Locating Subsurface Gravel with Thermal Imagery: A Progress Report

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A method is developed for locating gravel deposits in vegetated areas using six-band thermal imagery. The geologic history of the region is reviewed to select a potential area of study. An overflight is made using a six-band multispectral scanner. The data are displayed on a monitor and a spectral signature is selected from areas of known gravel deposits. A typical gravel signature demonstrates a strong absorption feature at the 9.2-μm wavelength. The data are then processed with a computerized system and redisplayed to delineate additional areas in the scene with a similar spectral signature. The display is transferred to a map, and the signature areas are located in the field. Exploratory drilling is used to verify the presence of gravel and to determine the thickness and extent of the deposit. During 1989 and 1990, gravel deposits totaling 1 million m^3 were discovered on national forest land near Alexandria, Louisiana, using this method. Concurrent studies are seeking to understand how the thermodynamic responses of materials contribute to the overall spectral radiant emittance in the thermal infrared spectrum. Ground instrumentation has been installed to support this effort. More time and effort are needed to advance the understanding of the physics of the method. The techniques developed can serve as a basis for further studies, directed towards extending the technology to a broad range of environments.

The need for gravel is as well established as the general knowledge of its abundance in certain areas across the Gulf of Mexico coastal plain, including lands within several national forests. Exploratory drilling between 1975 and 1988 had revealed few exploitable deposits. During this 14-year period, only five major deposits, totaling less than 1 million m^3 of gravel, were located on national forest land. Efforts to locate gravel deposits using thermal imagery began in 1983 with the acquisition of 30-m resolution thermal infrared multispectral scanner (TIMS) imagery over the Kisatchie National Forest near Alexandria, Louisiana. A report on preliminary results was published in 1986 (*1*). Shortly after the preparation of that report, data processing was halted because of hardware problems. In May 1987, processing of the original imagery was resumed. In October 1987, the Forest Service Southern Region (R8) and NASA Stennis Space Center (SSC) Science and Technology Laboratory (STL) prepared a joint proposal to further develop TIMS aggregate exploration technology for submission to the NASA Earth Observations Commercial Applications Program (EOCAP). Other early efforts were centered on organizing and coordinating software capabilities of STL and R8. Two scenes of the original TIMS imagery from the Kisatchie National Forest, 15 km square, were rectified to a standard map base to evaluate new aircraft image-to-ground coregistration software at NASA/STL. Subsequently, additional scenes were rectified at the Forest Service facility in Atlanta, Georgia. Rectifying the imagery to map coordinates greatly facilitated location of image points in the field for verification of results. It also allows entry of potential gravel sites into a geographic system with map data. The development of image rectification and improvements in image processing techniques, have resulted in the discovery of 1 million m^3 of gravel deposits on the Kisatchie National Forest during 1989 and 1990.

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ENVIRONMENTAL SETTING

Some understanding of the origin of emplacement of these gravel deposits provides a model for understanding their occurrence and improves the chances for the success of gravel exploration efforts.

Deposition of these Pleistocene gravels occurred after periods of glacial buildup when ocean levels were down and the main river channels had cut deep gorges, leaving the subsidiary streams with increased gradients to reach the main channels. Higher velocities in these steeper reaches increased the bed loads and separated fines from gravels. Wherever the gradient flattened, coarse material settled out and formed banks of gravel as the fines washed downstream. During the warm interglacial periods that followed each glaciation, melting ice brought heavy rainfall and torrents of runoff carrying huge sediment loads that separated into gravel banks below these steeper reaches where abrading streams developed. As the oceans rose again, filling in the main channels, these abrading areas were gradually flattened and covered over by progressively finer material. Isostatic uplift caused by the receding glaciers, and the subsequent erosional processes, often left these erosion-resistant gravels on the ridge tops of present-day topography, hidden by thin layers of sand and vegetation. Widespread scattered surficial gravel 1 or 2 in. in thickness overlying deep sand complicates the process of discovery.

