Positioning Integrity for Intelligent Vehicles

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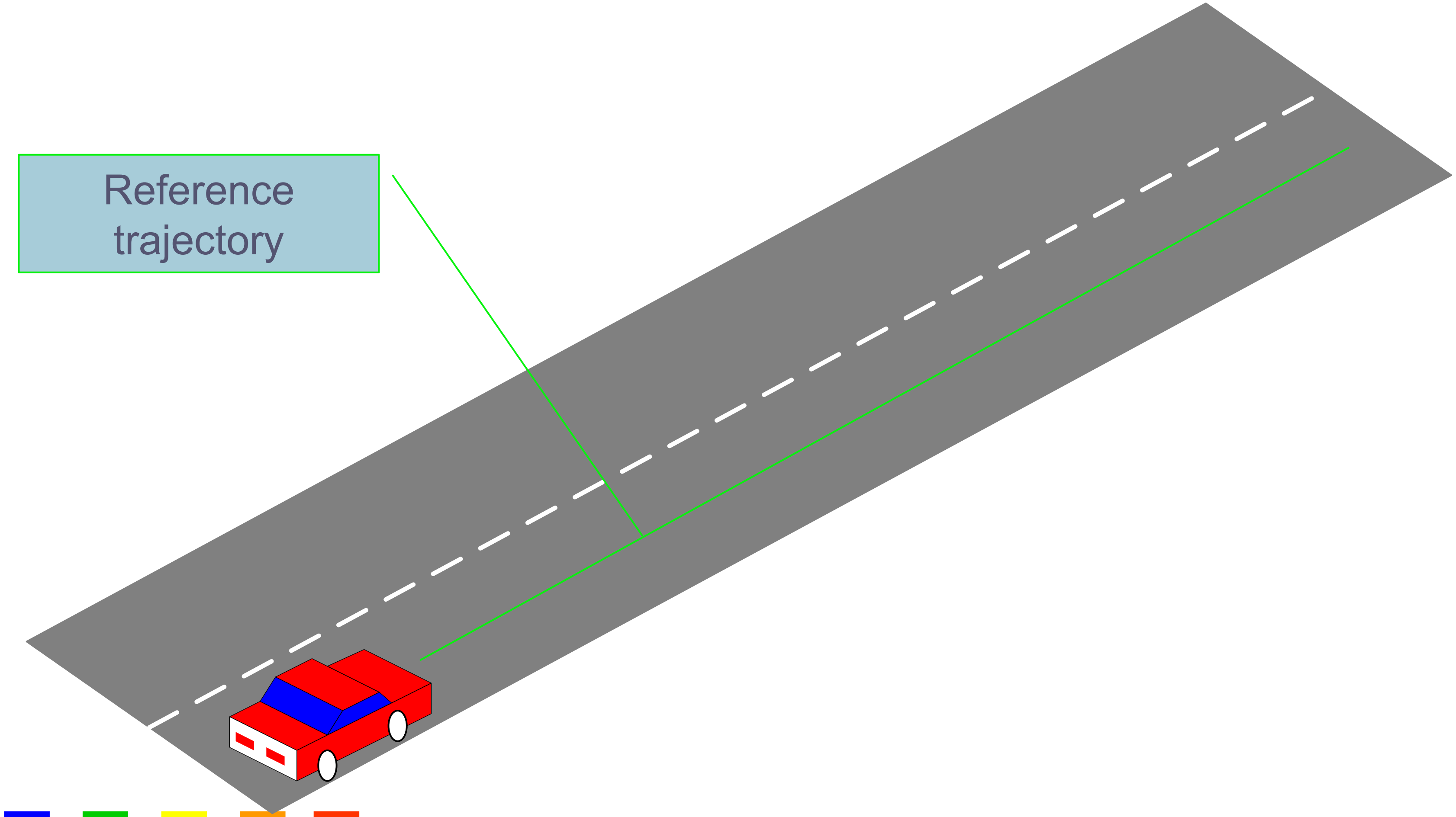
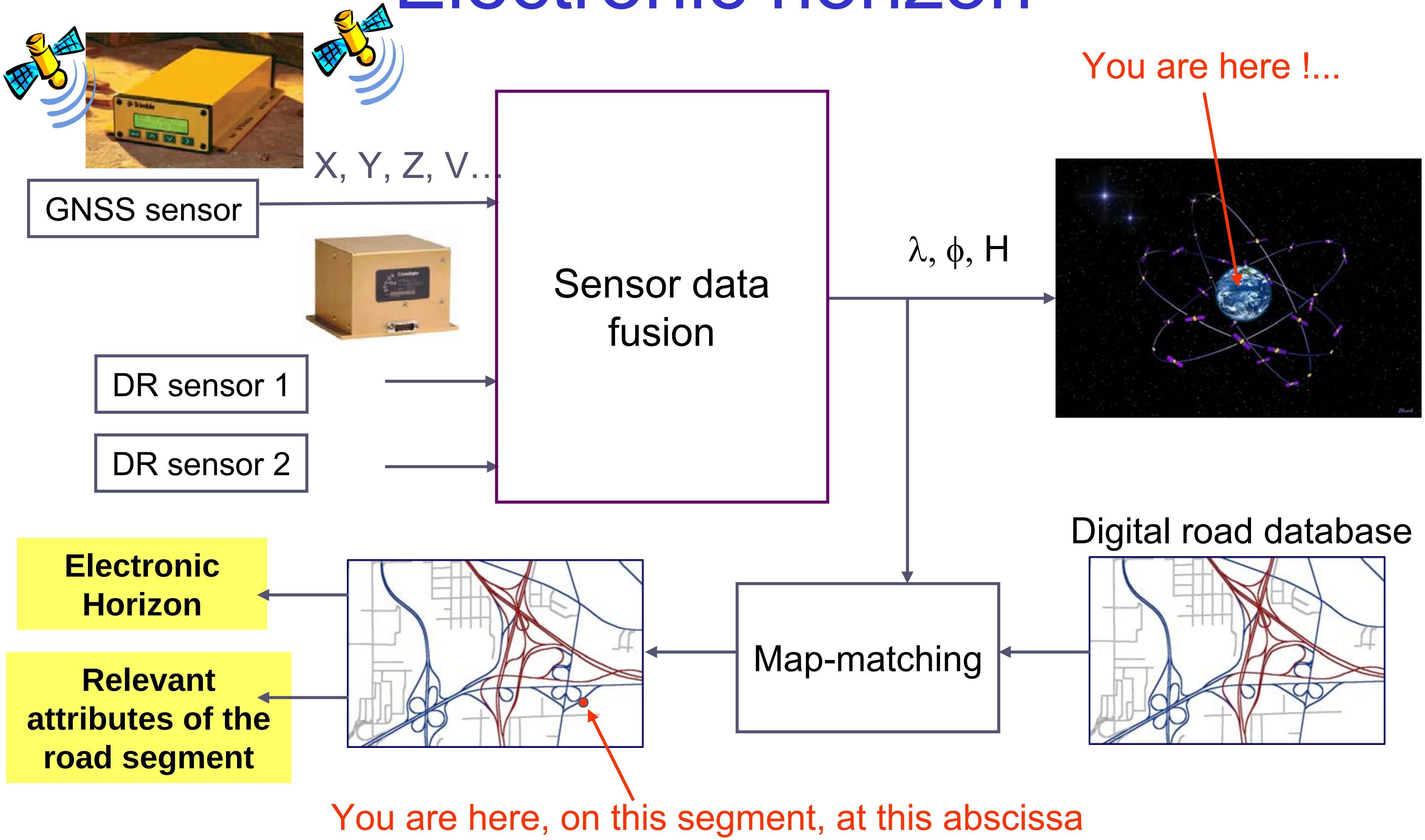
Planed trajectory following

