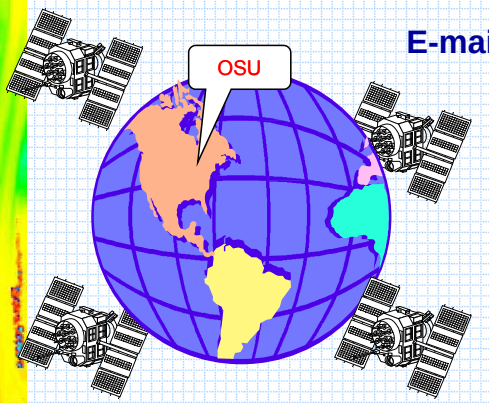
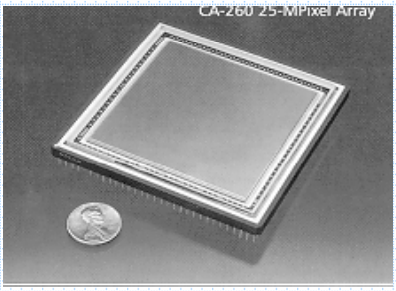
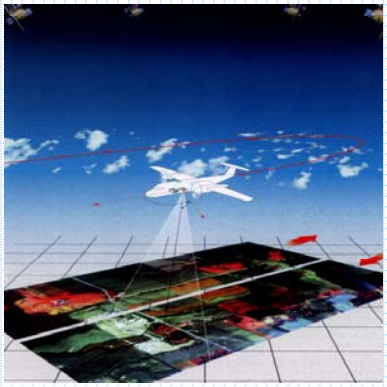
The State-of-the-Art in Airborne Data Collection Systems – Focused on LiDAR and Optical Imagery

Charles K. Toth

Center for Mapping
The Ohio State University
Phone: 614-292-7681
E-mail: toth@cfm.ohio-state.edu

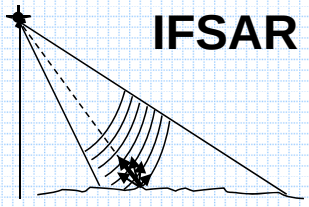






100th Anniversary Photogrammetric Week (PhoWo 09)
University of Stuttgart, September 7-11, 2009

Airborne Data Collection Systems



ADS80

Acknowledgement

- Intergraph Corporation
- Leica Geosystems
- Trimble Applanix
- Microsoft Vexcel Imaging
- BLOM ASA
- Optech International
- Fugro EarthData Group

Outline

- ✓ Introduction
- ✓ Georeferencing/Sensor orientation
- ✓ Laser scanning systems
- ✓ Digital camera systems
- ✓ Applications
- ✓ Performance assessment of LiDAR and CCD systems
- ✓ Future trends/Summary

Outline

- ✓ **Introduction**
- ✓ Georeferencing/Sensor orientation
- ✓ Laser scanning systems
- ✓ Digital camera systems
- ✓ Applications
- ✓ Performance assessment of LiDAR and CCD systems
- ✓ Future trends/Summary

Airborne Mapping

- ✓ Aerial photography started with flying (WWI era)
- ✓ Massive developments in camera design resulted in large format aerial mapping cameras
  - ❖ Large film format (23 cm by 23 cm image)
  - ❖ Near perfect optical system (measured in how closely the camera projection system matches the ideal pin-hole camera model)
  - ❖ Large ground coverage at good spatial resolution
- ✓ Workhorse of mapping for a long time
- ✓ Until the millennium 90+% of spatial data was acquired by film-based large format aerial cameras (2,000 worldwide)
- ✓ In process of moving to totally digital systems, it was the last stronghold of analog systems in mapping
- ✓ Totally digital airborne data acquisition systems, including direct georeferencing discussed at PhoWo 99

Technology Evolution

Mobile Mapping Technology		
Navigation sensors	Fully operational GPS	Mid 90s'
	GPS/Gyro/wheel counter (terrestrial platforms)	Mid 90s'
	GPS/IMU (airborne platforms)	Mid/late 90s' for commercial use
	GPS/IMU (terrestrial platforms)	Late 90s'
Optical imaging sensors (passive)	Video-resolution CCD sensors	Mid 90s'
	High-resolution CCD sensors	Late 90s'
	Large-format digital cameras (airborne platforms)	From 2002
Active imaging sensors	Airborne LiDAR	Late 90s'
	Mobile LiDAR	Since 2005
	SAR	Early/mid 90s'

Image understanding/computer vision

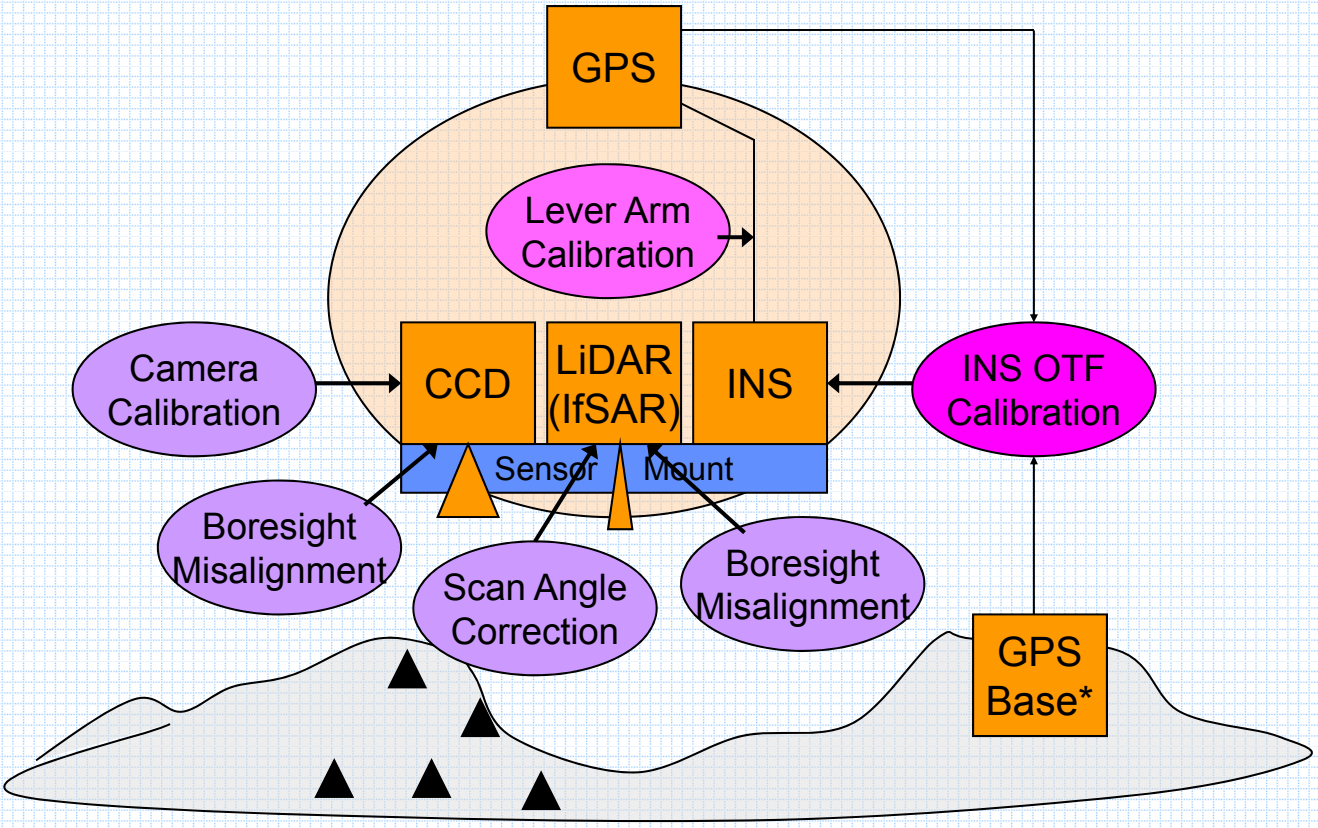
Outline

- ✓ Introduction
- ✓ **Georeferencing/Sensor orientation**
- ✓ Laser scanning systems
- ✓ Digital camera systems
- ✓ Applications
- ✓ Performance assessment of LiDAR and CCD systems
- ✓ Future trends/Summary

GPS/IMU-based Direct Georeferencing

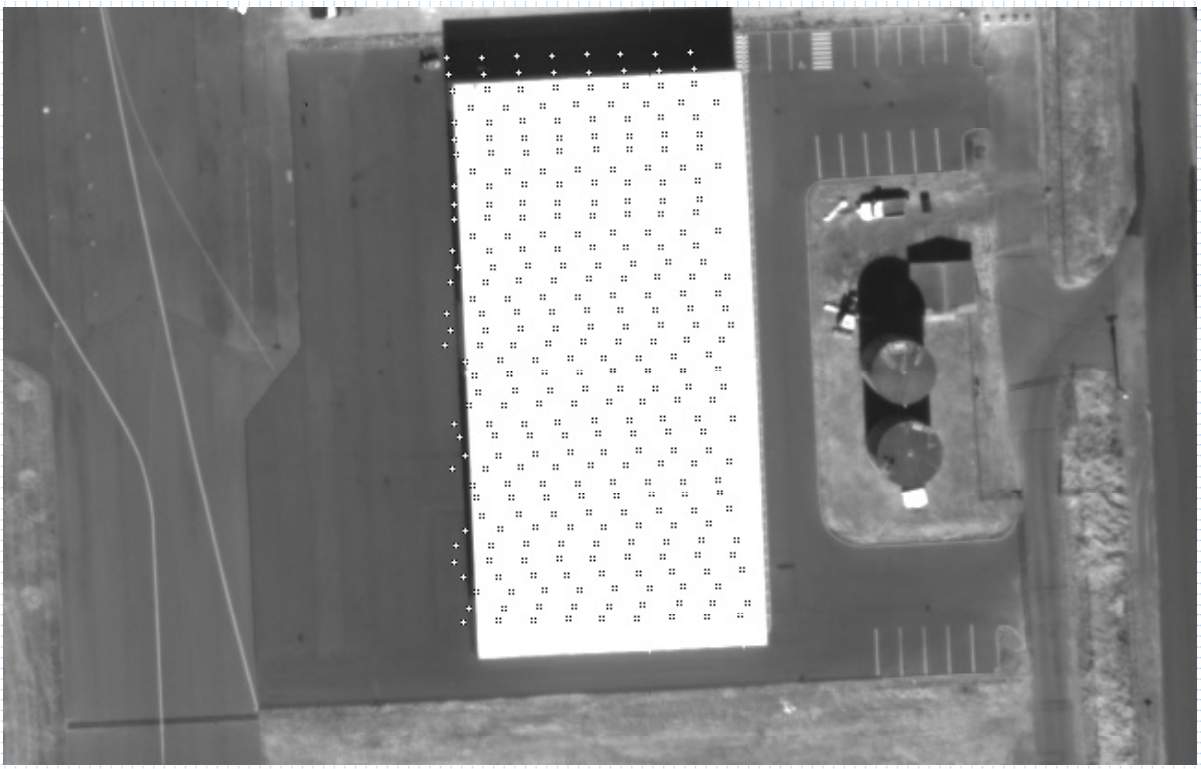
- ✓ Platform orientation by direct measurements:
  - ❖ GPS absolute positioning at moderate rate
  - ❖ IMU relative positioning and attitude determination at high rate
- ✓ Loose/tight integration in Extended Kalman Filter (EKF)
- ✓ Several commercial systems available
- ✓ Extrapolation error characteristics (AT: interpolation)
- ✓ Navigation solution is obtained in global frame
- ✓ Gravity field is important
  - ❖ Needed in EKF
  - ❖ An emerging solution to convert to local frame
- ✓ Critical issues:
  - ❖ Spatial relationship between sensors is essential (lever arm, mounting bias, boresight misalignment, etc. calibration)

System Calibration

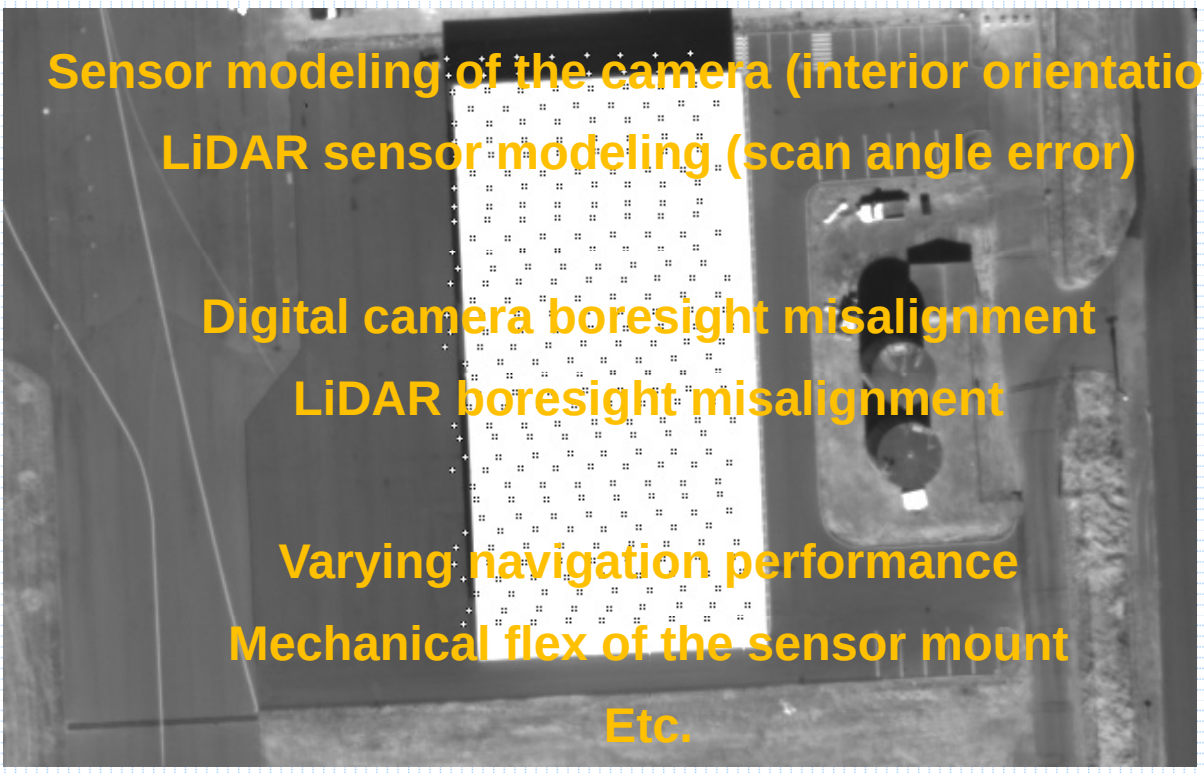


* GPS reference could be based on GPS base station or network solution, etc.

Misalignment between LiDAR Points and Imagery



What Could Be the Problem?