This description represents the environmental setting in which, because of their ready availability and effectiveness in performing reconnaissance surveys of large areas, various electrooptical remote sensing methods are currently being tested. Of these methods, thermal infrared remote sensing techniques have shown the most promise. The use of NASA's TIMS has produced imagery that exhibits a promising correlation with known subsurface gravel deposits.

IMAGE ACQUISITION

The TIMS was developed by STL as a definition tool for future satellite-borne, geology-oriented sensors. First flights were made in summer of 1982, and first imagery for the U.S. Department of Agriculture, Forest Service (USFS) was obtained in October of 1983 over the Kisatchie National Forest in Louisiana, and 1 year later over the Desoto National Forest in Mississippi and the Okmulgee district in Alabama (*1*). More recently, in September 1989, additional imagery was obtained over the Desoto National Forest. TIMS is an electrooptical line scanner currently operating in the airborne mode, sensing in six narrow bands in the range of 8.2 to 12.2 μm.

Band	*Spectral Coverage, μm*
1	8.2 to 8.6
2	8.6 to 9.0
3	9.0 to 9.4
4	9.4 to 10.2
5	10.2 to 11.2
6	11.2 to 12.2

Average spectral sensitivity is approximately 0.1°C. The instrument was recently completely dismantled and refurbished by STL to ensure its continuing standard of performance. The sensor is flown in a Lear 23, a C130, or a modified U2 aircraft. Instantaneous field of view (IFOV) and lateral coverage of flightlines depend on aircraft altitude. The altitude of these aircraft may be varied within operational limits, between 2000 and 24 000 m, to provide an IFOV ranging from 5 to 60 m. The initial imagery obtained for the USFS in 1983 and 1984 was from the Lear 23 at an altitude of 12 000 m above terrain and provided data with 30-m pixels and a swath width of approximately 18.7 km (*2*).

The six bands of data obtained from the TIMS operation are in digital format. This format provides a relative measure of the emissivity from the ground surface soil minerals at each of the six wave lengths within the midinfrared range, and makes it possible to plot a spectral signature for each 30-m pixel. A 30-m pixel provides ample detail of surface deposits, which often spread over broad areas with little variation.

Good imagery for gravel exploration has been obtained in the predawn hours of late September to early October, at altitudes of 9000 to 12 000 m, following periods of at least 10 days without rainfall.

The season, time of day, weather, and altitude have all been found to be important factors in obtaining imagery that can be successfully interpreted. The season affects the relative solar heat storage and thermal emission from surface deposits. The time of day affects the direction of heat flow in the earth. Dry weather during the period immediately before image acquisition is essential to the differentiation of materials. These items will be discussed in greater detail later.

IMAGE PROCESSING

Since preparation of the first report (*1*), the hardware used for processing the imagery has been upgraded from a Data General S250 to an MV15000 with a 600-megabyte fixed disk and two 200-megabyte removable disk drives. A second 600-megabyte fixed disk was installed early in 1989. This increased data processing capacity has permitted a study of available data on a scale that was previously not possible. Because of delays in completion of software and hardware installation and procedure development, processing of NASA tapes obtained in 1983 and 1984 containing TIMS early-morning 30-m resolution imagery from Louisiana, Mississippi, and Alabama did not get underway until May 1987. Installation of Erdas software, Version 7.2, during summer 1987 greatly improved image processing capabilities.

The SIXBP program (six-band plot), which provides a display on the monitor screen of the six band values of the pixel at the cursor location together with a plot of the signature placed on the RGB screen, was developed early in 1989 using the ERDAS Toolkit (Figure 1).

Quartz gravel and coarse sand provide a unique spectral signature in the midinfrared range spanned by the TIMS, with a strong absorption feature in Band 3 (*3*). Initial effort at interpreting the imagery consisted of displaying Bands 1, 3, and 6 on the RGB monitor where known gravel pits were seen to be brightly delineated; known gravel deposits showed a stronger absorption in Band 3 than adjacent soil deposits. An image processing technique was then developed to attempt to identify all areas containing gravel deposits. The technique involves isolating a slice of data that contains a desired spectral signature, producing an image that includes only those areas exhibiting the gravel signature, and displaying the potential gravel sites with background reference data to identify areas for field evaluation.

