

MEMS Sensors – State of the Art and Future Trends in Mapping and Navigation Applications

Dr. Naser El-Sheimy
Professor and Canada Research Chair
University of Calgary, Canada
Scientific Director – Tecterra

- Progress of Geo-referencing
- Mobile Mapping Systems (MMS)
- The Potential of MEMS Sensors
- Sensors and Integration Problems
- Achievable Accuracies for Land MMS
- Future of Pedestrian and Portable MMS
- Potential for Airborne MMS
- Summary

Indirect Georeferencing

Ground Control Points (GCPs) were the only required source of information for providing the georeferencing parameters and suppressing undesirable errors through AT.

GPS-AT

- The start of direct determination of exterior orientation parameters in aerial photogrammetry
- The first investigations to use GPS for the determination of the projection centers in AT

Direct Georeferencing

- The first implementation of the DG concept for Land Mobile Mapping at the UofC and OSU in early 1990s.
- The first sale of a DG product for commercial airborne mapping applications in 1996 by ApplAnix Corp, Canada.

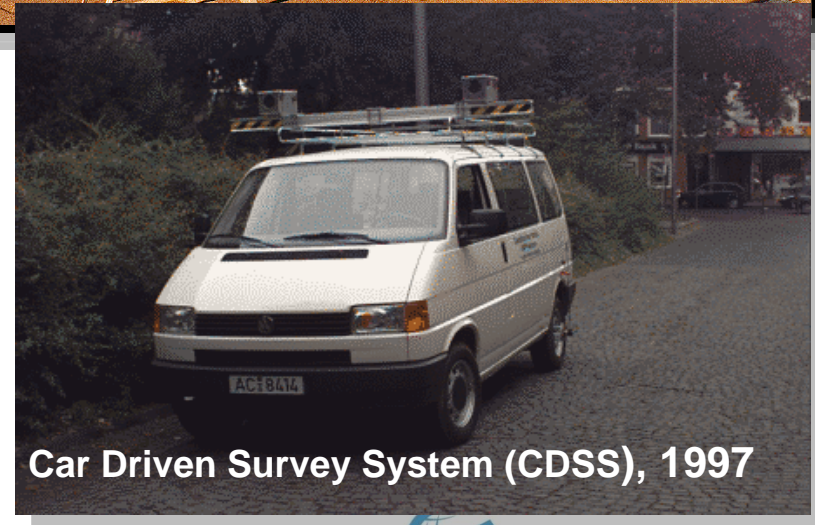
1960-1970

1980 - 1990

1990 - date

MMS – Early Systems

Position Yourself Ahead of the Crowd



- Mostly Stereo-based systems
- B/W low resolution analog cameras
- GPS and dead-reckoning is the standard (VISAT – GPS/INS)
- Accuracy: 0.3 – few meters
- Limited production and image interval
- Limited operational speed of the vehicle

VISAT Van

Position Yourself Ahead of the Crowd



Digital Cameras



- 6 to 12 cameras
2048 x 2048
- Integrated GPS,
Inertial Navigation
System and
Distance Measuring
Instrument
- Image capture at 1 to 10m
interval with no speed limitation
- Autonomy of 500 miles/day
- High accuracy (10-20 cm absolute) in all survey
conditions

Position Yourself Ahead of the Crowd



Trends in Street Level MMS

Position Yourself Ahead of the Crowd

The screenshot displays the VISAT Station 4.01.120 software interface. The main window is divided into several panels:

- Mosaic View:** Shows an aerial view of a road intersection with green arrows indicating camera positions and elevation data (e.g., 1,442, 1,441, 1,440, 1,439, 1,438, 1,437).
- Image View:** Shows a street-level view of a road with a crosswalk. A yellow crosshair is positioned on the road surface. Metadata for the image includes: Survey: MOW gewestwegen pilot Kuurne, Image Index: Set 47, Camera 1, Creation Date: Wednesday, July 01, 2009 @ 3:45:52 PM, Street Address: Flemish Region, Belgium.
- Measurement Editor:** Shows details for a new GIS Object - 1628 (New) of type Point. It also shows details for a new GIS Point - C8F8 (New) with coordinates (Easting: 519,124.035, Northing: 5,636,092.10, Height: 62.674 m, Longitude: e003°16'18.5, Latitude: n050°52'34.2, Sld Dev: 0.015 m, Parallax: 0.0000).
- Thumbnail Strip:** Shows a row of six thumbnails for different camera sets (Set 47, Camera 5 to Camera 8).
- Bottom Panel:** Shows the current survey name (MOW gewestwegen pilot Kuurne) and GIS server status (Disconnected).

Trends - MMS Data Inside ESRI Arcmap

Position Yourself Ahead of the Crowd

The screenshot displays the ESRI ArcMap software interface. The main map area shows a cadastral map with various colored polygons representing land parcels. Overlaid on this map is a network of green lines with arrows, representing MMS (Magnetic Measurement System) data. Numerous small, multi-colored dots are scattered across the map, likely representing individual measurement points. The interface includes a standard menu bar (File, Edit, View, etc.), a toolbar with various GIS tools, and a 'Table Of Contents' panel on the left. The 'Layers' panel lists several data layers, including 'TOP_S_AANDUIDING', 'TOP_S_AFSLUITER', 'TOP_S_AFVALBAK', 'TOP_S_BOOM', 'TOP_S_BRANDKRAA', 'TOP_S_BRIEVENBUS', 'TOP_S_DRAINAGEPL', 'TOP_S_DWA_RIOOL', 'TOP_S_GASKAST', 'TOP_S_HECTOMETE', 'TOP_S_KABELKAST', 'TOP_S_KATODISCHI', 'TOP_S_LICHTMAST', 'TOP_S_LOZINGSPUT', and 'TOP_S_MONIUMFNT'. A 'VISAT Station' window is open on the right, showing a 3D perspective view of the same area. This window includes a 'Connect...' button, 'Surveys' and 'Bookmarks' menus, and a scale indicator set to 0. Below the main 3D view is a 'Thumbnail Strip' containing five camera views labeled 'Set 0, Camera 7', 'Set 0, Camera 4', 'Set 0, Camera 1', 'Set 0, Camera 3', and 'Set 0, Camera 6'. The status bar at the bottom indicates the current location as 'Almere pilot deel 2' and the map projection as 'Map: WGS_1984_UTM_Zone_31N (32631)'. The 'VISAT Station' and 'Feature Class Settings' toolbars are also visible.

- Example of typical cost
 - Navigation-grade INS
 - Dual-frequency GPS
 - Van
 - Computer, 6 cameras, etc.