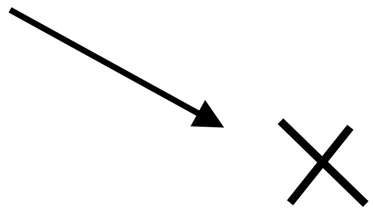


Electronic horizon



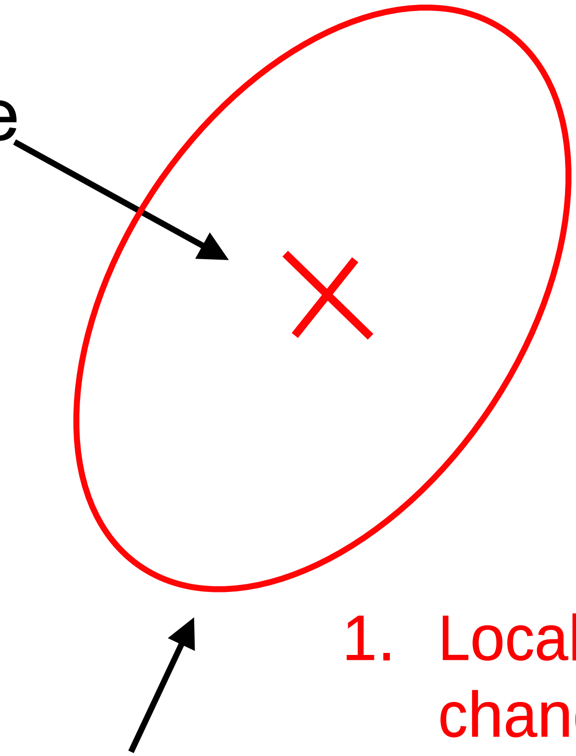
The good old days

You are here!



Modern Times

Maybe you are here...



in this area with a confidence of 99%

1. Localization errors change often
2. They are often non negligible

Quality of Service

- International Civil Aviation Organization
- 4 attributes
  - Accuracy
  - Integrity
  - Availability
  - Continuity of service

Required Navigation Performances

Typical operation(s)	Accuracy horizontal 95%	Accuracy vertical 95%	Integrity	HAL	VAL	Time to alert
En-route	3.7 km (2.0 NM)	N/A	$1\text{-}10^{-7}$/h	7.4 km (4 NM)	N/A	5 min
En-route	0.74 km (0.4 NM)	N/A	$1\text{-}10^{-7}$/h	3.7 km (2 NM)	N/A	15 s
En-route, Terminal	0.74 km (0.4 NM)	N/A	$1\text{-}10^{-7}$/h	1.85 km (1 NM)	N/A	15 s
Initial approach, Intermediate approach, Non-precision approach, Departure	220 m (720 ft)	N/A	$1\text{-}10^{-7}$/h	556 m (0.3 NM)	N/A	10 s
Non-precision approach with vertical guidance (APV-I)	220 m (720 ft)	20 m (66 ft)	$1\text{-}2\times10^{-7}$ per approach	556 m (0.3 NM)	50 m (164 ft)	10 s

