zaelke, Introductory Address to A View from Space: Digital Earth Applications for Environmental Law and Resource Management Workshop (Jan. 26, 2001), *summary available at* http://earthpace.com/conference/confsumindex.htm.

tools for visualizing and solving complex legal and environmental problems.

The use of digital technologies in performing tasks or making decisions that are vulnerable to legal dispute presents significant challenges to the courts in understanding how the information was derived, processed, and presented and in weighing the probative value of the information against its potential to confuse. Despite the tremendous opportunity for technologies to enable more informed, cost-effective decisions, issues of credibility, acceptability, and other evidentiary hurdles are impeding the integration of these technologies into the routine operations performed by public and private environmental stewards. Until scientists and attorneys work together to educate triers of fact to develop protocols for general acceptance, courts will be reluctant to work through the associated complex science and mathematics necessary to assign evidentiary value to the information. Thus, uncertainty about the information's viability in court will stifle the growth of the commercial remote sensing market and delay the development of applications, which will confirm that remote sensing and digital information systems can greatly improve environmental management.

This article (1) describes the basic technologies and capabilities of earth science satellites and digital information systems to open readers' minds to possible applications, (2) evaluates evidentiary hurdles to the acceptance of remotely-sensed and other digital information in the courts, (3) presents an analysis of opportunities to integrate these systems in environmental assessment and resource management, and (4) concludes that the removal of evidentiary impediments will improve environmental protection, result in cost-saving or cost-avoidance in decision-making, and accelerate the growth of commercial remote sensing and GIS industries.

II. THE PROCESS, TECHNOLOGY, APPLICATION, AND MARKET OF REMOTE SENSING DATA

This section describes the basic technologies and capabilities of satellite remote sensing and the data flow processes from collection through presentation. The potential for error during each process is highlighted, establishing bases for evidentiary challenges. Part II. A details the remote sensing data collection process, Part II. B describes historic and currently available remote sensing satellites, Part II. C provides examples of how practitioners are applying remote sensing technologies to environmental problems, and Part II. D presents an overview of the commercial remote sensing markets.

A. *The Remote Sensing Basics*

1. Introduction to Remote Sensing Processes

The term 'remote sensing' can generally be defined as "the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device not in contact with the object, area, or phenomenon under investigation."[2] This broad definition includes cameras, ocean buoys, and RADAR devices. These general remote sensing devices have undergone adaptations over the last century to make observations of the Earth and its physical process from aircraft and satellites.

Airplanes have been used since the 1930s to carry cameras and sensors to study the earth.[3] Cameras collect images of part of Earth's surface, with the final aerial photograph usually consisting of a series of overlapping vertical photos that form the basis for mapping. Airplanes are also used to carry sensors. For example, the Side-Looking Airborne Radar (SLAR) instrument is used by the United States Geological Survey (USGS) for various projects in the conterminous United Statesand Alaska to map geologic features, detect mineral and energy reserves, and identify potential environmental hazards.[4]

Satellites are also used to collect images and data about the earth. Earth-observing satellites, as they are referred to, carry sensors, which are capable of recording wavelengths across the entire electromagnetic spectrum, from infrared to visible radiation. Some satellites carry sensors that collect data passively by recording radiation that is radiated or reflected from Earth's surface or atmosphere. Other satellites collect data actively by emitting radiation and then recording what is reflected back to them from Earth's surface or atmosphere.

2. THOMAS LILLES & RALPH KIEFER, REMOTE SENSING AND IMAGE INTERPRETATION 1 (1994).

3. *See* John E. Estes, *Remote Sensing Core Curriculum, Vol. 1 Air Photo Interpretation and Photogrammetry* (1999), *at* http://umbc7.umbc.edu/~tbenja1/santabar/rscc.html (last visited Feb. 18, 2002).

4. Earth Resources Observation Systems (EROS) Data Center, *Side-Looking Airborne Radar Guide*, U.S. Geological Service, *at* http://edcwww.cr.usgs.gov/glis/hyper/guide/slar (last visited Feb. 18, 2002).

Passive Remote Sensing

Passive systems[5] collect data from energy that is reflected or radiated off the Earth's surface and atmosphere.[6]

> A typical image derived from an infrared passive sensor consists of small equal areas referred to as pixels[7] arranged in regular rows and columns. Each pixel has a numerical value called a digital number (DN) that records the intensity of electromagnetic energy measured for the area of ground represented by the pixel. The DN range from 0 to some higher number on a gray-scale. Each pixel is also given x and y coordinates to place it. The image can therefore be described in strictly numeric terms on a three-coordinate system with x and y locating the pixel and z giving the DN displayed as a gray scale intensity value.[8]

Passive sensors are described in terms of their spatial, spectral, and temporal resolutions. The spatial resolution of a sensor is the smallest area that is recorded as a separate unit (pixel).[9] For instance, one-meter spatial resolution means that one pixel of a digital image represents an area on the Earth's surface measuring one meter in length by one meter in width. Spectral resolution refers to the number and dimension of bands (or wavelengths) of the electromagnetic spectrum that a sensor records.[10] The higher the number of bands, the greater the sensor's ability to distinguish between objects. Temporal resolution, also known as repeat time, is the frequency with which a sensor passes over the same area.

Active Remote Sensing

Active remote sensing devices, on the other hand, emit high-energy electromagnetic radiation and record the relative amount and pattern of the energy that is reflected back. Many of these devices operate at wavelengths that not only penetrate cloud cover, but also vegetative cover and soil surfaces.[11] The tradeoff for greater imaging capabilities, however, is increased complexity in data interpretation, as compared to passive sensor data interpretation.

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5. Author's note: passive systems operate either as infrared sensors that monitor the reflectance of radiation emanating from an object or surface, or as panchromatic (PAN) sensors that produce black and white image data.

6. FLOYD F. SABINS, JR., REMOTE SENSING: PRINCIPLES AND INTERPRETATION 17 (2d ed. 1987).

7. Author's note: pixel is derived from a contraction of "picture element."

8. SABINS, *supra* note 6, at 235.

9. JAMES B. CAMPBELL, INTRODUCTION TO REMOTE SENSING 14 (2d ed. 1996).

10. JOHN R. JENSON, INTRODUCTORY DIGITAL IMAGE PROCESSING: A REMOTE SENSING PERSPECTIVE 3 (2d ed. 1996).

11. Campbell, *supra* note 9, at 210.

Data Processing

After the satellite records the data, it is transmitted to a ground station for calibration and storage. The data may undergo various levels of processing before it is made available to the user. These levels range from simply correcting for transmission errors to performing advanced correction and analysis with model algorithms,[12] depending on the needs of the scientists or user.[13]

Once the data has undergone initial processing techniques, users may apply it for various purposes, from the simple production of an enhanced image to the more complex creation of image maps, thematic maps,[14] and spatial databases.[15] The data may also be used to develop statistical observations and graphs of the observed phenomena.[16] To create maps and spatial databases, the initial data must be combined with other spatial data. An effective method to analyze the remote sensing data with reference to other spatial data is in a geographic information system (GIS).

Remote Sensing Data Integration with Geographic Information Systems (GIS)

Geographic information systems (GIS) are defined as computer systems capable of assembling, storing, manipulating, and displaying geographically referenced information (i.e. data points identified with respect to their location).[17] GIS store information about the world as

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12. For a complete review of remote sensing data processing, *see* generally JENSON *supra* note 10 (in particular, Chapter 7 "Image Enhancement").

13. *See generally* NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA) GODDARD SPACE FLIGHT CENTER, MTPE/EOS DATA PRODUCTS HANDBOOK VOL. 1 (Stephen W. Wharton and Monica Faeth Myers eds., 1997) [hereinafter EOS Vol. 1] (describing science data products available from *Earth Observing System Data and Information System (EOSDIS) missions and projects relating to the Tropical Rainfall Measuring System, the Terra mission, and the Data Assimilation System)*, *available at* http://eospso.gsfc.nasa.gov/eospso_homepage.html (last visited Feb. 18, 2002).

14. Author's note: a thematic map shows the locations of physical characteristics belonging to a theme (for example, roads, forests, houses, elevation, rivers).

15. Author's note: the Association for Geographic Information (AGI) defines "spatial database" as "the storage of geographic data in a prescribed format, including the location, shape, and description of geographical features as well as the relationships between different features. A spatial database usually includes coordinates and topological information." *Geographic Information System (GIS) Dictionary*, AGI, *at* http://www.geo.ed.ac.uk/agidict/ (last visited Feb. 18, 2002).

16. JENSON, *supra* note 10, at 2.

17. AGI, *supra* note 15.

a collection of thematic layers that can be linked together by geography.[18]

Remote sensing data applications and GIS have an established history of interdependency. GIS provides a format to distribute remote sensing data and to derive useable information from the data. Remotely-sensed data is also a critical means to create base GIS maps and update many data layers in the GIS.[19] The integration of remotely-sensed data and GIS is particularly attractive because 1) the conversion of remotely-sensed raster-format data to GIS vector-format data is inexpensive and 2) remote sensing data offers a cost-effective way to visualize large geographic areas in a digital format.[20]

There are two defining features of all GIS: the ability to overlay spatial data and the ability to change as new data becomes available. The first key feature of GIS programs is the capability to overlay multiple sets of databases into a map format that graphically explains the relationships between the data. Spatial data (points, boundaries, and lines) comprise the base of the map and can be supplemented with tabular data (tables linked to the maps with further information) and image data (such as that from satellites).[21] This powerful and versatile concept has proven invaluable for solving many real-world problems, from recording details of land use planning applications to modeling global atmospheric circulation cycles. The second key feature of GIS is their status as "dynamic maps" that can be updated and altered as needed. These maps may also be manipulated to perform scientific analyses and to create models of different environments.

In a simplistic example of GIS application, a map of city streets could be combined with latitude/longitude-referenced traffic flow data to create a map that reveals areas of frequent accident occur-

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18. *See generally* THE HISTORY OF GEOGRAPHIC INFORMATION SYSTEMS: PERSPECTIVES FROM THE PIONEERS (Timothy Forsman ed., 1998) (providing a complete study of the history of GIS).

19. John Estes & John Jenson, *Development of Remote Sensing Digital Image Processing and Raster GIS*, *in* THE HISTORY OF GEOGRAPHIC INFORMATION SYSTEMS: PERSPECTIVES FROM THE PIONEERS (Timothy Forsman ed., 1998) at 178.

20. Ross Lunetta et al., *Remote Sensing and Geographic Information System Data Integration: Error Sources and Research Issues*, 57 PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING 677, 678 (1991). *See also* INTEGRATION OF GEOGRAPHIC INFORMATION SYSTEMS AND REMOTE SENSING (Jeffrey Star *et al.*, eds., 1997) (arguing that GIS enables the efficient combination of remotely-sensed data with other information and, therefore, offers the best means for satisfying the expanding demands for a variety of data requirements).

21. *See generally* Environmental Systems Research Institute (ESRI), *What is GIS?*, *at* http://www.gis.com/whatisgis/index.html (last visited Feb. 18, 2002) (providing a general overview of geographic information systems).

rence, potential detour routes, and even alternatives to improve traffic routing and alleviate rush hour stress. The same base map also may be reused to show, for example, changes in traffic patterns across time.

B. *Remote Sensing Satellites*

United States Government Remote Sensing Programs

The United Statesbegan the current phase of Earth observation from space with the launch of the first Landsat satellite (ERTS-1/Landsat-1) in 1972.[22] Currently, the United Stateshas ten Earth-observing satellites in orbit.[23] Three of these are NOAA satellites (NOAA-J, NOAA-K, and NOAA-L) that comprise the NOAA Polar Operational Environmental System (POES). These NOAA satellites all carry the Advanced Very High Resolution Radiometer (AVHRR) sensor that is used for measuring vegetation densities, crop yields, ocean temperatures, forest fire danger zones, and snow cover.

The other seven are NASA satellites: Landsat 5, Landsat 7, Terra, Tropical Rainfall Measuring Mission (TRMM), Earth Probe - TOMS, Quick Scatterometer (QuikScat) and Earth Observing-1 (EO-1).[24] Landsat 7 is used for general Earth observations including forestry, crop monitoring, land cover, land use, and watersheds.[25] It carries the Enhanced Thematic Mapper Plus (ETM+), which boasts improved data collection capabilities from previous Landsat missions.[26] Terra differs from Landsat in that it is dedicated to observing process more than land features. Terra carries five different sensors, each having unique applications, ranging from land temperature and snow/glacier cover measurements (ASTER), to cloud cover and radiant energy (CERES), to pollution measurements (MOPITT), to aero-

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22. Ed Sheffner, *Welcome to the Landsat Program*, California State University, Monterey Bay, *at* http://geo.arc.nasa.gov/sge/landsat/landsat.html (last modified Oct. 5, 1999).