- **\$100,000** (20-30% of budget)
- \$20,000
- \$30,000
- \$\$\$

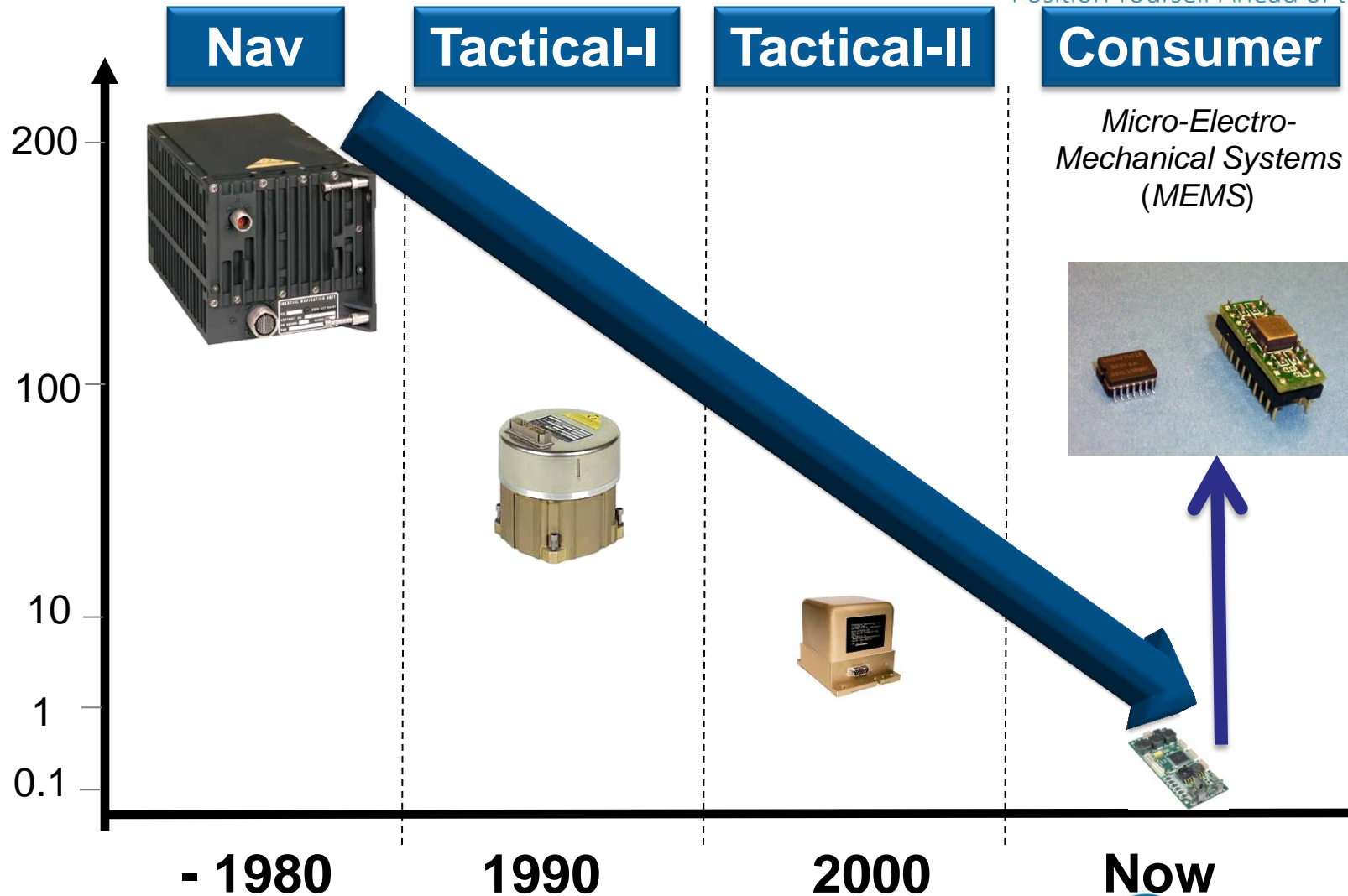
> \$300,000

⌘ Widespread adoption of current systems has been limited by their high cost



Roadmap of Inertial Technology

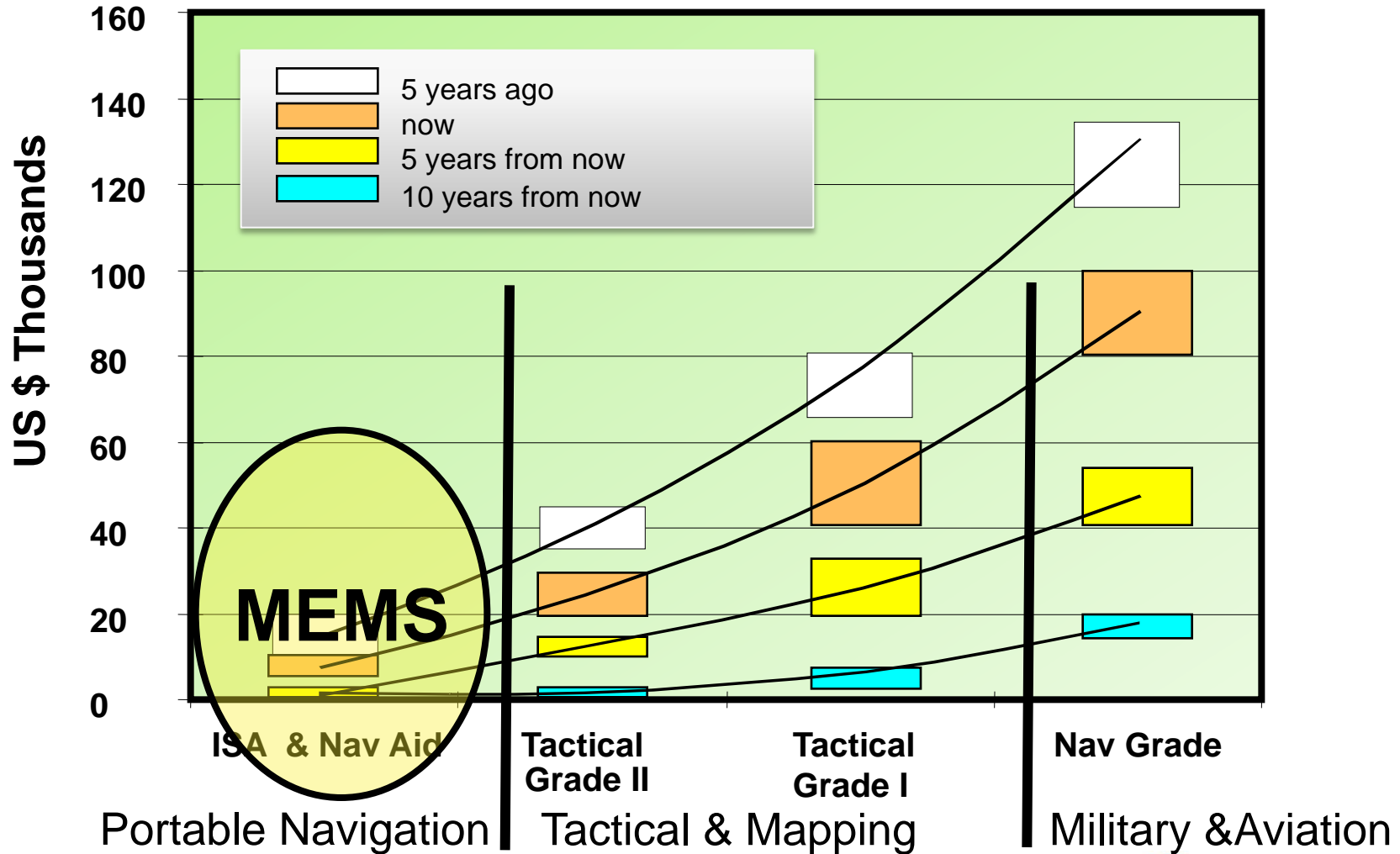
Size/Performance/Price



Position Yourself Ahead of the Crowd

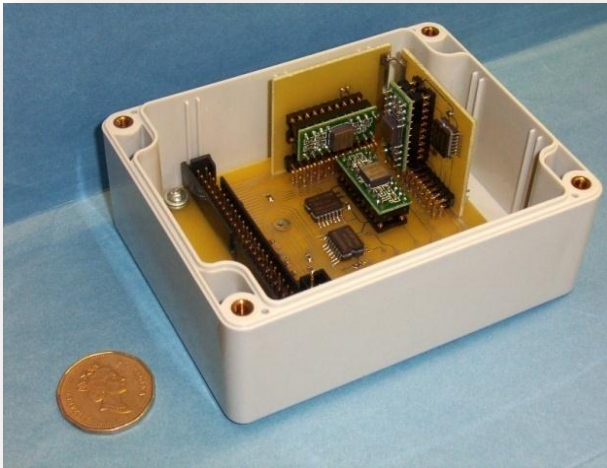
INS – Price Roadmap

Position Yourself Ahead of the Crowd



MEMS IMU - An Example

Position Yourself Ahead of the Crowd



UofC IMU - Developed by employing off-the-shelf MEMS sensors with an average sensor cost 60\$

	ADI Gyro (ADXRS150EB)	ADI Accel. (ADXL105A)
Range	$\pm 150 \text{ deg/s}$	$\pm 5 \text{ g}$
Cross-axis Sensitivity	$\pm 1 \text{ deg}$	$\pm 1 \text{ deg}$
Bias error	$\pm 24 \text{ deg/s}$	$\pm 2500 \text{ mg}$
Bias instability (100 sec) *	0.01 deg/s	0.2 mg
Scale factor error	$\pm 10\%$	$\pm 10\%$
Price**	USD 100	USD 25

Advantages

- Low cost
- Small size
- Low power

Disadvantages

- Large bias and SF error
- Thermal drift

MEMS IMU – Lab Calibration

Position Yourself Ahead of the Crowd

- Bias
- Scale factor
- Cross-axis

Error Model for Calibration (Gyros)

$$\begin{bmatrix} U_x \\ U_y \\ U_z \end{bmatrix} = \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix} \cdot \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} + \begin{bmatrix} U_{0x} \\ U_{0y} \\ U_{0z} \end{bmatrix}$$



Effects of calibration

	Before	After
Bias	< 25 deg/s < 2500 mg	< 0.5 deg/s < 6 mg
Scale Factor	< 10 %	< 0.1 %
Cross-axis	< 1.0 deg	< 0.2 deg

Possible Ways to Improve the Positional Accuracy?

- Use of additional velocity aiding in body frame
 - Zero Velocity Update (ZUPT) when possible
 - Non-holonomic constraints
 - Odometer
- Integration Filter Level - Advanced Algorithm
 - Unscented Kalman filter (UKF)
 - Integration of EKF/UKF and Artificial Neural Network (ANN)
- Sensor Level (multi-sensors, barometers, mags)
- Backward Smoothing

