A Multi-Sensor Aerogeophysical Study of Afghanistan

J. Brozena,[1] V. Childers,[1] J. Gardner,[1] R. Liang,[1] J. Jarvis,[1] and J. Bowles[2]
[1]*Marine Geosciences Division*
[2]*Remote Sensing Division*

A multi-sensor, multidisciplinary aerogeophysical survey over much of Afghanistan was recently conducted by investigators from NRL and the U.S. Geological Survey. The survey was flown aboard an NP-3D Orion aircraft operated by VXS-1. Sensor systems installed on the P-3 included dual gravimeters, scalar and vector magnetometers, a digital photogrammetric camera, a hyperspectral imager, and an L-band polarimetric synthetic aperture radar. Data from all sources was precisely co-registered to the ground by a combination of interferometric-mode Global Positioning System and inertial measurements. The data from this integrated mapping mission supports numerous efforts in Afghanistan: combat operations, economic exploration for oil, gas, and minerals, humanitarian missions, development of civil infrastructure, and agriculture resource management. This mission has also advanced the state of the art in integrated multi-sensor airborne remote sensing.

INTRODUCTION

Afghanistan is one of two active combat zones in the global war on terrorism (GWOT). The country faces dual challenges: suppressing Taliban and al-Qaeda operations and developing the basis of a legal and sustainable economy that minimizes popular support for terrorist activity. A major airborne remote sensing and mapping project conducted by the Naval Research Laboratory (NRL), the U.S. Geological Survey (USGS), and Scientific Development Squadron One (VXS-1), covering more than half of Afghanistan, contributed to both these objectives. The project marked a technological milestone in the integration and successful operation of the largest set of diverse airborne geophysical sensors ever flown. It is also noteworthy in that it was the first deployment of NRL scientists into a combat theater since World War II.

Sensors aboard the aircraft included digital true-color photogrammetric and hyperspectral optical imaging, imaging synthetic aperture radar (SAR), and both gravity and magnetic potential-field mapping systems. Rapid-turnaround photogrammetric imagery was provided to the International Security Assistance Force (ISAF) for use in current combat operations. To date, more than 150 combat missions have made significant use of these data. The rapid delivery was enabled by the use of new techniques in digital image processing and precise internal georegistration without ground control. This technology is revolutionizing aerial photogrammetric mapping by reducing both costs and processing time. Some of these data have been provided to the Riverine Analysis Team at the Naval Oceanographic Office (NAVOCEANO) for support of Special Operations Forces. The integrated mapping mission similarly enhances economic and national development. Areas of application include reconnaissance geologic exploration for oil, gas, and mineral resources. The mission also supports civil infrastructure needs such as cadastral surveying, urban planning and development, and pipeline/powerline/road routing and construction. The data can be used for agriculture and hydrologic resource management, earthquake hazard analysis, and base-maps for humanitarian relief missions. The data sets also support basic research by NRL scientists working in the areas of sensor fusion, automated analysis techniques, riverine support, and geodesy.

SURVEY METHODS

The survey was flown aboard a research NP-3D Orion aircraft operated by the U.S. Navy's scientific development squadron VXS-1, formerly the Flight Support Detachment of NRL. Sensor systems installed on the P-3 (Fig. 1) included the following:

- dual ZLS air-sea gravimeters;
- a Geometrics 823A scalar magnetometer coupled with an Applied Physics 539 3-axis fluxgate magnetometer for compensation of the aircraft field;
- an Applanix DSS 301 digital photogrammetric camera with an integrated POS-AV 410 Inertial Measurement Unit (IMU)/Kinematic-mode Global Positioning Systems (KGPS) positioning system;

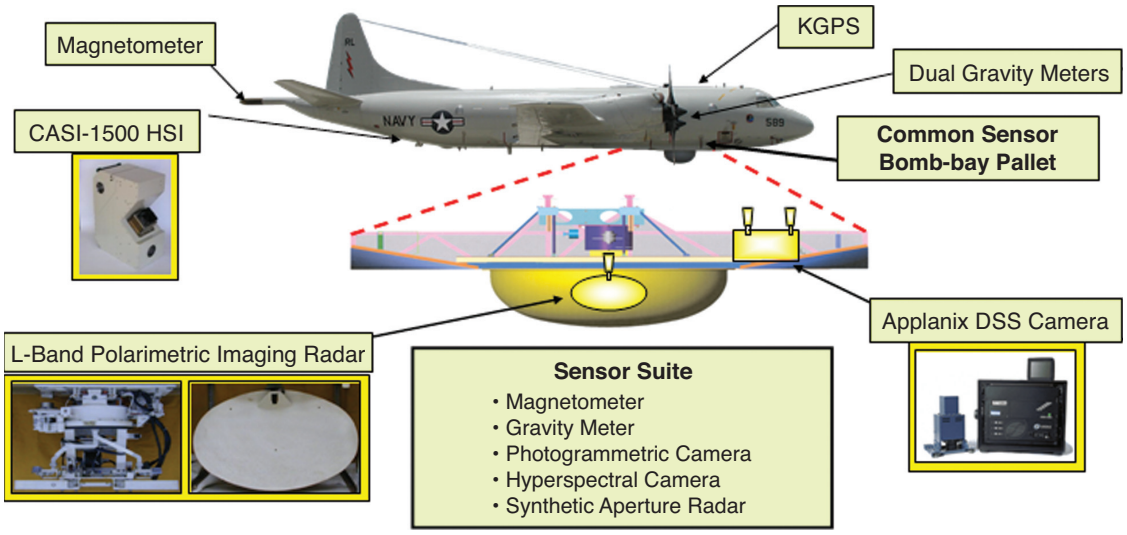


FIGURE 1
Sensor systems installed on the Orion NP-3D research aircraft for the Afghanistan aerogeophysical survey.

