

# Terrain-based navigation: LiDAR- and terrestrial scanner-supported navigation concept

## Part II: TLS-based navigation

Novel geolocation technology for geophysical sensors for  
detection and discrimination of unexploded ordnance

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# Outline

- Motivation
- System design
  - Quadruple integration: GPS/IMU/PL/TLS
  - TLS-based navigation concept
- System implementation
- Simulations and performance assessment
- Conclusions

GPS – Global Positioning System

IMU/INS – inertial measurement unit/inertial navigation system

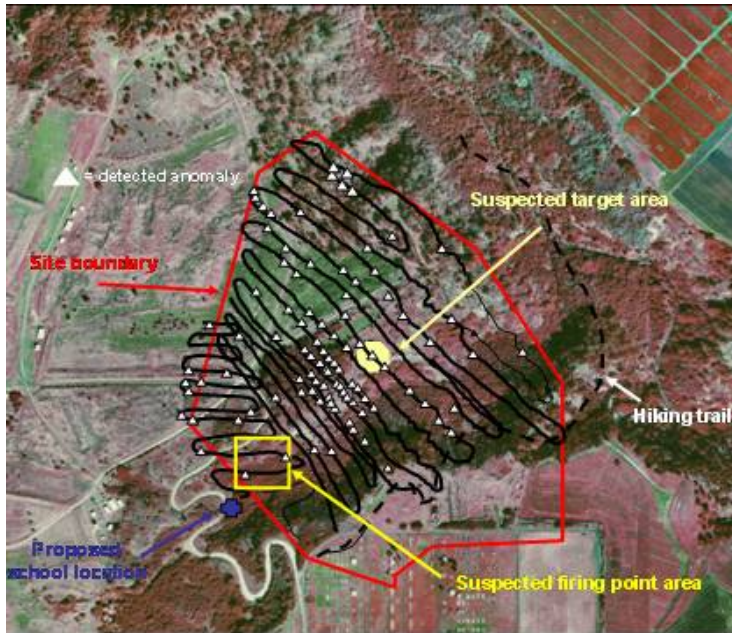
PL - pseudolite

TLS - terrestrial laser scanning

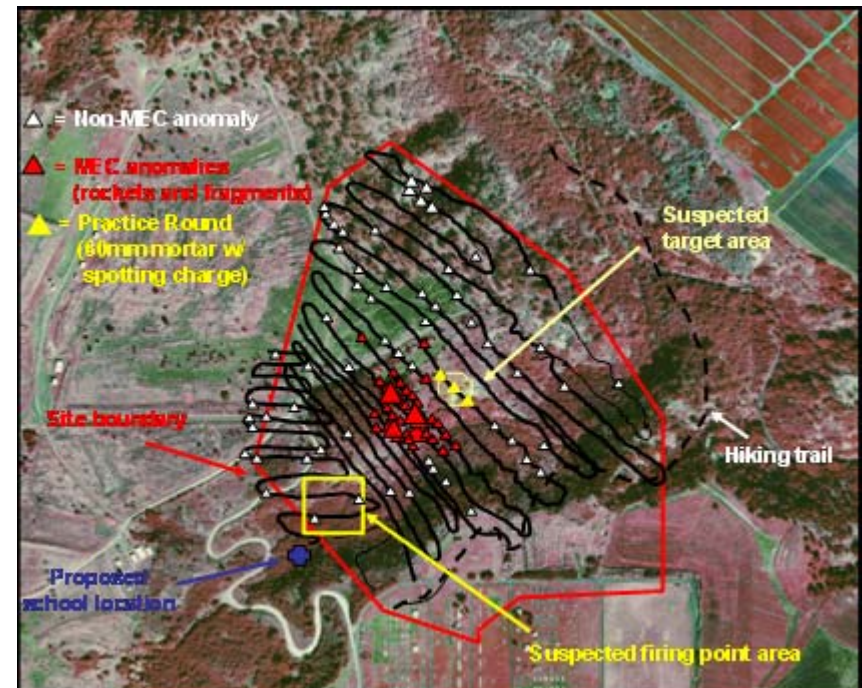
# I. Motivation

- Detection and remediation of MEC (munitions and explosives-of-concern) sites is one of the DoD's most pressing environmental problems
- Geophysical mapping – standard approach to site investigation and buried object identification
  - Mag and flag
    - Screening of the entire site, and identifying portions for further investigation/local interrogation
    - Technicians walk survey transects laid out in a field
  - Local interrogation (EM survey)
- Unexploded ordnance (UXO) excavation and removal
- Over 90% of objects excavated are found to be non-hazardous (COST!)

# I. Motivation



Anomalies detected after “mag and flag” (left) and anomalies identified after refined EM mapping (bottom)



# I. Motivation

- Using current sensor technologies, object discrimination is based on detailed spatial mapping of magnetic or electromagnetic signatures
- Requires geolocation of the individual sensor readings with a relative accuracy of about 1 cm
  - 3D image is reconstructed from multiple images taken from different angles/location of the EM sensor
- By virtue of topography or vegetation, many sites are not amenable to DGPS (differential GPS)

# I. Motivation

- **Project Goal**

Design, implement and test a high accuracy hybrid navigation device that can address the stringent requirements of a man-portable geophysical mapping system, and is capable of maintaining high relative positioning accuracy in GPS-challenged environments

