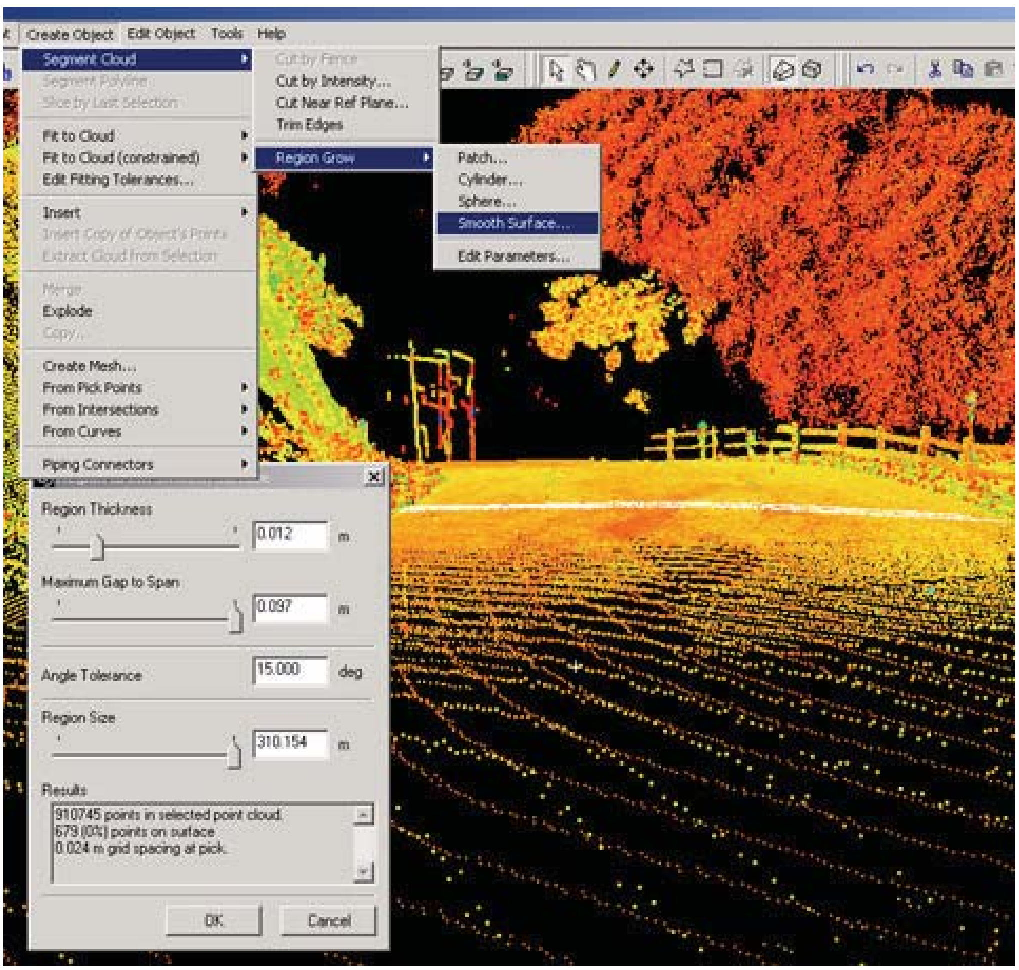
ADVANCED SURVEYING AND MAPPING TECHNOLOGIES

Systems Overview & Applications

Publication No. FHWA-CFL/TD-08-002 **May 2008**



U.S. Department of Transportation
Federal Highway Administration

Federal Lands Highway
Commitment to Excellence

Central Federal Lands Highway Division
12300 West Dakota Avenue
Lakewood, CO 80228

FOREWORD

Within the primary role of transportation engineering and stewardship of highways and bridges over federally owned, and Tribal, lands, the Office of Federal Lands Highway (FLH) of the Federal Highways Administration (FHWA) promotes development and deployment of applied research and technology applicable to solving transportation related issues. The FLH provides technology delivery, innovative solutions, recommended best practices, and related information and knowledge sharing to Federal agencies, Tribal governments, and other offices within the FHWA.

Surveying and mapping in support of environmental planning, design, right of way, construction, and rehabilitation is essential throughout the project delivery process. Due to the nature of typical FLH projects, including remote locations and challenging terrain, these important tasks often represent critical elements to schedule and cost. The FLH has long recognized the importance of high quality, efficient surveying and mapping technology, having pioneered development and deployment of innovative solutions such as electronic data collection and processing, and global navigation satellite system (GNSS) surveying. These experiences, and others, have demonstrated the value in recognizing advances before they become routine or obsolete.

This study was undertaken to assess, in a comprehensive way, the state and applicability of emerging technologies for surveying and mapping work. Particular focus was directed toward ground based laser scanning and airborne positioning and mapping systems. As one of the few professional design and construction agencies with national scope, the FLH provides leadership for sound professional practices. This study of Advanced Surveying and Mapping Technologies is directed at fulfilling that leadership role, while ensuring value for our client's projects.

F. David Zanetell, P.E., Director of Project Delivery
Federal Highway Administration
Central Federal Lands Highway Division

Notice

Quality Assurance Statement

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16. Abstract

This report presents a study, with resulting conclusions, to investigate emerging surveying and mapping technologies, and their applicability to typical assignments of the Office of Federal Lands Highway (FLH) of the Federal Highways Administration (FHWA). This study, conducted in 2002 and 2003 included a review of professional publications, interviews with internal and external consumers and providers of surveying and mapping data, together with field evaluations of certain specific systems. While the study was open to the broad spectrum of emerging technologies at the time, particular focus was directed toward ground based laser scanning and airborne positioning and mapping systems.

Field evaluations of different laser scanner systems, over a previously mapped project, details the advantages and limitations of the instruments and software, and highlights specific conditions most favorable to ground based laser scanning methods. Testing of airborne positioning and attitude determination using global navigation satellite system (GNSS) surveying combined with an inertial guidance system (INS) was shown to provide significant efficiencies for route surveying, particularly where ground control surveys are restricted due to terrain or environmental constraints.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	Millimeters	mm
ft	feet	0.305	Meters	m
yd	yards	0.914	Meters	m
mi	miles	1.61	Kilometers	km
		AREA		
in^2	square inches	645.2	Square millimeters	mm^2
ft^2	square feet	0.093	Square meters	m^2
yd^2	square yard	0.836	Square meters	m^2
ac	acres	0.405	Hectares	ha
mi^2	square miles	2.59	Square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	Milliliters	mL
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	Grams	g
lb	pounds	0.454	Kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	Lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	Newtons	N
lbf/in^2	poundforce per square inch	6.89	Kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	Inches	in
m	meters	3.28	Feet	ft
m	meters	1.09	Yards	yd
km	kilometers	0.621	Miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	Acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	Gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	Ounces	oz
kg	kilograms	2.202	Pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	Poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The subject study was performed in 2002 and 2003 to assess the applicability of advanced surveying and mapping technologies to typical assignments at the Federal Lands Highway Divisions of the Federal Highways Administration. Ground-based laser scanning systems had been identified as an emerging technology that could have applications for surveying and mapping tasks. The study included field demonstration of laser scanning methods on an existing project site in Riverside, California. Visibility limitations from steep terrain and dense brush prevented successful topographic mapping over many of the target locations. Ground-based laser scanning found advantage in those limited applications where visibility and access was not overly complicated, and where the rich detail and accuracy afforded by point cloud data could be exploited. Possible example applications could be documentation of historical resources, or detailed mapping of structures. Airborne Light Detection and Ranging (LiDAR) is similar to ground-based laser scanning, but its downward looking perspective, and the rapid linear coverage, is more applicable to route surveying. Massive amounts of data points are available from a LiDAR mission, providing possibilities for visualizations and virtual topographic mapping through the point cloud data. Airborne LiDAR also finds limitations with visibility through dense vegetation, so heavily forested areas and thick brush are not the best applications. Consideration must also be given to the inability of LiDAR to accurately identify breaklines. Projects with critical features such as curbs or drainage features may require additional work to be correctly depicted. The study included demonstration of airborne positioning technology used in LiDAR systems. The demonstration project used GPS and inertial measurement to supplement ground control for analytical photogrammetry. This combination afforded a 75% reduction in the required ground control for the project.

Since these demonstrations, Central Federal Lands Highway Division has continued to explore new instrumentation and software to enhance surveying and mapping functions. Continuing education and vision will be necessary to prepare for technological changes still emerging.

CHAPTER 1 – INTRODUCTION

The subject project was completed under Contract No. DTFH68-00-D-00002, as Task Order No. DTFH68-02-T-00018. The investigation and study was tasked to assess the application of advanced surveying and mapping technologies to typical project assignments completed by the Central Federal Lands Highway Division (CFLHD) of the Federal Highways Administration (FHWA). Particular emphasis was placed on ground-based laser scanning instruments for topographic mapping projects. Field demonstrations of two laser-scanning instruments were conducted over previously mapped segments of Bautista Canyon Road (CA PFH 224) in Riverside County, California. Professional publications and manufacture's literature was reviewed to describe the different capabilities of the hardware and software studied.

A half-day seminar was developed and presented to personnel at the three Federal Lands Highway Divisions (FLHD). This seminar provided an overview of available surveying and mapping technologies, together with advantages and disadvantages as applied to typical project assignments. Copies of the slides presented in this training are included in Appendix A.

CHAPTER 2 – SPATIAL DATA SCIENCES AND TOOLS

Surveying and mapping exists within, and is greatly influenced by, a larger context of spatial data science. This broad subject area includes technologies such as information management, remote sensing, geographic information systems (GIS), the Internet, and other communication technologies. To look only at the specifics of surveying and mapping applications would ignore the significance of this rapidly changing context. Central Federal Lands Highway Division, like most other design services organizations, is asked to provide answers to complicated issues with increasingly faster turnaround, and to incorporate into them the data and analysis from a wide range of sources. The availability of off-the-shelf data sources such as stock aerial imagery and pre-packaged digital terrain data offers faster turnaround for decision makers. It also demands increased knowledge and understanding of geodetic datum, map projections, and relative accuracies for those who are charged with assembling this information. Continuing education and training programs then become an important component for any organization serious about implementing advanced technologies.

Free and inexpensive data sources were identified as one of the most valuable resources available to augment conventional surveying and mapping data collection. This value is not only from the reduced cost of the data, but more importantly from the time savings afforded. Some of the possible sources of available surveying and mapping data are listed in the following Table 1.

Table 1. Possible sources of data.

Data Type	URL	Approx. Cost
USGS Digital Ortho Quads	http://wgsc.wr.usgs.gov/doq/	Inter-Agency Agreement
Black and white ortho imagery, 1 meter pixels, 1:12,000 plotting scale		
USGS Digital Elevation Models	http://edc.usgs.gov/products/elevation/dem.html	Inter-Agency Agreement
10-30 meter posting, 7 meter RMS		
BLM Public Lands Survey, GCDB	http://www.lsi.blm.gov/lsis/map.htm	Free
Shape files (ESRI) of Public Lands Survey System, Sections, Township and Range		
Airphoto USA Orthophoto	http://www.airphotousa.com/	$50/Sq. Mi.
Annual color ortho imagery, 0.5-1.0 meter pixels, predominantly metropolitan areas, available from various vendors and distributors, county-wide data bundles		
Satellite Data	http://www.spaceimaging.com/	Min 100Km^2 GSA Pricing
Largest of several vendors: True color and multi-spectral imagery up to 1 meter resolution, Digital Elevation Models, 12 meter posting, 7 meter RMS		

Digital ortho imagery is enthusiastically embraced for project planning and design at CFLHD. Standard products for every new photogrammetic mapping project are black and white, ortho-rectified imagery, at a resolution of 1 meter pixel size. Image files are referenced into plan and profile sheets, and are often used for various exhibits and site studies. One of the unique applications CFLHD has employed to distribute aerial imagery to a wider range of audiences is an Internet application called Terra Explorer by Skyline Software Sytems http://www.skylinesoft.com/. Terra Explorer provides an on-line interface to 3-D ortho imagery where users are able to view a project from any angle, or fly through a project zooming in and out at will. The Skyline Software site has stock imagery of many major cities and prominent landmarks. A more powerful tool available through the site is the ability to have unique project data converted to the Terra Explorer file formats and posted for access by others on a project team. Similar applications to Terra Explorer have been developed for specific CFLHD projects and distributed to decision makers on interactive CD ROM (see: Bear Tooth Highway , WY04, US Route 212, for an example).

Remote sensing is a common theme for much of what is included in this study. These technologies are particularly appealing to the Federal Lands Highway Divisions as by nature they can afford "don't touch" capability needed to successfully work within the sensitive, and sometimes hazardous, areas encountered. The following is a list of remote sensing applications and their contrasting characteristics:

Table 2. Characteristics of remote sensing applications.