- an ITRES Corporation CASI-1500 hyperspectral imager (HSI); and
- an L-band polarimetric SAR built by NRL.

Several Ashtech geodetic-quality GPS receivers were also installed, but the primary positioning and attitude data for the various sensors were provided by the POS-AV system.

The aircraft and the science party were based at Kandahar Airfield. Logistics and flight operations were challenging, as Afghanistan is an active war zone and combat operations for much of southern Afghanistan are staged out of Kandahar. The P-3 aircraft required extensive modifications to operate in the combat theater including the addition of a flare/chaff dispenser and optical launch warning systems to counter surface-to-air missiles, infra-red strobes, secure communications channels, a low-observable paint scheme, and foamed fuel tanks to reduce the danger of ground fire. Combat takeoff and landing procedures were also required because of the potential for ground attacks. Differing optimal survey conditions for the various sensor systems combined with the dangerous operating conditions made survey planning and execution particularly difficult. Flight restrictions specified that data legs be flown at relatively high altitudes above ground level due to the threat of surface-to-air fire. While this restriction reduced the resolution of the gravity and magnetic measurements, it did allow collection of data over an approximate 4 km wide swath for the optical sensors, and a circa 15 km left of flight track nadir swath of SAR imagery. Flight ceiling limits for the aircraft limited coverage of the country to areas with elevations less than about 3,700 m, making it impossible to survey over the highest areas of the Hindu Kush and Pamir mountains (these mountain ranges extend over the central and northeastern portions of the country, as seen in Fig. 2). However, this still allowed coverage of more than half of the country. Each line was flown at a constant barometric altitude with the survey line altitudes stepping generally upward from west to east along with the topography.

The project was laid out as three essentially distinct blocks: the northern, western, and eastern blocks (Fig. 2). Primary track spacing was 4 km, but was increased to 8 km in the northern block due to time and financial constraints. Several tie line flights and data transits of opportunity helped to maximize data coverage. Aircraft ground speed averaged between 300 and 380 kts, which is faster than considered optimal for high-resolution gravity, hyperspectral, or photogrammetric data collection. However, the increased speed allowed the survey of approximately 125,000 line-km of data tracks and more than 330,000 km^2 of imagery coverage in the 220 mission flight-hours allotted for the survey.

DATA COLLECTION AND PROCESSING

Photogrammetry

More than 65,000 high-resolution photogrammetric images were collected using an Applanix Digital Sensor System (DSS) Model 301 airborne digital camera mounted in the bomb bay of the aircraft. The DSS incorporates a 4 Kpixel × 4 Kpixel three-color sensor digitized with 12-bit resolution. The 55-mm lens used for this survey provides a 37° field of view. The camera can be cycled as fast as 2.5 seconds (although rates of 7–9 seconds were sufficient for operational altitudes and speeds) to produce 60% image overlap

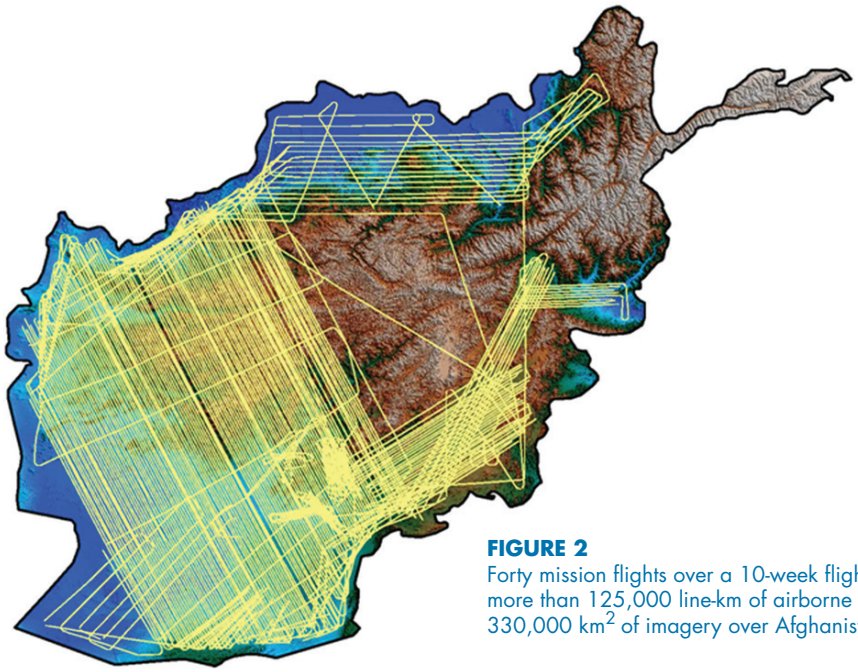


FIGURE 2
Forty mission flights over a 10-week flight period produced more than 125,000 line-km of airborne survey tracks and 330,000 km^2 of imagery over Afghanistan.

