Abstract

Over the past couple of decades, there have been a number of navigation trends that have driven the desire to improve our ability to navigate in all environments. Previously, the primary desire was to navigate single, stand-alone systems (such as a car), but now, the desire is increasingly to have simultaneous navigation awareness of multiple interdependent systems (such as a traffic notification system in a car). Previously, navigation capability was not always counted on, but increasingly navigation is considered to be an assumed infrastructure (like knowing the lights will come on when you turn on the light switch). Previously, navigation accuracy of 5-10 m seemed almost extravagant when other worldwide navigation options prior to GPS had accuracies more on the order of 1-2 km. Now, there are many applications that require meter or sub-meter level accuracy (such as precision agriculture). Previously, due to cost, power, and size constraints, it was generally only feasible to know where the "big things" are (such as airplanes). Now, navigation is desired on more and more, smaller and smaller objects (such as cell phones).

While GPS has been the driving factor behind most of these trends, there are limitations to GPS that have become more evident over time as we have increasingly come to rely on navigation. The shortfalls in GPS could be called the "navigation gap." Recent advancements in high-sensitivity GPS have helped to decrease the size of this gap, but there still remains a gap where availability, accuracy, or reliability of GPS by itself is not sufficient for many applications. Ironically, it is in just such urban/indoor locations where many people spend most of their time. (In fact, odds are that you would have a hard time obtaining a high accuracy GPS fix wherever you are reading this paper!)

Summarizing, it would be desirable to develop a navigation system that (a) supports an indefinite mission duration, (b) supports real-time 3D location performance, (c) supports localization in urban environments and inside residential and most commercial buildings, (d) supports operation in an unknown (unmapped) or sparsely known (partially mapped) environment, (e) supports localization from the power-off condition and requires no separate starting location initialization of the user equipment, (f) supports individual isolated user terminals, (g) shall be able to re-acquire the navigation capability after a temporary loss, (h) is low-cost and low-weight, (i) does not require user motion to work, (j) shall have a level of integrity (assurance), accuracy, availability and continuity of service consistent with the tactical mission requirements.

This talk focuses on the latest technology trends for navigating in difficult urban, indoor, and underground environments where typical Global Positioning System (GPS) receivers do not function. Several of the latest alternative navigation (Alt-Nav) technologies will be presented. The challenge is to tightly integrate these technologies to achieve navigation performance similar to that is achieved in today's GPS integrations. An Alt-Nav integration vision for the future is given with some example configurations that improve overall navigation system robustness.

THE AIR FORCE RESEARCH LABORATORY
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Got GPS?

The Navigation Gap

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Navigation Trends

- **Position, Nav, & Time (PNT) is increasingly important**
  - We want to be sure we have it, anywhere, at any time
- **GPS by itself cannot guarantee anywhere, any time availability**
  - We must therefore turn to alternative approaches
  - Alternative approaches may be (and usually are) inferior to GPS, at least in some measure
- **On principle, it's not a good idea to set up a single point of failure**
  - Reliance on GPS alone means that anything that disrupts GPS (intentionally or unintentionally) will have significant impact
  - If backup systems are in place, then GPS disruptions are not nearly as significant

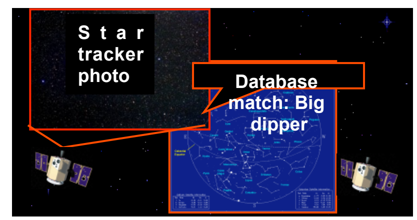
Navigation Trends

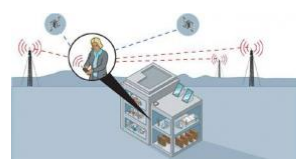
Then		Now/Future
Single, stand-alone systems	→	Multiple interdependent vehicles work together to achieve goal (requires navigation)
Precise navigation as a "nice-to-have"	→	Complete dependence on reliable navigation (PNT as an assumed infrastructure)
Navigation accuracy: 5-10 m is just fine	→	Sub-meter to cm-level accuracy *required* ("Accuracy is Addictive")
We want to know where the "big things" are	→	We want to know where everything is

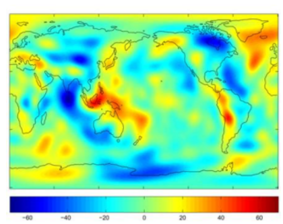
Pushing Us Towards Alternative (non-GPS) Navigation

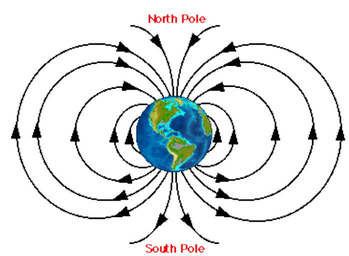
Introduction

- **Navigation Trends**
- **Motivation—why alternative navigation techniques?**
- **Navigation Methods & Alternative nav techniques:**
  - Laser radar (lidar)-aided inertial navigation
  - Vision-aided inertial navigation
  - Stellar navigation
  - Doppler, SAR radar, etc.
  - Signals of opportunity
  - Nature-Inspired
  - Gravimetry









- **Robust Integration is required**

Reliance Only On GPS

Could this happen to you??

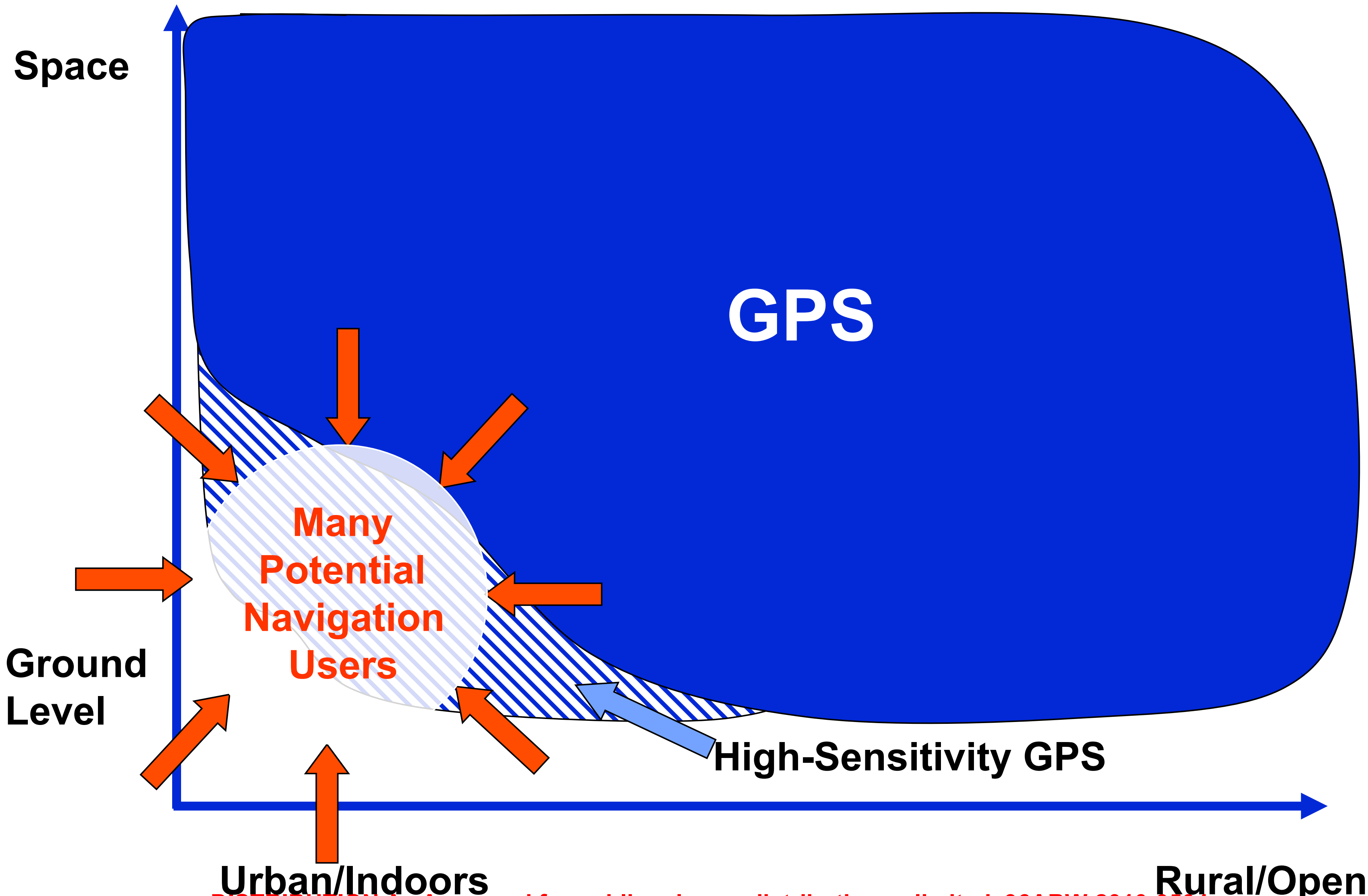
Or This??

