# AmeriSat - Requirements Analysis for a Hyperspectral Land Remote Sensor Constellation for Energy Exploration

*Specifications for a Complete, Routine, and Operational Hyperspectral Geological Survey of the United States and Miscellaneous Regions at 1:24,000 as part of the USGS National Map*

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## Introduction

The physical and economic well being of the United States of America depends upon a stable and affordable supply of abundant energy. Energy security for the United State of America will continue to depend primarily on fossil and nuclear fuels for the next few decades at a minimum. Efficient and successful exploration for new sources of energy requires precise and consistent geological surveys. Despite years of global exploration activity, much of the world and indeed even the United States has *not* been geologically surveyed at a scale appropriate for energy exploration, environmental hazard analysis, environmental protection or land use planning.

## Need for a Precise U.S. Geological Survey at 1:24,000 as part of the USGS National Map and Gateway to the Earth

Energy exploration requires a precise, consistent and accessible U.S. Geological Survey at 1:24,000. For example, although the basic unit of geological analysis, the formation (a significant layer or body of rock), is defined as being mapable at a scale of 1:24,000, less than a tenth of the more than 55,000 1:24,000 scale USGS topographic quadrangles have ever been mapped geologically and these maps are inconsistent at best. This is especially ironic given that almost all other U.S. Geological Survey location data are available in the form of high-quality 1:24,000 scale quadrangles (Figure 1).

Energy exploration takes place on a scale of tens of meters, not kilometers and depends on precise moderate resolution spatial information to make certain that exploration roads are constructed safely and responsibly and so that seismic crews can negotiate proposed seismic lines with a minimum of environmental impact. Similarly, seismic shot points are surveyed to meter-scale precision and exploration wells costing upwards of $10 million each must be located precisely relative to geologic structure, land ownership, elevation and location. This is especially true in the case of directional drilling and detailed three-dimensional seismic surveys. Hard and soft rock mining operations require similar precision for sampling and successful recovery of ore and fossil fuels as well as the safety of the miners.

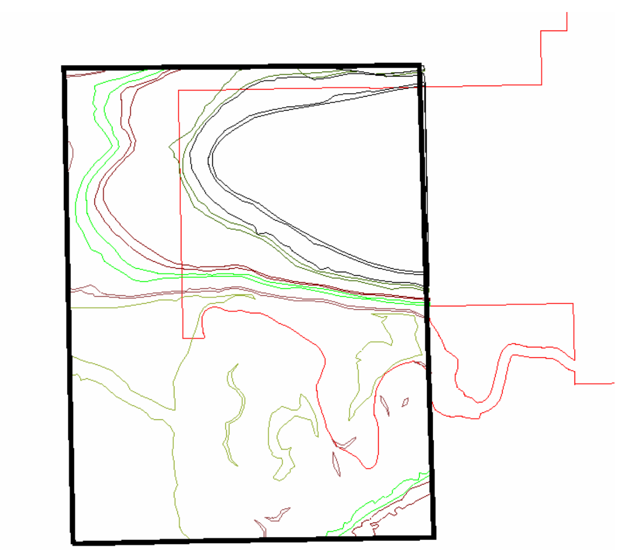

Figure 1. Simplified outline map derived from one of the few existing 1:24,000 U.S. Geological Survey geological quadrangle maps. Subsequent figures show this outline map superimposed upon Landsat, ASTER and AVIRIS imagery for comparison.

## Land Remote Sensor Comparison for the 1:24,000 U.S. Geological Survey

As part of the specification development process for a land remote sensing system for the 1:24,000 geological survey necessary for more efficient energy and mineral exploration, we compared the effectiveness of historical, current and proposed multispectral and hyperspectral imaging instruments capable of remotely sensing the visible, near-infrared, short-wave infrared, and thermal-infrared regions of the electromagnetic spectrum (Table 1). This spectral versatility is necessary to differentiate and to identify the geological formations to be surveyed in a semi-automated manner (Dwyer et al., 1995).

We chose a test site in an area known to produce petroleum, coal, oil shale and uranium. These were the same test site considerations identified by Bailey et al. (1984) in their comparison of the Landsat Multispectral scanner (MSS) and Thematic Mapper (T.M.) instruments flown on Landsats 1 through 5. Their results will not be repeated here although we have chosen the same primary test site on the western edge of Dinosaur National Monument to facilitate comparison of historical, current and proposed land remote sensing systems for geological surveys. We begin with an evaluation of the suitability of the Landsat satellites for geological surveys at 1:24,000 before considering two alternatives (ASTER and ALI/HYPERION) as prototypes for the next-generation of geological survey satellites. We then propose specifications for a new series of next generation land remote sensing satellites for the USGS named AmeriSat.