The visual reference to the signature form provided by the SIXBP program was extremely helpful in making quick evaluations of potential gravel sites, and greatly speeded up the study process. By the summer of 1989, an improved six-band gravel signature for lightly timbered areas that produced spectacular results in the field was identified (Figure 2). This signature aided in the discovery of 600,000 m^3 of gravel deposits during 1989 and 1990. In 1990, a second signature was identified (Figure 2) for moderately timbered areas. This signature has been used to locate an additional 400,000 m^3 to date. Many areas identified by the imagery as potential gravel deposits have yet to be explored.

A major goal of the investigation is to develop gravel deposit inventory maps for each national forest. In December 1989, an ERDAS image file of a portion of the Kisatchie National Forest previously rectified by STL/NASA, and processed using the revised procedures, was converted to an ARC-INFO polygon file. A map was subsequently produced on the Calcomp 5835XP high-speed color electrostatic plotter on which the potential gravel deposits were plotted over cartographic data derived from primary base maps for the forest (Figure 3). The superior quality of this product ensures its future use as both an office reference and a tool for field exploration.

FIELD RECONNAISSANCE AND EXPLORATORY DRILLING

Once a potential gravel signature is identified and a map of signature areas developed, the next step is to locate those areas in the field. Remote sites should be plotted on a U.S. Geological Survey quad to take advantage of topographic data. Geographic details such as roads, prominent topography, and drainages offer the best guides to field location.

FIGURE 1 A TIMS thermal image of the Williana, La., area with a display of the spectral signature for the pixel under the cursor (white cross), produced with the SIXBP software program.

Where these are lacking, accurate location is difficult or impossible except through the use of Global Positioning Satellite (GPS) systems and accurately georeferenced data.

In unroaded areas, when the general vicinity is known the area must be traversed on foot to look for signs of surface gravel. A thorough reconnaissance can involve several hours of hiking. Because pine straw and dry leaves will obscure surface minerals, the ground cover must be kicked aside at intervals. Often even surface gravel will be covered by several inches of sandy soil, and the only clues are offered by animal burrows, where a few pieces of gravel can usually be observed adjacent to the burrow entrance if there is any gravel in the area. Plowed fire breaks, erosion troughs, and uprooted trees offer other opportunities to inspect subsurface material. Most subsurface gravel deposits will outcrop somewhere because of undulations in topography. If sufficient signs are present, a small bulldozer can be used to clear away enough vegetation to allow a drill rig to pass.

The surface area of a deposit is an important factor in determining quantities, and can be estimated by counting the signature pixels. A 1-m-thick deposit over 1 hectare contains 10 000 m^3 of sand and gravel. Initial drilling at intervals of 70 m to a depth of 5 to 8 m will establish approximate volumes.

A truck-mounted drill rig employing 6-in-diameter augers is used for the field exploration by the Forest Service in the Southern Region. This drill rig is located on the Kisatchie National Forest, and is operated by the work supervisor at the Catahoula District Work Center. A small bulldozer, normally used in site preparation, is available for clearing vegetation. For the past 10 years, 2 to 3 weeks each year have normally been scheduled for gravel deposit exploration. Since 1987, the drilling effort has been guided largely by TIMS imagery.

During the several weeks of drilling and reconnaissance in 1987 and 1988, only one sizable deposit of 50 000 m^3 was discovered. This deposit was surficial in nature, spread over 6 hectares of ground, with exposed banks of gravel on the steeper slopes. Other areas investigated during this period had only a few centimeters of gravel or less than 1 m of sand containing 5 to 15 percent gravel.