- **GPS leads driver into tight spot, stays wedged for three days**

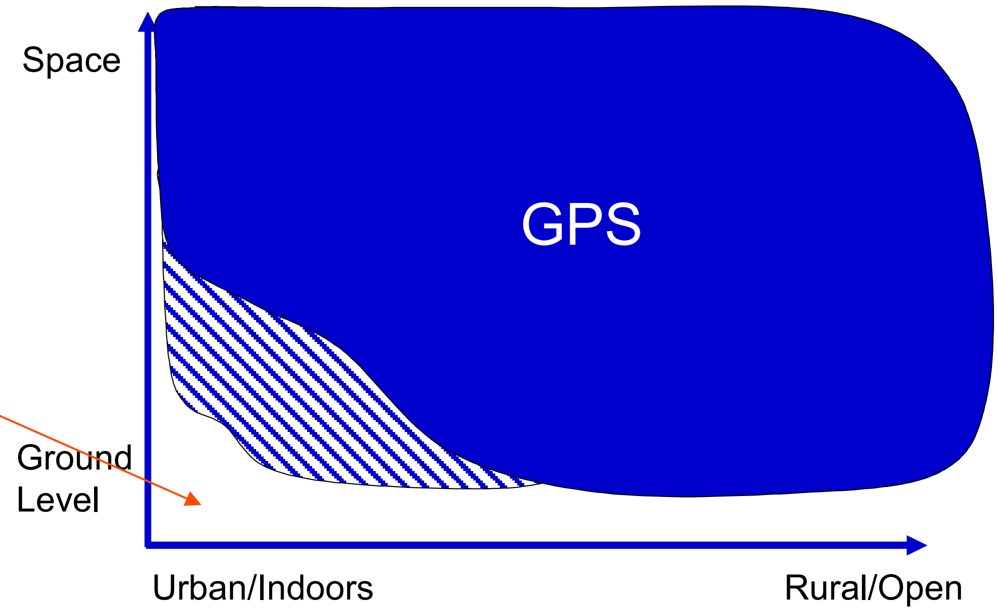
- **Driver turns right and drives onto train tracks**

- **Driver follows GPS onto pedestrian walkway, into cherry tree**

The Navigation Gap



How Can We Fill the Navigation Gap ?

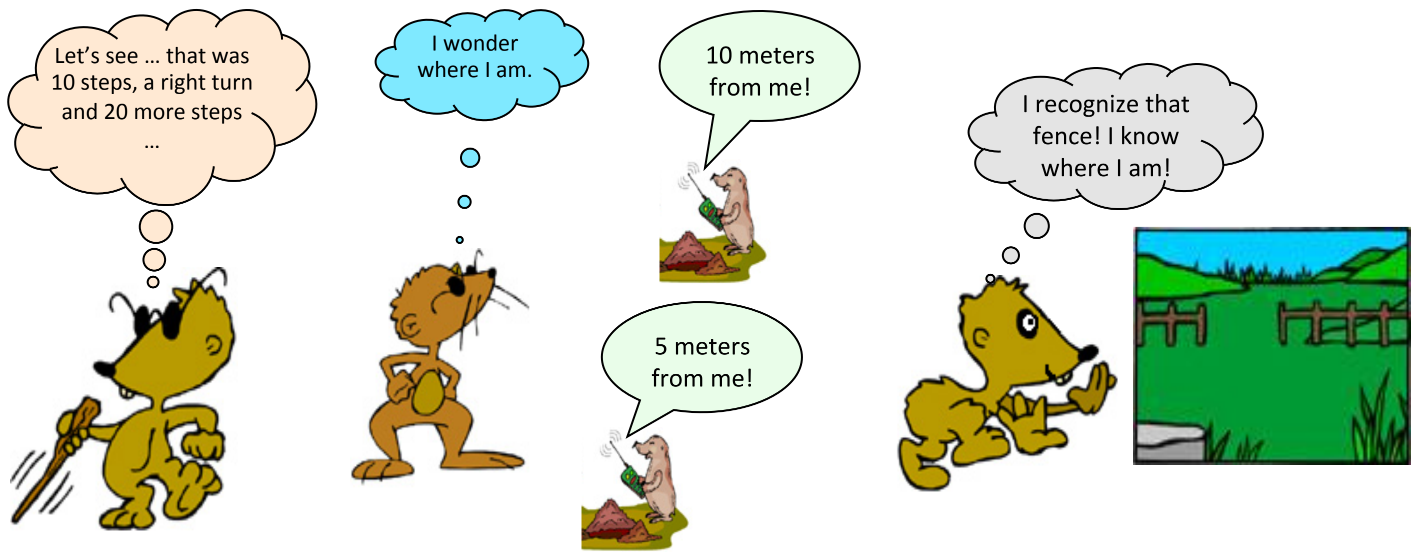


How can we fill the gap?

- **Inertial?…Not by itself**
- **High-sensitivity GPS?…Helps, but doesn't fill the gap**
- **Alternative Navigation Approaches**
  - **Image/lidar/doppler/DR aiding of inertial**
  - **Beacon-based navigation (includes pseudolites)**
  - **Navigation using signals of opportunity (SoOP)**
    - **RF signals that are not intended for navigation**
    - **Bio-Inspired Navigation**

Fundamental Navigation Methods

- **Dead Reckoning (*e.g.* inertial navigation)**
- **Externally Dependent (*e.g.* GPS)**
- **Database Matching (*e.g.* celestial navigation)**



Dead Reckoning **Externally Dependent** **Database Matching**

Motivation for Multi-Sensor Integration

Many (prospective) applications require *accurate* and *reliable navigation* solutions *in urban environments*:

- **UAV and UGV missions**
- **Surveillance and reconnaissance**
- **Search and rescue**
- **Automotive (lane keeping, cooperative vehicle safety)**
- **Mapping (geographical information systems (GIS) in urban canyons), etc.**