Table 1. Current satellites capable of remotely sensing the complete VIS/NIR/SWIR/MIR/TIR spectrum necessary for geological surveys.

| Spacecraft/Instrument | Landsat-7 / ETM+ | EO-1/ALI | EO-1/Hyperion (AVIRIS prototype used for this study) | Terra/ASTER | AmeriSat Constellation |
|---|---|---|---|---|---|
| | | | | | (ALI+ / Hyperion+) |
| | | | | | |
| Spectral Range | 0.4-2.4<br>10.7-12.7<br>microns | 0.4-2.4 microns | 0.4-2.5 microns | 0.5-0.9<br>1.6-2.4<br>8.1-11.7<br>microns | 0.4-2.5 microns |
| Panchromatic Bands | 1 | 1 | 0 | 0 | 1/1 |
| Visible Bands | 3 | 6 | 60 | 2 | 6/35 |
| Near Infrared Bands | 1 | 2 | 60 | 2 (stereo) | 3/35 |
| Short Wave Infrared | 1 | 1 | 60 | 1 | 1/172 |
| Middle Infrared Bands | 1 | 1 | 60 | 5 | 1 |
| Thermal Band | 1 | 0 | 0 | 5 | 1 |
| Spatial Resolution | 15, 30, 60 m | 10, 30 m | 30 m | 15, 30, 60 m | 30 m/15 m |
| Swath Width | 185 km | 37 km | 7.5 km | 60 km | 185/30 km |
| Spectral Coverage | Discrete | Discrete | Continuous | Discrete | Both |
| Pan Band Resolution | 15 m | 10 m | N/A | N/A | 10 m |
| Stereo | no | no | no | yes | yes |
| Number of Bands | 7 | 10 | 220 | 14 | 10 and 220 |
| Number of Spacecraft | 1 | 1 | 1 | 1 | 4-6 |
| Temporal Resolution | 16 days | 16 days | 16 days | 16 days | 4-8 days |
| | ( 8 days with Landsat-5) | | | | |
| | | | | | |
| Source: NASA EO-1 briefing materials | | | | | |

Summary of Current Satellites Capable of Remotely Sensing Visible/NIR/SWIR/MIR/TIR Electromagnetic Radiation (Satellites Good for Geologic Surveys)

Natural materials exhibit a very broad "rainbow" of "color". Only a very narrow slice of this rainbow is visible to human beings. A series of civilian (USGS/NASA) satellites has been designed to view an increasingly complete spectrum in steadily narrower slices of the "rainbow" known as bands and in steadily increasing spatial detail. Table 1 summarizes current satellites that are capable of remotely sensing throughout the visible (VIS), near infrared (NIR), short wave infrared (SWIR), Middle Infrared (MIR), and Thermal Infrared (TIR) part of the electromagnetic spectrum. These satellites are capable of seeing all of the parts of the electromagnetic spectrum necessary to differentiate geologic formations in the case of multispectral (less than 100 bands) satellites and even to identify the types of minerals in the geologic formations in the case of hyperspectral (generally greater than 100 bands spaced closely enough to create spectra from images) satellites.

These space-borne imaging instruments (or air-borne prototypes of very recent and proposed space-borne systems) were compared with each other as well as historical systems to gauge their effectiveness with regard to improving the efficiency of resource exploration and management at 1:24,000. As one might expect, this comparison demonstrated that improved spectral resolution (finer slices of the rainbow) and improved spatial resolution (the ability to see smaller objects) resulted in progressively more useful imagery for energy exploration.

Landsat MSS Series

The first series of geological survey satellites, the Landsat multispectral scanner (MSS) satellites were crude but provided regional imagery of some use in energy exploration (4 bands at 80 meter resolution). These satellites could miss whole football fields and yet they provided the first views of the earth from space for most geologists, researchers and the public. Research with these images did contribute greatly to the development of plate tectonic theory and suggested improvements for future satellites for resource exploration. Examples of MSS imagery over the Dinosaur Quarry Quadrangle test site used here are available in Bailey and Anderson (1982) and Bailey et al., (1982, 1984).