Sensor modeling of the camera (interior orientation)

LiDAR sensor modeling (scan angle error)

Digital camera boresight misalignment

LiDAR boresight misalignment

Varying navigation performance

Mechanical flex of the sensor mount

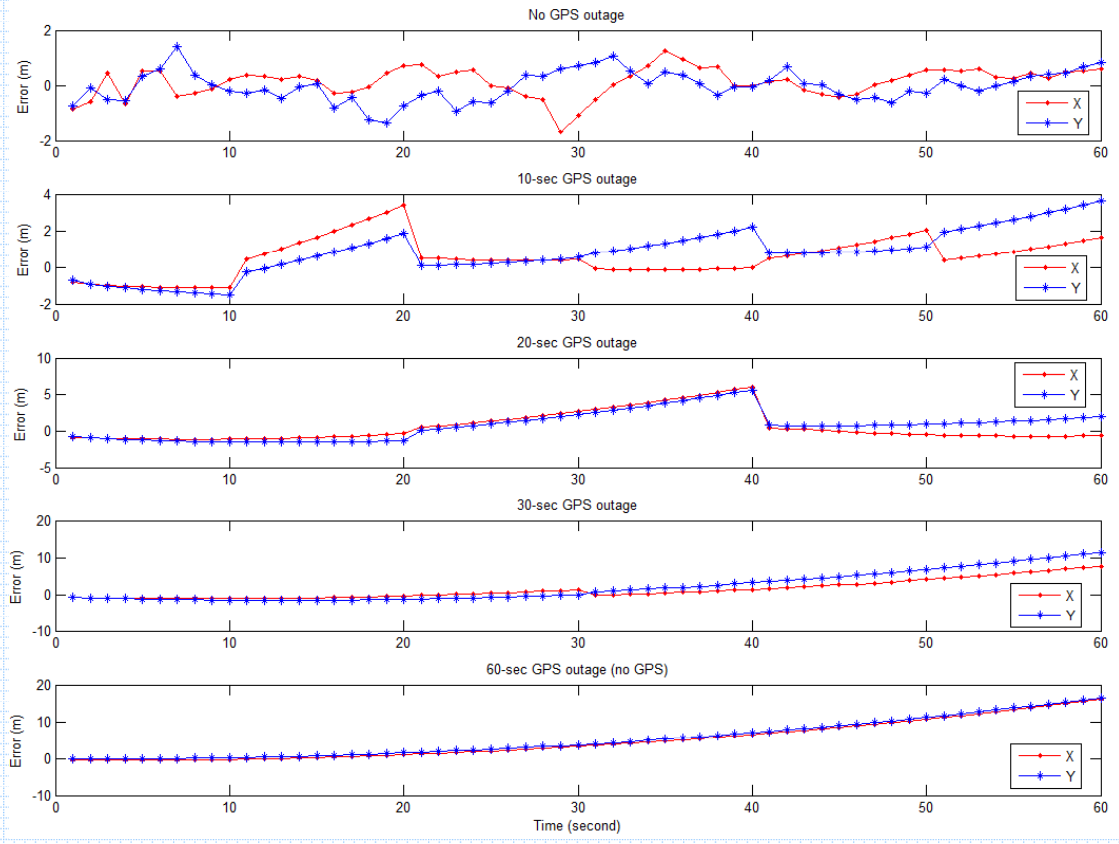
Etc.

GPS/IMU-based Direct Georeferencing

- ✓ Platform orientation by direct measurements:
  - ❖ GPS absolute positioning at moderate rate
  - ❖ IMU relative positioning and attitude determination at high rate
- ✓ Loose/tight integration in Extended Kalman Filter (EKF)
- ✓ Several commercial systems available
- ✓ Extrapolation error characteristics (AT: interpolation)
- ✓ Navigation solution is obtained in global frame
- ✓ Gravity field is important
  - ❖ Needed in EKF
  - ❖ An emerging solution to convert to local frame
- ✓ Critical issues:
  - ❖ Spatial relationship between sensors is essential (lever arm, mounting bias, boresight misalignment, etc. calibration)
  - ❖ IMU selection (position and attitude accuracy correlated)

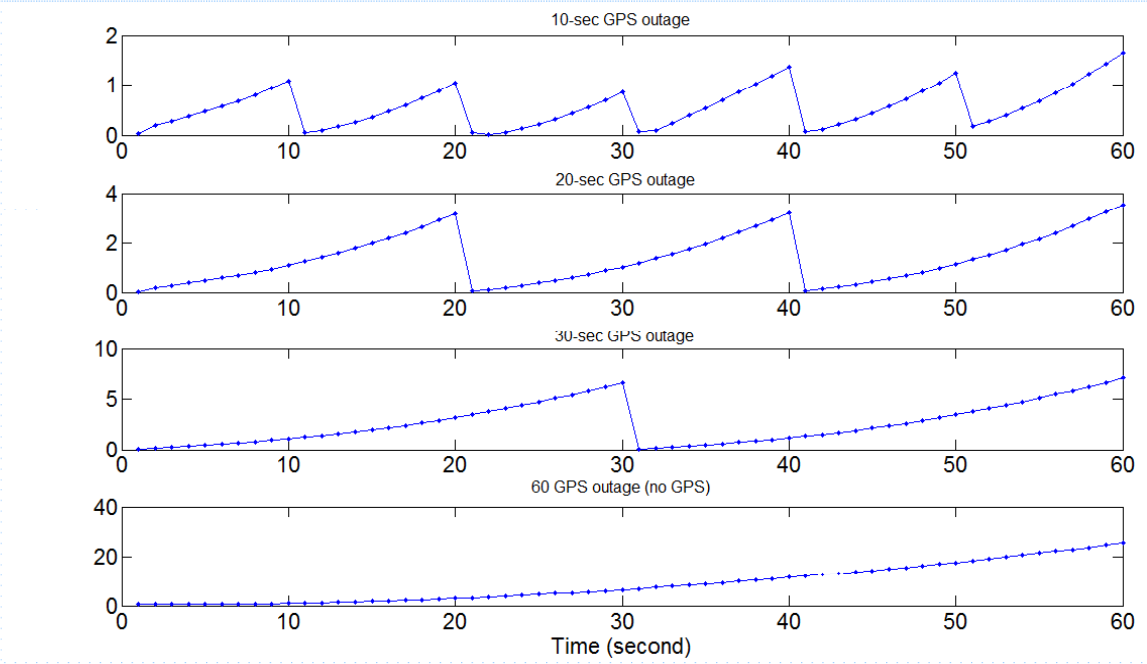
GPS/IMU Solution

GPS: 1 m, IMU: MEMS



GPS/IMU Solution

GPS: 3 cm, IMU: tactical grade



IMU drift during a GPS period < GPS accuracy
(Note position and attitude accuracy are correlated)

GPS Alternatives

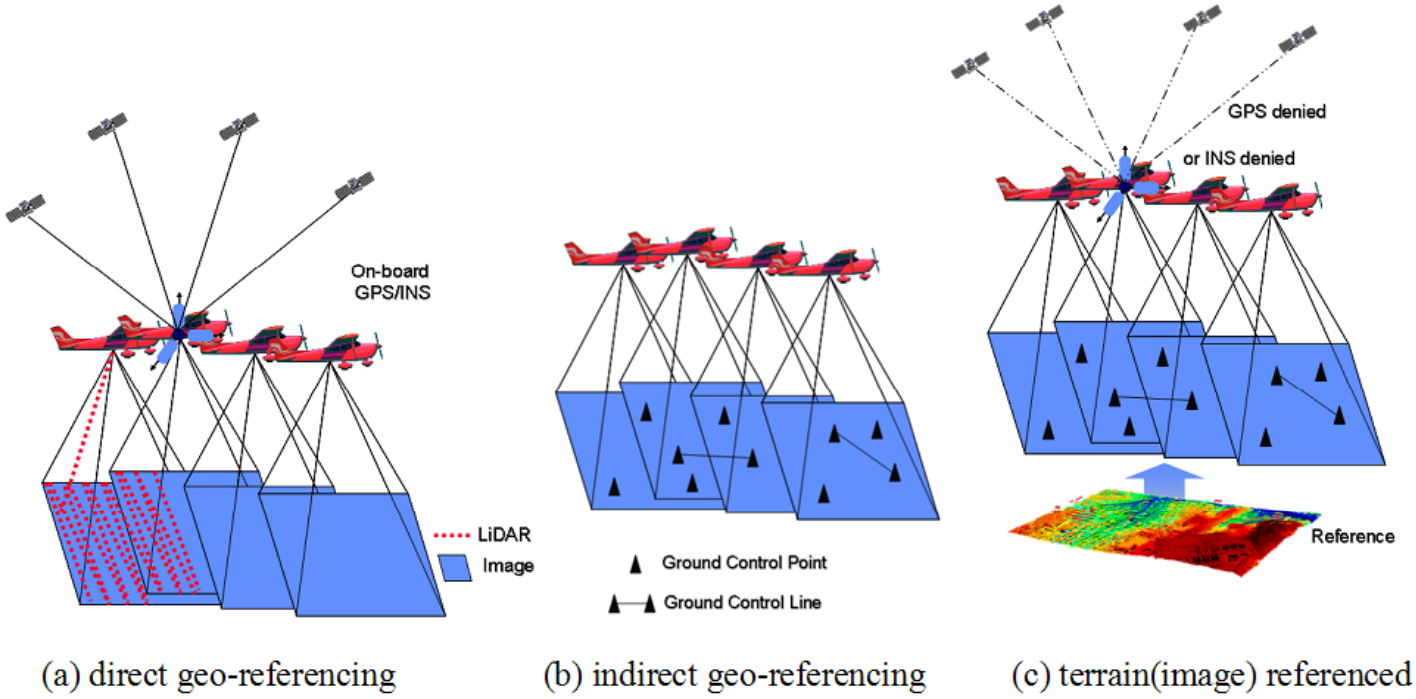
	Accuracy	Real-time/Post-processed
Pseudorange	10 m-level	Post-processed
Pseudorange-based differential	m-level	Post-processed
WAAS/EGNOS pseudorange	m-level	Real-time
Differential with base station	cm-level (*)	Post-processed/Real-time
Differential with network solution(**)	cm-level	Real-time/ Post-processed
Satellite based differential correction	sub-m level	Real-time
RTK	cm-level	Real-time
VRS (CORS-based)	cm level	Real-time
PPP	sub-dm level	Post-processed

(*) baseline-dependent
(**) CORS - Continuously Operating Reference Stations

Global Navigation Satellite Systems (GNSS)

COMPASS

Georeferencing Alternatives



- **Global GIS/CAS/image databases are increasingly becoming available**
- **GPS/IMU/TRN can improve robustness and downstream mapping processes**

Outline

- ✓ Introduction
- ✓ Georeferencing/Sensor orientation
- ✓ **Laser scanning systems**
- ✓ Digital camera systems
- ✓ Applications
- ✓ Performance assessment of LiDAR and CCD systems
- ✓ Future trends
- ✓ Summary

Airborne LiDAR/Laser Scanning Systems (ALS)

- ✓ Rapid developments in the past five years
- ✓ Improving laser power
- ✓ Increasing PRF (200 kHz)
- ✓ Multiple pulse technology (2)
- ✓ Improving point density
- ✓ Feature extraction
- ✓ Excellent ranging accuracy (1 cm for hard surfaces)
- ✓ Multiple return capability (3-4 m separation)
- ✓ Intensity image
- ✓ Waveform processing capability (expected to be used broadly)
- ✓ Miniaturization (smaller footprint, less power)

Sensor	Mode	Scan Freq. [Hz]	Pulse Freq. [kHz]	Scanning Angle [º]	Beam Diverg. [mrad]	Pulse Energy [µJ]	Range Resolution [cm]	Pulse Length [ns]	Digitizer [ns]
Optech 2033	Oscillating	0-70	33	±20	0.2/1.0	N/A	1.0	8.0	N/A
Optech 3100	Oscillating	0-70	33-100	±25	0.3/0.8	<200	1.0	8.0	1
Optech Gemini	Oscillating	0-70	167	±25	0.15/0.25/0.8	<200	3.0	7.0	N/A
Optech Orion	Oscillating	0-100	167	±25	0.25	<200	2.0	7.0	N/A
TopEye MkII	Conic	35	5-50	14,20	1.0	N/A	<1.0	4.0	0.5
TopoSys I	Line	653	83	±7.15	1.0	N/A	6.0	5.0	N/A
TopoSys II Falcon	Line	653	83	±7.15	1.0	N/A	2.0	5.0	1
Trimble Harrier	Rotating polygon	160	160	±30	0.5	N/A	2.0	4.0	1
Leica ALS50	Oscillating	25-70	83	±37.5	0.33	N/A	N/A	10	N/A
Leica ALS50-II	Oscillating	35-90	150	±37.5	0.22	N/A	N/A	10	1
Leica ALS60	Oscillating	0-100	200	±37.5	0.22	N/A	3.0-4.0	5.0	1
Riegl LMS-Q560	Line	160	240	±30.0	0.3	8	2.0	4.0	1
Riegl LMS-Q680	Line	200	240	±30.0	0.4	8	2.0	4.0	1