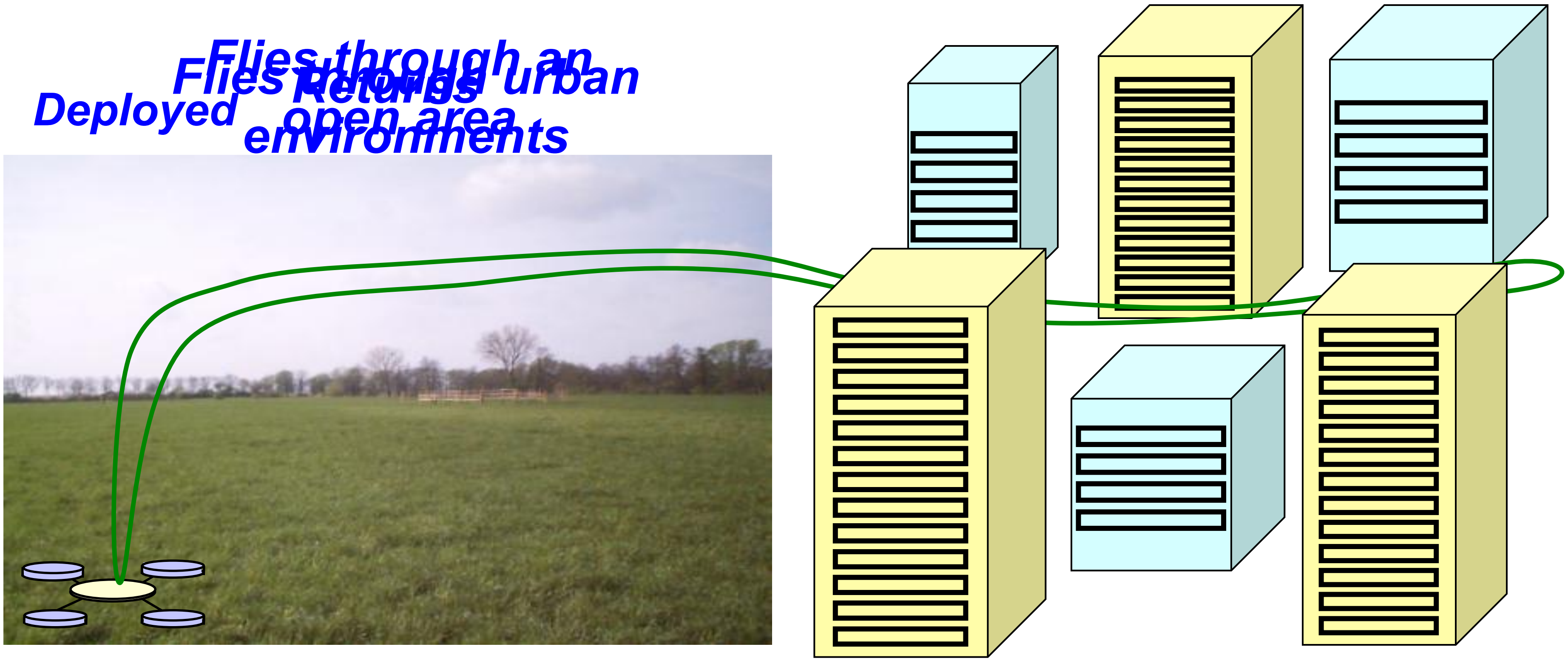
Many of these applications require *m-level to decimeter-level accuracies*, while maintaining *integrity*, *availability* and *continuity* of the navigation solution.

***GPS* delivers *fragmented performance* in *urban environments* :**

- **Satisfactory performance in most rural and suburban scenarios;**
- **Limited performance in urban canyons**

Motivation for Multi-Sensor Integration

To enable operation of UAVs at *any time* in *any environment*, a *Precision Navigation, Attitude, and Time (PNAT) capability* on-board the vehicle is *required*.

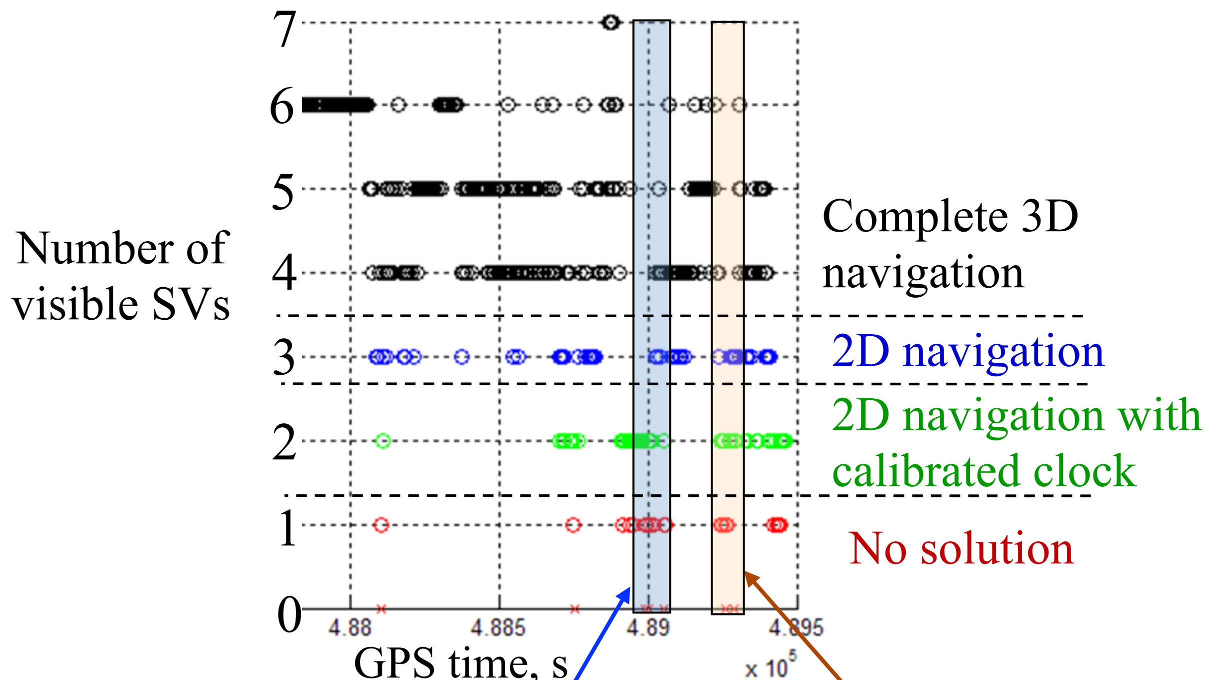


- **Different flight segments may impose different requirements regarding navigation and guidance capabilities of the vehicle: *open field vs. urban canyon***
- **If used stand-alone, none of the existing navigation technologies can satisfy these requirements**