Landsat TM Series

The second series, the Landsat thematic mapper (TM) satellites, provided much more complete coverage of the spectrum and moderately useful spatial detail (5 and 1 bands at 30 and 120 meters respectively) (Figures 2 and 3). While this series could have been quite useful to regional resource exploration (e.g., Beck et al., 1995)

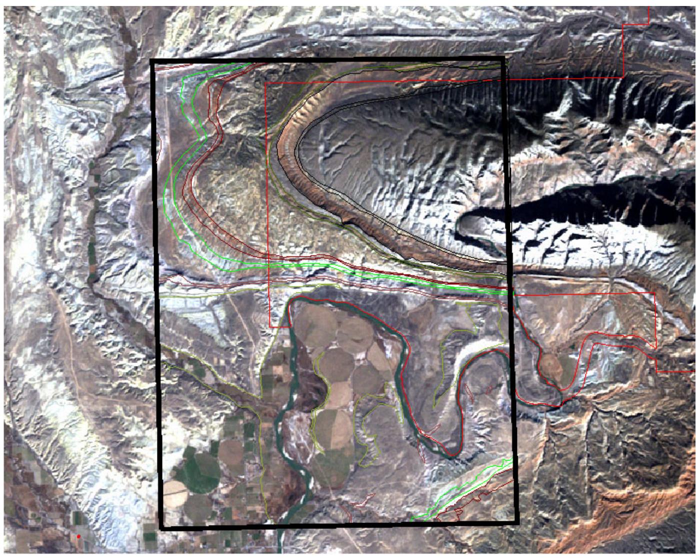

Figure 2. Simplified outline map derived from one of the few existing 1:24,000 U.S. Geological Survey geological quadrangle maps superimposed upon a Landsat-7 ETM+ visible image. The image quality is good but not sufficient for energy exploration.

Landsat ETM+ Series

Although the Landsat system is absolutely crucial with regard to maintaining the continuity of our record of global change and to support regional early warning systems with regard to food supplies, the rate of deforestation, outbreaks of plant diseases, drought, and land use change, its technology is more than two decades old and the 5 band, 30 meter multispectral data it produces are not sufficiently detailed for practical geological surveys at the 1:24,000 scale.

ASTER on TERRA

The advanced spaceborne thermal emission and reflection radiometer (ASTER) is a Japanese/U.S. instrument on a Japanese satellite that has many improvements over the U.S. Landsat ETM+ series of satellites but has several features that limit its use for energy exploration. While ASTER has a greater number of bands with greater radiometric sensitivity than Landsat, ASTER's bands do not have the same spatial resolution throughout the visible and infrared parts of the spectrum. This requires the geologist to artificially coarsen the visible bands or to artificially resample the infrared bands before statistical processing. Both processes result in fuzzy images (Figure 4) of dubious statistical validity.

*ASTER's (as well as Landsat's) spatial resolution is too coarse to be of extensive use in petroleum exploration (Figures 2, 3, and 4).* This is because most geological surveys are the starting point for subsurface seismic interpretation and the choice of locations for exploration wells. Petroleum geologists typically record the geologic formation at each shot point (small wells filled with lots of dynamite) along a seismic survey line in areas of good geologic exposure (where you can see the rocks at the surface). These shot points or VIBROSEIS stations (places where heavy trucks shake the ground) are typically spaced every 25 meters along a seismic line to create the artificial seismic waves later recorded by microphones.

The seismic wave arrival time patterns are interpreted with the aid of surface geology to tell geophysicists the type of rock and the expected speed of the seismic waves. They then use this time and speed information to calculate the depth of the various rock units and their structure beneath the ground surface with the help of powerful computers. Meanwhile, the geologists also collect samples to determine the likelihood of a source of petroleum, the likelihood of a porous and permeable reservoir, the likelihood of a seal to trap the petroleum beneath the surface, and measure the angle of the layers (if any) at the surface to provide a series of known starting points for subsurface interpretation. These data points are then used to locate the contacts between geologic units with a spatial precision of approximately 5 to 15 meters at a scale of 1:24,000.

