Overview of Research Activities at The Ohio State University Satellite Positioning and Inertial Navigation (SPIN) Laboratory

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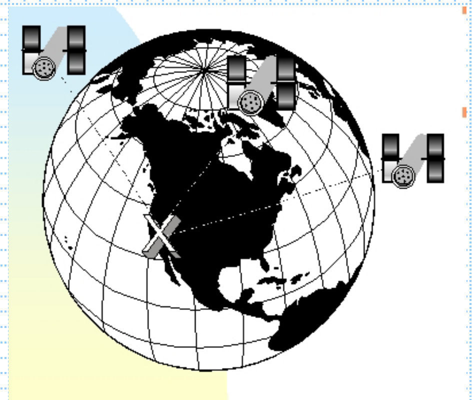


Who we are

- ✓ Satellite Positioning and Inertial Navigation (SPIN) Laboratory was established in 2002 as an interdisciplinary research center affiliated with the Department of Civil and Environmental Engineering and Geodetic Science (CEEGS) and the Center for Mapping (CFM)
- ✓ Research and technology transfer center supported by federal and state government and industrial funds
  - To serve as a focal point for interdisciplinary research in the field of geospatial information technology
  - To facilitate the government-industry cooperation for commercial benefits via connection to CFM
  - *Focused on geospatial information technologies, including navigation, imaging, remote sensing and geodetic science, using*
    - Global Positioning System (GPS) and inertial navigation systems (INS)
    - Visualization, photogrammetry and imaging
    - Robust estimation techniques and modern signal processing technology
    - Sensor and data fusion

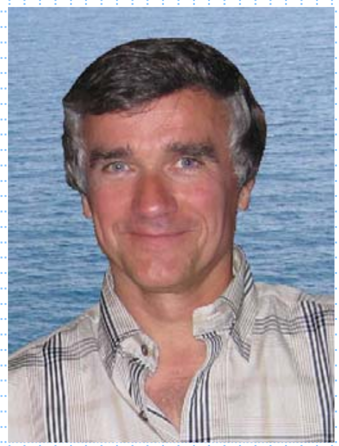
SPIN Laboratory 1/3

- ✓ SPIN performs basic and applied research, with a focus on applied research projects that may yield commercially viable mapping and positioning technologies in areas such as:
  - GPS algorithms
  - GPS/inertial integration
  - Light Detection and Ranging (LiDAR) and digital imaging
  - Geospatial data georegistration, acquisition, analysis and interpretation
  - Mobile mapping
- ✓ Interdisciplinary collaboration across OSU campus:
  - Geodetic and geoinformation science, computer science
  - Electrical engineering, civil and transportation engineering, environmental engineering, agricultural engineering
  - Anthropology, geography, geological sciences, landscape architecture, natural resources, etc.

SPIN Laboratory 2/3

- ✓ Permanent staff
  - ❖ One full time faculty member
  - ❖ One full time senior research staff member
- ✓ 2-4 post-doctoral researchers
- ✓ 12-14 MS and PhD students

Dorota Grejner-Brzezinska
SPIN, CEEGS



Charles Toth
SPIN, CFM

SPIN Laboratory 3/3

- ✓ Extended and versatile research program
  - 0.5 to 1 million/year in research grants
  - Primary sponsoring agencies (Federal/state/industry)
    - **National Geospatial-Intelligence Agency (NGA)**
    - **US Air Force (AF)**
    - **National Geodetic Survey (NGS)**
    - **Department of Defense (DOD)**
    - **National Science Foundation (NSF)**
    - **National Aeronautics and Space Administration (NASA)**
    - **US Department of Transportation (US DOT)**
    - **Ohio Department of Transportation (ODOT)**
    - **Northrop Grumman**
    - **Topcon Positioning System, Inc.**
    - **Trimble**
    - **Lockheed Martin Corporation**
    - **Electronics and Telecommunication Research Institute (ETRI) Korea**

Primary research areas 1/3

- Global Positioning System
  - Algorithms, software, applications
    - Network-based RTK (real time kinematic)
    - GPS-based ionospheric research/modeling
    - Precision orbit determination of GPS and Low Earth Orbit (LEO) satellites
  - Pseudolites (in collaboration with the University of New South Wales and Locata Inc., Sydney/Canberra, Australia)
- Inertial navigation system (INS)
  - GPS/INS integration for navigation and geolocation of imaging and LiDAR systems
- Ultra-tight integration between the imaging and GPS/INS modules
  - LiDAR (Light Detection and Ranging)
  - Imaging

Primary research areas 2/3

- ✓ Precise timing and sensor synchronization
- ✓ Calibration algorithms and techniques for multi-sensor navigation systems
- ✓ Nonlinear Bayesian filters for navigation as an alternative to Extended Kalman Filter (EKF)
- ✓ Knowledge-based systems for complex navigation environments
  - GPS-challenged environments
  - Artificial neural networks
  - Fuzzy logic
  - Fuzzy Kalman Filter
- ✓ Multi-sensor integration for personal navigation
- ✓ Collaborative navigation
- ✓ Integrated mobile mapping systems

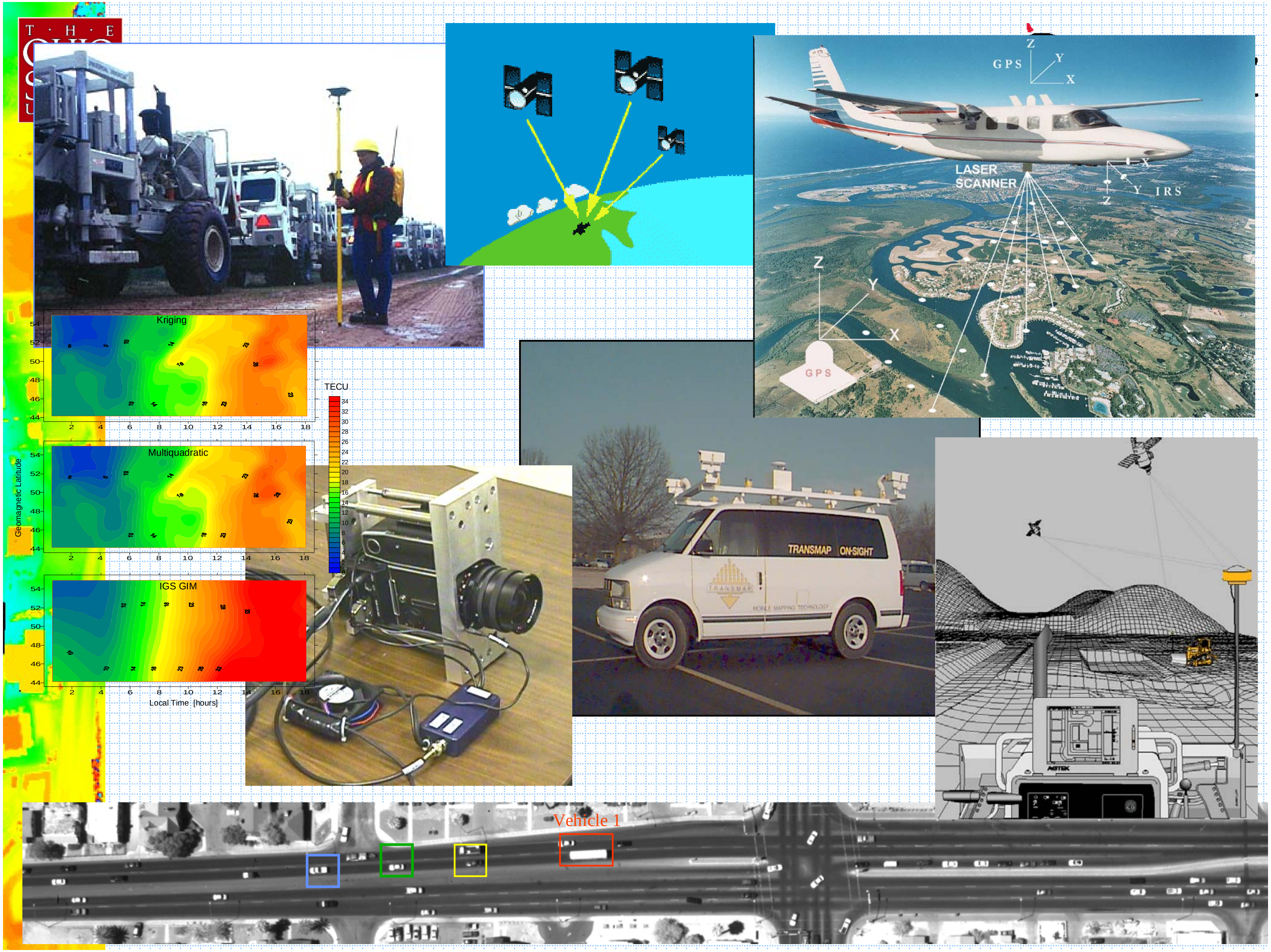
Primary research areas 3/3

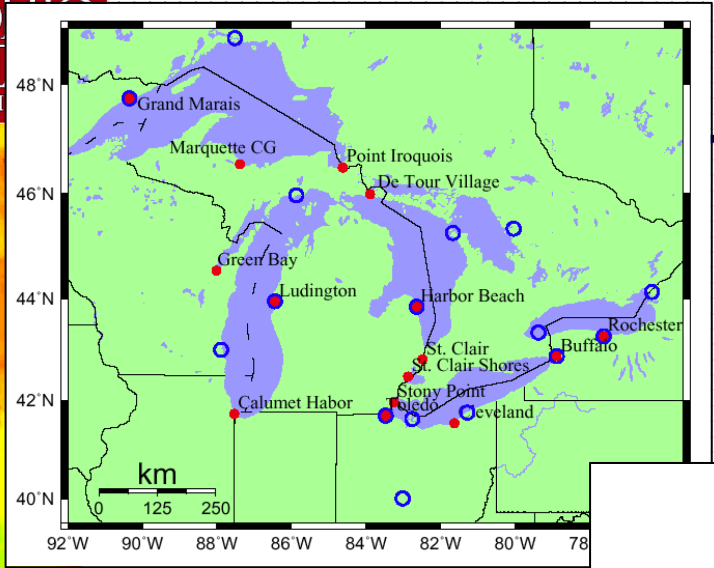
- ✓ LiDAR surface modeling and building extraction
  - ❖ Airborne and high resolution satellite imaging and LiDAR
    - Characterize global and regional terrestrial surfaces that are critical to geodynamic modeling and change detection/monitoring
- ✓ LiDAR and LADAR[1] based navigation (indoor and outdoor)
- ✓ Feature extraction and image analysis
- ✓ Remote sensing in transportation flows (GPS, INS, imaging sensors and modeling)
  - ❖ OSU was the national headquarters of the National Consortium for Remote Sensing in Transportation – Flows (NCRST-F)
  - ❖ Sponsored by Federal DOT and NASA (2002-2005)

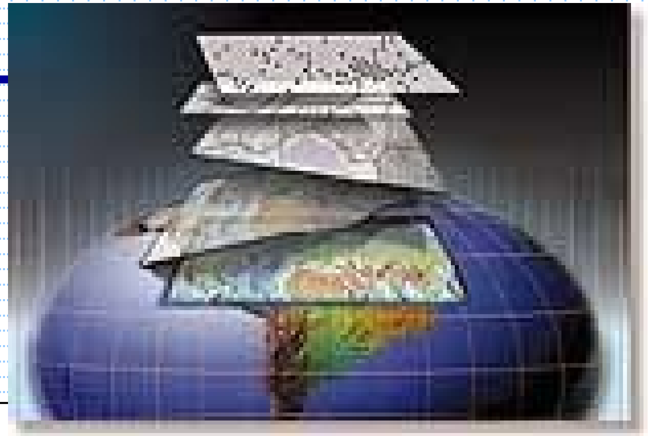
[1]**LA**ser **D**istance **AR**ray

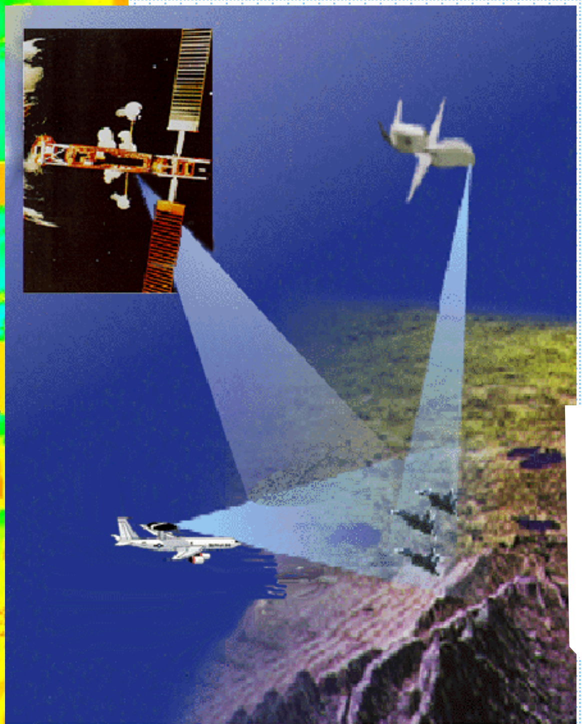
Available Resources

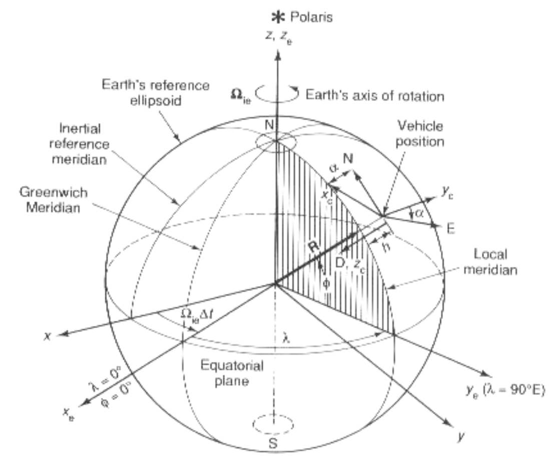
- ✓ Navigation grade IMUs
  - ❖ Two Honeywell H764G
  - ❖ One Northrop-Grumman LN100
- ✓ Tactical and consumer grade IMUs
  - ❖ One Honeywell HG1700, Northrop-Grumman LN200 and Crossbow 400CC
- ✓ Geodetic grade GPS receivers: 4 Trimble 5700 + 3 Novatel OEM4 + 2 Legacy and 2 HyperLite Topcon
- ✓ 4 IN200 pseudolites
- ✓ Lockheed-Martin 16Megapixel digital camera
- ✓ Cannon EOS Mark II 1D 17Megapixel digital camera
- ✓ In-house developed network-based RTK and rapid static software
- ✓ In-house developed GPS/INS integration (loose and tight)
- ✓ In-house developed multi-sensor integration for personal navigation
- ✓ In-house developed multi-sensor integration including image-based/LiDAR navigation