23. University of Wisconsin Environmental Remote Sensing Center (ESRC), *Earth Observation Satellites: Current*, [hereinafter *Current EOS*], *at* http://www.ersc.wisc.edu/resources/ERSC.html (last visited Feb. 18, 2002). S*ee Earth Observation Satellites: Future, at* http://www.ersc.wisc.edu/ resources/EOSF.html (last visited Feb. 18, 2002) (providing information about future satellite systems).

24. *See* NASA GODDARD SPACE FLIGHT CENTER, EOS DATA PRODUCTS HANDBOOK VOL. 2 (Claire Parkinson & Reynold Greenstone eds., 2000.) [hereinafter EOS VOL. 2] 16-18, *available at* http://eospso.gsfc.nasa.gov/eospso_homepage.html (last visited Feb. 18, 2002).

25. *Id*. at 38.

26. *Id*.

sol and smoke plume imaging (MISR), to ocean productivity and temperature ranges (MODIS).[27]

The five sensors carried on the TRMM satellite are all committed to record tropical and subtropical atmospheric parameters such as rainfall, lightning, and cloud cover.[28] The TOMS sensor carried on the Earth Probe craft observes rates of ozone depletion, daily UV exposure, UV-absorbing aerosols and data on dust, smoke, and ash in the troposphere.[29] The SeaWinds sensor carried on QuikScat uses specialized radar to measure near-surface wind speed and direction.[30]

International Remote Sensing Programs

International efforts have pioneered the development of active remote sensing satellites. Canadian Space Agency's RADARSAT-1[31] and the European Space Agency's Remote Sensing satellites (ERS-1 and -2)[32] carry radar sensors that emit and record microwave signals, permitting observations independent of weather or daylight conditions.

France, India, Russia, Japan, and the China-Brazil team all operate successful passive satellite programs. France controls the Systeme Pour l'Observation de la Terre (SPOT), which is comprised of satellites SPOT 1, SPOT 2, and SPOT 4. The payload of the SPOT satellites consists of two high-resolution-visible (HRVIR) sensors that can operate in either panchromatic[33] (SPOT pan) or multispectral (SPOT xs) modes with a resolution of 10-20 meters depending on the mode. SPOT has many applications, including land use, water resources research, coastal monitoring, crop production, and deforestation. SPOT-4 also carries a wide-angle (2000 km) system referred to as VEGETATION that will be used for international crop monitoring.[34]

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27. *See* Michael D. King & David D. Herring, *Monitoring the Earth's Vital Signs*, SCI. AM. Apr. 2000, at 92, 95-97 (providing an excellent introduction to Terra's sensors). Author's note: the applications described in this article do not represent the sensors' full range of capabilities.

28. EOS VOL. 1, *supra* note 13 at 17-37.

29. *See generally* Scott Green, *Total Ozone Mapping Spectrometer (TOMS),* NASA, *at* http://toms.gsfc.nasa.gov (last visited Feb. 18, 2002) (providing information, data, and images from the TOMS instruments).

30. EOS VOL. 2, *supra* note 24 at 18.

31. Canadian Space Agency, *Introduction to RADARSAT, at* http://www.space.gc.ca/csa_sectors/earth_environment/radarsat/radarsat_info/default.asp (last modified Jan. 17, 2002).

32. European Space Agency, *Earth Observation Missions, at* http://earth.esa.int (last revised Apr. 26, 2002).

33. Author's note: a panchromatic sensor produces black and white images only.

34. *See generally* Spot Image, *The VEGETATION Users Guide*, *at* http://www.spotimage.fr/data/images/vege/vegetat/book_1/e_frame.htm (last visited Apr. 27, 2002).

The Indian Space Research Organization (ISRO) currently operates four Earth-observing satellites; the most recently launched (IRS-P4/Ocenasat) focuses on oceanic research.[35] Other Earth-observing systems (EOS) include Russia's Resurs-O1 series, Japan's ADEOS system, and the CBERS satellite that is operated jointly by China and Brazil.[36]

Commercial Satellite Systems

The U.S. government has encouraged the development of independent commercial satellites[37] and many U.S. companies have designed and launched their own satellites. Orbital Imaging Corporation (ORBIMAGE) and Space Imaging, Inc.[38] both have successful satellites in orbit that carry high-resolution sensors. ORBIMAGE[39] operates two satellites. The first, OrbView-1, is designed to monitor atmosphere. The second, OrbView-2 (SeaStar), carries a sensor called SeaWiFS (Sea-viewing Wide Field-of-view Sensor) that was developed in conjunction with NASA.[40] SeaWiFS is designed to monitor ocean temperature and productivity. Space Imaging operates one satellite, IKONOS,[41] which boasts 1-meter resolution capabilities in the panchromatic (black and white) range and 4-meter resolution in the multispectral range. IKONOS has applications ranging from imaging coral reefs to aiding highway planning.

C. *Remote Sensing Applications*

The potential applications of these satellite sensors are vast. This section briefly describes some of the possible environmental applications, focusing on environmental enforcement, land use planning, forestry, agriculture, water resources, fisheries, wetlands, watersheds, climate change, and disaster management.

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35. *Programmes: Indian National Satellite System,* Indian Space Research Organisation, *at* http://www.isro.org/programmes.htm (last visited Apr. 27, 2002).

36. *Current EOS, supra* note 23.

37. YAHYA A. DEHQANZADA & ANN M. FLORINI, SECRETS FOR SALE: HOW COMMERCIAL SATELLITE IMAGERY WILL CHANGE THE WORLD 18 (2000).

38. Space Imaging, Inc., *Overview*, *at* http://www.spaceimaging.com/aboutus/overview2.htm (last visited Apr. 27, 2002).

39. Orbital Imaging Corporation (ORBIMAGE), *ORBIMAGE Low Resolution Imagery from Orbview-2, at* http://www.orbimage.com/prods/orbview_2.html (last visited Feb. 22, 2002).

40. NASA, *An Overview of SeaWIFS and the SeaStar Spacecraft, at* http://seawifs.gsfc.nasa.gov/SEAWIFS.html (last visited Feb. 22, 2002).

41. Space Imaging, Inc., *IKONOS, at* http://www.spaceimaging.com/aboutus/satellites/IKONOS/ikonos.html (last visited Feb. 23, 2002).

Environmental Enforcement

The U.S. Environmental Protection Agency (EPA) [42] conducts four types of satellite and aerial remote sensing projects to support the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, also known as the Superfund Act), the Resource Conservation and Recovery Act (RCRA), and in other EPA regulatory programs and investigations.[43] The projects are: (1) emergency response to hazardous material release that requires rapid site assessment; (2) single-date analysis to update old data on the current conditions of the site; (3) intensive site analysis of current and historic images, to obtain an understanding of changing conditions over time; and (4) waste site inventories over large areas to locate possible disposal sites.[44] Images from these projects can standalone or be used in conjunction with topographic maps,[45] digital elevation data, and other features stored in GIS databases.[46]

Further use of remote sensing (both satellite and aerial photography) as a tool in environmental forensics is discussed in a two-part paper by Brilis, *et al*.[47] The paper outlines the general approach to be followed when planning the use of remote sensing in environmental forensics.[48] The accuracy of locational data and the use of metadata are identified as two critical items to ensure that a final image can withstand veracity issues when used for courtroom presentation.[49]

Recently, interest has developed in using satellites to monitor and enforce multilateral environmental agreements (MEAs), such as

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42. Author's note: the EPA's National Exposure Research Laboratory (NERL) is headquartered in the Research Triangle Park in North Carolina. It is one of the three national laboratories that conducts research for the EPA's Office of Research and Development. The NERL conducts research that leads to improved methods to predict human and ecosystem exposure to harmful pollutants**.**

43. U.S. ENVIRONMENTAL PROTECTION AGENCY (EPA), REMOTE SENSING PROGRAM FOR EPA: FY 2000 PROGRAM SUMMARY, 2 (2001).

44. *Id.* (discussing all four of the listed project types).

45. Author's note: a topographic map is one that displays elevation and landform information, usually in the form of contour lines.

46. EPA, *supra* note 43 at 2.

47. *See generally* George Brilis et al., *Remote Sensing Tools Assist in Environmental Forensics, Part I: Traditional Methods*, 1 J. ENVTL. FORENSICS 63, 63-67 (2000), *and* George Brilis et al., *Remote Sensing Tools Assist in Environmental Forensics, Part II: Digital Methods,* 2 J. ENVTL. FORENSICS 223, 223-29 (2001) (providing an overview of the use of aerial photography, topographic mapping, and photgrammetry in environmental enforcement actions), *available at* http://www.academicpress.com/envforens.

48. *Id*.

49. *Id*.

the Kyoto Protocol.[50] Remote sensing data may be used in the future to ensure compliance with MEA requirements by both direct enforcement and by more indirect means, such as deterring noncompliance through high levels of transparency.[51]

Land Use Planning and Change

Passive sensors, including those on the NOAA-AVHRR, IKONOS, Landsat, and SPOT satellites, are used in a broad range of forest and land use applications. These applications include estimations of primary production, biomass, crop yields, and to chart vegetation type, deforestation, desertification, forest boundaries, forest harvest, soil erosion, and bush or forest fires. Landsat 7's EMT+ sensor is especially useful in studying land use change because its data has been archived since the first Landsat mission in 1972. Passive sensors have also been used to observe and monitor changes associated with storm, flood, and fire damage.

Forestry

Forestry applications for passive remote sensors include tree species surveys, monitoring clear cut operations, planning and observing burn areas, and studying successional forest growth.[52] The U.S. Forest Service (USFS) relies primarily on the data from Landsats 5 & 7 for forest monitoring because of the low cost and large scene size. Landsat data is particularly applicable to forest change monitoring because data from previous Landsat missions is archived and available for accurate comparison with data from the current Landsat mission.[53] The

50. *See generally* Socioeconomic Data and Applications Center, *Remote Sensing and Environmental Treaties: Building More Effective Linkages*, *Report of a Workshop* (Dec. 4-5, 2000), Center for Int'l Earth Science Info Network (CIESIN), *at* http://www.ciesin.org/publications.html (last visited Mar. 15, 2002).

51. *See generally* Karen Kline & Kal Raustiala, *International Environmental Agreements and Remote Sensing Technologies,* Workshop on Remote Sensing and Environmental Treaties: Building More Effective Linkages, Dec. 4-5, 2000, *at* http://www.ciesin.org/publications.html (last visited Apr. 3, 2002) (discussing potential beneficial uses of remote sensing technology in relation to multilateral environmental agreements).

52. *See* Canadian Centre For Remote Sensing, *Fundamentals of Remote Sensing Tutorial, at* http://www.ccrs.nrcan.gc.ca/ccrs/eduref/tutorial/tutore.html (last modified Nov. 6, 2001).

53. Author's note: one of the most important features of Landsat is its Data Continuity Mission. Archived Landsat data from MSS and TM can be accurately used with current Landsat ETM+ data because the data has been calibrated to ensure that the earlier data represents the same values as the current data.

USFS also uses SPOT data in conjunction with Landsat data to increase the level of detail in sensitive areas.[54]

Active sensors, carried on the RADARSAT and ERS satellites, are capable of making course scale distinctions between cover types such as late successional forests, newly planted forests, clear cut forests, burn areas, agricultural areas, and deserts. Active sensors are valuable tools for monitoring crop regulation compliance, forest clearing, and for taking general inventories of world forest densities.

Agriculture

The United States Department of Agriculture (USDA) is conducting research to determine the potential uses of remote sensing (both aerial and satellite) in the agricultural sector. Promising applications include measuring leaf area indices (LAI - a quantitative indicator of leaf stress), identifying soil properties by their spectral signals, evaluating crop productivity, and providing a valuable data source for crop simulation models.[55] A high-tech type of farming known as "precision agriculture," uses satellite data to characterize specific sections of a field by certain variables (such as water or nutrient levels). Once the characteristics and geographic coordinates of the field section are in a computer, additions such as water, pesticides, and fertilizers can be efficiently controlled in response to the specific needs of each section thereby reducing the amount of pollutants introduced to the environment while producing healthier crops.[56]

Water Resources and Fisheries

SeaWiFS is designed to monitor oceans and track water indicators such as turbidity, sediment load and transport, primary production by marine phytoplankton, algal blooms, chlorophyll content, dissolved oxygen, and pH.[57] Other applications include managing coral reefs, monitoring pollution and oil spills, and characterizing and monitoring short-term and long-term fish habitat. Terra's MODIS and AVHRR sensors record observations of sea surface temperature,

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54. HENRY LACHOWSKI, GUIDELINES FOR THE USE OF DIGITAL IMAGERY FOR VEGETATION MAPPING (USDA Report OEM-7140-24, 1995).