Given the 25 meter spacing of seismic survey points and the need to locate geologic contacts with a precision of 5 to 15 meters at 1:24,000, *the ideal satellite for geological surveys would have a spatial resolution of at least 15 meters* (a four-fold increase in data density over 30 meter data) or finer. This requirement for 15 meter spatial precision means that the 30 and 60 meter spatial resolution of the short wave infrared and thermal bands of the ASTER instrument are too coarse for geological surveys of use to day-to-day petroleum exploration. Despite these limitations, some ASTER data will undoubtedly be used for regional exploration projects given the lack of more suitable alternatives.

The public domain ASTER data are interesting scientifically because of their ability to differentiate (but usually not identify) more rock types than Landsat-7. The ASTER data will have enormous educational and research value for many decades into the future.

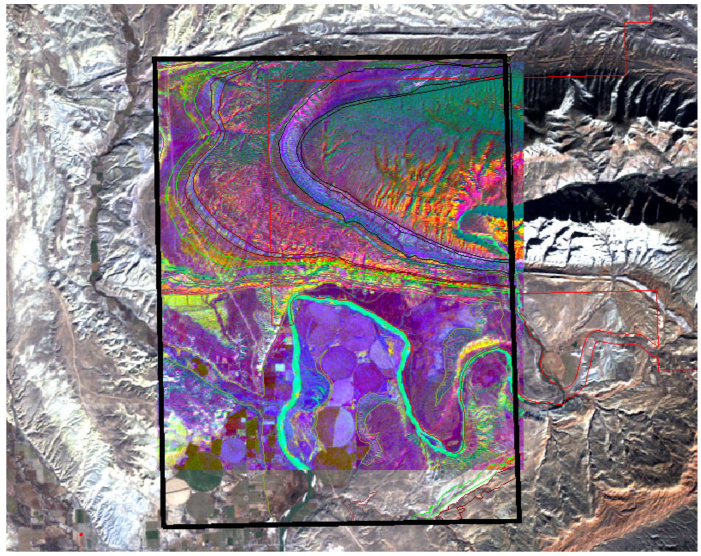

Figure 3. Simplified outline map derived from one of the few existing 1:24,000 U.S. Geological Survey geological quadrangle maps superimposed upon a Landsat-7 ETM+ principal components image. The image quality and differentiation of many of the geologic formations are fair to good but not sufficient for energy exploration. Several formations were missed by this 30 meter image.

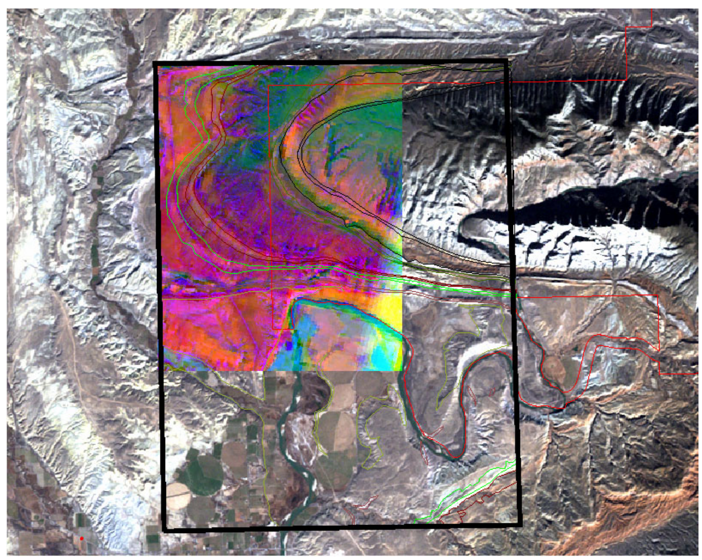

Figure 4. Simplified outline map derived from one of the few existing 1:24,000 U.S. Geological Survey geological quadrangle maps superimposed upon an ASTER principal components image. The image quality is poor because not all of ASTER's bands have the same spatial resolution. Its differentiation of the geologic formations is fair to good but far from sufficient for energy exploration. Many formations were missed by this 15/30 meter image.

<u>ALI on EO-1</u>

The Advanced Land Imager (ALI) on the Earth Observing (EO-1) satellite represents a new generation of technology designed to provide scientific continuity with the Landsat TM and ETM+ series of satellites. It promises to be more useful for regional geological surveys than Landsat ETM+ given the addition of four more 30 meter visible and near infrared bands and a 10 meter panchromatic band to assist with geometric registration. *The most valuable feature of ALI is that all of the multispectral bands have the same spatial resolution.* This is the ideal case for the statistical extraction of the maximum amount of spectral information. ALI does lack the thermal bands carried by the Landsat TM, Landsat ETM+ and ASTER satellites. Although the thermal band is of great value scientifically, it is rarely used in petroleum exploration.