Outline

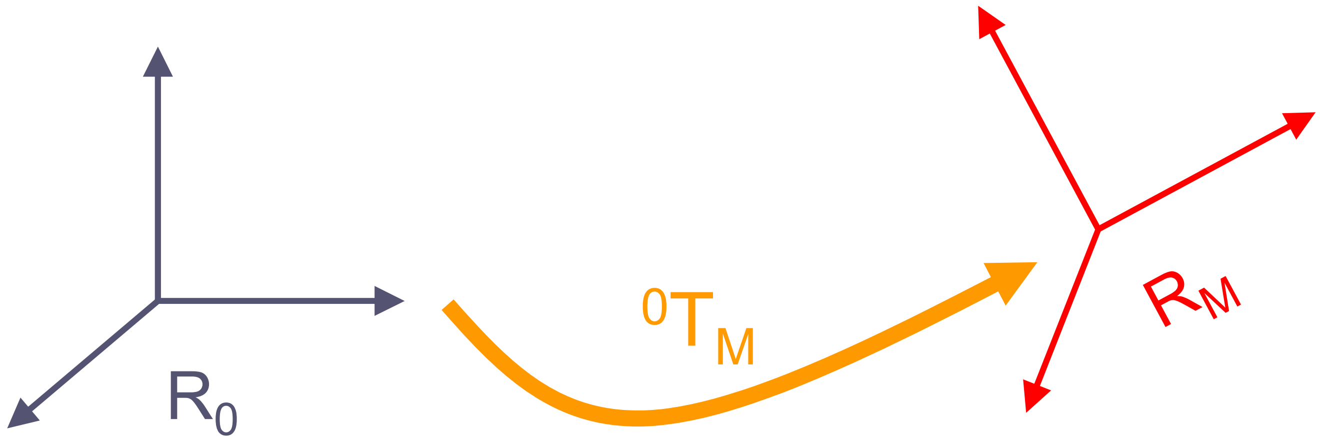
Scope: managing localization uncertainty for intelligent vehicles real-time applications

1. Localization fundamentals
2. Classical integrity monitoring scheme
   - developed for aeronautics
3. Application to intelligent vehicles
4. A new strategy using bounded errors

Part 1
Localization fundamentals

Metric self-localization

- Also called positioning
- Ability of a system to determine its pose in a reference frame



- using sensor measurements done on known landmarks, with the help of dead-reckoning sensors if necessary.

Static Localization

$$y_k = h(x_k, m)$$

y_k**:** measurement vector
m**:** map or landmarks coordinates
x_k**:** unknown parameters (pose included)
h**:** observation model

Usual problems:

- non linear equations
- measurements redundancy

Dynamic localization

$$\begin{cases} x_k = f(x_{k-1}, u_k) \\ y_k = h(x_k, m) \end{cases}$$

u_k: dead-reckoning measurements

f: evolution model

Usual problems:

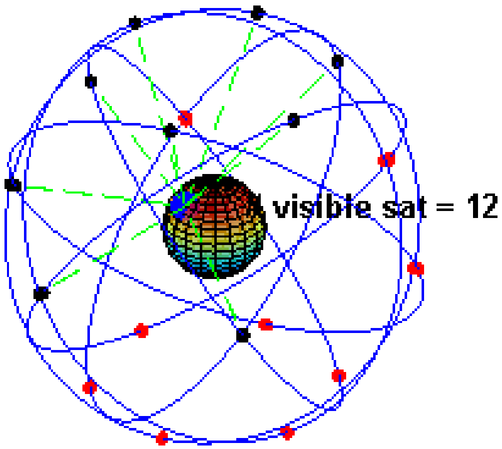
- non linear equations
- few exteroceptive measurements
- the movement helps in reconstructing the pose

Localization for Intelligent Vehicles

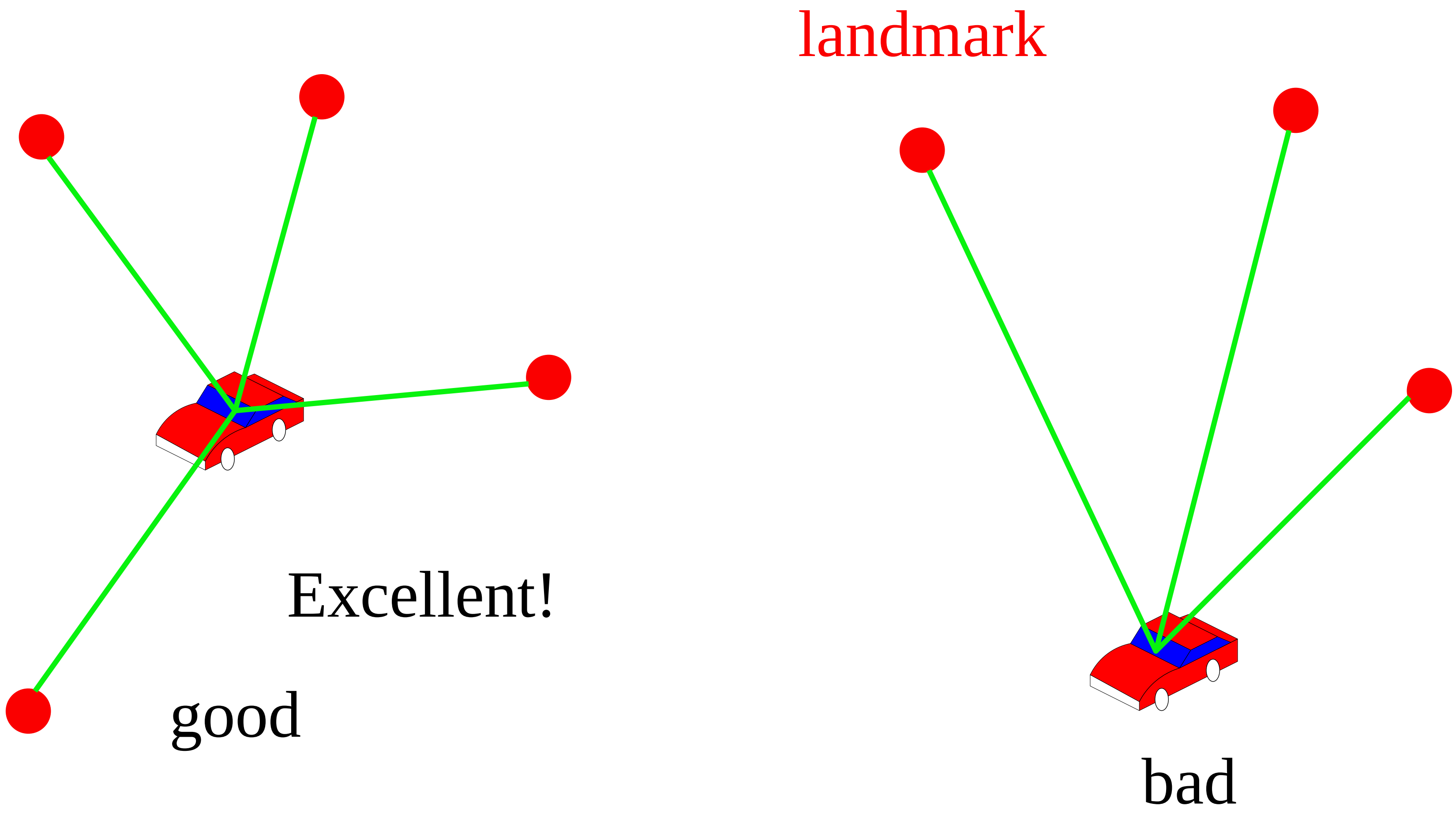
- An absolute system is necessary
  - At least to initialize a dead-reckoning system
  - GPS very affordable
- Dead-reckoning sensors are easily accessible
  - Wheel speed sensors
  - Yaw rate gyro
  - CAN bus