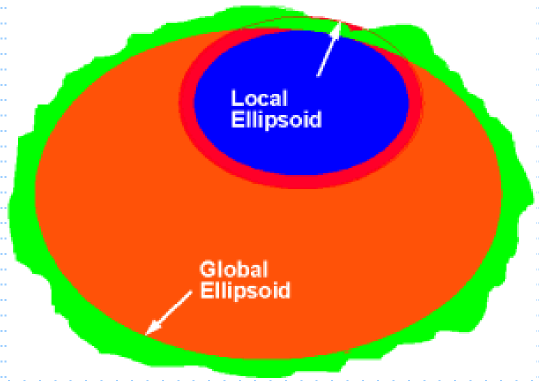

Kriging
Multiquadratic
IGS GIM
TECU
Geomagnetic Latitude
Local Time [hours]
GPS
LASER SCANNER
IRS
TRANSMAP ON-SIGHT
Vehicle 1

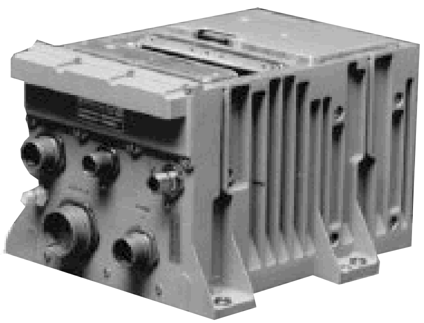




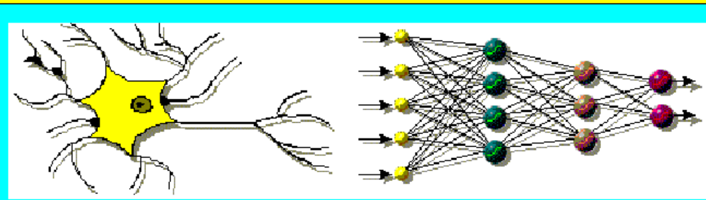




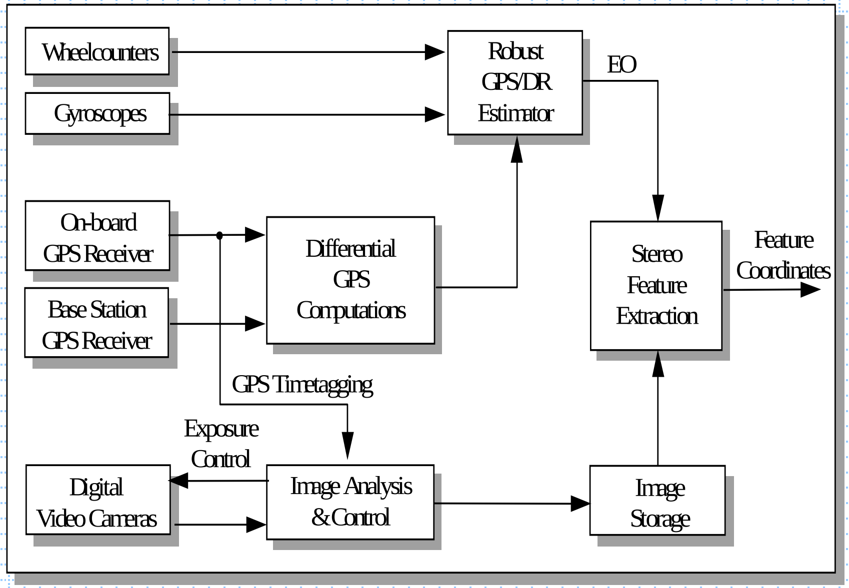




Neural Networks For Object Recognition From Sequential Mapping Images



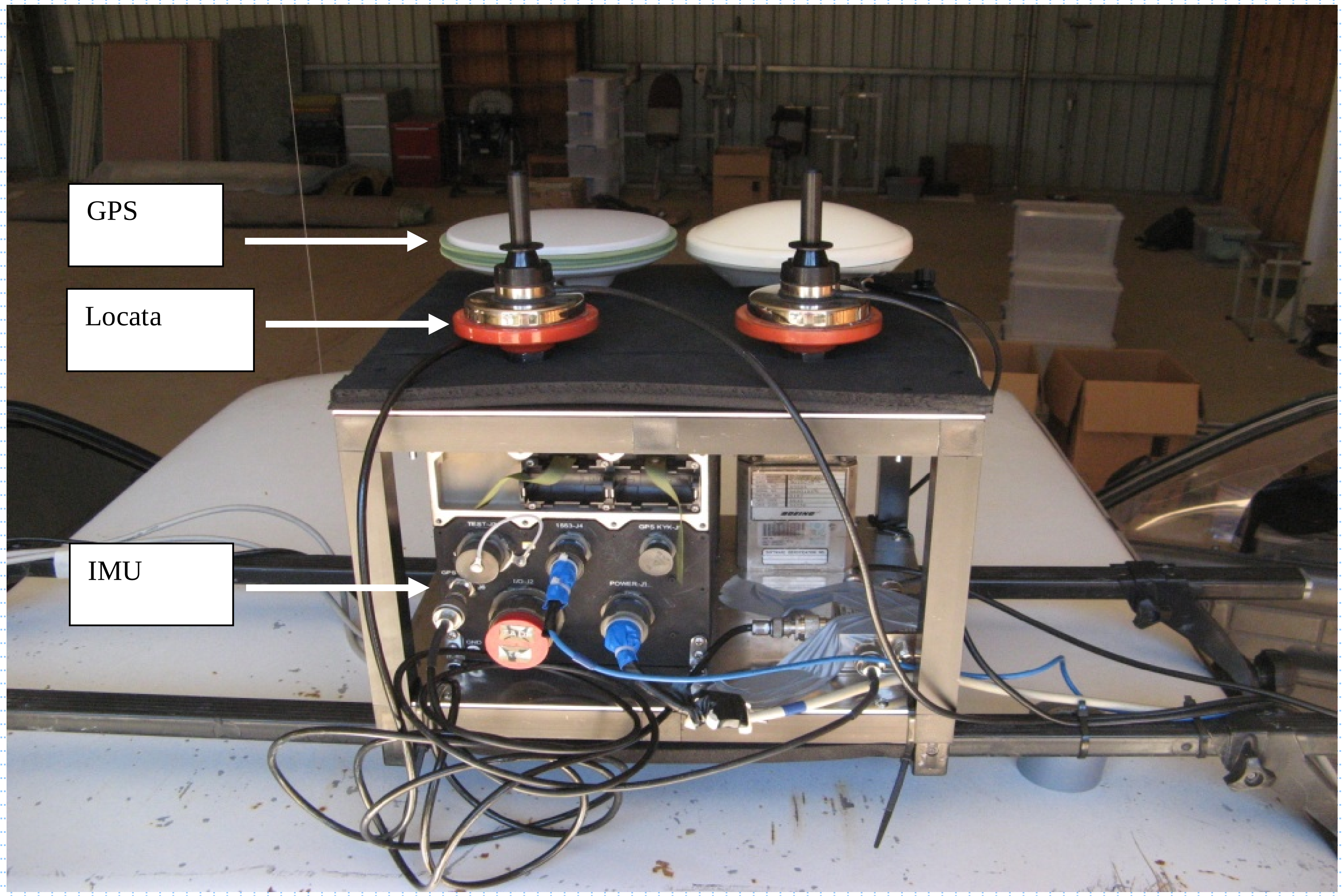
GPSVan™: first Mobile Mapping System
GPSVan™: on high-rails, railroad survey



GPSVan™: TRANSMAP, spin-off company

Newest MMS for ODOT: centerline mapping

Multi-sensor HW configuration



Examples of recent navigation related research projects

- ✓ Flash LADAR for indoor and outdoor tracking
- ✓ Height modernization in Ohio
- ✓ Personal navigation
- ✓ Network-based GPS RTK and rapid-static GPS
- ✓ GPS timing/synchronization for airborne and land-based multi-sensor geospatial data acquisition platforms
- ✓ Tightly integrated GPS/INS navigation module for airborne and land-based multi-sensor georeferencing
- ✓ High-accuracy hybrid geolocation technology supporting geophysical surveys for UXO[1] detection and discrimination
- ✓ Rapid city modeling from precisely georeferenced LiDAR/HSI[2] data using closed-feedback error loop
- ✓ Autonomous vehicle navigation

[1]Unexploded Ordnance
[2]Hyper-spectral Imagery

Flash LADAR for indoor and outdoor tracking and navigation

Project Description

- Project Sponsor: DAGSI[1]/AF
- Principal Investigators: Dorota Brzezinska and Charles Toth
- Post-doctoral researchers: Hongxing Sun
- Graduate student:
  - Nikki J. Markiel

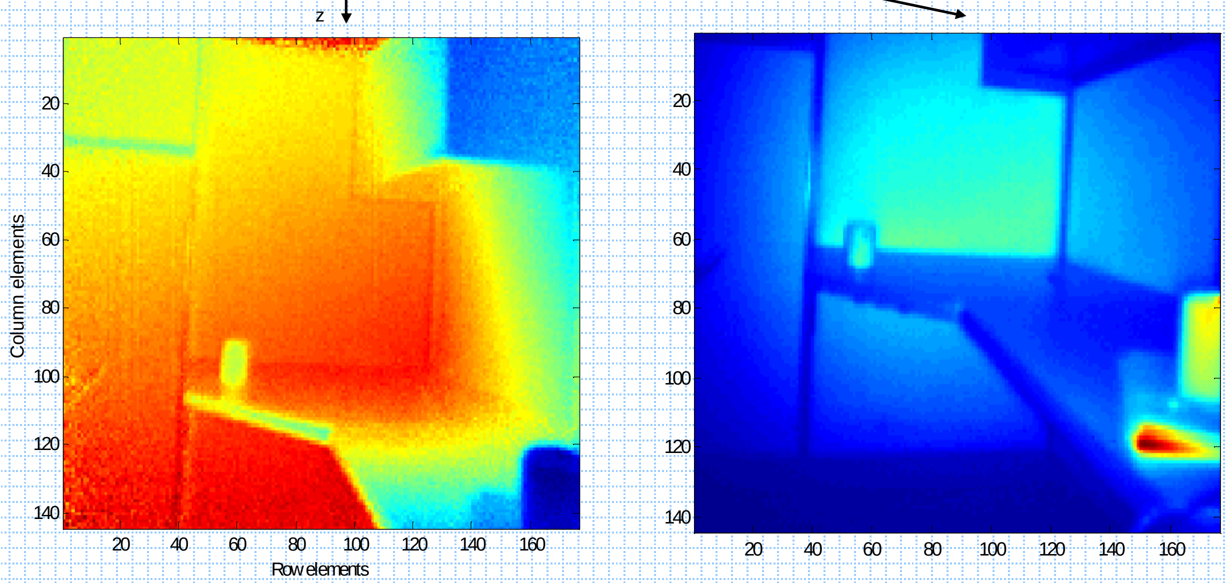
Project Objectives

- Identify corresponding features in the image space obtained from an unknown spatial position
- Separate static and non static features
- Use static features to support IMU[2] position fix during GPS loss of lock
- Sub-decimeter image-to-image co-registration accuracy