In 1989, following the improvements in processing techniques, six deposits of 7000 to 15 000 m^3 were discovered in

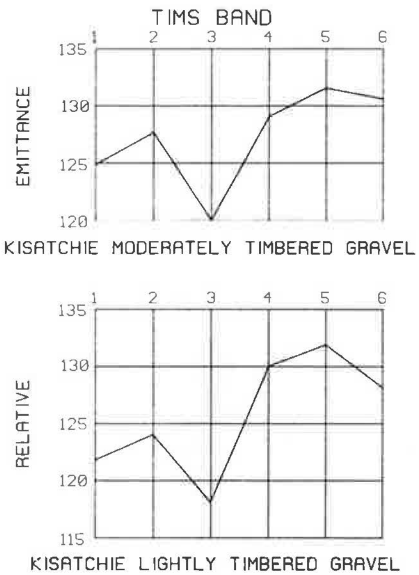

FIGURE 2 TIMS six-band spectral signatures for gravel deposits on the Kisatchie National Forest near Alexandria, La.

the Williana area during a 1-week period in July; and four deposits totaling an estimated 250 000 m^3 were discovered in the Pollock, Rock Hill, and Lake Kincaid areas during 1 week in December. During 2 weeks in August 1990, four deposits totaling an estimated 750 000 m^3 were discovered in the Pollock and Fishville areas. Thicknesses of these deposits varied from 1 to 6 m. All had less than 1 m of overburden. Two potentially large deposits, currently inaccessible to drilling except on the periphery, were identified in the Bentley area. A number of other signature areas remain to be investigated.

This wealth of discoveries occurring during 4 weeks of effort is entirely without precedent, and can only be attributed to the success of the TIMS spectral signature as a means of identifying gravel deposits.

THE SPECTRAL LINK TO MINERAL DEPOSITS

Three factors provide the predominate causes in the striking differences between spectral signatures of gravel deposits and deposits of other, finer-grained materials. These factors are the energy absorption of the quartz molecule in TIMS Band 3, the fraction of silt and clay in the material, and the thermal inertia of the material.

The energy absorption is caused by the stretching of the molecular bonds between the oxygen and silicon atoms that occurs in making up the SiO_2 molecule and its linkages. In order to maintain this configuration, the molecule must absorb energy from outside itself in the wave lengths associated with the TIMS Band 3. This process provides the striking signature associated with quartz. Clean, dry, coarse grains provide the strongest signatures. Impurities from clay minerals or other rock minerals, organic materials, excessively fine material, and moisture all tend to dilute the effect.

The association of coarse sand with gravel deposits is directly related to the velocity of flow in the channel. The depositional velocity for 2-cm-diameter particles has been found to be approximately 2.5 m/sec, and for 2-mm diameter, 0.5 m/sec. Particles finer than 2 mm resist settlement until still water is reached; thus there is little opportunity for the fine and coarse materials to intermingle (*4*). Coarse sand and gravel settle out in moving water, whereas fine sand, silt, and clay require a pond-like environment. This separation is further accentuated by shifts in channel location on the valley floor. A river carrying a coarse-grained load will develop a straight, shallow channel, but will change to a meandering, deep channel when the bedload becomes silt and clay (*5*). Thick gravel deposits are built up by fast shallow flows in wide, thin layers interspersed with coarse sand as the velocity varies with the seasonal runoff. When the upstream channel banks begin to provide finer-grained material, the river meanders and deepens, moving to an adjacent location and leaving the coarse-grained deposit intact.

The predominance of coarse sands found associated with gravel deposits identified by the TIMS gravel signatures indicates that these signatures are characteristic of coarse-grained quartz deposits, and conversely, that the strong energy absorption in TIMS Band 3 is maximized by coarse-grained quartz. These phenomena may be related to the total particle surface area in uniformly sized materials, which increases rapidly as the particle diameter drops below 2 mm. For example, the surface area increases from 10^3 to 10^6 cm^2 per cm^3 when the diameter drops from 3 to 1 mm. Photon energy is constant for each wavelength. The greater surface area scatters photon