REMOTE SENSING TECHNOLOGY	CHARACTERISTICS
Satellite Imagery	Relatively large coverage areas >10^2 Km Up to 1 meter resolution Available in visible light and beyond visible spectrum Current data can be costly $1,000 and up
Aerial Photography	Stock data available for urban areas at low price Project specific missions are common Familiar data products, topography ortho imagery USGS Ortho Quads by inter-agency agreement
Light Detection and Ranging (LiDAR)	Design-level DTM data (1 meter contours) Mass points only, no breaklines or imagery Very dense point spacing (3 meters or less) May or may not penetrate vegetation
Synthetic Aperture Radar (InSAR)	Satellite based or high-level aircraft Uses radio wave signal Planning-level DTM data Multiple passes for accurate change detection (<10cm)
Reflectorless Survey Total Station	Laser measures discrete points (e.g. radio tower) Survey accuracy (<5cm) Beam diffraction (e.g. around corners, narrow angles)
Laser Scanning	Very dense point cloud (10cm or less) Extreme point accuracies possible (5mm) View angle not favorable for ground topography Sophisticated software for mapping geometric objects

CHAPTER 3 - PROJECT STUDY APPLICATION: LASER SCANNING

A primary emphasis of this study is the emergence of ground-based Light Detection and Ranging (LiDAR) systems, known as “Laser Scanning”. Laser scanning instruments emit a pulsed laser signal with enough intensity to be uniquely detected by the instrument on its return signal from most reflective surfaces. Time travel of the light beam provides distance from the instrument to the reflected surface, and the pulsed signal is rapid enough that thousands of points can be recorded in seconds. Each point is recorded as a discrete three-dimensional coordinate relative to the instrument axis, with an attribute relating to intensity of the returning signal. Collectively a scan of points, known as a “Point Cloud” contains tens of thousands of points depicting rich detail of the scene as viewed from the instrument. In addition to the ground, the scene includes trees, brush, cars, people, and anything else that can be “seen” from the instrument-viewing angle. It does not include “shadows”, or those features that are behind something else. Herein begins to show the limitations of this technology as it is applied to conventional topographic mapping assignments. With heavily-obscured terrain, such as forested or brush-covered areas, extracting the ground points from the noise, in a data set that can reach well over a million points, can be extremely challenging. Software is making great advances in solving these problems. Advanced statistical algorithms are able to analyze blocks of data points and “grow” surfaces based upon anticipated geometric conditions. Nothing can be done; however, in shadows where data doesn’t exist. And at some point, noise becomes so dominant that no amount of computer processing can extract the good from the bad. Scenes can be accurately merged together, and the data set fit to project coordinates and elevations, by common feature objects and unique targets placed in the scene. This process is very similar to analytical aerotriangulation in photogrammetric mapping, and likewise demands preplanning and conventional control surveying to position the laser scanning targets. An experienced operator becomes key to the success of a laser scanning project. The operator must be able to position the instrument and control for the scene so as to capture the required detail, and provide for enough geometric integrity to accurately place each scene within the project control system.

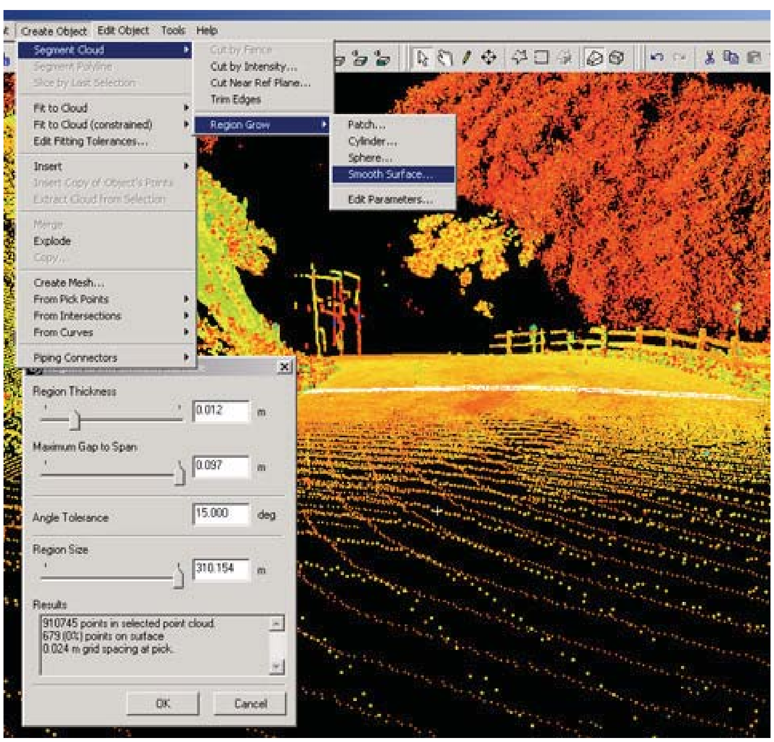


Figure 1. Screen Shot. Laser scanning software provides sophisticated algorithms for computing geometric objects and surfaces from point cloud data.

Some laser scanning equipment provides options for interactive data collection, and others operate in a point-and-shoot mode. Operator identification of targets and detail scanning of specific regions are examples of possible operator intervention during the scanning collection. Other variations in the instruments include the range or distance the laser can operate at, and the horizontal and vertical viewing angle within an individual scene. All surveying type laser scanners collect a digital picture of the scene in addition to the data points. The following table lists the most common laser scanning instruments and a few characteristic features.

Table 3. Characteristics of most common scanning instruments.

MANUFACTURE	3rdTech	Cyra Technologies	MENSI	Optech, Inc.	Riegl USA	Trimble
PRODUCT	DeltaSphere-3000	Cyrax 2500	GS100	ILRIS 3D	LMS Z420	Callidus
FDA Laser Class	IIIa	2	2	1	2	1
Accuracy at Specified Distance	0.4 in at 40 ft	6mm from 0-50m	6mm at 100m	10mm at 100m	20mm at 1000m	5m at 30m
Maximum Range	40 ft	100m	100m	1500m	1000m	80m
Field of View Vertical	145	40	60	40	90	140
Field of View Horizontal	360	40	360	40	360	360
Scanner Weight	22 lbs	20.5 kg	13.6 kg	12 kg	14.5 kg	13 kg
Computer Control Requirements	PC Laptop	PC Laptop	Pocket PC or Laptop	PCMCI Card	Laptop	Incl. Field Laptop
Battery Life	8 Hrs	8 Hrs	4 Hrs	2.5 Hrs	8 Hrs	?

As described above, application software for laser scanning is easily as important as the instrument its self. For one, the massive amounts of DTM data that must be processed would overwhelm any conventional CADD software. Point cloud data must be accessed and manipulated in a rigorous database application specifically focused on manipulating and analyzing points and surfaces. CloudWorks from Cyra Technologies includes numerous features targeted to the surveying and mapping market. In addition to being able to efficiently handle millions of data points and providing sophisticated filtering and analysis tools, CloudWorks allows the analyst to "survey" within the virtual environment represented by the point cloud. Just as a rodman on a topographic survey would locate specific objects in the field and identify them with feature codes, the analyst is able to mark points and establish break lines, then identify them with the same feature code list that is used to process conventional topographic surveys. All laser scanning application software includes tools to clean the point cloud data as this is the single biggest challenge for any LiDAR task. Finding and identifying the ground amid thousands upon thousands of points defines the success or failure of LiDAR derived topography.

LASER SCANNING FIELD DEMONSTRATIONS

The Bautista Canyon Road project (CA PFH 224) in Riverside County, California was selected as a demonstration site for two laser scanning instruments. The project was chosen because it had been recently mapped with conventional photogrammetry, and because there were different areas of terrain that ranged from ideally suited for laser scanning solution to areas that were almost certain to fail. Bautista Canyon Road is very typical of

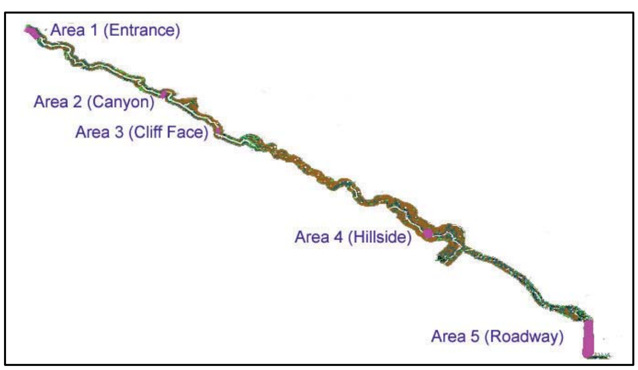


Figure 2. Map. Bautista Canyon Road Demonstration Sites.

CFLHD surveying assignments with a linear, mostly dirt-surfaced route, and including many areas of steep terrain and dense brush, and some areas with oak trees, in character with the forests so often encountered on CFLHD projects.

Six days of field data collection were completed in June of 2002 over five different target sites. Scanning work used equally a Cyrax 2500 instrument and an Optech instrument. It should be noted that both instruments experienced equipment breakdowns during the field schedule. This experience illustrates the complicated nature of these first-generation instruments for use in field environments. All equipment performed to manufactures specifications outside of the noted breakdowns.

Site Number 1, Bautista Honor Camp Entrance

Figure 3. Photo. Cyrax 2500 Laser Looking Towards Entrance.

The first target area, Site number 1, was at the entrance to Bautista Honor Camp along Bautista Canyon Road. Mapping the detail found in the Honor Camp entrance area provided the best location to demonstrate the strengths of laser scanning technology. Trees, walls, signs and park benches were revealed in clear and precise detail. Even the raised lettering on the entrance sign showed clearly in the point cloud scenes. Both scanners were able to collect the data necessary to map the site's topography to at least the accuracy provided from the original photogrammetry (i.e. plotting scale of 1:500 with 0.5 meter interval contours). Site number 1, of approximately 4,000 square meters, took each system four to five hours to collect the multiple scenes needed to depict the entire ground area without extensive shadowing. Processing the point cloud data into a typical topographic mapping CADD file required approximately four hours of analyst's time. Adding to that an hour of conventional

Figure 4. Photos. Point cloud data was able to reveal rich detail of the texture on the camp entrance sign

control surveying to position targets linking the scenes to the project control system, and the laser scanning project consumed twelve or more man-hours with perhaps three different experience levels required. The same topographic mapping project, completed by conventional total station survey methods would have consumed three or four hours of crew time, and three or four hours of an analyst. Two different experience levels and a total of twelve man-hours would have been needed for a similar conventional topographic survey. Due to trees, hillsides and other line-of-sight obstructions, the longer range of the Optech scanner (300 meters vs. 50 meters) did not provide any distinct advantage over the Cyrax scanner for this experiment.

The laser scans provide additional information that typically would not have be collected by field survey methods, and simply would not have be seen at all by aerial photogrammetry. The entrance sign and supporting wall structure are one example of this additional information. Heights and widths of walls, accurate tree trunk diameters, and the bolt pattern on the gate can be accurately picked out of the point cloud data for Bautista Canyon Road. Here then in this extremely rich detail depiction begins to emerge the most significant advantage of laser scanning over other mapping technologies.

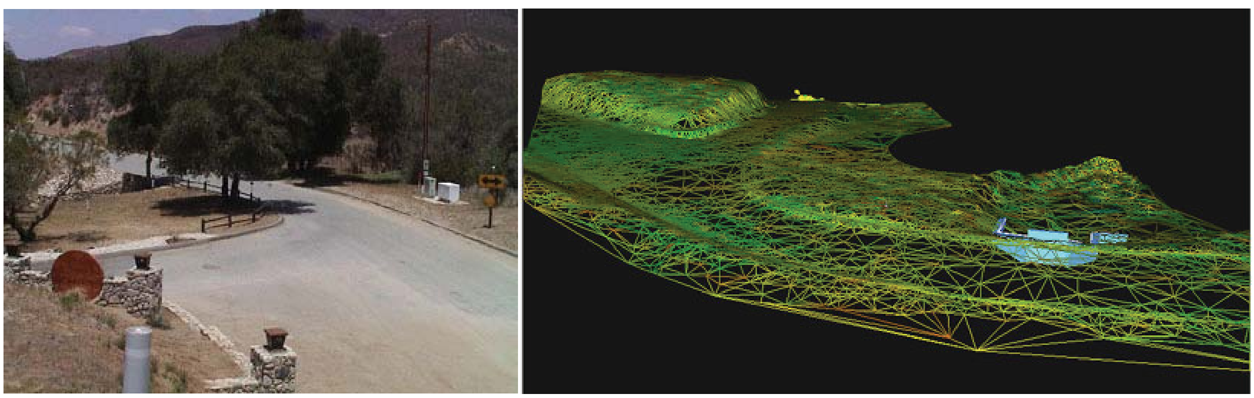


Figure 5. Photos. Rich detail of information.