[1] Dayton Area Graduate Studies Institute
[2] Inertial Measurement Unit

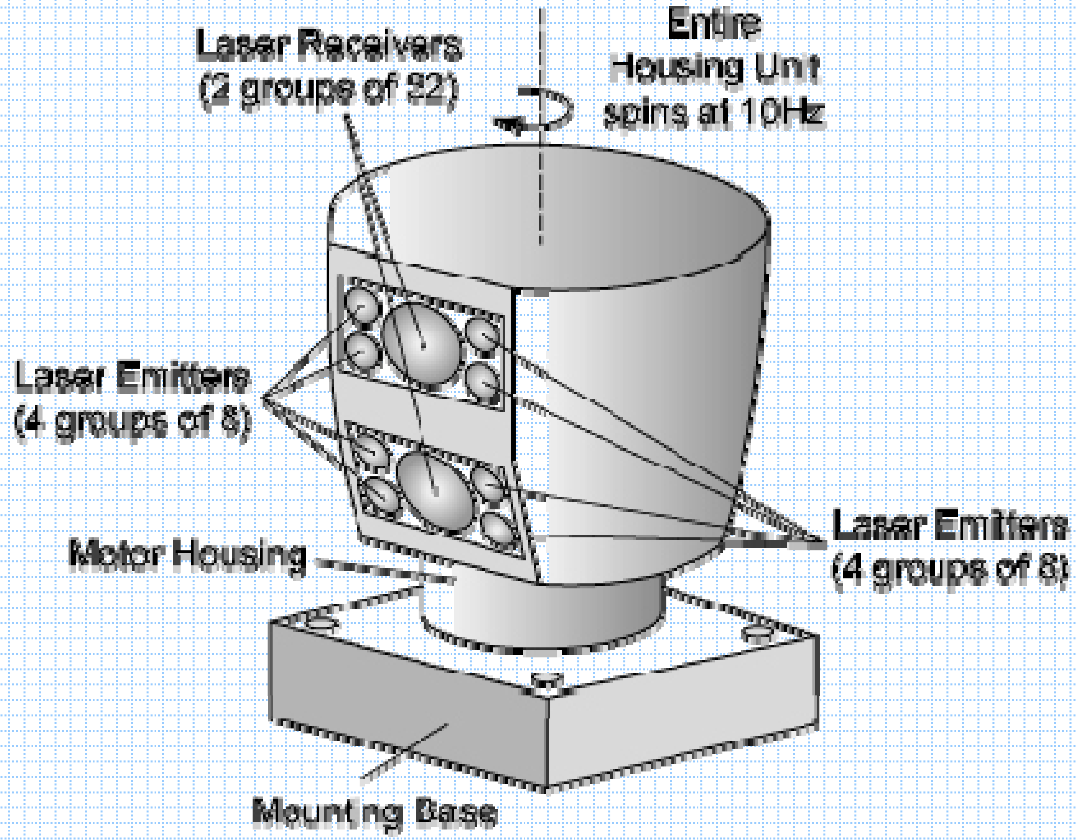
Flash LADAR for indoor and outdoor tracking

- 3D Imaging by
  LAser **D**istance **AR**ray
- Modulated infrared light source
- Sub-centimeter resolution of ranging data
- XYZ and intensity data



Pulsed linear array laser system: Velodyne

Most valuable sensor at the DARPA Urban Challenge in 2007



Terrestrial LiDAR-based vehicle navigation and Mobile Mapping Systems

Height modernization

Project Description

- ✓ Project Sponsor: NGS
- ✓ Principal Investigators: Dorota Brzezinska and Charles Toth
- ✓ Graduate student:
  - ❖ Karla Edwards

Project Objectives

- ✓ To provide accurate height information for all types of positioning and navigational needs
- ✓ To improve and maintain a high accuracy, accessible national height reference system (i.e. the height component of the National Spatial Reference System (NSRS))
- ✓ Close coordination with Division of Commerce / National Oceanographic Administration Agency (NOAA) / National Geodetic Survey (NGS)

Personal navigation

Project Description

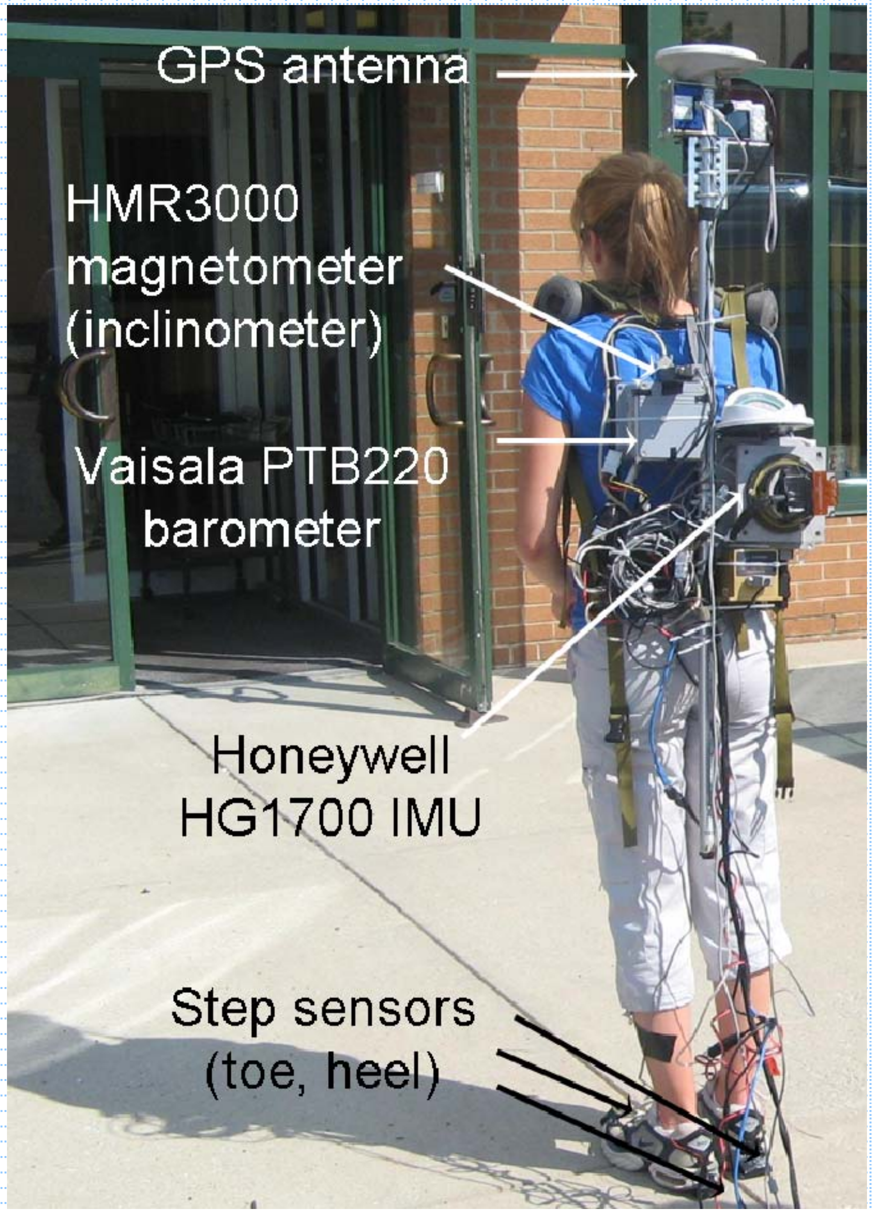
- ✓ Project Sponsor: NGA
- ✓ Principal Investigators: Dorota Brzezinska and Charles Toth
- ✓ Graduate students:
  - ❖ Shahram Moafipoor, Yudan Yi, Yonseok Jwa

Project Objectives

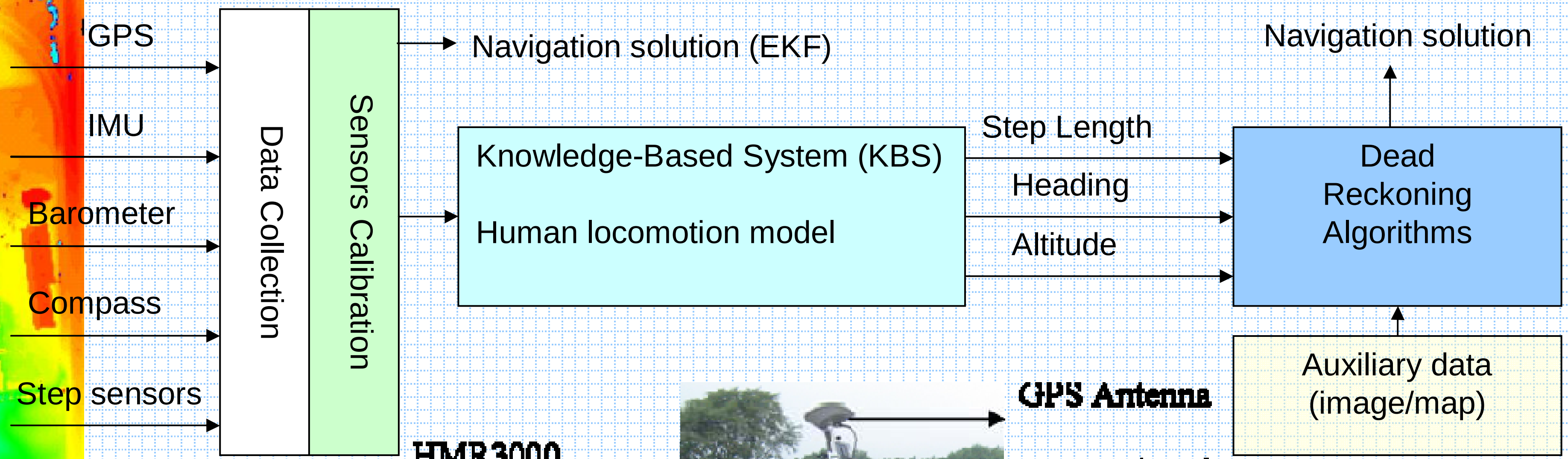
- ✓ To develop an accurate and reliable portable navigation and tracking device for ground personnel in combat and emergency situations
- ✓ To form theoretical foundations for such a system by developing the algorithmic concept of a basic GPS-based, MEMS IMU-augmented personal navigator system with an open-ended architecture
- ✓ Develop knowledge-based system for modeling human dynamics and sensor calibration to support dead-reckoning mode
  - ❖ Fuzzy logic
  - ❖ Artificial neural networks
- ✓ Continuous 3-5 m CEP50% (circular error probable) accuracy

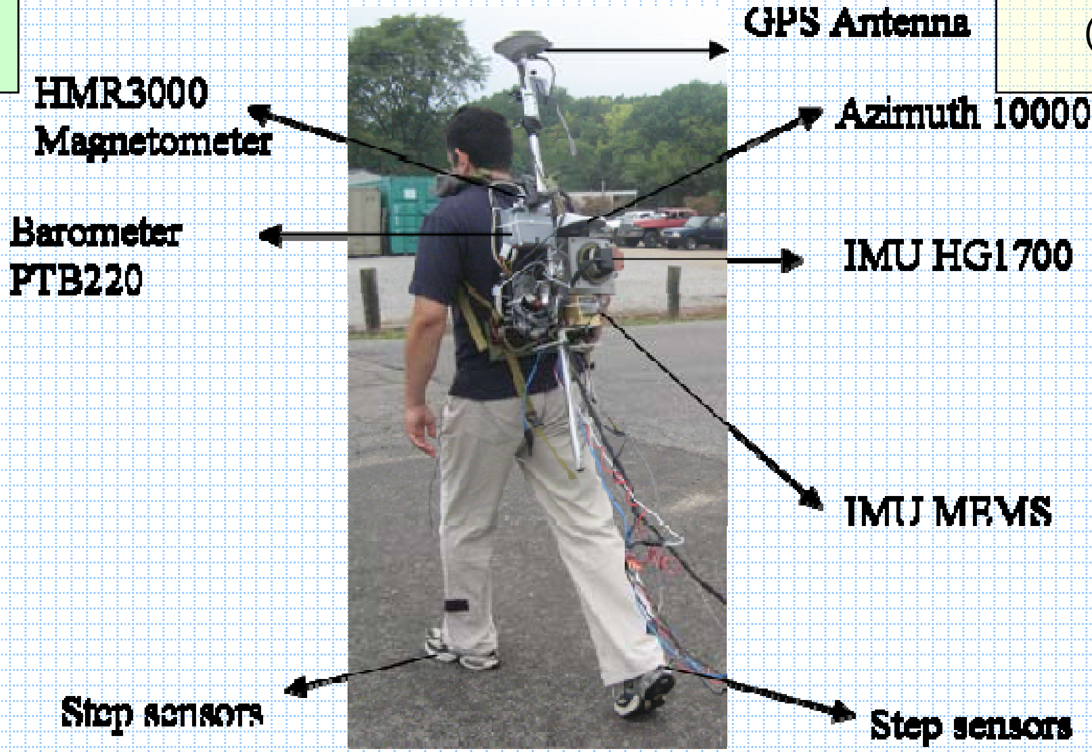
Overview of the System: Backpack Configuration