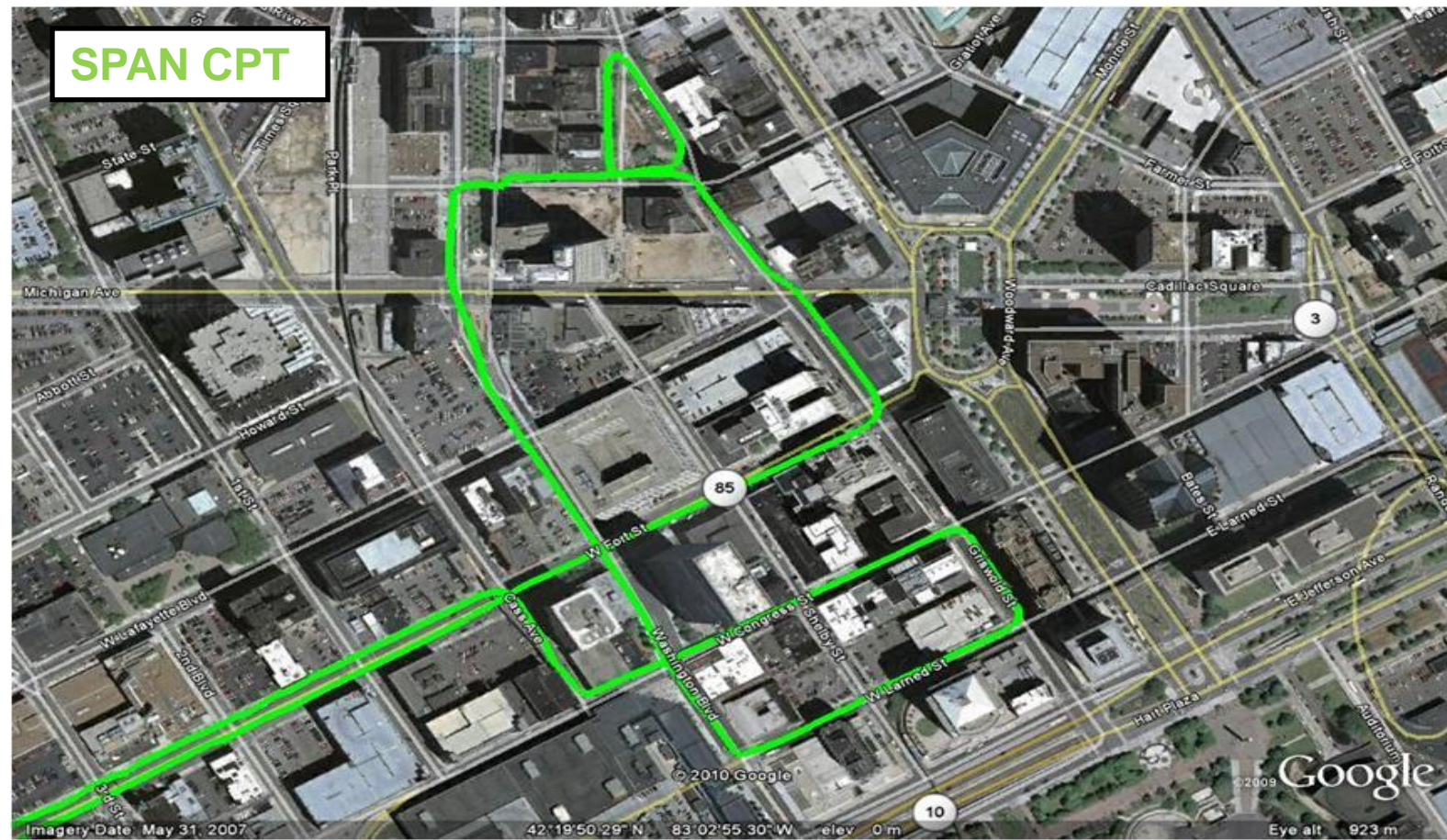
Real-time 3D vehicle navigation in downtown Detroit

GPS signal outages/degradations
Tethered sensors to the vehicle frame

Navigating Detroit

Position Yourself Ahead of the Crowd

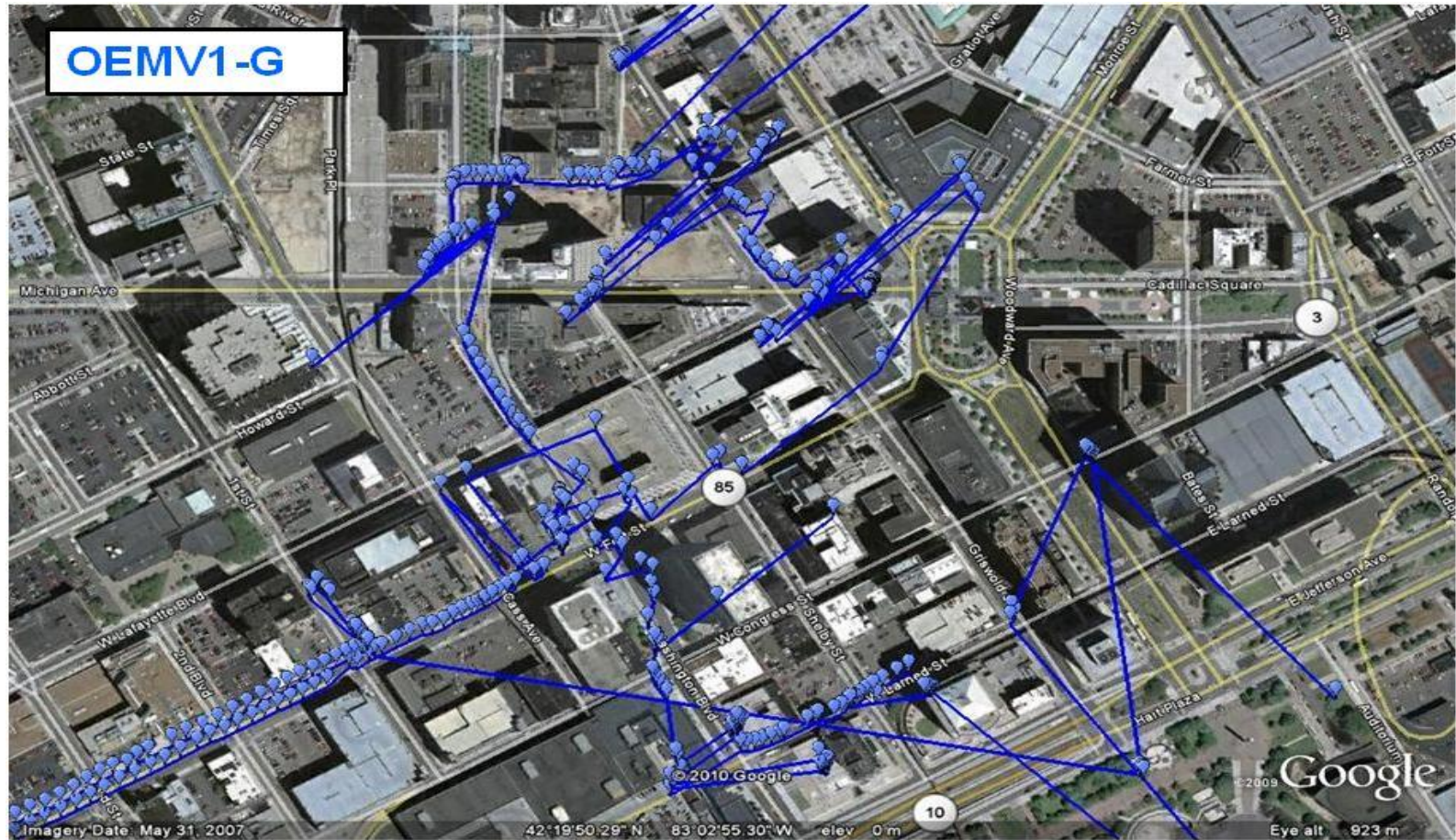
TPP: 1 gyro + 3 accels (~\$60), OBDII and OEMV-1G
Reference: Control points set by vehicle OEM



OEMV1-G performance

Position Yourself Ahead of the Crowd

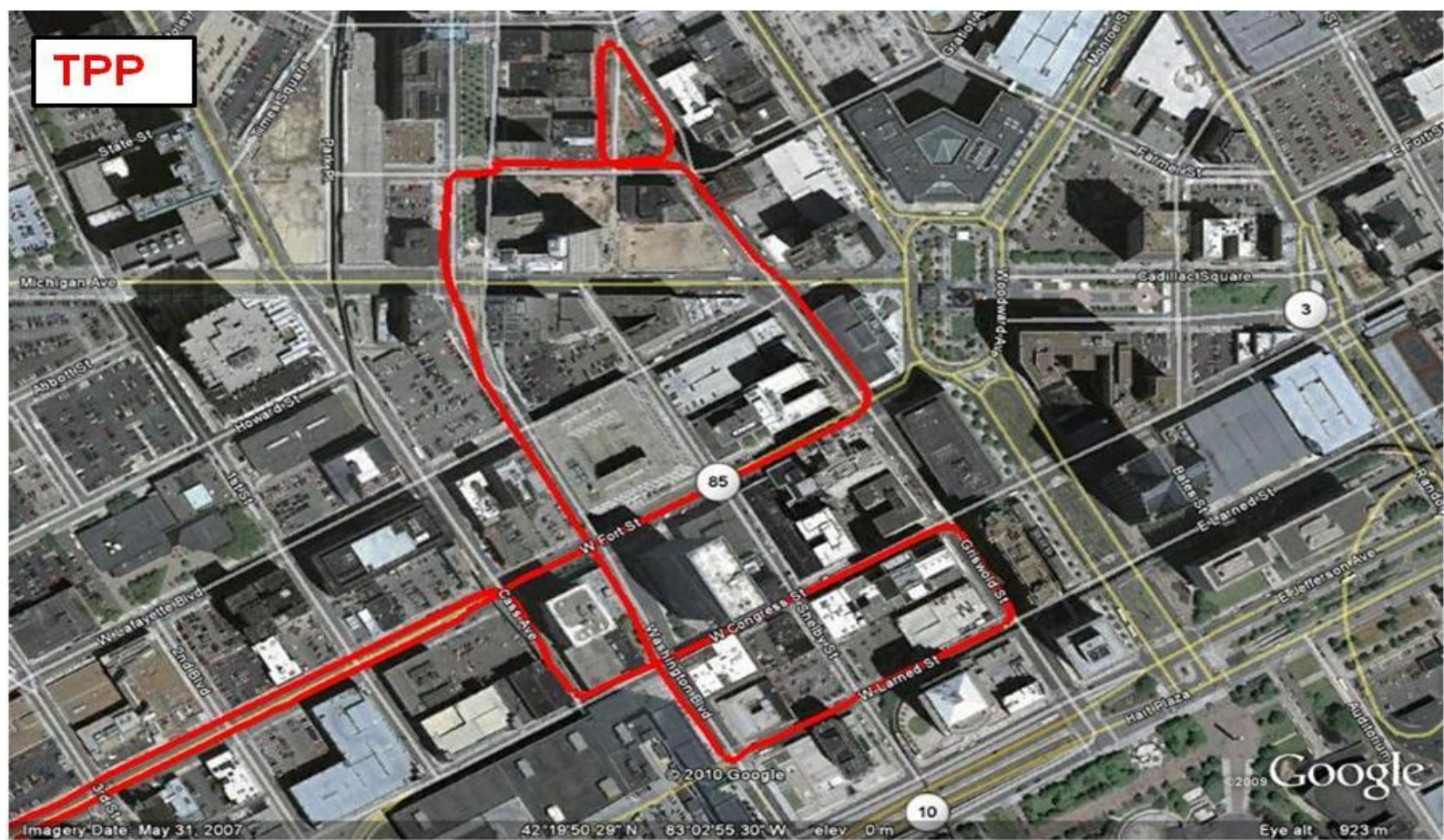
NovAtel OEMV1-G > 400 metre errors, avg ~ 20 metres



