Multisensor fusion over the World Trade Center disaster site

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Abstract. The immense size and scope of the rescue and clean-up of the World Trade Center site created a need for data that would provide a total overview of the disaster area. To fulfill this need, the New York State Office for Technology (NYSOFT) contracted with EarthData International to collect airborne remote sensing data over Ground Zero with an airborne light detection and ranging (LIDAR) sensor, a high-resolution digital camera, and a thermal camera. The LIDAR data provided a three-dimensional elevation model of the ground surface that was used for volumetric calculations and also in the orthorectification of the digital images. The digital camera provided high-resolution imagery over the site to aide the rescuers in placement of equipment and other assets. In addition, the digital imagery was used to georeference the thermal imagery and also provided the visual background for the thermal data. The thermal camera aided in the location and tracking of underground fires. The combination of data from these three sensors provided the emergency crews with a timely, accurate overview containing a wealth of information of the rapidly changing disaster site. Because of the dynamic nature of the site, the data was acquired on a daily basis, processed, and turned over to NYSOFT within twelve hours of the collection. During processing, the three datasets were combined and georeferenced to allow them to be inserted into the client's geographic information systems.
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1 Introduction

The September 11, 2001 attack on the World Trade Center resulted in a seemingly insurmountable rescue and clean-up effort that will continue for months to come. Side by side, firefighters, rescue workers, city, state, and national officials battle the rubble at what has been dubbed Ground Zero. The recovery has been difficult at best, with fires blazing beneath, piles shifting and collapsing. The shear magnitude of the effort is daunting to the most determined recovery worker. Information was and remains the key to reclaiming the World Trade Center site.

Airborne remote sensing was one method to quickly and frequently gather detailed information about the entire disaster area. Hours after the September 11, 2001 attack on the World Trade Center, the New York State Office for Technology (NYSOFT) was tasked with gathering and managing the airborne data collection over Ground Zero. On September 14, they enlisted the help of EarthData International, an airborne mapping and remote sensing company based in Gaithersburg, Maryland. The EarthData team quickly determined that the combined use of three sensors would provide the most detail to the recovery workers on the ground. The light detection and ranging (LIDAR) system, a high resolution digital camera, and a thermal camera would provide highly accurate maps of the site, allowing measurement of the rubble and shifts in the surrounding buildings, as well as monitoring the movement and temperatures of the fires burning below.

2 Data Collection Overview

EarthData's rapid response team was assembled at EarthData Aviation's hangar in Hagerstown, Maryland. However, the aircraft, which at the time was southwest of Washington D.C., had to be outfitted for the project. Since the airspace was closed to all flights, special flight permission and coordination was needed just to fly the aircraft to Hagerstown. Once the Navajo Chieftain arrived at the hangar, the equipment installation and premission checkout began. At the same time, preparations were being made to relocate a subset of EarthData's data processing team, complete with computers and all peripherals, to the NYSOFT offices in Albany, New York. By early afternoon on September 15, the EarthData team had established a data processing center in Albany.

The Navajo Chieftain, with a two-man crew of a pilot and an airborne operations coordinator, flew from Hagerstown on the morning of September 15 to conduct the first flight over Ground Zero, collecting LIDAR and digital photography data. The plane landed in Albany in the early afternoon and the data was rushed to the processing center where several products were generated for the rescue and recovery teams. The LIDAR provided a digital elevation model (DEM) that may be viewed as a three-dimensional perspective of the scene. Elevations can be determined from the DEM to within 15-cm accuracy. From this data, engineers and teams on the ground could calculate the volume of the rubble piles and track their movement and changes, as well as those of other damaged, but standing, buildings.

Simultaneously, the digital images were merged together to provide one large high-resolution, geometrically correct image over the disaster site. The data, transferred to NYSOFT within 8 to 12 h after landing, was delivered to engineers, rescue workers, and recovery teams in the field. At sunrise on September 16, the Navajo Chieftain was again flying over ground zero, this time to collect thermal imagery. The data was immediately processed in Albany, delivered to NYSOFT, and the New York State Police escorted the thermal images to the site at the city pier, where they were imported into a geographic information system that allowed emergency response crews to locate and track the movement or abatement of the underground fires.

After the two initial data collections were complete, a routine was established that generally involved thermal data collection in the morning, with LIDAR and digital imagery collected midday. A total of 43 missions were flown between September 15 and October 22, 2001. There were only four days with no data collection due to unfavorable weather conditions or scheduled aircraft maintenance.

3 Sensor 1: LIDAR System

Light **d**etection **a**nd **r**anging (LIDAR) systems for mapping purposes are used to generate digital elevation models (DEMs). EarthData's AeroScan LIDAR system, developed by LH Systems of Westford, Massachusetts, scans the ground at a high data rate, emitting a laser pulse and measuring the time of return of the reflective energy to determine the distance from the sensor to the object. This range information is combined with data from a positioning and orientation subsystem to generate the three-dimensional coordinate of the object.