GPS Limitations

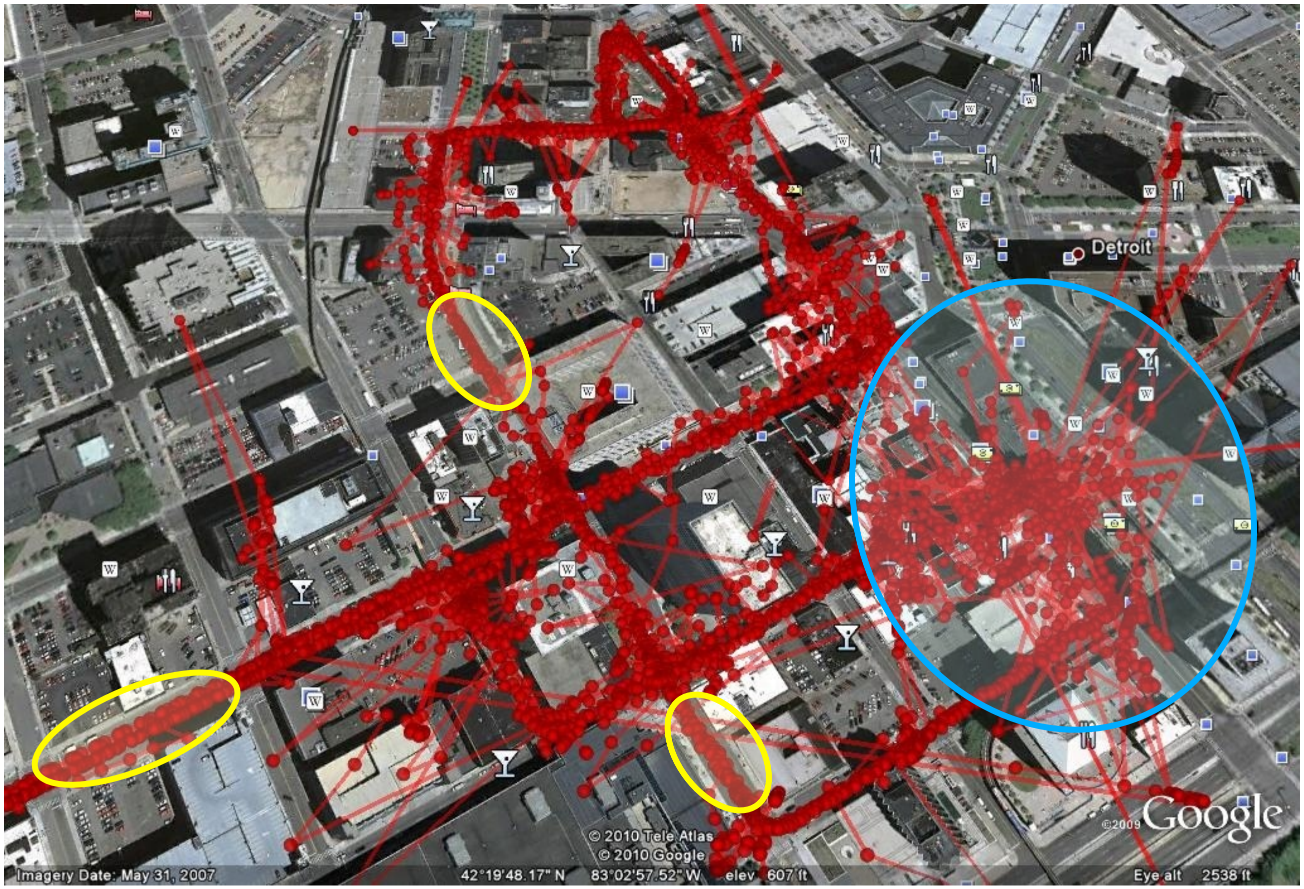
Most GPS receivers report *fragmented satellite availability* in urban areas

Satellite availability with NovAtel OEM-4 GPS receiver in Athens, OH



Example of GPS Limitations

GPS-based trajectories in urban environments (downtown Detroit, MI)

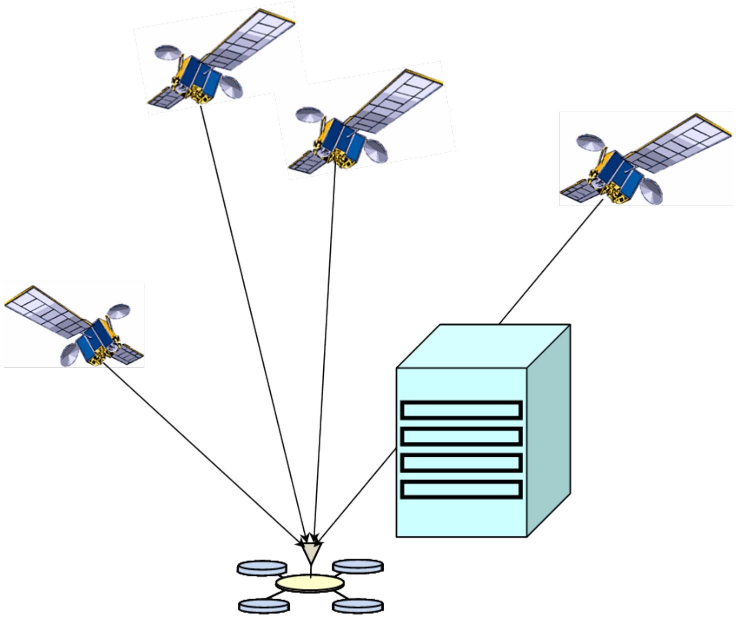


***Relatively open areas*:** **Satisfactory performance**

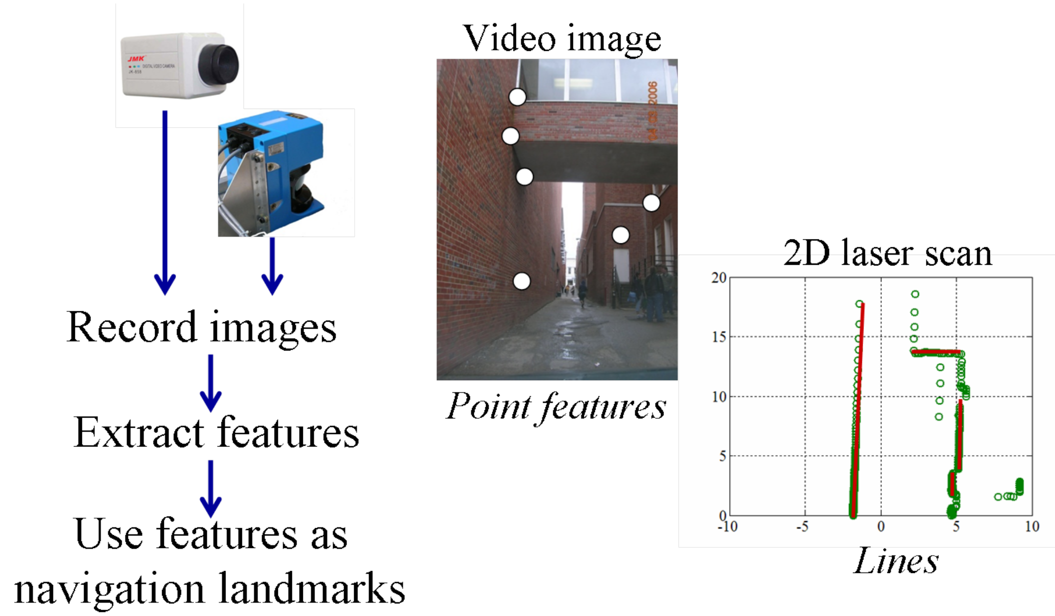
***Dense urban environments*:** **Large discontinuities**