TPP performance

Position Yourself Ahead of the Crowd

TPP real-time 3D < 5.9 metres 95% using \$60 1G3A + OEMV1-G + odometer



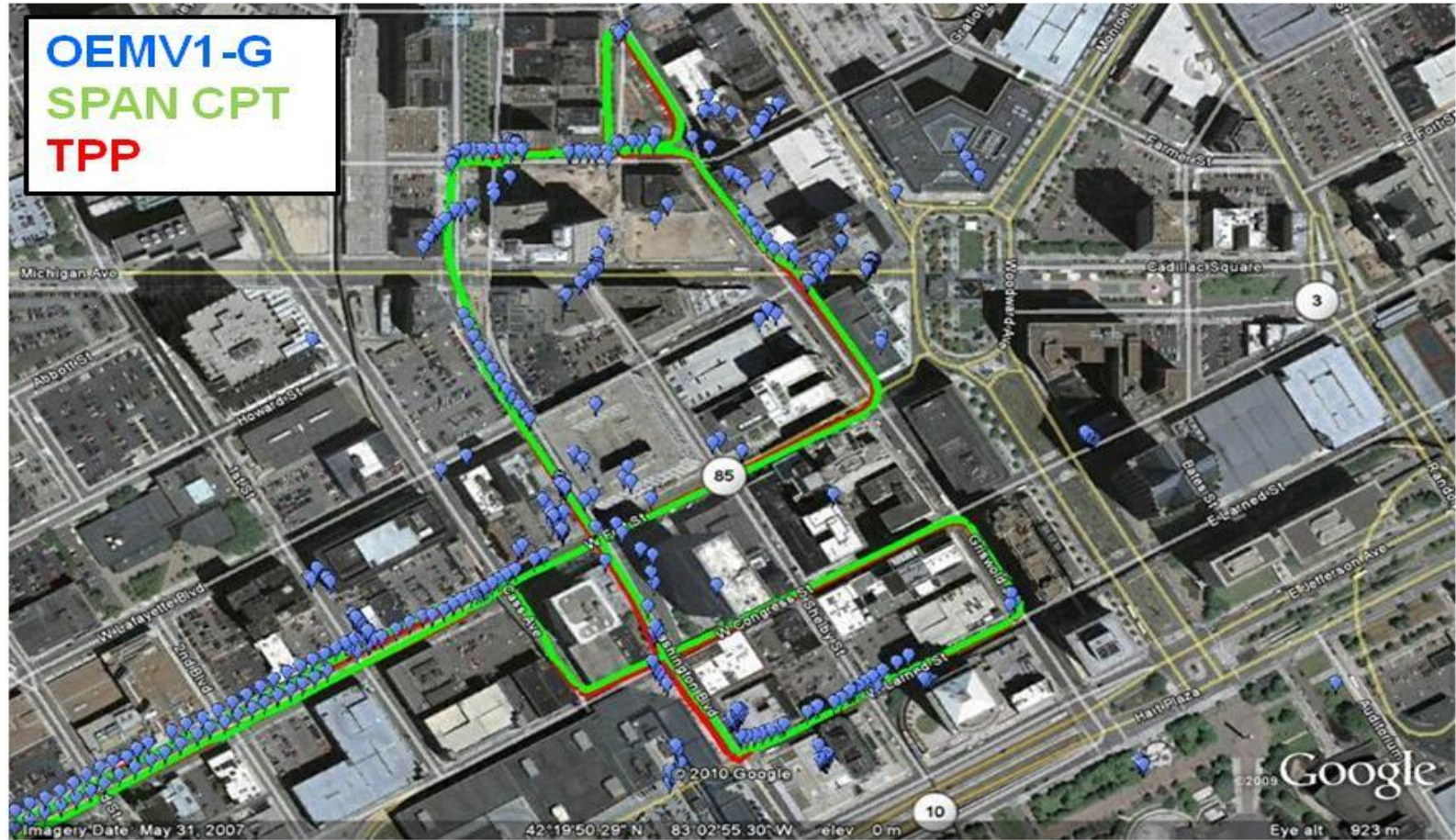
\$60 TPP vs \$40k reference

Position Yourself Ahead of the Crowd

OEMV1-G > 400 metres

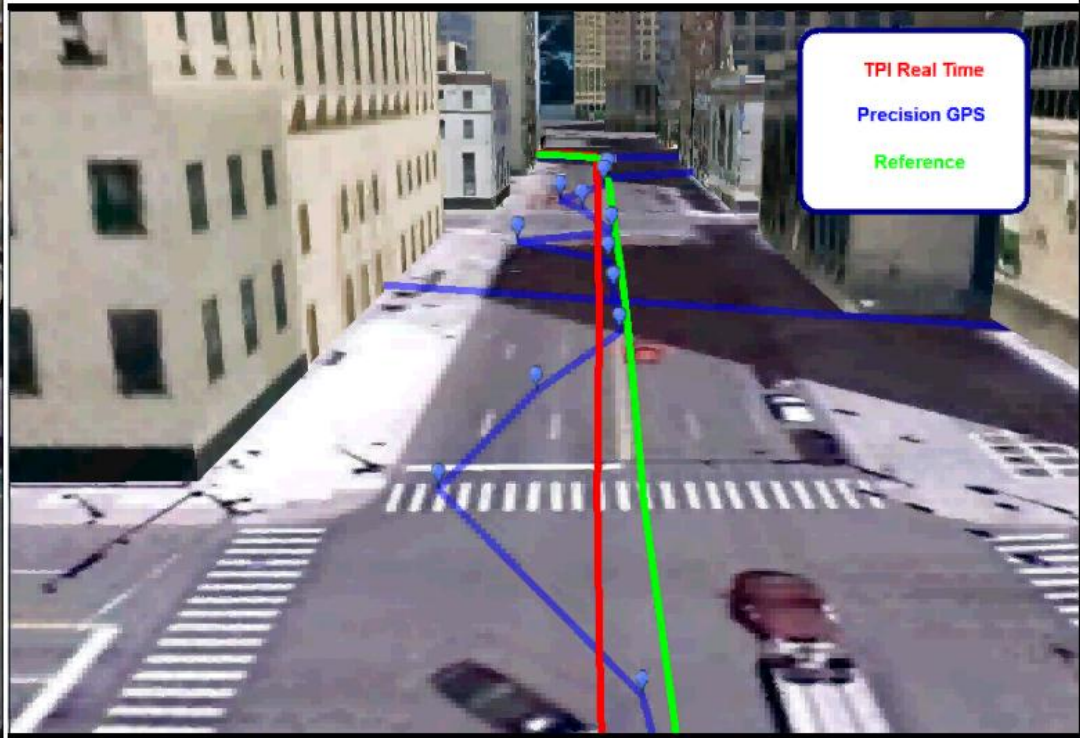
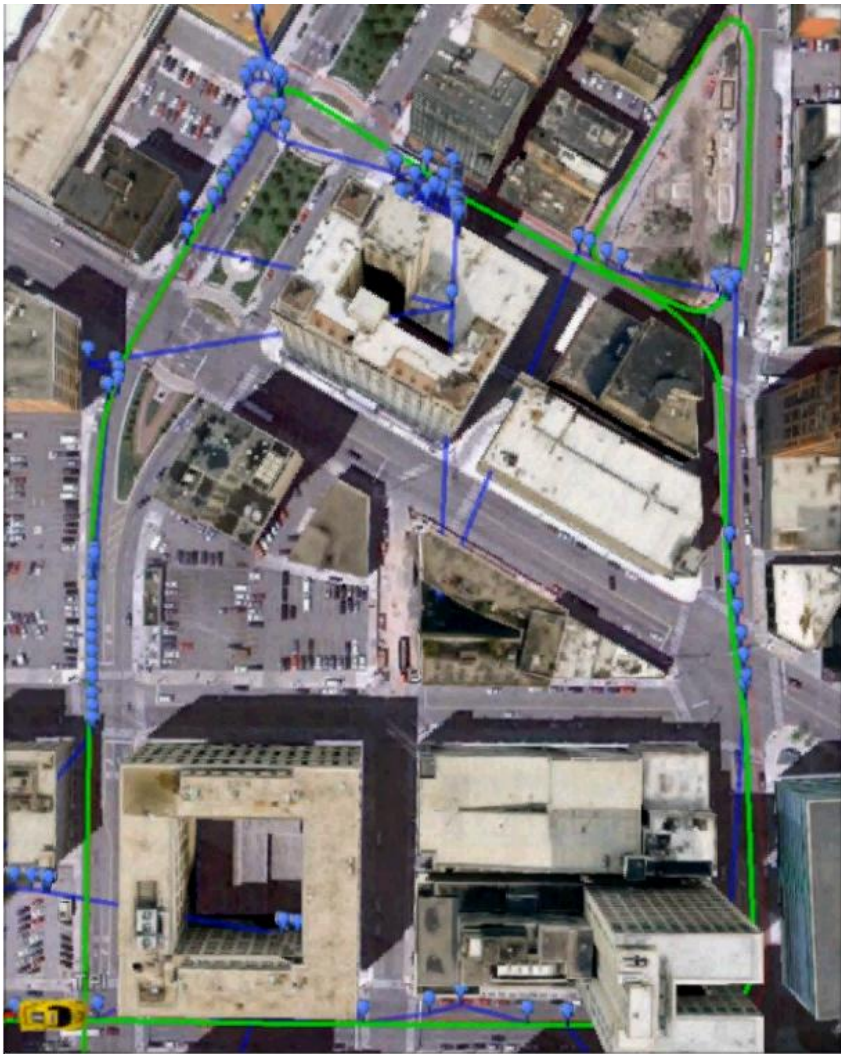
Reference post-processed < 2.1 metres 95% (~\$40k)