## II. System design

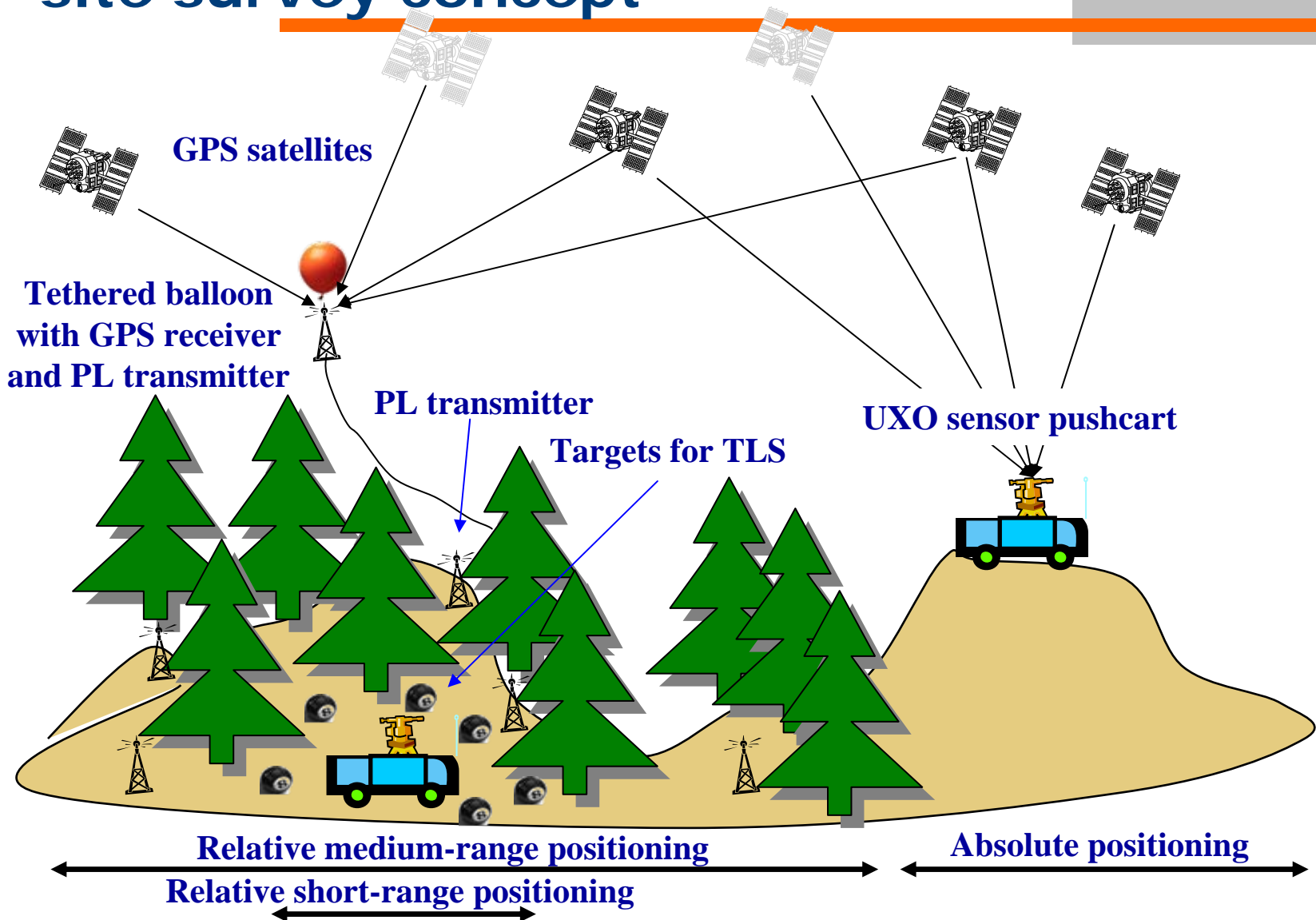
- Quadruple-integration of GPS, INS, pseudolite (PL), and terrestrial laser scanning (TLS) to assure accuracy, continuity and integrity of the navigation solution
- Three-tier MEC site survey concept
- Novel integration approach of incorporating TLS technology to facilitate high relative positioning accuracy in GPS-challenged environments

# II. System design

System	Advantage	Disadvantage
<b>GPS</b>	Absolute location High accuracy position and velocity (attitude is optional)	Line-of-sight system
<b>PL</b>	Absolute location Works well in confined environments (function of geometric configuration and multipath)	Line-of-sight system
<b>INS</b>	Self-contained system	Relative navigation solution Drifts in time
<b>TLS</b>	High accuracy position High accuracy attitude	Relative navigation solution

The benefits of the integrated system

# II. System design: three-tier MEC site survey concept



# II. System design

- TLS positioning and navigation technology

Specifications	Trimble GX Laser Scanner
Laser Wavelength	532 nm
Laser Power	<1 mW
Beam Diameter at Specified Distance from the Scanner	1.5 mm at 25 m (autofocus)
Measurement Technique	Time-of-flight
Average Data Acquisition Rate	Depends on application
Maximum Data Acquisition Rate	5000 pps
Distance Accuracy at Specified Distance	7 mm at 100 m
Position Accuracy at Specified Distance	12 mm at 100 m
Angular Accuracy (seconds of arc)	12" horizontal / 14" vertical
Minimum Range	1 m
Maximum Range at Specified Reflectivity	200 m at 99% reflectivity
Field of View (vertical angle)	60°
Field of View (horizontal angle)	360°
Maximum Sample Density	16 points/cm <sup>2</sup> @ 100 m



# II. System design

## TLS-based resection:

$$X_1^n + R_{b1}^n X_{P,1}^{b1} - X_2^{n0} - R_{b2}^{n0} X_{P,2}^{b2} = -\delta X_2^n + X_{P,2}^{n0} \varepsilon$$

$$r_{A,1}^{b1} = r_{2,1}^{b1} + R_{b2}^{b1} r_{A,2}^{b2}$$

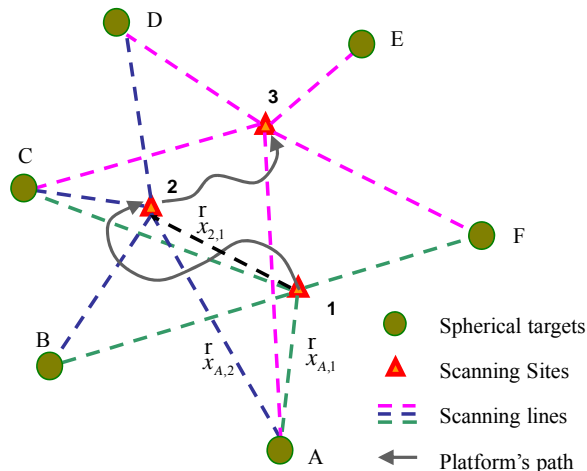
$$X_{P,1}^{b1} = X_{2,1}^{b1} + R_{b2}^{b1} X_{P,2}^{b2}$$