Integrated Navigation Example

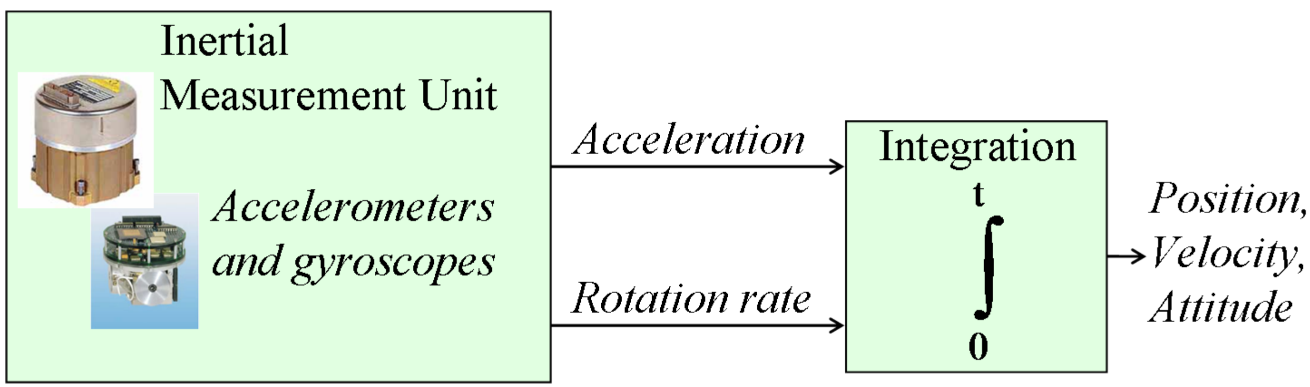
GPS



Feature-Based Navigation

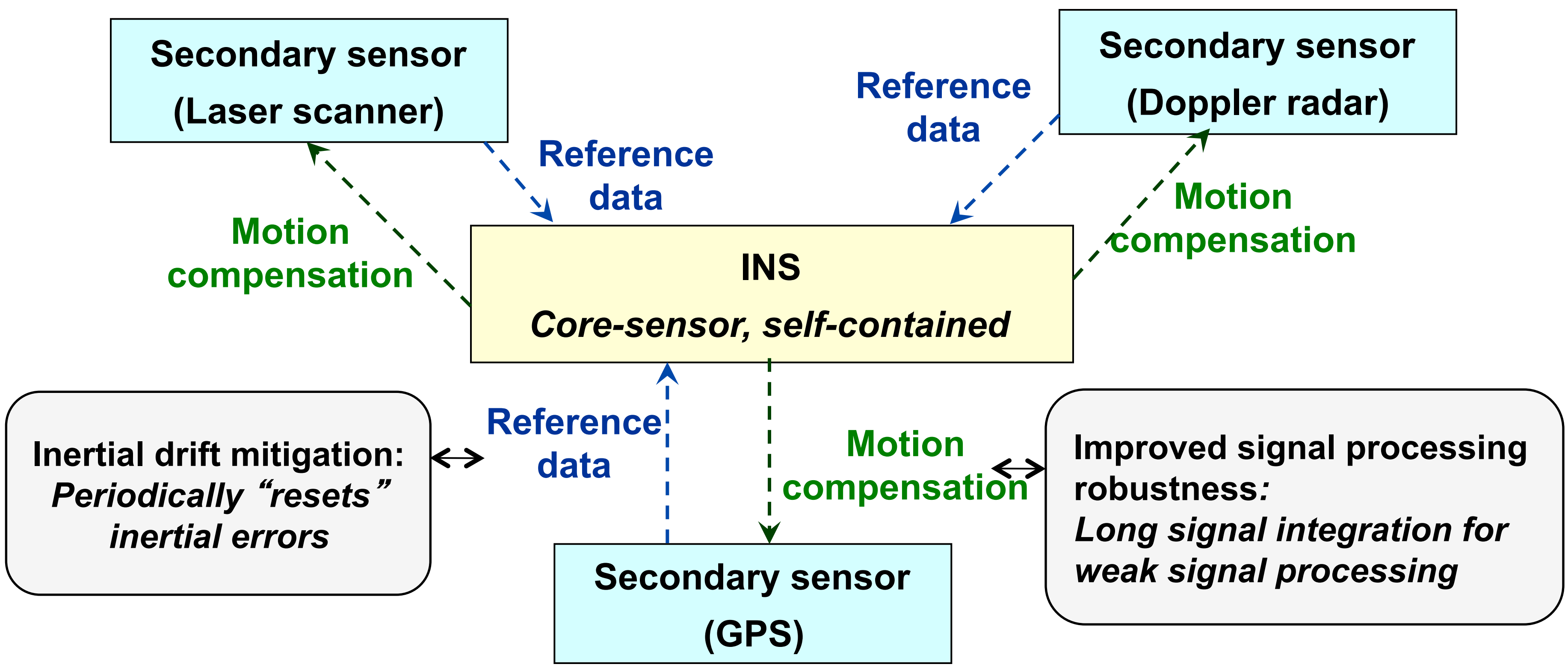


Inertial Navigation



Generic Integration Approach

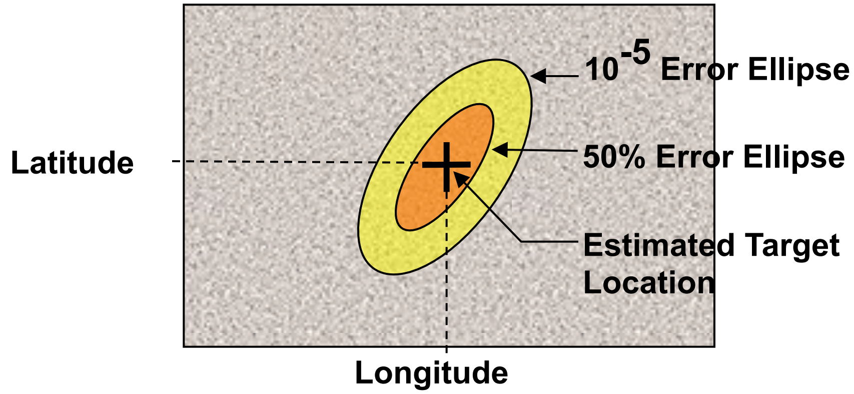
- ➢ Chose a core sensor;
- ➢ Build on top of it;
- ➢ The core sensor needs to work in any environment



➢ ***Integration result***: **"semi"-*self-contained* system (works *anywhere*) with *limited drift* (works *anytime*)**

Main Benefits

- Improved navigation performance:
  1) Integrity (assured navigation)
  2) Accuracy
  3) Continuity
  4) Availability