TPP real-time 3D < 5.9 metres 95% using \$60 1G3A + OEMV1-G + odometer





Trusted Positioning



Real-time vehicle solution

Position Yourself Ahead of the Crowd

GNSS Outage Duration (seconds)	Avg. Distance Travelled (metres)	Horizontal Position Error RMS (metres)	Vertical Position Error RMS (metres)*
10s	131	1.70	0.57
30s	330	4.61	1.00
60s (1 min.)	814	9.63	1.66
120s (2 mins.)	1817	17.74	2.65
300s (5 mins.)	4015	41.12	5.26
600s (10 mins.)	8245	105.24	9.07

Navigation Hardware (\$70)

- u-blox LEA-6H (\$25)
- ADXRS450 (\$30)
- ADXL312 (\$10)
- OBDII chip(\$5)

**The addition of a low-cost barometer bounds the vertical error to < 1 m*

Performance of Low Cost Land MMS

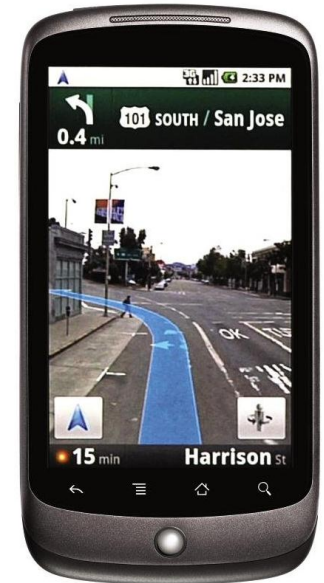
Position Yourself Ahead of the Crowd

	Forward filtering	Backward Smoothing	Smoothing with non-holonomic constraints + Odometer
Position accuracy (RMS) with stable GPS update	1 m	0.5 m	0.1 m
Maximum position drift during GPS gaps	150 m	2.0 m	1.5 m
Attitude error in general (RMS)	1.5 deg	0.6 deg	0.35 deg
Maximum attitude drift with absence of kinematics	6.5 deg	1.6 deg	1.6 deg

Imagine

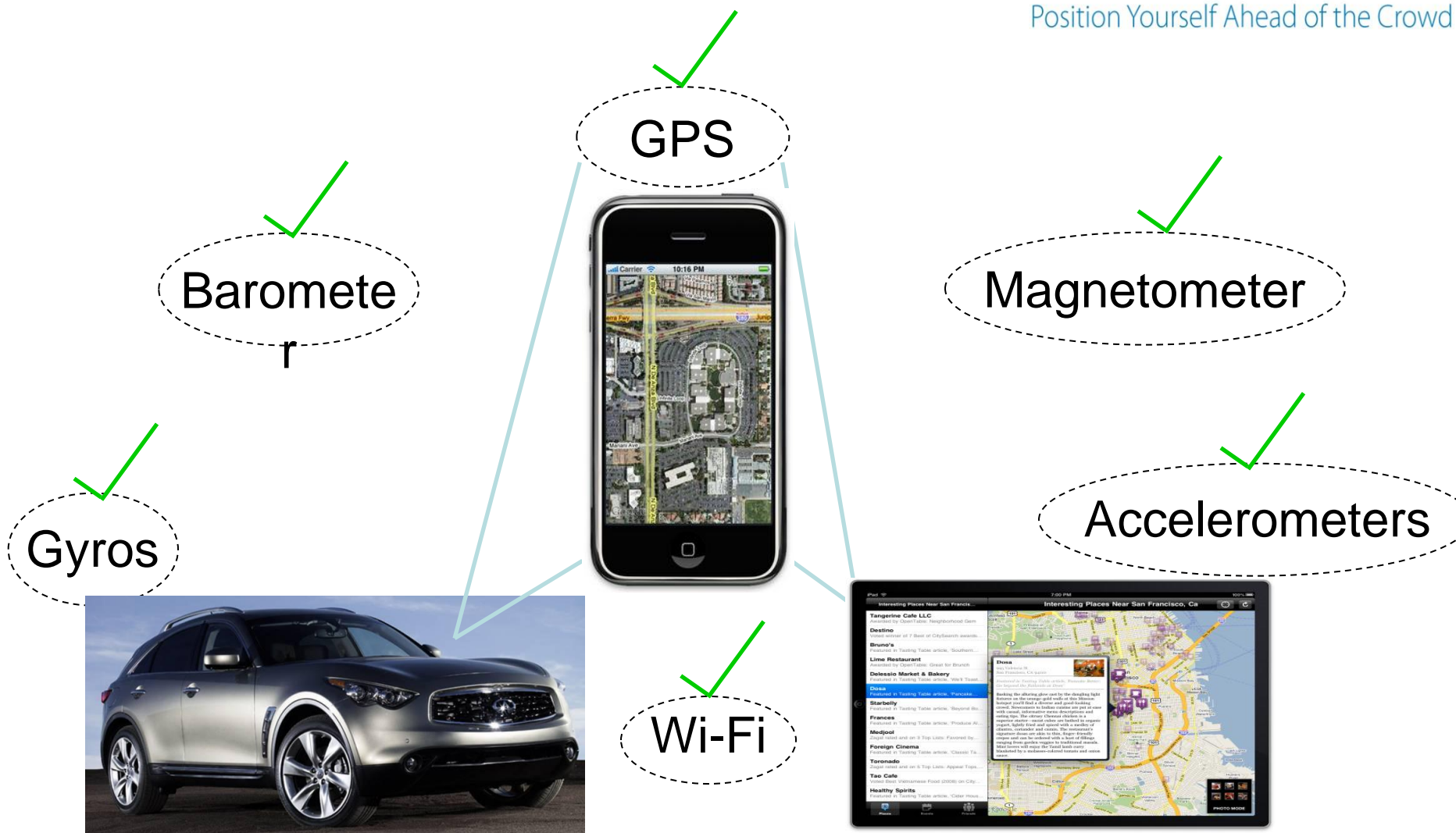
Position Yourself Ahead of the Crowd

- A next generation portable device (e.g. cell phone) that can
 - Provide seamless indoor-outdoor-urban navigation
 - Use pre-existing sensors and wireless technologies in portable electronic devices
 - Provide both device and user orientations
 - Operate autonomously across consumer platforms, including walking and driving
 - Operate as your handheld Mobile Mappers
- This will enable and expand markets such as
 - Indoor MMS
 - Indoor LBS and advertising
 - Social networking
 - User awareness and security
- **Is this possible? Now?**



Harnessing the Power of Sensor

Position Yourself Ahead of the Crowd



GPS

Baromete

Magnetometer

Gyros

Accelerometers

Wi-Fi





MEMS in Action

Pedestrian Positioning Indoors

Severe GPS multipath & signal outages with 3D movement of person

T-PN video

Position Yourself Ahead of the Crowd

- Using low cost MEMS sensors and GPS
 - ITG-3200 gyroscopes (\$2)
 - BMA150 accelerometers (\$2)
 - BMP085 barometer (\$1)
 - U-blox LEA-6H (\$20)
- [Click here to start video](#)