The system used for data collection over the World Trade Center site consists of two major subsystems, the scanner assembly and the equipment rack, which can be further subdivided into individual components (see Fig. 1).

The scanner assembly contains a laser power supply that generates energy and transmits it to a diode-pumped laserhead operating at a wavelength of 1064 nm and a maximum pulse rate of 15 kHz. The laser provides the sensor with a minimum range of 350 m and a maximum range of 7,700 m.[1] A single photodiode detects the energy leaving and returning to the system. Outgoing laser energy is reflected off a large mirror that oscillates to aim the energy toward the earth. The mirror, driven by a galvanometer, sweeps the ground perpendicular to the direction of flight at frequencies up to 25 Hz with an off nadir scan angle from 2.5 to 37.5 deg. The perpendicular scan coupled with the forward motion of the aircraft creates a continuous sinusoidal scan pattern on the ground (see Fig. 2). The angular position of the mirror is measured by a high-accuracy optical encoder, which is sampled every time a laser pulse is emitted, giving the angular position of the mirror at the time of emission.

Fig. 1 The LIDAR system.

Positioning and orientation information is obtained from the positioning and orientation system (POS). The first component of the POS is a dual frequency global positioning system (GPS) receiver that is used to determine position (latitude, longitude, and altitude) of a GPS antenna mounted on top of the aircraft. An inertial measurement unit (IMU) records all movement and the orientation of the scanner body (roll, pitch, heading, three axis velocity, and acceleration) for the entire airborne data collection mission (see Fig. 2).

The equipment rack contains a system control computer that provides the operator with a single graphical user interface (GUI) to control all elements of the LIDAR system. The LIDAR control computer sends commands to and receives data from the various components of the system, while a data logging computer records information on the scanner position, timing, and ranges from the LIDAR sensor and the images from the Kodak 16.8i digital panchromatic camera.

3.1 *Creation of a Single Data Point*

Prior to take-off, the operator powers the equipment and begins recording the GPS and IMU data from the POS unit. As the aircraft approaches the job site, the operator powers the LIDAR system, using the control computer to set the appropriate scan rate and pulse rate and to begin generation of the energy emitted from the laser transmitter at the desired pulse rate. Once over the job site, the operator sends the command to commence data logging of LIDAR information, including the encoder reading, the range to the ground, and the GPS time of emission.

The path of a single pulse begins with the laserhead emission. At the time of the pulse, a small portion of the energy travels to the detector to create a start pulse. The remaining pulse energy reflects off of the scanning mirror toward the ground, while a simultaneous encoder reading is made.

The emitted laser energy travels through the atmosphere toward the ground. The energy is then reflected off of objects on or above the surface of the earth and returns to the sensor. Each returning bundle of energy above a predeter-

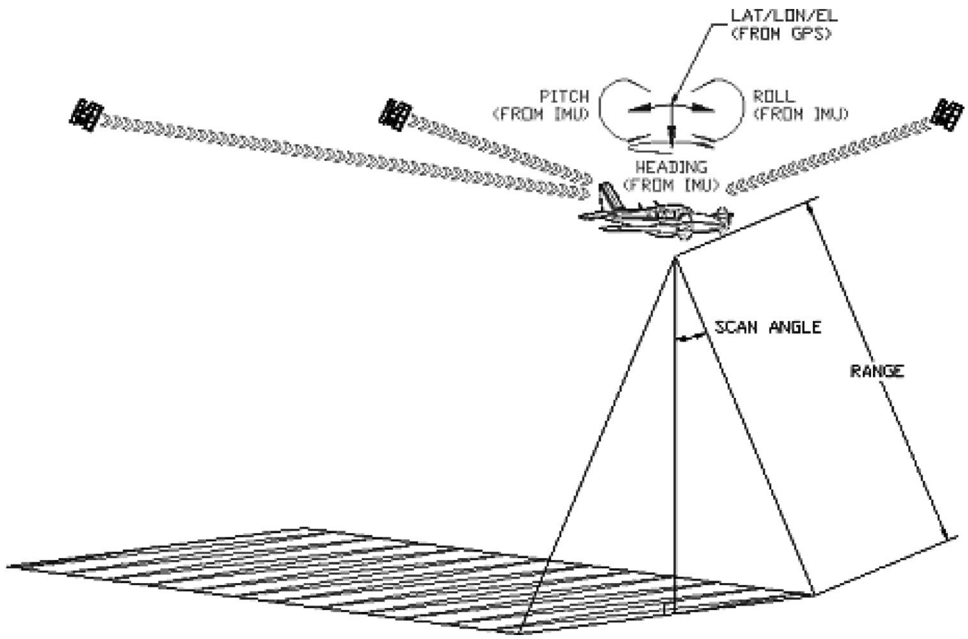

Fig. 2 Operational overview (courtesy of Leica Geosystems, LH Systems of Westford, Massachusetts).

mined energy level is considered a return. For example, the energy pulse may first hit the top of a tree canopy with a portion that reflects back toward the sensor yielding a return. The remaining portion of the energy continues to travel toward the ground, yielding a second return. This system can record up to five such returns for each emitted pulse.