Laser Waveform Characteristics

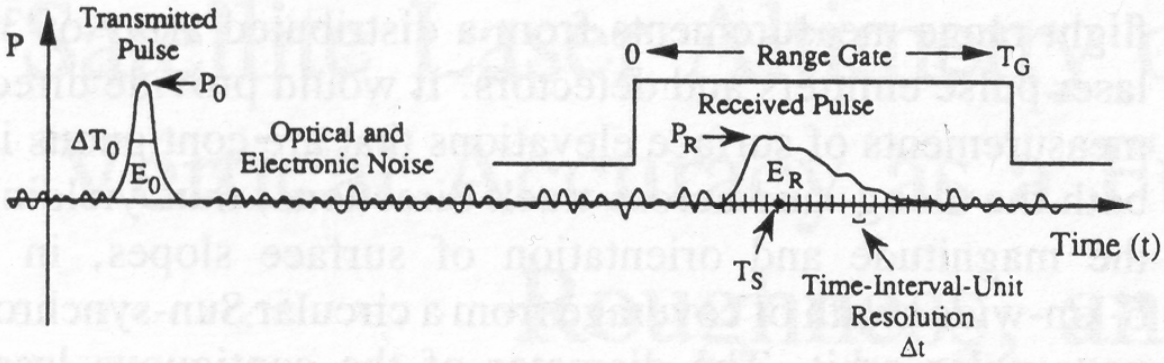


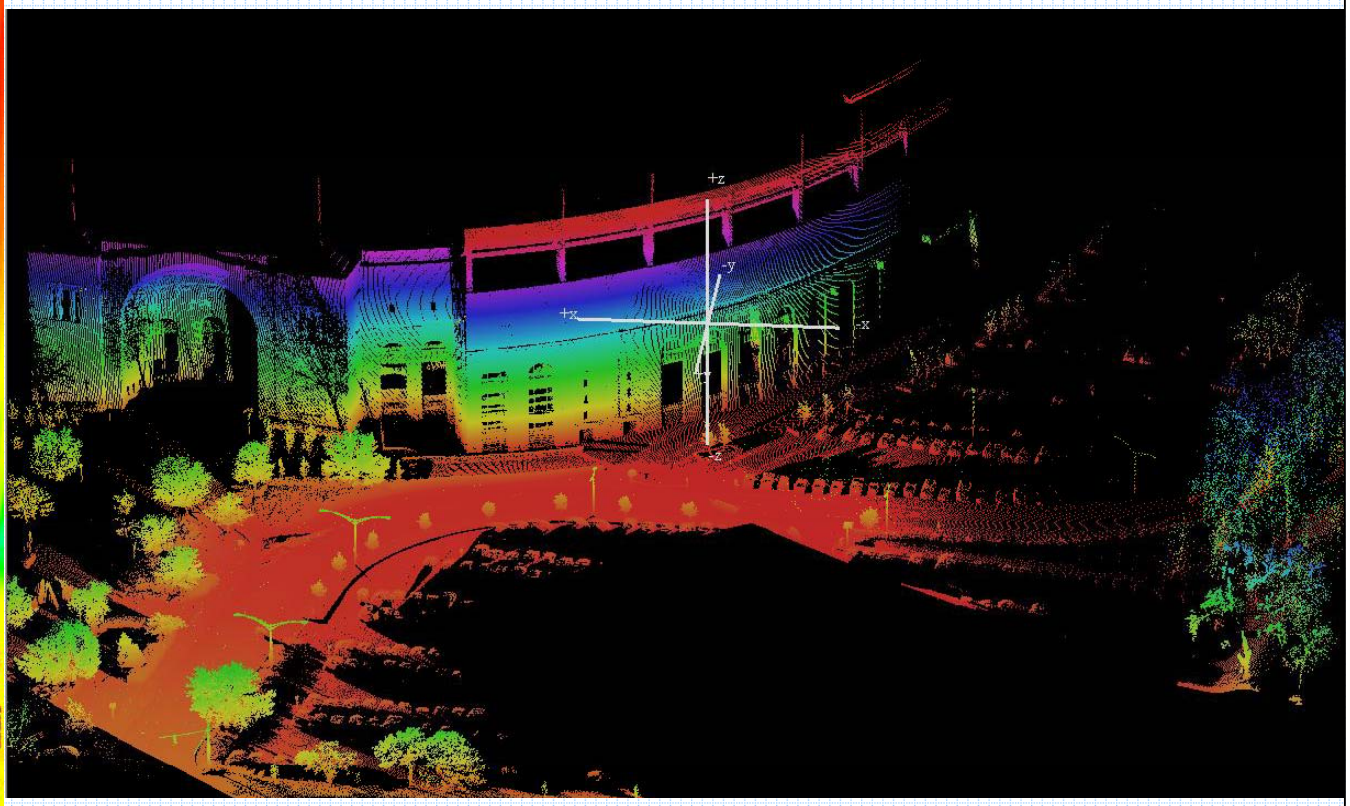
Fig. 1. Conceptual illustration of range to the surface measurement showing signal strength (*P*) as a function of time (*t*) for transmitted and received laser pulse. Adapted from [11].

From Bufton, 1989, *Proc IEEE*

Potential for:

- Improved peak(s) detection
- Surface orientation estimation
- Feature extraction (forestry)

Mobile LiDAR



The “Horseshoe”, The Ohio State University, Optech Lynx

Outline

- ✓ Introduction
- ✓ Georeferencing/Sensor orientation
- ✓ Laser scanning systems
- ✓ **Digital camera systems**
- ✓ Applications
- ✓ Performance assessment of LiDAR and CCD systems
- ✓ Future trends/Summary

Airborne Digital Camera Systems

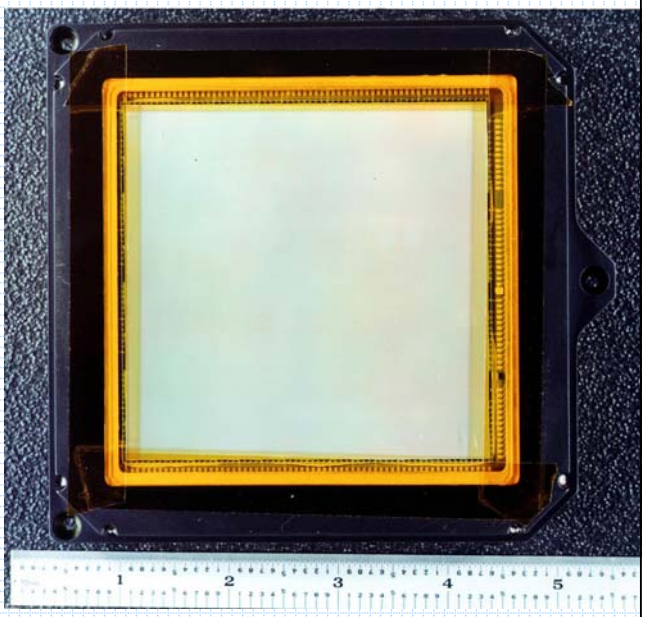
- ✓ Very rapidly advancing field, large number of manufacturers, most systems are based on CCD sensors (CMOS is medium/low end)
- ✓ A variety of designs (large footprint at good GSD):
  - 3-line, frame sensor model
  - Single/multiple sensor
  - Single/multiple camera head
  - Scanning camera head(s)
- ✓ Improving spatial resolution:
  - Smaller pixel size may results in better optical resolution; 1/(2 pixel size), 10 micron ~ 50 lp/mm
  - Large-format systems: 100-200 Mpixel
  - Medium-format systems: 30-60 Mpixel
- ✓ Improving radiometric characteristics:
  - Grey values (dynamic range, resolution, SNR)
  - Panchromatic and multi-spectral (Bayer-pattern, separate sensors)
  - Travel, time, phase, polarization (secondary)
- ✓ Potential for real-time processing via automation

CCD Features

- Bad pixels (no faultless chip)
- Quantum efficiency (> 60 %)
- Charge transfer efficiency (0.999999)
- Thermo sensitivity (cooling)
- Dark current
- Linear characteristic
- Shuttering
  - Mechanical (less preferred)
  - Electronic (interline CCD, only linear/small arrays)

Color 14404 x 3
Trilinear CCD, 6.5 µ

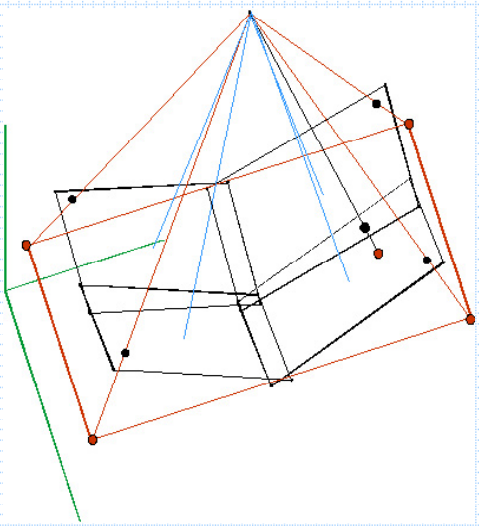
Pixel size: 8.75 µ
Image size: 9K x 9K
(80 mm by 80 mm)



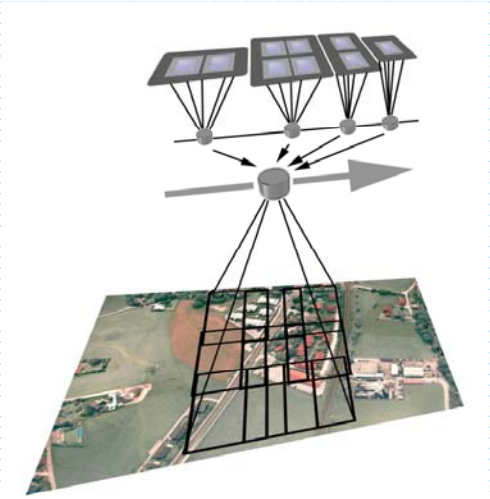
Frame CCD: 50-60 (16) Mpixel
Interline CCD: 16 (2) Mpixel

Virtual Image Formation

Sub-images, taken by different camera heads at the <u>same time</u>, are combined (<u>oblique camera orientation</u>)



Sub-images, taken by different camera heads at <u>different times</u>, are combined (<u>parallel image sensor planes</u>)



Virtual image is distortion free (ideal pin-hole camera model)

Large-format, multihead, frame cameras

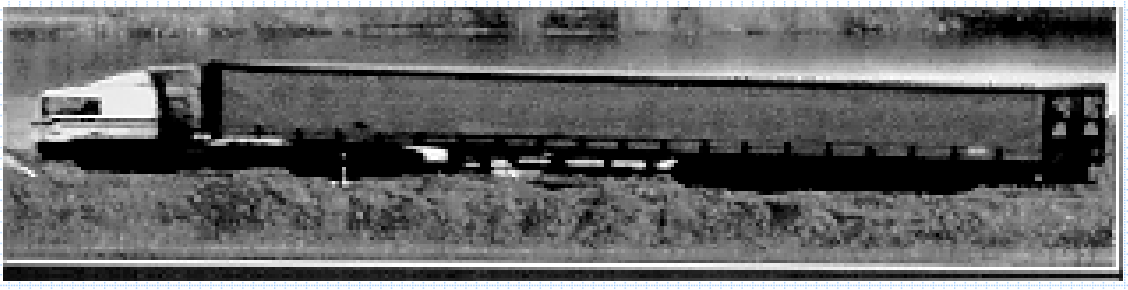
System	Image Size [pixel]	CCD Sensor Size [pixel]	Number of Sensors	Pixel Size [micron]	Dynamic Range [bits]	Maximum Frame Rate [sec/image]	Field of View (FOV)	GPS/IMU	Software
DMC Digital Mapping Camera Intergraph	13,824 x 7,680	7,000 x 4,000 (pan) 3,000 x 2,000 (multispectral)	4 + 4	12	12	2.1	69.3° x 42°	Optional Integrated	Any system (frame camera model)
UltraCamX Vexcel Microsoft	14,430 x 9,420 (pan) 4,008 x 2,672 (MS)	3,680 x 2,400	9 + 4	7.2	14	1	55° x 37°	Optional Integrated	Any system (frame camera model)
UltraCam XP and WA Vexcel Microsoft	17,310 x 11,310 (pan) 5,770 x 3770 (RGB & NIR)	5,570 x 3,770	9 + 4	6	14	2	55° x 37° 83° x 56°	Optional Integrated	Any system (frame camera model)
DiMAC DIMAC Systems	10,500 x 7,200	7,216 x 5,412	2 (2)	6.8	16	2.1	34° x 26° or 66° x 48°	Optional Integrated	Any system (frame camera model)
RolleiMetric AIC x4 Trimble	13,000 x 10,000	7,228 x 5,428	4	6.8	16	3	60/72/100 mm lens 80° x 65° 70° x 45° 50° x 30°	Optional Integrated	Any system (frame camera model)
Quattro DigiCAM IGI-Systems	13,000 X 10,000	7,216 x 5,412	4	6.8	16	1.9	50/100 mm lens 85° x 60° 50° x 30°	Optional Integrated	Any system (frame camera model)

Large-format linescanner cameras

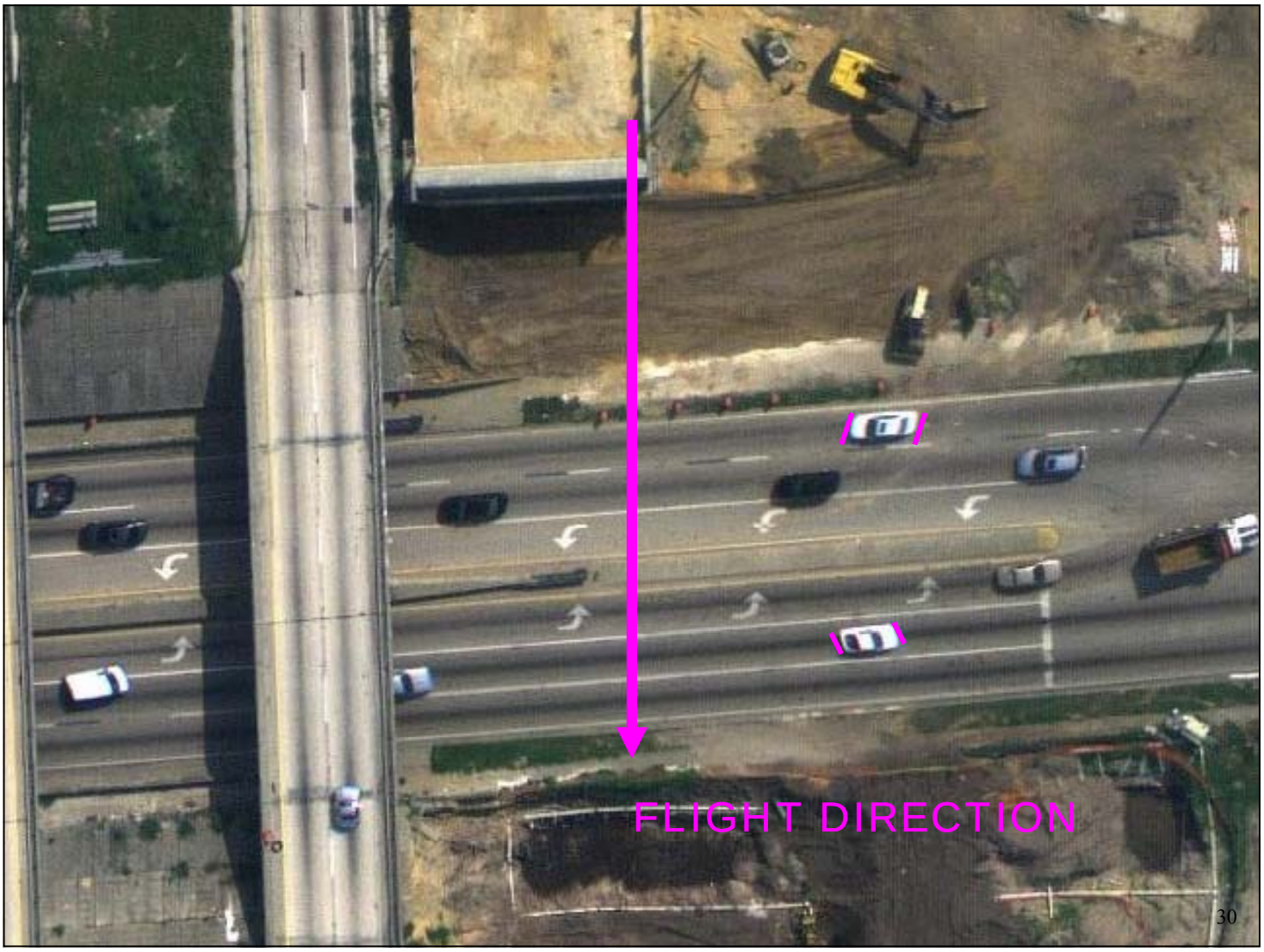
System	Image Size	CCD Sensor Size	Number of Sensors	Pixel Size [micron]	Dynamic Range [bits]	Maximum Frame Rate [image/sec]	Field of View (FOV)	GPS/IMU	Software
ADS40 Airborne Digital Sensor Leica GeoSystems	12,000 x any	12,000 (2x)	3 (2x) + 4	6.5 (3.25)	14	n/a	64°	Mandatory Integrated	GPro, ORIMA, SocetSet, Virtuozo, KLT Atlas. DIGI3, ImageStation
ADS80 Leica GeoSystems	12,000 x any	12,000	3 + 5	6.4	12	n/a	64°	Mandatory Integrated	As for ADS40
JAS150 (HRSC) Jena-Optronik	12,000 x any	12,000	5 + 4	6.5	16	n/a	30°	Mandatory Integrated	JenaStereo, SocetSet
4-DAS-1 Wehrli Associates	8,002 x any	8,002	3 (x3) + 1	9	14	n/a	39°	Mandatory Integrated	Proprietary
SI-250 Startimager	14,400 x any	14,400	10	5	9	n/a	17°, 23°, 40°	Mandatory Integrated	Proprietary