MEMS on Android OS

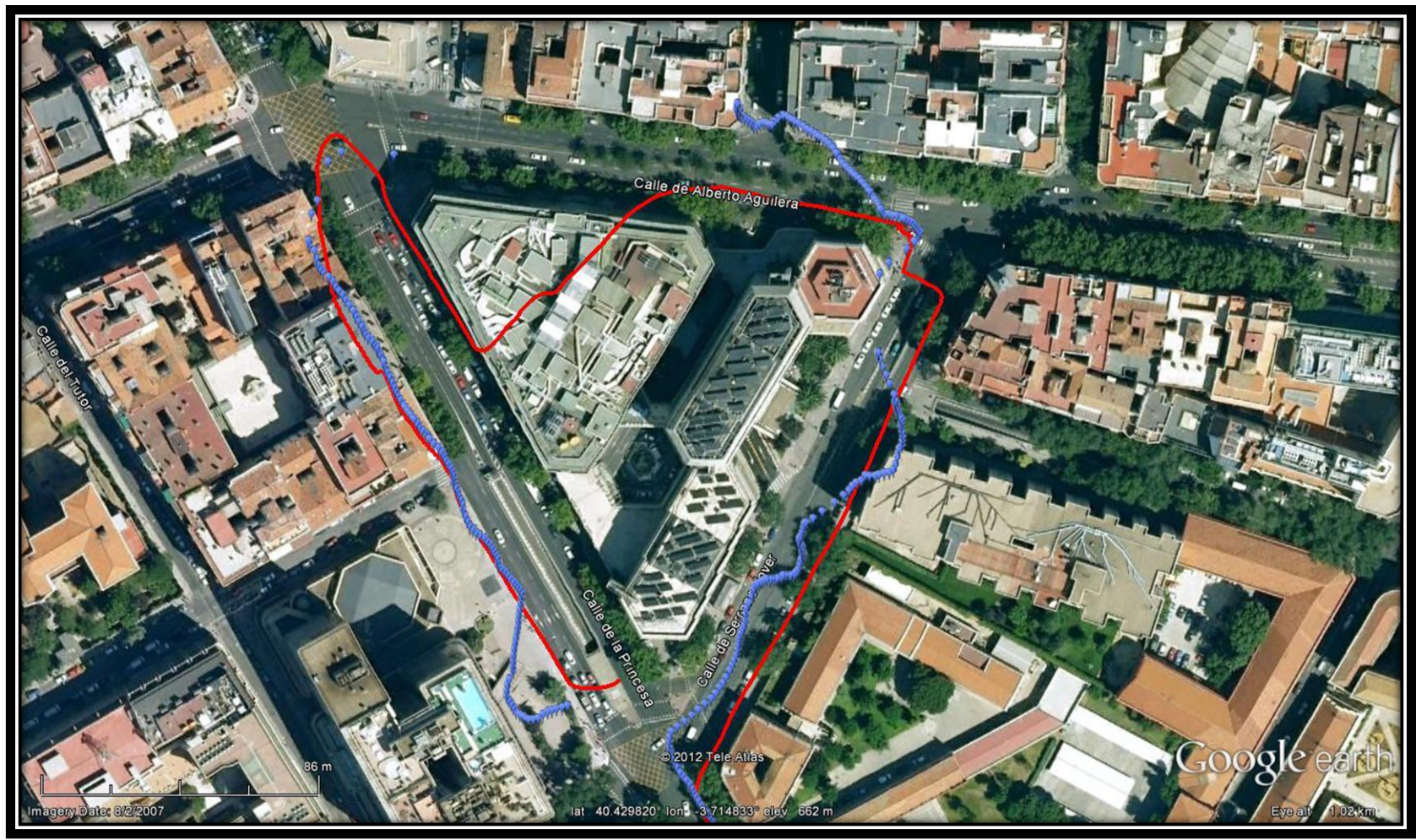
- Samsung Galaxy Nexus
 - MPU-3050 gyroscopes (\$2)
 - BMA180 accelerometers (\$2)
 - BMP085 barometer (\$1)
 - SiRF Star IV GPS (\$4)
- Processor
 - 1.2 GHz ARM
 - Android OS
 - 20-100 Hz navigation solution



T-PN results in Madrid

Position Yourself Ahead of the Crowd

- Bridges GPS positioning gaps indoors



Mobile + Vehicle navigation

Mobile unit left on the seat of the vehicle with communication to vehicle to obtain speed

Mobile unit on seat

Position Yourself Ahead of the Crowd

- MEMS 3D solution
- Vehicle to mobile communication
 - Wired or wireless
- Un-tethered: left on the seat to jitter and rotate



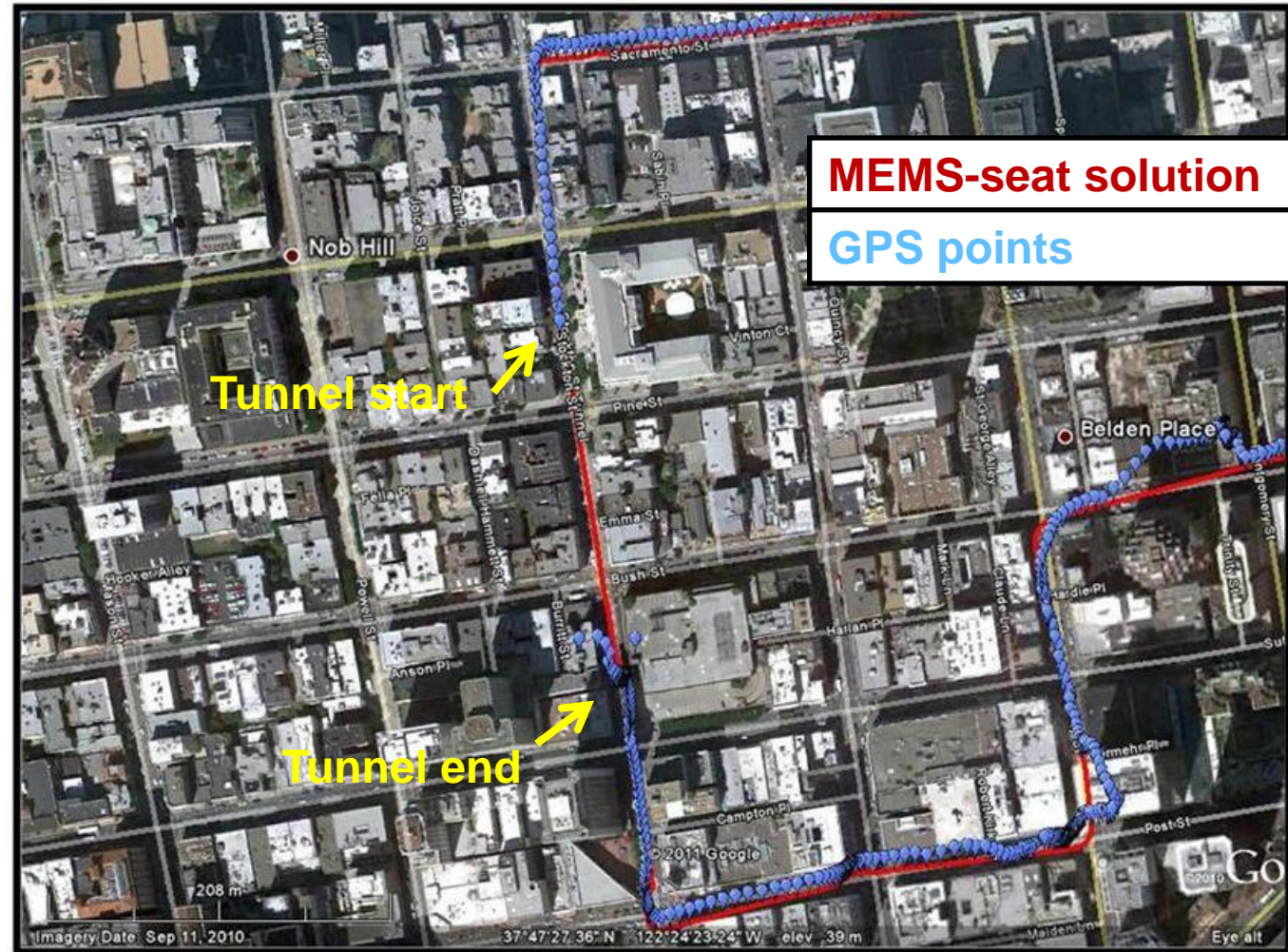
Driving downtown SF



Tunnel # 2 in downtown SF

Position Yourself Ahead of the Crowd

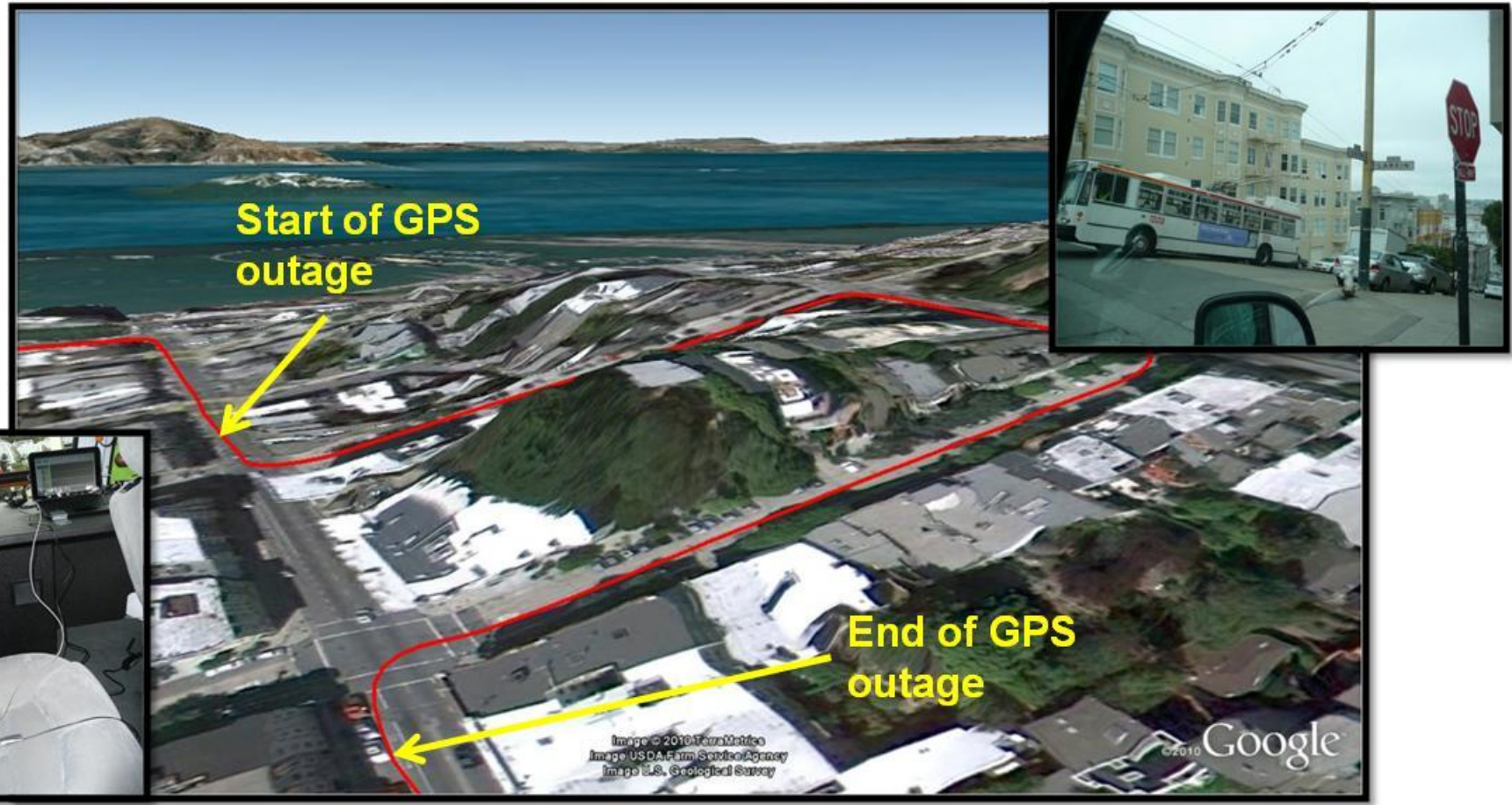
- TPP bridges the tunnel gap and smoothes the noisy GPS