As reflected energy returns to the LIDAR system, it is reflected off of the scanning mirror and into the receiver that records the elapsed time of the returning pulse. The time interval between the start and return pulse is measured by using an ultrahigh frequency oscillator (subnanosecond time interval counter). Using the oscillator time interval between the start and return pulses, the range between the LIDAR system and the reflected object can be calculated. All the pertinent information related to that specific pulse is then recorded by the data logging computer. The recorded information includes the GPS time of emitted pulse, encoder reading, and elapsed time of each return pulse.

The process described is repeated 15,000 times a second during the airborne data collection.

3.2 *Basics of LIDAR Data Processing*

After the airborne data collection, the raw LIDAR data consists of only times and scan angles that must be transformed into a DEM. The first step of DEM creation is the GPS and IMU processing. The GPS phase data is processed using continuous kinematic survey techniques, resulting in a trajectory centered about the phase center of the aircraft's GPS antenna, accurate to within approximately 10 cm.

The next step is to process the IMU data. Several pieces of information are required, including the calculated GPS position and the location of the GPS antenna and the scanning mirror in relationship to the IMU. These locations are defined by a series of linear offsets and coarse orientation angles. The IMU data is then processed using Kalman filters to integrate the inertial measurements and the precise phase differential GPS positions. Now the geodetic position and the orientation (omega, phi, and kappa) of the scan mirror at any point in time are known.

The next step is to utilize the time and ranging data collected by the data logger. This data is used in conjunction with the known sensor position and orientation to calculate a three-dimensional coordinate on the ground using GPS time as the common link between the two data sets.

Although in theory the calculations to determine the coordinate of a point on the ground may seem obvious, there are many steps involved. Transformations must be performed between many different coordinate frames, including the IMU frame, the scanner-housing frame, the earth-centered earth-fixed frame, and the final mapping frame, just to obtain a single coordinate. The effect of the atmosphere on the travel path and travel time of the laser pulse must also be considered. Additionally, a series of small corrections must be applied to the orientation angles obtained from the IMU. These corrections, known as boresite angles, account for small variations between the known mounting of the IMU and the actual measurements being obtained. Mathematical models representing systematic effects of the sensor are also applied to the data.

After completion of the LIDAR data processing a LIDAR DEM (mass point file) is generated. The LIDAR DEM is then compared to a series of ground control points to verify its accuracy. These ground control points can come from various sources, but are generally established using conventional static GPS surveying methodologies. During these comparisons, the LIDAR DEM routinely agrees vertically to within 15 to 20 cm of the ground control points. This level of processing results in a DEM representing all returns from the reflective surface.

4 Sensor 2: Digital Camera System

In addition to the LIDAR system, EarthData used a high-resolution digital camera to collect data over the World Trade Center site. The goal of this data collection was to quickly provide rescue workers with a more classic image product over Ground Zero.

The digital camera system used, a Kodak Megaplus Model 16.8i, is rigidly mounted to the LIDAR sensor housing and utilizes the same positioning and orientation system described before. The camera is fabricated into a single housing approximately $11.4 \times 10.16 \times 25.4$ cm and is designed to accept a Rollei series lens. For this project, a 90-mm focal length lens was used. The camera features a charge-coupled-device (CCD) array containing 4096 (H) $\times$ 4098 (V) light sensitive pixels, with each pixel measuring 9 μm, zero fill factor. The camera provides 8-bit output with 256 gray levels per pixel.[2]

The system is operated and monitored with a control computer and software developed by the Ohio State University Center for Mapping. This computer is connected to the camera via RS422 serial communications. The system operator can view captured images in real time through the system control software and make any changes necessary to achieve the proper exposure. Individual frames are captured by receipt of a control pulse from the aerial survey control tool (ASCOT) software from LH Systems. ASCOT is a precision navigation system that provides GPS-based navigation information to the pilot and triggers the camera at specific GPS locations. The camera system is time synchronized to the GPS for subsequent position and orientation determination of each exposure using the same GPS and IMU sensors as the LIDAR. These parameters are commonly referred to as exterior orientation parameters.

Once the data collection is complete, the data is transferred from the aircraft to the office via removable hard drives. Any necessary postprocessing is then performed on the data.