$$R_{b1}^n X_{P,1}^{b1} = X_{2,1}^n + R_{b2}^n X_{P,2}^{b2}$$

$$X_1^n + R_{b1}^n X_{P,1}^{b1} = X_2^n + R_{b2}^n X_{P,2}^{b2}$$

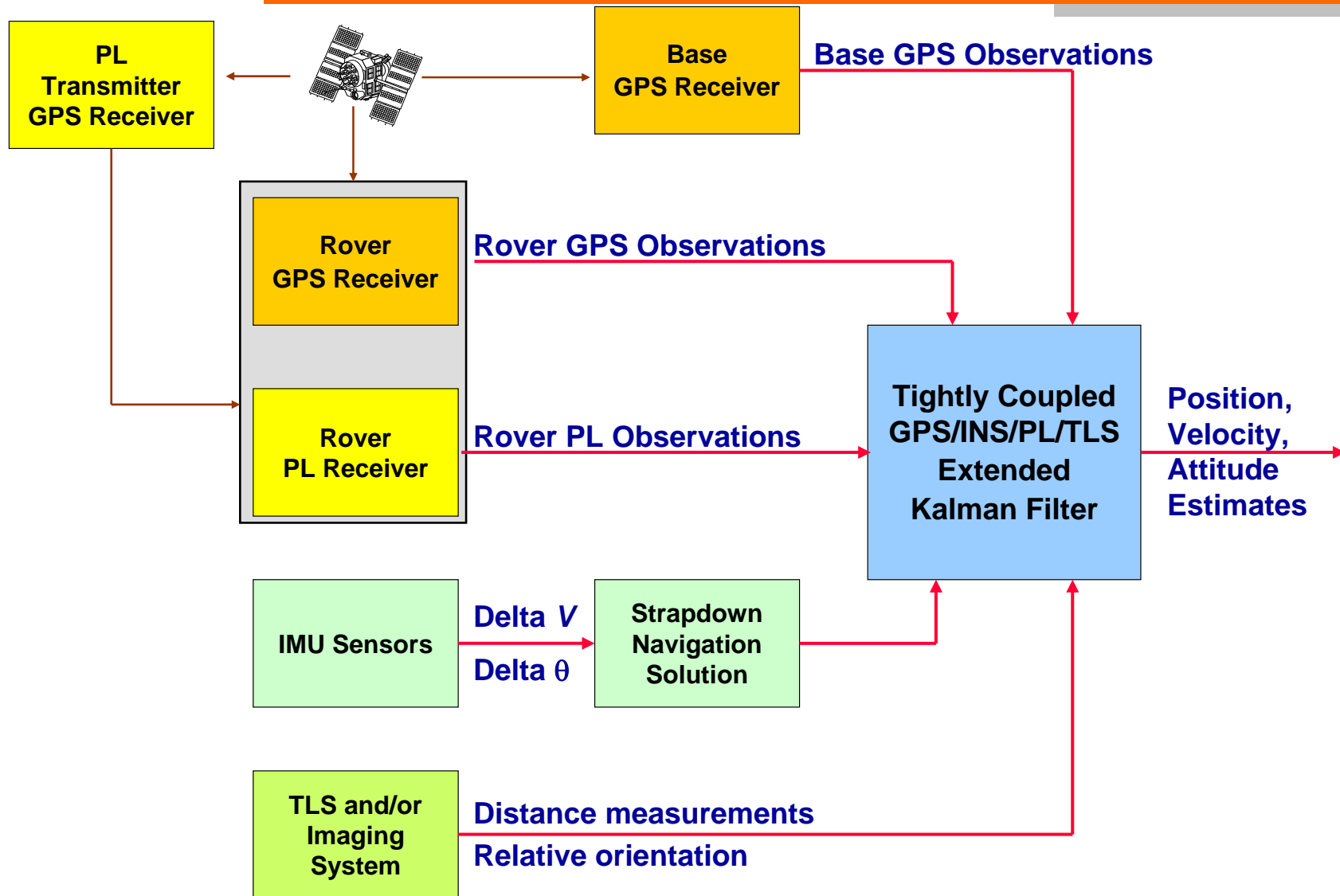
$$X_1^n + R_{b1}^n X_{P,1}^{b1} = X_2^{n0} - \delta X_2^n + (I - E) R_{b2}^{n0} X_{P,2}^{b2}$$

- $X_1^n$  coordinates of site 1 in the navigation frame
- $R_{b1}^n$  transformation matrix from the first local frame of TLS to navigation frame
- $X_{P,1}^{b1}$  the first frame coordinates of the common targets observed at site 1
- $X_2^{n0}$  approximate coordinates of site 2 in navigation frame
- $R_{b2}^{n0}$  approximate transformation matrix from the second local frame of TLS to navigation frame
- $X_{P,2}^{b2}$  coordinates of the common targets observed at site 2 in the second frame (TLS body frame at second location)
- $\delta X_2^n$  coordinate error vector
- $X_{P,2}^{n0}$  skew-symmetric matrix of the coordinate vector
- $\varepsilon$  attitude angle error vector



Derive platform's position and attitude changes by measuring range and angular directions to spherical target centers, then feed them to the Kalman Filter for INS calibration and navigation solution estimation