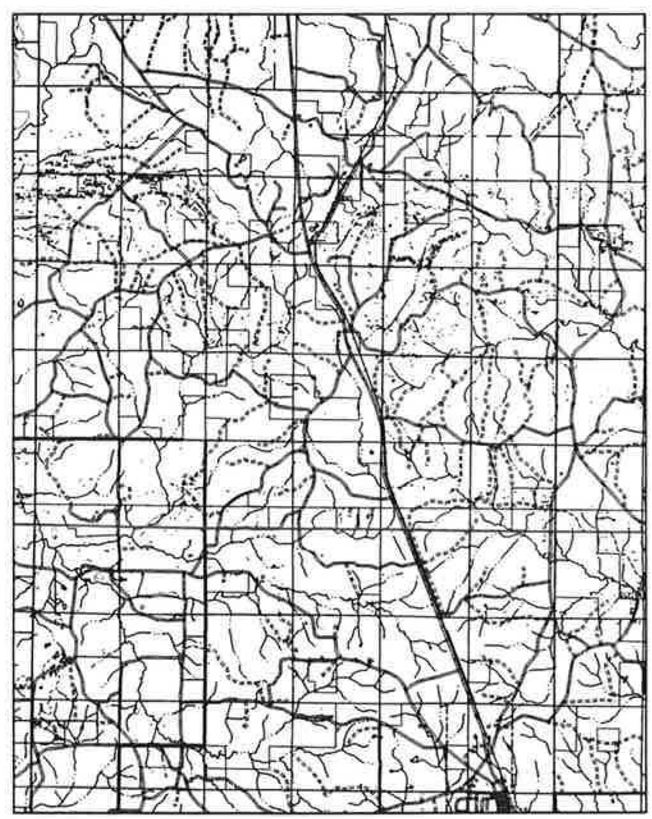

FIGURE 3 A gravel inventory map of the Williana, La., area. Hatched areas, indicating gravel deposits, were generated by processing rectified TIMS imagery and converting to ARC-INFO for plotting with an electrostatic plotter.

emission, causing a loss of energy and a corresponding shift to lower wavelengths. The greater surface area increases the energy available for absorption at the wavelength in TIMS Band 3. In the example, there are 1000 times more opportunities for a photon collision in the 1-mm particles than in the 3-mm particles. Silt particles have diameters in the same range as the radiation wave length, and scattering becomes the dominating effect (*6*). Thus a marked decrease in Band 3 emission (and correspondingly greater dip in the signature at this point) can be expected for the coarser-sized quartz materials, those whose diameters exceed 2 mm, as compared to the finer-grained quartz.

Thermal Inertia Factor

The thermal inertia of materials provides for striking contrasts in surface temperatures. Thermal inertia expresses the resistance of a material to temperature change. Materials of high thermal inertia change temperature only slowly, lagging behind changes in adjacent materials with low thermal inertia. A deposit of sand and gravel, for example, has a higher thermal inertia than a deposit of sand. Soil moisture, which increases as soil grain size decreases, also produces a higher thermal inertia.

Thermal inertia affects the temperature level of natural deposits. Periodic heating of the earth's surface from the sun provides two waves, the diurnal wave, affecting up to 1 m of depth, and the annual wave, affecting up to 20 m of depth. The actual depth of penetration depends on the properties of surface materials; denser materials generally have higher diffusivity and exhibit greater penetration. The diurnal wave is superimposed on the upper end of the annual wave, providing distinctly different surface temperatures for different materials, particularly when comparing day to night together with summer to winter.

The TIMS imagery obtained in 1983 to 1984 was flown in October at 2 a.m. on the assumption that the maximum annual ground temperatures had been attained at this time of the year, and during the early morning hours the maximum outflow of diurnal heat was occurring. The combination of maximum summer heating together with early morning cooling provides a unique effect associated with materials of high thermal inertia. Gravel and sand deposits always show cooler in the imagery than adjacent nongravel and sand deposits, although warmer than the damp bottom land. This perception was recently borne out by data from micrometeorological monitoring stations installed by NASA/STL. The resulting steep temperature gradient between the warm gravel body and its cool surface increases the rate of photon emission and further accentuates the Band 3 absorption dip.

Vegetation Factor

The spectral signature used to identify gravel deposits in this study is a mineral signature, related to vegetation only by the degree of dilution resulting from vegetation cover. The cover encountered in the 1983 imagery is by no means opaque. In the thickest forested areas, sunlight filters through to spot the shadows on the forest floor. The ground cover is made up of pine straw and dried leaves, neither of which can offer substantial obstruction to photon emission. Organic top soil is generally thin, especially on coarse-grained gravel deposits, and contains a large fraction of the parent soil exposed at the surface. Thus, photon emission from mineral grains can reach the scanner in flight overhead.