4.1 *Basics of Digital Imagery Processing*

When initially collected, the digital images are arrays of grayscale pixels that must be related to actual locations on the ground. A constant offset exists between the GPS unit, the IMU, and the camera focal plane, each of which has an independent reference frame. The GPS operates in the WGS84 coordinate frame, the IMU in the inertial frame, and the camera in its own body reference frame. The relationship between each of these components is determined through several calibration processes. One of the processes is the measurement of the offset between the GPS antenna and the IMU using standard survey measurements. The second process involves a comparison of the position and orientation computed from an aerotriangulation solution over a boresite with the results from the GPS/IMU solution. The resultant alignment angles are then used in the inertial solution to compute a set of exterior orientation parameters (X, Y, Z, roll, pitch, heading) for all photographs. Figure 2 depicts these parameters relative to the aircraft. Thus the exterior orientation parameters provide the location and orientation of the camera for every image.

The next step in the image processing is orthophoto rectification. Rectification is the process of projecting an image to the mapping plane and removing displacements due to relief.[3] The rectification process requires several pieces of information, including the digital images, exterior orientation parameters, interior orientation parameters (defining camera geometry), and LIDAR digital elevation data to correct for terrain relief issues. Using these inputs, the images are processed with proprietary orthophoto rectification software to remove image displacement due to topographic relief and the pitch, roll, and heading of the aircraft at the time of exposure as well as distortions in the camera lens and CCD array. All of the orthophotos are checked for missing data and distortions of above-ground features. Finally, adjoining images are overlapped to verify a clean geometric fit.

Radiometric processing is used to adjust image tones to account for variations between photos that may be caused by uneven lighting conditions during data capture, and mosaic cut lines are selected between adjoining images. The center portion of the frames are used to reduce apparent building lean from optically oblique look angles, and the cut lines are selected to avoid cuts through elevated manmade features. Feathering of the match lines between frames hides the seam, resulting in a single image mosaic made of multiple smaller images.

5 Sensor 3: Thermal Infrared Camera System

The third sensor used over the World Trade Center site was a thermal infrared camera system. The thermal camera selected was the FLIR ThermaCAM PM 695, a radiometric thermal camera developed by FLIR Systems of North Billerica, Massachusetts.

The PM 695 is a handheld camera that was developed for a wide variety of applications including predictive maintenance of industrial plant subsystems. Because it was designed as a handheld sensor, the dimensions of the PM 695 are relatively small at $22.1 \times 13.2 \times 14.0$ cm and it

Table 1 Data collection scenarios over the World Trade Center site.

Thermal		
Flying height	915 m AMT	
Airspeed	90–115 knots	
Average swath width	192 m	
Field of view	12 deg	
Ground sample distance	0.61 m	
LIDAR		
Flying height	915 m AMT	1524 m AMT
Airspeed	100–130 knots	90–115 knots
Laser pulse rate	15 kHz	15 kHz
Average swath width	405 m	675 m
Field of view	25 deg	25 deg
Scan rate	13 Hz	13 Hz
Post spacing	2–5 m	2–5 m
Digital Camera		
Flying height	915 m AMT	1524 m AMT
Airspeed	100–130 knots	90–115 knots
Average swath width	372 m	620 m
Field of view	23 deg	23 deg
Ground sample distance	0.09 m	0.15 m