Key factors for the performance

- Landmark identification
  - Let consider discernable landmarks
- Geometrical configuration
- Measurements error
  - Noise
  - Outliers (faults)



Geometrical configuration



Dilution of precision

$$y_k = h(x_k, m)$$

Extended transformation (linearization)

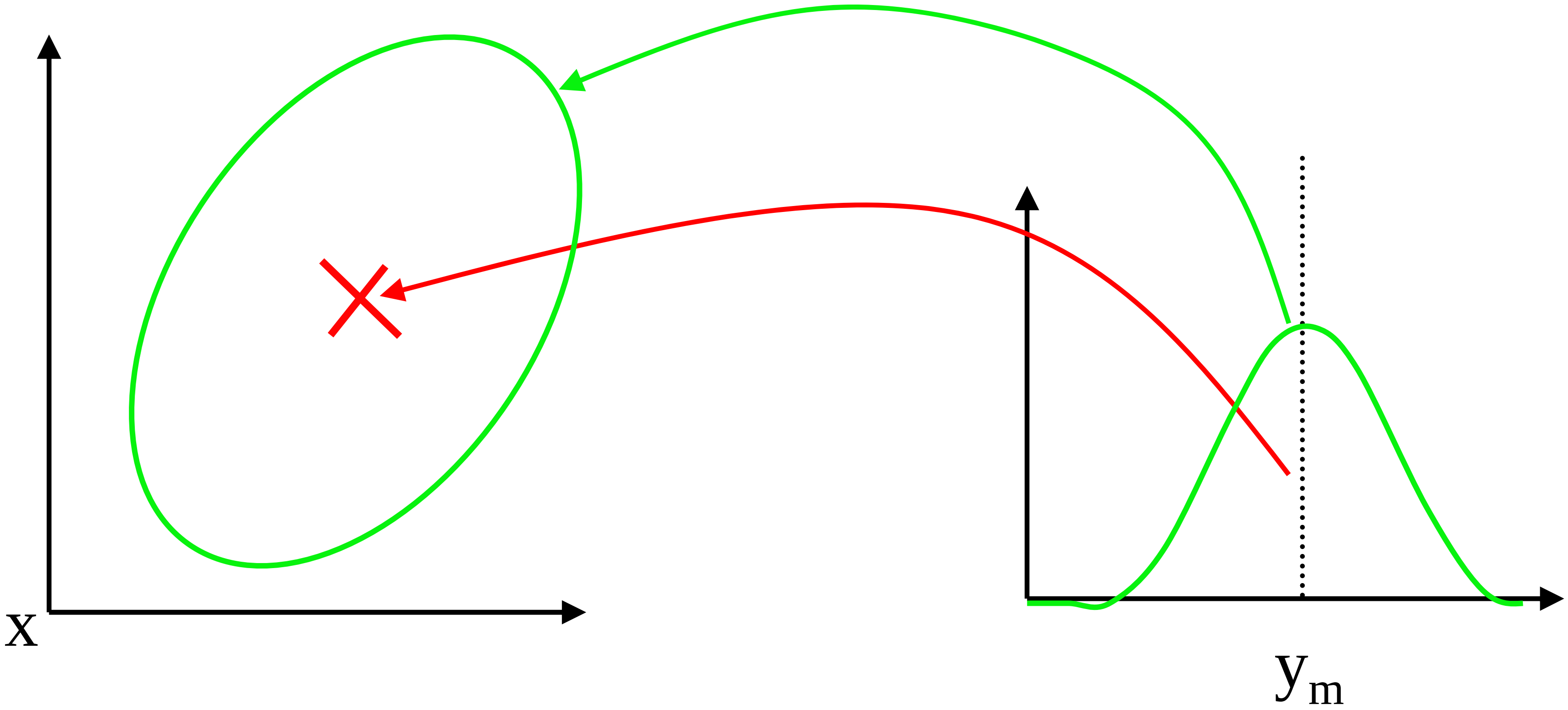
$$P_y = \left[\frac{\partial h}{\partial x}(\hat{x}_k, m)\right] P_x \left[\frac{\partial h}{\partial x}(\hat{x}_k, m)\right]^T = H P_x H^T$$