55. *U.S. Water Conservation Research Laboratory: Remote Sensing Research Program,* U.S. Dept. of Agric., *at* http://www.uswcl.ars.ag.gov/EPD/remsen/rsmiss.htm (last visited Mar. 25, 2002).

56. TADLOCK COWAN, *Precision Agriculture: A Primer*, Congressional Research Service Report RS20515 (2000), *at* http://www.cnie.org/NLE/CRSreports/Agriculture/ag-97.cfm (last visited Mar. 25, 2002).

57. Gene Carl Feldman, *SeaWiFS Project Homepage, at* http://seawifs.gsfc.nasa.gov/SEAWIFS.html (last visited Mar. 25, 2002).

which is directly relevant to fisheries due to individual species' temperature requirements for survival and propagation. The sensor may also help predict migration routes.[58] Active sensing technologies are capable of measuring sea level, wave height, surface wind speed, current fronts, eddies, and surface temperature, as well as locating ocean floor features such as trenches and seamounts. Active sensors have also been used to track oil spills, effluent discharges, and algal blooms.

Wetlands and Watersheds

Wetlands monitoring may employ a combination of land-observation and ocean-observation satellites. ETM+ data can be used to delineate wetland areas, make topographical observations, and to detect illegal development.[59] Active systems can provide consistent and accurate observations of dynamic wetland parameters such as tidal and seasonal patterns, climate, hydrology, topography, vegetation, and soil type.[60] Satellite data and images can also be used to delineate the flow of water through watersheds, and can even be used to track pollutants. Furthermore, using algal productivity as an indicator, scientists are able to monitor whether high levels of nutrients pollute areas of a watershed.[61]

Climate Change

In the past decade, various ozone-monitoring sensors have been launched to study global climate cycles. These include the TOMS sensor and many of the sensors on Terra and future EOS satellites. AVHRR data from NOAA's POES satellites is used in conjunction with RADARSAT to monitor the polar ice sheets and iceberg movements. The EOS satellites, beginning with the Terra, were designed specifically for monitoring climate conditions, including the observation of aerosols, cloud cover, fires, ocean productivity, pollution, solar radiation, sea ice, and snow cover.[62]

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58. *See* Timothy Gubbels et al., *Putting NASA's Earth Science to Work*, 1 J. ENVTL. FORENSICS 17 (2000).

59. Elijah Ramsey, *Using Remote Sensing to Monitor Global Change,* National Wetlands Research Center Fact Sheet June 1997, *at* http://www.nwrc.usgs.gov/climate/fa96_97.pdf (last visited Mar. 25, 2002).

60. *Id.*

61. David Sandalow, *Remote Sensing and Foreign Policy*, Remarks at the Symposium on Viewing the Earth: The Role of Satellite Earth Observations and Global Monitoring in International Affairs (June 6, 2000), *at* http://www.gwu.edu/~spi/vtespeech.html (last visited Mar. 25, 2002).

62. *See* King & Herring, *supra* note 27 at 92-97.

Disaster Management and Emergency Response

Remote sensing technologies can provide the government with the ability to avoid much of the damage caused by unforeseen natural disasters. While weather satellites have monitored hurricanes and tornados since the 1960s, other satellite sensors, such as ETM+ and MODIS, have potential applications for disaster management and response. Scientists have used ETM+ data to monitor patterns in floods, droughts, beach erosion, and volcanic activity over time. MODIS and ASTER data can forecast severe weather with a great degree of reliability, potentially saving states millions of dollars in unnecessary evacuation and emergency response.[63] For forest fire emergencies, TOMS data can identify and monitor the occurrence of forest fires, especially in remote areas,[64] while AVHRR data can create maps denoting fire-susceptible areas.[65] NOAA-POES and NOAA-GOES (Geostationary Operational Environmental Satellite[66]) are used to make weather observations including predicting local weather, tracking weather in real time globally and locally, understanding and predicting hurricanes and other severe weather, studying phenomena such as El Niño, La Niña, the Gulf Stream and other global current patterns, and observing the dynamics between the land temperature, ocean processes, and the atmosphere.

D. *The Remote Sensing Market*

History of Commercial Remote Sensing

The commercial satellite remote sensing market was initiated in 1972, around the time that the launch of the first Landsat mission (then referred to as ERTS-1) was being discussed. The success of commercial weather and communications satellites led the U. S. to believe that a land-observing satellite would eventually be able to pay for itself as private markets for the data grew. While the commer-

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63. W. Campbell, Comments at the ELIS Workshop, NASA Applied Information Branch (Jan. 26, 2001) (proceedings on file with author).

64. Patrick Barry, *Watching Wildfires from Space, at* http://www.spacescience.com/headlines/y2000/ast04aug_1m.htm?list (last visited Mar. 25, 2002).

65. Gubbels, *supra* note 58, at 14.

66. Author's note: a geostationary satellite is one that is always in the same position (appears stationary) with respect to the rotating Earth. Yoram Kaufman, *Earth Observatory Glossary*, NASA, *at* http://earthobservatory.nasa.gov/Library/glossary.php3 (last visited Mar. 25, 2002).

cialization of Landsat has not been viewed as a success,[67] it paved the way for the growth of the data distribution and value-added product industry sectors.

Private companies launching satellites can profit both as data collectors, and as intermediaries between raw data providers and the ultimate consumers. However, few private companies have launched successful Earth observation satellites. Between 1993 and 2000, following the passage of the 1992 Land Remote Sensing Commercialization Act, NOAA issued only seventeen licenses for private commercial satellites.[68] Of the first four companies to launch private satellites, the two successes have been Space Imaging, Inc. and Orbital Imaging Corp. (OrbImage).[69]

Associated Geospatial Technologies

Image-based GIS and photogrammetry[70] comprised 69% of the geospatial activities market in 2000, with mapping, civil government, environmental, transportation, and national/global security markets controlling the highest percentage of sales.[71] The market leader, Environmental Systems Research Institute (ESRI), controlled nearly $300 million of the $845 million total worldwide GIS software market

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67. Author's note: the first Landsat Act was enacted in 1984. Land Remote-Sensing Commercialization Act, 98 Stat. 451 (1984) (authorizing the commercialization of the U.S. remote sensing program) (current version *at* 15 U.S.C. § 5601). In 1985, EOSAT was awarded the contract for marketing and distribution of Landsat data. Due to various complications and delays in policy and science, the commercialization of Landsat was not a great success, and control was returned to the government. *See* Land Remote-Sensing Commercialization Act, 9106 Stat. 4163 (1992) (returning control of Landsat to the U.S. government) (current version *at* 15 U.S.C. § 5601). NASA and the Department of Defense assumed responsibility of Landsat-7, with data archive responsibility falling to the USGS. COMMITTEE ON EARTH STUDIES OF THE NATIONAL RESEARCH COUNCIL SPACE STUDIES BOARD, EARTH OBSERVATIONS FROM SPACE 114 (1995).

68. Timothy Stryker, National Oceanic and Atmospheric Administration (NOAA), *Licensing of Commercial Remote Sensing Satellite Systems*, *at* http://www.licensing.noaa.gov/list.htm (last visited Apr. 3, 2002).

69. Author's note: the other two companies, WorldView Inc/EarthWatch (with the satellite Earlybird) and EOSAT (with Landsat 6), both failed because the satellites did not launch successfully.

70. Author's note: photogrammetry is defined as the science and technology of obtaining reliable measurements, maps, digital elevation models, and other GIS data primarily from aerial and space photography. *See Career Brochure*, American Society for Photogrammetry and Remote Sensing (ASPRS), *at* http://www.asprs.org/career/career_frame.html (last visited Apr. 3, 2002).

71. NASA-ASPRS, *10-Year Industry Forecast*, *at* http://www.asprs.org/asprs/news/forecast.html (last modified Mar. 19, 2002).

in 1999.[72] ESRI products provide a broad variety of applications to industries ranging from telecommunications and engineering to humanitarian assistance and environmental conservation.[73] Intergraph holds the second largest market share, $238.7 million, of the total industry software market.[74] Intergraph is the industry leader in providing GIS services and products to the utilities and telecommunications sectors, and is also an industry leader in public safety, transportation, and mapping sectors.[75]

Due to the significance of the GIS market, commercial satellite companies such as Space Imaging and OrbImage have formed business relationships with GIS providers, predominantly ESRI. These two growing industries have both been aided by advances in the integration of remote sensing imagery and geographic information systems. Satellite data and images provide geospatially-referenced data for inclusion into GIS layers and can be used to create digital elevation models or other applications for GIS.

> ESRI's software can ingest, enhance, and classify IKONOS imagery and utilize it just like any other data layer in a GIS analysis. The imagery can serve as an incredibly detailed basemap upon which other layers are laid, or it can be used as an up-to-date data source from which various land cover and elevation features are extracted to populate multiple GIS layers.[76]

The ASPRS/NASA Ten-Year Industry Forecast

Currently, NASA and the American Society for Photogrammetry & Remote Sensing (ASPRS) are conducting a 10-year market survey of the remote sensing industry as defined by the "Space Act Agreement" between NASA and ASPRS.[77] In the first phase of the

72. Daratech, Inc., ESRI, *Geographic Information Systems Markets and Opportunities 2000*, *at* http://spatialnews.geocomm.com/dailynews/2000/may/02/esri2.html (last visited Mar., 15, 2002).

73. ESRI, *Industry/Specialty Solutions*, *at* http://www.esri.com/industries.html (last modified Apr. 27, 2002). ESRI sells "scaleable" software called ArcGIS, which is available for a range of user needs. Intergraph sells Intergraph Mapping and Information Systems (IMSI) software, which is specialized by application.

74. Shelley Miller, *Intergraph Continues its Leadership in the GIS Worldwide Market*, *at* http://www.intergraph.com/press00/daratech_rlsf.asp (last visited Mar. 15, 2002).

75. *Id.*

76. Brian Soliday, *Successful IKONOS Launch Offers New Source of GIS Data*, ESRI, *at* http://www.esri.com/news/arcnews/spring00articles/successful-ikonos.html (last visited Apr. 3, 2002).

77. Author's note: signed in Aug., 1999, the *Domestic Nonreimbursable Space Act Agreement Between National Aeronautics And Space Administration John C. Stennis Space Center And American Society For Photogrammetry & Remote Sensing For Development Of A Remote Sensing Industry Forecast* ("the Space Act Agreement") joins ASPRS' and NASA's Commer-

study, the team determined the baseline forecast of the U.S. Remote Sensing Industry (RSI) and associated geospatial activities.[78] Four key findings emerged from the first phase of the study: (1) The U.S. Remote Sensing Industry in 2000 was valued at $2.2 billion[79] and is expected to grow at an average of 10-15% per year over the next five years, 2010;[80] (2) Currently the photogrammetry market is the largest Geospatial Market in terms of sales. Research and development for remote sensing, however, is considerably larger than that for photogrammetry or image-based GIS; (3) Across all three sectors,[81] the most active commercial markets are mapping/geography, environment, civil government, national/global security, and transportation. Environmental applications were rated one of the top four applications in all three sectors; and (4) For the government sector, mapping, earth natural science research, and natural resource management were found to be the three most important missions.

Obstacles to Industry Growth

Numerous obstacles block the full realization of the remote sensing market. The Carnegie Endowment for International Peace identifies four critical factors that will ultimately decide the size of the market: the extent of government interference, the cost of commercial imagery, the time the data takes to reach the consumer, and the ability of the market to educate and interest consumers.[82] Workshops have further addressed the problems related to acceptance of remote sensing technologies.[83] Issues ranging from a lack of access to stan-

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cial Remote Sensing Programs (CRSP) to determine the current baseline of and develop a 10-year forecast for the remote sensing industry. Space Act Agreement, *available at* http://www.asprs.org/asprs/news/archive/ASPRS_SAA_FINAL.doc (last visited Apr. 27, 2002).