- ✓ GPS receiver
  - ❖ Dual-frequency Topcon Legacy
- ✓ IMU
  - ❖ Honeywell HG1700 (tactical grade) Barometer
  - ❖ Vaisala PTB220A
- ✓ Magnetometer compass
  - ❖ Honeywell HMR3000
- ✓ Step sensors
  - ❖ Located in the shoe soles
- ✓ Human as navigation sensor
  - ❖ Determine the locomotion pattern
  - ❖ Supports navigation in 2D
    - Step length (SL) prediction
    - Step direction (SD) determination
  - ❖ Vertical coordinate from barometer



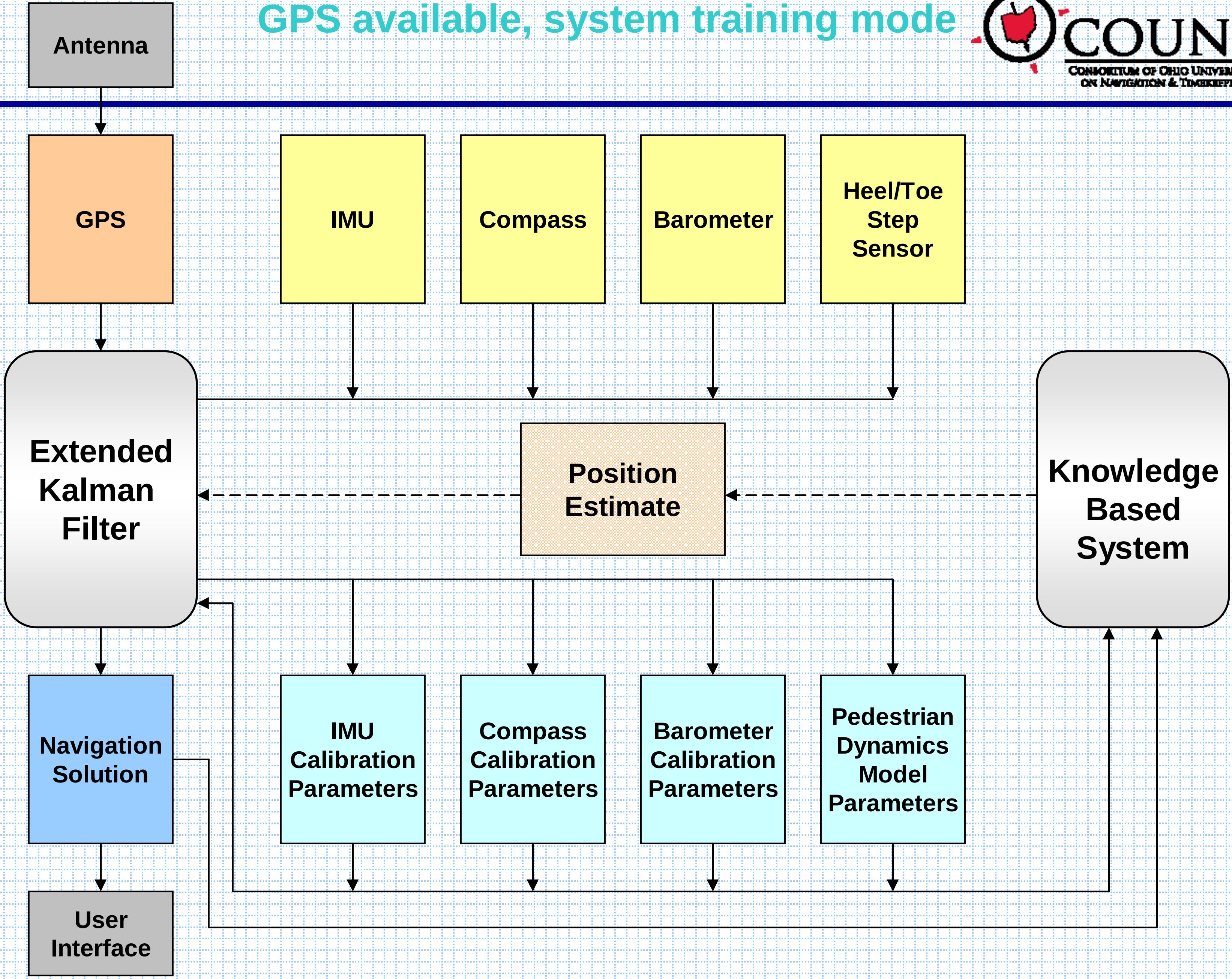
Personal navigator: generic architecture



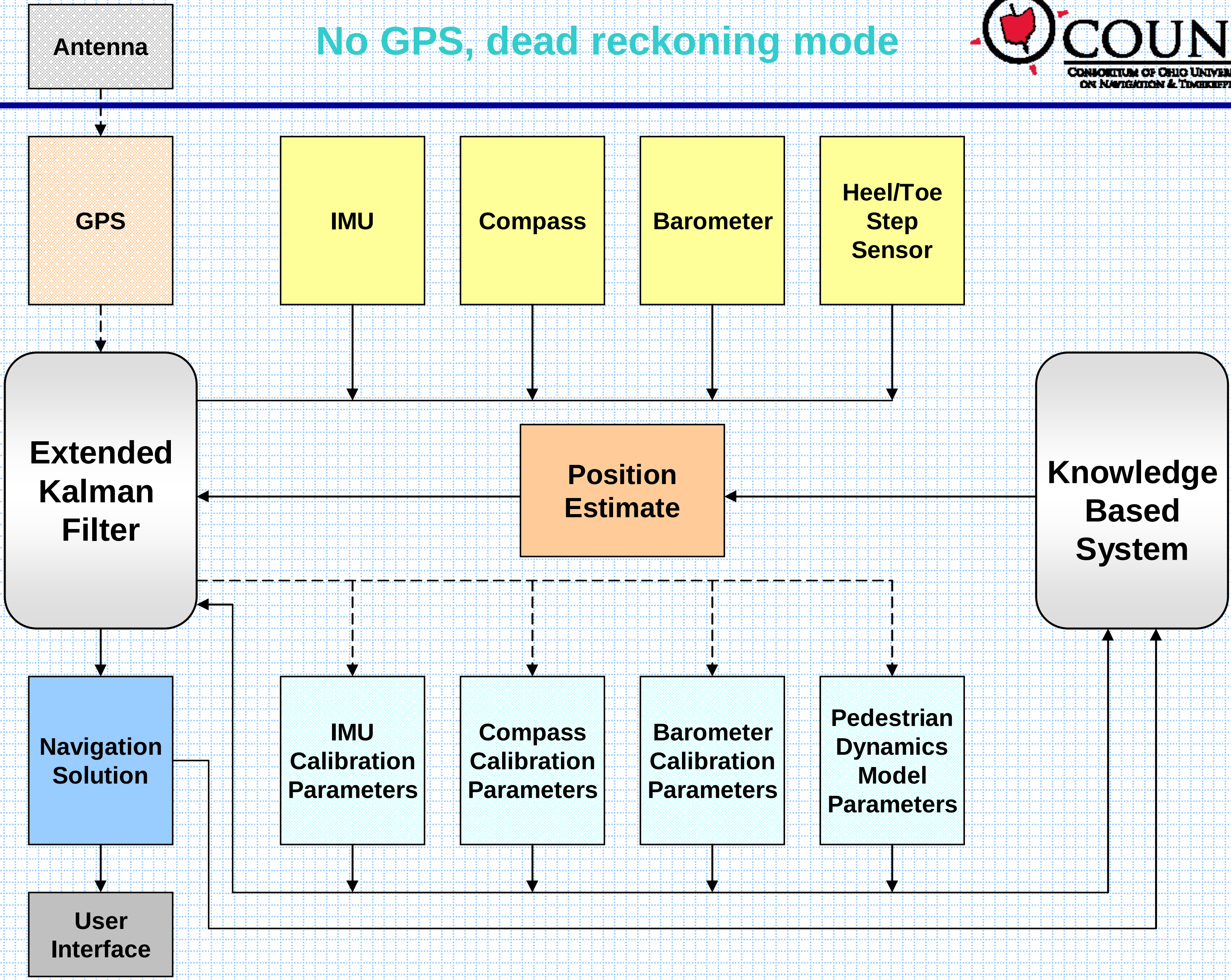


MEMS = micro-electro-mechanical system

GPS available, system training mode



No GPS, dead reckoning mode



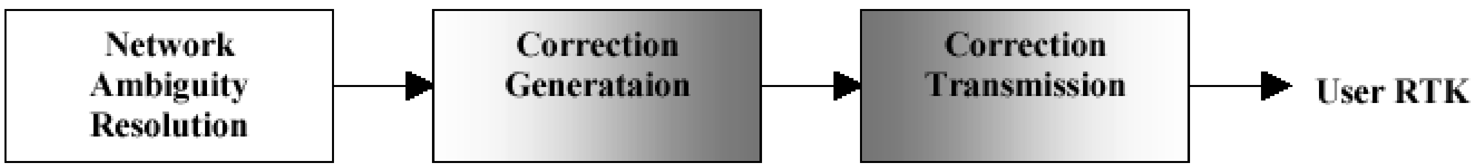
Network-based GPS RTK and Rapid Static GPS

Project Description

- ✓ Project Sponsor: NGS
- ✓ Principal Investigator: Dorota Brzezinska
- ✓ Post-doctoral researchers: Pawel Wielgosz, Israel Kashani, Niyazi Arslan
- ✓ Graduate students
  - ❖ Chang-Ki Hong, Karla Edwards

Project Objectives

- ✓ Design and implement regional high-resolution ionospheric model to support fast ambiguity resolution
- ✓ Design and implement network-based GPS RTK algorithms using regional and local (up to 200 km separation) permanently tracking GPS networks
- ✓ Cm-level rover positioning accuracy for baselines over 100 km



Network-based GPS RTK and Rapid Static GPS

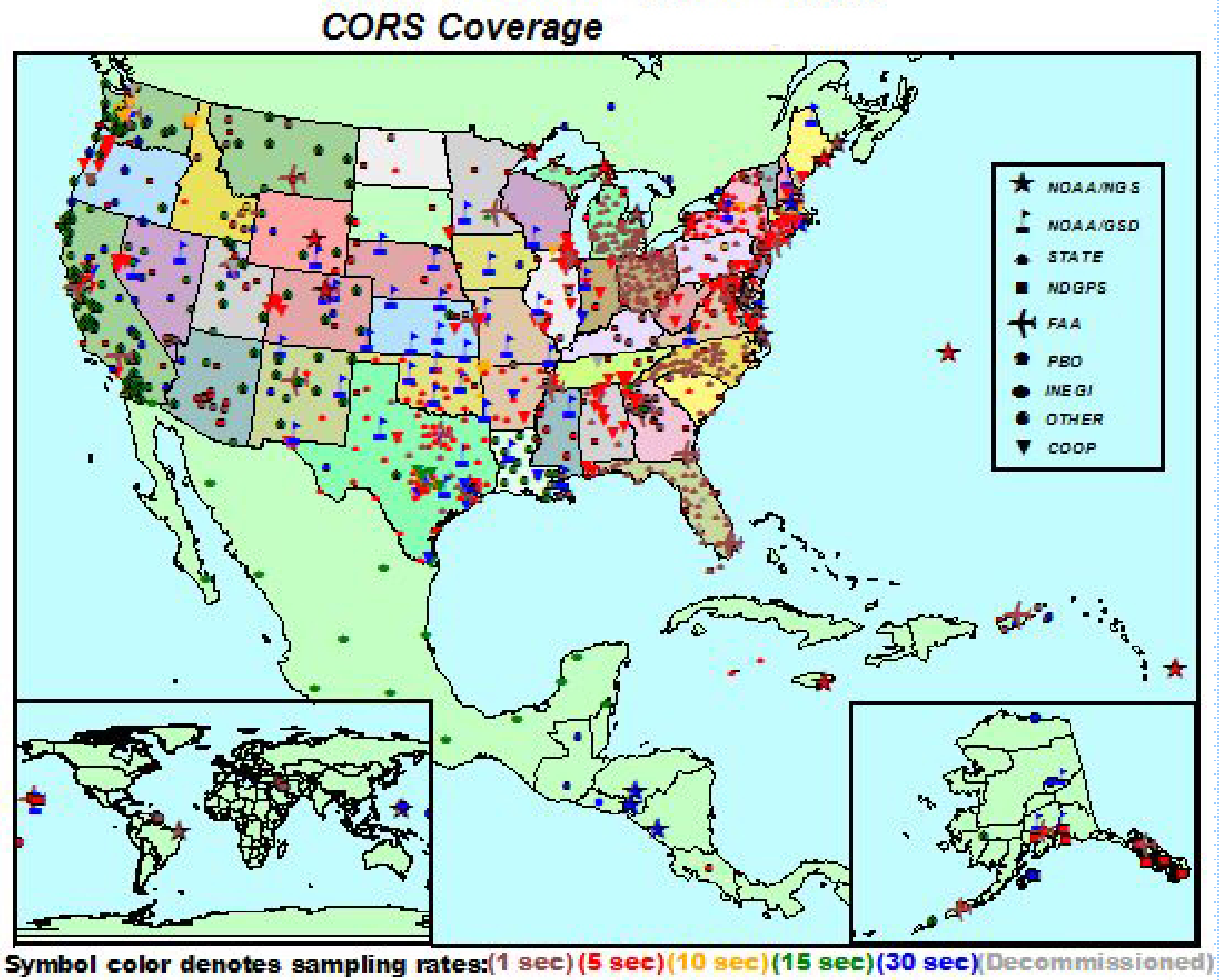
Accomplishments:

- ✓ 15 minutes of user data required → OPUS-RS[1]
  - ❖ "Regular" OPUS requires minimum of 2 hours of user static data Results are e-mailed back to the user
- ✓ Online implementation by NGS staff
- ✓ Project status: completed
- ✓ Recent work
  - ❖ New implementation of ionosphere modeling and network-based solution
    - Un-differenced ionospheric correction estimation
    - Least-squares collocation method used for prediction/interpolation of the ionospheric corrections to provide their variances at user's location
    - Graduate student: Chang-Ki Hong
  - ❖ Troposphere modeling and its impact on site coordinate accuracy (height)
    - Graduate student: Jiyhe Park

http://www.ngs.noaa.gov/OPUS/OPUS-RS.html

[1]Online Positioning User Service-Rapid Static

Network-based GPS RTK and Rapid Static GPS



National CORS network (http://geodesy.noaa.gov/CORS/)

GPS timing/synchronization for airborne and land-based multi-sensor geospatial data acquisition platforms

Project Description

- ✓ Project Sponsor: NGA, ETRI, NASA
- ✓ Principal Investigators: Charles Toth and Dorota Brzezinska
- ✓ Graduate students:
  - ❖ Yudan Yi, Jake Oh, Young-Jin Lee

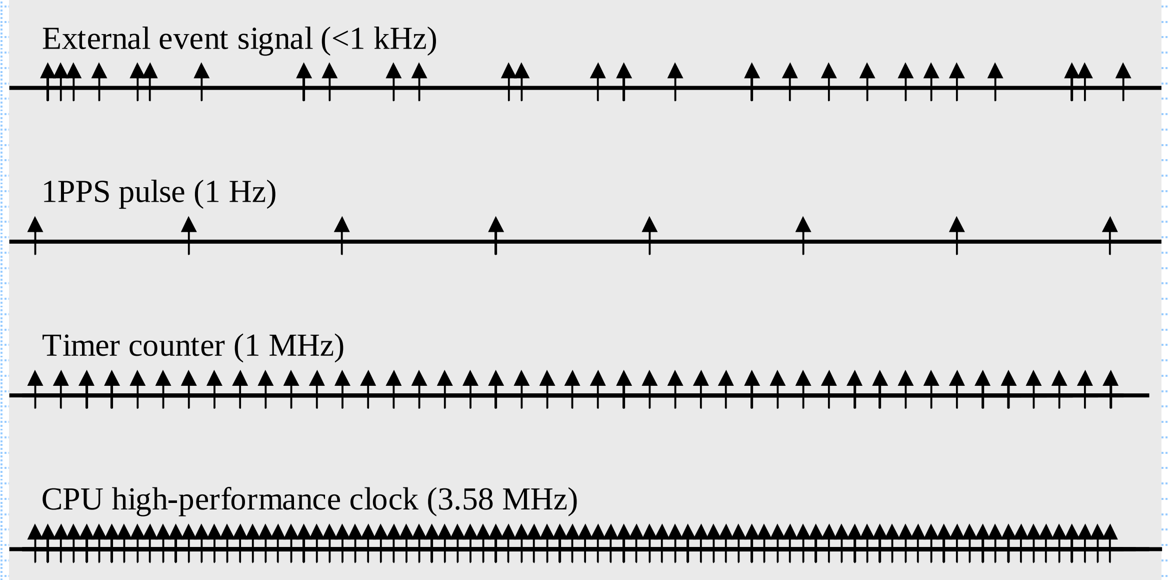
Project Objectives

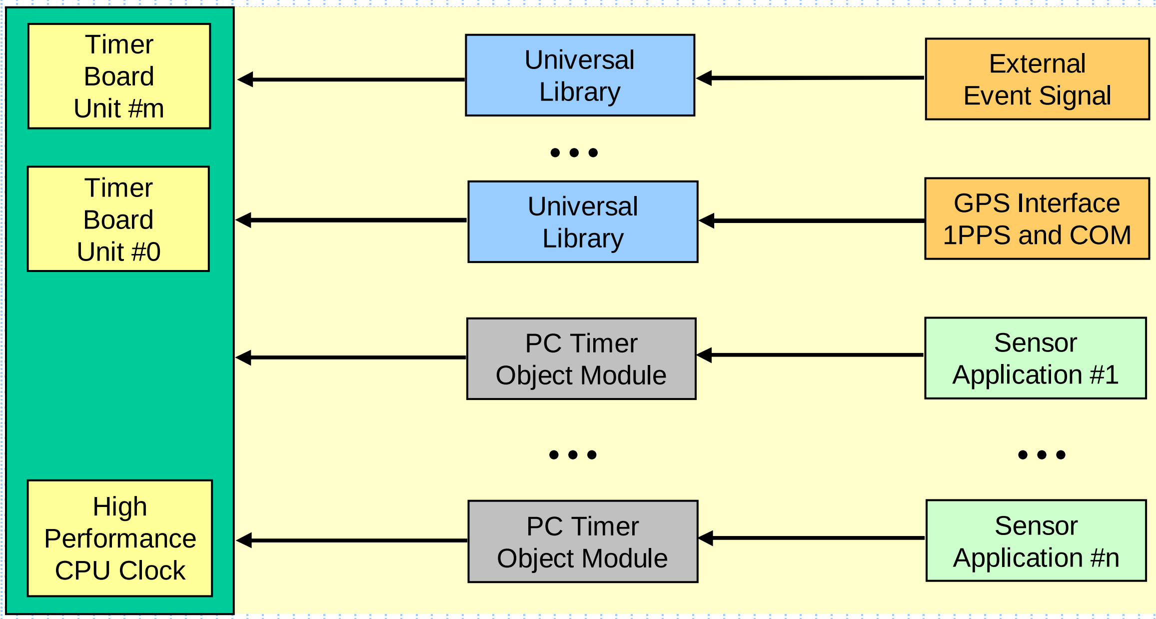
- ✓ Design and implement high-accuracy real-time GPS time synchronization for multiple sensor types (navigation and imaging) for a moving platform
- ✓ Focus on software solution and minimize hardware component
- ✓ 0.5 millisecond timing accuracy on a standard PC-based data acquisition platform

GPS timing/synchronization for airborne and land-based multi-sensor geospatial data acquisition platforms

Unsynchronized sensors

- Digital cameras
- Laser scanners
- Mid- and low-range IMUs
- Various sensors such as compass, barometer, etc.

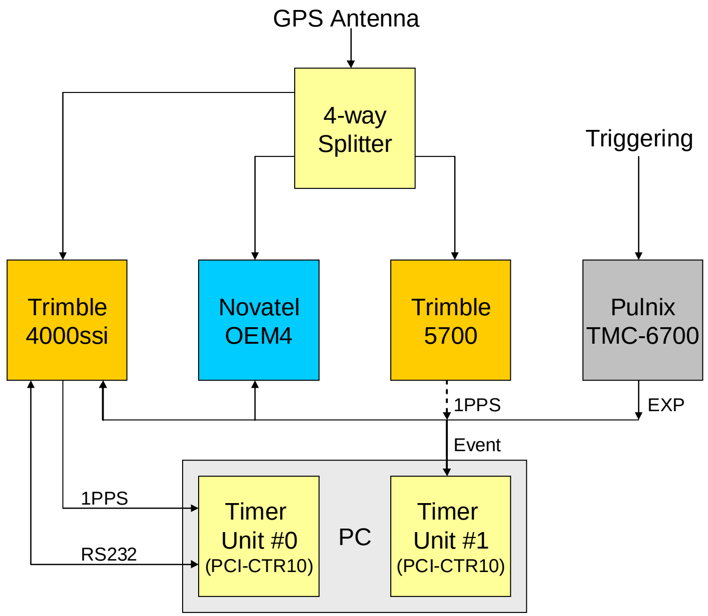


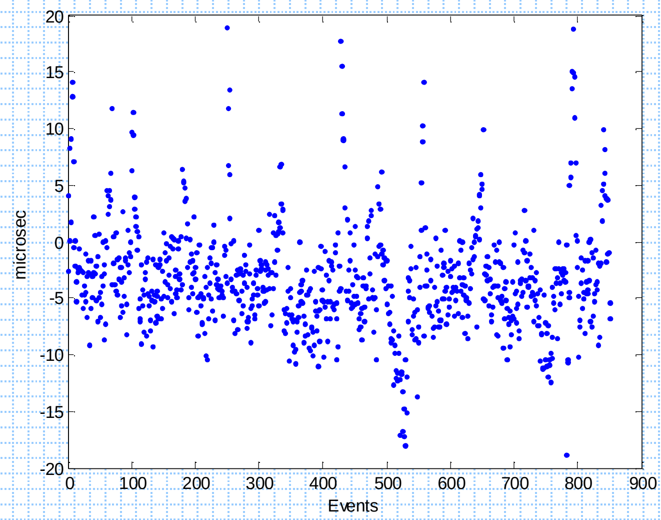


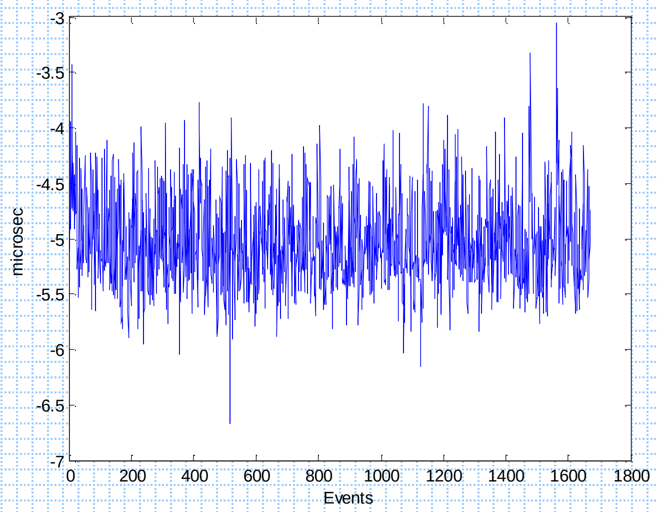
PC-based data acquisition

- Flexible architecture
- Multiple data streams
- Post-processing
- Real-time option

GPS timing/synchronization for airborne and land-based multi-sensor geospatial data acquisition platforms







Performance validation

- GPS 1PPS time-tagging (left)
  - 1PPS signal independently tagged by PC system and GPS receiver (figure shows a 5 μs bias and few μs precision)
- Digital camera strobe time-tagging (above)
  - Pulnix camera was acquiring images at 5 FPS, images recorded on the same PC (figure shows larger precision)

Tightly integrated GPS/INS navigation module for airborne and land-based multi-sensor georeferencing

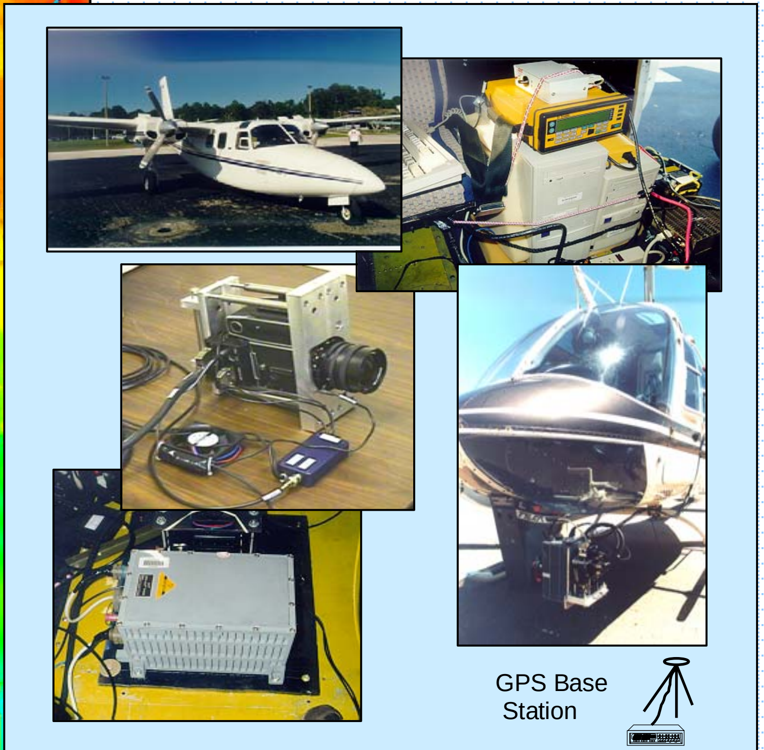
Project Description

- ✓ Project Sponsor: NASA, ODOT, Northrop Grumman (Litton Systems)
- ✓ Principal Investigators: Charles Toth and Dorota Brzezinska
- ✓ Graduate students:
  - ❖ Yudan Yi, Eva Paska, Nora Csanyi May, Qian Xiao