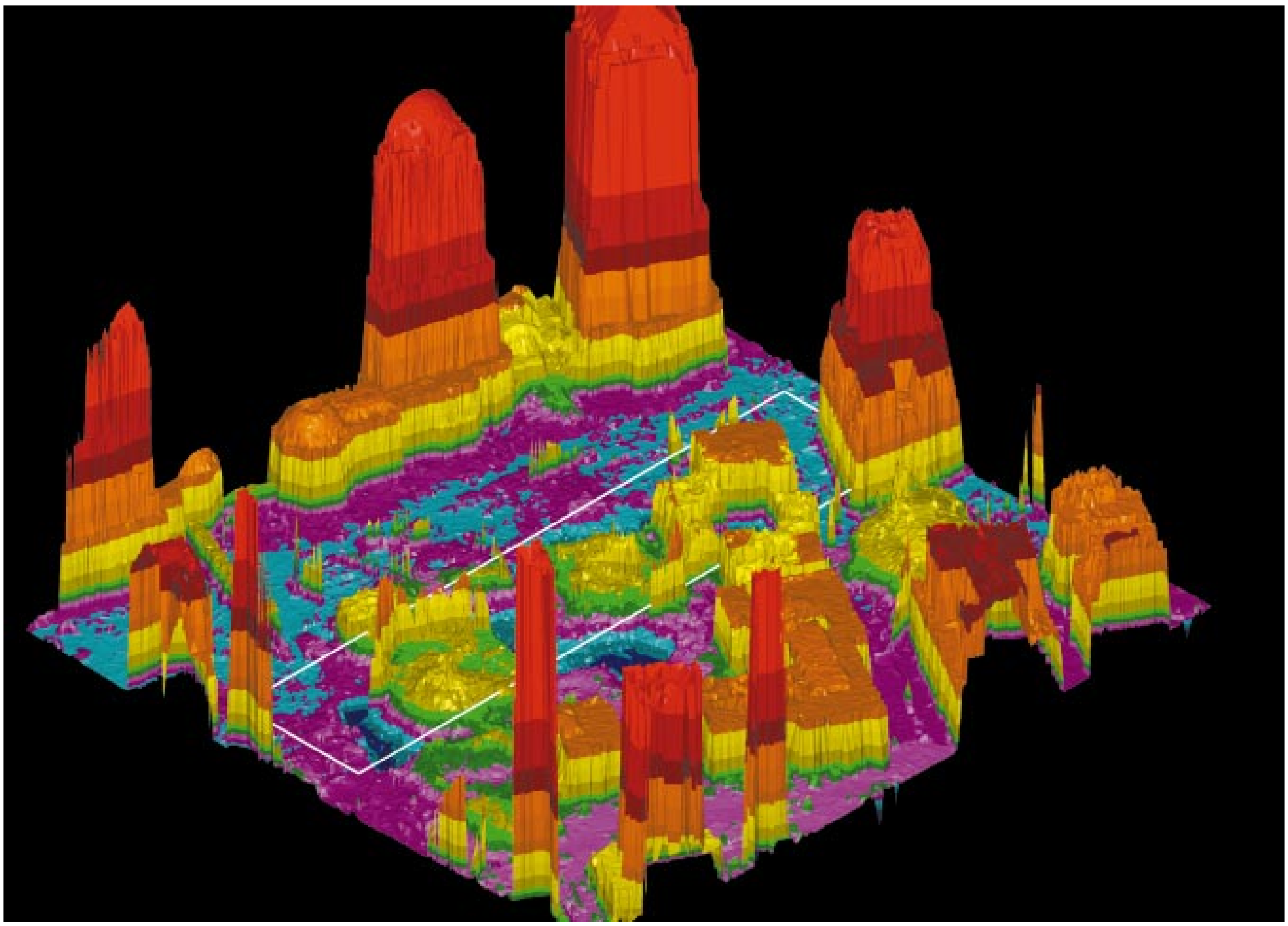

Fig. 3 LIDAR 3-D perspective of the World Trade Center site. The image is color-coded based on elevation.

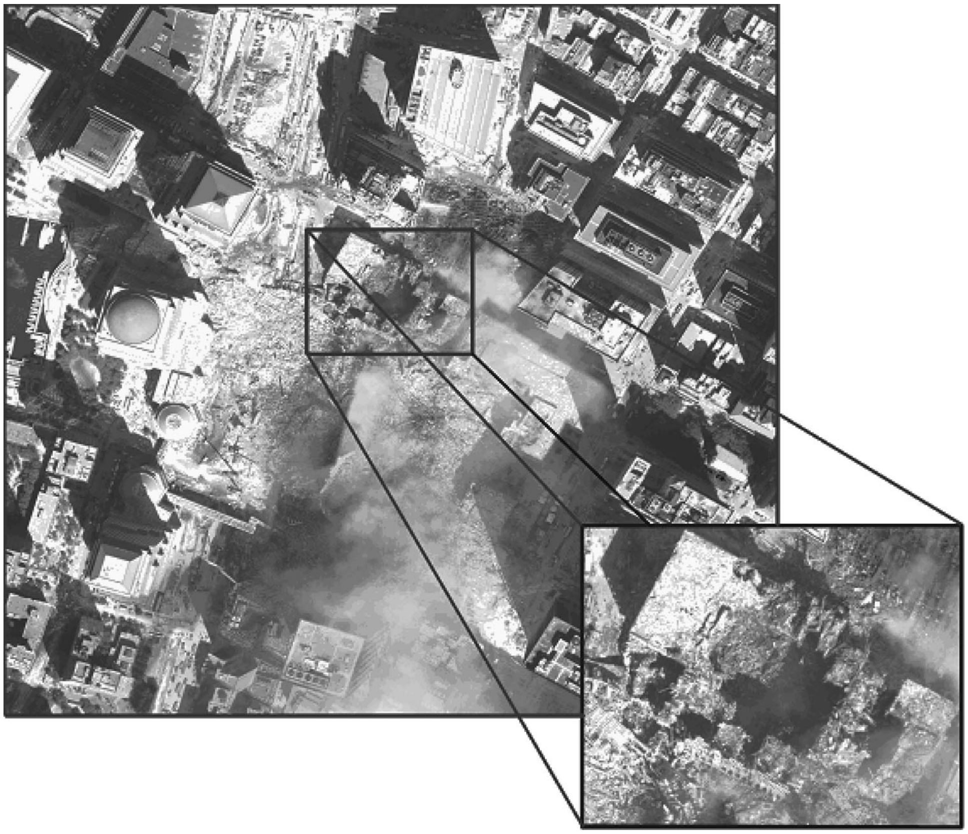

Fig. 4 Digital orthophoto over World Trade Center site taken September 15, 2001, with detail of Building 6.