- **Motion artifact due to continues imaging (image lines are captured)**
- **GPS/IMU-based georeferencing is mandatory**

Scanning-related Motion Artifacts



Camera motion



Medium-format multihead frame cameras

System	Image Size	CCD Sensor Size	Number of Sensors	Pixel Size [micron]	Dynamic Range [bits]	Maximum Frame Rate [sec/image]	Field of View (FOV)	GPS/IMU	Software
Spectra View8 Airborne Data Systems	8,000x 2,672	8,000x 2,672 4,000x 2,672	2 + 4	9	12	n/a	64°	Optional Integrated	Any system (frame camera model)
DSS 439 Applanix Trimble	7,216 x 5,412	7,216 x 5,412	2	6.8	12	3	40/60 mm lens 62° x 49° 44° x 34°	Built in	Any system (frame camera model)
Dual Head Trimble Aerial Trimble	7,228 x 5,428 8,924 x 6,732	7,228 x 5,428 8,924 x 6,732	2	6.8 6	16	1.9 1	50/80/120 mm lens 69° x 55° 52° x 40° 23° 17°	Optional Integrated	Any system (frame camera model)
Dual DigiCAM IGI-Systems	7,216 x 10,000	7,216 x 5,412	2	6.8	16	1.9	50/100 mm lens 85° x 60° 50° x 30°	Optional Integrated	Any system (frame camera model)

Medium-format singlehead frame cameras

System	Image Size	CCD Sensor Size	Number of Sensors	Pixel Size [micron]	Dynamic Range [bits]	Maximum Frame Rate [sec/image]	Field of View (FOV)	GPS/IMU	Software
SI5 Spectral Instruments	10,580 x 10,560	10,580 x 10,560	1	9	16	2	74° x 74°	Optional	Any system (frame camera model)
UltraCamL Vexcel Microsoft	9,735 x 6,588	9,735 x 6,588 5,320 x 3,600	1+1	7.2	14	2	53° x 37°	Optional	Any system (frame camera model)
DiMAC LIGHT DIMAC Systems	7,200 x 5,400	7,216 x 5,412	1	6.8	16	2.5	34° x 26° or 66° x 48°	Optional Integrated	Any system (frame camera model)
DSS Applanix Trimble	5,436 x 4,092	5,436 x 4,092	1	9	12	2.5	40/60 mm lens 62° x 49° 44° x 34°	Built in	Any system (frame camera model)
DSS 439 Applanix Trimble	7,216 x 5,412	7,216 x 5,412	1	6.8	12	3	40/60 mm lens 62° x 49° 44° x 34°	Built in	Any system (frame camera model)
DigiCAM IGI-Systems	5,440 x 4,080 7,216 x 5,428	5,440 x 4,080 7,216 x 5,428	1	9 6.8	16	2.5 1.9	35/40/80 mm lens 69° x 55° 52° x 40° 33° x 25°	Optional Integrated	Any system (frame camera model)
Trimble Aerial (AIC Rollei) Trimble	5,440 x 4,080 7,228 x 5,428 8,924 x 6,732	5,440 x 4,080 7,228 x 5,428 8,924 x 6,732	1	9 6.8 6	16	1.7 1.9 1	50/80/120 mm lens 69° x 55° 52° x 40° 23° 17°	Optional Integrated	Any system (frame camera model)
NexVue Spectrum Imaging	4,080 x 4,080	4,080 x 4,080	1	9	12	2.5	50/90 mm lens 23° x 23° 42° x 42°	Optional Integrated	Any system (frame camera model)
RCD105 Leica GeoSystems	7,162 x 5,389	7,162 x 5,389	1 (1)	6.8	12	0.49	35/60/100 mm lens 69.7° x 55.3° 44.2° x 34° 27.4° x 20.8°	Optional Integrated	Any system (frame camera model)
RMK D Intergraph	6096 x 6500	6096 x 6500	4	7.2	14	1	45 mm lens 52° x 55°	Optional Integrated	Any system (frame camera model)

Outline

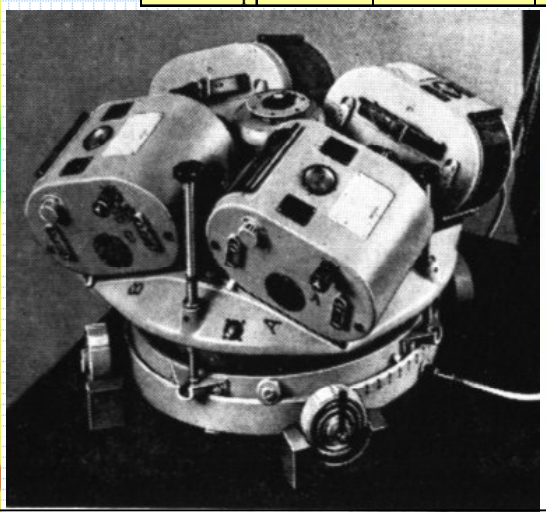
- ✓ Introduction
- ✓ Georeferencing/Sensor orientation
- ✓ Laser scanning systems
- ✓ Digital camera systems
- ✓ **Applications**
- ✓ Performance assessment of LiDAR and CCD systems
- ✓ Future trends/Summary

Applications

- ✓ Conventional applications:
  - Visualization
  - Vector mapping/feature extraction
  - Surface extraction
  - Orthopohoto production
  - Classification
- ✓ Better performance (compared to scanned film imagery)
  - ✓ Superior radiometry results in improved matching (6-7 bits of scanned imagery vs. 10-12 bits of direct digital image)
- ✓ Emerging application fields:
  - Oblique imagery for visualization (city models)
  - Emergency mapping/rapid mapping
  - Transportation/traffic flow monitoring
- ✓ Supporting technologies:
  - Highly automated processing, including georeferencing and feature extraction
  - Real-time processing
  - Communication/data link

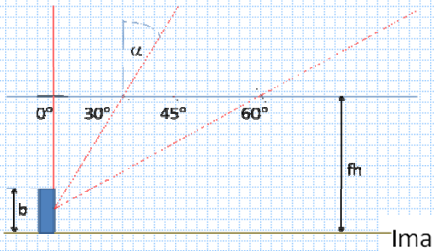
Microsoft Bing

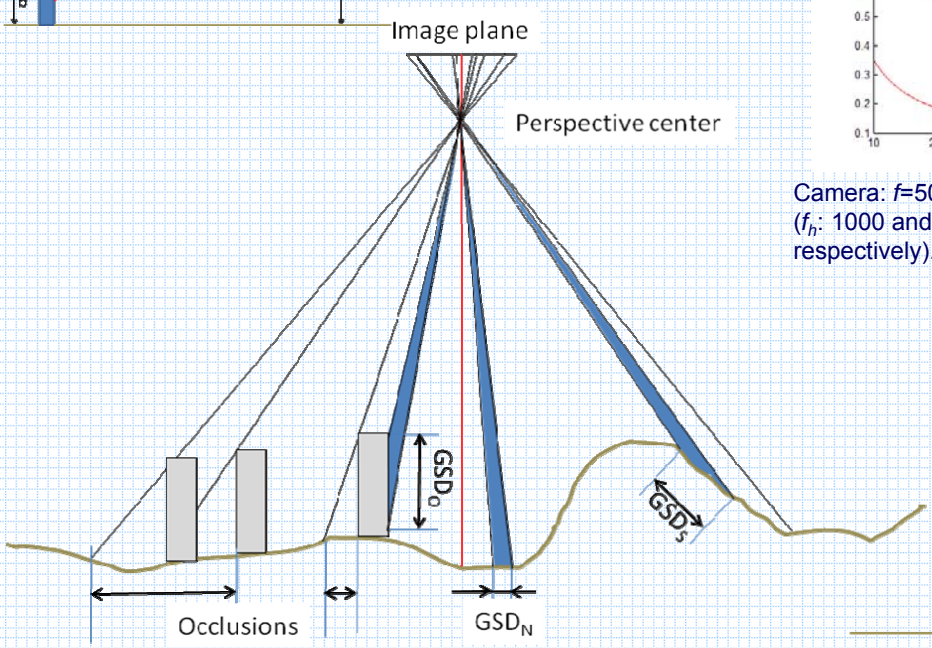
Oblique camera systems									
System	Camera Heads	CCD Sensor Size	Number of Sensors	Pixel Size [micron]	Dynamic Range [bits]	Maximum Frame Rate [sec/image]	Oblique Angle [°]	GPS/IMU	Software
3-OC Wehrli Associates	3	8,002	3	9	14	n/a	45	Mandatory Integrated	Proprietary
MIDAS Track'Air	4 + 1	4,992 x 3,328	5	7.2	8	2.5	30-60	Optional	Proprietary
Pictometry BLOM	4 + 1	n/a	n/a	n/a	n/a	n/a	n/a	Built-in	Proprietary
3K DLR	3	4,992 x 3,328	3	7.2	8	2.5	n/a	Built-in	Proprietary
Dual DigiCAM Oblique IGI-Systems	4	7,216 x 5,412	4	6.8	16	1.9	45	Optional Integrated	Any system (frame camera model)
A3 Visionmap	2	4,006 x 2,666	2	9	12 (8)	0.07	±50	Optional	Proprietary

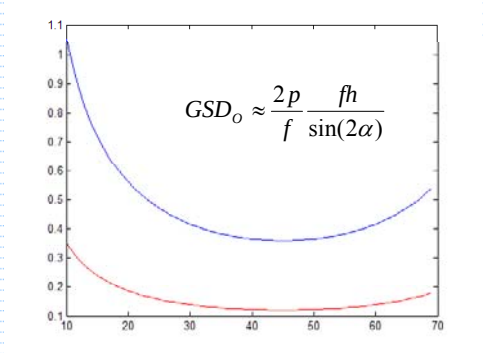


Recon Optical Stepping Camera

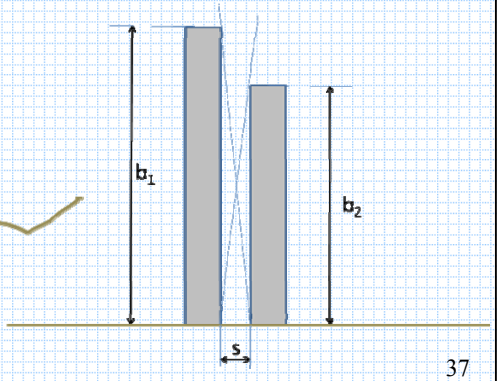
Vertical vs. Oblique Imagery







Camera: f=50 mm and pixel size=9μ
(f_h: 1000 and 300 m are marked by red and blue, respectively).



Outline

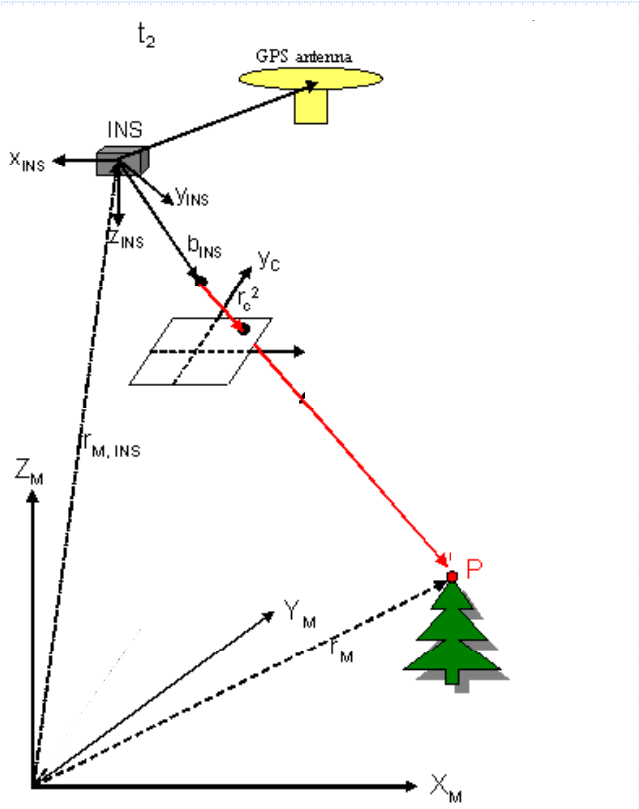
- ✓ Introduction
- ✓ Georeferencing/Sensor orientation
- ✓ Laser scanning systems
- ✓ Digital camera systems
- ✓ Applications
- ✓ **Performance assessment of LiDAR and CCD systems**
- ✓ Future trends/Summary

Achievable Point Positioning Accuracy

- Detailed individual analysis of all the major error sources to show the individual contribution of each error source to the overall error budget as a function of flight parameters
  - Define expected parameters for calibration and QA/QC (Quality Assurance/Quality Control) methods
- Comprehensive analysis tool for the achievable point positioning accuracy with airborne mobile mapping systems considering all the major error sources to support sensor selection/system configuration

- Additional aspects
  - Sensor resolution, radiometry
  - Sensor optical/mechanical quality
  - Software support
  - Vendor loyalty, technical support
  - Weight, power, etc.

Point Positioning with Direct Georeferencing



$$r_M = r_{M,INS} + R_{INS}^{M}\left(s \cdot R_C^{INS} r_c + b_{INS}\right)$$

r_M	—	3D coordinates of object point in mapping frame
$r_{M,INS}$	—	Time dependent 3D INS coordinates in the mapping frame, provided by GPS/INS (refers to the origin of the INS body frame)
R_{INS}^{M}	—	Time dependent rotation matrix between the INS body and mapping frame, measured by INS
R_C^{INS}	—	Boresight matrix between the INS body and sensor frame C
r_c	—	Image coordinates of the object in sensor frame C
s	—	Scaling factor that varies for each point (known for LiDAR, undefined for image)
b_{INS}	—	Boresight offset vector

Error Sources of Airborne LiDAR and Digital Camera Systems: Overview

	LiDAR	Digital camera
Navigation solution errors	Errors in sensor platform position and attitude – shifts and attitude errors	
Sensor calibration errors	Scan angle error	Errors in interior orientation parameters (focal length, principal point shifts, lens distortion parameters)
	Range measurement error	
	Error in reflectance-based calibration	
Inter-sensor calibration errors	Boresight misalignment between the IMU body frame and sensor frames (laser sensor or camera) – shifts and angular errors	
	Error in measured lever arm (vector between GPS antenna and INS reference point)	
Miscellaneous errors	Effect of beam divergence – Footprint	Errors in image coordinate measurement
		Impact on camera window in pressurized cabin, etc.
	Sensor mounting rigidity	
	Time synchronization	
	Effect of atmospheric refraction	

Object space conditions are not considered
- Micro/macro surface characteristics
- Dynamic content, etc.