Project Objectives

- ✓ Design and implement high-accuracy tightly-coupled GPS/INS navigation module for airborne and land-based multi-sensor georeferencing
- ✓ Centimeter level accuracy of the image data acquisition platform

Airborne Integrated Mapping System AIMS™



AIMS™ Characteristics

- Fully digital airborne data acquisition system
- Single high-resolution imaging sensor
- Direct platform orientation by tightly coupled GPS/INS
- Typical fit to ground truth
  - 2-30 cm for flying height of ~ 300m

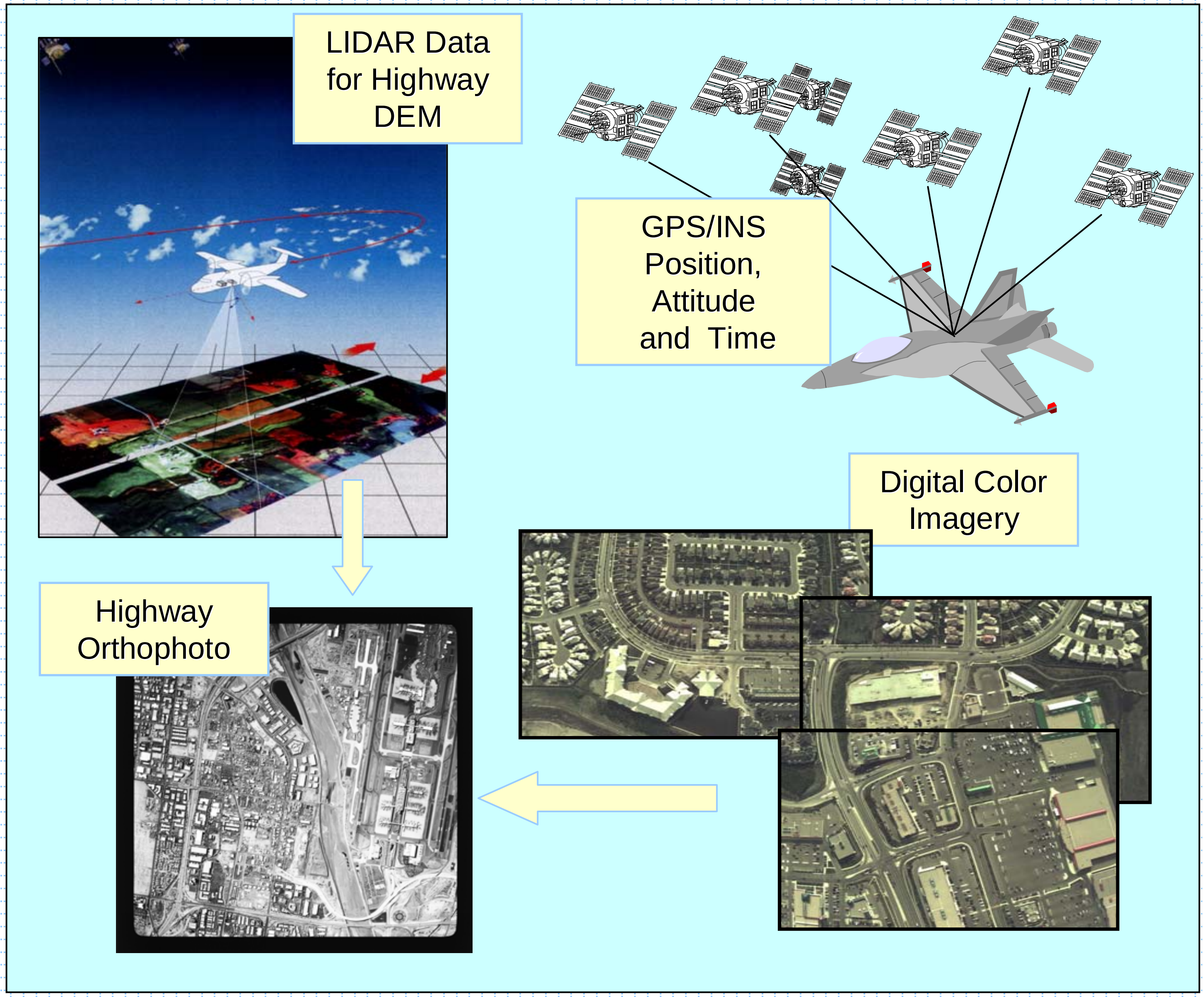
AIMS™ Applications

- Large-scale topographic mapping
- Corridor surveys of the transportation infrastructures
- Military reconnaissance
- Potential for real-time applications

New capabilities →

- Near real-time processing power
- High quality direct georeferencing and timing
- Better and faster sensors
- New sensors (LiDAR)

Multi-sensor fusion
New applications


LIDAR Data for Highway DEM
GPS/INS Position, Attitude and Time
Digital Color Imagery
Highway Orthophoto

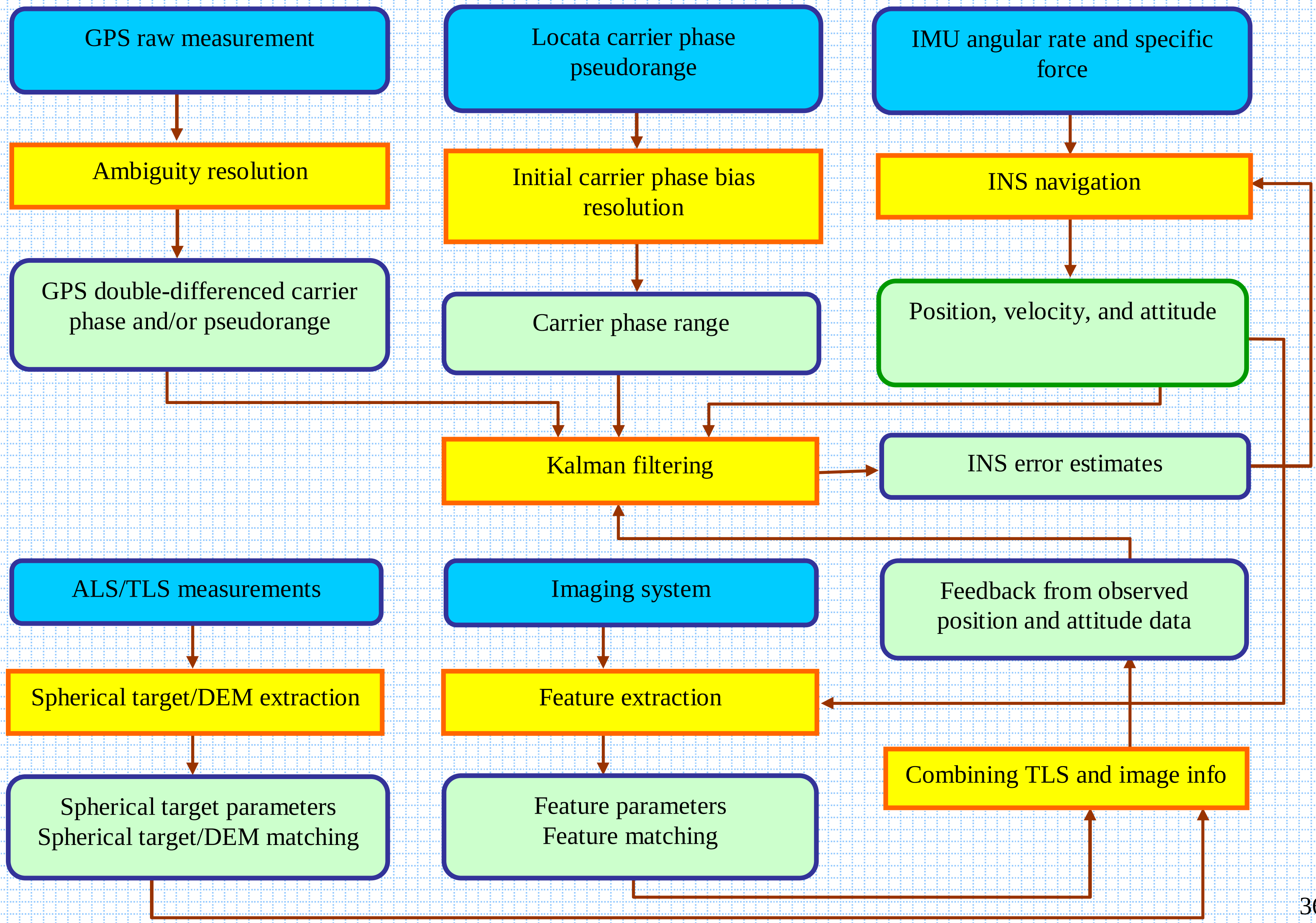
AIMS-PRO

- ✓ Novel quadruple integration
  - GPS (GNSS)
  - Pseudolite (PL) technology
  - IMU (handles various IMU classes, from high- to low-end sensors)
  - Feedback from imaging module to implement terrain-referenced navigation
    - Such as TLS[1] with specialized targets for highest accuracy in GPS-challenged environments or multiple image overlap based relative orientation from optical imagery, DEM/GIS, etc.
- ✓ Multiple approaches to GPS solution:
  - Single baseline (differential kinematic solution)
  - Network-based differential kinematic solution
  - Precise point positioning technology (PPP)
- ✓ Implementation redesign
  - Post-processed and real-time capable
  - Better portability
  - Flexible structure
  - Improved diagnostics capabilities
- ✓ First application in the SERDP project (see slide 29 for reference)

[1] Terrestrial Laser Scanning

[2] Digital Elevation Model/Geographic Information Systems

AIMS-PRO


GPS raw measurement
Locata carrier phase pseudorange
IMU angular rate and specific force
Ambiguity resolution
Initial carrier phase bias resolution
INS navigation
GPS double-differenced carrier phase and/or pseudorange
Carrier phase range
Position, velocity, and attitude
Kalman filtering
INS error estimates
ALS/TLS measurements
Imaging system
Feedback from observed position and attitude data
Spherical target/DEM extraction
Feature extraction
Combining TLS and image info
Spherical target parameters
Spherical target/DEM matching
Feature parameters
Feature matching

High-accuracy hybrid geolocation technology supporting geophysical surveys for UXO detection and discrimination

Project Description

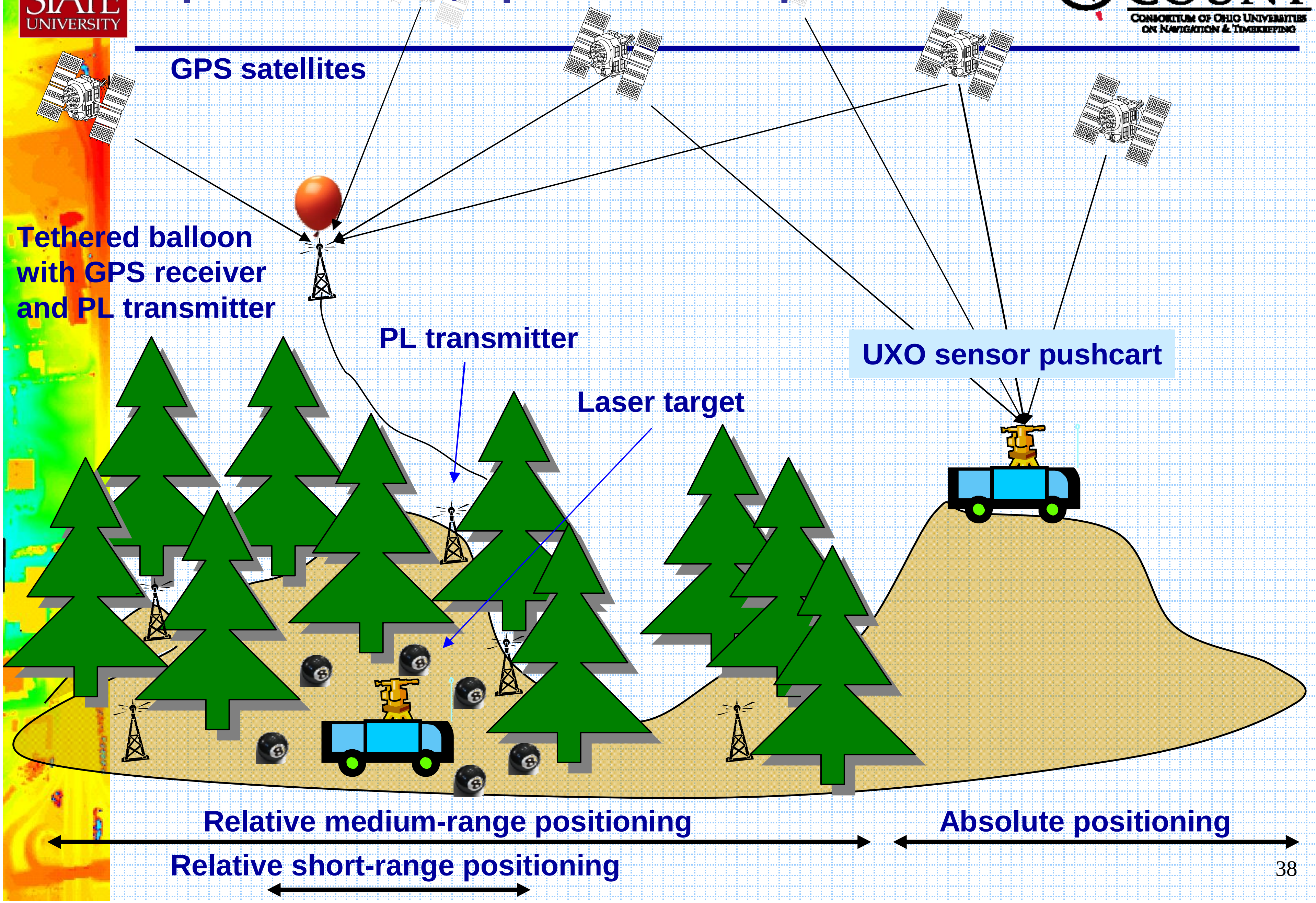
- ✓ Project Sponsor: SERDP[1]/DOD
- ✓ Project Collaborators: AFIT, AFRL, ODOT, University of New South Wales, Sydney, Australia, Locata Inc., Canberra, Australia
- ✓ Principal Investigators: Dorota Brzezinska and Charles Toth
- ✓ Post-doctoral researchers: Hongxing Sun
- ✓ Graduate students:
    - ❖ Xiankun Wang, Young-Jin Lee, Shahram Moafipoor