Multiple thermal bands do have the ability to differentiate rock types however and at least one thermal band at the same resolution as the VIS, SWIR and MIR bands would be useful. ALI data for the Utah test site only recently became available. ALI is better than Landsat ETM+ and ASTER in terms of signal-to-noise ratio. It will be very useful for regional geologic reconnaissance but its 30 meter resolution is too coarse for 1:24,000 scale geological surveys. Similarly, *ALI's discrete spectral coverage (limited number of widely spaced bands) prevents the use of USGS-*

*developed automated mineral identification and mapping software* (http://speclab.cr.usgs.gov) to create the "first draft" of each quadrangle before field checking and refinement.

As will be shown below, hyperspectral 15 meter spatial resolution satellite image data, while not ideal for very detailed geological mapping, are a powerful tool that will usually be adequate for rapid geological surveys at the 1:24,000 scale (Figure 5). This spatial resolution represents a good compromise between our needs for economic/environmental security as well as defense/intelligence security.

Hyperion on EO-1 and its AVIRIS "Proxy"

Hyperion is a hyperspectral sensor that records a continuous series of 220 very narrow bands from the visible throughout the short wave infrared part of the electromagnetic spectrum (wavelengths of 0.4–2.5 microns). This is an extremely important feature for rapid semi-automated geological surveys for energy at 1:24,000 scale (Dwyer et al., 1995). This is because the USGS has developed software that compares the amount of "light" reflected from the earth's surface in each one of these bands to laboratory measurements of a wide variety of minerals (as well as plants). Each mineral has a unique signature that can be used to identify it from space (Clark, 1999; Clark and Rousch, 1984; Clark et al., 1993; Gaffey et al., 1993; Salisbury, 1993; Swayze et al., 2000).

The USGS software looks at each pixel in the image and its spectrum of "light" (Clark and Swayze, 1995; Dwyer et al., 1995). It then compares this spectrum of "light" with USGS digital libraries of mineral spectra to identify the minerals in each pixel before mapping them. These computer generated first drafts of geologic maps can then be field checked by geologists who examine the nature of the contacts between the geologic formations before completing the maps.

While actually identifying the minerals in each formation from the satellite is the optimum case, the large amount of spectral information recorded by hyperspectral instruments can be distilled statistically to differentiate rock types on the ground with extraordinary effectiveness far beyond that of the human eye. These distilled statistical images can be created within a few minutes on a modern laptop computer. The geologist then simply traverses each quadrangle and assigns an identity to each of the geologic formations imaged without having to follow every contact on foot.

Hyperion data for the test site have only recently become available. Therefore this study began with AVIRIS data as a proxy for Hyperion. A simple comparison of Hyperion vs. AVIRIS has been added to the end of this study accordingly. The conclusion is that AVIRIS was a reasonable proxy for Hyperion but that future hyperspectral satellites should be designed to imitate AVIRIS as much as possible given its higher spatial resolution and higher signal-to-noise ratio. An example of one of these statistically distilled hyperspectral images from AVIRIS recorded from an ER-2 aircraft (a forward principal components analysis) over the Utah test site is shown in Figure 5. The continuous spectral coverage and 20 meter spatial resolution of this early proxy for Hyperion demonstrates extraordinary improvement in the ability to differentiate (and identify) geologic formations.