78. Author's note: the study defines the business segments of the remote sensing industry as: Data Collection, Data Processing, Intermediaries (consultants, value-added products, etc), and Support Elements (hardware, software, etc). It also defines "remotely-sensed data" as information obtained from aircraft or spacecraft. Associated geospatial activities include image-based GIS and photogrammetry.

79. Author's note: this estimation is the result of a survey of commercial firms engaged in any business segment of the Remote Sensing Industry.

80. Author's note: projected growth percentages forecasted by Industry CFOs and CEOs.

81. Author's note: the applicable sectors were remote sensing, image-based GIS, and photogrammetry.

82. DEHQANZADA & FLORINI, *supra* note 37, at 19-22.

83. Author's note: examples of such work include Environmental Legal Information Systems' (ELIS) *A View from Space: Digital Earth Applications in Environmental Law and Resource Management Workshop* held Jan. 2001 and the Center for International Earth Science Information Network's (CIESIN) *Remote Sensing and Environmental Treaties: Building More Effective Linkages* held Dec. 2000 *available at* http://www.ciesin.org/publications.html (last visited Mar., 15, 2002).

dardizing data sets to "disconnects" between data providers and data users have been recognized, but not yet solved.[84] However, one of the most pivotal obstacles, which must be overcome before others can be addressed, is that of acceptance of satellite data in a courtroom.

III. ERROR AND UNCERTAINTY

Introduction

Section I revealed the potential satellite remote sensing and GIS technologies hold in legally mandated decisions regarding the environment. This section details the technical processes that move information from raw data to a usable product, and highlights the potential for error in each of these processes. As the information is passed through the information chain, it may be lost, distorted, or mishandled, thereby increasing the likelihood that a court will exclude it from evidence in a legal proceeding.

A. *Satellite Data Error*

Remote sensing information flow is a complex process involving five phases: (1) pre-launch calibration, (2) data ingest (collection), (3) digital image processing, (4) storage and archiving, and (5) retrieval and application.[85] Satellite data must be transformed from newly-collected petabytes of binary code, to calibrated data occupying terabytes of storage area, to gigabytes that are usable for modeling and observational systems, to megabytes that can be used in daily applications.[86] Potential for error exists in all of these transformations, but NASA and other satellite developers are continually creating and improving calibration tools to reduce amount of potential error. For most satellites, data handbooks exist that detail collection and calibration procedures.

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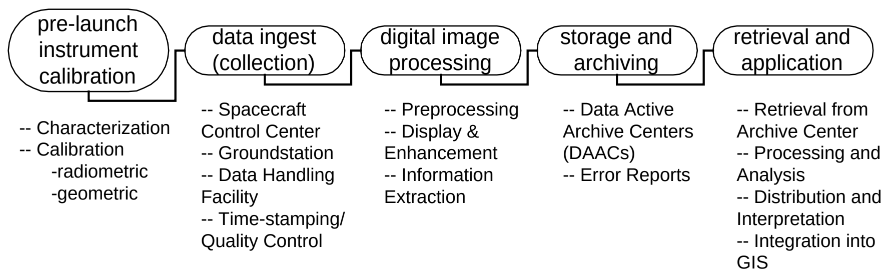
84. *See generally* Socioeconomic Data and Applications Center's (SEDAC) Center for International Earth Science Information Network (CIESIN), *Remote Sensing and Environmental Treaties: Building More Effective Linkages: Report of a Workshop*, *at* http://sedac.ciesin. columbia.edu/rs-treaties/rs_treaties.pdf (last visited Apr. 27, 2002).

85. *See generally* NASA, *Landsat 7 Science Data Users Handbook: Chapter 8*, *at* http:// ltpwww.gsfc.nasa.gov/IAS/handbook/handbook_htmls/chapter8/chapter8.html (last visited Mar. 15, 2002).

86. W. Campbell, *supra* note 63.

Figure 1: Satellite Remote Sensing Data Information Flow Chart



Created by ELIS. Information adapted from Jenson's 1996 Introductory Digital Image Processing: A Remote Sensing Perspective and from the "Landsat 7 Science Data Users Handbook," 2001.

Pre-launch

During the pre-launch correction process, scientists characterize and calibrate all satellite sensors to ensure accuracy. First they 'characterize' the instruments, a process that involves performing a set of operations to quantitatively express the instrument's response to the conditions experienced in orbit.[87] Then they calibrate the sensor radiometrically (with respect to the electromagnetic spectrum) and geometrically, both pre-launch and repeatedly while in orbit, to reduce error resulting from sensor failure and space "noise."[88] The launch of Landsat 7 introduced in a new generation of calibration strategies to bring its radiometric accuracy within a ± 5% uncertainty over the five-year life of the mission.[89] All of the EOS satellites, including Terra, will also have onboard calibration instruments that will be monitored independently, and with respect to one another, throughout the fifteen-year mission.[90]

87. Richard Irish, *Landsat 7 Science Data Users Handbook 2001*, *at* http://ltpwww.gsfc.nasa.gov/IAS/handbook/handbook_htmls/chapter8/chapter8.html (last visited Mar. 15, 2002).

88. EOS, *EOS Calibration Program*, *at* http://eospso.gsfc.nasa.gov/calibration/calpage.html (last visited Apr. 27, 2002). Space noise refers to any random disturbance that obscures the clarity of a signal.

89. Irish, *supra* note 87. Landsat 7 has three onboard calibration devices that are regularly tested against known stable energy sources. *Id.*

90. NASA, *The EOS Data Calibration Strategy*, *at* http://terra.nasa.gov/Brochure/Sect_6-1.html (last visited Apr. 27, 2002).

Data Ingest (Collection)

To minimize error in receiving the data, satellites have counterpart ground systems (ingest systems) that receive, calibrate, and store the same data. The Landsat ground system, for example, includes ground stations for uplinking commands and receiving data, a spacecraft control center, and a data handling facility.[91] Once the data is received by the ingest system, it is time-stamped and undergoes extensive quality and statistical sampling. Monitors located in control centers constantly observe the data for anomalies; Calibration software corrects incoming data and flags questionable data.

Digital Image Processing

Once the digital pixels are obtained, they must undergo a three-step process to generate a meaningful product: (1) preprocessing, (2) display and enhancement, and (3) information extraction.[92] Preprocessing generally involves a first round of corrections that eliminate error caused by sensors and by environmental factors. Preprocessing also corrects the image geographically, so that the data corresponds to the representative point on Earth. Information enhancement adjusts pixels either individually or simultaneously to change the magnification, filtering, and textures of the image. Information extraction involves interpreting the pixels into recognizable patterns using primary colors. The enhancement processes are carefully controlled. Recently, scientists have employed both "expert systems," in which the computer draws from a stored database of human knowledge to determine the best depiction of the data, and "neural networks," in which the computer is 'taught' what decisions to make interpreting the data.[93]

Storage and Archiving

The ground systems that receive and process data may also be used to store data. Both raw data and processed imagery is usually stored in duplicate to protect against loss. In the U.S., NASA has es-

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91. Yoram Kaufman, *Landsat Ground System Fact Sheet*, *at* http://earthobservatory.nasa.gov/Library/Landsat/landsat4.html (last visited Apr. 3, 2002). For more technical specifications of the Landsat ground system *see Landsat 7 Science Data Users Handbook: Chapter 4*, NASA, *at* http://ltpwww.gsfc.nasa.gov/IAS/handbook/handbook_htmls/chapter4/chapter4.html (last viewed Apr. 27, 2002).

92. John Jensen & Mark Jackson, *The Remote Sensing Process*: *Introductory Digital Image Processing*, *at* http://www.cla.sc.edu/geog/rslab/rsccnew/fmod1.html last visited Apr. 3, 2002).

93. *Id.*

tablished nine Data Active Archive Centers (DAACs).[94] Each DAAC focuses on a specific scientific discipline and is responsible for processing, archiving, and distributing data from the Earth-observing satellite missions, including Landsat, Terra and future EOS missions, and SeaWiFS. Each DAAC also provides a full range of user support and data access.

Retrieval and Application

Consistent with the 'scientific method,' a scientist states the problem encountered, determines a hypothesis, and then locates data to support or dispute the hypothesis.[95] Since NASA launches its satellites with particular research goals in mind, scientists hoping to use the satellite data for other purposes may find themselves working backwards, trying to identify a question that the data supports. While data may be used for purposes other than the original mission, decisions must be carefully made to ensure that other applications are legitimate. For example, the limitations of each sensor must be weighed against the potential application.[96] Satellite providers such as SPOT and IKONOS are taking advantage of the interest in commercial satellite applications by providing features such as global coverage, pointable sensors, spatial resolution ranging from 1 to 10 meters, and high spectral resolution.

Once the data has been processed and the correct application has been determined, the data must be transformed to match the needs of the scientist or other end-user. This transformation may include further algorithmic analyses, finer definition of the spatial resolution, or overlaying images with other accumulated information. It may also include data-distribution and interpretation. Each of these calculations and functions has the potential to introduce error.

Since errors are inherent in the method of GIS data collection, further error may also arise when the remote sensing data and images are integrated with the spatial data contained in a GIS. A brief discussion of GIS information error is set forth below.

94. Author's note: the nine DAACs are: Marshall Space Flight Center, Langley Research Center, Goddard Space Flight Center, Jet Propulsion Laboratory, The National Snow and Ice Data Center, EROS Data Center, Alaska SAR Facility, Oak Ridge National Laboratory and the Socioeconomic Data and Applications Center. *See* http://nasadaacs.eos.nasa.gov to access DAACs.

95. *Id.*

96. Campbell, *supra* note 63.

B. *Geographic Information Systems Error*

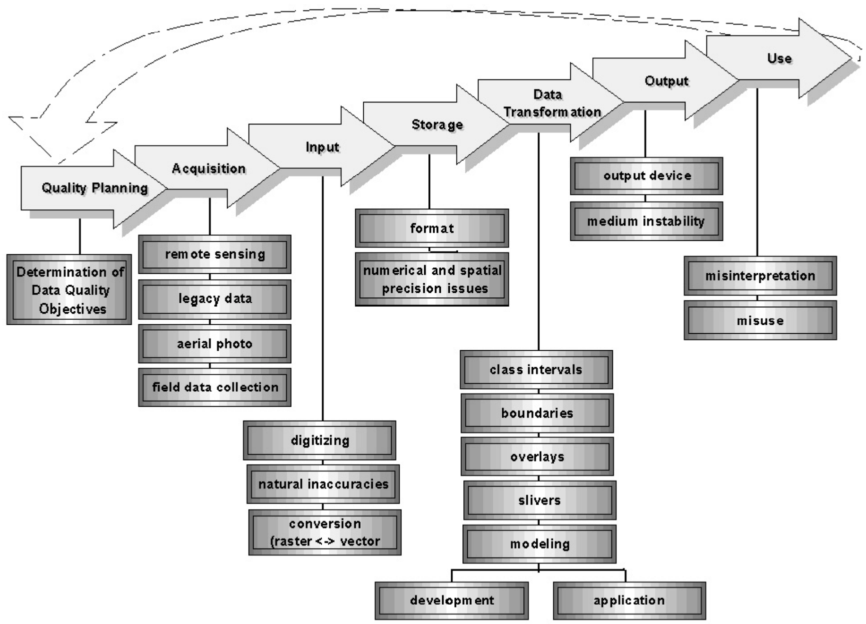
ESRI defines GIS as an organized collection of computer hardware, software, geographic data, and personnel designed to efficiently capture, store, update, manipulate, analyze, and display all forms of geographically referenced information.[97] This definition emphasizes the complex transformations that GIS data undergoes in moving from raw data to map layers. The six steps in the GIS process are acquisition, input, storage, data transformation, output, and use (see Figure 2). Error can occur in each of these steps and will then be compounded through the data information chain.[98] Furthermore, specific errors may result from integrating remotely-sensed data into a GIS, having considerable consequences on the reliability of the output data.[99]

97. ESRI, *GIS Glossary 2001*, *at* http://www.esri.com/library/glossary/glossary.html (last visited Mar. 25, 2002).

98. Jennifer L. Phillips, *Information Liability: The Possible Chilling Effect of Tort Claims Against Producers of Geographic Information Systems Data*, 26 FLA. ST. U. L. REV. 743, 746-48 (1999).

99. *See* Ross Lunetta et al., *Remote Sensing and Geographic Information System Data Integration: Error Sources and Research Issues*, 57 PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING 677-687 (1991) (offering a complete analysis of errors in the integration remotely-sensed data with geographic information systems).