allowing for stereo analysis. Pixel size, or ground sample distance, varied between 85 and 135 cm. Photogrammetric images are corrected for camera calibration factors and dark pixel noise before being georeferenced using positioning data collected by the integrated POS-AV system. The POS-AV IMU provides measurements disciplined by differential dual-frequency, differential carrier-phase GPS (KGPS) to directly georeference each image pixel, thus providing precise photogrammetry without ground control. GPS positioning for this survey was particularly difficult because of the long flight baselines required by the geographic extent of the survey. Stationary differential GPS base stations were maintained at Kandahar Airfield, Kabul, Herat, and Sheberghan during survey operations in order to support multi-base station reduction of the KGPS data. The remote base stations improved the aircraft trajectories significantly during the flight segments since some baselines were more than 600 km from Kandahar. We estimate that the final rms 3-D aircraft positioning accuracy is better than 30 cm overall, with better than 10 cm over shorter flight baselines (< 300 km). Ortho-corrections are applied to the images to account for parallax errors caused by imaging variable topography at oblique angles. A 30-m posting digital elevation model (DEM) from the National Geospatial-Intelligence Agency (NGA) Shuttle Radar Topographic Mission (SRTM) was used for this correction. Data collected during a high-altitude boresight calibration flight over the airfield demonstrated sub-pixel absolute horizontal positioning (< 1 m) by comparison with precisely surveyed ground control points, and about twice this in the vertical from stereo analysis. Absolute pixel positional accuracy degrades somewhat on the long straight tracks (up to 500 km) since turns are required to separate gyro and accelerometer bias drift in the IMU. This translates primarily into an increasing yaw error along the track with time. However, image tie-point aerotriangulation between successive images and in adjacent image strips (if there is sufficient sidelap) allows correction of much of this error. Absolute pixel position errors are estimated to be < 2 m on average, and relative positioning within mosaiced aerotriangulated images is on the order of 1 m.

Hyperspectral Imagery

Hyperspectral imagery was collected with a CASI-1500 system mounted in the bomb bay of the aircraft. The camera collects a 1500-pixel-wide push-broom swath through a 40.5° field of view with up to 288 spectral bands (0.4–1.0 μm) that were averaged down to 72 bands to improve signal-to-noise, and a dynamic range of 14 bits. The image pixel size was approximately 3 m (cross-track) × 5 m (along-track) and an integrated CMIGITS GPS (non-differential)/IMU provided attitude data for the camera. There is ongoing experimentation using the higher-resolution attitude data collected from the more accurate Applanix POS-AV IMU used for the photogrammetric data processing in order to increase the data accuracy.

Gravity

A pair of ZLS Corporation air-sea gravimeters were mounted in the center of the aircraft fuselage. The

airborne gravimeter data were corrected for aircraft vertical acceleration, Eötvös effect (correction for horizontal velocity over a curved, rotating earth), and normal reference gravity field based on aircraft positioning from the POS-AV system. High-frequency noise is attenuated by a low-pass filter resulting in along-track resolution of approximately 20–25 km (half-wavelength) at the average survey speed. The 4-km track spacing over-samples the field at survey altitudes, but improves the signal-to-noise characteristics of the gridded data set. Averaging data from the two gravimeters further reduces the noise.

Free-air anomalies corrected for the survey altitude were employed as the basic data set during preliminary analysis. Simple and complete Bouguer maps were produced from SRTM topography, calculating slab Bouguer and terrain corrections, and upward-continuing the corrections to the average survey elevation before combining with the at-altitude free-air anomalies. For final processing, all profiles are upward-continued to a constant altitude to eliminate any track-to-track discrepancy in signal content caused by the different measurement altitudes; they are then adjusted based on crossover analysis, and the Bouguer anomalies are recalculated. Crossover analysis on the initial free-air anomaly data indicates an rms measurement error for the survey of approximately 2 mGals (1 mGal = 10^{-3} cm/sec^2).

Magnetic Data

Scalar and vector magnetometers were mounted in the non-magnetic tail boom of the aircraft. Aircraft magnetic field effects on the scalar magnetometer were corrected using information from the vector magnetometer and removed in post-processing using standard compensation procedures. This compensation proved very effective (rms residual of < 0.1 nT) considering that the P-3 is a large four-engine turboprop aircraft with a gross weight of more than 50,000 kg. Diurnal solar variations were obtained from ground magnetic base stations operated at Kandahar, Kabul, Herat, and Faizabad. For initial processing, the only accessible station was the Kandahar base station; this improved data quality significantly, but fairly large diurnal effects were still visible in some areas, particularly over the mountainous areas that could be surveyed. In the coming months, several different strategies of multi-base station correction will be tried prior to re-leveling the data.

Synthetic Aperture Radar (SAR)

SAR data was collected using a prototype unit designed by the Radar Division at NRL to collect L-band polarimetric phase data. The SAR antenna, also designed for specific requirements by the Radar Division, was mounted in a large radome attached to the bomb bay of the aircraft. Center frequency was 1300 MHz with a bandwidth of 10 MHz. The data collection system was designed to handle more than double this bandwidth, but time and financial constraints precluded upgrading the RF section to the desired higher bandwidth, resulting in an effective pixel size of 3 m (along-track) × 15 m (cross-track). Even at this reduced bandwidth, typically more than 300 GBytes of phase-data per flight were collected, totaling more than 10 TBytes for the entire survey.

RESULTS

Photogrammetric Data

Digital true-color photomosaics are currently being produced from the 65,000 photogrammetric images collected during the airborne mapping mission. Figure 3 shows a piece from a photomosaic of Kajake dam that was provided in the field to ISAF forces. ISAF troops used the photomosaics for planning a major campaign against Taliban forces attacking the dam and nearby villages during the deployment. In addition to the basic imagery products, elevations and slopes calculated from the stereo imagery models proved to be extremely useful for planning troop and vehicle movement trafficability, planning helicopter landing zones, and performing line-of-sight analysis for determination of cover and visibility. Products from the Kajake dam flight were produced and delivered to combat personnel within 48 hours of landing, a dramatic contrast to the months usually required for conventional photogrammetric operations. Both hard and soft copies of the imagery were loaded onto hand-held GPS units and provided to combat troops. The unclassified nature of the imagery proved to be a significant operational advantage for combat forces in the field who typically are not allowed to carry classified maps and images.