The 1983 imagery was acquired in predawn hours from an altitude of 12 000 m (with 30-m pixels). Vegetation has not been a problem with this imagery except in heavily timbered areas. In 1989, NASA acquired predawn imagery over the Desoto National Forest in Mississippi, at 9000 m (with 22.5-m pixels) and at 4000 m (with 10-m pixels), over the same terrain. Although the 9000-m imagery clearly identified several known gravel deposits both in timbered and open areas, the 4000-m imagery showed only vegetation. Thus, the threshold altitude for sampling mineral matter over vegetated terrain lies between 4000 and 9000 m.

This effect may be explained by the way the scanner records the predominant radiation spectrum. The primary sustained radiation source is the earth's mineral surface with its store of solar heat in the top few meters, represented in size to the scanner by the pixel size. Secondary radiation comes from cooler vegetation ranging in size from leaf to tree, often existing in clumps of trees interspersed with openings. When flying at lower altitudes, individual trees or clumps of trees are pixel-sized, and the earth contribution is limited by its small area; the flat vegetation spectrum predominates and the mineral signature is lost. At higher altitudes, individual trees and clumps are much smaller than the pixel; the earth openings present within each pixel, including those between leaves, combine their effects to reveal the primary pixel-sized earth radiator, which is now much larger, and the mineral signature predominates.

Moisture Factor

The single greatest deterrent to acquisition of usable imagery is surface moisture. Moisture absorbs heat from the soil and effectively destroys the mineral spectral signature. Several image acquisition flights, in 1984, 1989, and 1990, suffered from rainfall up to 4 days before the flight, resulting in imagery that is useless for gravel deposit inventory. Surface moisture completely alters the nature of the image, and shows only patterns of vegetation. The spectral signature immediately following a period of rainfall is relatively uniform over the entire image, with low points in Bands 1, 4, and 6; high points in Bands 2, 3, and 5, assuming the shape of saw teeth.

NASA INVOLVEMENT

NASA's scientific interests are in determining how the thermodynamic responses of surface minerals contribute to the overall spectral radiant emittance in the thermal infrared spectrum. This understanding will contribute greatly to extending the use of such imagery for natural environmental applications. A major objective of this cooperative supporting study is to determine under what physical limitations and restrictions thermal infrared imagery can be used to discriminate gravels from surrounding materials in a variety of environmental settings. This will be accomplished through extensive empirical measurement and modeling of the radiometric response over several regimes of soil moisture, humidity, vegetation, and atmospheric condition.

During FYs 1989 and 1990, NASA focused its efforts on conducting controlled experiments to determine when the differential thermal response of surface materials such as gravels, sands, and clays with inherently differing thermodynamic properties peaks during annual and diurnal heating cycles, exhibiting high contrast in thermal images. This information will be used to program data acquisitions during periods of the greatest temperature differentials between targeted gravel deposits and surrounding background materials.

In order to accomplish this objective, a set of remote instrument stations were designed and engineered to monitor surface heat flow parameters, and installed at STL for testing, both at a graveled and a nongraveled control site. These modified micrometeorological stations measure the following properties: incoming and outgoing short- and long-wave radiation (0.3 to 50 μm); net radiation; air, surface, and subsurface temperatures at three depths; wind speed; relative humidity; soil moisture; and conductivity. From these measurements, heating and cooling response can be calculated for the materials present, using known models to predict intervals of maximum temperature differences. Figure 4 shows a block diagram and schematic of system components.

A known gravel deposit at the new Black Creek Seed Orchard at the W. W. Ashe Nursery on the Desoto National Forest in southeastern Mississippi was selected because of its proximity to STL. Exploratory drilling with the Forest Service's drill rig revealed a half-million m^3 of gravel deposits over the surface, 5 to 8 m in thickness. The micrometeorological stations were transported to the site and installed within the gravel deposit, and in an adjacent ungravelled silty soil, in early July 1989. A telemetry connection to STL for data monitoring has since been installed. During September 1990, two additional stations with telemetry were installed on the Kisatchie National Forest in Louisiana following a period of testing at STL.