Figure 2: Geospatial Information Lifecycle and Sources of Error



George M. Brilis, U.S. Environmental Protection Agency (EPA)

Acquisition

Data for GIS is collected from many sources, including field observations, old maps, and remotely-sensed data. Error occurs in the data collection process in many ways, including when existing erroneous maps are used as source data, when *in situ* data is incorrectly collected or recorded, or when remotely-sensed data is poorly analyzed or already contains error.

Input

Errors can be introduced during the data input process by inaccuracies in digitizing due to human operator error or equipment malfunction. Inaccuracies may also be inherent in the geographic feature (e.g., forest boundaries do not occur as sharp edges, although they may be depicted in such a manner). If the data is run through an algorithm or is converted between raster-format and vector-format incorrectly, further errors may occur.

GIS data that is collected and referenced using a Global Positioning System (GPS) receiver is subject to error in the GPS satellites. Currently, an average GPS receiver has an "autonomous accuracy" range of ± 5-10 meters depending on the sensor quality, the environment in which the recording was taken, and the latitude at which the recording was taken.[100] The errors affecting a receiver with autonomous accuracy are: distortions of the signal by the atmosphere, distortions of the signal by ground interference, error caused by gravitational pull, timing errors from the atomic clocks aboard the satellites, and basic geometric error with respect to the receiver.[101] Scientists using a receiver with Differential GPS (DGPS) capabilities can have real-time accuracies in the ± 1-5 meter range, and even to sub-meter and sub-centimeter accuracy, depending on the quality of the receiver.[102]

Storage

Error in the data storage process can occur when the media of physical storage (e.g. disk, tape, ftp) has insufficient memory, or degrades over time. Furthermore, transfer from one format to another may result in errors or omissions.

Data Transformation

Once the data is in the GIS, it can be transformed into a variety of forms, including class intervals, boundaries, overlays, slivers, and modeling development and applications. Each transformation has the potential to introduce error.

Output and Use

To ensure the highest level of accuracy, parameters must be checked. These would include the collection date, the history of the data set, the proportion of the area covered by the available data, how well the chosen classification represents the data, and the amount and distribution of field measurements. The likelihood of data misinterpretation and misuse should also be taken into account. Human error may be introduced when data is reconfigured to a useable dataset, when it is manipulated by those producing the GIS, or when it is used to support professional modeling and analysis.[103]

100. E-mail from Andrew Harrington, Product Manager, Mapping and GIS Systems Division, Trimble Navigation, Ltd. to Meredith Reeves, Law and Technology Program Associate, Center for International Environmental Law (Aug 9, 2001) (on file with author).

101. Trimble Navigation Limited, *How GPS Works, at* http://www.trimble.com/gps/how.html (last visited Apr. 27, 2002).

102. Harrington, *supra* note 100.

103. Phillips, *supra* note 98, at 746-48.

IV. EVALUATING THE OBSTACLES OF INTRODUCING REMOTE SENSING DATA INTO THE COURTROOM

Introduction

This section evaluates evidentiary barriers to the acceptance of remote sensing data and other digital information in the courts. Section A applies pertinent legal tests to remote sensing data. The section identifies potential barriers to the demonstrative use of such information and to the admission of the data into evidence. Section B examines case law to show the actual treatment of remote sensing data in the courts; factors that were significant to the inclusion or exclusion of the data are identified. Section C examines a case involving DNA evidence to demonstrate how courts analyze novel scientific information. Finally, Section D provides recommendations to mitigate the evidentiary problems of remote sensing data.

A. *Applying the Legal Tests*

Several legal tests control the admission of remote sensing data into evidence. In federal courts, these tests are found in *Daubert v. Merrell Dow Pharmaceuticals, Inc.*,[104] the Federal Rules of Evidence (FRE), and the U.S. Constitution. In state courts, additional tests are found in state evidence statutes, and state constitutions.[105] Many state courts also apply tests articulated in *Daubert*[106] or *Frye v. United States*.[107]

Daubert, decided in 1993, is the most recent Supreme Court decision explicating criteria for admitting scientific evidence in federal courts.[108] For seventy years prior to *Daubert*, federal (and some state) courts applied the "general acceptance" test from *Frye*.[109] *Daubert*

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104. 509 U.S. 579 (1993) (stating the rule for admitting scientific evidence). *See* Kumho Tire Co. v. Carmichael, 526 U.S. 137 (1999) (extending *Daubert* to technical evidence). Courts might view remote sensing as scientific evidence, technical evidence, or something in between.

105. Ned Miltenberg, *Out of the Fire and Into the Fryeing Pan Or Back to the Future*, TRIAL 18, at 23 (Mar. 2001).

106. 509 U.S. 579.

107. *Frye v. United States*, 293 F. 1013 (D.C. Cir. 1923). Miltenberg, *supra* note 105, at 23 (stating that 23 states still apply the *Frye* test). *Daubert* is not binding on states because it interpreted a federal rule.

108. *Daubert*, 509 U.S. 579.

109. *Frye*, 293 F. at 1014 ("[W]hile courts will go a long way in admitting expert testimony deduced from a well-recognized scientific principle or discovery, the thing from which the deduction is made must be sufficiently established to have gained general acceptance in the particular field in which it belongs."). *See* Paul R. Rice, *A View From Space: Digital Earth Applications* (ELIS conference proceedings, on file with author).

overturned *Frye* at the federal level, holding that the FRE provided the primary test.[110] The *Daubert* court also provided guidelines for analyzing the admission of scientific evidence under the FRE, such as the "general acceptance" factor.[111] This Part first examines the admissibility of remote sensing data under *Daubert*, *Frye*, and the FRE. It then analyzes the data's admissibility under the U.S. Constitution.

1. *Daubert, Frye*, and the FRE

Due to the complex nature of remotely-sensed data, it is probable that the evidence will need to be elucidated via expert testimony. If such is the case, satisfying the *Daubert* standards for admission of expert witness testimony will be a necessity in cases that rely on remotely-sensed evidence.

Daubert held that expert witness testimony regarding scientific data or principles is only admissible under the FRE if the evidence is both relevant and reliable.[112] To determine relevance, the Court examined Rule 104(a) and Rule 702.[113] Rule 104(a) allows courts to inquire about the admissibility of evidence,[114] whereas Rule 702 discusses the role of expert witness testimony regarding scientific and technical information.[115] While experts should explain remote sensing data given the complex scientific and technical nature of the data,[116] the data can be admitted independently.[117] Under Rule 104(a), the *Daubert* Court determined that, to be admitted, scientific information must apply to the facts in issue.[118] And under Rule 702, the Court required that the evidence "assist the trier-of-fact to understand the evidence or to determine a fact in issue."[119] Remote sensing data can meet these 'relevance' criteria by relating to and helping to articulate the particular facts in issue.

Meeting the "reliability" element of the *Daubert* categorization is not so simple. Analyzing Rule 702, the *Daubert* Court found that sci-

110. *Daubert*, 509 U.S. at 586. Since *Daubert* interpreted a Federal Rule of Evidence, the holding is not binding on state courts. *See also* Miltenberg, *supra* note 105.

111. *Daubert.* at 593-95.

112. *Id*. at 589. *Daubert* focused on interpreting Rule 702.

113. *Id*. at 589, 592.

114. FED. R. EVID. 104(A).

115. FED. R. EVID. 702.

116. *See* Sharon Hatch Hodge, Comment, *Satellite Data and Environmental Law: Technology Ripe for Litigation*, 14 PACE ENVTL L. REV. 691, 718 (1997). The Federal Rules of Evidence relevant to experts include: FED. R. EVID. 702, 703, 704, and 705. *Id.* at 718 nn.177-81.

117. Hodge, *supra* note 116, at 717.

118. *Daubert*, 509 U.S. at 592-93.

119. *Id.* at 589.

entific validity establishes a standard of reliability.[120] To determine scientific validity (and hence, reliability), the Court suggested five criteria: (1) whether the information is derived by the scientific method, (2) whether the information has been subjected to peer review or publication, (3) whether the relevant scientific community "generally accepts" the information, (4) consideration of the actual or potential rate of error of the scientific technique, and (5) whether standards for controlling the technique's operation exist.[121] In creating guidelines for the admission of scientific evidence, the *Daubert* Court emphasized "principles and methodology, not the conclusions that they generate."[122] The Court envisioned a flexible inquiry, explicitly stating that many factors could control the admission of evidence and that its suggested criteria were not definitive.[123]

a. Application of the *Daubert* Reliability Criteria to Remote Sensing

Derivation by the Scientific Method

Brilis, *et al.*[124] have compared the *Daubert* criteria to EPA quality assurance and peer review policies and procedures, and applied them to an analytical chemistry scenario. Applying *Daubert's* five reliability criteria to remote sensing data, experts should first show that the data and its underlying principles resulted from the scientific method.[125] Remote sensing experts should therefore demonstrate that the theories behind their data, and any applications of those theories,

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120. *Id*. at 590 n.9.

121. *Id.* at 593-95.

122. *Id.* at 595.

123. *Id.* at 593.

124. George M. Brilis et al., *Quality Science in the Courtroom: U.S. EPA Data Quality and Peer Review Policies and Procedures Compared to the Daubert Factors*, 1 J. ENVTL FORENSICS 197, 200-02 (2000).

125. *Daubert,* 509 U.S. at 593. The Court cited several scholarly definitions for "scientific method," ('Scientific methodology today is based on generating hypotheses and testing them to see if they can be falsified; indeed, this methodology is what distinguishes science from other fields of human inquiry.' Michael D. Green, *Expert Witnesses and Sufficiency of Evidence in Toxic Substances Litigation: The Legacy of* Agent Orange *and Bendectin Litigation*, 86 NW. U. L. REV. 643, 645 (1992). *See also* Carl G. Hempel, Philosophy of Natural Science 49 (1966). ("The statements constituting a scientific explanation must be capable of empirical test"); Karl R. Popper, Conjectures and Refutations: The Growth of Scientific Knowledge 37 (5th ed. 1989) ("The criterion of the scientific status of a theory is its falsifiability, or refutability, or testability") (emphasis deleted)). *Id*. *See also* Webster's New World College Dictionary 1284 (4th ed. 1999) (defining 'scientific method' as "a method of research in which a hypothesis is tested by means of a carefully documented control experiment that can be repeated by any other researcher.").

were developed by generating hypotheses, testing them through experiments, and establishing conclusions. For example, experts could show how the technique by which satellite sensors recognize trees on the ground was derived through the scientific method: an area of an image is believed to be old growth forest, this belief is solidified based on comparisons of known areas of old growth forest from other similar imagery, and ground-truthing verifies that the suspected area was in fact old growth forest.

Peer Review and Publication

Experts should expect courts to inquire about peer review and publication of techniques and underlying theories of the remote sensing process. The *Daubert* Court found peer review and publication of scientific information helpful, but not correlative, in demonstrating reliability.[126] The Court reasoned that submission of theories or techniques to publications with subsequent peer review increased the probability of error detection.[127]

"General Acceptance": The Frye Test

The *Daubert* Court also reaffirmed that the general acceptance of a technique or theory by the relevant scientific community (formerly set out as the standard in *Frye*)[128] could be a significant factor in admitting evidence.[129] If few scientists support a theory, *Daubert* cautions courts to view the evidence skeptically.[130] Proving "general acceptance" would, of course, be crucial in the 23 states where *Frye* controls.[131] Consequently, experts should attempt to establish the broad acceptance of remote sensing techniques and theories. Citations in scientific journals that have published favorable papers on the subject,[132] scientists supporting the techniques or theories,[133] and secondary legal authority such as law review articles can facilitate this es-

126. *Daubert*, 509 U.S. at 593.

127. *Id.* at 594.

128. *Frye*, 293 F. at 1014.

129. *Daubert*, 509 U.S. at 594.

130. *Id.*

131. *See* MILTENBERG, *supra* note 105, at 23. *See, e.g.,* People v. Venegas, 954 P.2d 525 (Cal. 1998) (interpreting the *Frye* test regarding DNA evidence).

132. *See* State v. Copeland, 922 P.2d 1304, 1312 (Wash. 1996) (declining to abandon the *Frye* test in favor of *Daubert* where novel scientific evidence is concerned); People v. Soto, 981 P.2d 958, 962-63 (Cal. 1999) (holding that published scientific commentary and national judicial authority weigh in favor of courtroom use of the unmodified produce rule in DNA forensic analysis).