Effect of Biases on Point Positioning (Approximate Formulas)

Error type		Error in local coordinate system		
		Δx	Δy	Δz
Positioning error	Δx_o	Δx_o	0	0
	Δy_o	0	Δy_o	0
	Δz_o	0	0	Δz_o
Angular error (attitude/boresight)	$\Delta\omega$	0	$h[\sin(\beta+\Delta\omega)-\sin(\beta)]/\cos(\beta)$ $\sim h\sin(\Delta\omega)\sim h\Delta\omega$	$h[1-\cos(\beta+\Delta\omega)/\cos(\beta)]$ $\sim h\Delta\omega\tan(\beta)$
	$\Delta\varphi$	$-h\sin(\Delta\varphi)$	0	$h[1-\cos(\Delta\varphi)]$
	$\Delta\kappa$	$-h\tan(\beta)\sin(\Delta\kappa)$	$h\tan(\beta)[\cos(\Delta\kappa)-1]\sim 0$	0
Range measurement error	Δr	0	$\Delta r\sin(\beta)$	$-\Delta r\cos(\beta)$
Scan angle error	$\Delta\beta$	0	$h[\sin(\beta+\Delta\beta)-\sin(\beta)]/\cos(\beta)$ $=h\sin(\Delta\beta)\sim h\Delta\beta$	$h[1-\cos(\beta+\Delta\beta)/\cos(\beta)]$ $\sim h\Delta\beta\tan(\beta)$
Footprint size	fp	$2h/\cos\beta\tan(\frac{\gamma}{2})$	$h[\tan(\beta+\frac{\gamma}{2})-\tan(\beta-\frac{\gamma}{2})]$	0

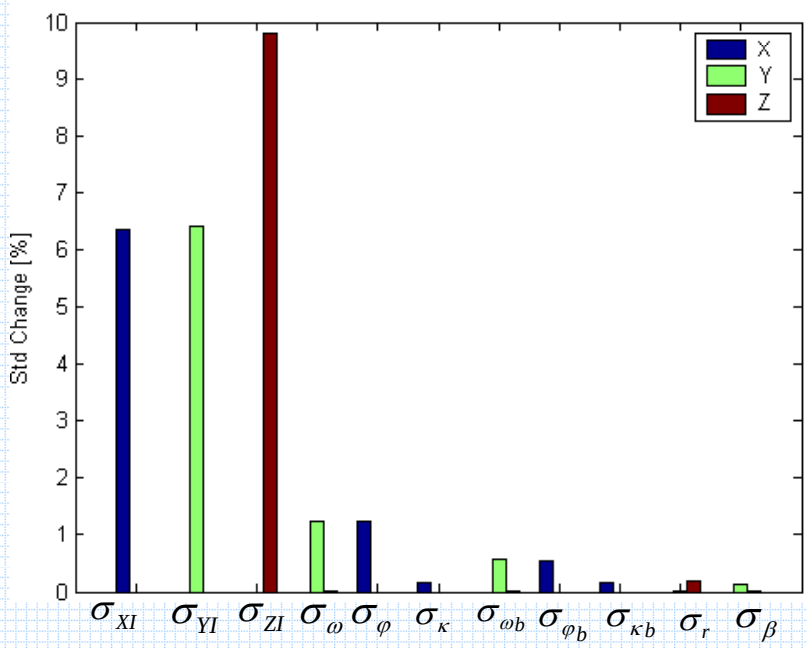
- Local coordinate system is defined as right-handed systems centered in laser reference point, x-axis is flying direction, y is position starboard, and z vertical
- Angular errors refer to the x, y, z axis
- Simplifying assumptions:
  - Terrain is flat
  - Flight line is horizontal (roll=pitch=0)

Typical Standard Deviation Values for State-of-the-Art LiDAR Systems

Parameter	Used Symbol	Value (1σ)
Position errors	σ_{XI} , σ_{YI}	5 cm
	σ_{ZI}	7.5 cm (1.5 σ_{XI}, $\sigma_{XI} = \sigma_{YI}$)
Attitude errors	σ_{ω} , σ_{φ}	15 arcsec
	σ_{κ}	30 arcsec (2 σ_{ω} , $\sigma_{\omega} = \sigma_{\varphi}$)
Boresight misalignment	$\sigma_{\omega b}$, $\sigma_{\varphi b}$	10 arcsec
	$\sigma_{\kappa b}$	30 arcsec
Ranging error	σ_{r}	1 cm
Scan angle error	σ_{β}	5 arcsec

Example accuracy plots are based on typical std values and ranges and typical flying heights and maximum scan angles for state-of-the-art LiDAR systems

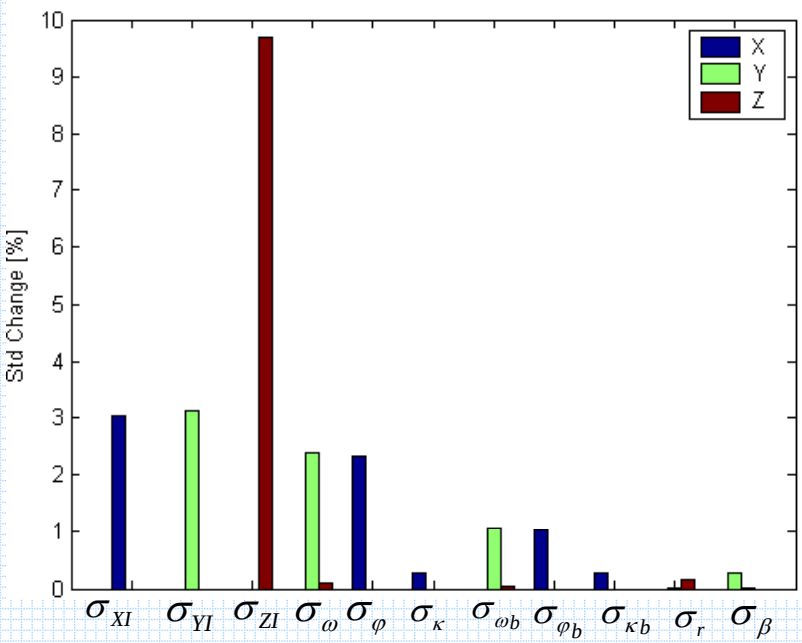
Accuracy Analysis Bar Charts



H=300 m
β=10º

Percentage of change in point positioning precision as an effect of 10% change in std of the various random errors (with respect to the reference average values listed in previous slide)

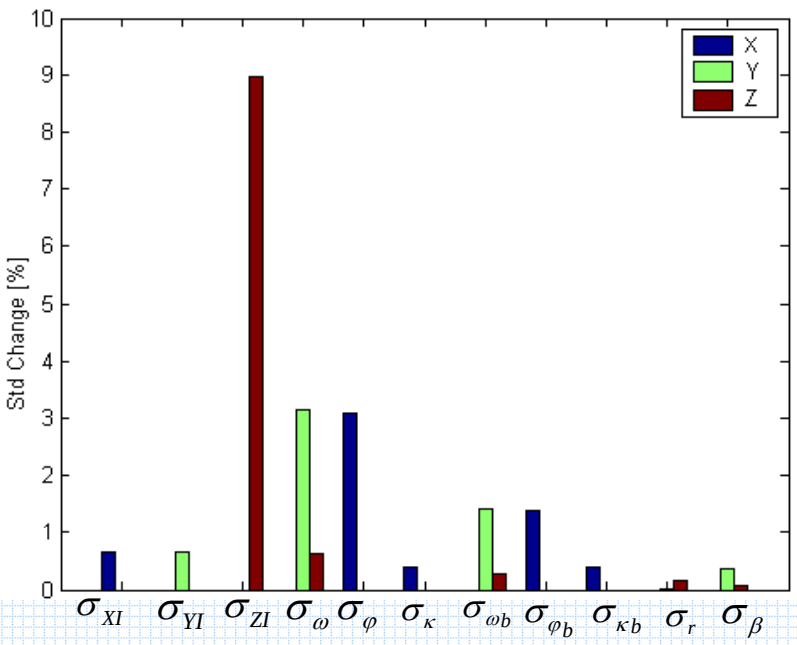
Accuracy Analysis Bar Charts



H=600 m
β=10º

Percentage of change in point positioning precision as an effect of 10% change in std of the various random errors (with respect to the reference average values listed in previous slide)

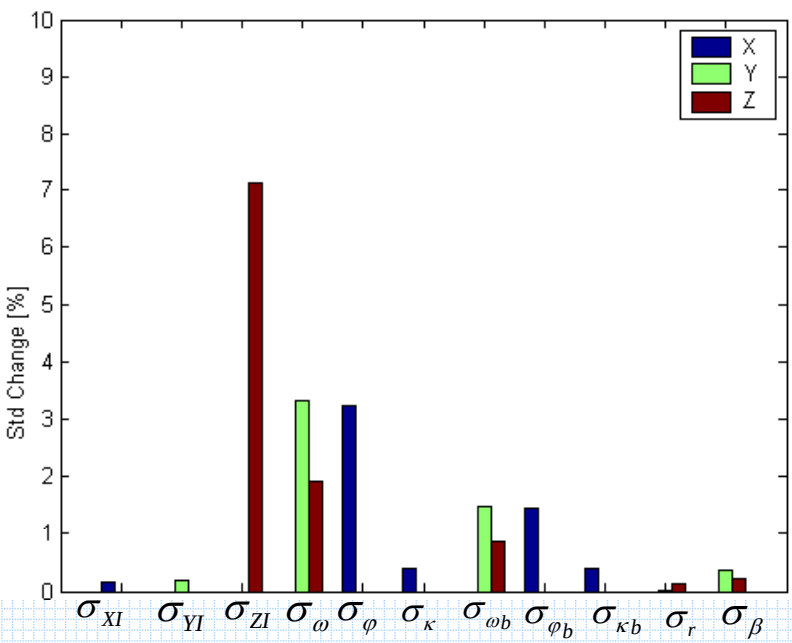
Accuracy Analysis Bar Charts



H=1500 m
β=10º

Percentage of change in point positioning precision as an effect of 10% change in std of the various random errors (with respect to the reference average values listed in previous slide)

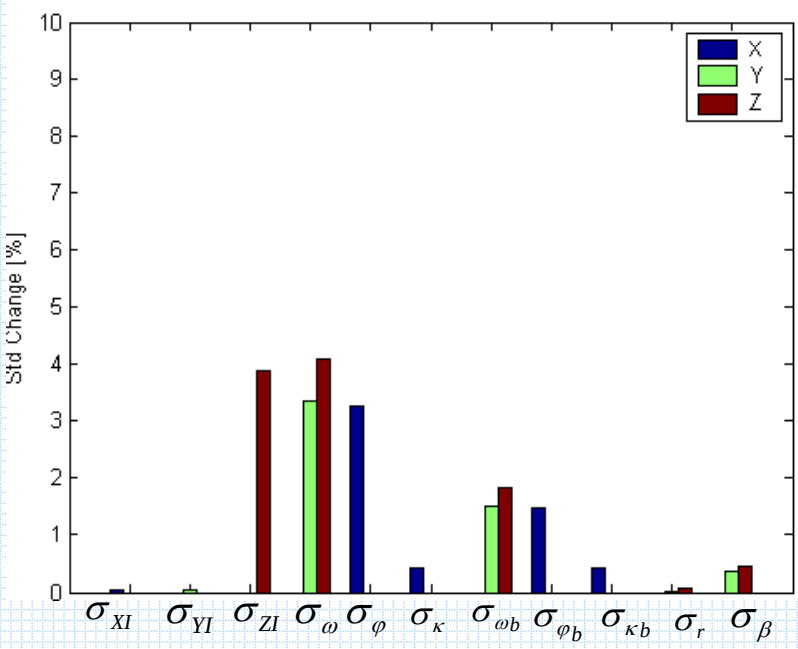
Accuracy Analysis Bar Charts



H=3000 m
β=10º

Percentage of change in point positioning precision as an effect of 10% change in std of the various random errors (with respect to the reference average values listed in previous slide)

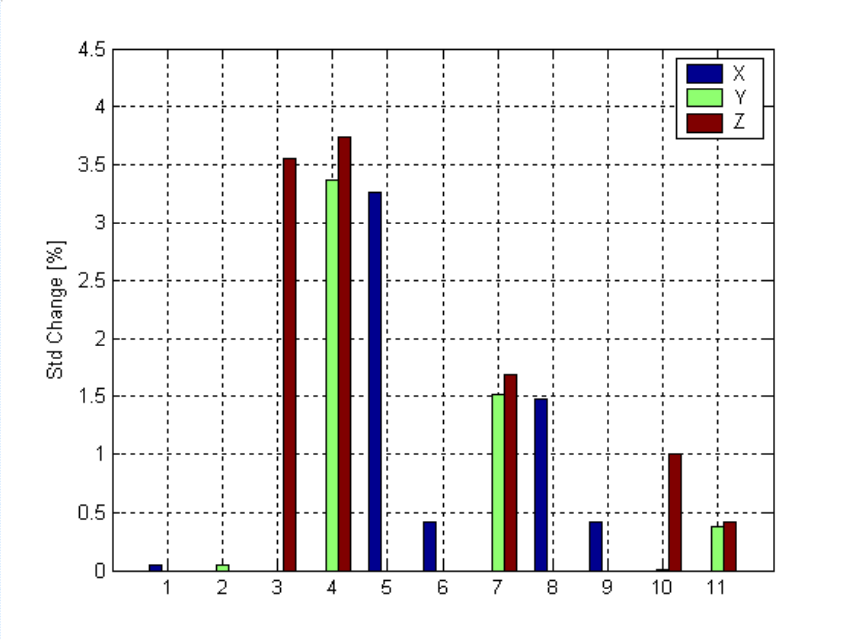
Accuracy Analysis Bar Charts



H=6000 m
β=10º

Percentage of change in point positioning precision as an effect of 10% change in std of the various random errors (with respect to the reference average values listed in previous slide)