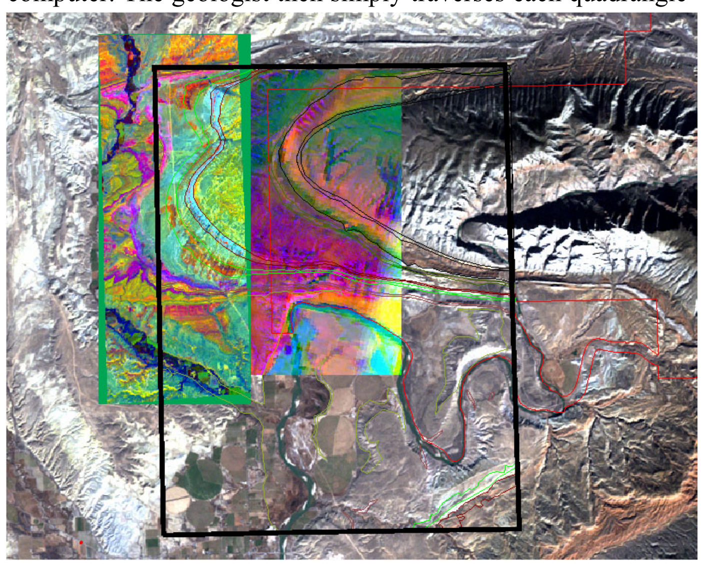

Figure 5. Simplified outline map derived from one of the few existing 1:24,000 U.S. Geological Survey geological quadrangle maps superimposed upon an AVIRIS hyperspectral principal components image. The image quality is good to excellent because all of the AVIRIS bands have the same spatial resolution. Its differentiation of the geologic formations is good to excellent. Nearly all of the geologic formations were found by this 20 meter spatial resolution image. The precision with which these formations and their boundaries are located is a little too coarse for petroleum exploration.

Experience with the 15 meter panchromatic band on Landsat-7 (most if its bands have 30 meter resolution) indicates that 15 meter resolution is necessary to confidently differentiate sampling sites at the 1:24,000 scale. As noted above in our discussion of energy exploration activities, 15 meters is probably the coarsest practical spatial resolution. To demonstrate this, we scanned one of the few (paper) 1:24,000 geological quadrangles available and, subsampled it to 15 meter spatial resolution before geometrically warping it to match our test satellite and aircraft imagery (Figure 6). As the reader can see, some of the detail has been lost but most of the key features are still visible.

The example shown in Figure 7 indicates that the current experimental Hyperion instrument must be upgraded to 15 meter spatial resolution for geological surveys useful to energy exploration. Our experience with 15 meter panchromatic data at 1:24,000 indicates that this is adequate and represents a four-fold (2 squared) increase in data density. All of these demonstration data were imported into an ArcView geographic information system to carefully verify the conclusions stated above (Figures 1–5).

Lithologic Identification vs. Discrimination - Utah "Whole Rock" spectral mapping with Hyperion and AVIRIS.
Hyperspectral data allow the identification as well as exceptional discrimination of even similar lithologies for geologic mapping for energy exploration.

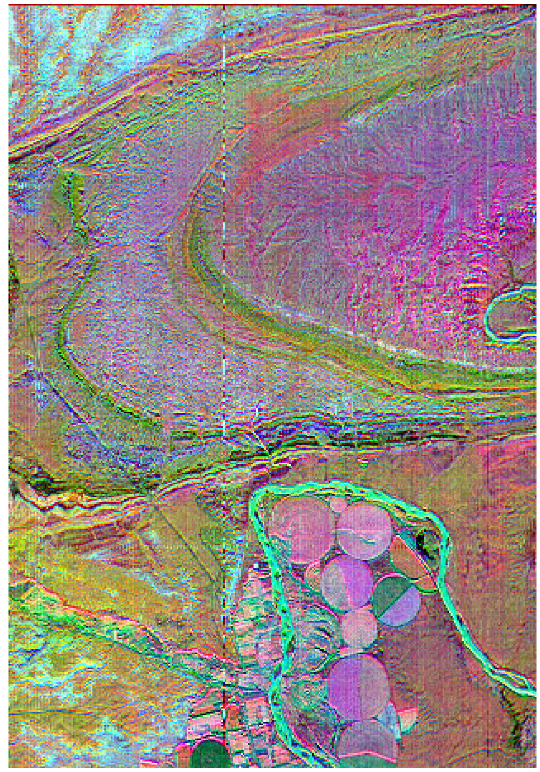

Figure 6. Advanced Land Imager (ALI) forward principal components of nine multispectral bands. The image differentiates most of the formations mapped by the USGS but does not allow for the direct spectral identification of lithology. Future systems would also benefit from higher spatial resolution on the order of 15 meters.