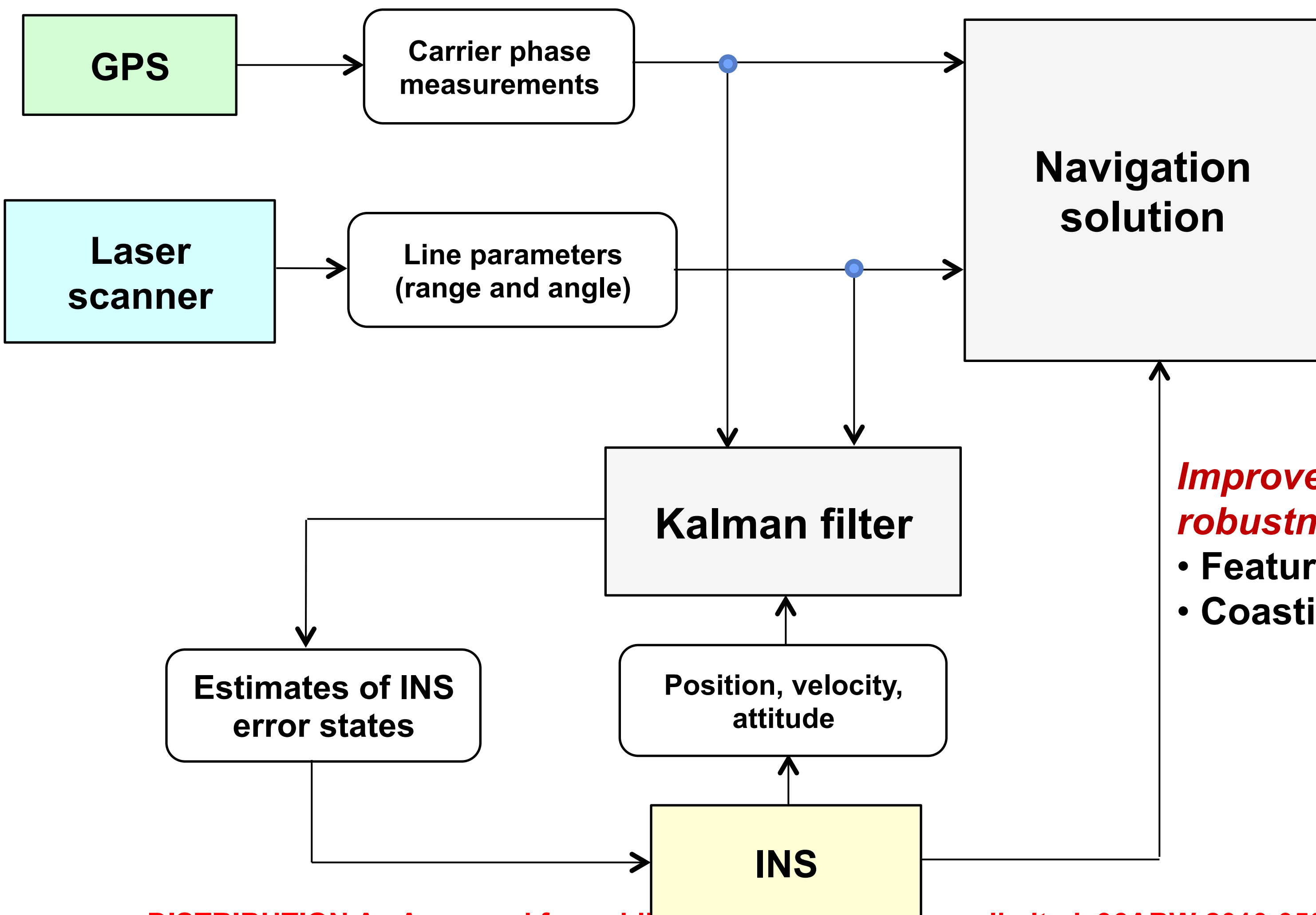


50% Error Ellipse contains 50% of the errors.
10^{-5} Error Ellipse contains 99.999% of the errors.

- Enhanced robustness of signal processing

Example of GPS/Laser/Inertial Integrated Implementation

➢ Range-domain data fusion (tight coupling)



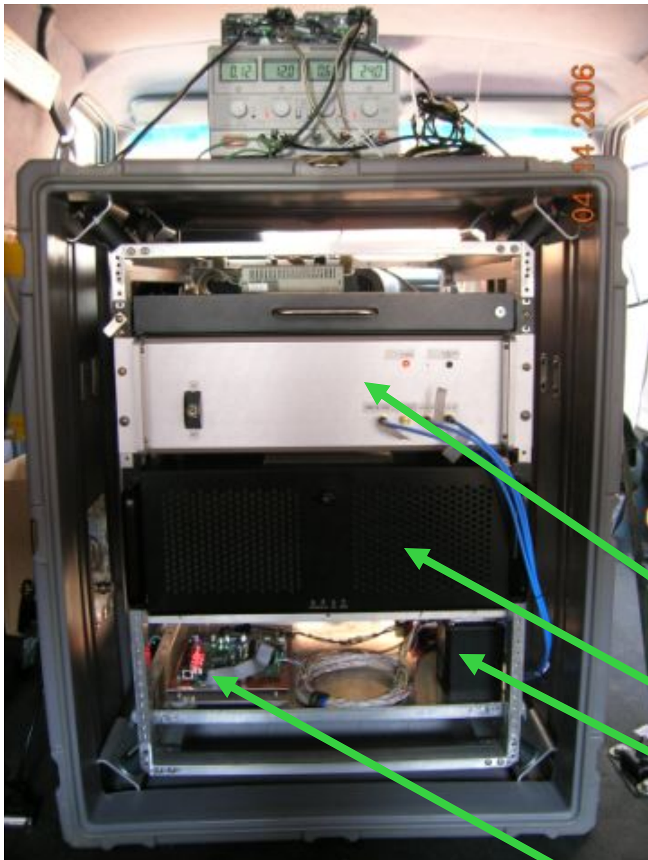
Improved solution robustness:
- Feature matching;
- Coasting