Project Objectives

- ✓ Develop reliable and accurate geolocation of UXO[2]/MEC[3] detection sensors → crucial for detection and proper discrimination of buried objects
- ✓ Use multi-sensor integration approach, as UXO/MEC environments are challenging (vegetation, no open sky required by GPS)
- ✓ Maintain cm to sub-decimeter level relative navigation accuracy across varying environments

[1] Strategic Environmental Research and Development Program
[2] Unexploded Ordinance
[3] Munitions and Explosives of Concern

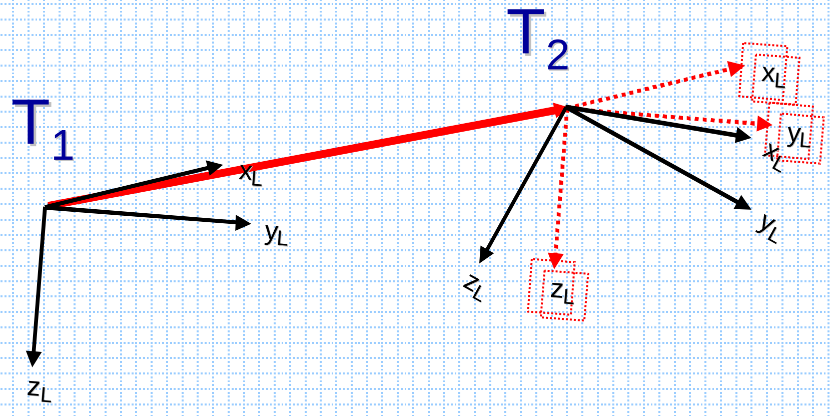
Specifications, operational requirements

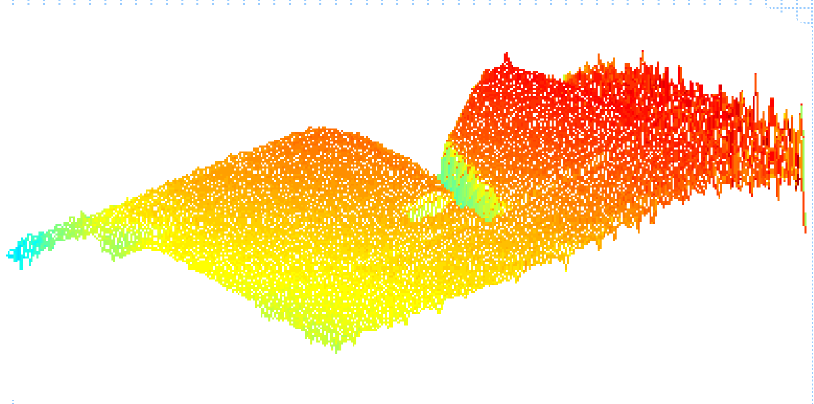


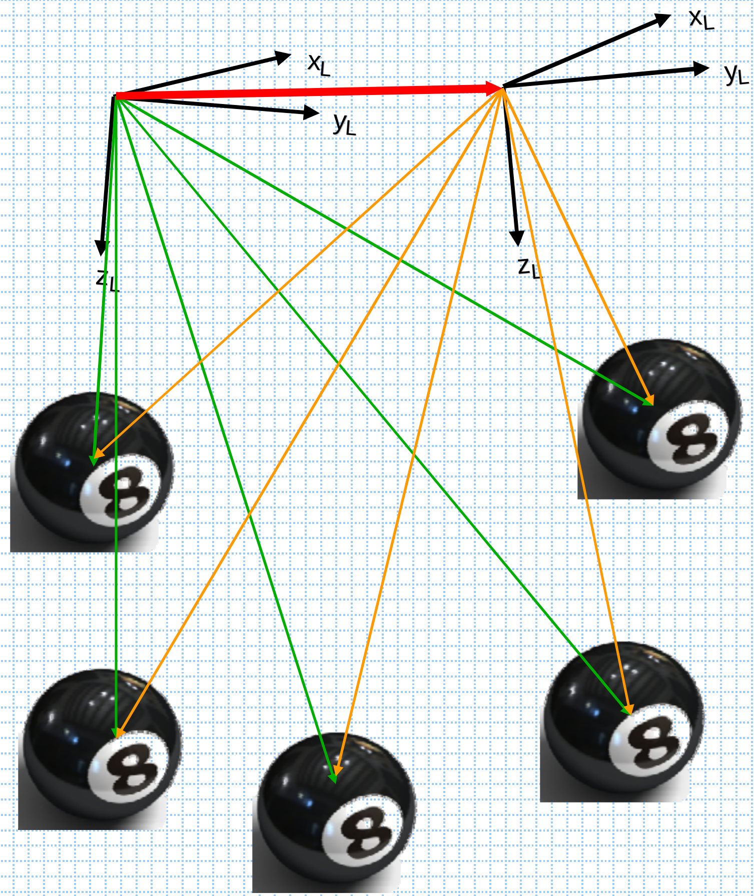
TLS surface matching, target extraction

Surface matching
- surface signal dependent
- robust because of large number of surface points

Target-based referencing
- surface independent
- robust because of simple shape of targets

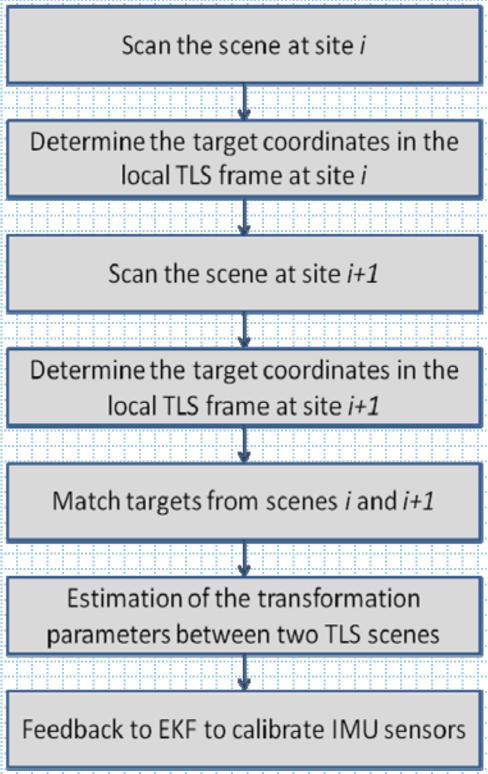


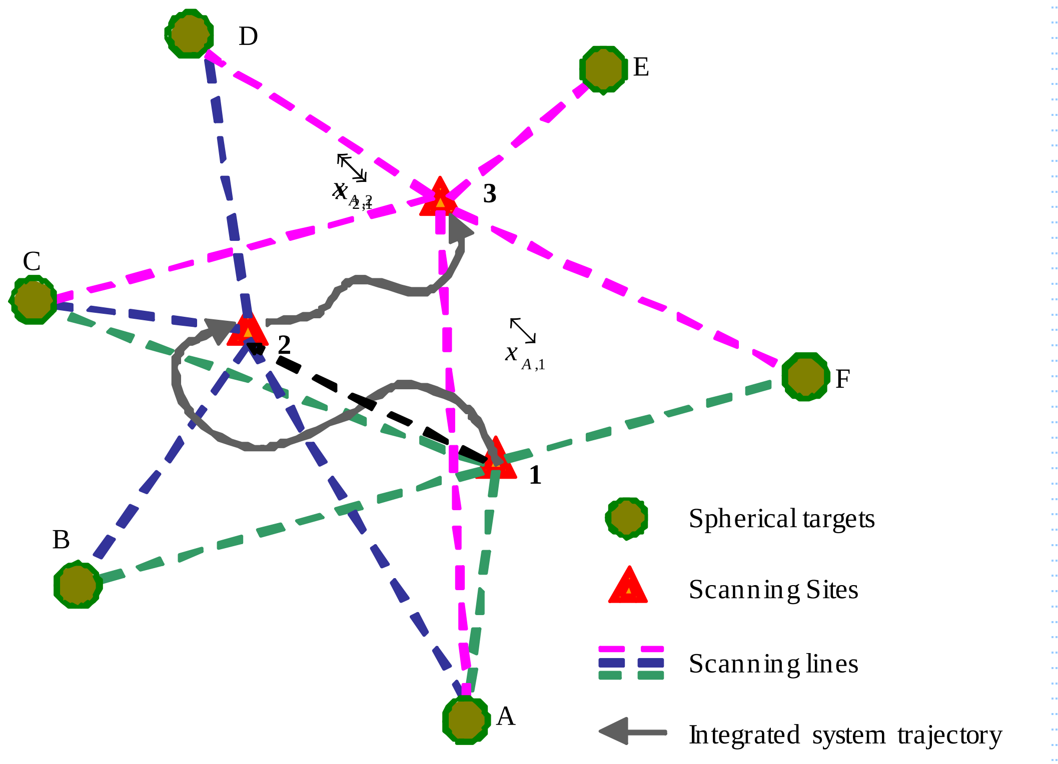




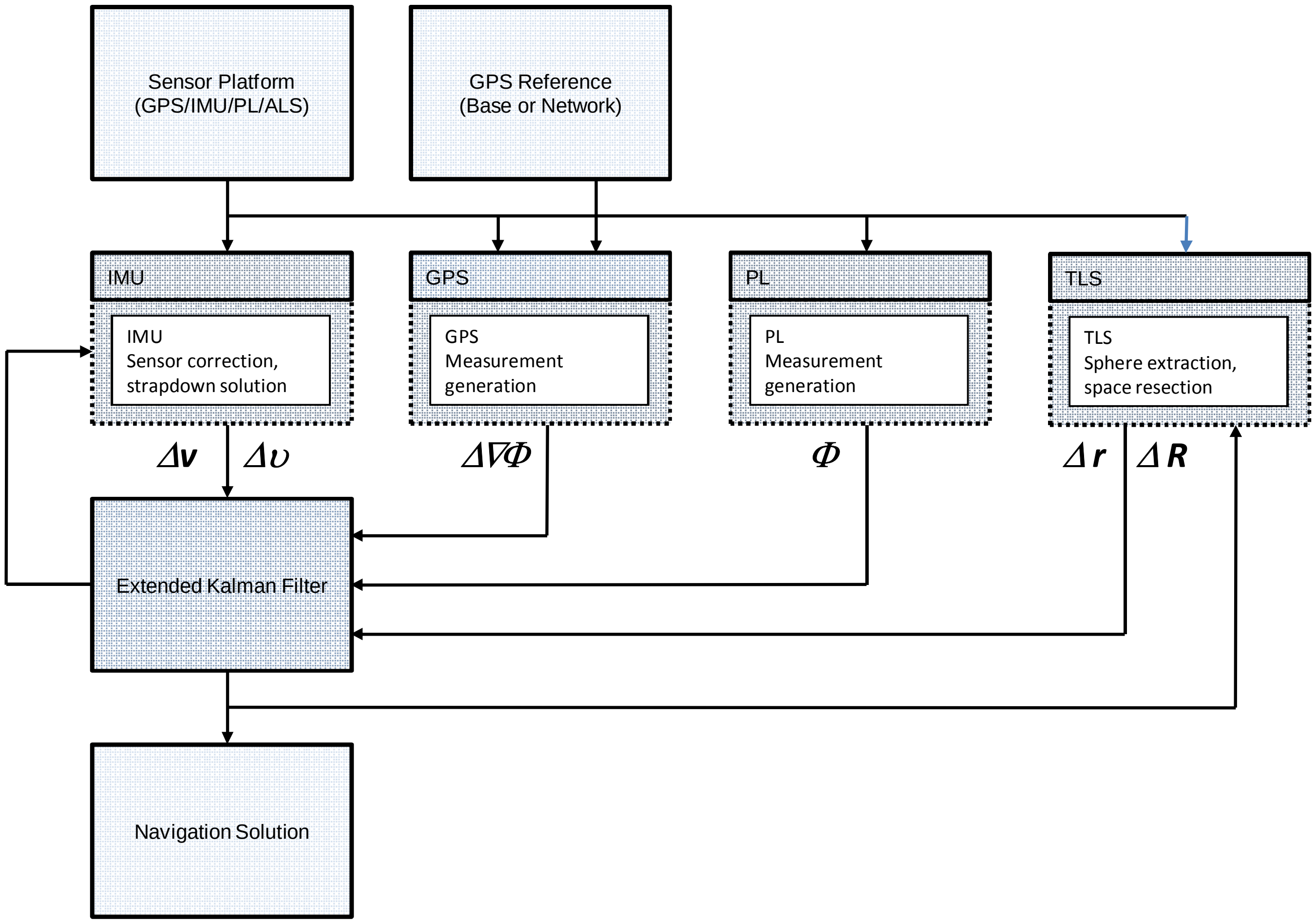
TLS feedback to navigation

- TLS provides platform position changes with errors less than 1cm in 3D
- TLS provides attitude change with the accuracy in the mrad range
- Direct feedback to EKF supports navigation and allows partial calibration of IMU errors





AIMS-PRO™ design architecture for the tight coupling mode, where Δv and $\Delta \upsilon$ are the rates of linear and angular velocities, respectively, Φ is the carrier phase range, $\Delta\nabla$ denotes the double-difference operator, and Δr and ΔR are linear and angular offsets between two TLS sites.