3D sensor-only positioning

Position Yourself Ahead of the Crowd

- GPS data was artificially removed for 3 minutes (entire hill)
- MEMS horizontal accuracy within 2 metres
- Addition of barometer kept the vertical accuracy within 1 metre



Positioning inside buildings

Position Yourself Ahead of the Crowd

- GPS was largely unavailable & inaccurate
- All turns and shape of trajectory are apparent with the sensor solution

TPP solution



TPP solution

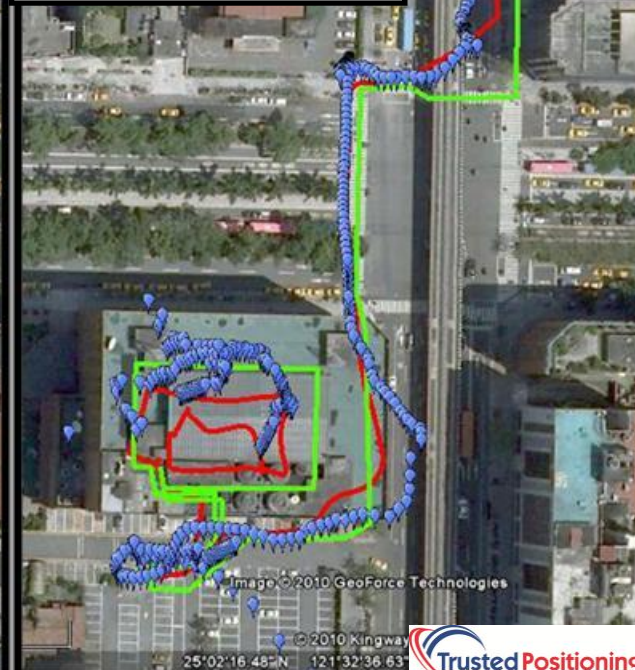
Reference path



TPP solution

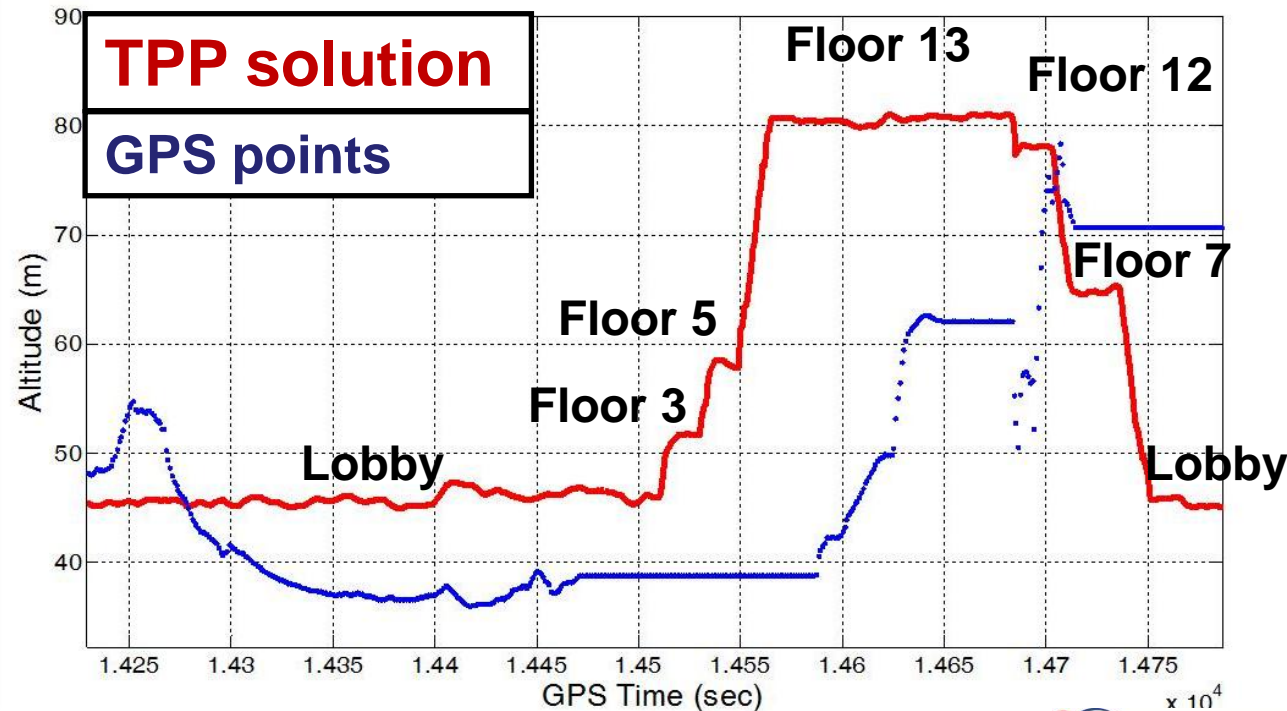
Reference path

GPS points



Height Estimation Performance

- Height aided by very low-cost barometer
- Stops at 3, 5 and exit at 13 on way up
- 13, 12, 7 and exit at 1 on way down



The Future Towards Low Cost Mapping Systems

Position Yourself Ahead of the Crowd



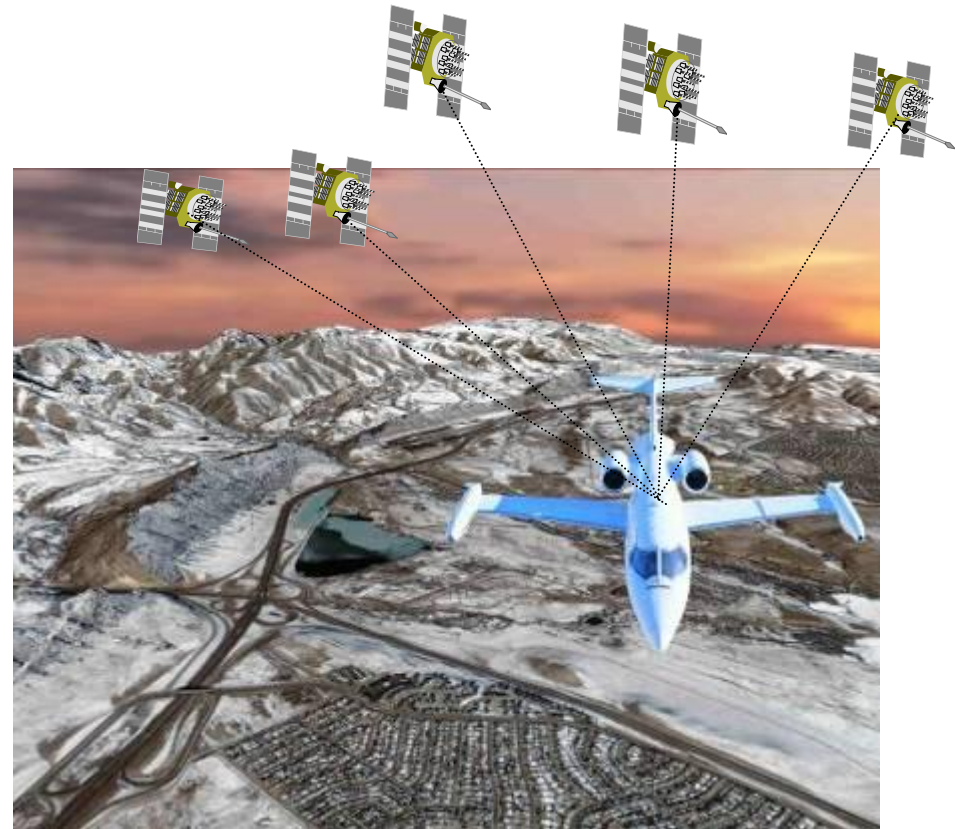
GPS (no Base Station)