Impact of Ranging Error

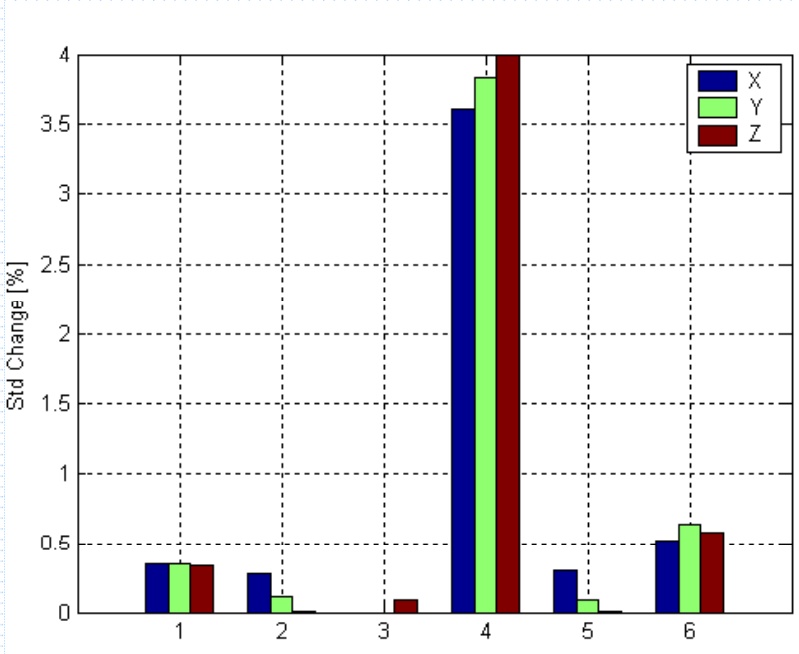


Considered Error Sources and Typical Magnitudes

Parameter		Used Symbol	Std for GPS/IMU
Navigation errors	Position	σ_{XI} σ_{YI} σ_{ZI}	5 – 7.5 cm
	Attitude (Roll, Pitch, Heading)	σ_{ω} σ_{φ} σ_{κ}	15, 15, 30 arc sec
Errors in detemined boresight angles	(Omega, Phi, Kappa)	$\sigma_{\omega b}$ σ_{φ_b} $\sigma_{\kappa b}$	7.5, 7.5, 15 arc sec
Errors in interior orientation parameters	Focal Length	σ_c	9 µm
	Principal Point	σ_{xo} σ_{yo}	4.5 µm
	Distortion parameters	N/A	N/A
Errors in image coordinate measurement		σ_m	5 µm

Example accuracy figures are based on the typical std values and value ranges of medium- and large-format cameras, and typical flying heights

Accuracy Bar Charts

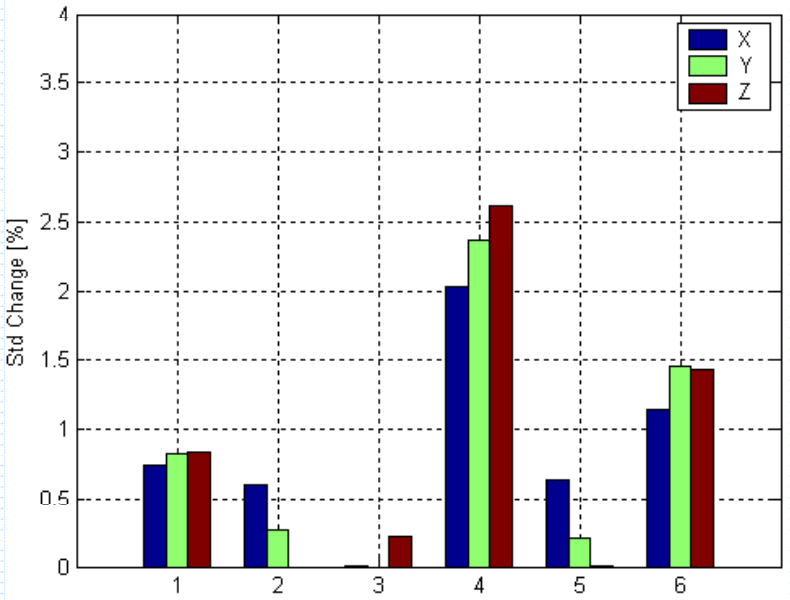


1:	σ_{m1} σ_{m2}
2:	σ_{xo} σ_{yo}
3:	σ_c
4:	σ_{X1} σ_{Y1} σ_{Z1} σ_{X2} σ_{Y2} σ_{Z2}
5:	$\sigma_{\omega b}$ $\sigma_{\varphi b}$ $\sigma_{\kappa b}$
6:	$\sigma_{\omega 1}$ $\sigma_{\varphi 1}$ $\sigma_{\kappa 1}$ $\sigma_{\omega 2}$ $\sigma_{\varphi 2}$ $\sigma_{\kappa 2}$

Percentage of change in point positioning accuracy as an effect of 10% change in std of various random errors (with respect to the reference average values listed in previous slide)

H=300 m, large-format camera

Accuracy Bar Charts

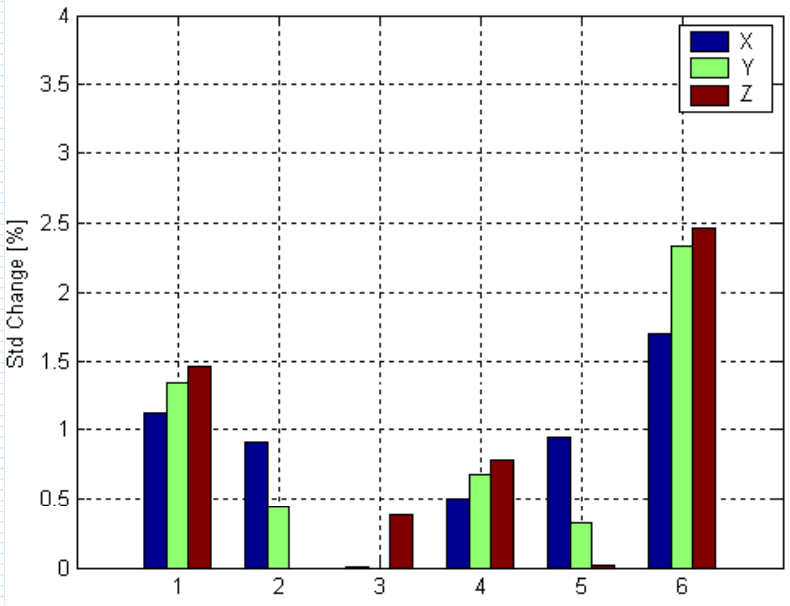


1:	σ_{m1} σ_{m2}
2:	σ_{xo} σ_{yo}
3:	σ_c
4:	σ_{X1} σ_{Y1} σ_{Z1} σ_{X2} σ_{Y2} σ_{Z2}
5:	$\sigma_{\omega b}$ $\sigma_{\varphi b}$ $\sigma_{\kappa b}$
6:	$\sigma_{\omega 1}$ $\sigma_{\varphi 1}$ $\sigma_{\kappa 1}$ $\sigma_{\omega 2}$ $\sigma_{\varphi 2}$ $\sigma_{\kappa 2}$

Percentage of change in point positioning accuracy as an effect of 10% change in std of various random errors (with respect to the reference average values listed in previous slide)

H=600 m, large-format camera

Accuracy Bar Charts

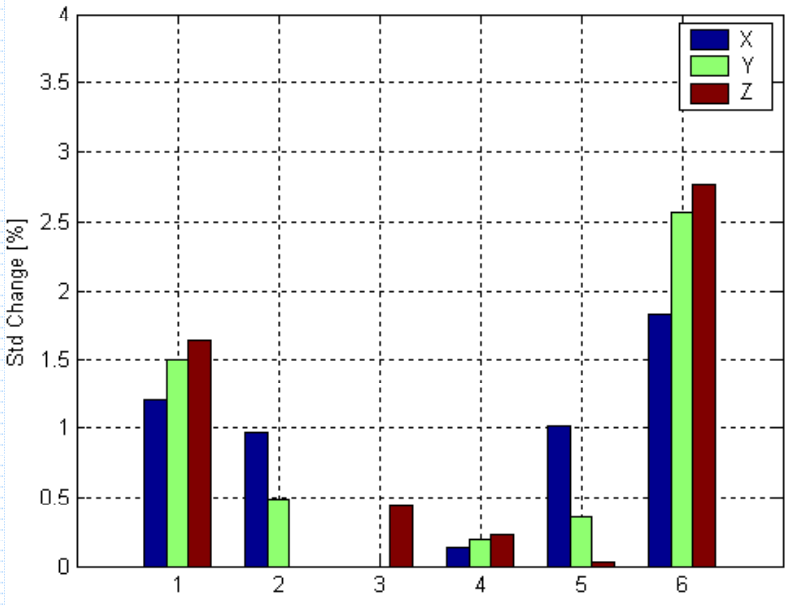


1:	σ_{m1} σ_{m2}
2:	σ_{xo} σ_{yo}
3:	σ_c
4:	σ_{X1} σ_{Y1} σ_{Z1} σ_{X2} σ_{Y2} σ_{Z2}
5:	$\sigma_{\omega b}$ $\sigma_{\varphi b}$ $\sigma_{\kappa b}$
6:	$\sigma_{\omega 1}$ $\sigma_{\varphi 1}$ $\sigma_{\kappa 1}$ $\sigma_{\omega 2}$ $\sigma_{\varphi 2}$ $\sigma_{\kappa 2}$

Percentage of change in point positioning accuracy as an effect of 10% change in std of various random errors (with respect to the reference average values listed in previous slide)

H=1500 m, large-format camera

Accuracy Bar Charts

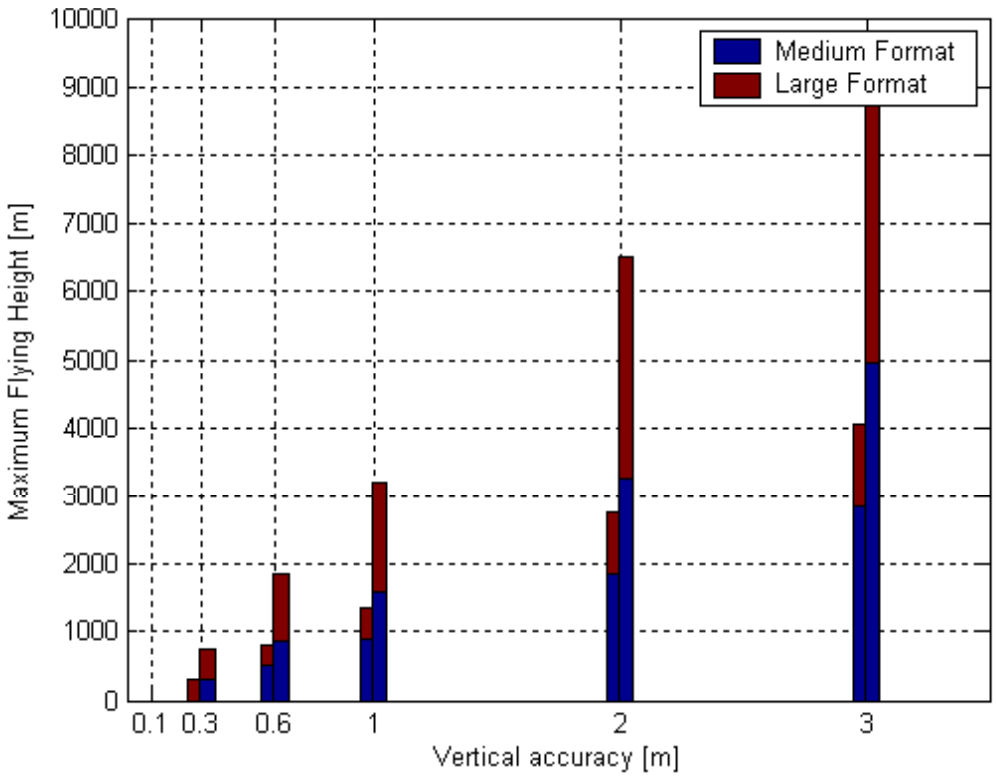


1:	σ_{m1} σ_{m2}
2:	σ_{xo} σ_{yo}
3:	σ_c
4:	σ_{X1} σ_{Y1} σ_{Z1} σ_{X2} σ_{Y2} σ_{Z2}
5:	$\sigma_{\omega b}$ $\sigma_{\varphi b}$ $\sigma_{\kappa b}$
6:	$\sigma_{\omega 1}$ $\sigma_{\varphi 1}$ $\sigma_{\kappa 1}$ $\sigma_{\omega 2}$ $\sigma_{\varphi 2}$ $\sigma_{\kappa 2}$

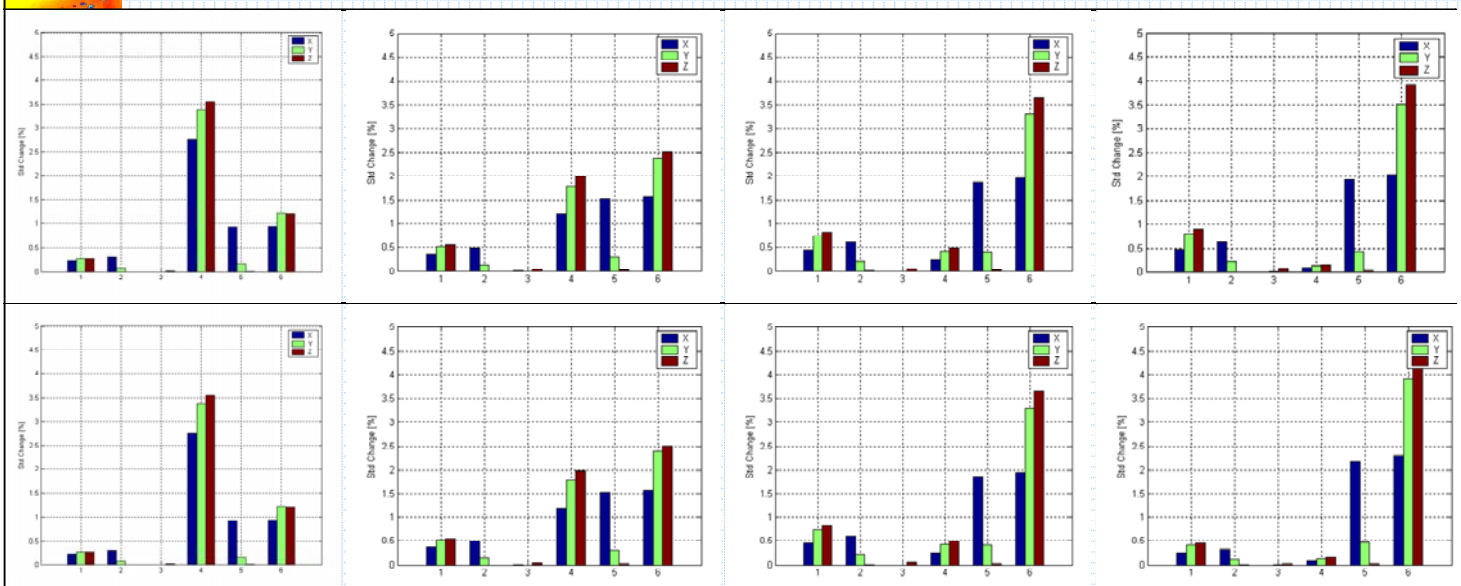
Percentage of change in point positioning accuracy as an effect of 10% change in std of various random errors (with respect to the reference average values listed in previous slide)