Site Number 2, Brushy Canyon

The second site location included in the study was a 400-meter "S" turn in Bautista Canyon Road where it crosses a small canyon. The canyon is filled with scrub oak and chaparral making any type of survey work difficult at best. Other than the visible sections of roadway, neither scanner was able to collect enough points through the dense brush to accurately reveal the bald earth topography. This site also demonstrated the difficulty using bulky equipment with cables and batteries and complicated components in typical field terrain. The preferred set-up vantage for the second site was on a small hill overlooking the canyon. Getting the Cyrax scanner and its associated laptop computer, Ethernet communications network, and power supply up even this short hike was something none of the crewmembers wanted to do more than once. It should be noted that aerial photogrammetry is also challenged by visibility though brush as was found on this site. No attempt was made to check the accuracy of the original photogrammetric mapping in this area.

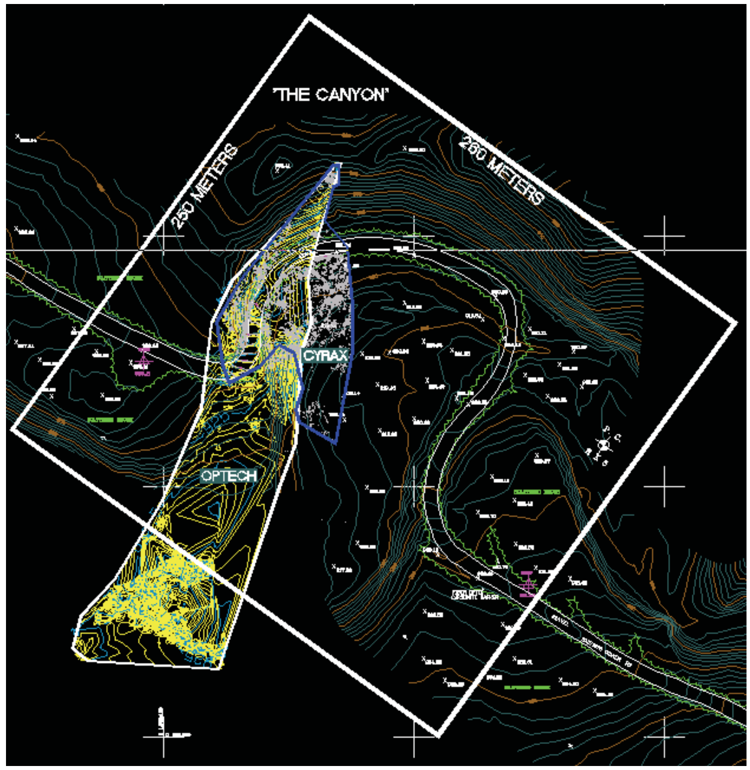


Figure 6. Plot. Very limited visibility through thick brush prevented accurate collection of the ground surface.

Site Number 3, Cliff Face

Site number 3 was selected to demonstrate the ability of laser scanning to collect topographic detail on a near vertical cliff face. The selected roadway segment included a four-meter-high cut slope on the uphill side, and a very deep brush covered canyon on the downhill side. Both scanners were able to collect sufficient point cloud data for the roadway surface and the cut slope face. Neither was able to map into the canyon and through the brush. The point cloud data depicted the cut slope face in far greater detail than was shown in the photogrammetric data. It was even superior to typical topographic mapping from conventional total station surveying. A reflectorless total station could have been used to individually locate each of the rock faces and rivulets making up the texture of the slope. The labor required to collect and analyze conventional topography of that detail would be extensive. Site #3 provided the most successful demonstration of laser scanning applicable to CFLHD mapping assignments. Where accuracy and detail of a visible surface are of utmost importance, laser scanning could provide an ideal solution.

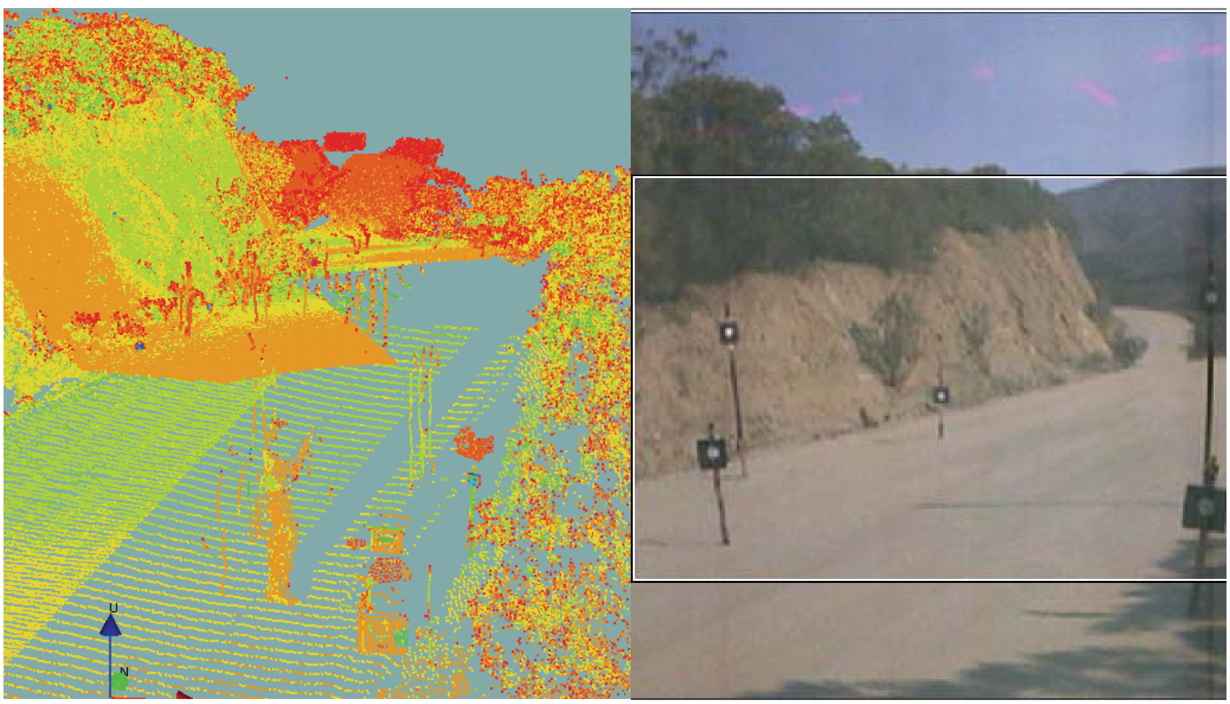


Figure 7. Photos. Targets placed in the scene are surveyed to register scans to the project coordinate system.

Site Number 4, Brushy Hillside

The fourth site also included an area of brush along Bautista Canyon Road. This 200-meter section looked more open than the canyon (Site #2) and was predominantly a hillside directly facing the scanner's viewing angle. This perspective was more favorable for laser scanning in that the instrument was able to look directly into the brush rather than crossing through it at an angle.

Site #4 was only mapped with the Cyrax instrument since the power supply on the Optech instrument broke for a second time and a replacement could not be shipped in time from the manufacture in Canada. The scanner was able to penetrate the brush and collect topographic point data for some of the ground surface. For approximately half of the hillside, the brush was too dense preventing sufficient data points to develop an accurate ground surface. The entire hillside in Site #4 was sufficiently visible from the air to compile design level topography using conventional photogrammetric methods.

Figure 8. Photo. Bulky equipment, cables and batteries present challenges to the field environment.

Figure 9. Photo. The brushy hillside directly facing the scanner provided limited success seeing to the ground surface.

Site Number 5, Open Roadway

The final site, number 5, was selected to demonstrate the ability of laser scanning to rapidly collect topographic mapping data in an open environment. The target area covers a strip of mostly open roadway for approximately one kilometer. A few visibility obstructions, such as signs, buildings, and cut-bank for the roadway presented some challenges for optimum scanning angles.

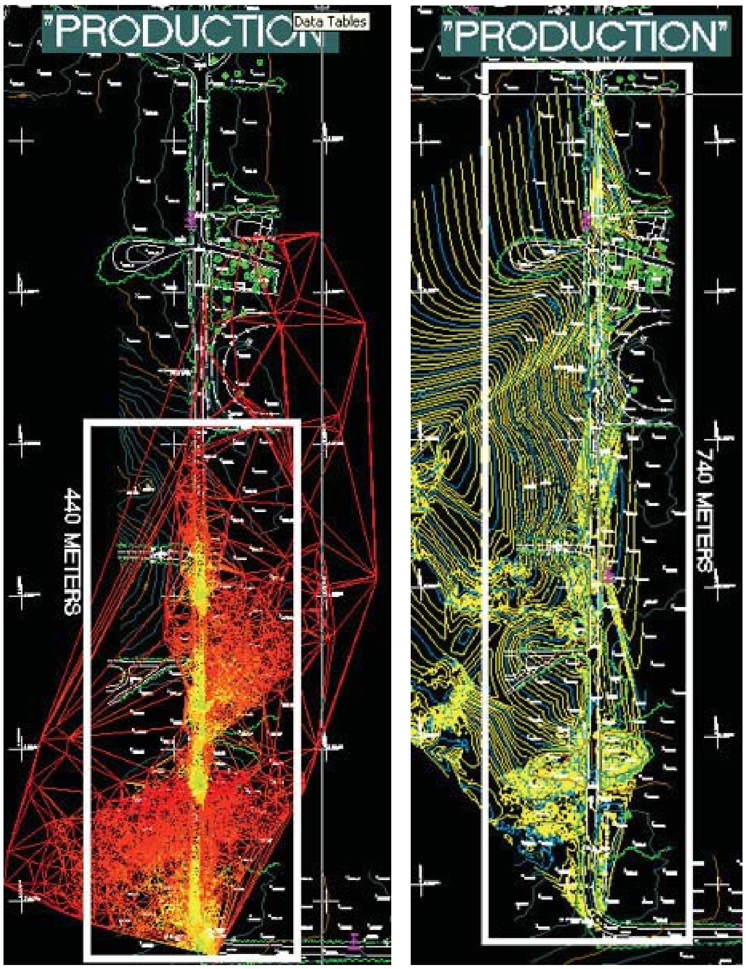


Figure 10. Plots. The longer range of the Optech scanner was able to collect 60% more data.

Both instruments were run collecting data sufficient point cloud data to derive design level topography. In eight (8) hours the Cyrax instrument collected a 440-meter segment of point cloud data. The Optech instrument with its longer range was able to collect 740 meters of point cloud data in four and a half (4.5) hours. An additional one and a half (1.5) hours of conventional control surveying was necessary to support each laser scanning demonstration. It was estimated that a conventional survey crew would have completed the one-kilometer segment in approximately eight (8) hours. Processing time for the topographic data was not considered in this demonstration, but is typically much less for conventional surveying as opposed to laser scanning. Again, the level of detail revealed by laser scanning could provide significant benefits on certain applications, but was not considered in this demonstration.

AIRBORNE LIGHT DETECTION AND RANGINE (LiDAR)

Similar to ground-based laser scanning, airborne LiDAR relies upon a high-speed, reflectorless, laser distance meter instrument to collect point cloud data from an airborne platform. The laser ranging instrument is matched to kinematic GPS point positioning, and an inertial measurement unit (IMU) to record angular velocity (yaw, pitch and roll) of the aerial platform. All three data measurement streams are time-tagged through the GPS time signature to facilitate simultaneous solution of position, angular attitude, and distance, to determine coordinates and elevations for discrete data points. The LiDAR system may be mounted in fixed-wing or rotary aircraft, from which design-level topographic data is possible. Typical point posting for current LiDAR is one meter, with an accuracy of 0.1 meter horizontal and vertical. These figures vary greatly depending upon the particular sensor and the altitude of the flight.

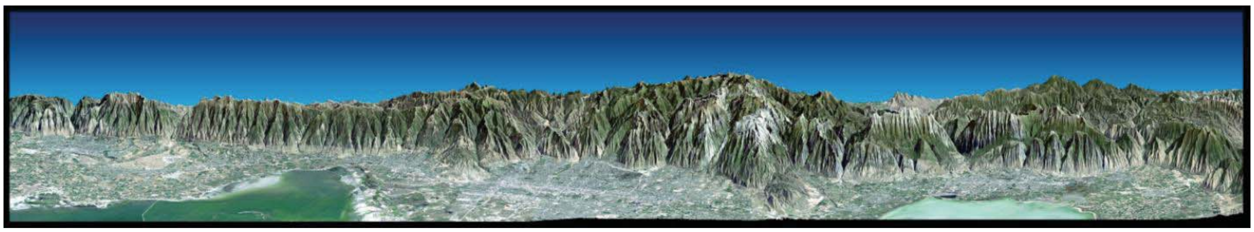


Figure 11. Photo. Colored relief image of Wasatch Range from Shuttle Radar Topography mission.