Orthorectified photomosaics of the Kajake reservoir and Helmand river area were also provided to the Riverine Analysis Team at NAVOCEANO to support Special Operations Forces. Although the turnaround times demonstrated in this project were considered extremely rapid, real-time kinematic (RTK) GPS positioning techniques and prototype image calibration and ortho-correction software now being tested have the potential to allow product delivery in near real-time.

As the photogrammetric mosaics of the remainder of the country are processed, they are being provided to USGS for economic analysis projects, to NGA for incorporation into DoD's imagery library of the country, to USAID for construction and development projects, and to the government of Afghanistan for

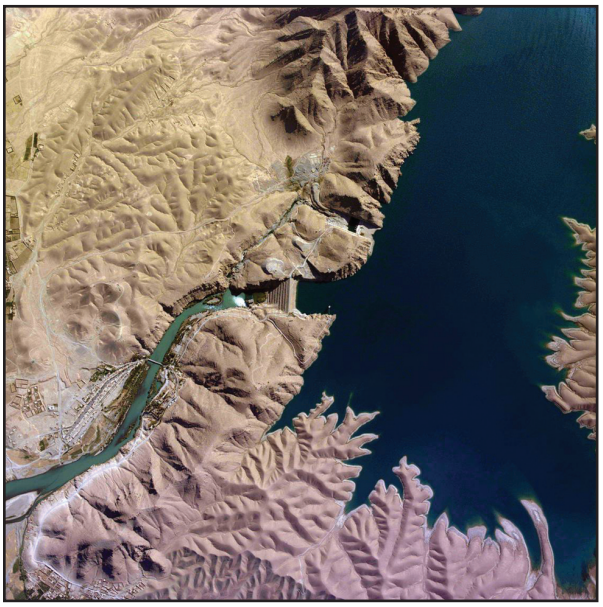


FIGURE 3
This image shows part of a digital photogrammetric mosaic produced over the Kajake dam and reservoir. Pixel ground sampling distance and absolute georegistration accuracy were approximately 1 m and 2 m, respectively. Stereo models for elevation and slope estimates were also produced for the region. These imagery data were provided to ISAF troops engaged in combat with Taliban forces in the area.

myriad uses. At the same time, the pipeline of imagery products to ISAF forces in Afghanistan is continuing to support current and future combat operations.

Hyperspectral Data

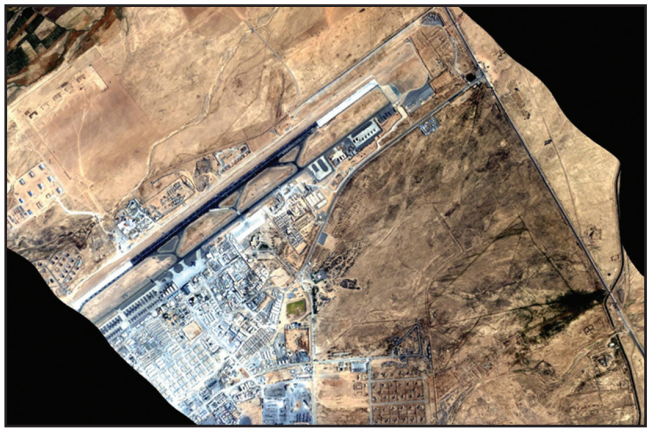
Analysis of the hyperspectral imagery is processing-intensive and is only in the initial stages. Spectral classification software allows automated identification of features such as vegetation, water, buildings, roads, and some soil and mineral types. Figure 4 shows a few such classifications for the area of Kandahar Airfield. Water depth (bathymetry) can also be estimated from the hyperspectral data should the water clarity be sufficient to allow the return of some photons from the bottom. The hyperspectral data are being provided to the Riverine Analysis Team at NAVOCEANO for bathymetry estimation, river trafficability, and other operational joint analysis with the photogrammetric data. The data will also be used to support exploration for minerals and studies in agriculture and hydrology for economic development of the country.

Gravity Data

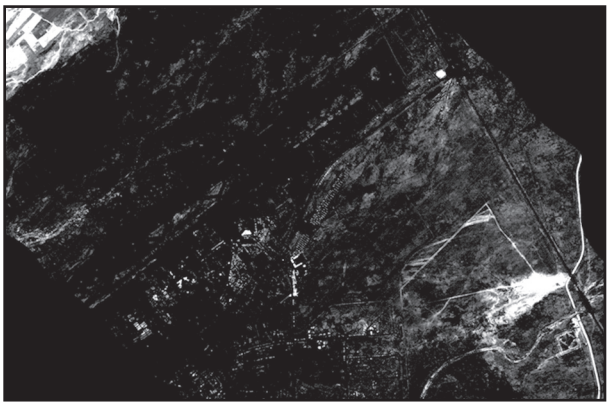
Gravity measurements are indicative of local mass distribution and are used operationally for corrections to high-end inertial navigation units on some strategic weapons systems, for definition of local vertical datums, for global earth gravity models, and for economic geology in oil, gas, and mineral exploration. As final data reduction is completed, the gravity data are being supplied to NGA for weapon-systems products and the WGS2006 gravity model, and to USGS and the government of Afghanistan for use in exploration geology for economic resources. The free-air gravity anomaly map (Figure 5(a)) is dominated by the extreme topography of the mountains that, even at survey altitude, produced a signal spanning more than 150 mGals. The complete Bouguer anomaly map (Figure 5(b)) removes first-order topographic effects and reveals the segmentation of Afghanistan into the large Helmand basin to the southwest separated from the Tadjik basin to the north by the folded and thickened crust of the central mountains. The Katawaz basin in the southeast is characterized by alternating parallel lineated Bouguer anomaly highs and lows that are anti-correlated with fault-parallel topography. The easiest way to generate such a non-isostatic pattern is large-scale compressional bowing of relatively constant thickness crust such that the topographic highs overlie upwarped higher density mantle, and the downwarped crust displaces mantle. The Kabul basin to the northeast near the Pakistani border appears to be out of isostatic equilibrium to an even greater extent with a relatively large negative Bouguer gravity anomaly (generally indicative of thickened crust) over a topographically depressed region. It is likely that the sedimentary sections in these relatively Bouguer-low areas are abnormally thick, and a possible source for oil and gas resources for the country. Magnetic depth-to-source calculations (see below) also provide estimates of the sedimentary thickness within these basins, showing large possible sedimentary sections. The existence of these basins was known prior to the survey, but the extent, shapes, and estimated depths were previously unknown.