133. *Soto*, 981 P.2d at 960.

tablishment.[134] Even if a court finds that remote sensing data has received minimal support from the scientific community, *Daubert* mandates the consideration of many factors and places the focus on methods, not conclusions.[135] *Daubert* encourages courts to admit new scientific information that is theoretically sound, though tested to a lesser degree than more widely accepted methods.

Potential for Error

The fourth *Daubert* criterion for assessing reliability is an evaluation of the scientific evidence's potential for error.[136] As described in the preceding section, potential for error exists in each step of the remote sensing process: data acquisition, input, storage, transformation, output, and use.[137] Courts, for instance, may consider flaws from incorrectly calibrated satellite instruments, inaccurate GIS digitization, spatial precision issues, distorted models, and data misinterpretation.[138] To avoid legal vulnerability, experts should describe procedures taken to minimize errors and explain to courts the trustworthiness of remote sensing data. Experts should also ensure that each step in the remote sensing process is clearly documented, particularly the image enhancement processes.[139] An error rate must also be accurately derived so that experts can demonstrate to the court that potential error was tracked and controlled. If the image's provider has not fully disclosed the image origin and error, experts should use the image with caution or discard it completely.[140]

As for potential data flaws, courts will consider "computer programming errors, equipment malfunction, data entry errors, and the

134. *See Copeland*, 922 P.2d at 1312.

135. *Daubert*, 509 at 593, 595.

136. *Id.* at 594.

137. *See* Figure 2.

138. *See supra* part III.A.

139. *See generally* A. J. Krouse *et al.*, *Satellite Imagery: The Space Odyssey in the Courtroom,* For the Defense: Defense Research Institute, *at* http://www.crowsey.com/spacearticle.htm (last viewed Apr. 3, 2002).

140. JULIE WARTELL & J. THOMAS MCEWAN, NAT'L INST. OF JUSTICE, PRIVACY IN THE INFORMATION AGE: A GUIDE FOR SHARING CRIME MAPS AND SPATIAL DATA, 11-14, 33 (2001). Created to be a GIS user guide for law enforcement agencies, this publication explains in detail the critical necessity of clearly documenting the information chain for GIS maps and developing standards for their use. *Id.* at 33. Disclaimers should be added to maps and spatial data released by law enforcement. *Id.* at 11-12. The attorney should look for these types of disclaimers when considering an image for use in trial and if the image provider does not give full disclosure of image error, one should approach its use with caution.

volume of electronic data."[141] Some courts, following older case law, will also require identification of the "computer program's original source, and procedures for input control including tests to assure accuracy and reliability."[142] Hence, remote sensing experts should expect courts to inquire about these factors, such as whether environmental conditions might have damaged equipment or if standard tests exist to test computer accuracy.

Standards

The final factor suggested by the *Daubert* Court in determining reliability was the consideration of the standards employed as controls on the technique.[143] When applying this factor to remote sensing evidence, courts might ask whether standards exist to calibrate satellite instruments, to store digital information, or to choose class intervals. To meet this factor, experts should demonstrate that the evidence satisfies qualified standards. If no standards currently exist, experts should form specific protocols that incorporate such standards in anticipation of legal challenges.

b. FRE Applicable to Remote Sensing

The *Daubert* standards reviewed above will only be applied to remotely-sensed data presented through expert testimony. Remote sensing evidence will be subject to several FRE, which are applicable whether or not an expert is called to testify. The implications of these rules for remote sensing evidence are considered individually below.

Relevancy, Authentication, and Foundation

Any evidence, scientific or otherwise, must be found relevant to the case, meaning that it must make a consequential fact more or less probable than would be deemed otherwise.[144] If used to aid witness testimony, the map must help the trier of fact understand the testimony.[145]

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141. Christine Sgarlata Chung and David J. Byer, *The Electronic Paper Trail: Evidentiary Obstacles to Discovery and Admission of Electronic Evidence*, 4 B.U. J. SCI & TECH. L. 5 para. 40 (1998) (citing MANUAL FOR COMPLEX LITIGATION, Section 21.446).

142. *Id.* at para. 41 (*quoting* United States v. Scholle, 553 F. 2d at 1125).

143. *Daubert*, 509 U.S. at 594.

144. *See* FED. R. EVID. 403. *See also* State of Connecticut v. Kirker, 707 A.2d 303, 306 (Conn. App. 1998) (inquiring into a map's relevance); State of Ohio v. Crawford, 1998 Ohio App. LEXIS 2603, 7 (finding a map to be relevant).

145. *Kirker*, 707 A.2d at 306.

Once evidence is found to be relevant, it must be authenticated.[146] Extrinsic authentication is necessary[147] unless the map fulfills one of the self-authentication exceptions listed in Rule 902 of the FRE.[148] A map published by the government, for instance, is self-authenticating under Rule 902(5).[149]

Finally, the evidence must have an adequate foundation; it must be accurate and reliable.[150] If accuracy cannot be confirmed, courts will not admit the evidence.[151]

Of these provisions, the main evidentiary hurdle for digital maps is reliability.[152] Courts will ask where the information in the map originated, how the information was transformed into digital form, and how the map itself was created.[153] Since computers create digital maps, the maps will face reliability challenges as computer evidence. Courts, for instance, will inquire into "computer programming errors, equipment malfunction, data entry errors, and the volume of electronic data."[154]

Courts will also closely consider the authenticity of digital maps, particularly where the map does not meet one of the aforementioned self-authentication exceptions.[155] As such, courts will follow Rule

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146. *See* FED R. EVID. 901(a) (requiring proof that the evidence is what its proponent claims it to be).

147. *See id*. *See also* State of Connecticut v. Wright, 752 A.2d 1147, 1156 (Conn. App. 2000) (map authenticated by GIS technician); *Crawford*, 1998 Ohio App. LEXIS 2603, 5 (finding that the expert authenticated the map).

148. *See* FED. R. EVID. 902 (containing 12 authentication exceptions, most of which could be relevant to maps depending on their creation and publication).

149. *See* FED R. EVID. 902(5) ("Official Publications. Books, pamphlets, or other publications purporting to be issued by public authority."). *See also* Bigger *ex rel.* Key v. Southern Railway Co., 820 F. Supp. 1409, 1414 (N.D. Ga. 1993) (finding that authenticity is not required with respect to official public documents under Rule 902(5) and holding that the Georgia DOT map met this exception).

150. *See* Zagaroli v. Pollock, 379 S.E.2d 653, 656 (N.C. App. 1989) (court found map admissible when map creator testified that it was accurate). *See also* T.R. Miller Mill Co. v. Ralls, 192 So. 2d 706, 714 (Ala. 1966) (a map is admissible when the surveyor is qualified and testifies to the map's accuracy).

151. Susman v. City of New Haven, 1995 Conn. Super. LEXIS 3363, 5; Swiney v. State Highway Department, 158 S.E.2d 321, 322 (Ga. App. 1967).

152. Chung & Byer, *supra* note 141, at para. 41 (stating that hearsay and reliability objections are obstacles to the admission of electronic data into evidence. *Id.* at para. 35.

153. *See Wright*, 752 A.2d at 1156-57 (GIS technician testified that he went to the actual locations depicted on the map, that he entered the data into a computer, and that the computer program used mathematical formulas to generate the map).

154. Chung & Byer, *supra* note 141, at para. 40 (citing MANUAL FOR COMPLEX LITIGATION (THIRD), § 21.446 (1995)).

155. *See* 40 C.F.R. § 136 (2000).

901(a),[156] requiring proof that the evidence is what its proponent claims it to be.[157] According to Rule 901(b)(9),[158] parties must prove that evidence encompassing a process or system, such as maps depicting remotely-sensed data, must produce an accurate result.[159] To satisfy these rules, the experts who collected the remotely-sensed data should describe how the process operates and their involvement.[160] Experts should also reference the data to ground information ('ground-truthing'), aerial photographs, and other maps.[161] Logs and records of the progression from collection to presentation of the data would also verify authenticity. Technologies including steganography[162] and cyclic redundant checksum[163] are continually being developed to assist in ensuring the authenticity of digital imagery.

Hearsay Issues

If a map, chart, or other media is admitted to make an assertion, the evidence may be objected to on hearsay grounds.[164] For example, remotely-sensed data could be used to create a map depicting high levels of pollution in a stream adjacent to the defendant's property. If the map is admitted to assert that the defendant caused such pollu-

156. FED. R. EVID. 901(a).

157. Hodge, *supra* note 116, at 719 . *But see* FED. R. EVID. 902(5), stating that maps issued by a public authority do not require expert authentication. *See* Biggers *ex. rel* Key, 829 F. Supp.at 1414-15 (denying plaintiff's motion to strike a state department of transportation map on grounds it is a "publication purporting to be issued by a public authority" under FED. R. EVID. 902(5)).

158. FED. R. EVID. 901(b)(9).

159. Hodge, *supra* note 116, at 717.

160. *Id.* at 719.

161. *Id.*

162. Author's note: detailed information about developments in steganography, which literally means 'covered writing,' is available at http://www.stegoarchive.com and at http://www.jjtc.com/stegdoc/sec101.html. Digital watermarking, discussed in detail at http://www.ee.princeton.edu/~minwu/ee580wmk_99.html is a type of steganography that can be used by the developers of GIS maps and remotely-sensed images as a hidden indication of authenticity.

163. Author's note: cyclic redundant checksum (CRC) is a technology that involves correlating a number to each change in the image so that there is a traceable chain of custody that defines the alterations made to a photograph or GIS map. CRC is a mathematical algorithm that is used to perform calculations of a set of data and produces a unique number that correlates to the data it processed. The number can then be used, for example, to check whether the data has been altered from the state it was in when the CRC was run (for additional information, *see* http://www.4d.com/acidoc/cmu/cmu79909.htm).

164. *See* FED. R. EVID. 801-803. Hearsay is defined as "a statement, other than one made by the declarant while testifying at the trial or hearing, offered in evidence to prove the truth of the matter asserted." FED. R. EVID. 801(c). If the evidence is used purely for demonstrative purposes, and not admitted to assert the truth of some supposition, it will not meet with a hearsay objection.

tion, it may meet with a hearsay objection. If the evidence is found to be hearsay, it will only be admissible if it can be categorized as an exception to the hearsay rules.[165] For example, Rules 803(6) and 803(8) will allow the admission of hearsay evidence that was generated by computer for use as a business or public record.[166]

Data Characterization

A final set of rules that may pertain to the use of remotely-sensed data involve the presentation of the evidence in the courtroom. Rule 1006 allows the admission of charts, summaries, and calculations that depict a body of data too voluminous to itself be admitted into evidence for practical reasons.[167] To avoid potential problems with admission under this rule, experts should testify that the data was correctly translated into these summary forms. If the evidence is admitted without the verification of expert testimony, Rule 1002 requires that the underlying data be admissible.[168] For example, if a chart includes data derived from satellite photos, courts or opposing attorneys could bar the admission of the chart if the original photos do not also meet the standards of admissibility.

2. Constitutional Hurdles

Besides *Daubert* and the FRE, the Constitution presents another obstacle that remote sensing data must overcome for admission into federal courts. The main constitutional issues facing remote sensing data are allegations of invasions of privacy and warrantless

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165. FED. R. EVID. 803 (outlining 23 exceptions to the prohibition on hearsay evidence).

166. Author's note: generally, if the evidence is created by businesses or public bodies in the regular course of their activities (as opposed to created specifically for the purpose of litigation), Rules 803(6) or 803(8), respectively, will allow admittance of the evidence. *See* Chung & Byer, *supra* note 141, at para. 35-39. *See also* United States v. Orozco, 590 F.2d 789, 793-94 (9th Cir. 1979) (finding that government computer records qualified as public records and thus survived hearsay objection by qualifying for public record hearsay exception). *But see* Wright, 752 A.2d at 1156-57. In *Wright*, which involved a computer generated map, the court did not mention hearsay objections. This result suggests that courts may not consider hearsay arguments regarding digital maps. *See also* United States v. Hayes, 861 F. 2d 1225, 1230 (10th Cir. 1988) (IRS computer records properly admitted under FED. R. EVID. 803(6)). In fact, courts could bypass a complex *Daubert* evidentiary analysis and admit remote sensing data under these rules. This avoidance, however, seems unlikely because remote sensing data encompasses more elements than computer evidence. But if a court considered the admission of remote sensing data under these rules, accuracy and reliability challenges should still be expected. *See* 5 JACK B. WEINSTEIN & MARGARET A. BERGER, WEINSTEIN'S FEDERAL EVIDENCE, § 803.13 (Joseph M. McLaughlin ed., 2d ed. 2001).