A similar system, using radio waves, or RADAR, as the sensor flown on either high-altitude aircraft or satellites, has been used to collect digital terrain data. Interferometric Synthetic Aperture RADAR (InSAR) uses two passes of RADAR imagery over the same ground area to develop a stereo image similar to conventional photogrammetry. It has most often been applied to planning-level mapping assignments, and also for land deformation monitoring projects, such as landslides, subsidence, and earthquakes. In February of 2000, the Space Shuttle Endeavour, equipped with InSAR, collected enough data in ten days to map 80% of the earth's surface to an accuracy of 20 meters horizontal and 16 meters vertical (90% probable error). The potential for topographic mapping from InSAR is significant, particularly for developing extremely large data sets for off-the-shelf digital terrain data, and mapping in areas where ground penetration of light waves is very limited (i.e. cloud cover and certain vegetation). The ability to use InSAR for design-level topographic mapping, while not impossible, appears unlikely in the immediate future. A separate study at CFLHD is being conducted to investigate the application of InSAR data for deformation monitoring on geotechnical projects.

Figure 12. Photo. Dual GPS antenna and LiDAR system mounted on helicopter.

Airborne LiDAR has proven to be a useful tool for topographic mapping work on typical FHWA assignments. Field demonstrations have been completed on projects including Guenella Pass, Beartooth Highway, and Lava Beds National Monument. Testing against conventional surveying and photogrammetric mapping shows favorable agreement at National Map Accuracy Standards. The following histogram was developed from conventional survey data points compared to LiDAR data compiled for a project in Oxnard, California. The imagery was flown by Airborne1at an average flying height of 800 meters using an Optech ALTM sensor.

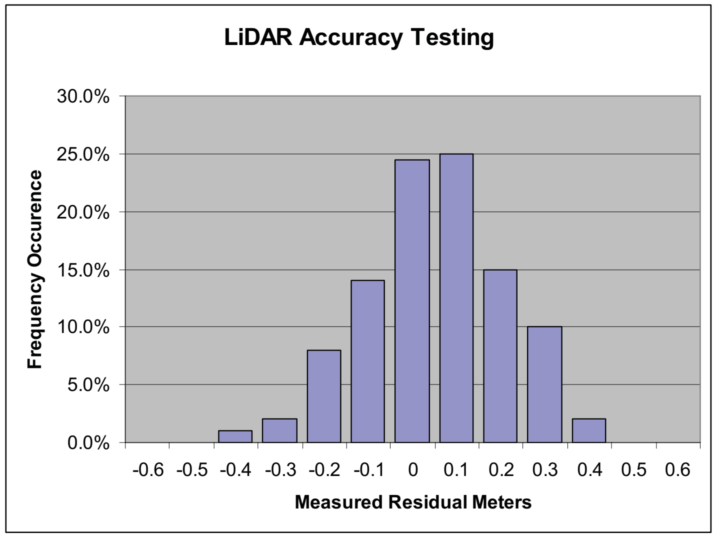


Figure 13. Chart. LiDAR accuracy histogram.

The viewing angle of airborne LiDAR is more favorable than ground-based laser scanning, to the site conditions typically found on FHWA projects. Trees and brush are much easier to see through from the vertical perspective, so more data points can be detected on the ground surface. Just as in ground-based laser scanning, filtering the point cloud data to isolate the ground points from the noise is defining of the success of the mission. Similar algorithms are used to grow surfaces from known geometric characteristics, and point attributes of signal intensity and first return/last return can also be applied to digital filters. Using different frequencies of light, LiDAR systems have been designed to capture mapping data including bathymetric mapping under shallow water, and the concentration of various gasses and chemicals in the atmosphere.

Two weaknesses stand out in LiDAR mapping technology as it is applied to topographic mapping assignments. Angular measurement from the IMU is limited to approximately 0.005 degrees using current ring-laser gyroscopes. This means that horizontal accuracy varies dependent upon flying height. Nearly 0.1 meters of angular uncertainty is incurred at a height of 1,000 meters. Since hardscape features such as curbs and buildings are less common on FLHD assignments, this limitation is not as significant as it might be for other applications. More significant is the inability of LiDAR to directly detect breaklines from the point cloud data. LiDAR points are at regular intervals along-track and across-track to the flight line. A grade break, such as a ravine, flow line, or edge of traveled way may or may not show up as points in the data set. Depending upon how many points happen to hit on the topographic breakline, an important feature may or may not be missed.

CONCLUSIONS AND RECOMMENDATIONS

Remote sensing using LiDAR technology will continue to advance its usefulness for surveying and mapping assignments. The successes achieved with airborne LiDAR at CFLHD already are providing advantages with improved mapping capability for environmentally sensitive areas, and the ability to collect and catalogue large data sets for possible expanded mapping coverage as projects change. Minimizing the location and number of aerial targets placed on a project not only saves cost, but also prevents possible damage from maintenance or brush cutting. Advances in software will certainly improve the ability to clean point cloud data for both airborne and ground based LiDAR making this data source increasingly attractive.

Currently, airborne LiDAR provides a viable option for mapping design-level digital terrain surfaces, where extensive breaklines and dense vegetation do not present significant challenges. It must be understood that the technology will not produce planimetric mapping for features such as edge of roadway or hardscape improvements. Nor will it directly provide orthophotography imagery. These typical mapping products will need to be derived by other methods, and the applicable costs factored into the work plan. Most likely this will require a separate, or simultaneous, aerial photogrammetry task. Cost savings can only be expected with LiDAR mapping on moderately large sized projects (nominally in excess of 10 Km^2), or on projects requiring only DTM data, such as floodplain studies. The limited number of these expensive systems currently in operation makes mobilization costs and timing a consideration.

Figure 14. Photo. Helicopter based LiDAR provided successfull digital terrain mapping for the Tarryall Road project.

Ground-based LiDAR, or laser scanning, is also applicable to certain surveying and mapping projects, though the range of appropriate assignments is much narrower. Generally, laser scanning shows greatest benefit in applications where great detail is desired and can be exploited. Three-dimensional modeling for historical preservation of artifacts or cultural features is one possible example. Detail of structural aspects of an existing bridge might be another. Typical topographic mapping assignments at FHWA are so limited by visibility, and generally do not demand extreme levels of detail, so that laser scanning does not find advantage.

CHAPTER 4 – PROJECT STUDY APPLICATION: PHOTOGRAMMETRIC AIRBORNE POSITIONING

Figure 15. Photo. Inertial measurement unit combined with GPS provides a complete position and attitude solution for airborne platforms.

Airborne LiDAR is an advanced application of airborne positioning technology. The ability to precisely position a moving platform, particularly an aircraft where stop-and-go is not a possibility, is a very recent innovation. Hydrographic surveying vessels were tracked with high-speed total station instruments, and sometimes with radio ranging equipment, but it was not until dual-frequency kinematic GPS receivers were matched with advanced ambiguity resolution software solutions in the mid 1990's that precise airborne positioning became practical. Prior to this advancement loss of lock on the GPS satellites would force abandonment of a flight to have the aircraft land and reacquire signal lock. Ambiguity resolution is for all practical purposes a pass or fail condition for precise GPS positioning. As long as the receiver successfully maintains lock on the integer ambiguities, sub-decimeter positions can be generated from each successive GPS measurement epoch. Failing successful ambiguity resolution, the GPS position immediately degrades to sub-meter reliability. With the ability to reacquire integer ambiguities in flight, photogrammetrists immediately began to experiment with precise airborne positioning to enhance aerotriangulation solutions used in photogrammetric mapping. One of the unknowns solved for in analytical aerotriangulation is real-world (or project) coordinates and elevation of the camera focal point at the instant of exposure. Deriving this value directly from GPS offers potentially increased accuracy and less need for ground control.

Figure 16. Photo. One-second GPS solutions are interpolated to obtain positions at the camera exposure centers.

Airborne GPS has found great success in minimizing the need for ground control in photogrammetric mapping where multiple flight lines are employed to map large regions, as in base mapping for GIS projects. The typical airborne project includes north-south flight lines, with east-west cross-flights to strengthen the analytical bundle adjustment. This has been necessary because the GPS positioning provides only discrete points for the photo centers, and the analytical solution must also solve for the rotation angles of the camera photographic plane. This geometric weakness has until recently left linear route surveys less applicable for airborne GPS. Inertial measurement technology combined with kinematic GPS offers the solution to airborne positioning for linear routes. In the combined solution, the IMU records the angular velocity, while the GPS records the photo center positions. Combined the two systems are complementary in that the discrete point positioning of the GPS constrains the drift common in inertial measurement. GPS on the other hand, is subject to instantaneous loss of lock and positioning accuracy. Reacquisition of integer ambiguities is aided in post processing by the more continuous data flow of the IMU. The IMU also records at a much higher data rate (100 Hz typically) than GPS, thereby minimizing the problems associated with erratic movement of the aircraft during flight.

FIELD DEMONSTRATION: SEVENMILE-GOOSEBERRY ROAD

Photogrammetric mapping for Sevenmile-Gooseberry Road in Salina, Utah was selected as a target demonstration project for inertial-aided airborne GPS positioning. The conventional photogrammetric mapping project included six (6) flight lines and 26 stereo models at 1:4,800 photo scale. Ground control was established sufficient to meet traditional analytical aerotriangulation needs. This included 27 aerial premarks along the 9 Km route. Two GPS base stations, set on previously established primary control, and one GPS receiver on board the plane aided the aerial photography mission. GPS data was recorded at one-second intervals throughout the flight. An Applanix PosAV system provided integration of GPS data with the inertial measurement unit mounted on the camera. A traditional aerotriangulation adjustment was performed without the aid of airborne positioning data providing mapping-quality results with an RMS of fit of 10 cm.

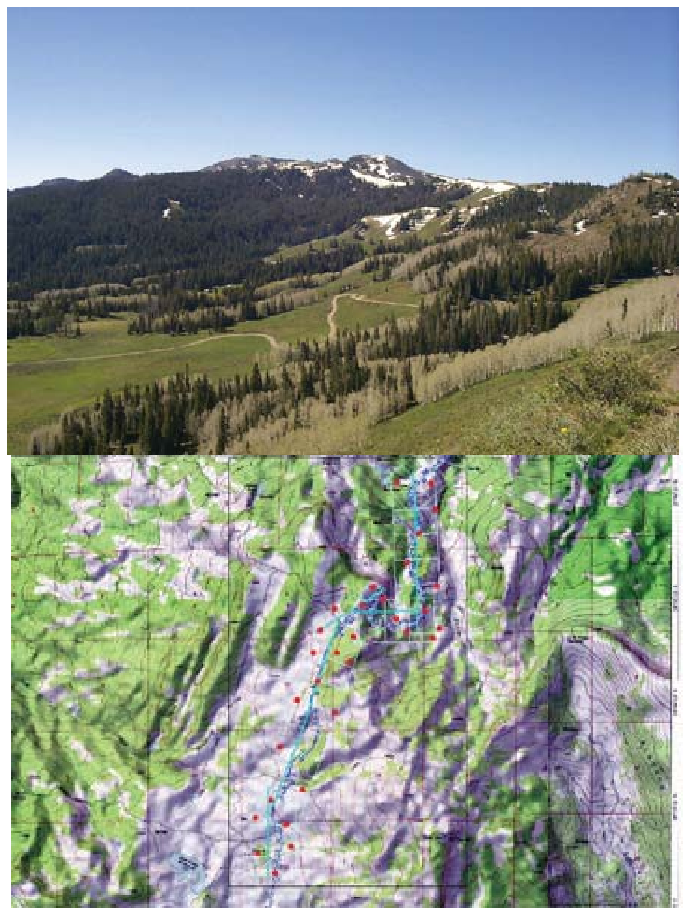


Figure 17. Photo and Map. Full analytical ground control was established along Sevenmile Road for the baseline data set. The flight plan included six flight lines and 26 stereo models.

The airborne positioning solution was processed in GrafNav software integrating the GPS observation data with the IMU data stream. Surveyed offsets from the aircraft GPS antenna to the camera focal point allowed computation of coordinates and elevations for the exact photo center at the mid point of the exposure time. The GrafNav solution includes position and orientation parameters of the camera film plane (Northing, Easting, Elevation, Phi, Kappa, Epsilon) in the project coordinate frame.