Magnetic Data

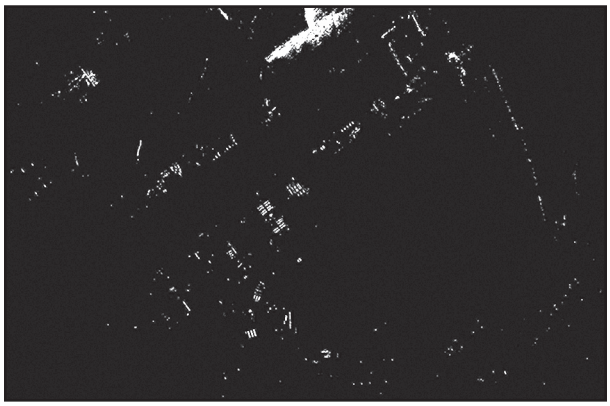
The local magnetic field in the region is created by the bulk induced and remnant magnetization of the source rock in the vicinity. As such, magnetic measurements yield useful information about local geologic structures and mineralogic assemblages of interest for economic geology. The spatial frequency content of the magnetic field variations at the aircraft altitudes flown also provide information about the distance to the causative magnetic source material since higher frequencies attenuate more rapidly with distance. Since sediments are largely non-magnetic, distance estimates based on frequency content can provide an estimate of sedimentary thickness overlying more magnetic basement rock. Additionally, there are operational requirements for magnetic data, primarily for magnetic



(a)

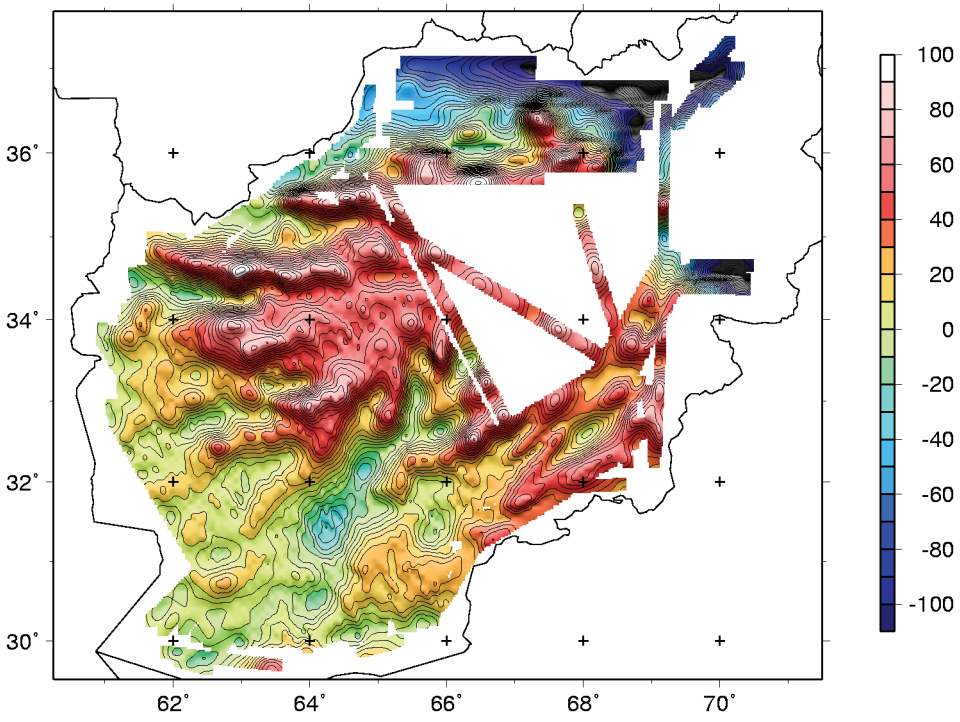


(b)