167. FED. R. EVID. 1006; Hodge, *supra* note 116, at 717.

168. *See* FED. R. EVID. 1002.

searches.[169] The Fourth Amendment states that "the right of the people to be secure in their persons, houses, papers, and effects, against unreasonable searches and seizures, shall not be violated."[170] Two Supreme Court cases, *Dow Chemical Co. v. United States*[171] and *Kyllo v. United States*,[172] address the application of the Constitution to remote sensing data.

In *Dow Chemical Co.*, the Court held that enhanced aerial photographs of an industrial facility taken by the EPA were admissible under the Fourth Amendment.[173] The Court found that though commercial areas receive constitutional privacy protection, this protection does not extend to the outdoor areas of industrial complexes.[174] The Court also found that homes and their outside areas receive a higher level of protection than commercial areas.[175] Still, in dicta the Court stated, "surveillance of private property by using highly sophisticated surveillance equipment not generally available to the public, such as satellite technology, might be constitutionally proscribed absent a warrant."[176] The Court feared that technology providing information not available to the naked eye would reveal intimate details, for example, imaging that could reveal actions occurring inside a building (e.g., conversations behind closed doors or people transporting documents).[177] Despite this concern, the Court noted that photos enhancing human vision were still admissible, provided that they do not reveal such intimate details.[178]

The Supreme Court's latest decision regarding remote sensing data's privacy and search issues is *Kyllo v. United States*.[179] *Kyllo* involved a police officer who used a thermal imaging device to detect heat emissions from a suspect's home.[180] Declaring this search unconstitutional, the Court held that when "the Government uses a device

169. Hodge, *supra* note 116, at 720. Hodge also states that "[o]ther possible areas of concern are violations of national security and industrial trade secrets," but she refutes these concerns. *Id.* at 721.

170. U.S. Const. Amend. IV.

171. Dow Chem. Co. v. United States, 476 U.S. 227 (1986).

172. Kyllo v. United States, 533 U.S. 27, (2001).

173. *Dow Chem.Co.*, 476 U.S. at 239.

174. *Id*. at 236.

175. *Id*. at 237 (citing Donovan v. Dewey, 452 U.S. 594, 598-99 (1981).

176. *Id.* at 238.

177. *Id.* at 239.

178. *Id.* at 238.

179. 533 U.S. 27 (2001).

180. *Id.*- The device was used to determine the possible presence of marijuana plants, which require intense heat lamps to grow indoors.

that is not in general public use, to explore details of the home that would previously have been unknowable without physical intrusion, the surveillance" is unconstitutional.[181] As in *Dow Chemical Co.*, the Court emphasized that homes receive a high level of privacy protection under the Constitution. The Court held that, in the home, "all details are intimate details," strongly indicating that any information obtained by remote sensing data from a home's interior without a warrant would be inadmissible.[182]

The Court did not define "general use" technology in either *Dow Chemical Co.* or *Kyllo*.[183] Lower courts are left to speculate on what level of use might rise to this standard. For example, remote sensors that track wetland deterioration might be deemed "general use" technology if they are routinely used by the government, or if the public accepted their use.[184] But if the device determined that someone illegally filled in a wetland in his or her backyard, that information could be inadmissible.[185] The main lesson that can clearly be drawn from *Dow Chemical Co.* and *Kyllo* is that, in the absence of a warrant, remote sensing data will only gain courtroom admission if it does not include intimate details of commercial activity or any details from private homes.

B. *Remote Sensing Case Law*

In addition to *Dow Chemical Co.* and *Kyllo*, many other cases involving remote sensing data exist. This section first describes cases where courts admitted remote sensing data without describing any analytical criteria used to judge its admissibility or value. The goal is to further illustrate the variety of cases involving remote sensing data. This section then examines cases where courts admitted remote sensing data, but actually discussed analytical factors in determining admissibility and value.

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181. *Id*. at 24.

182. *Id.* at 19.

183. *Id.* at 24; *Dow Chem. Co.*, 476 U.S. at 238.

184. *See* Elijah Ramsey, *Using Remote Sensing to Monitor Global Change*, National Wetlands Research Center Fact Sheet 1997, *at* http://www.nwrc.usgs.gov/climate/fs96_97.pdf (last visited Mar. 15, 2002).

185. Federal Water Pollution Control Act (CWA) § 404, 33 U.S.C. § 1344 (2001) (requiring permits for filling wetlands). *See* Oliver v. United States, 466 U.S. 170, 179 (1984) (holding that "an individual may not legitimately demand privacy for activities out of doors in fields, except in the area immediately surrounding the home").

1. Variety of Cases

Many cases exist in which courts admitted remote sensing data. Boundary dispute cases provide one category of examples. In *I&M Rail Link v. Northstar Navigation*, satellite photos were used to determine whether a barge accident occurred in Illinois or Iowa.[186] In *In re Vernon Sand & Gravel, Inc.*, aerial photographs were dispositive in settling a land acreage discrepancy.[187] Remotely-sensed photographs have also played a role in International Court of Justice boundary dispute cases (See Box 1).[188]

186. I&M Rail Link v. Northstar Navigation, 21 F. Supp. 2d 849, 855 (N.D. Ill. 1998).

187. *In re* Vernon Sand & Gravel, Inc., 93 B.R. 580, 583 (Bankr. N.D. Ohio 1988).

188. Frontier Dispute (Burkina Faso v. Republic of Mali), 1986 I.C.J. (Dec. 22) (satellite photos aided in border dispute); Kasikili/Sedudu Island (Namibia v. Botswana), 1999, I.C.J. (Dec. 13) (satellite and aerial photography used to determine boundaries).

Box 1: Satellite Data in International Courts

In 1996, Botswana and Namibia brought a boundary dispute before the United Nations International Court of Justice (ICJ), requesting that the Court determine:

> "on the basis of the Anglo-German Treaty of 1 July 1890 [an agreement between Great Britain and Germany respecting the spheres of influence of the two countries in Africa] and the rules and principles of international law, the boundary between Namibia and Botswana around Kasikili/Sedudu Island and the legal status of the island." [Article 1]

The uninhabited Kasikili Island (referred to as Sidudu Island in Namibia) is located in the Linyanti (Chobe in Namibia) River, which lies in the northeastern-most part of Botswana. The language of the 1890 Treaty stated that the center of the main channel of the Linyanti (Chobe) River formed the boundary between Botswana and Namibia.

The ICJ heard arguments to determine the specific location of the river's main channel, defined by parameters including depth and width of the channel, the rate of flow of the river, bed profile, and navigability. Namibia claimed that the main channel was one of the southern channels , while Botswana claimed it was a northern channel was the main one. Satellite images from the Landsat MSS and TM sensors taken in June 1975 and aerial photography taken between 1925 and 1985, along with other evidence, were used by experts to define the width and depth of the channels, leading to a conclusion that the northern channel waas the main channel.

In December 1999, the Court determined:

> (1) By eleven votes to four, that the boundary between the Republic of Botswana and the Republic of Namibia follows the line of deepest soundings in the northern channel of the Chobe River around Kasikili/Sedudu Island; and
> (2) By eleven votes to four, that Kasikili/Sedudu Island forms part of the territory of the Republic of Botswana; and
> (3) Unanimously, that the nationals and flag-bearing vessels of the Republics of Botswana and Nambia shall enjoy equal national treatment in the two channels around Kasikili/Sedudu Island.

Another category of remote sensing cases involves satellite weather data. In *Cobb v. United States*, the plaintiff claimed that a "freak" wave injured him when he was a guest on a Navy destroyer.[189] However, because satellite data indicated that no storms were in the area at that time, and because the officers and crew of the destroyer could not have reasonably foreseen the wave, the *Cobb* court ruled for the defendant.[190] In another military tort action involving weather, *Scruggs v. United States*, an F-16 military aircraft and the plaintiff's civilian plane almost collided in mid-air.[191] The plaintiff testified that a

189. Cobb v. United States, 471 F. Supp. 102, 103 (M.D. Fla. 1979).
190. *Id*. at 105-07.
191. Scruggs v. United States, 959 F. Supp. 1537, 1541 (S.D. Fla. 1997).

cloud prevented him from flying at a higher altitude.[192] The court ruled for the government because satellite data showed that the area was free of clouds.[193]

Environmental remote sensing cases comprise a third category. Based on satellite photos, the court in *Gasser v. United States* concluded that flooding had increased in the area of interest.[194] Further, the court "rejected the defendant's expert testimony in favor of the evidence provided by satellite photographs."[195] Satellite photos were also dispositive in *United States v. Reserve Mining Co.*[196] In this case, the plaintiffs used the photos to show widespread dispersion of tailings and upwelling phenomena throughout the water.[197] The *Reserve Mining* court ultimately found that the defendant's discharge violated the Clean Water Act.[198] Further, in *St. Martin v. Mobil Exploration & Producing U.S. Inc.*, the plaintiffs introduced aerial photographs to show the erosion of their marsh due to open ponds produced by the defendants.[199] Based partly on the photos and an expert witness who interpreted them, the court concluded that the defendants caused the land degradation.[200]

2. Critical Cases

As shown above, many decisions involving remote sensing data fail to discuss the data's admissibility or evidentiary value. Still, many decisions provide some indication of how courts will treat such data. This section analyzes several decisions and identifies factors (beyond the constitutional questions reached in *Dow Chemical Co.* and *Kyllo*) that courts have used to exclude, include, or evaluate the merits of remote sensing evidence.

A lack of expert testimony caused problems for remote sensing data in several cases. In *United States v. Kilgus*, the court did not admit data from a thermal imaging device, like the one used in *Kyllo*.[201] Problematic to the court was the customs officer's lack of training in

192. *Id*.
193. *Id*.
194. Gasser v. United States, 14 Cl. Ct. 476, 496 (1988).
195. Hodge, *supra* note 116, at 700 (analyzing *Gasser,* 14 Cl. Ct. at 496).
196. United States v. Reserve Mining Co., 380 F. Supp. 11 (D. Minn. 1974).
197. *Id.* at 39.
198. *Id*. at 77.
199. St. Martin v. Mobil Exploration & Producing U.S. Inc., 224 F.3d 402, 407 (5th Cir. 2000).
200. *Id*..
201. United States v. Kilgus, 571 F.2d 508 (9th Cir. 1978).

interpreting the device's data and in understanding its underlying theories.[202] Also crucial to the court's decision was that the device was commonly used for the generic identification of objects, not for the unique purposes which were subject in the case.[203] A lack of experts caused problems in *Velsicol Chemical Corp. v. State of New Jersey DEP*.[204] Although the *Velsicol* court admitted into evidence maps that were created by infrared aerial photography, the court refused to admit the report based on the maps without expert testimony to qualify their admission.[205] Hence, the lessons from *Kilgus* and *Velsicol* are: (1) provide training for the people that use the technology and (2) call expert witnesses to explain or authenticate remote sensing data.

In other cases, courts have been unwilling to equate remote sensing data with the testimony of actual witnesses. For example, the court in *West-Oviatt Lumber Co. v United States* admitted satellite photos into evidence, but the court found fault with the USFS failure to ground-truth information derived from the photo.[206] The court suggested that if the lack of ground verification had been the evidence's only flaw, the court may have been inclined to find for the defendant.[207] The lesson from *West-Oviatt Lumber Co.* is to ground-truth remote sensing information if possible. Perhaps as courts and society become familiar with remote sensing information and such technology becomes generally accepted, the importance of ground verification may diminish. For now however, ground-truthing and the accompanying eye witness verification play a critical role.

Many state courts also place significant weight on whether the evidence has gained "general acceptance" in the scientific community, also known as the *Frye* test.[208] As noted in Part A above, 23 states use *Frye* as the standard for admittance of scientific evidence.[209] For instance, in *State of Washington v. Hayden*, the defendant claimed that the trial court erroneously admitted digitally enhanced images of his fingerprints into evidence.[210] But because police departments had

202. *Id*. at 510.

203. *Id*.

204. Velsicol Chem. Corp. v. State of New Jersey D.E.P., 442 A.2d 1051 (N.J. 1982).

205. *Id*. at 1053.

206. West-Oviatt Lumber Co. v United States, 40 Fed. Cl. 557, 566 (1998).

207. *Id*.

208. *Frye v. United States*, 54 App. D.C. 46, 293 F. 1013 (D.C. Cir. 1923).