If $Py = \sigma^2 I$ then $P_x = \sigma^2 \left(H^T H\right)^{-1}$

Dilution of Precision

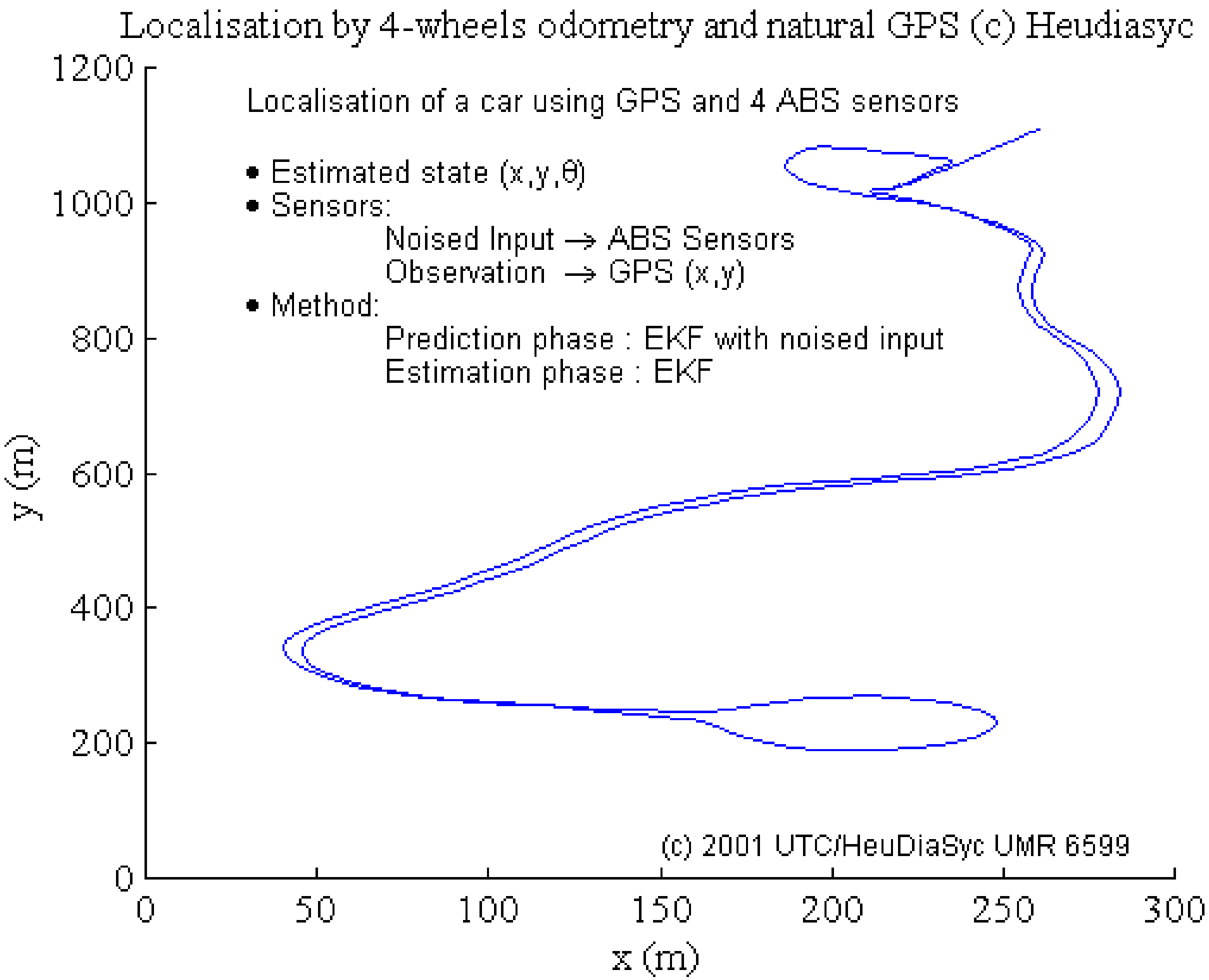
$$DOP = \sqrt{\mathrm{trace}\left(H^T H\right)^{-1}}$$