H=3000 m, large-format camera

Performance Metrics: Determination of Maximum Flying Height



UltraCam L vs. UltraCam XP

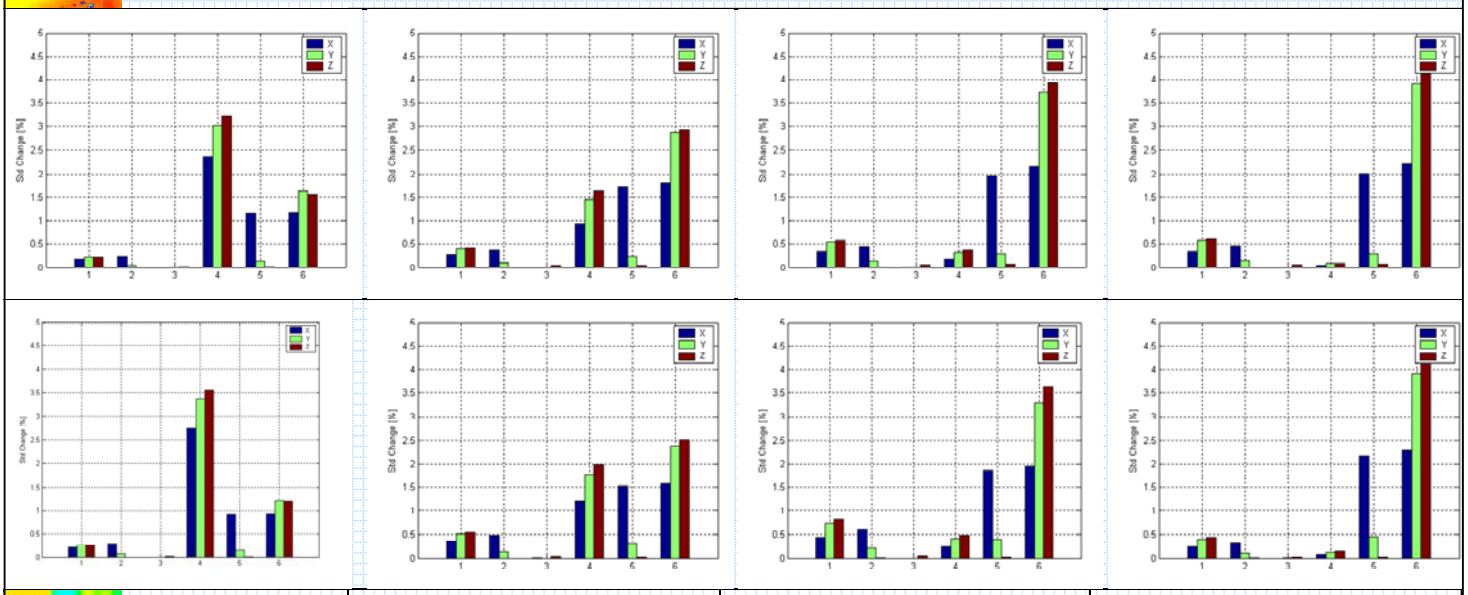


300 m	600 m	1500 m	3000 m

Errors:

1. Image measurement
2. Principal point
3. Focal length
4. Photo center position
5. Boresight misalignment
6. Sensor attitude

UltraCam WA vs. UltraCam XP



300 m	600 m	1500 m	3000 m

Errors:
1. Image measurement
2. Principal point
3. Focal length
4. Photo center position
5. Boresight misalignment
6. Sensor attitude

Outlook

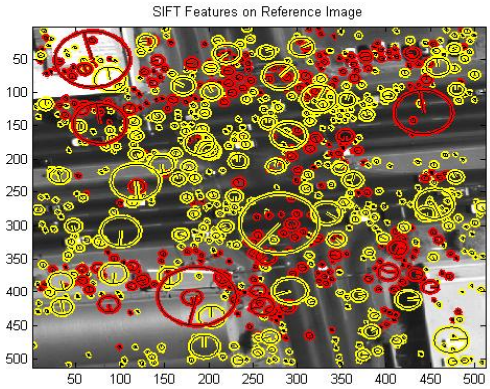
Technology:
- ✓ Sensor development (behind the curve of Moore's law)
- ✓ Generic computer system developments
- ✓ Georeferencing infrastructure (GNSS, IMU) developments
- ✓ Communication, network/database developments

Systems:
- ✓ Medium format camera systems (competing with large format?)
- ✓ Improving spectral characteristics (growing number of bands)
- ✓ Miniaturization (more platforms)

Algorithmic developments:
- ✓ Algorithmic research is key to progress
- ✓ Matching (stereo vs. LiDAR point cloud)
- ✓ Sensor data/feature/object fusion
- ✓ Proliferation of 3D data in general (web developments)
- ✓ Terrain-based navigation (feature/object extraction/matching)

SIFT Matching of Aerial Imagery

- Testing based upon 4K x 4K aerial images indicates potential for 15,000~20,000 SIFT features to be generated per image
- Estimate for standard aerial image → 5 x 10^5 features
- Matching bounded by $O(n^c + k)$, $0 \le c \le 1$, k = #features
- Scale-space solution



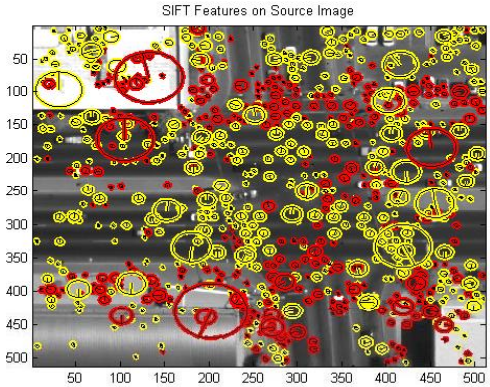
Circles represent location, orientation, and "size" of descriptor