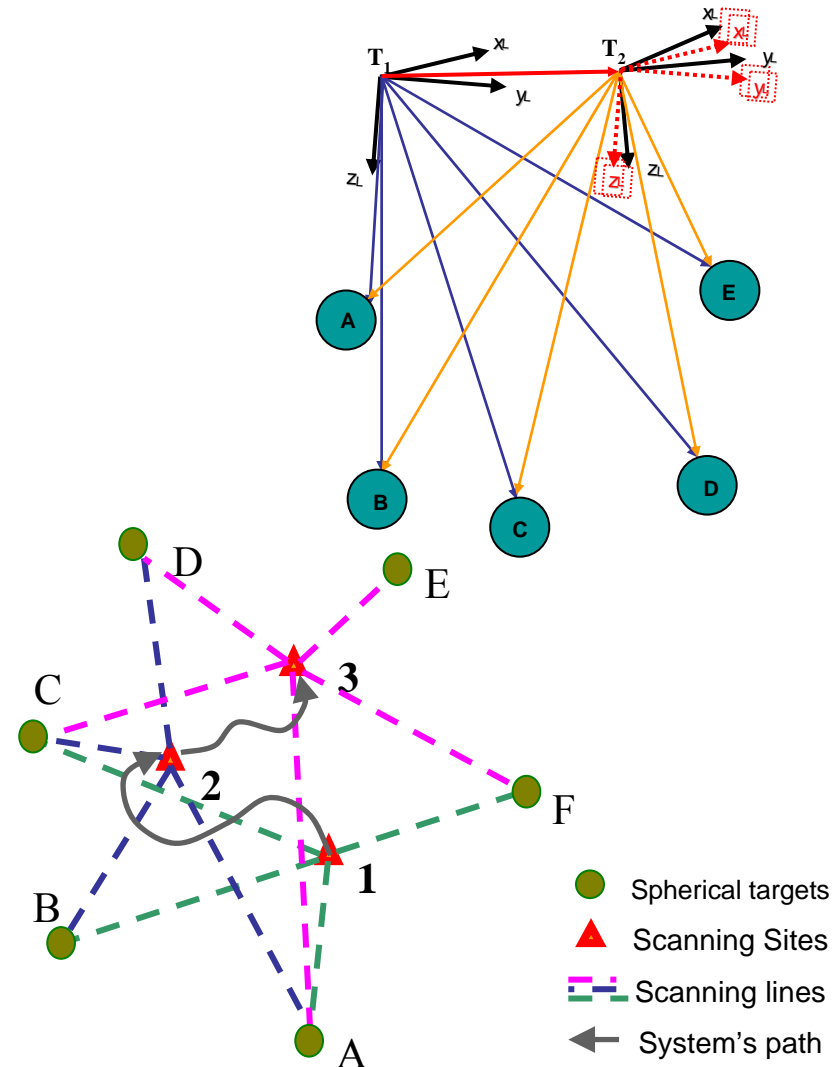
# II. System design



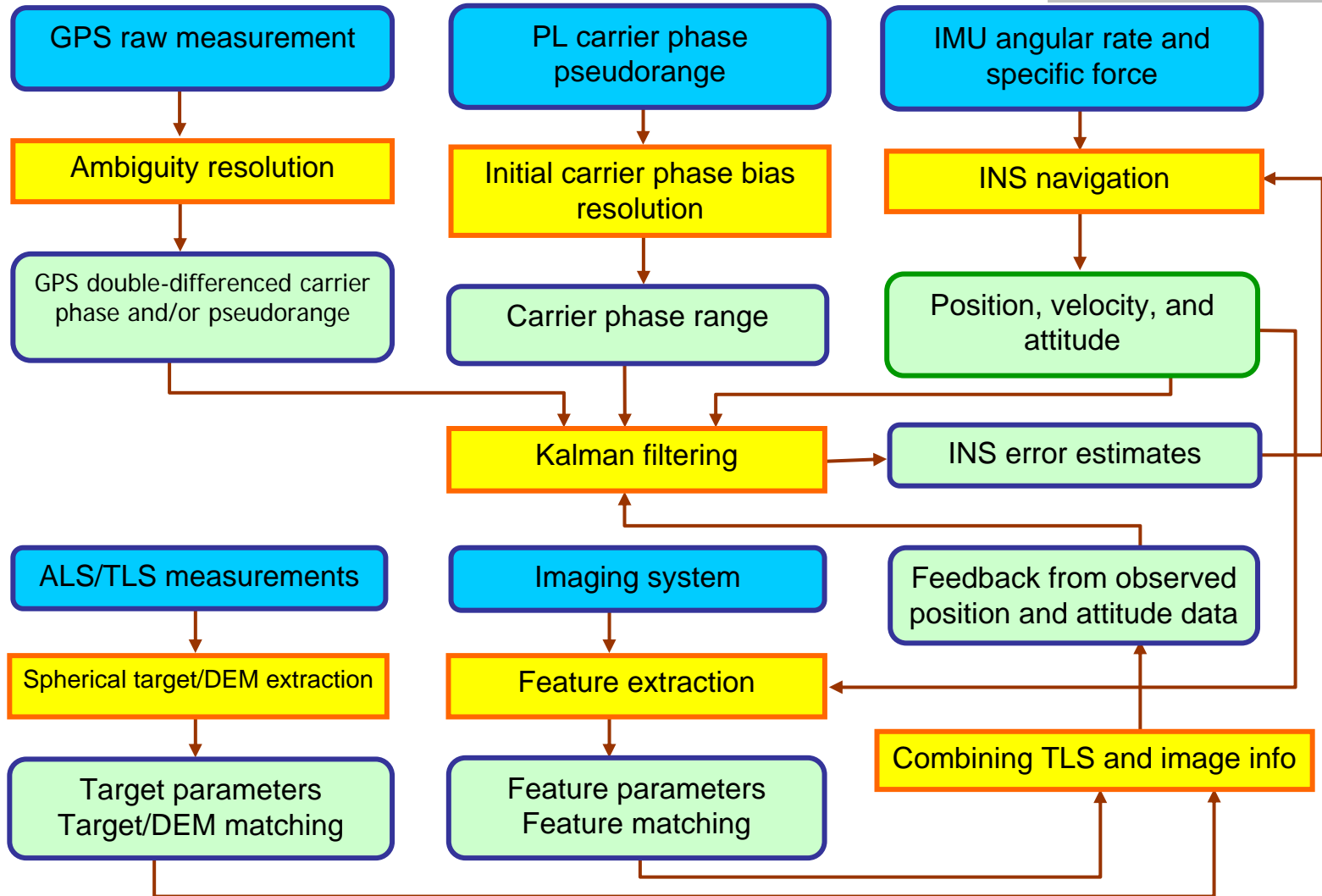
# II. System design

## TLS-based Navigation:

- Used in wooded areas
- Employs spherical targets
- Target scanning
- Target center estimation
  - Fitting of spherical model to a point cloud
- Target matching from two TLS locations
- TLS-based resection
  - Fed to EKF
- INS calibration
- Navigation solution



# III. System implementation



AIMS-PRO™ design architecture

# III. System implementation

Extraction of spherical targets and estimation of the coordinates of their centers:

- Look up table (LUT) for laser point indexing
- Spherical point classification
  - Smallest range variation algorithm
  - Region growing algorithm
- Least squares fitting
- Refinement of the coordinates of spherical target centre
  - Average the estimated sphere candidates that are close to each other
  - Resize the search window and re-search sphere points
  - Apply least squares fitting again

# III. System implementation

## Least squares fitting:

- Fit sphere to selected points
- Determine the sphere center

$$(x_0 - x_i)^2 + (y_0 - y_i)^2 + (z_0 - z_i)^2 = r^2$$

$$r - r_i = \frac{x_i - x_0}{r_i} \delta x + \frac{y_i - y_0}{r_i} \delta y + \frac{z_i - z_0}{r_i} \delta z + e_i$$

$$\tilde{e}^T P \tilde{e} \rightarrow \min$$

$$\hat{\sigma}_0 = \sqrt{\frac{\tilde{e}^T P \tilde{e}}{n - 3}}$$

$x_0, y_0, z_0$  – the approximate sphere center

$x_i, y_i, z_i$  – the  $i^{\text{th}}$  measured sphere point

$r$  – sphere radius (known)

$r_i$  – distance from the  $i^{\text{th}}$  point to approximate center

$\delta x, \delta y, \delta z$  – corrections to sphere center coordinates

$e_i$  – residual

$\tilde{e}$  – estimates of the residuals

$P$  – weight matrix

# III. System implementation

Matching of target centers observed from two locations of TLS:

1. Index sphere centers observed from both locations
2. Find line segments between consecutive points in both data sets that have the same length
  - Match line segment between two targets
3. Find the point pairs in both data sets that have the same sum of distances to the end points of the matched line segments (i.e., lines between sphere centers)
4. Determine the matching end point pairs of the line segments from the already matched point pairs