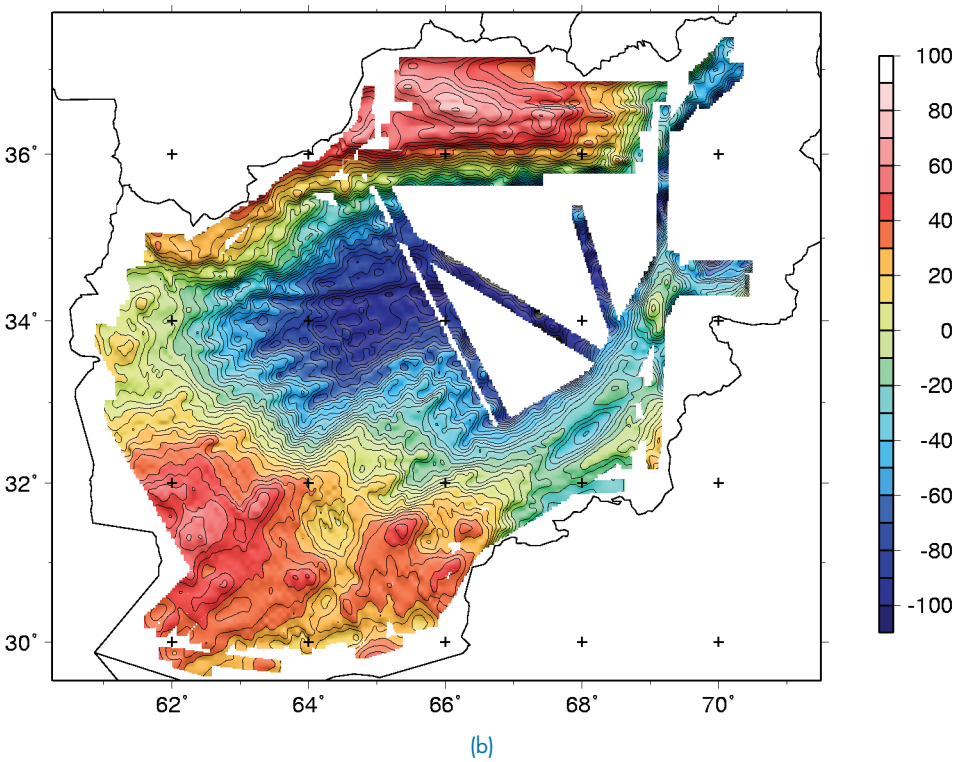


(c)

FIGURE 4
(a) Synthetic true-color imagery of Kandahar Airfield synthesized from the 288 band (0.4–1.0 μm) CASI-1500 hyperspectral imager. (b) Automated feature analysis for vegetation in the area of Fig. 4(a) produced from the hyperspectral data by calculating similarity to spectral signature of chlorophyll. (c) Same as (b) but matching the spectral signature of buildings in the area of the airfield.



(a)



(b)

FIGURE 5
(a) Free-air gravity anomaly map showing the relative gravity highs produced by the mountains (warm colors) compared to the relative lows of the plains. Units are mGals (1 mGal = 10^{-3} cm/sec^2 ~ 1 µg). (b) Complete Bouguer gravity anomaly map produced by removing an estimate of the mass effects of topography and elevation. The residual anomaly is indicative of subsurface mass variations and deviations from the assumptions used in the modeling. At this scale, the largest effects can be attributed to crustal thickening over the mountainous regions (cool colors) and to thick sections of less dense sediments that fill the crustal depressions of basin regions (warm colors). The sedimentary basins are of great interest for oil and gas exploration.

compass variation corrections. The information content of the magnetic data collected for this survey was limited by the high-altitude flights required for safe operation. However, it is expected that the final result will be a very good quality regional survey because of the low measurement noise, over-sampled track spacing, careful use of distributed base stations, and consistency of the survey parameters of the large area. Useful geologic information can be observed even in the preliminary data (Fig. 6). The final processed data will provide an excellent medium- to long-wavelength basis for the selection and control of future low-altitude aeromagnetic surveys. Several commercial historical data sets were obtained by USGS prior to deployment to Kandahar. In general these data, when upward-continued to flight altitudes, fit well with the new data after adjustment. The exception to this is a survey over the mountainous central region. It is believed that residual discrepancies in this case are related to errors in the reported altitudes of the historical data set.

SAR Data

The primary use of the SAR data will be in inversion to mineral types and properties from radar reflectivity. The data will also be used to supplement the optical imagery in geologic analysis of faulting, bedding, and rock foliation. Feature analysis for man-made objects and buildings may also be possible. Since some ground penetration is possible at L-band frequencies, there may also be some visible signatures of buried streambeds and perhaps old roads for hydrologic and archeological research. At this time, only unfocused (uncorrected for aircraft attitude and trajectory) SAR images have been produced for verification and quality control of the data set (Fig. 7).

CONCLUSION

Despite the difficulties of first-time integration of a large component of complex and diverse sensors, and operation in a combat environment, the aerogeophysical project is considered to be a complete success. The Navy flight and ground maintenance personnel safely completed 100% of desired missions with no mishaps or significant problems. Nearly 20 Tbytes of raw data were collected from the various systems, with literally no data lost to hardware or software problems over the course of the 40 mission flights. Analysis of the enormous data set will occupy scientists at numerous institutions for some time, but even at this stage, the contributions to operational support of GWOT and to advances in the state of the art in airborne remote sensing are substantial. Additionally, the environmental data collected from the suite of sensors is invaluable to the economic redevelopment of Afghanistan.