209. Miltenberg, *supra* note 105, at 23.

210. Washington v. Hayden, 950 P.2d 1024, 1025 (Wash. Ct. App. 1998).

been using this technology since 1987,[211] and because all experts agreed that the scientific community "generally accepted" this technology, the court allowed the evidence and upheld the defendant's conviction.[212]

Some federal courts also rely heavily on the "general acceptance" factor. The Court of Appeals for the Seventh Circuit in *Nutra Sweet Co. v. X-L Engineering Co.* evaluated the acceptability of the expert's technique for interpreting aerial photographs.[213] The court found the technique was "generally accepted" in the scientific community.[214] Crucial to the court's decision was the expert's testimony that interpreting aerial photographs is an accepted technique in the field, and that the EPA requires that its employees use this technique.[215] Based on the "general acceptance" element and the fact that the expert had extensive experience in the field, the court held that the evidence was reliable under *Daubert*.[216] Thus, it is crucial to the admittance of remote sensing data that the expert establish "general acceptance" by the scientific community.

C. *Illustrative Case of Novel Scientific Information*: United States v. Bonds[217]

Since remotely sensed data would be considered novel scientific evidence, demonstrating how courts treat other novel types of evidence is telling. In *United States v. Bonds*, the Sixth Circuit Court of Appeals evaluated a decision to admit DNA evidence,[218] which was considered novel scientific evidence at the time.[219]

Applying *Daubert's* "reliability" requirement, the Court first analyzed the "scientific testing" element.[220] The court stated, "[T]he theory behind matching DNA and calculating probabilities, and the

211. *Id*. at 1028.

212. *Id*.

213. Nutra Sweet Co. v. X-L Eng'g Co., 227 F.3d 776, 788 (7th Cir. 2000).

214. *Id*. at 789.

215. *Id*. at 788.

216. *Id*. at 789.

217. United States v. Bonds, 12 F.3d 540 (6th Cir. 1994).

218. *Id*. at 557. The lower magistrate court analyzed the evidence under the *Frye* standard because *Daubert* had not been decided at that time.

219. *Id.* at 550.

220. The Court also analyzed the *Daubert* "relevance" requirement. The Court found that the defendant's DNA matched "at least to some extent the DNA found in the crime scene sample." *Id.* According to the Court, this evidence was relevant to whether the defendant was present at the crime scene on the night of the murder. *Id*. The Court also noted that the evidence would help the jury determine the defendants' guilt. *Id*.

particular technique employed by the government lab can in fact be tested."[221] The court also found that the government tested its own methodologies through internal proficiency studies, validation studies, and environmental impact studies.[222] The court determined that these studies could be used to show whether the government lab produced reliable and reproducible results.[223]

Next, the court considered whether the government's DNA evidence had been peer-reviewed. The court found that many of the articles that the government introduced did not appear in peer-reviewed scientific journals.[224] But the court was satisfied because the articles introduced still revealed the government's theories and techniques to the scientific community and several had been peer-reviewed.[225]

In examining the potential rate of error, the *Bonds* court found that the government conducted "internal proficiency tests to determine an error rate."[226] The court found, however, that the government's calculation of the error rate was deficient, failing to conduct external blind proficiency tests or to provide specific references to the error rate.[227] But since *Daubert* held that the "reliability" criteria were non-exclusive, and since the scientific community "generally accepts" DNA evidence, the *Bonds* court gave lesser weight to the "error rate" factor.[228] The court also noted that since the scientific community "generally accepts" the evidence, it must accept the error rate as well.[229]

The *Bonds* court next held that the scientific community "generally accepted" the DNA evidence.[230] "General acceptance," according to the court, is "when a substantial portion of the pertinent scientific community accepts the theory, principles, and methodology underlying scientific testimony because they are grounded in valid scientific principles."[231] The court found that newness, lack of absolute certainty, and substantial criticism did not necessarily imply that

221. *Id*. at 558.
222. *Id*.
223. *Id*.
224. *Id*. at 559
225. *Id*.
226. *Id*. at 560.
227. *Id*.
228. *Id.*
229. *Id*. Throughout this discussion, the Court never stated the calculated error rate.
230. *Id.* at 565.
231. *Id.* at 561.

the information was inadmissible.[232] The court also found that both the theory underlying DNA profiling and the chosen methodology of DNA testing must be "generally accepted" to meet this *Daubert* element.[233]

After considering the *Daubert* reliability factors, the *Bonds* court examined other applicable Federal Rules of Evidence. The court first examined Rule 703, which considers the factual bases of expert data.[234] Persuaded by the government, the court found that the "government experts' testimony was based on facts and data reasonably relied upon by experts in molecular biology and population genetics."[235] The court next scrutinized the magistrate judge's use of Rule 706, which gives courts the choice to appoint their own expert witnesses.[236] The court found that the judge's appointment, reliance, and conclusions about the expert witness upheld the DNA's admissibility.[237] Finally, the court analyzed Rule 403.[238] Rule 403 mandates the exclusion of relevant evidence if its probative value is substantially outweighed by any unfair or prejudicial effects that it might have, such as misleading the jury or wasting time.[239] The court held that the government's DNA evidence complied with Rule 403 because it linked the defendant to the murder scene in the absence of more direct evidence.[240]

In conclusion, the *Bonds* court's application of *Daubert* to novel DNA evidence differed slightly from the straight legal application of *Daubert* to remote sensing evidence in Part A. The *Bonds* court did not examine whether standards for controlling the government's technique existed. Instead, it found that the "magistrate judge's findings underlying general acceptance encompass" these standards.[241] The *Bonds* court also placed a greater emphasis on the general acceptance factor[242] and analyzed some of the FRE, such as Rule 403.[243]

232. *Id*.

233. *Id*. at 562.

234. FED. R. EVID. 703.

235. *Bonds*, 12 F.3d at 566.

236. FED. R. EVID. 706.

237. *Bonds*, 12 F.3d at 567.

238. FED. R. EVID. 403.

239. *Id*.

240. *Bonds*, 12 F.3d at 567.

241. *Id*. at 560,567

242. *Id.* at 561. The Court wrote more about the "general acceptance" factor than the other factors, perhaps because the magistrate judge admitted the evidence under *Frye*.

243. *Id*. at 567.

Hence, attorneys and experts should prepare strongly for "general acceptance" inquiries and Federal Rule challenges.

D. *General Recommendations*

Throughout this paper, numerous suggestions are offered to scientists and lawyers in order to mitigate remote sensing data's evidentiary problems. This Part highlights some of those recommendations and adds several more.

First, scientists should establish and follow standards for applying remote sensing science. Showing compliance with general standards for instrument calibration, data storage, and data processing would help satisfy *Daubert* elements and further convince courts that the evidence is reliable. Even if standards for the entire remote sensing industry are not developed, scientific labs should develop their own standards and ensure that they can justify them in court.

Along with standards, scientists should continue to develop remote sensing techniques that minimize error and ensure accuracy. Scientists should continue to publish extensively on remote sensing science and devote more time to reviewing their peers' work. These suggestions would further persuade courts and the public that remote sensing evidence is reliable, while also helping to satisfy a *Daubert* element.

Experts should certainly strive to clearly explain remote sensing science once in the courtroom. Since judges decide whether to admit the evidence and often do not have science backgrounds, experts should explain the fundamentals of remote sensing science and reference the science to common knowledge.

A final suggestion is the creation of a Federal Evidence Advisory Panel to make rules for admitting remotely-sensed data as evidence. As shown above, judges currently make the rules by interpreting the FRE. But the FRE are vague, leaving judges much discretion. An advisory panel, composed of scientists, lawyers, judges, and policymakers, might help ensure reliability and elucidate the criteria necessary for admitting scientific evidence.

V. SOME THOUGHTS ON POTENTIAL APPLICATIONS FOR THE USE OF DIGITAL INFORMATION IN ENVIRONMENTAL MANAGEMENT

Environmental Legal Information Systems (ELIS), a cooperative venture funded by NASA,[244] is dedicated to creating a web-based education and action toolbox for increasing awareness of the ways that earth science data and environmental laws interrelate. A recent focus of ELIS has been to identify legally mandated decisions for which remote sensing and other digital technologies could create operational efficiencies and improved environmental protection results. This Part considers some possible applications of remote sensing information in creating efficiencies in environmental decision-making.

Emergency Response

Remote sensing and other digital technologies have the potential to play a critical role in preparation, response, assessment, and restitution for natural resource damage related to an oil spill. As required by the Oil Pollution Act of 1990 (OPA 90), the government agencies responding to an oil spill must protect public health, welfare, and the environment.[245] Furthermore, it is a legal responsibility of the government to assess the damage to natural resources resulting from a release of oil to environment.[246] Digital data can provide before, during, and after images of the oil spill areas, the locations of sensitive natural resources, coastline maps, and weather and tide patterns in the affected area.[247]

Environmental Assessment

Remote sensing and other digital technologies can respond to the needs of agencies conducting environmental assessments, particularly of large, remote areas or of coverage over a long time scale. Potential users include (1) U.S. Federal agencies, who are required to produce Environmental Impact Statements (EIS) for all major federal projects under the National Environmental Policy Act of 1969 (NEPA)[248] and

244. Author's note: ELIS is a cooperative agreement between NASA, the University of Maryland Baltimore County, the Center for International Environmental Law, the Universities Space Research Association, and the Law Library of Congress.

245. 33 U.S.C. §§ 2701-2761 (1994).

246. *Id.*

247. Author's note: for more information, refer to the ELIS Website for demonstration emergency response project, *at* http://athena.csee.umbc.edu:9080/ELIS.new/home.jsp.

248. Environmental Impact Statements (EIS) are required "on proposals for legislation and other major Federal actions significantly affecting the quality of the human environment." NEPA § 102(2)(c).

(2) the World Bank and other development banks who fund projects that require Environmental Assessments (EA). The World Bank requires that all new projects provide an assessment[249] of the environmental impacts of the proposed project and an analysis of viable alternative projects. Digital tools can be used to monitor the long-term progress and impact of the proposed projects, as well as assist in the analysis of alternative projects. Furthermore, remote sensing may provide for the long-term monitoring to check whether the predictive modeling in the EIS and EA were accurate. These long-term monitoring capabilities may lead to the development of laws with a system of punitive damages if actual damage deviates from the predicted impacts of a project.

V. Conclusion

A nearly infinite number of actualized and potential applications of remote sensing and digital technologies to environmental management exist, from watershed planning to emergency response to developing assessments of the impacts of climate policy on coastal zones. However, the evidentiary hurdles to the use of these technologies may depress their potential environmental and economic benefits. The court and the public's unfamiliarity with remote sensing, the cost of data and imagery, and the complex science and training necessary to analyze the data and imagery all have a deterrent effect on the use of GIS and remote sensing.

Clearly the use of digital technologies presents significant challenges to the courts in understanding how the information was derived, processed, and presented. Courts must weigh the probative value of the information against its potential to confuse. Despite the tremendous opportunity for technologies to perform tasks or make decisions, enabling more informed, cost-effective decisions, such technology is vulnerable to legal dispute due to issues of credibility, acceptability and other evidentiary hurdles. These difficulties impede

249. The World Bank. Operational Policy (OP) 4.01: Environmental Assessment. Jan., 1999. (OP 4.01 (1)). The Bank requires an environmental assessment (EA) of projects proposed for Bank financing to help ensure that they are environmentally sound and sustainable, and thus improve decision making. (OP 4.01 (2)). An EA evaluates a project's potential environmental risks and impacts in its area of influence, examines project alternatives, identifies ways of improving project selection, siting, planning, design, and implementation by preventing, minimizing, mitigating, or compensating for adverse environmental impacts and enhancing positive impacts, and includes the process of mitigating and managing adverse environmental impacts throughout project implementation. The Bank favors preventive measures over mitigation or compensatory measures, whenever feasible.

the integration of the technology into the routine operations performed by public and private environmental stewards.

Until scientists and attorneys can work together to develop protocols for general acceptance, courts will continue to be reluctant in considering the associated complex science and mathematical questions as would be necessary to assign evidentiary value to the information. A serious dialogue needs to occur between the scientific and legal communities, resulting in a set of principles or rules of evidence that govern how courts review remotely sensed and digital information. Once the rules of engagement are established and legal hurdles are cleared, businesses and governments will be much more likely to invest in these novel and useful technologies, incorporating them into regular operations.

A solid basis in good science continues to evolve and the establishment of procedures to guide the process from pre-launch calibration through collection through image processing through storage thought retrieval through application. These efforts will only succeed with investment by both the public and private interests. A true sign of acceptance will be seen in the way we do business regarding the environment, namely the creation of a virile, mature commercial remote sensing market.