Yellow circles

- Unmatched features

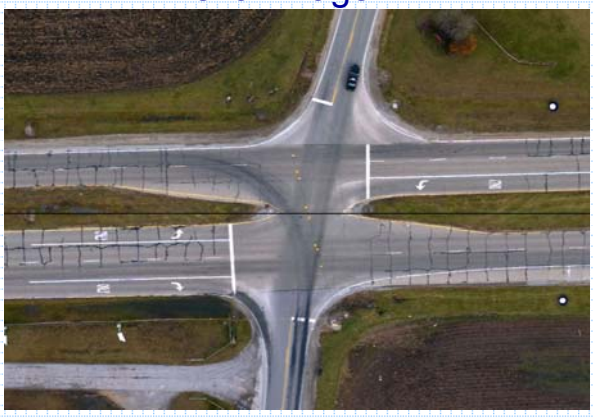
Red circles

- Matched features

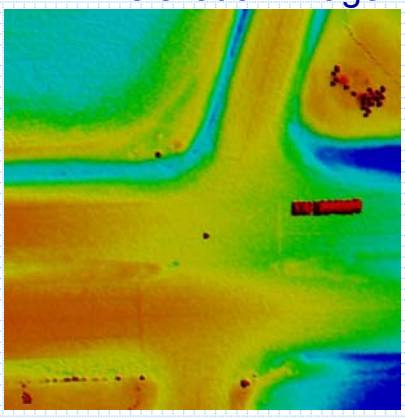


Matching Imagery Acquired by Different Sensors

Aerial image



LiDAR elevation image

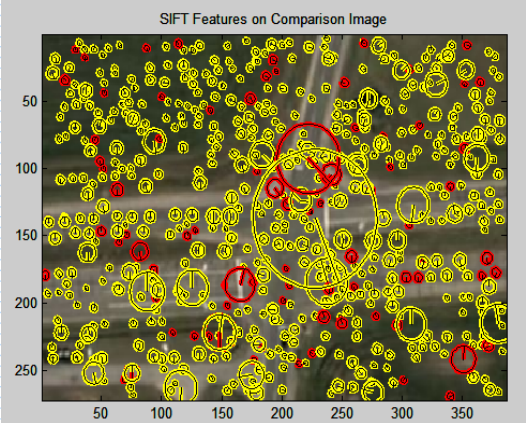


Google image

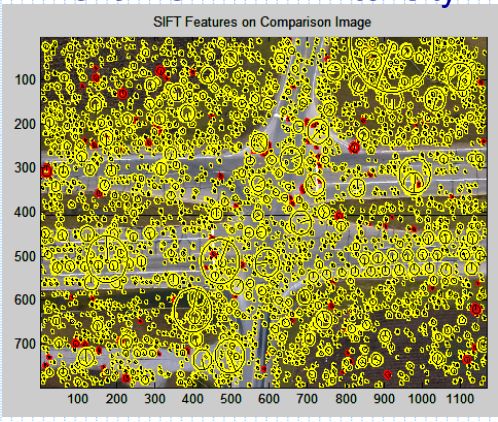
LiDAR intensity image

Select SIFT Matching Examples

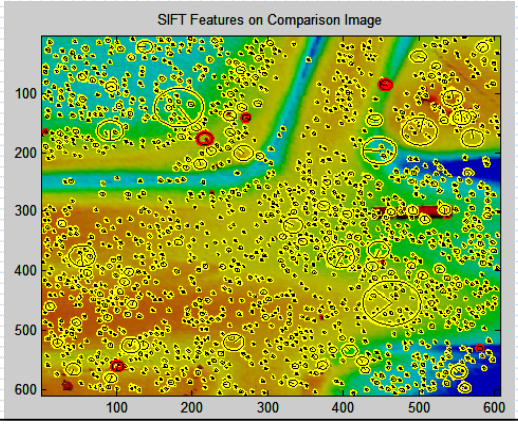
Aerial vs. Google



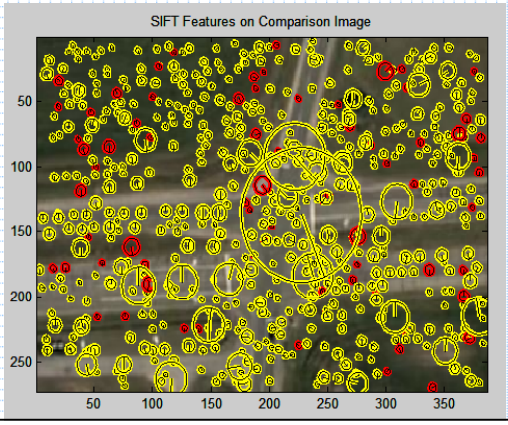
Aerial vs. LiDAR Intensity



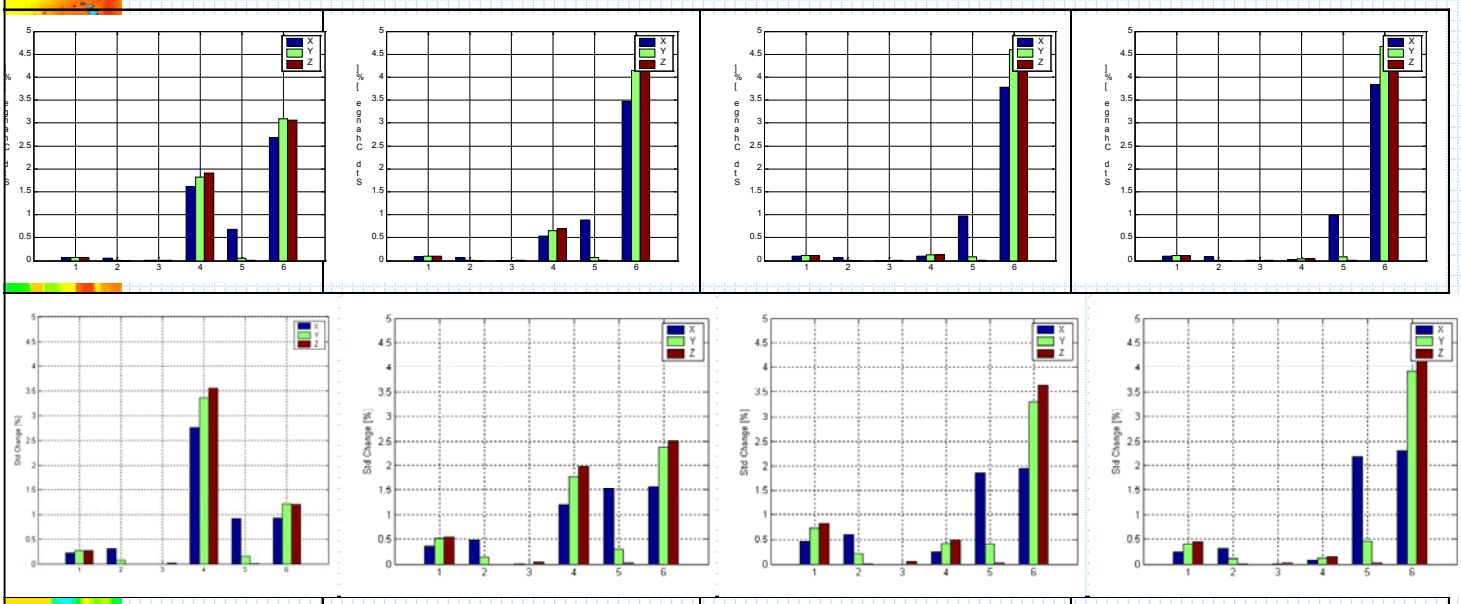
Google vs. LiDAR elevation



LiDAR Intensity vs. Google



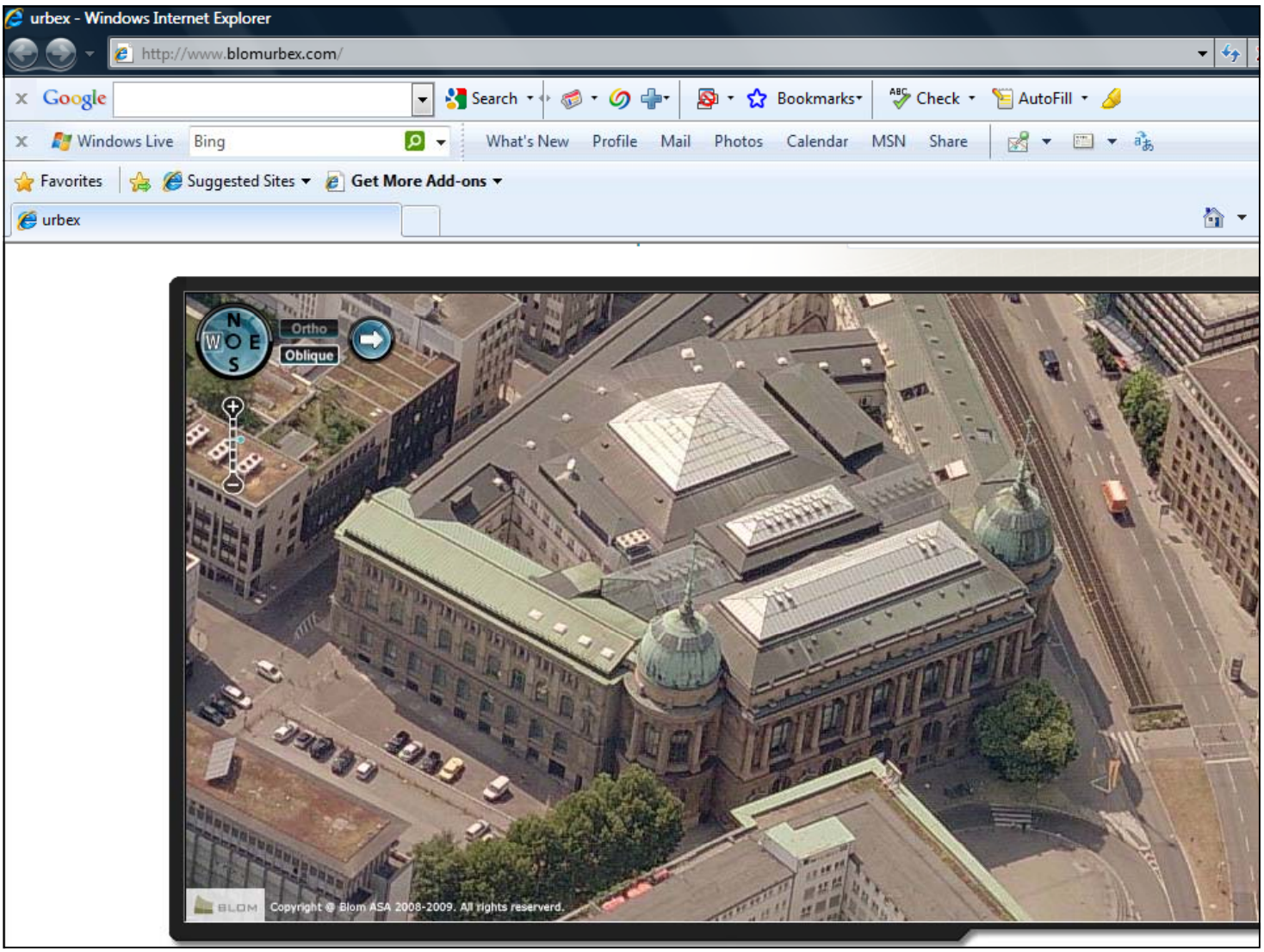
DMC vs. UltraCam XP

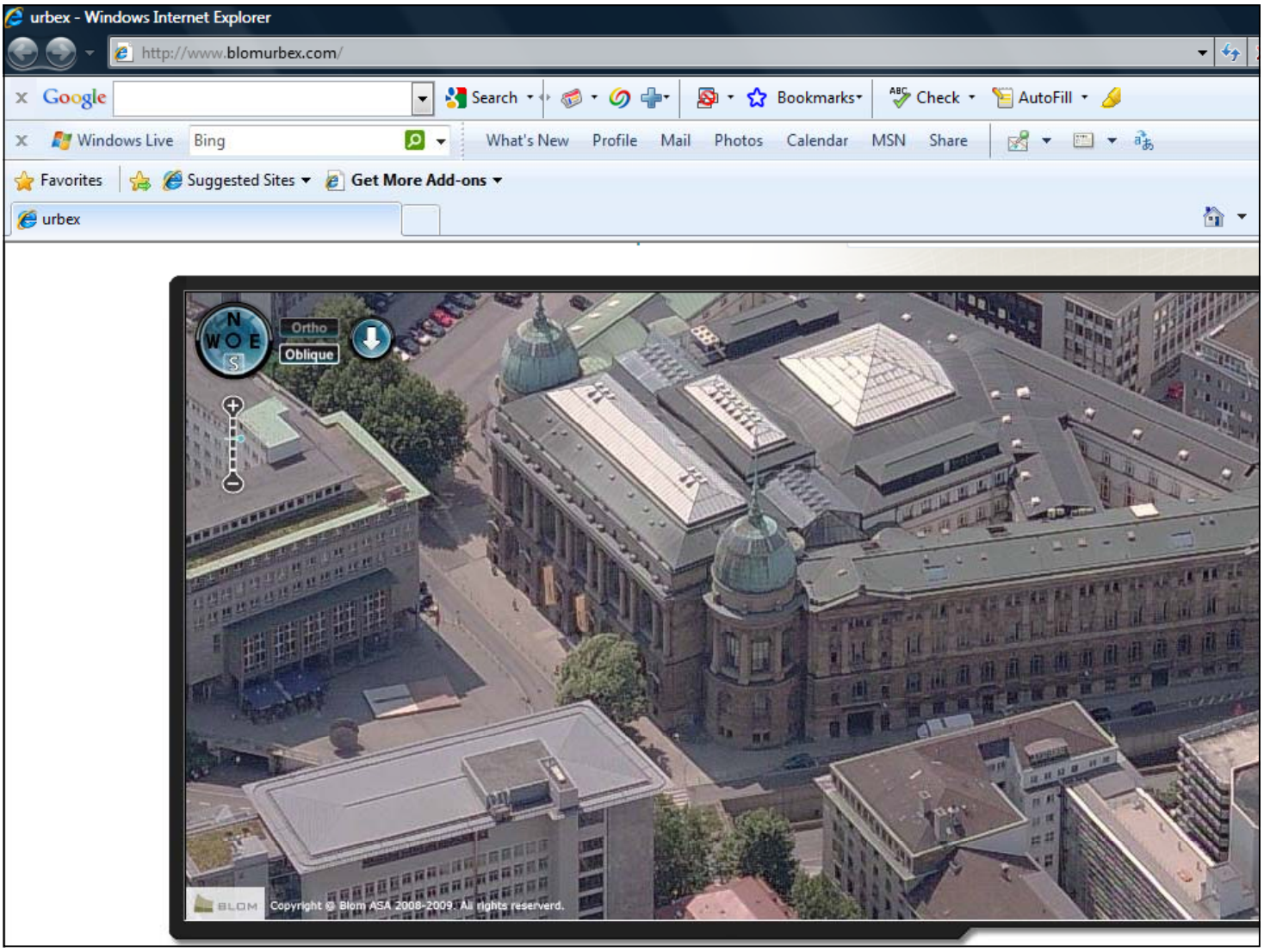


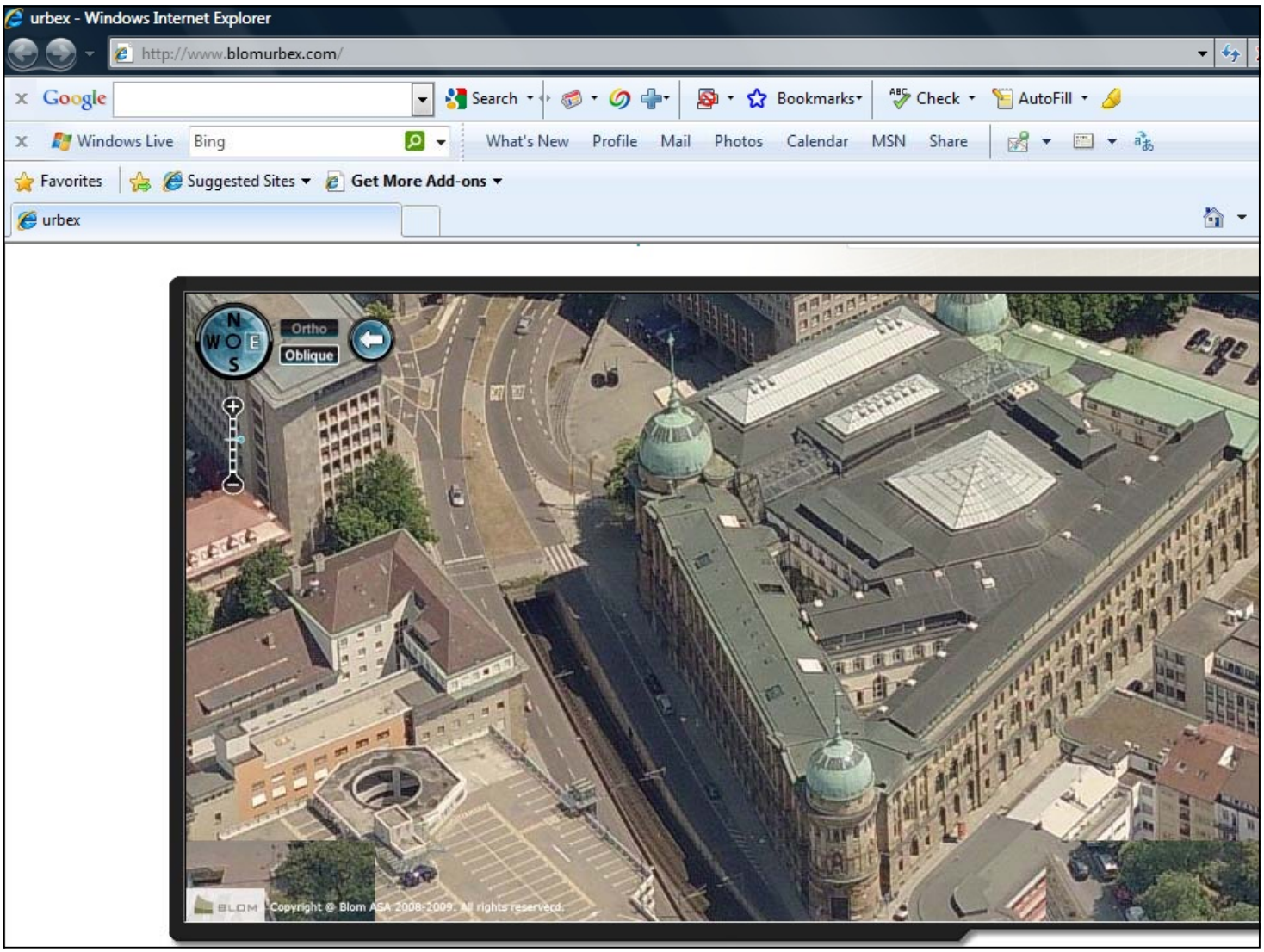
300 m	600 m	1500 m	3000 m

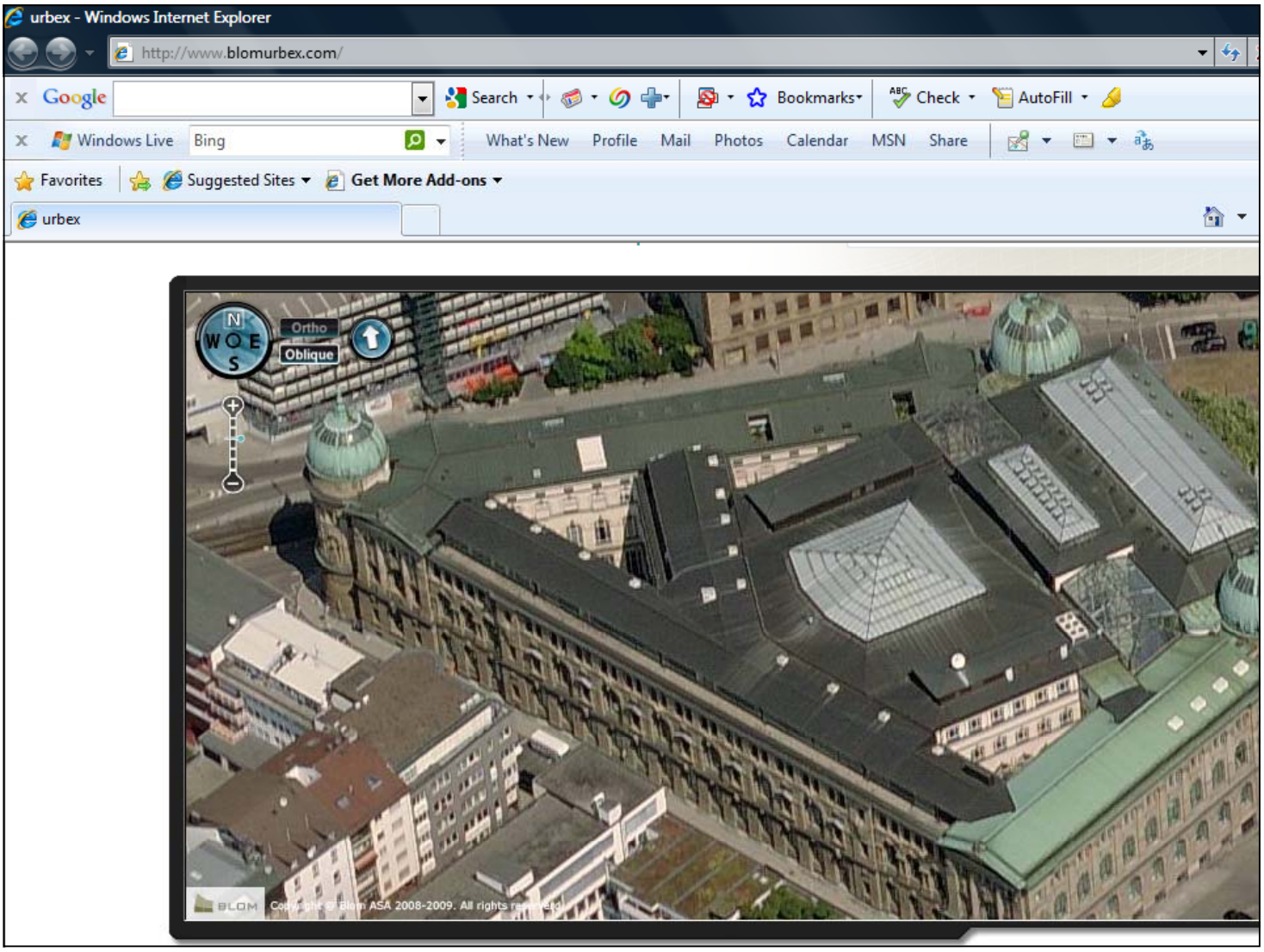
Errors:

1. Image measurement
2. Principal point
3. Focal length
4. Photo center position
5. Boresight misalignment
6. Sensor attitude


urbex - Windows Internet Explorer
http://www.blomurbex.com/
Google
Search
Bookmarks
Check
AutoFill
Windows Live
Bing
What's New
Profile
Mail
Photos
Calendar
MSN
Share
Favorites
Suggested Sites
Get More Add-ons
urbex
N
W O E
S
Ortho
Oblique
BLOM
Copyright © Blom ASA 2008-2009. All rights reserverd.


urbex - Windows Internet Explorer
http://www.blomurbex.com/
Google
Search
Bookmarks
Check
AutoFill
Windows Live
Bing
What's New
Profile
Mail
Photos
Calendar
MSN
Share
Favorites
Suggested Sites
Get More Add-ons
urbex
N
W O E
S
Ortho
Oblique
BLOM
Copyright © Blom ASA 2008-2009. All rights reserverd.


urbex - Windows Internet Explorer
http://www.blomurbex.com/
Google
Search
Bookmarks
Check
AutoFill
Windows Live
Bing
What's New
Profile
Mail
Photos
Calendar
MSN
Share
Favorites
Suggested Sites
Get More Add-ons
urbex
N
W
E
S
Ortho
Oblique
BLOM
Copyright © Blom ASA 2008-2009. All rights reserved.


urbex - Windows Internet Explorer
http://www.blomurbex.com/
Google
Search
Bookmarks
Check
AutoFill
Windows Live
Bing
What's New
Profile
Mail
Photos
Calendar
MSN
Share
Favorites
Suggested Sites
Get More Add-ons
urbex
N
W
E
S
Ortho
Oblique
BLOM