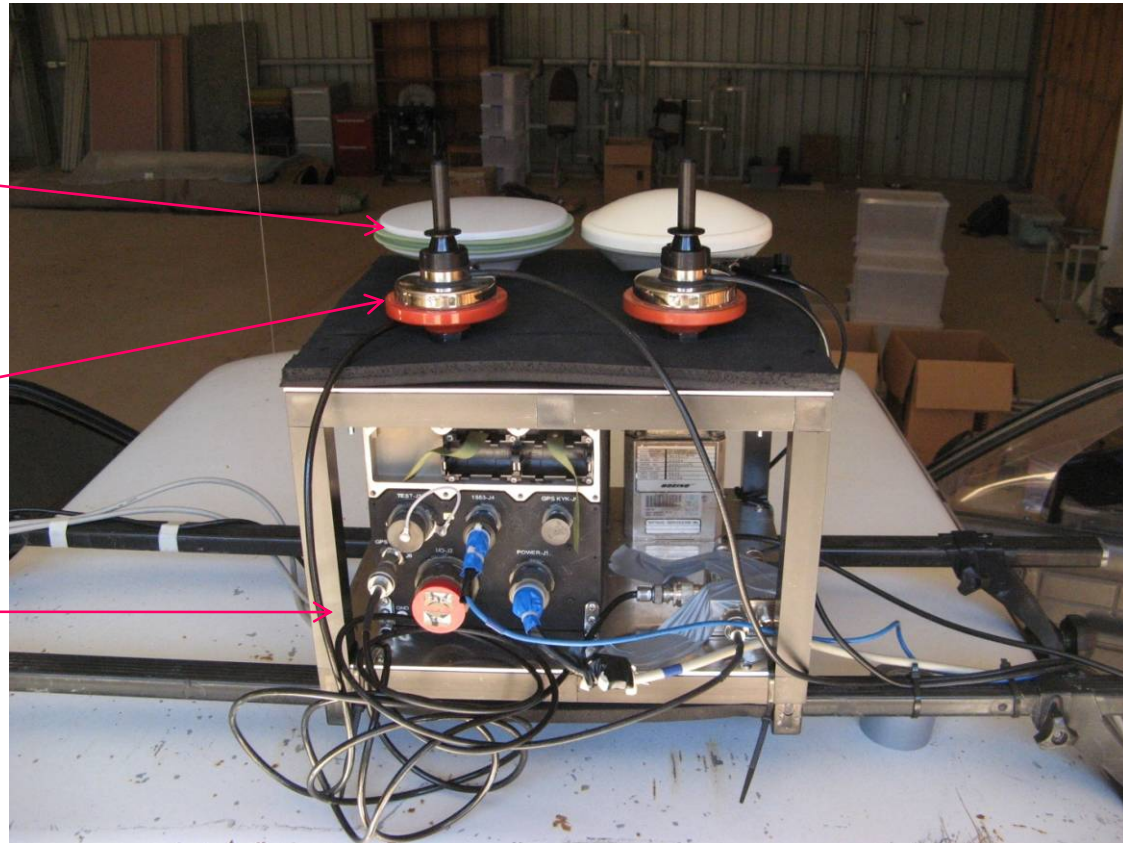
# III. System implementation

## GPS/INS/PL test equipment

GPS

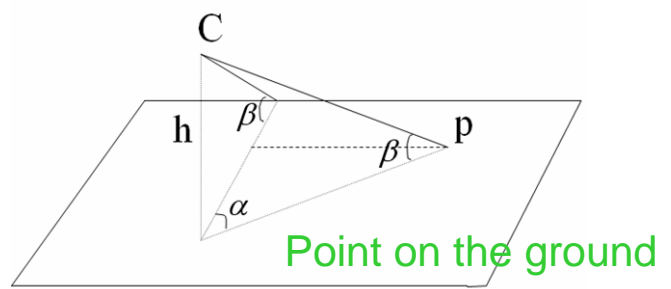
Locata PL

IMU



# IV. Simulations and performance assessment

## Simulation of laser point cloud

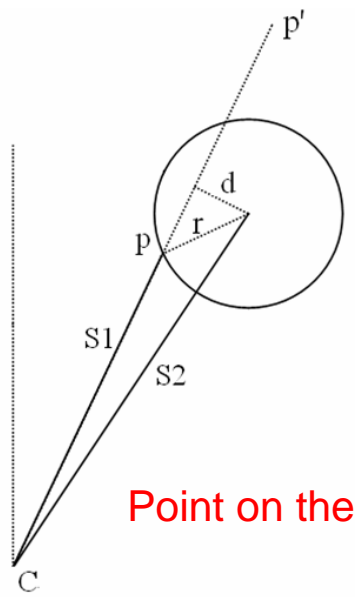
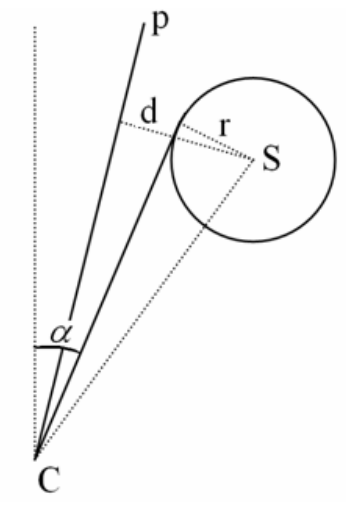


$$\begin{cases} x_p = x_c + h \cdot \cot \beta \sin \alpha \\ y_p = y_c + h \cdot \cot \beta \cos \alpha \\ z_p = 0 \end{cases}$$

$$d = \frac{|(\vec{p} - \vec{C}) \times (\vec{C} - \vec{S})|}{|\vec{p} - \vec{C}|}$$

where

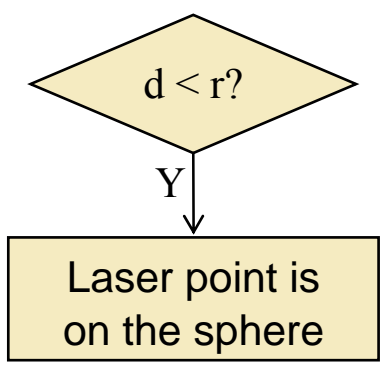
$$\begin{aligned} \vec{p} &= (x_p, y_p, z_p)^T \\ \vec{C} &= (x_c, y_c, z_c)^T \\ \vec{S} &= (x_s, y_s, z_s)^T \end{aligned}$$



$$\begin{cases} x_p = x_c + s1 \cdot \cos \beta \sin \alpha \\ y_p = y_c + s1 \cdot \cos \beta \cos \alpha \\ z_p = z_c + s1 \cdot \sin \beta \end{cases}$$

where

$$s1 = \frac{r}{d} \cdot s2 \cdot \cos \left( \cos^{-1} \left( \frac{d}{r} \right) + \sin^{-1} \left( \frac{d}{s2} \right) \right)$$

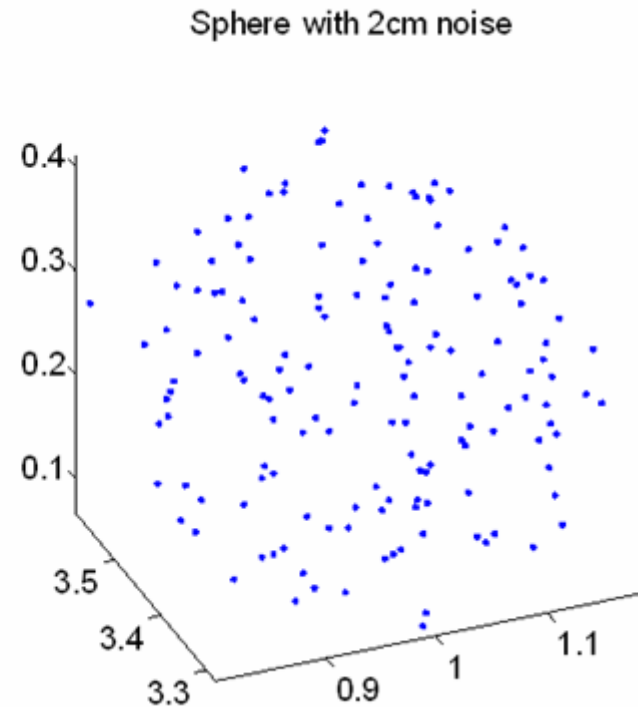
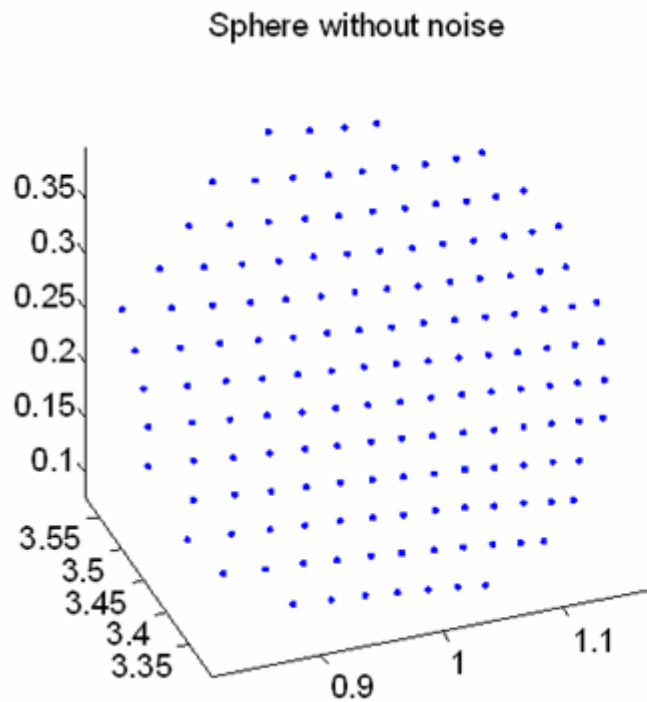