[Sponsored by the government of Afghanistan, ONR, and NGA] ★

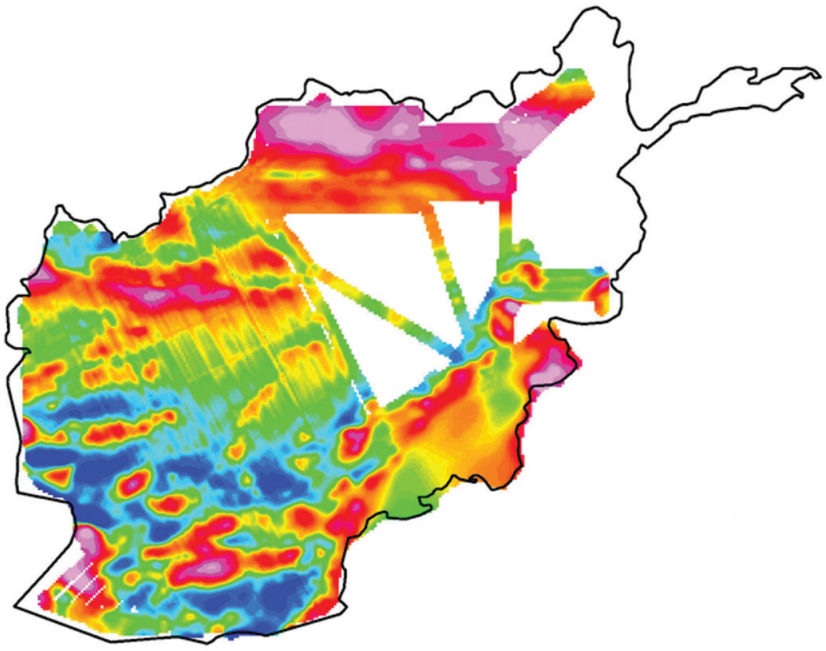


FIGURE 6
Magnetic anomaly map corrected for diurnal variation at Kandahar Airfield. Note the residual diurnal artifacts (streaks following the flightlines) over some high areas of the Hindu Kush mountains. The magnetic data are useful for calculating bulk estimates of the magnetic properties of the local rocks and the depth to the magnetic source material, both useful in oil, gas, and mineral exploration.

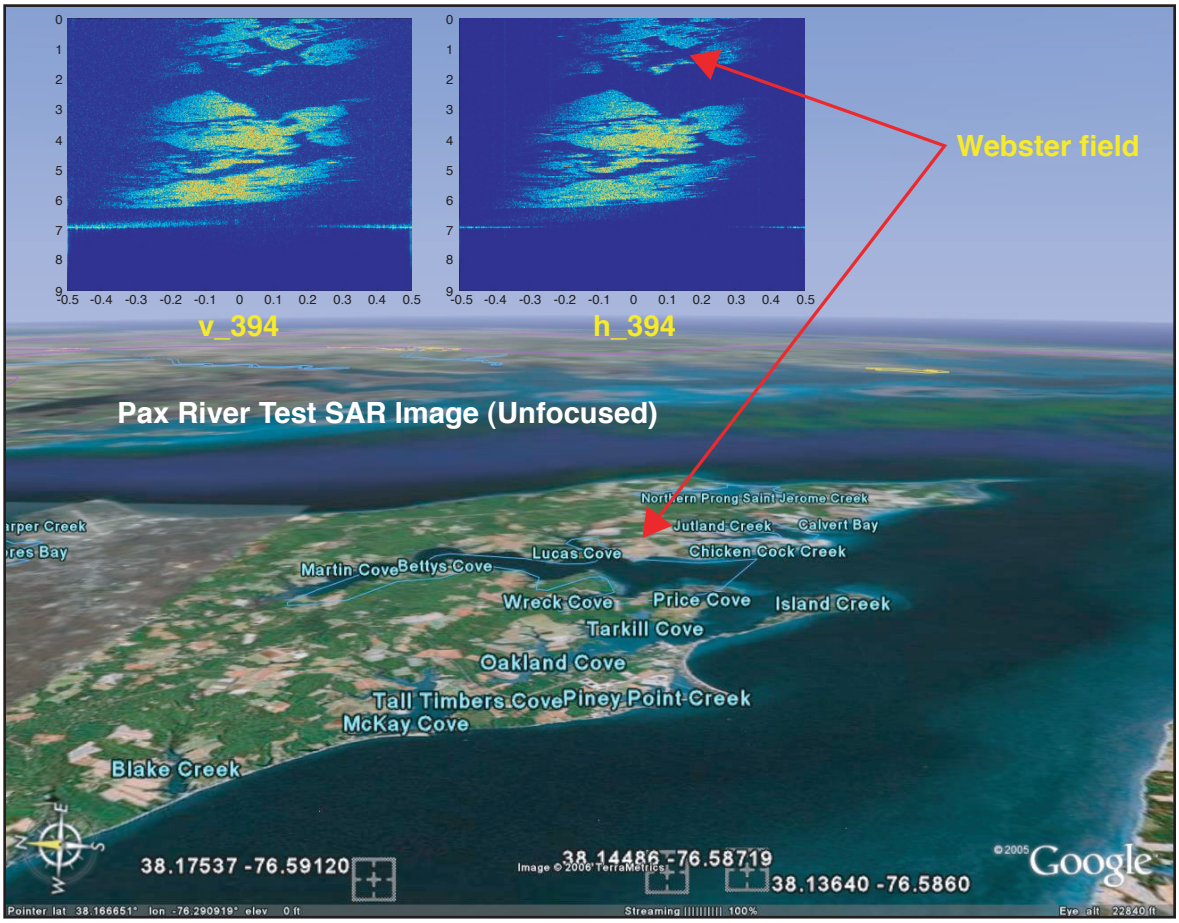
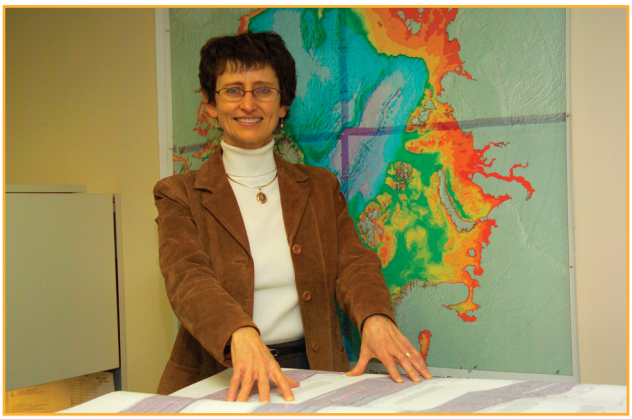