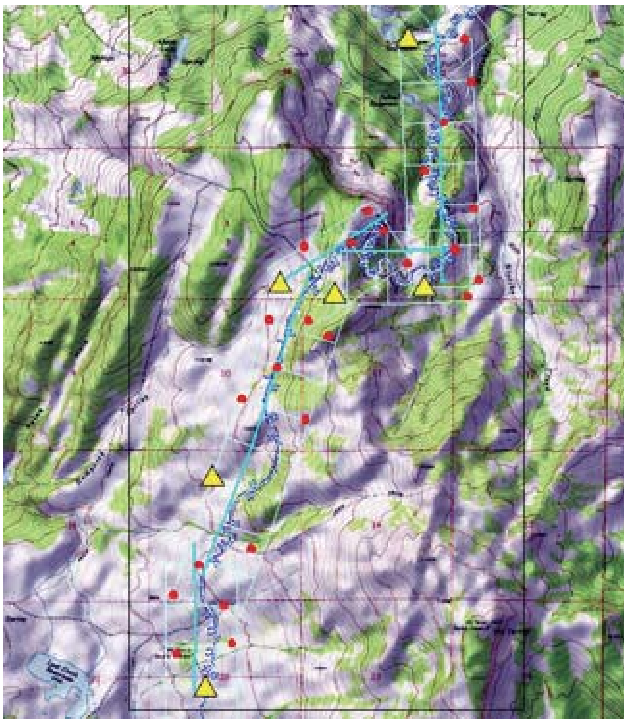


Figure 18. Map and Photo. Optimum photogrammetric solution, using inertial-aided airborne GPS, was found using 6 of the 27 aerial premarks. This methodology offers reduced cost along with reduced impact to the natural environment.

Three separate aerotriangulation adjustments were run including the airborne solution data. Each successive adjustment removed additional ground control points. An optimum solution was found with 6 of the 27 aerial premarks removed from the adjustment. This adjustment produced an RMS of fit of 7 cm in horizontal and 12 cm in vertical, with a 75% reduction in the required ground control. This is particularly significant in that much of the redundant control is found in the wing-points that often are difficult and costly to target, and could reside in sensitive areas. In this demonstration, the additional cost for airborne positioning and processing amounted to $6,500. The equivalent cost for the 21 aerial premarks eliminated was over $10,000.

FIELD DEMONSTRATION: LAVA BEDS NATIONAL MONUMENT

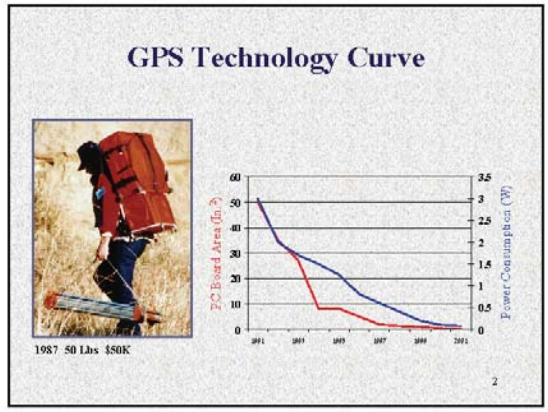
The combination of airborne inertial aided positioning combined with LiDAR and simultaneous aerial photography becomes very attractive for mapping solutions. The systems, as described, provide complimentary functions, and by themselves have proven gains in efficiency and economics. Aerial photography is needed to provide real-world imagery and to compile breaklines. LiDAR is very efficient at collecting digital terrain data; the exact data needed to ortho rectify aerial imagery. And GPS with inertial provides the geometric relationships necessary to compile photogrammetric mapping. In theory, an airborne platform collecting stereo imagery, point cloud data, together with position and attitude information, has everything necessary to compile topography and orthophotography. Merrick and Associates in Denver, Colorado is one of the first innovators to assemble such an aircraft. The single engine aircraft is equipped with a high-resolution digital mapping camera, inertial-aided GPS, and LiDAR system. A demonstration project using this system was flown in over a portion of Lava Beds National Monument in August 2003. A dense grid of mass points, provided from the LiDAR system, was supplemented with breaklines collected interactively from the stereo photogrammetry. Initial quality control checks against field surveying indicated an RMS of fit of 5 cm.

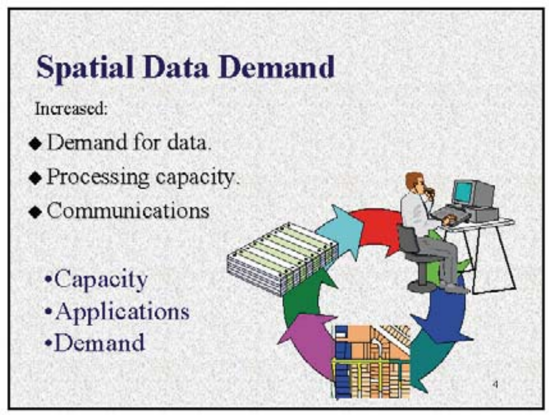
CHAPTER 5 – SUMMARY AND FUTURE TRENDS

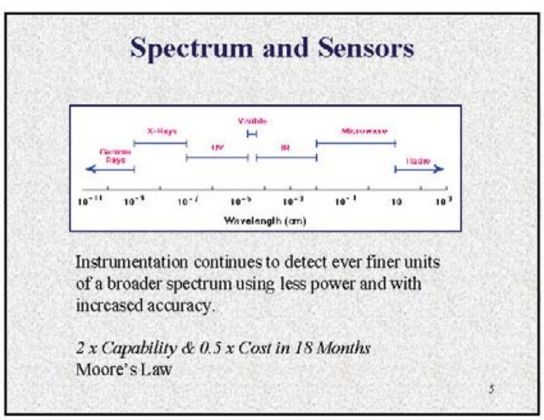
Emerging technologies such as automated machine guidance and intelligent vehicle highways will continue to drive the demands for real-world spatial data and true 3-D designs. Interestingly, high demand, high dollar positioning activities such as intelligent vehicle systems don't necessarily require accurate positions, but their demands for extremely high levels of reliability (i.e. 3 to 5 sigma criteria, 99.999% system confidence) are achieved through many of the same techniques that make real-time survey-quality positioning possible. In the years ahead, miniaturization will catch up with desires for a laser scanner that resembles today's total station instruments in size and cost. Applanix, the manufacture of the airborne positioning system used for Sevenmile Road, is already promoting a backpackable combination of inertial-aided real-time GPS that will take GPS surveying under trees, inside buildings and tunnels. Real-time GPS networks are appearing today that literally spell the end to ever visiting a horizontal or vertical control point in the future. When high-speed bandwidth reaches everyone's desks, designers will no longer be satisfied with even emailed CADD files to replace standard blueprints. Project websites with interactive applications and fly-through movies will be the expectation in the next decades.

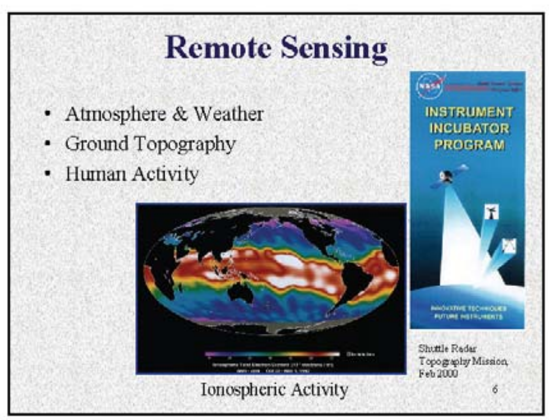
Through projects such as those described above, the Federal Lands Divisions of the Federal Highways Administration have taken a deliberate active position to understanding and implementing technological innovations. Developing these innovations into operational methods will demand further investigations and motivated personnel supported with continuing education and training.

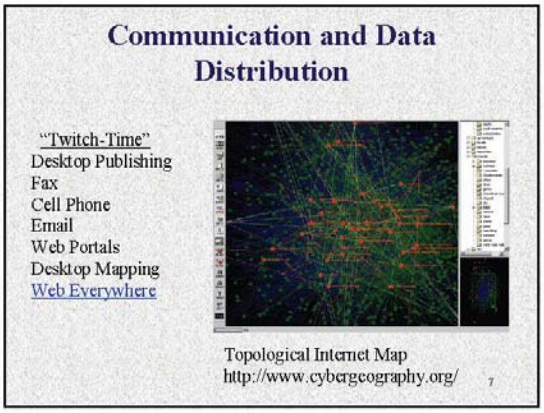
APPENDIX A – ADVANCED SURVEYING TRAINING SLIDES

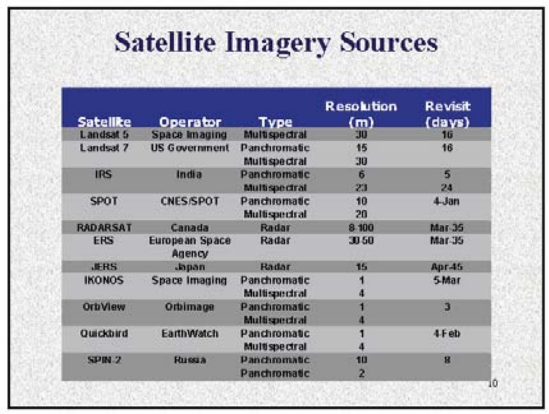




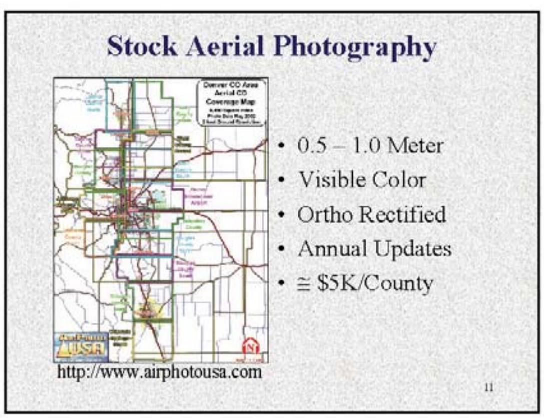


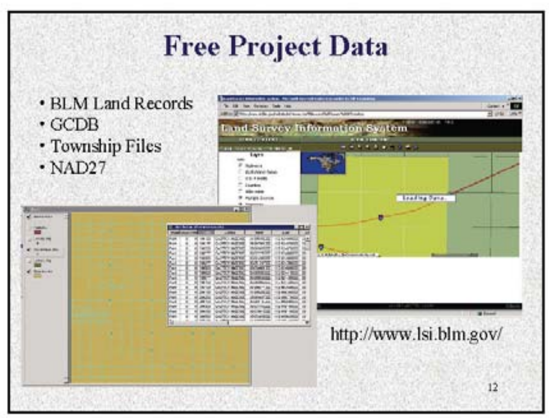


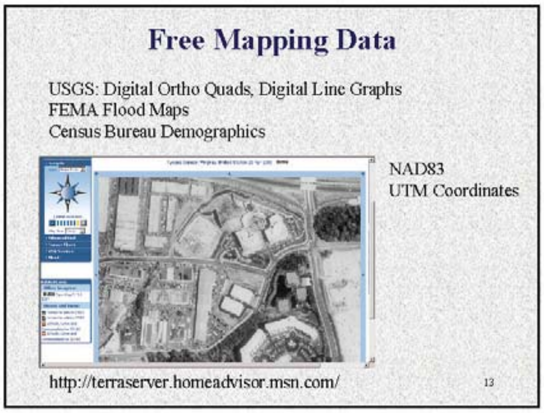


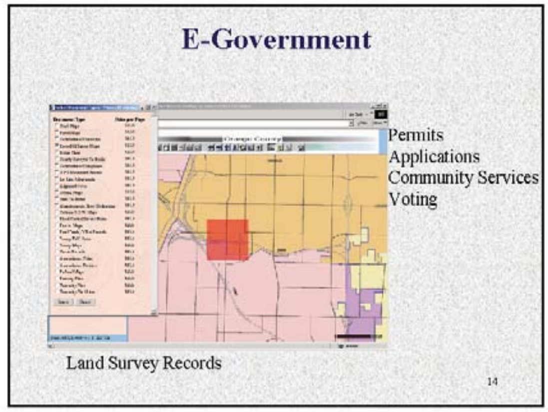


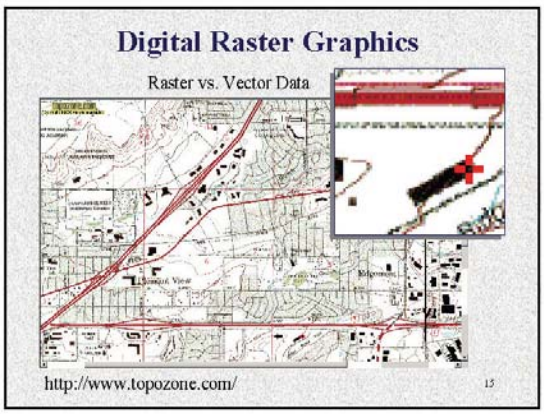
Satellite	Operator	Type	Resolution (m)	Revisit (days)
Landsat 5	Space Imaging	Multispectral	30	16
Landsat 7	US Government	Panchromatic	15	16
		Multispectral	30	
IRS	India	Panchromatic	6	5
		Multispectral	23	24
SPOT	CNES/SPOT	Panchromatic	10	4-Jan
		Multispectral	20	
RADARSAT	Canada	Radar	8-100	Mar-35
ERS	European Space Agency	Radar	30-50	Mar-35
JERS	Japan	Radar	15	Apr-45
IKONOS	Space Imaging	Panchromatic	1	5-Mar
		Multispectral	4	
OrbView	Orbimage	Panchromatic	1	3
		Multispectral	4	
Quickbird	EarthWatch	Panchromatic	1	4-Feb
		Multispectral	4	
SPIN-2	Russia	Panchromatic	10	8
		Panchromatic	2	