Note:  $\vec{C}, \vec{S}, h,$  and  $r$  are known for the simulation

# IV. Simulations and performance assessment

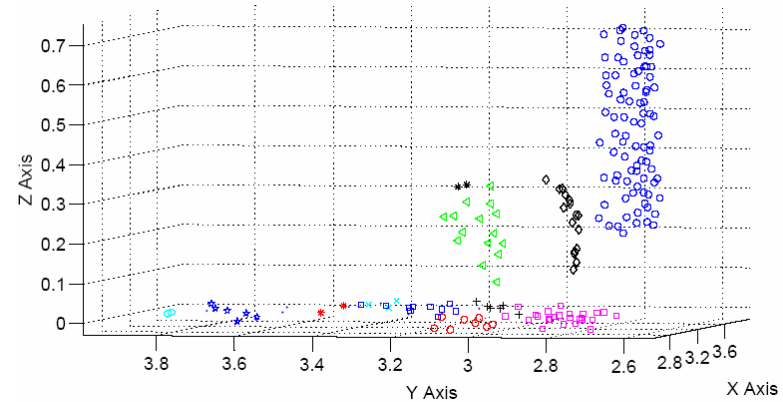
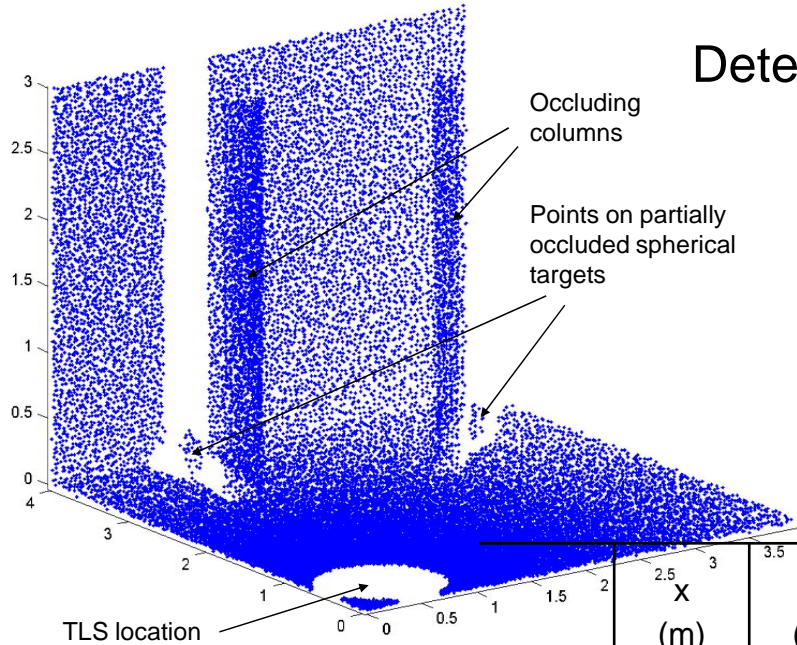


Simulation of laser point cloud with and without random noise



# IV. Simulations and performance assessment

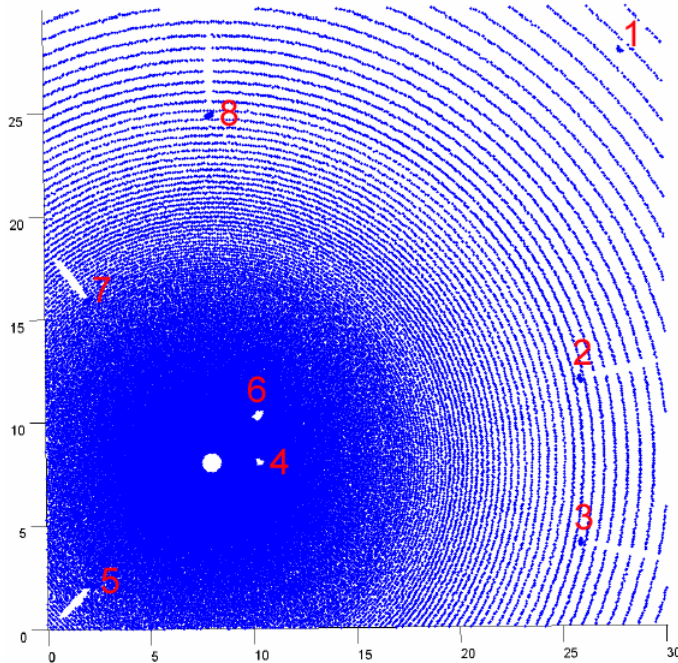
## Determination of the spherical target centers



- 4x4m
- 2 spheres
- Occlusion
- 2cm noise

	X (m)	y (m)	z (m)	Pos. Err (mm)	Extracted points			
					Sp. 1	Sp. 2	Other	Succ. Rate
Coarse Result	0.999	3.501	0.195	4.9	21	0	0	63.6%
	0.997	3.503	0.193	8.0	22	0	0	66.7%
	3.003	3.000	0.201	3.4	0	16	0	38.1%
	2.695	2.732	2.682		0	0	15	false
	1.345	0.050	-0.194		0	0	41	false
	0.031	0.034	0.198		0	0	33	false
	0.042	0.962	0.198		0	0	45	false
Final result	0.997	3.503	0.193	8.0	22	0	0	66.7%
	3.003	3.000	0.199	3.5	0	33	0	71.4%
True value	1.0	3.5	0.2		33			
	3.0	3.0	0.2			42		

# IV. Simulations and performance assessment



Determination of the spherical target centers

- 30x30m
- 8 spheres
- 2cm noise

Experiment Design

	x (m)	y (m)	z (m)	Distance to scanner (m)	Points
Scanner	8.0	8.0	2.0	--	--
Sphere 1	28.0	28.0	0.2	28.3	7
Sphere 2	26.0	12.0	0.2	18.5	38
Sphere 3	26.0	4.0	0.2	18.5	33
Sphere 4	10.0	8.0	0.2	2.7	2438
Sphere 5	2.0	2.0	0.2	8.7	179
Sphere 6	10.0	10.0	0.2	3.4	1365
Sphere 7	2.0	16.0	0.2	10.2	135
Sphere 8	8.0	25.0	0.2	17.1	44