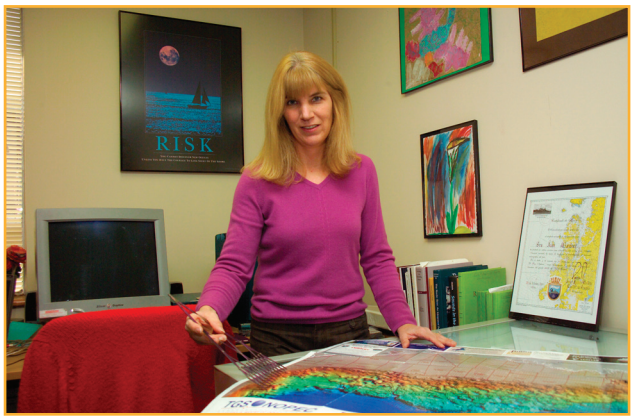
FIGURE 7
Test SAR imagery produced in the vicinity of Patuxent River Naval Air Station prior to deployment to Kandahar. The images have not yet been focused to compensate for variations in aircraft motion and attitude.

THE AUTHORS

JOHN BROZENA is head of the Marine Physics Branch of NRL's Marine Geosciences Division. He received his B.A. in physics from the University of Virginia in 1976, an M.A. in applied mathematics from the University of Maryland in 1986, and a Ph.D. in geophysics from Cambridge University in 1996. He has worked on the development of airborne remote sensing techniques for the past 30 years at NRL and in the process has acquired more than 5000 flight-hours experience in various research projects in geophysics, geodesy, acoustics, and oceanography.



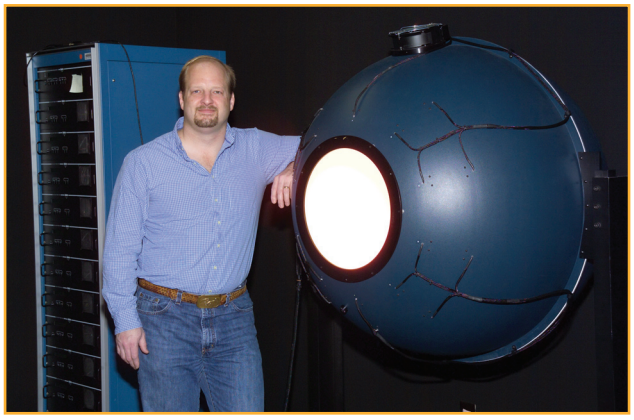
VICKI CHILDERS earned a Ph.D. in geophysics from Columbia University in 1996 with a specialty in airborne gravimetry. She came to work in the Marine Physics Branch in 1996 as a Postdoc and was then hired into the branch. Her work has expanded to include the applications of airborne gravity to geodesy, oceanography, and the assessment of satellite gravity fields from altimetric satellites and the Gravity Recovery and Climate Experiment (GRACE). She is also pursuing the use of radar and laser altimeters for sea ice thickness estimation. Most recently, she has expanded into the field of digital photogrammetry with the Rampant Lion airborne survey in Afghanistan. She has led the effort to establish a center of excellence at NRL for the collection and processing of digital photogrammetric imagery.



JOAN M. GARDNER received her B.S. in geological science from New Mexico State University in 1983, and an M.S. in marine science from Moss Landing Marine Laboratories in 1990. She received a Ph.D. in geology from George Washington University in 2001 under the NRL Edison Memorial Graduate Training Program. She has been employed as a geologist with the Marine Physics Branch since 1993. Her past research activities at NRL have been concentrated on the geologic and geoacoustic characterization of the seafloor through the fusion of data from different acoustic imaging sensors. More recently she has worked on development of a sensor suite to do high-resolution airborne mapping of geologic land surfaces and subsurface geologic basin structures.

ROBERT T. LIANG received his B.S. degree in electrical engineering in 1993 and his M.S. in telecommunications and computers in 1999 from George Washington University. He came to NRL in 1990 as a Co-op student. He is the senior engineer for the Marine Physics Branch, where he has designed and flown numerous airborne sensing and data acquisition systems aboard NRL aircraft. He also has participated in several shipboard experiments.

JIM JARVIS is a retired Naval officer. He received his commission via the Aviation Officer Candidate program at Pensacola, Florida, and completed flight training in June 1969. His Navy career included two operational tours at Moffet Field, California, flying the P-3C; a tour as an instructor in the basic training command; studies to earn a master's degree in acoustical physics from the Naval Postgraduate School; a one-year afloat staff tour with the U.S. Middle East Force Staff; and his final tour flying the P-3 at NRL. Upon retiring from active military duty, Jim joined the Marine Physics Branch in January 1990. Mr. Jarvis has specialized in GPS techniques for precise aircraft positioning. His work with the Marine Physics Branch has taken him all over the world, from Greenland to Antarctica, and from Svalbard to Afghanistan.



JEFFREY BOWLES received a Ph.D. in plasma physics from the University of California, Irvine, in 1992. At the Naval Research Laboratory his work turned to hyperspectral imaging for remote sensing applications. He is currently head of the Coastal and Optical Experiments Section in the Remote Sensing Division. His research is centered in coastal oceanography with efforts in new instrument development and hyperspectral data analysis algorithms. Additionally, he has worked on instrument calibration and characterization, and on aircraft deployments of hyperspectral imagers. He has coauthored five patents, 16 refereed papers, two book chapters, and more than 50 conference proceedings or presentations.