Noise



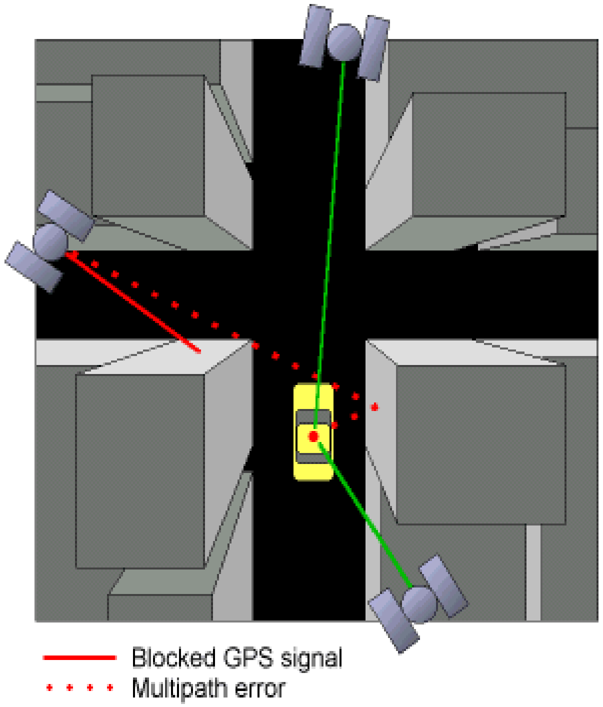
Basic equation : precision = σ.DOP

Precision estimation varies a lot



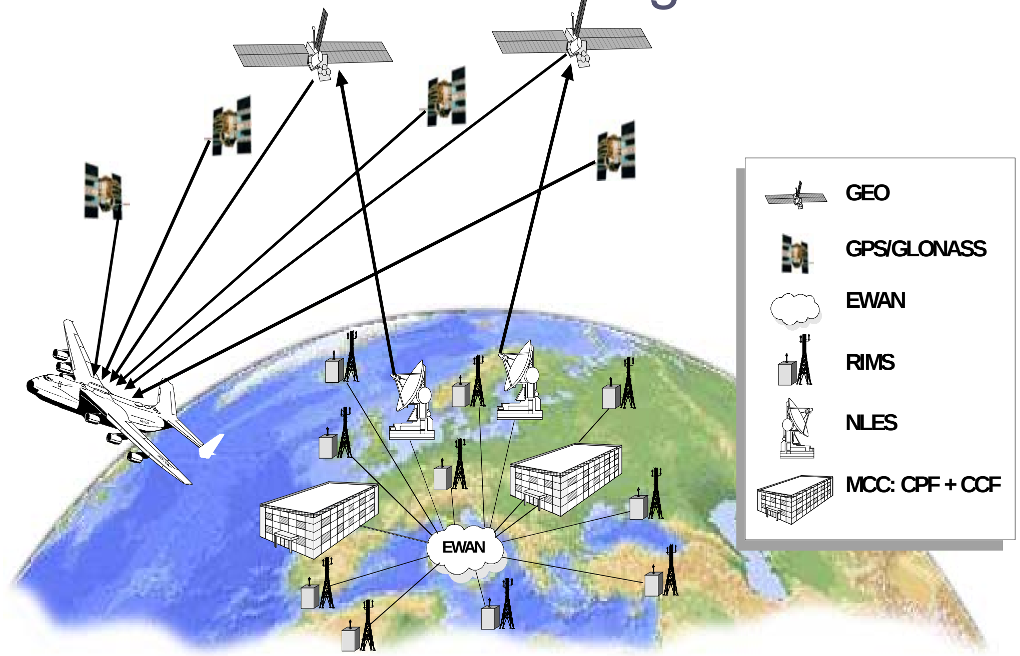
Outliers

- Measurements not compatible with the noise model
- Example: GPS outliers
  - Satellites failures
  - Signal In Space propagation troubles
    - Ionosphere
    - Interferences
    - Jamming or malicious damage
  - Multipath
    - NLOS multipath



Solutions

- External Monitoring
  - Ground Stations which monitor GNSS signals
  - SBAS
    - EGNOS,
    - WAAS,
    - MSAS