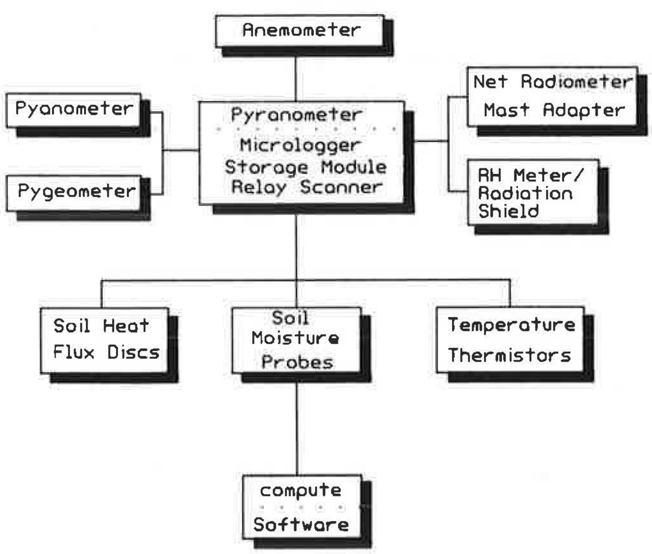

FIGURE 4 A block diagram of NASA's micrometeorological station installed on the Desoto National Forest.

From the initial month of data recorded by the stations installed on the Desoto National Forest, it was obvious that the largest temperature differentials were caused by the summer solar insolation maxima and a brief lag time for ground warming caused by thermal inertia. It also became apparent that the gravels heated and cooled more rapidly over the diurnal cycle than the deposit of finer-grained sediments. Summer data show the gravels to be up to 14°C warmer during the day with the differential peak occurring around 2:30 p.m. The corresponding predawn differential peaks at up to 4°C cooler for the gravels at 6:30 a.m.

In order to provide a correlation between ground and aircraft data, three missions of three lines each were flown with the calibrated airborne multispectral scanner (CAMS). The missions were flown at the times stated on the afternoon of August 18, and during the predawn hours and the afternoon of August 19 to catch the peaks of the diurnal cycle. The CAMS is an internally calibrated scanning spectroradiometer with eight bands in the visible and reflective near-infrared spectrum and one wide thermal infrared band. Images have been geometrically rectified to UTM coordinates, reduced to temperature differences, and processed into actual differences of thermal inertia present at those points in time. The processed values agree closely with values calculated from in situ measurements.

FUTURE EFFORTS

Although a good preliminary understanding of the TIMS imagery for the Kisatchie National Forest has been attained during the past 2 years of effort, much remains to be done. The procedures developed using the initial data set must be tested with imagery of the same locations in other years, other times of the year, and at other locations with differing soil cover. Soil monitoring data must be combined with weather station data to determine optimum time or times during the year for obtaining the best imagery. The use of data combinations from two or more times of the year for the same location should be studied. Efforts should be made to develop a better understanding of the physics involved.

Work currently underway on and around the Ashe Nursery on the Desoto National Forest in Mississippi offers the first opportunity to pursue these objectives. This site provides all the components required for such a study: imagery, ground data, and known gravel deposits.

Additional sites under consideration include the Sam Houston and Davy Crockett National Forests in east Texas, and reflights of the Kisatchie National Forest in Louisiana. Other areas under consideration include national forest land in Arizona, Colorado, and Idaho. This list of potential sites will probably expand as the study progresses.

CONCLUSIONS

Significant progress has been achieved in understanding the uses of TIMS imagery for gravel deposit exploration on the Kisatchie National Forest in Louisiana. Tentative gravel signatures have been identified that provided reliable results in field tests performed during 1989 and 1990. These investigations have resulted in the discovery of 1 million m^3 of gravel deposits. Data developed solely from the TIMS imagery has successfully been used to produce a tentative geographic information system gravel deposit inventory map for selected areas of the Kisatchie National Forest.

The information developed can be used as a basis for further study into the means of using TIMS imagery for gravel exploration in a broad variety of environments.

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