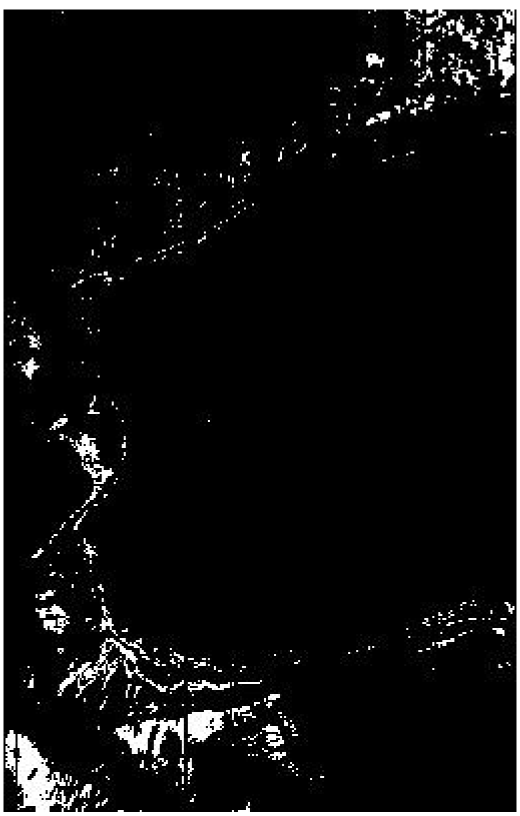

Figure 7 (left). Atmospherically corrected Hyperion spectral angle map (SAM) of the same area showing pixels similar to the whole rock spectrum shown in Figure 8.

The 160 bands result in a relatively complete spectrum for every pixel in the image above. Spectra measured in the field or in the laboratory from field samples (Figure 8) can then be compared to each pixel in the image across all of the bands to see if they are similar to a user defined similarity index such as a user defined spectral angle threshold. Pixels passing the similarity test are then shown as white pixels on an output image. The following image is a map of occurrences of pixels relatively similar to the field spectrum shown below.

Examples of similarly processed AVIRIS hyperspectral data for (nearly) the same area are shown below (Figure 9). The reader will see that the "whole rock" spectra (as opposed to spectra from spectral libraries of individual minerals) help make up for the relatively low signal-to-noise ratio and larger pixel size in Hyperion relative to AVIRIS.

Nonetheless, the higher spatial resolution and higher signal-to-noise ratio of AVIRIS allow the precise mapping of strata with outcrop widths on the order of a single pixel with amazing continuity as in the spectral angle mapper result in Figure 9.

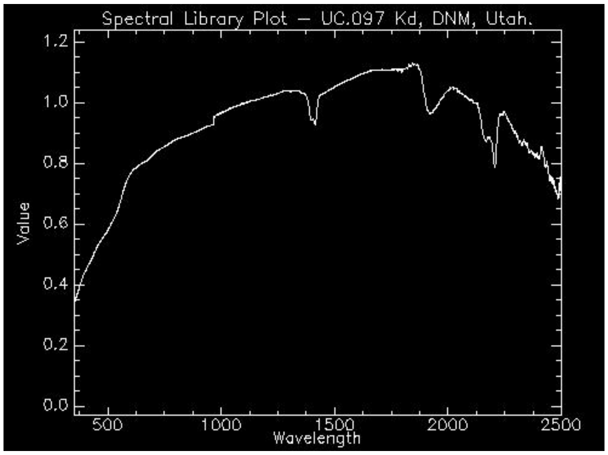


Figure 8. “Whole Rock” spectrum UC.097 (White sandstone from a dipslope of the Cretaceous, Dakota Formation characterized by hoodoo weathering and a good kaolinite doublet in the SWIR.