Test Setup

NovAtel L1/L2
pinwheel antenna

GPS antennas

Laser scanner



Software radio RF components

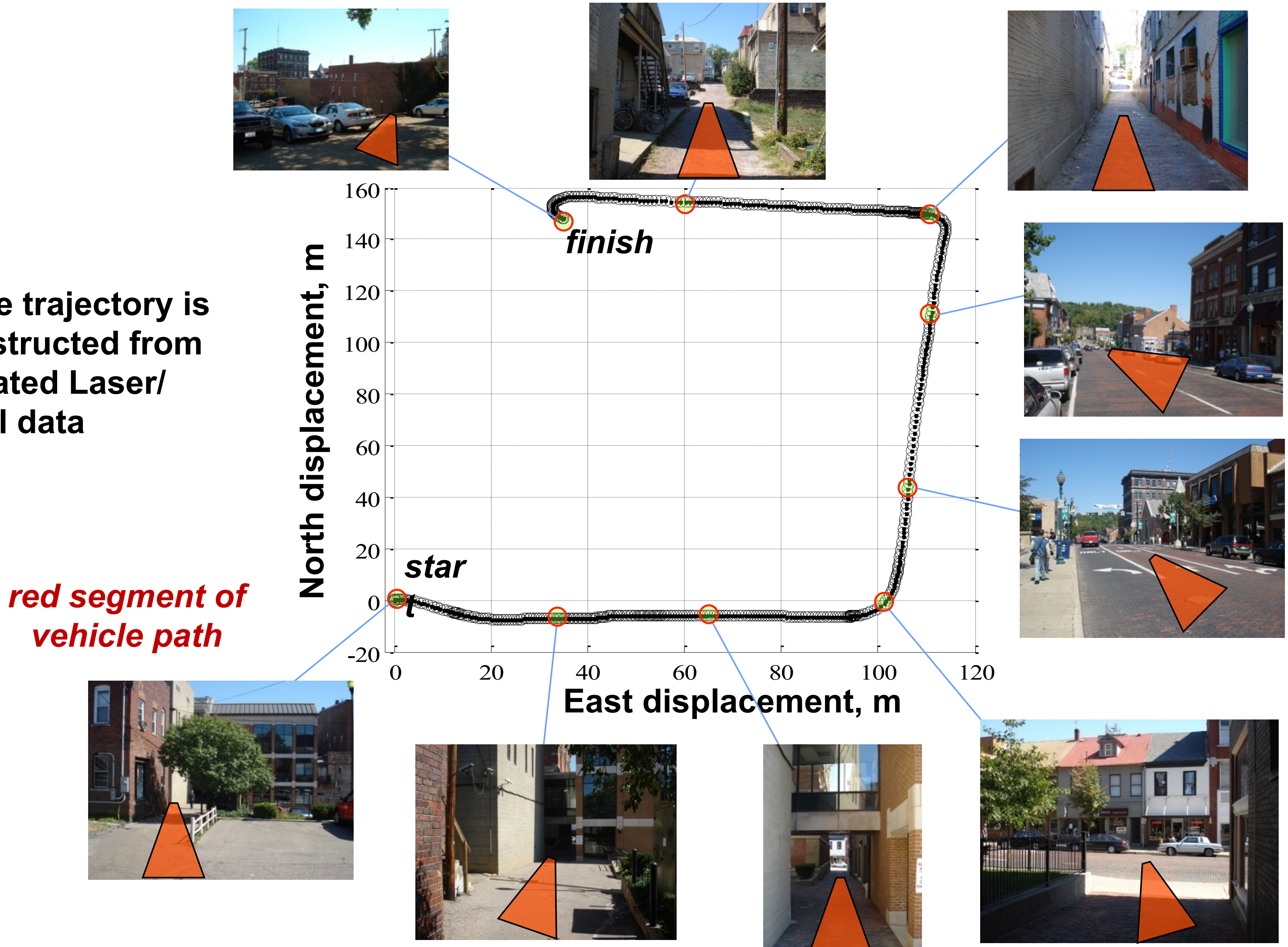
Software radio digital components

Inertial Measurement Unit (Systron Donner DQI)

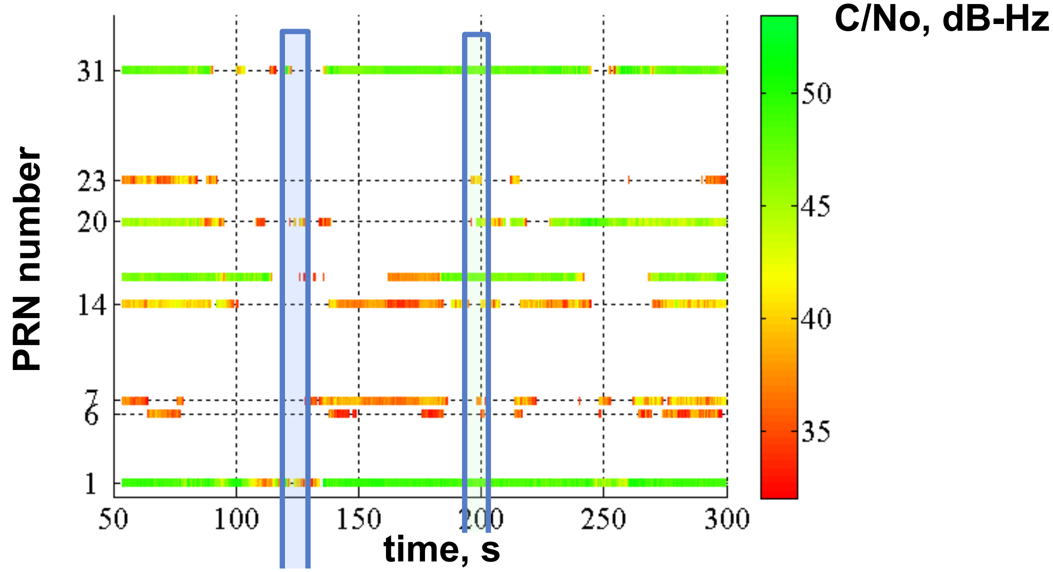
Laser/IMU synchronization
and data collection board