weighs only 1.9 kg. The detector is an uncooled microbolometer focal plane array that contains 320 by 240 pixels. The sensor has a spectral response from 7.5 to 13 μm and a thermal sensitivity of 0.1°C at 30°C. The sensor can detect in a temperature range of -40 to 1500°C.[4]

The PM 695 provides the user with several data storage techniques, one of which is writing a continuous stream to a video recording device. In addition, the camera can record individual frames to a PCMCIA card, which is the method applied during the data collection over Ground Zero. The PCMCIA card provides an easy medium for data transfer between the aircraft and the processing center.

5.1 *Basics of Thermal Imagery Processing*

After the thermal imagery is captured, the native 14-bit radiometric thermal data is loaded into the FLIR Systems Researcher software to perform an initial analysis of the dataset. This analysis pinpoints minimum and maximum temperatures in the entire scene, as well as user-defined areas of interest.

The thermal data is then exported into a comma-separated file, ready to import into other software packages. Once the individual frames are exported, they are adjusted for compatibility with an 8-bit grayscale and then converted into 8-bit images. The individual images are then mosaicked together to form a single TIFF image. The TIFF images are georeferenced to the orthophotos by selecting common tie points in the two images and performing a mathematical transformation. After the georeferencing, extraneous noise hot spots, such as cranes and vehicles in the case of the World Trade Center site data, are removed. The thermal data is then cut at specific areas to create a rectangular image. Finally, the image is converted to a 32-bit file, the original temperature range is restored, and it is saved in a file format for geographic information system (GIS) applications.

For quality control, the temperature range of the final image is compared to the temperature range of the original thermal histogram. The data file is overlaid on the orthophotography in a GIS software package, comparing the horizontal locations of objects to ensure a consistent dataset.

6 Multi-Sensor Fusion Over the World Trade Center Site

Although the exact data collection over the World Trade Center site varied slightly from day-to-day based on weather and onsite requests, a standard was established for collection of what would be defined as a full day of flight. On these days, the aircrew departed their mission base in Albany, New York, arriving over Ground Zero around seven o'clock in the morning. The aircrew then collected thermal imagery and digital imagery at 915 m above mean terrain. At this time in the morning there was minimal solar heating, so the ground and other objects in and around Ground Zero were relatively cool, allowing the hot spots to stand out clearly. The digital imagery collected during the early flight was delivered to the client as a quick, unrefined