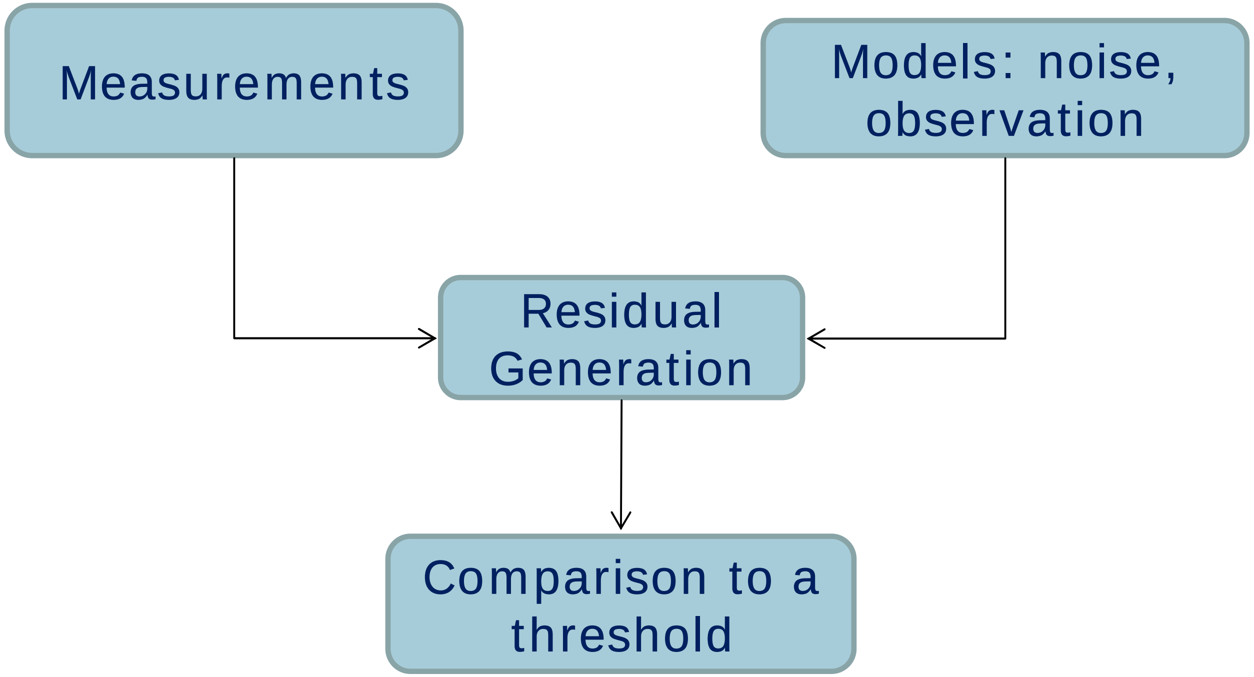


- Autonomous Monitoring
  - Idea: to exploit the measurement redundancy

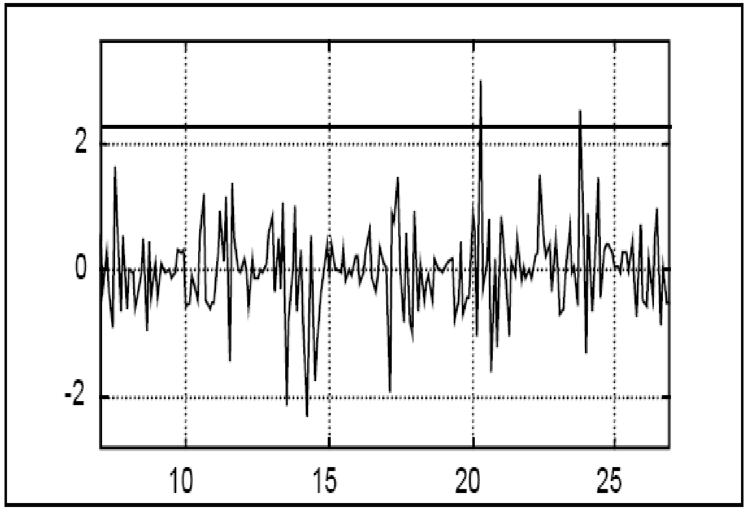
Part 2
Classical integrity monitoring scheme

Usual scheme: Fault Detection (FD)

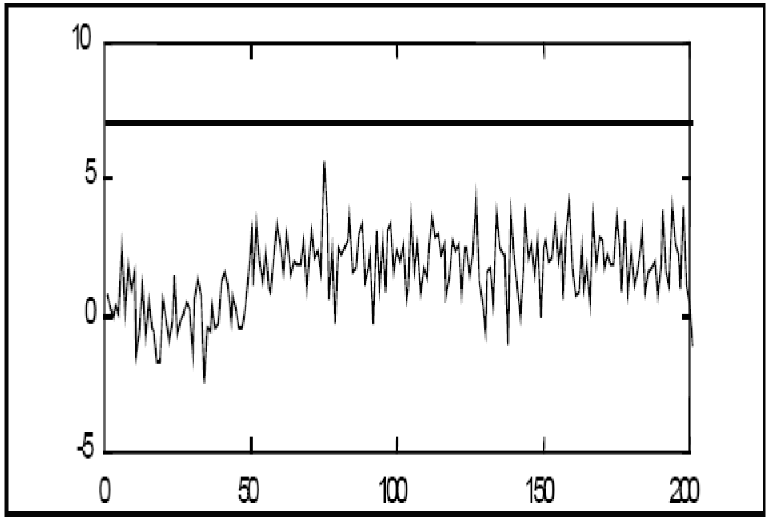
To eliminate doubtful measurements before computing the localization



FD using residuals



False alarm



Missed detection

Risk 1:

To eliminate healthy data and lose information

Risk 2:

To keep misleading information ➔ to compute incorrect localization zones

Residuals generation

Estimation of the measurements:

$\hat{y}_k = h(\hat{x}_k, m)$

where $\hat{x}_k$ is an estimate of the pose.