Attitude Sensors



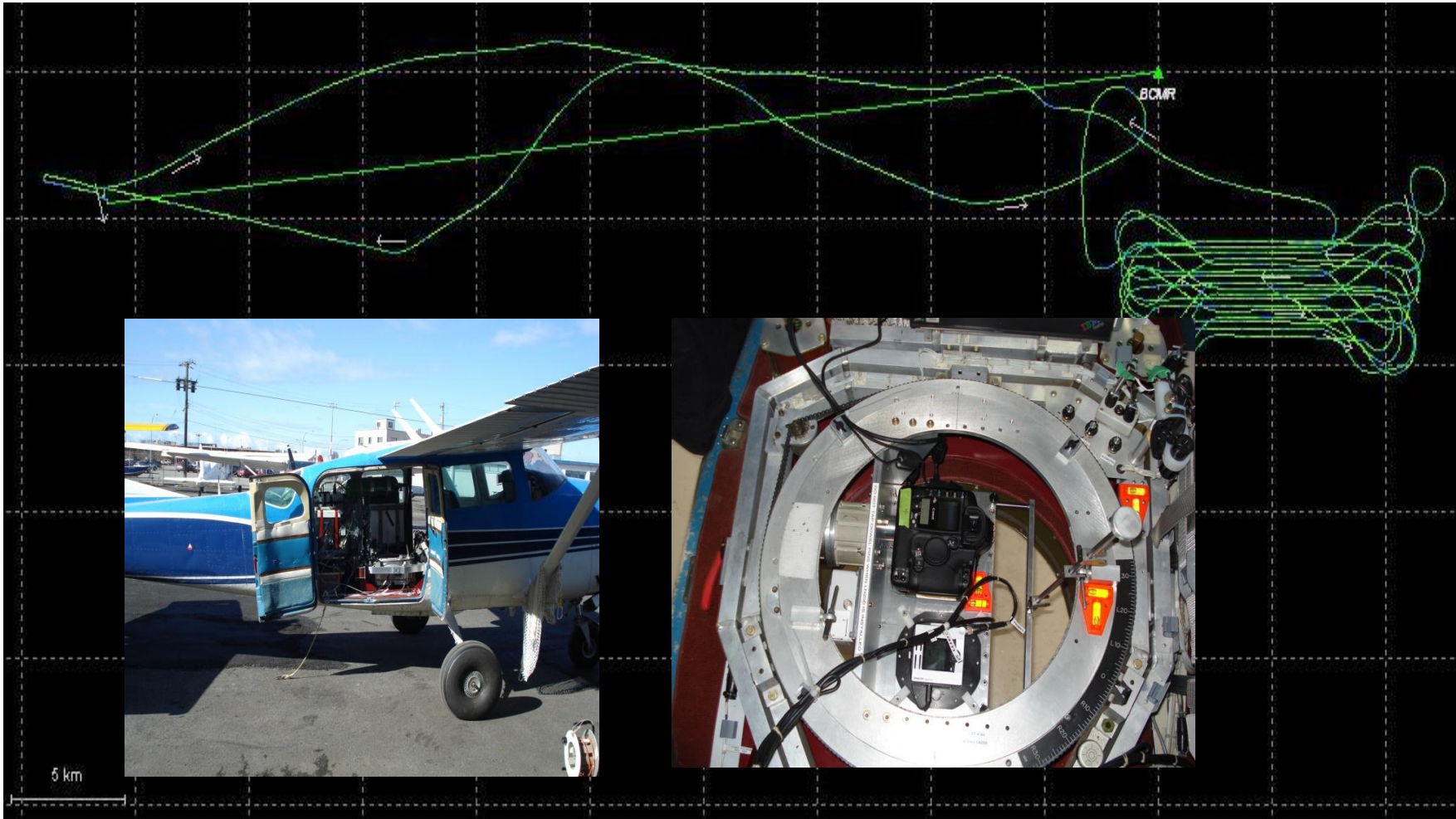
Digital Camera



- Real-time mapping/monitoring of remote areas
- Minimal cost through the utilization of low cost components
- No need for ground work → Lower cost

Low Cost Airborne MMS

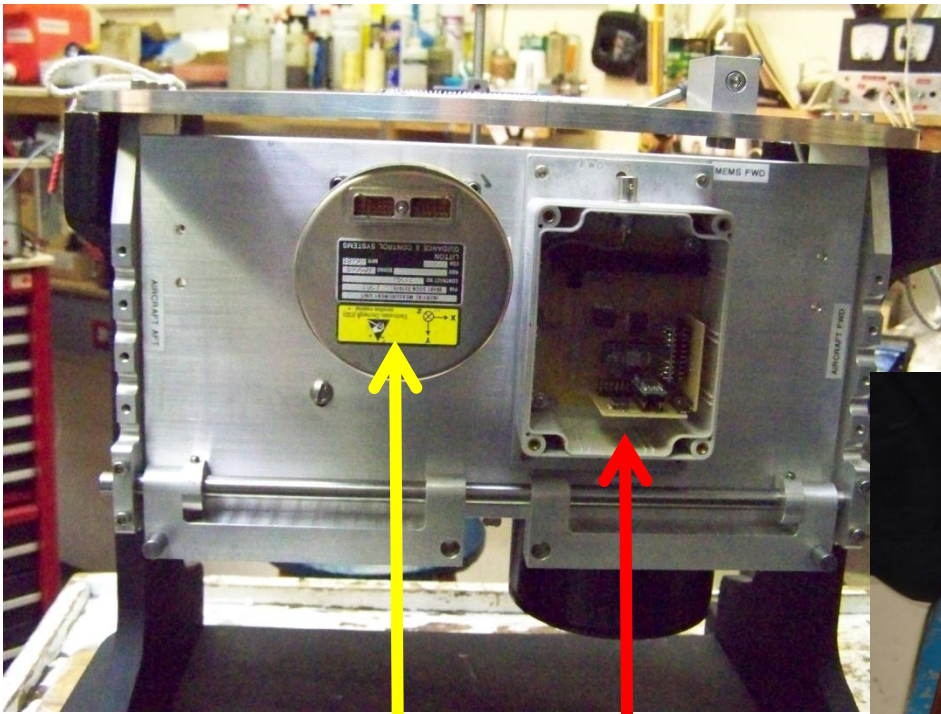
Position Yourself Ahead of the Crowd



Inertial Systems Setup

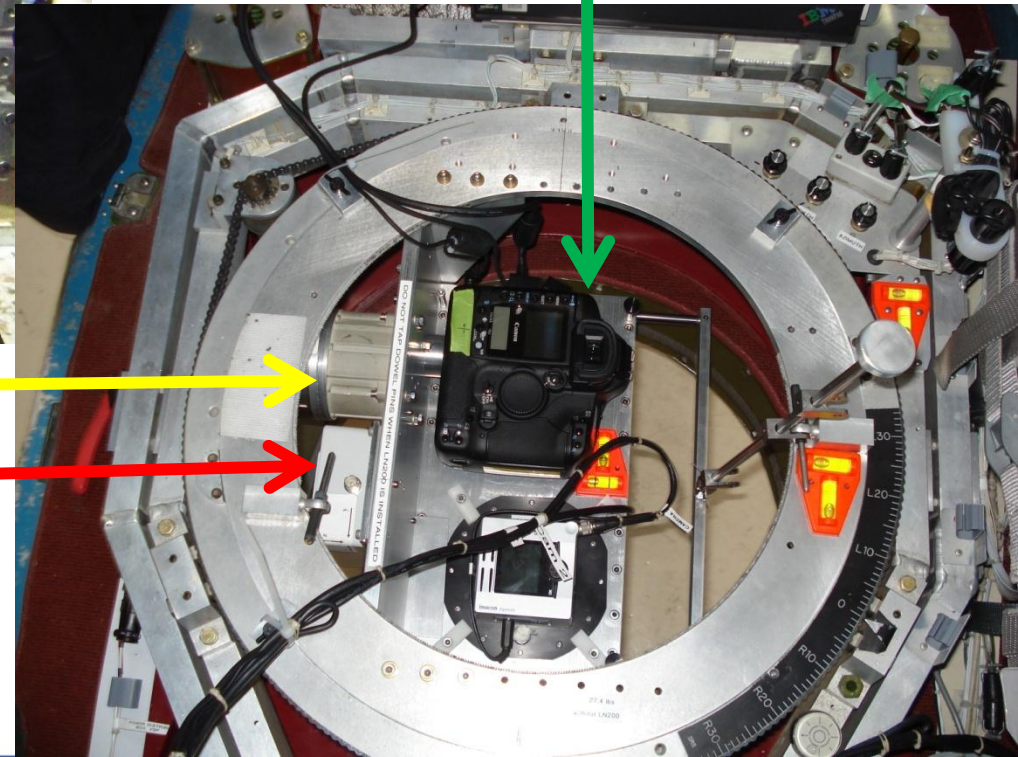
Position Yourself Ahead of the Crowd

**Kodak DCS 14N
(4536 x 3024
pixels)**



LN200

**UofC MEMS
IMU**



Including all 16 Flight lines	Error Statistics (deg)			
	Mean	Min	Max	RMS
Roll	0.0	-0.75	1.21	0.28
Pitch	0.0	-1.15	1.07	0.44
Heading	0.2	-2.5	3.8	1.8

- ❑ The LN200/DGPS solution has been used as a reference
- ❑ The alignment of the MEMS IMU is based on static levelling (for roll and pitch) and 5-7 minutes on-the-fly alignment for heading estimation
- ❑ The average misalignment between the MEMS IMU and the LN200 (0.2, 0.3, and 1.2 deg) was removed when computing the mean values
- ❑ Promising results for Integrated Sensor Orientation

Summary

Position Yourself Ahead of the Crowd

1. MEMS inertial navigation has shown promising performance today.
2. It will keep improving with the fast upgrading of the MEMS sensors in the market. The cost of the systems is also expected to drop down quickly with the blooming sensor manufacture.
3. Recent testing of MEMS-based IMU/GPS system clearly show that \$30-70 systems can meet the requirements for LBS, vehicle navigation and land based MMS systems.
4. Promising potential of using low-end MEMS inertial sensors for airborne MMS (e.g. Right of Way (ROW) of highways and Oil&Gas pipelines)

With the technology push and the market pull, MEMS inertial systems is going to reach the performance of Tactical Grade IMU Soon.