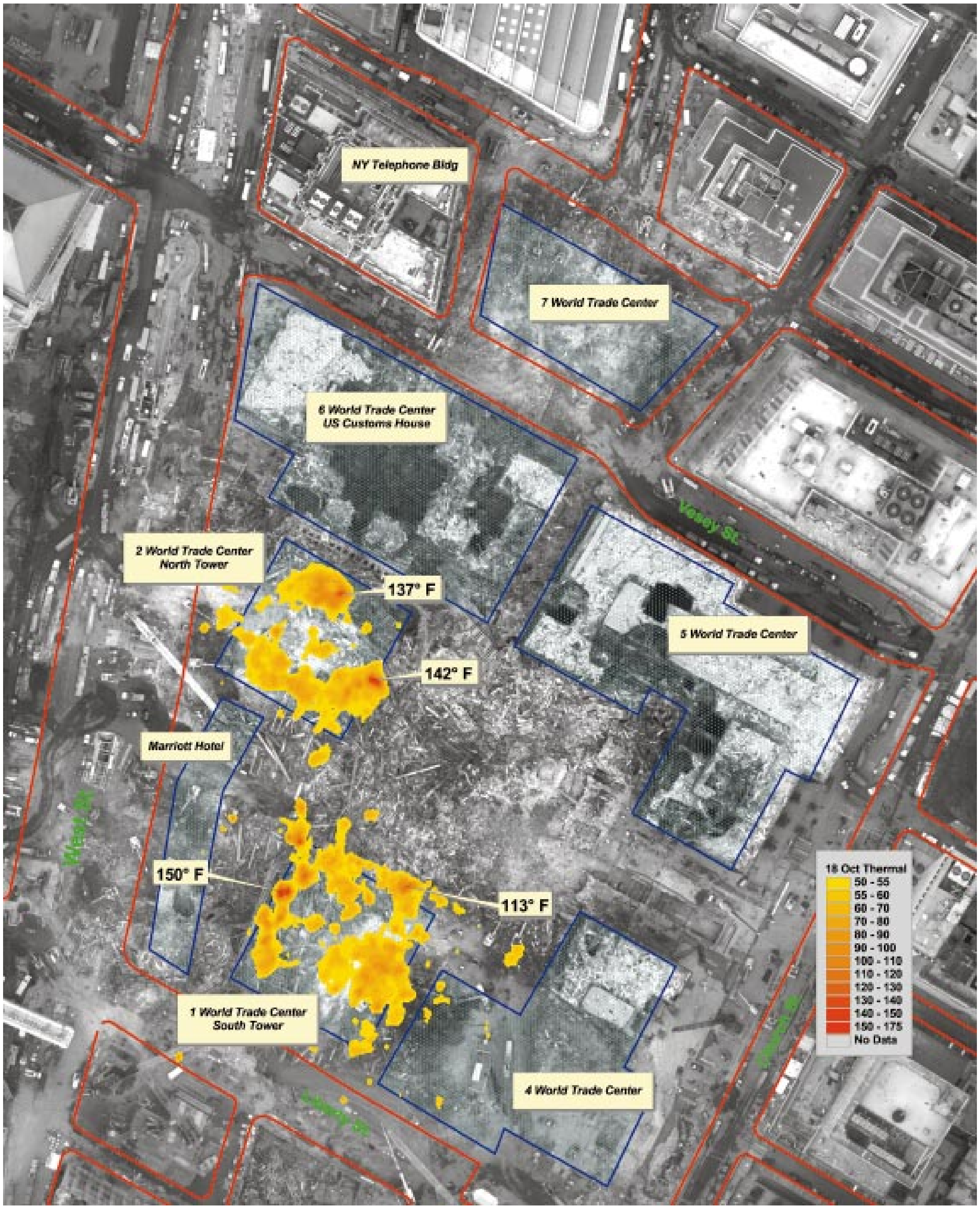

Fig. 5 Thermal data collected over the World Trade Center site on October 18, 2001, overlaid on digital orthophotography collected on October 7, 2001. Building footprints are shown in blue and streets are shown in red.

look at the disaster site. A second flight occurred midday when the sun was higher and in a favorable position over the job site to reduce the shadows from the tall buildings. The afternoon flight data was collected at 1524 m above mean terrain. During this data collection, LIDAR data was collected along with digital imagery, providing the data that would be used to generate the final DEM and image products. In addition to the flights over the project area, the afternoon flights also included a series of boresite or calibration lines. The various collection scenarios over the World Trade Center site are summarized in Table 1.

All data was transferred to the processing center in Albany from the aircraft using removable hard drives and PCMCIA cards. The GPS and IMU data for the mission were processed using the previously described procedures. Next, the LIDAR boresite flight lines were analyzed to develop the boresite angles and confirm final calibration for the flight. The data was then compared to a series of ground control points established by the National Geodetic Survey (NGS) at Liberty State Park to refine and evaluate the vertical accuracy of the DEM. Finally, all of the LIDAR data was processed with the newly developed boresite angles and calibration data.

For the World Trade Center site, the client required digital elevation models of the reflective surface so that they could see all of the debris, buildings, and rubble. After the initial processing, the LIDAR data was processed with an automated filter to remove obvious noise. In addition, a technician reviewed the data as a final quality control step. The processed LIDAR data was then transformed into the New York State Plane Coordinate System, Long Island Zone as requested, and trimmed so that only the data near Ground Zero was delivered. With this relatively minor amount of user intervention, the final LIDAR DEM was complete. Figure 3 is a graphic representation of the digital elevation model data.

The digital imagery, like the LIDAR, was transferred to the office via removable hard drives. The images were then examined and a subset selected over the area of interest based on quality. The images were orthorectified, radiometrically adjusted, and mosaicked, as described before. During the orthorectification process, the LIDAR DEM was used to correct relief displacement in the photography.

Upon completion of these steps, the final area of interest was then cut from the geometrically and radiometrically corrected orthophoto mosaic and the image was visually checked to insure quality. Figure 4 is an example of a typical orthophoto mosaic over the World Trade Center site. These orthophotos were instrumental in constructing a base layer map for geographic information systems used by emergency crews.

After the LIDAR processing and ortho-mosaicking were finalized, both the LIDAR and the digital image data sets were georeferenced or related directly to the user coordinate frame on the ground. Therefore, in geographic information systems (GIS) software packages, they would physically lie on top of one another and coordinates of features could be read from the data. For example, local New York City data was also used in a GIS to correlate preexisting features such as power and water lines to the debris field.