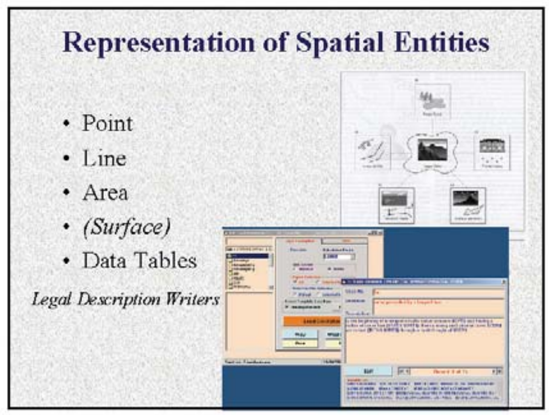


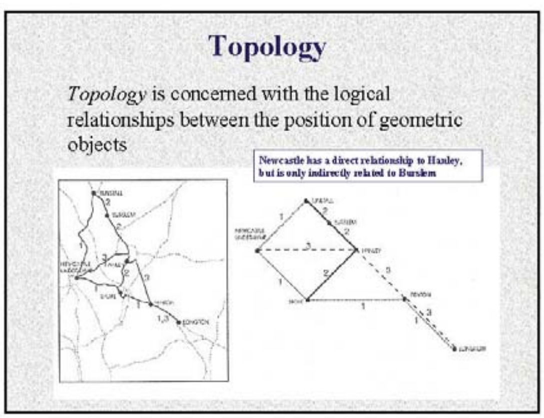


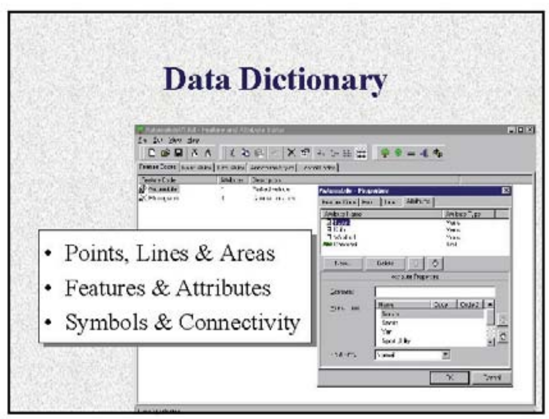

Free Mapping Data
USGS: Digital Ortho Quads, Digital Line Graphs
FEMA Flood Maps
Census Bureau Demographics
NAD83
UTM Coordinates
http://terraserver.homeadvisor.msn.com/
13

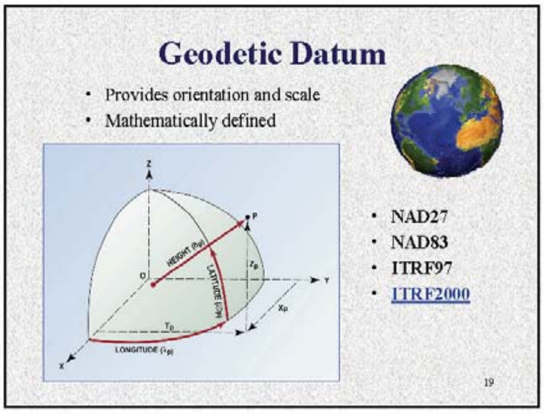

E-Government
Permits
Applications
Community Services
Voting
Land Survey Records
14

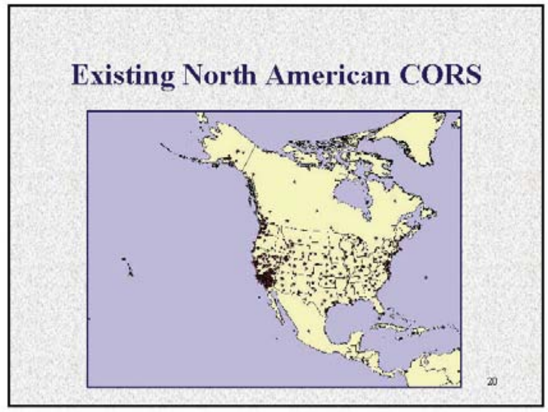

Digital Raster Graphics
Raster vs. Vector Data
http://www.topozone.com/
15

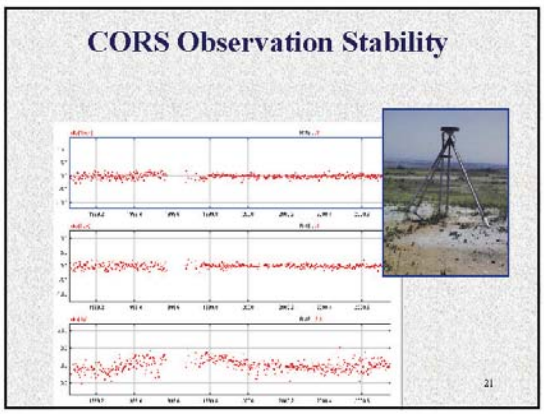

Representation of Spatial Entities
• Point
• Line
• Area
• (Surface)
• Data Tables
Legal Description Writers

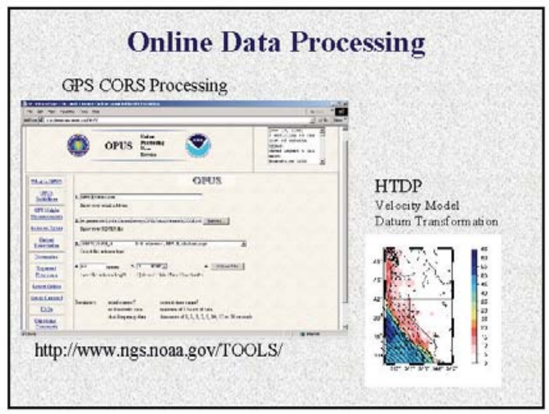

Topology
Topology is concerned with the logical relationships between the position of geometric objects
Newcastle has a direct relationship to Hanley, but is only indirectly related to Burslem

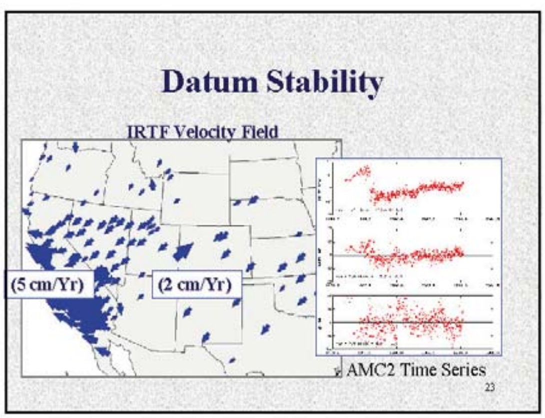

Data Dictionary
• Points, Lines & Areas
• Features & Attributes
• Symbols & Connectivity

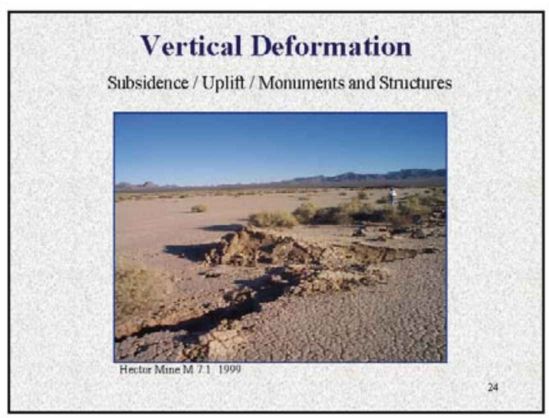

Geodetic Datum
Provides orientation and scale
Mathematically defined
NAD27
NAD83
ITRF97
ITRF2000
19

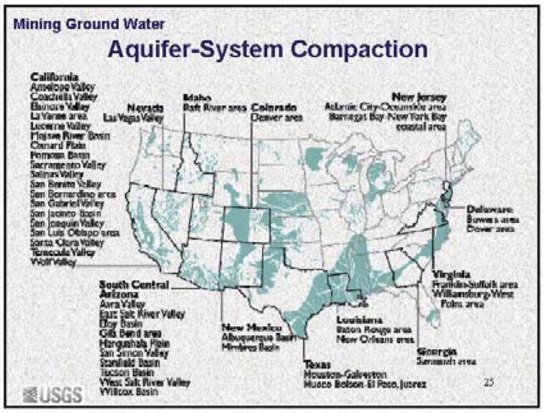

Existing North American CORS
20

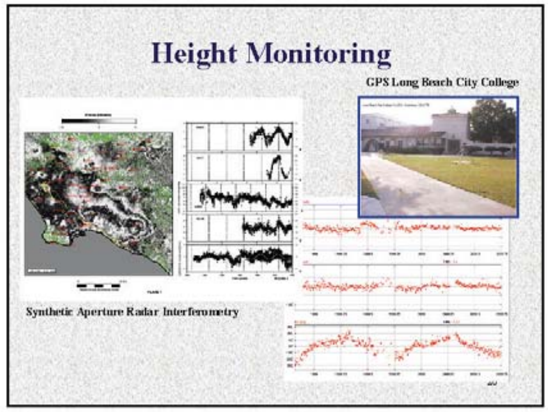

CORS Observation Stability
21

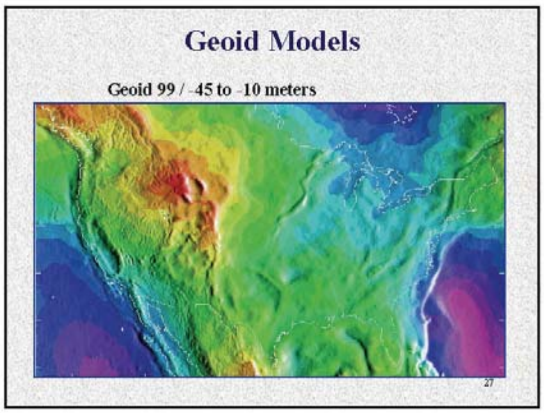

Online Data Processing
GPS CORS Processing
HTDP
Velocity Model
Datum Transformation
http://www.ngs.noaa.gov/TOOLS/


Datum Stability
IRTF Velocity Field
(5 cm/Yr)
(2 cm/Yr)
AMC2 Time Series
23

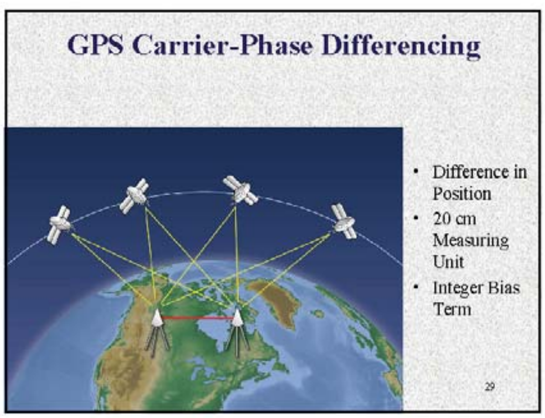

Vertical Deformation
Subsidence / Uplift / Monuments and Structures
Hector Mine M 7.1 1999
24


Mining Ground Water
Aquifer-System Compaction
California
Antelope Valley
Coachella Valley
Lucerne Valley
Mojave River Basin
Oxnard Plain
Pomona Basin
Sacramento Valley
Salinas Valley
San Benito Valley
San Bernardino area
San Gabriel Valley
San Jacinto Basin
San Joaquin Valley
San Luis Obispo area
Santa Clara Valley
Temecula Valley
Wolf Valley
Nevada
Las Vegas Valley
Raft River area
Colorado
Denver area
New Jersey
Atlantic City-Oceanside area
Barnegat Bay-New York Bay coastal area
Delaware
Bowers area
Dover area
Virginia
Franklin-Suffolk area
Williamsburg-West Point area
South Central Arizona
Avra Valley
East Salt River Valley
Eloy Basin
Gila Bend area
Harquahala Plain
San Simon Valley
Stanfield Basin
Tucson Basin
West Salt River Valley
Willcox Basin
New Mexico
Albuquerque Basin
Mimbres Basin
Louisiana
Baton Rouge area
New Orleans area
Georgia
Savannah area
Texas
Houston-Galveston
Hueco Bolson-El Paso, Juarez
USGS
25


Height Monitoring
GPS Long Beach City College
Synthetic Aperture Radar Interferometry


Geoid Models
Geoid 99 / -45 to -10 meters
27


National Height Modernization
$12+ billion estimated value
• National terrain model
• Nationwide watersheds
• Special flood hazards
• Coastal erosion
• Maritime navigation
28