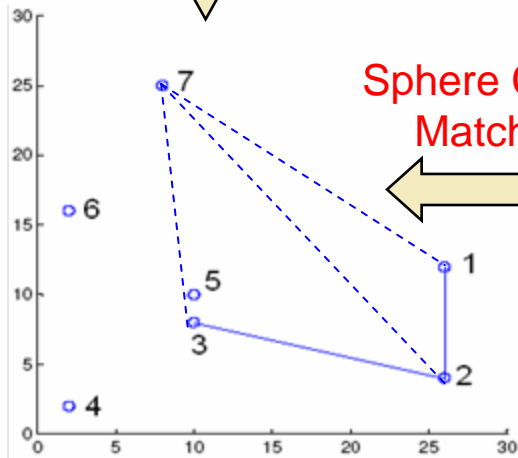
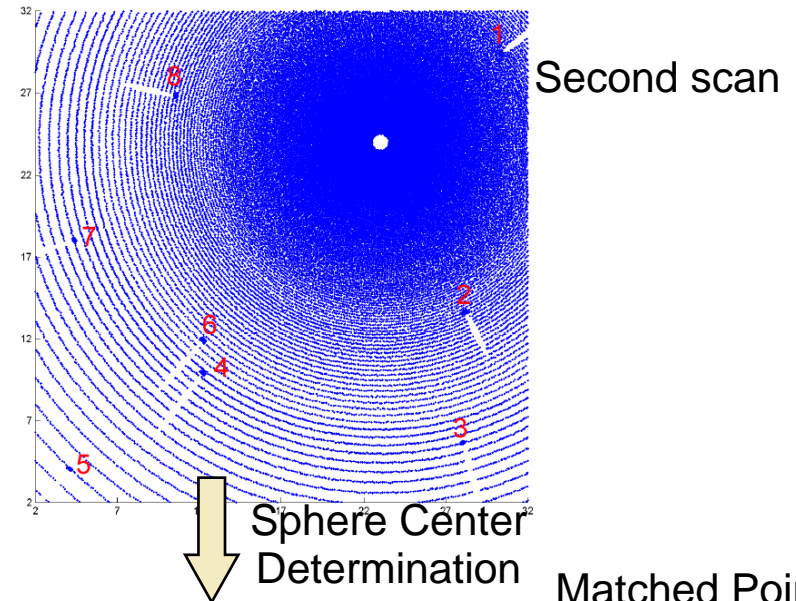
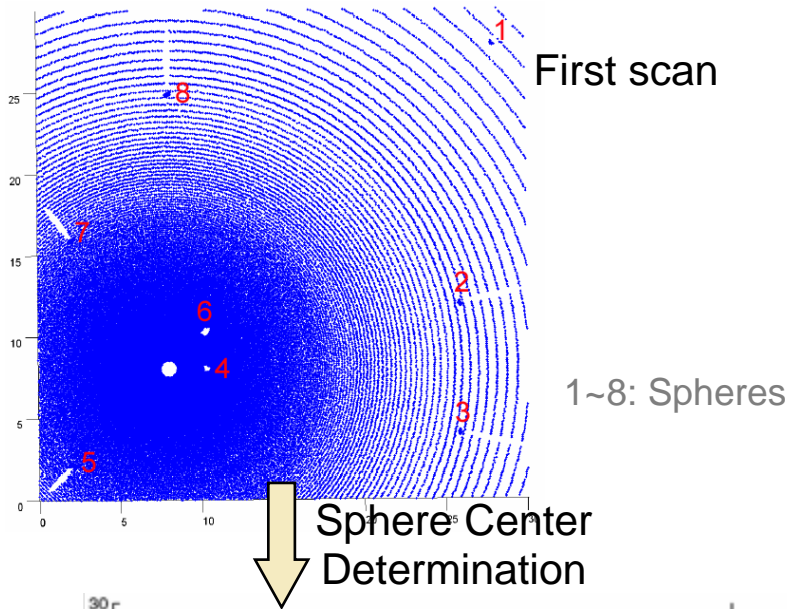
Sphere	x (m)	y (m)	z (m)	Pos. Err (mm)	Extracted points		
					Sphere	Other	Succ. Rate
2	26.002	11.991	0.200	8.9	30	0	79.0%
3	25.999	4.012	0.210	16.3	27	0	81.8%
4	9.975	8.002	0.204	25.5	719	0	29.5%
5	1.998	2.009	0.205	10.1	121	0	67.6%
6	10.004	9.978	0.199	21.8	644	0	47.2%
7	2.000	16.001	0.201	1.7	91	0	67.4%
8	7.981	24.993	0.191	21.9	28	0	63.6%