The final dataset to be processed and referenced was the thermal imagery, using the process described before. In addition, a quick look of the thermal data was provided as a summary sheet for the immediate area surrounding the World Trade Center Towers. The summary sheet contained a representative thematic image of the area with an associated temperature scale. In addition, hot spots and scene temperatures were identified and listed in a table on the summary sheet. This information was then immediately forwarded to NYSOFT for distribution. Figure 5 is an example of a thermal data set, including the temperature range scale, overlaid on an orthophoto. Several points of interest and temperatures have been identified for informational purposes.

7 Benefits of Fused Airborne Datasets as a Critical Recovery Tool

The terrorist attacks against the United States on September 11, 2001 have made their mark on the nation and indeed the world. The clean-up efforts remain a challenge to the emergency agencies and personnel who still face the round-the-clock task of reclaiming the World Trade Center site.

The necessity for frequent updates on conditions at the disaster site dictated the use of digital sensors. By using digital sensors, the number of steps required to generate the final product were reduced, thus minimizing delivery time. In addition, the digital products allowed the datasets to be fused together shortly after collection. Although each dataset provides useful information by itself, the fused dataset is much more powerful. The digital images may show a rubble pile, but with overlaid LIDAR data, the elevation of the pile can be quickly queried and volumes calculated. The thermal images identify hotspots, but when the thermal is overlaid on the digital images, the rescue workers can quickly orient themselves on the ground.

Although much ground-based data was also collected and used by emergency crews, the airborne data provided a synoptic view of the disaster site. This provided a base for accurate display and location of data collected by the emergency crews. Additionally, the multisensor data aided the emergency crews in deployment of assets, rapid location of underground utilities buried in the rubble, volumetric calculations of the debris removal, and monitoring progress and extinction of the numerous fires. The World Trade Center disaster emphasized the criticality of providing the right data in a timely manner and format for emergency response situations.

Careful analysis of the optimum data set required for various emergency response situations will result in identifying the ideal suite of sensors required to provide the needed information. EarthData is currently involved in such an effort, and continues its work toward defining the various emergency response data collection platforms.

The World Trade Center disaster has been a learning experience. This experience is a model on which to base the new generation of emergency response agencies. Through this experience both vendor and end user are continuing to realize the how, what, where, and when of emergency response mapping. Optimization of the data types and the methodologies of data integration into current and future GIS systems are the objectives for the mapping profession.

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Craig Rodarmel is an engineer for EarthData Aviation located in Hagerstown, Maryland. He works with the LIDAR system and focuses primarily on LIDAR data processing and related issues. In addition, he works with the processing of the GPS and IMU data. He is also currently involved in the acquisition and implementation of new sensor technology into the EarthData group. He was responsible for the LIDAR data processing and assessment and thermal data integration for the WTC project. He holds an MS in civil engineering and a BS in civil engineering and land surveying engineering from Purdue University, West Lafayette, Indiana.

Lawrence Scott is a California licensed land surveyor with more than 20 years of experience. He has been involved with geodetic applications of GPS since 1988. Prior to his involvement with GPS, his focus was in high precision geodetic control surveys using classical methods of triangulation, invar leveling, and large area networks in both field survey and office reduction. His responsibilities at EarthData Aviation have included airborne GPS and inertial measurement technologies, as well as photogrammetric control. His unique position at EarthData Aviation has been in mission planning, execution, and data reduction. He has been at the forefront of EarthData Aviation's LIDAR program from hardware development to field data collection as well as quality control and post-mission assessment. For the WTC projects his involvement was equally divided among all facets of the data collection for all 43 sorties.

Deborah Simerlink is currently the Technical Operations Manager at EarthData Aviation. She started with the company four years ago as the systems engineer for the AeroScan LIDAR system acquisition and implementation. She has been involved in the development of GPS, IMU, and LIDAR data processing procedures, as well as technical support of all of EarthData's data collection equipment. She is also a key player in the integration of new technologies into production work flow. She was responsible for project management, client interface, and GPS and IMU data processing for the WTC project. She holds a BS degree in systems engineering from Wright State University, Dayton, Ohio.

Jeffrey Walker works at EarthData Aviation where he is responsible for research in the areas of surveying, mapping, geodesy, photogrammetry, remote sensing, and GIS, and for the development of models and systems for collection and analysis of spatial data. This research includes providing software support and technical expertise in the integration of various technologies into advanced digital and automated information systems. For the WTC project, he was responsible for establishing the computer network at the Albany data processing office. He was also instrumental in sensor integration and data exploitation. He holds a MS in surveying engineering from Purdue University, West Lafayette, Indiana, and a BS degree in computer science from Old Dominion University, Norfolk, Virginia.