GPS Carrier-Phase Differencing
• Difference in Position
• 20 cm Measuring Unit
• Integer Bias Term
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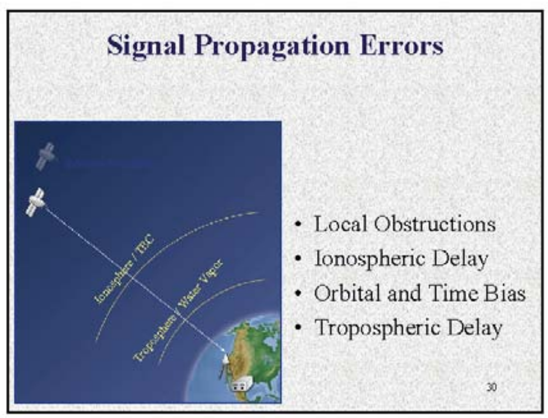
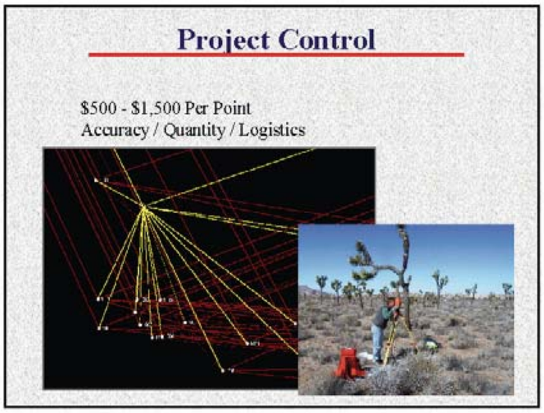
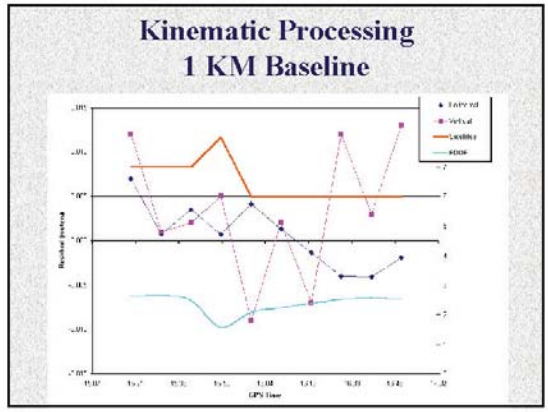
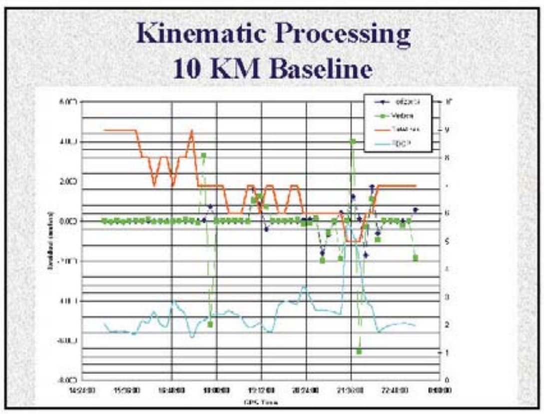
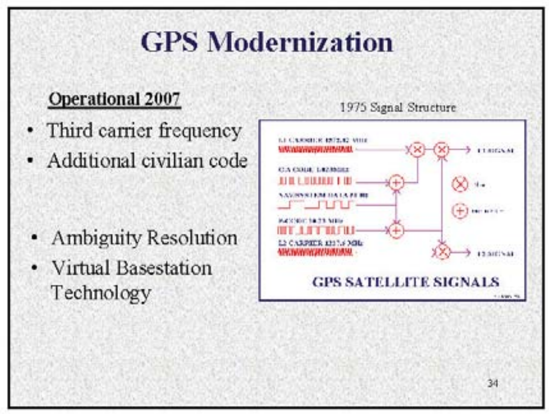
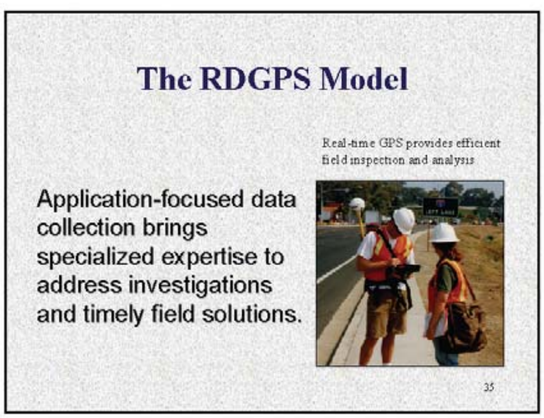

Signal Propagation Errors
Ionosphere / TEC
Troposphere / Water Vapor
• Local Obstructions
• Ionospheric Delay
• Orbital and Time Bias
• Tropospheric Delay
30

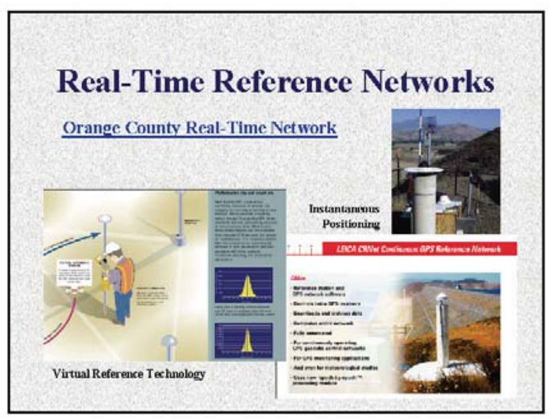

Project Control
$500 - $1,500 Per Point
Accuracy / Quantity / Logistics

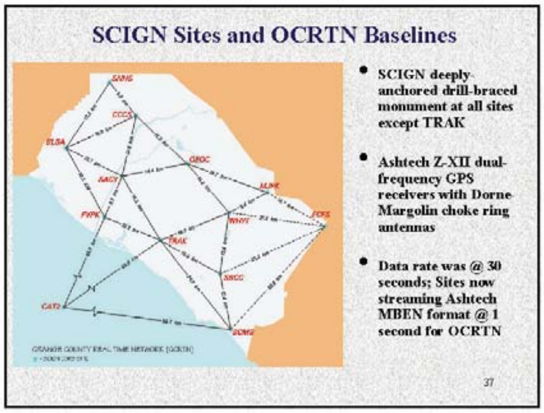

Kinematic Processing
1 KM Baseline

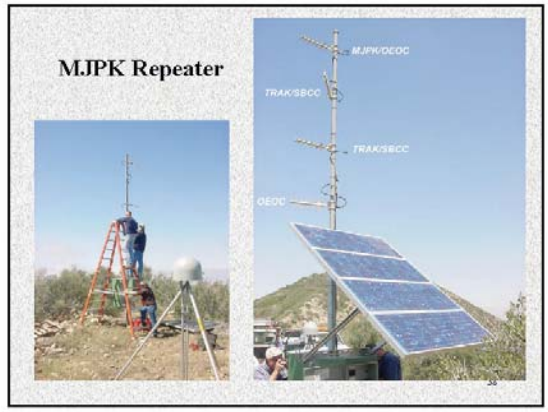

Kinematic Processing
10 KM Baseline


GPS Modernization
Operational 2007
• Third carrier frequency
• Additional civilian code
• Ambiguity Resolution
• Virtual Basestation Technology
1975 Signal Structure
GPS SATELLITE SIGNALS
34

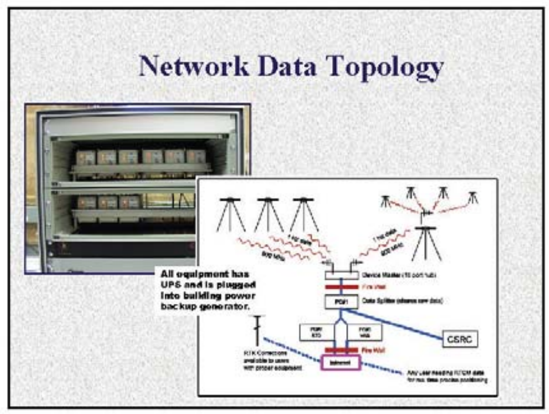

The RDGPS Model
Real-time GPS provides efficient field inspection and analysis
Application-focused data collection brings specialized expertise to address investigations and timely field solutions.
35


Real-Time Reference Networks
Orange County Real-Time Network
Instantaneous Positioning
Virtual Reference Technology

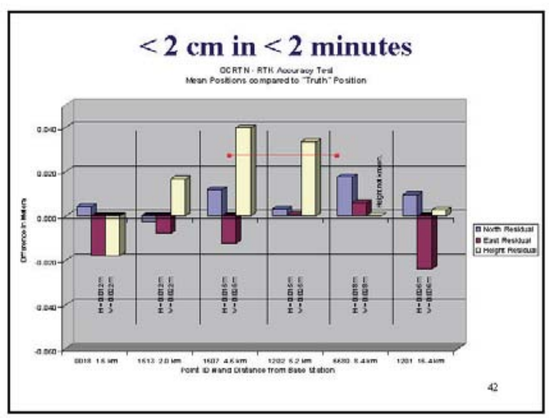

SCIGN Sites and OCRTN Baselines
SCIGN deeply-anchored drill-braced monument at all sites except TRAK
Ashtech Z-XII dual-frequency GPS receivers with Dorne Margolin choke ring antennas
Data rate was @ 30 seconds; Sites now streaming Ashtech MBEN format @ 1 second for OCRTN
37

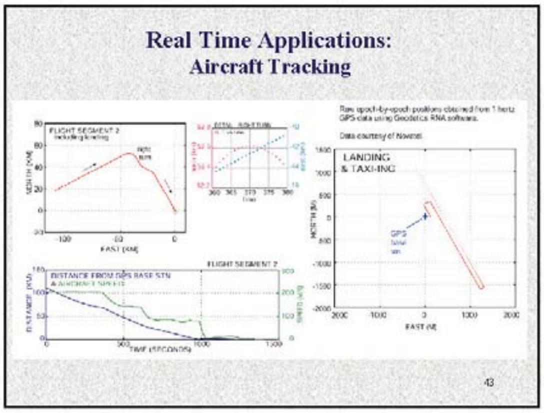

MJPK Repeater
MJPK/OEOC
TRAK/SBCC
TRAK/SBCC
OEOC

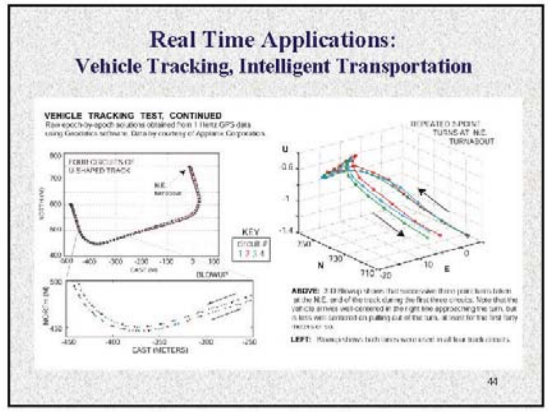

Control Center Antennas
WHYT / SACY
MJPK/OEOC
FVPK / CAT2
TRAK / SBCC
SCMS

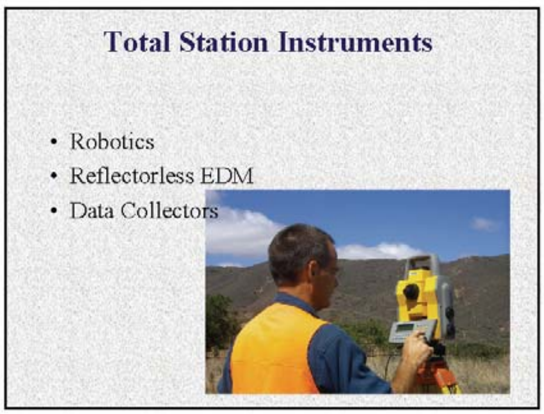

Network Data Topology
All equipment has UPS and is plugged into building power backup generator.
CSRC

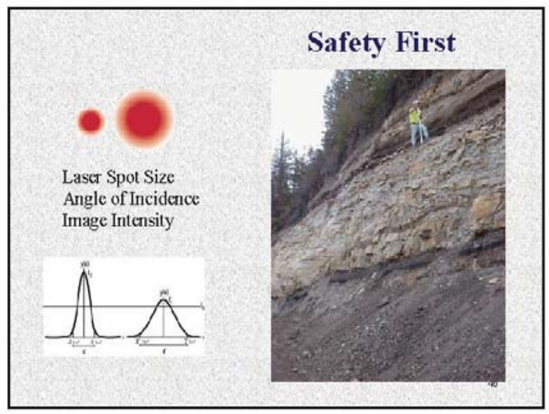

OCS - OCRTN – RTK Equipment
Ashtech Z-Xtreme receiver
Ashtech Geodetic-IV antenna
TDS Ranger data collector
Raven II CDPD modem
2-meter bi-pod
Wireless Internet $65/Month