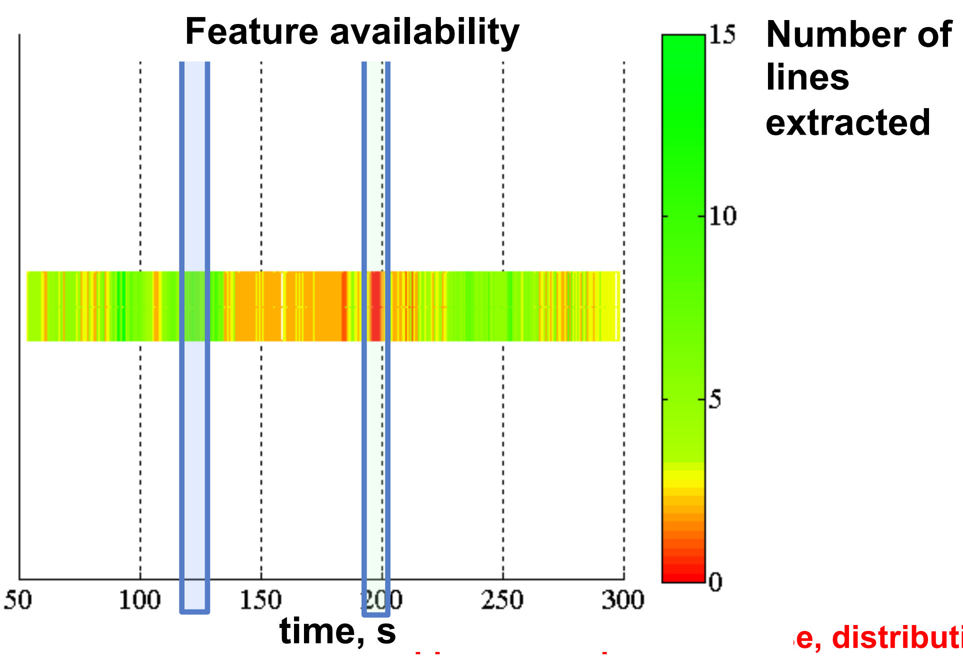
Urban Test Scenario

Vehicle trajectory is reconstructed from integrated Laser/ Inertial data



Urban Test Scenario: *Results*

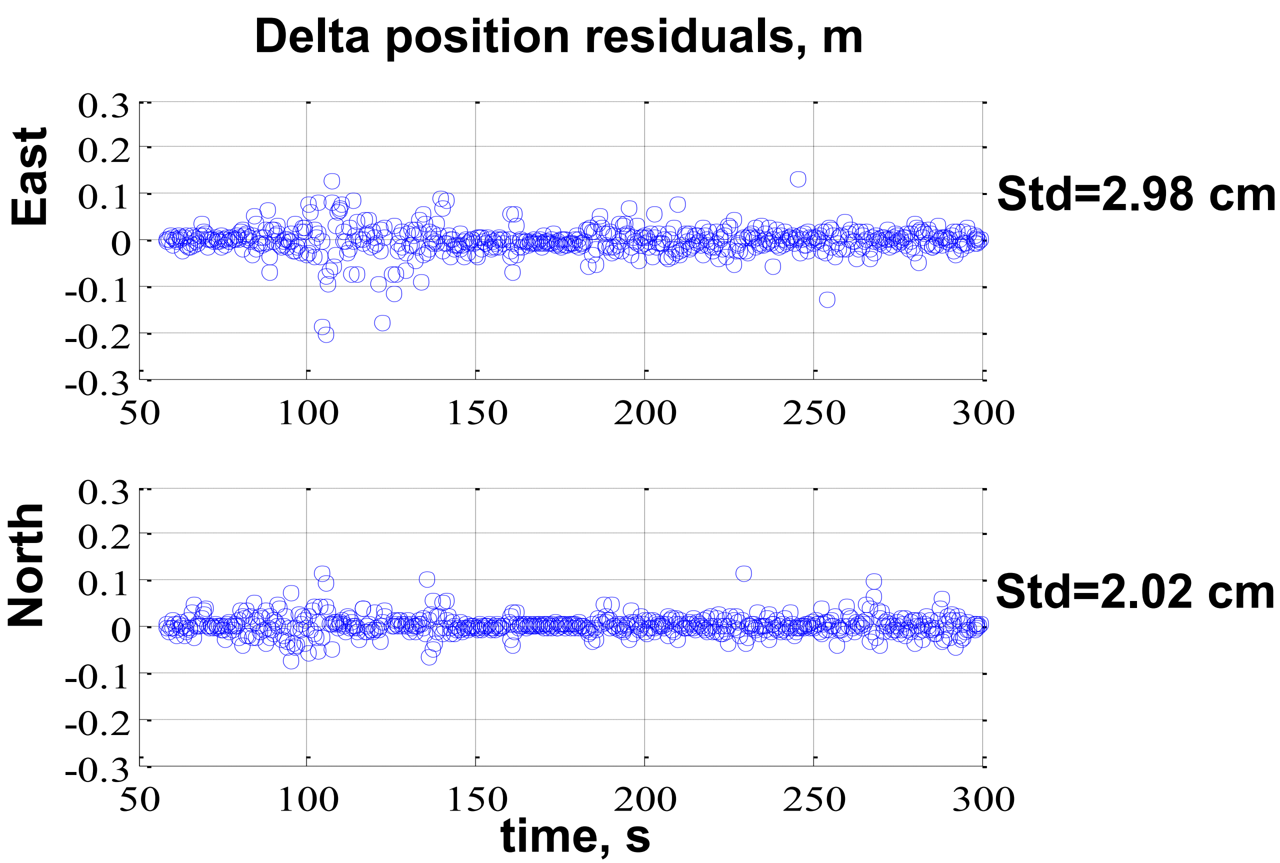




Urban Test Scenario: *Results*

Cm-accurate trajectory reconstruction **capabilities are demonstrated:**

- ***Standard deviation of residuals in the delta position solution is at a cm-level***



Motivation for Multi-Aperture Sensing

Biological sensors with wide *field-of-regard*

Enhanced situation awareness, especially, in cluttered environments (urban canyons, indoors, forestry areas): *look forward, backward, and to the sides*

Multi-aperture view

What are the benefits for navigation?

- **Increased number of high-quality vision features**
- **Improved feature geometry (better DOPs)**
- **Improved range initialization capabilities**

Summary

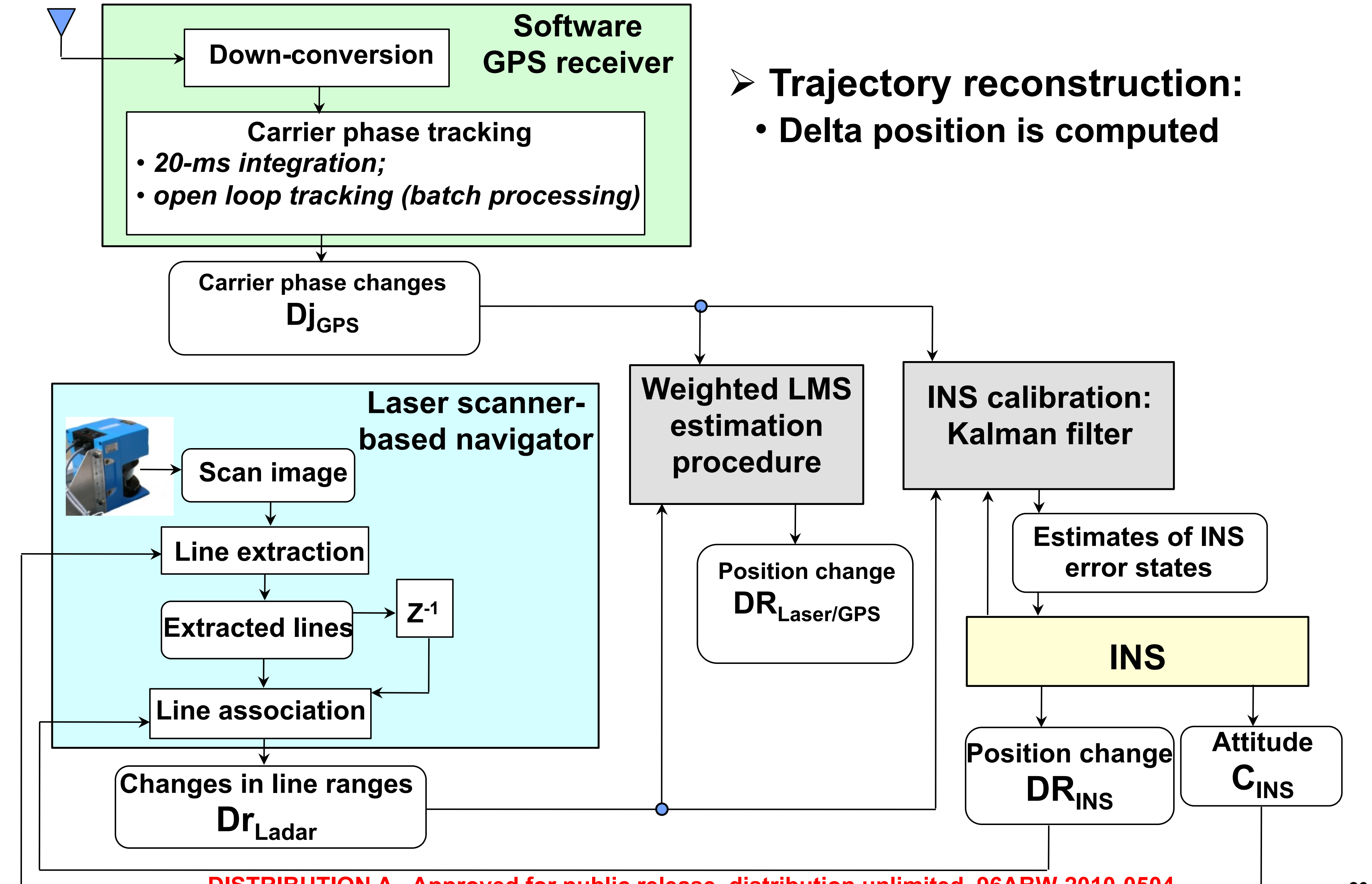
- PNT is an essential part of our infrastructure
  - Accuracy and availability are addictive
- GPS and similar systems are amazing, BUT….
  - A GAP remains where availability, accuracy, and/or reliability are required
- Alternative navigation technologies and integration methods are a must to fill the GAP
  - Promising technologies include:
    - Laser radar (lidar)-aided inertial navigation
    - Vision-aided inertial navigation
- Inertial Measurement Units are core PNT sensors

Acknowledgements

- **Special thanks to:**
  - **Air Force Research Laboratory**
  - **Air Force Institute of Technology**
  - **Ohio University**
  - **University of Florida**

Test Implementation

- Trajectory reconstruction:
  - Delta position is computed



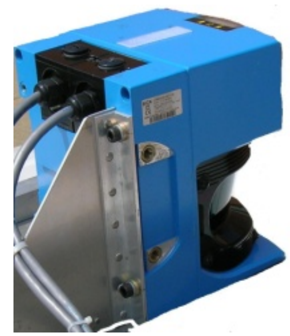
Vision-Based vs. Laser-Based

Pros:

- **Passive sensor**
- **Enables 3D navigation** **(once the image depth is resolved)**

Cons:

- **Unknown image depth** **depth resolution methods exist (stereo vision, use of digital terrain elevation maps), but have their limitations**



Pros:

- **Provides ranging measurements**

Cons:

- **Generally limited to 2D navigation** **(XY coordinates and azimuth angle): 3D laser scanners exist, but those are currently too expensive &not readily scalable for most applications;**
- **Active sensor: may present some limitations for defense applications**