Note that RF spaceborne (GPS) and ground (PL) networks are not shown.

Field testing

Rapid city modeling from precisely georeferenced LiDAR/HSI data using closed-feedback error loop

Project Description

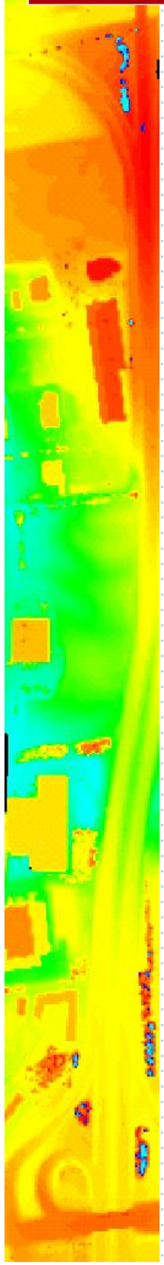
- ✓ Project Sponsor: NGA
- ✓ Project collaborators: AFRL, ODOT, ITRES Research Ltd.
- ✓ Principal Investigators: Dorota Brzezinska and Charles Toth
- ✓ Post-doctoral researchers: Naci Yastikli and Hongxing Sun
- ✓ Graduate students
  - ❖ Young-Jin Lee, Jake Oh, Shahram Moafipoor, Nora Csanyi May

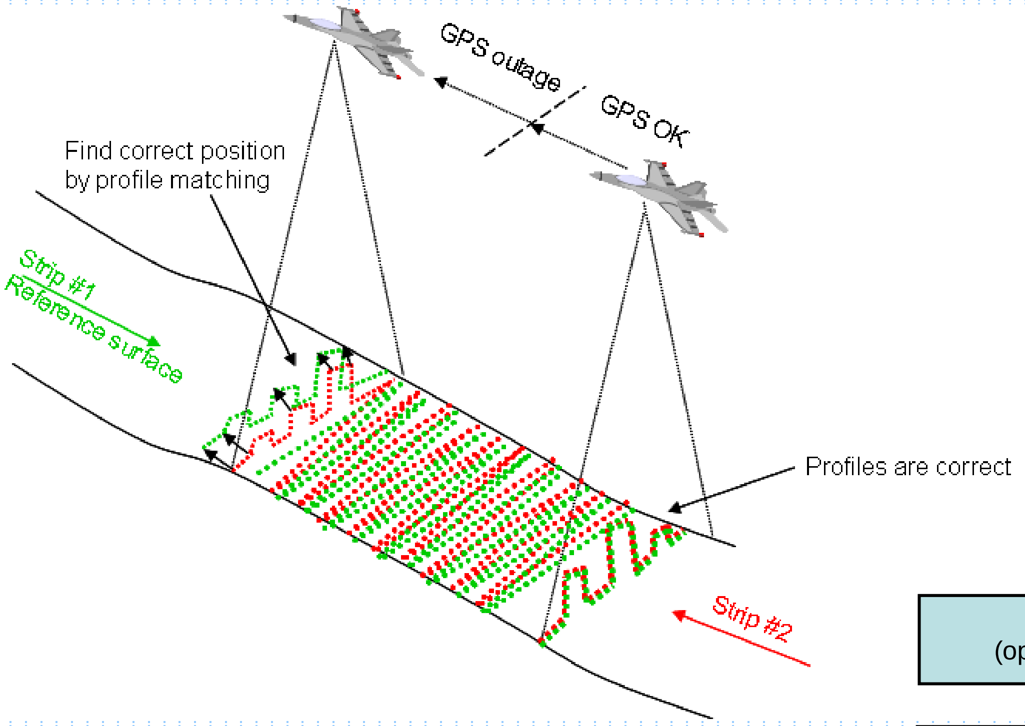
Project Objectives

- ✓ Develop fast and fully automated technique for city/terrain model extraction from airborne LiDAR and HSI[1] data
- ✓ Design an intelligent closed-feedback error loop between the imaging and georegistration (GPS/INS) modules
  - ❖ Terrain-based navigation using airborne LiDAR
- ✓ Ensure continuity, reliability, integrity and high accuracy of the geolocation solution – critical to extracting reliable object information from large volumes of image data

[1] Hyper-spectral imagery

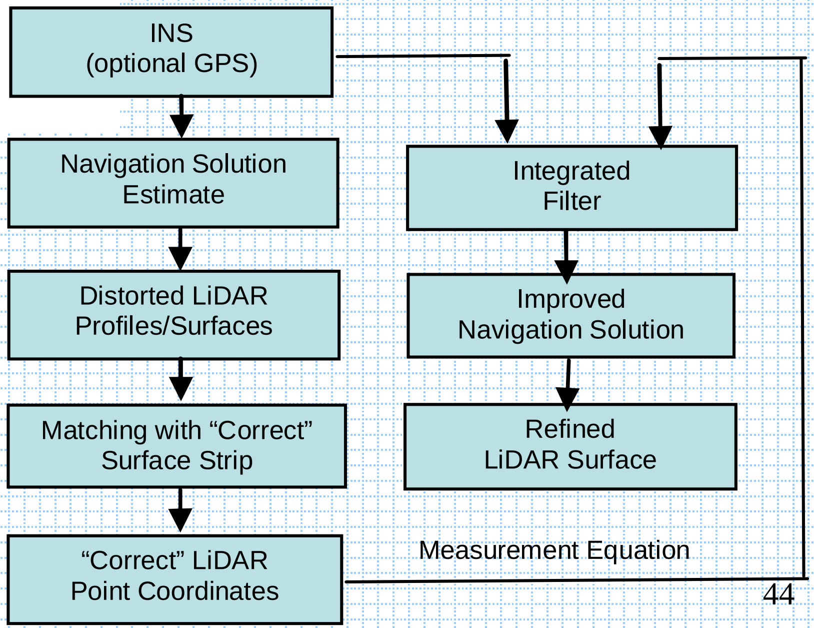
Rapid city modeling from precisely georeferenced LiDAR/HSI data using closed-feedback error loop



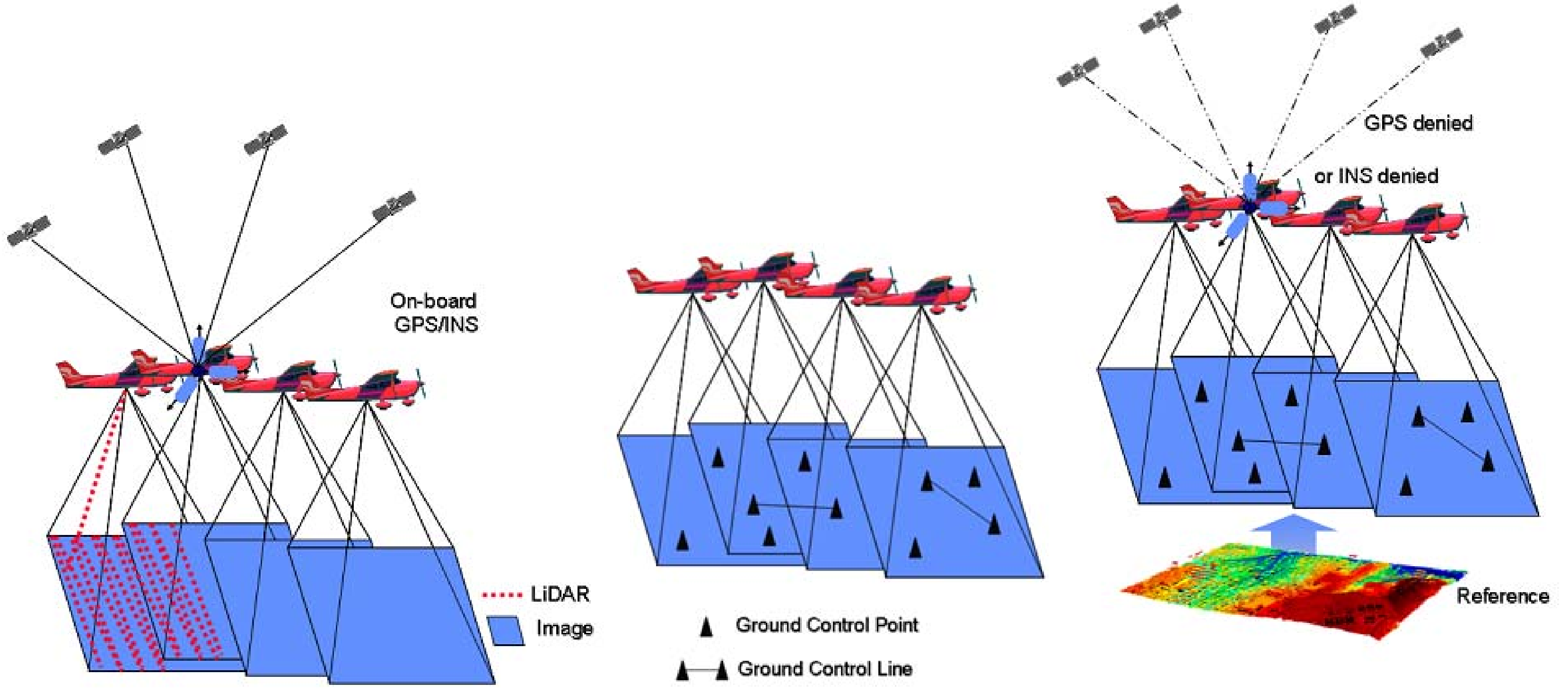


Closed-feedback error loop concept:

Terrain-based navigation using airborne LiDAR



Georeferencing vs. terrain-referenced navigation



(a) direct geo-referencing (b) indirect geo-referencing (c) terrain(image) referenced

Autonomous vehicle navigation

Project Description

- ✓ Project Sponsor: OSU, Topcon, TRC
- ✓ Principal Investigators: Umit Ozguner, Keith Redmill, Charles Toth and Dorota Brzezinska
- ✓ Graduate students
  - ❖ Eva Paska plus 10+ ECE students

Project Objectives

- ✓ 2007 DARPA Urban Challenge
- ✓ Position and orientation localization, with GPS blackouts
- ✓ Sensing of vehicle environment and state in a complicated, off-road and structured environments
- ✓ Long term autonomy and vehicle control over an unknown course and terrain
- ✓ Reliable obstacle and moving object avoidance - crucial for urban environments

Introducing The OSU ACT –
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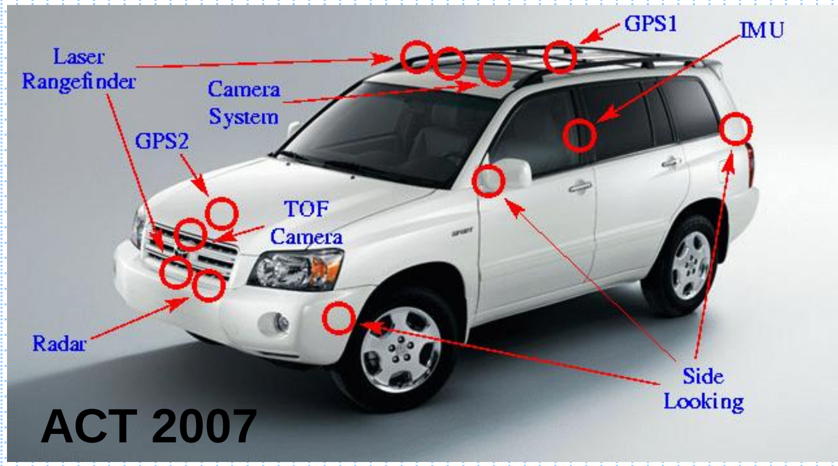

- Lane tracking
- Car following
- Intersections, traffic circles
- Passing
- Obstacle avoidance
- Parking
- Dynamic route planning