< 2 cm in < 2 minutes
OCRTN - RTK Accuracy Test
Mean Positions compared to "Truth" Position
North Residual
East Residual
Height Residual
Point ID and Distance from Base Station
42

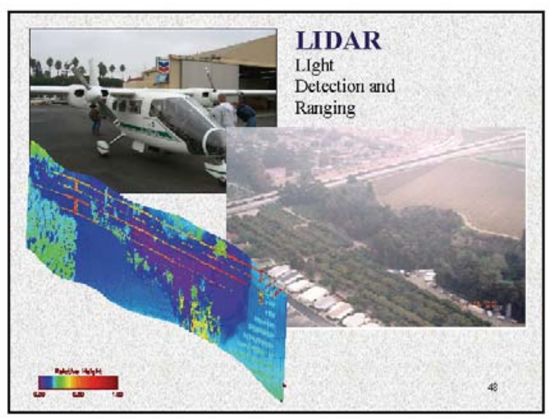

Real Time Applications:
Aircraft Tracking
FLIGHT SEGMENT 2
LANDING
& TAXI-ING
DISTANCE FROM GPS BASE STN
FLIGHT SEGMENT 2
TIME (SECONDS)
EAST (M)
NORTH (M)
43

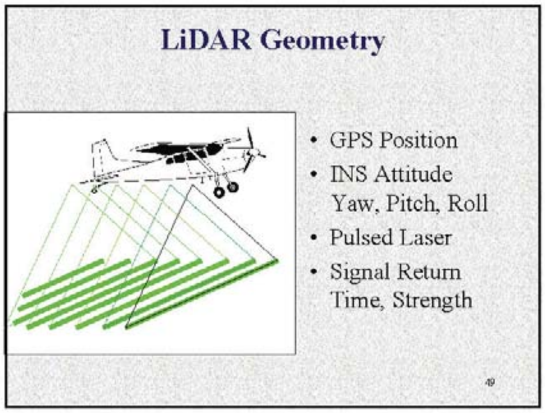

Real Time Applications:
Vehicle Tracking, Intelligent Transportation
VEHICLE TRACKING TEST, CONTINUED
KEY
EAST (METERS)
44


Total Station Instruments
• Robotics
• Reflectorless EDM
• Data Collectors


Safety First
Laser Spot Size
Angle of Incidence
Image Intensity

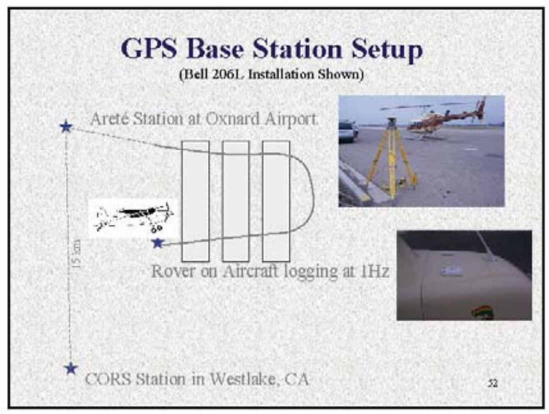

Laser Scanning Tests
cyrax

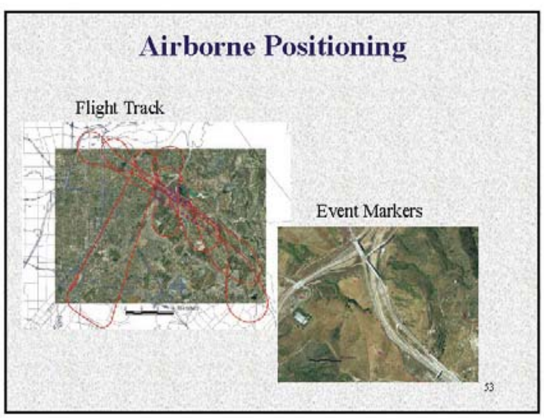

LIDAR
LIght
Detection and
Ranging
48

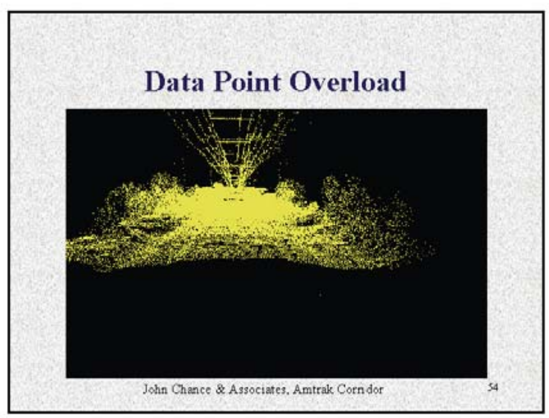

LiDAR Geometry
• GPS Position
• INS Attitude
Yaw, Pitch, Roll
• Pulsed Laser
• Signal Return
Time, Strength
49

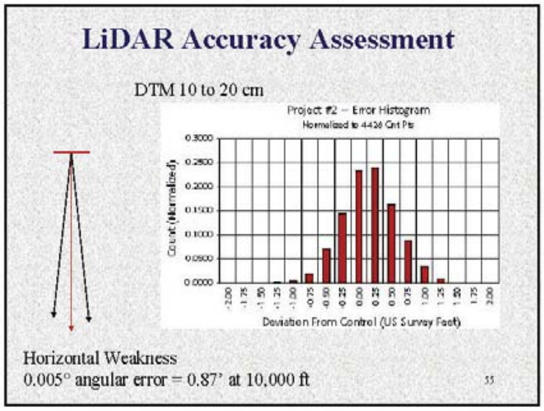

LiDAR Helicopter Installation
View from below. Receiver and laser exit optics visible.
Bell 206L Helicopter. Laser and Sensor are on the left and forward. Control and data acquisition computer is on the right and aft. (Aspen Helicopter Inc.)
50

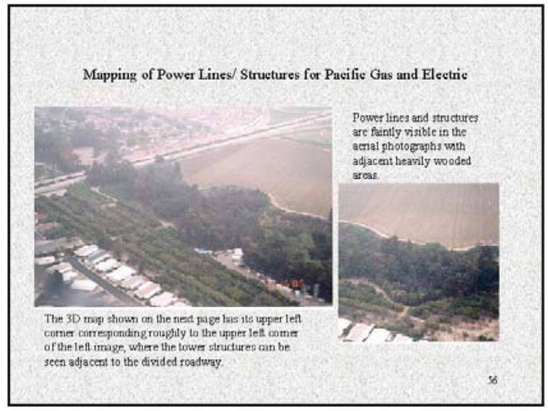

LiDAR Fixed Wing Installation
Transceiver installs in mid-body section of the Partenavia Explorer (Aspen Helicopter Inc.)
Test mirror used for field alignment shows transmit and receive optics
51

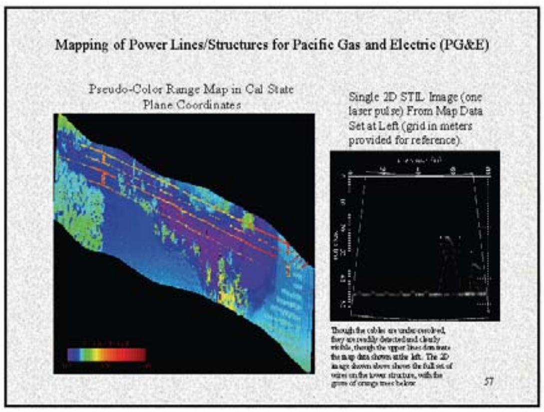

GPS Base Station Setup
(Bell 206L Installation Shown)
Areté Station at Oxnard Airport
15 km
Rover on Aircraft logging at 1Hz
CORS Station in Westlake, CA
52

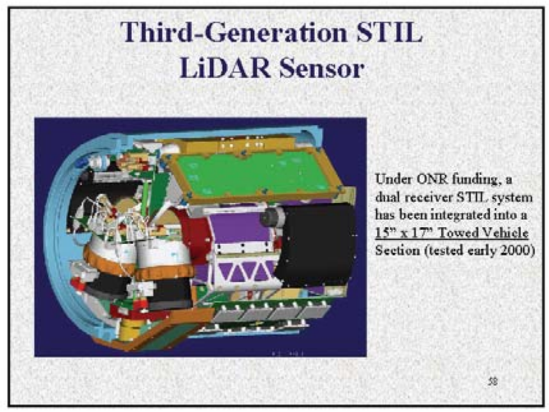

Airborne Positioning
Flight Track
Event Markers
53

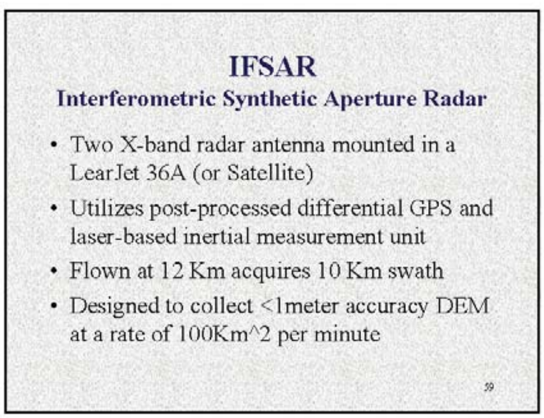

Data Point Overload
John Chance & Associates, Amtrak Corridor
54

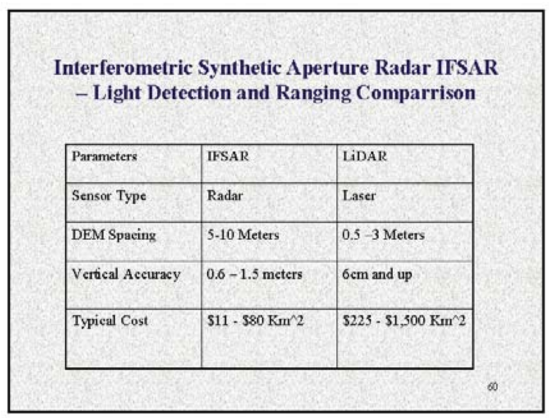




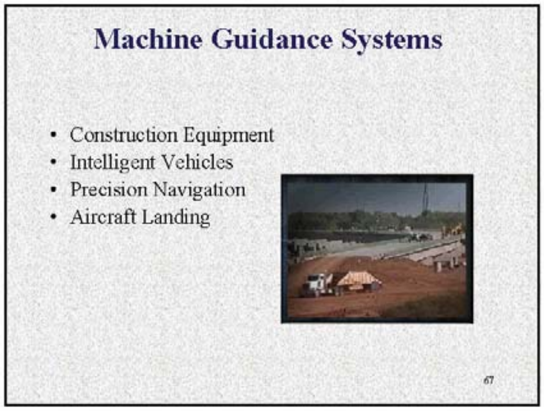


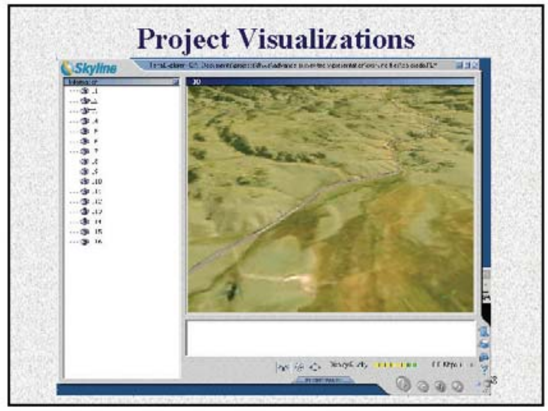




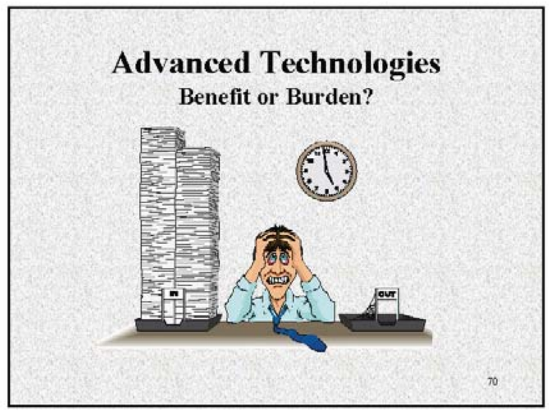


Parameters	IFSAR	LiDAR
Sensor Type	Radar	Laser
DEM Spacing	5-10 Meters	0.5 –3 Meters
Vertical Accuracy	0.6 – 1.5 meters	6cm and up
Typical Cost	$11 - $80 Km^2	$225 - $1,500 Km^2


Machine Guidance Systems
• Construction Equipment
• Intelligent Vehicles
• Precision Navigation
• Aircraft Landing
67


Project Visualizations
Skyline


Project Visualizations
69


Advanced Technologies
Benefit or Burden?
OUT
70