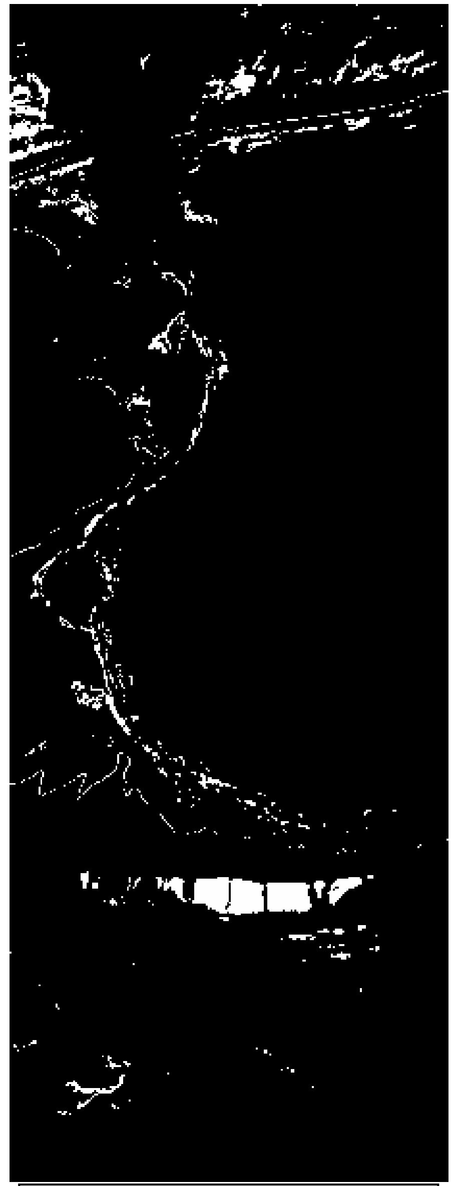

Figure 9. Atmospherically corrected AVIRIS spectral angle map (SAM) of the same area showing pixels similar to the whole rock spectrum shown in Figure 8.

Pixels passing the similarity test are then shown as white pixels on an output image. Figure 9 is a map of occurrences of AVIRIS pixels similar to the sample reference spectrum in Figure 8. The results are more precise than those of Hyperion, presumably due to its higher signal-to-noise ratio and smaller pixel size. Future hyperspectral satellites should attempt to simulate AVIRIS to the extent possible. Spatial resolutions finer than 15 meters would be useful for energy exploration.

As a further guarantee of defense/intelligence security, all 15 meter hyperspectral imagery purchased from commercial suppliers by the U.S. government should be in the care of the USGS. This will provide U.S. government key control of the data stream and allow selective black outs of sensitive areas while meeting the genuine need for affordable, high-quality satellite imagery for energy exploration and U.S. economic-environmental security.

Conclusion - AmeriSat

The 1:24,000 scale United States geological survey needs to be completed in order to ensure the economic security of the United States in the 21st century. A new series of land remote sensing satellites meeting the following specifications must be constructed, launched *and used* to meet this need. We refer to this constellation of U.S. geological survey satellites as AmeriSat. Most of the satellite technology necessary to complete the 1:24,000 U.S. geological survey already exists. Satellite systems capable of accelerating the survey to completion in less than two decades must meet the following requirements:

1. Continuity with the Landsat series (ALI with stereo and a thermal band).
2. 15 meter hyperspectral coverage of the 0.4 to 2.5 micron wavelength region.
3. A minimum swath width of 30 km to minimize seams within quadrangles.
4. Free automated data delivery via FTP, or at cost of media (relative to the cost of the satellites).
5. Off-nadir pointing capability for emergency response.
6. A constellation of four identical satellites, with a fifth on orbit spare satellite in constant reserve. There are 55,000 quadrangles to cover and the earth is frequently cloudy. This constellation and its ground systems will be approximately 70 percent of the cost of the AmeriSat system.

7. A partnership with academia, industry and the public from the beginning. The USGS does not have enough people to get the job done. This partnership should be budgeted at 10% as well.
8. USGS quality control of all geological quadrangle maps to guarantee consistency and availability in GeoTiff (loss-less raster) and ArcView shape files (as separations similar to those in USGS DLGs). This will also probably cost around 10% of the total project.

A summary of AmeriSat's general specifications is listed in Table 2.

<u>Cost</u>
We estimate that the project will cost approximately $250M/year for the next 20 years. Satellite hardware and ground station construction costs will probably consume 70% of these funds during years 1–4 and again during years 10–14, assuming a 6–8 year lifespan for each satellite. Funding will be focused on applications during non-construction years.

Table 2. Summary of AmeriSat specifications.

| Features | Specifications |
|---|---|
| | |
| Spectral Range | 0.4-2.5 microns |
| Panchromatic Bands | 1/1 |
| Visible Bands | 6/35 |
| Near Infrared Bands | 3/35 |
| Short Wave Infrared | 1/172 |
| Middle Infrared Bands | 1/1 |
| Thermal Band | 1 |
| Spatial Resolution | 30 m/15 m |
| Swath Width | 185/30 km |
| Spectral Coverage | Both |
| Pan Band Resolution | 10 m |
| Stereo | yes |
| Number of Bands | 10 and 220 |
| Number of Spacecraft | 4-6 |
| Temporal Resolution | 4-8 days |
| Emergency Pointing Capability | (similar to Hyperion on EO-1) |

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