Extracted Spheres

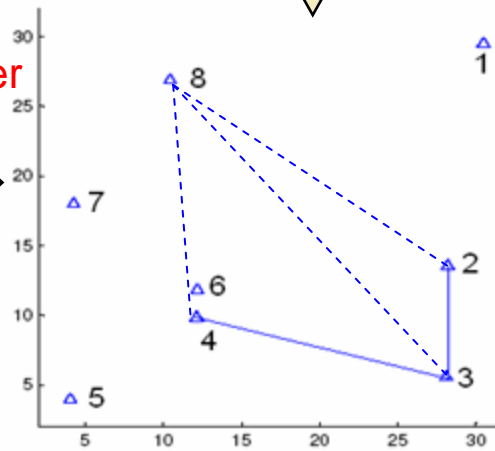
Sphere 1 was missing

# IV. Simulations and performance assessment

## Sphere Center Matching



Sphere Center Matching

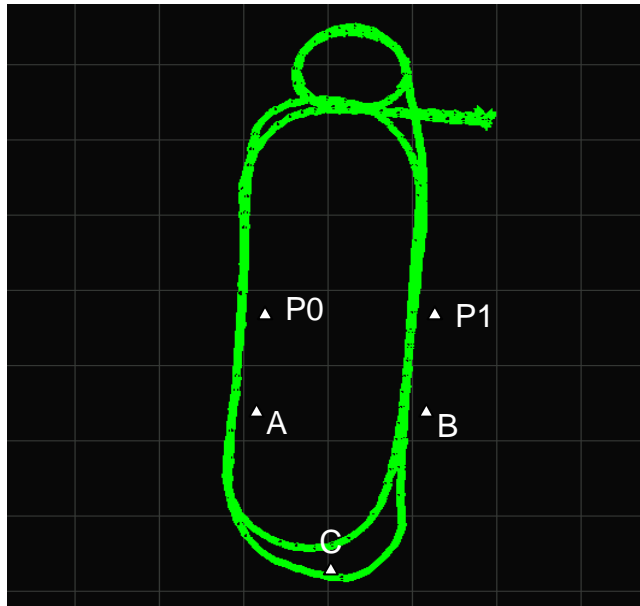


Matched Points

Point in left	Point in right
---	1
1	2
2	3
3	4
4	5
5	6
6	7
7	8

# IV. Simulations and performance assessment

## Simulation of integrated system navigation



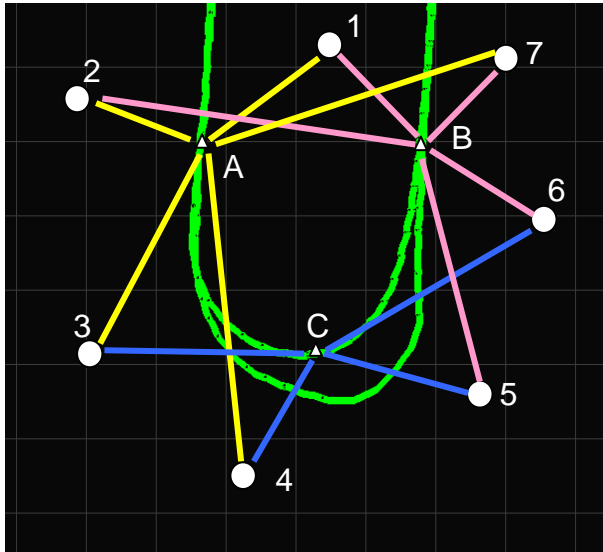
Specifications	IMU	BASE GPS	ROVER GPS
Sensor	HG1700	Trimble 5700	Topcon Dual frequency
Data rate	100Hz	1Hz	1Hz
Gyro drift	2deg/h, 0.125deg/h <sup>1/2</sup> , sf=10ppm		
Accerolometer bias	1mg, 0.2mg <sup>1/2</sup> , sf=120ppm		

Simulated GPS gaps of the points in the test

Point	Time [Second of the week]	GPS gap duration [s]	Accumulated Time [s]
P0	243930	0	0
A	243939	9	9
B	243974	35	44
C	244028	54	98
P1	244048	20	118

# IV. Simulations and test results

## Simulation of integrated system navigation



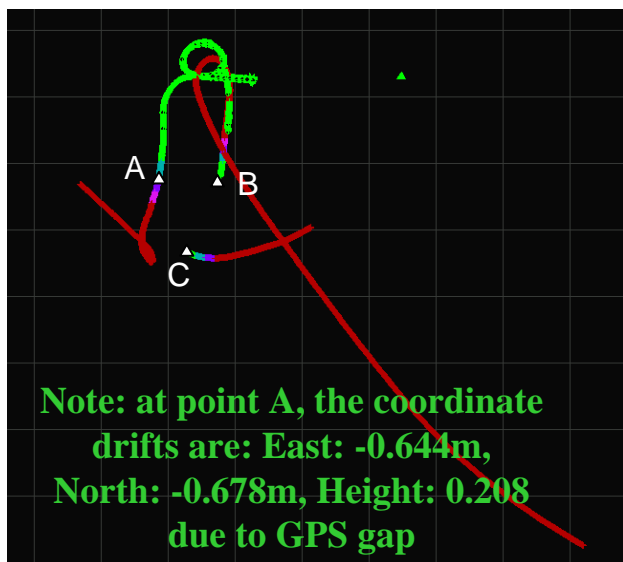
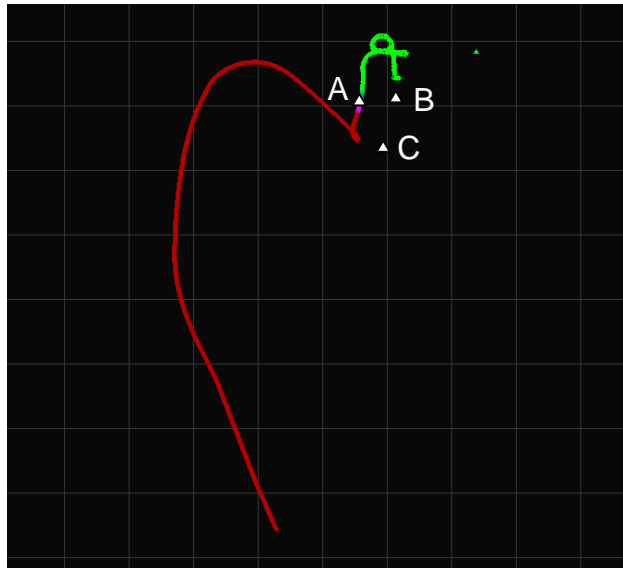
The TLS simulated data in the TLS scanning frame.

Site	Sphere	Distance (s)	Horizontal Angle (deg)	Vertical Angle (deg)	Notes
A	1	7.340	220	2	S
	2	6.210	105	4	S
	3	11.220	30	-2	S
	4	18.090	350	0	S
	7	21.850	235	-3	S
B	2	18.808	266.59187805	-6.20845546	C
	1	8.336	277.74569464	11.71056285	C
	7	10.112	40.87128774	37.36826204	C
	6	6.800	135	-2	S
	5	20.500	168	-1	S
C	3	14.207	202.06151728	-25.86502364	C
	4	7.802	223.89167109	-32.24995079	C
	5	11.502	22.64077644	34.33226501	C
	6	15.680	316.36843051	7.52941834	C

Note: S: simulated

C: Calculated based on the simulated result.

# IV. Simulations and test results



Note: at point A, the coordinate drifts are: East: -0.644m, North: -0.678m, Height: 0.208 due to GPS gap

Simulated navigation results Units: [m]

Site	Scen.	East	$\Delta E$	North	$\Delta N$	Height	$\Delta H$
A	1	9949.776		29440.229		208.845	
	2	9949.132	-0.644	29439.551	-0.678	209.053	0.208
	3	9949.132	-0.644	29439.551	-0.678	209.053	0.208
B	1	9962.902		29442.600		208.716	
	2	9943.350	-19.552	29420.931	-21.669	214.511	5.795
	3	9962.242	-0.660	29441.928	-0.672	208.920	0.204
C	1	9955.848		29426.748		208.629	
	2	9928.387	-27.461	29265.178	-161.57	233.514	24.885
	3	9955.205	-0.643	29426.078	-0.670	208.854	0.225

Units: [°]

Site	Scen.	Pitch	$\Delta P$	Roll	$\Delta R$	Yaw	$\Delta Y$
A	1	-12.97501		6.90475		176.136	
	2	-13.07485	-0.099	6.97790	0.073	176.842	0.706
	3	-13.07485	-0.099	6.97790	0.073	176.842	0.706
B	1	-13.69120		6.01653		356.437	
	2	-13.60511	0.086	5.95168	-0.064	357.555	1.118
	3	-13.80067	-0.109	6.08753	0.071	357.139	0.702
C	1	-12.57203		5.32256		268.697	
	2	-12.96881	-0.396	6.12517	0.802	275.839	7.142
	3	-12.67154	-0.100	5.39570	0.073	269.406	0.709

- Scenario 1: GPS/INS integration  
 2 : INS only  
 3 : INS/TLS integration

## V. Conclusions

- Concept design of quadruple integration of GPS/INS/PL and TLS was presented
- The preliminary results of the estimation of the spherical target center from TLS point cloud indicate cm-level accuracy with data noise up to 2 cm (relatively high for TLS)
  - In the simulation test, position differences are less than 2 cm and the attitude differences are less than  $0.01^\circ$  between INS/TLS and GPS/INS solution
- The sphere extraction algorithm takes 3~4 minutes for a data set of 80000 points, and the sphere center matching takes less than ten seconds
- More test under different scenarios are underway
- Actual field data sets will be tested next



# Acknowledgement

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Research contributions of Drs. Charles Toth and Hongxing Sun, and a graduate student, Xiankun Wang, are greatly appreciated

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