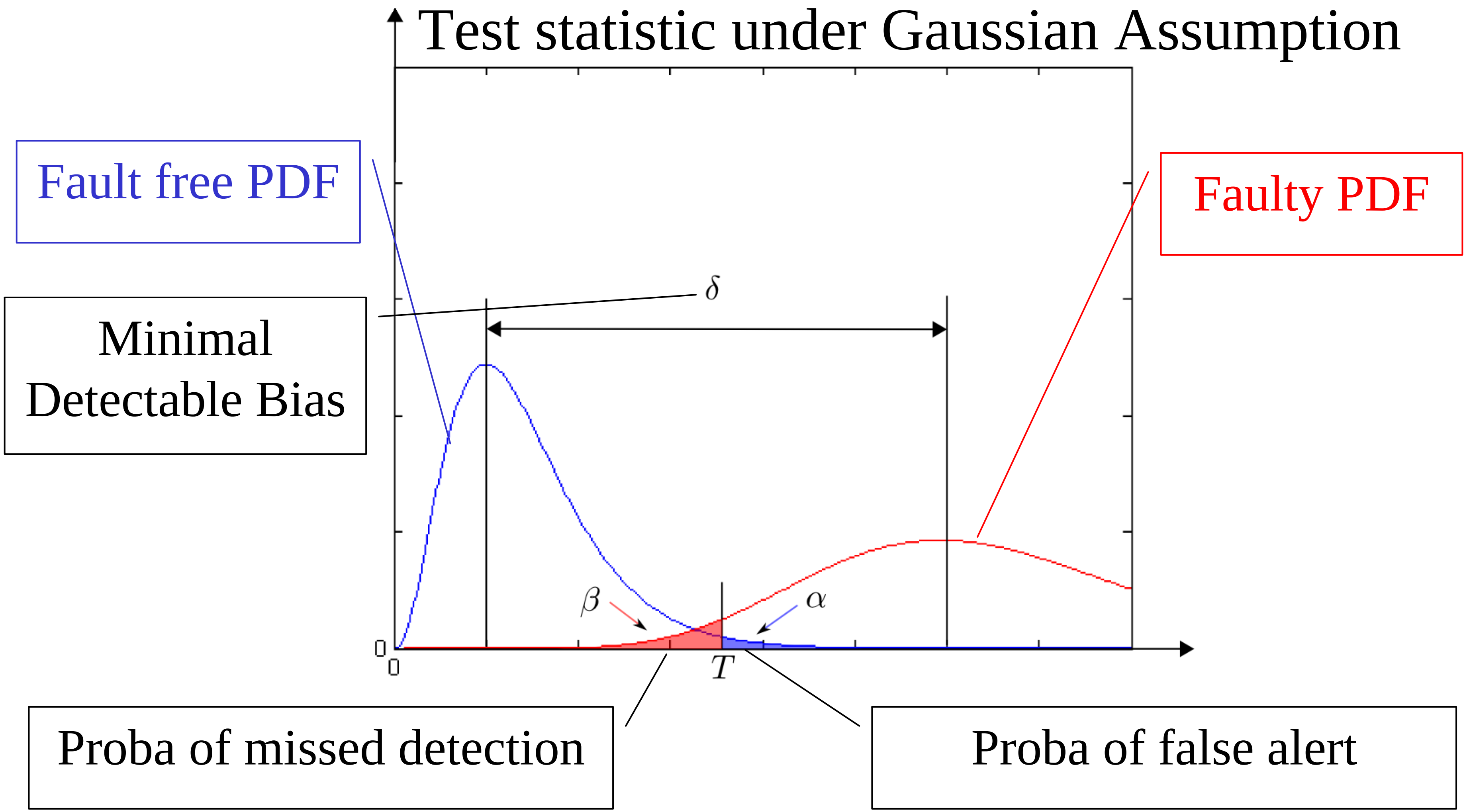
Residuals

$\epsilon_k = y_k - \hat{y}_k$

Sum of the squared errors (SSE):

$SSE = \epsilon_k^T . \epsilon_k$

How to choose the threshold ?



Impact of an undetected fault

Linearization $dy_k = H.dx_k$

Residuals $\varepsilon_k = y_k - h(\hat{x}_k) = (I - HH^+)\cdot dy_k$

Residuals with faults $\varepsilon_k = (I - HH^+)\cdot(dy_k + E)$

If there is only one fault b_i on satellite i $E = \begin{bmatrix} 0 & \dots & b_i & \dots & 0_m \end{bmatrix}$

The error is $e_i^2 = \left(H^{+\ 2}_{(1,i)} + H^{+\ 2}_{(2,i)} + \dots\right)\cdot b_i^2 = \left(HSlope_i \cdot \sigma \cdot \sqrt{\delta}\right)^2$

Worst case $ARP = \max_i \{HSlope_i\}\cdot \sigma \cdot \sqrt{\delta}$

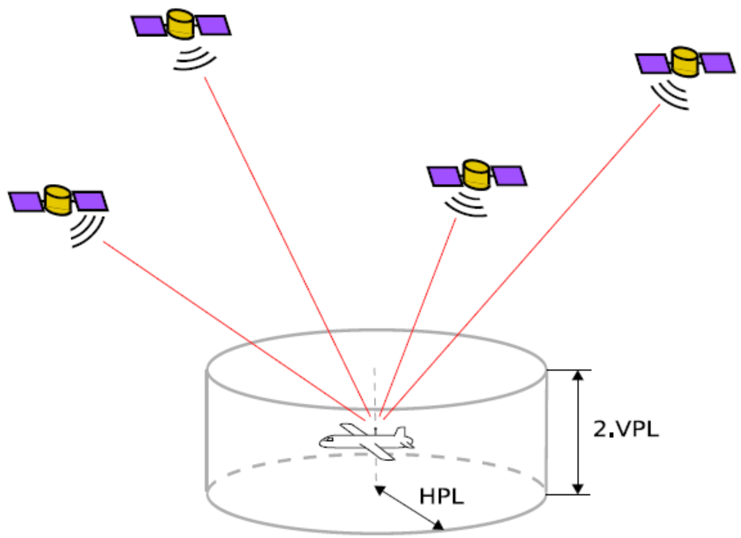
Approximate Radius of Protection (ARP)

Protection Level (PL)

- Combination of noise and an undetected fault

$$PL = \mathrm{DOP} \cdot \sigma + \max_i \{HSlope_i\} \cdot \sigma \cdot \sqrt{\delta}$$

- The PL depends on:
  - The geometry
  - The noise statistics
  - P_{FA} and P_{MD}
- The PL doesn't depend on:
  - The current measurements
  - It can be predicted before navigation



Uncertainty Level (UL)

- The HUL is similar to the HPL except the HUL reflects the actual errors in the measurements and the current geometrical configuration

$$UL = \mathrm{DOP}_{\mathrm{current}} \cdot \sigma + \max_{i} \left\{ HSlope_{i,current} \right\} \cdot fct\left(\left\| \varepsilon_k \right\| \right)$$

- UL is useful for real-time monitoring

Part 3
Application to intelligent vehicles

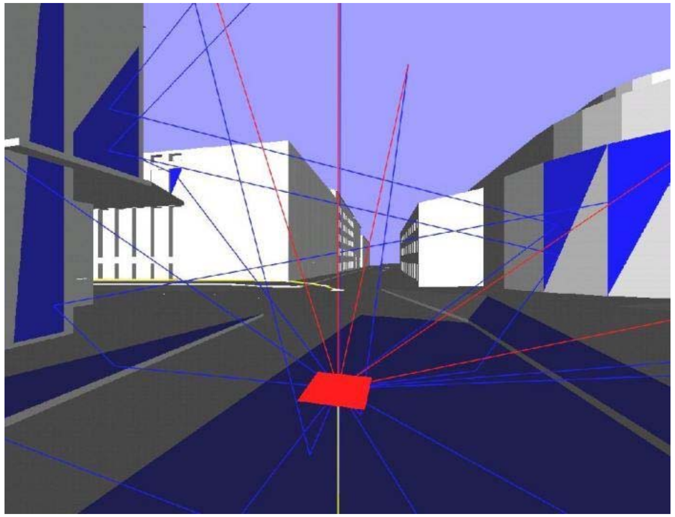
Olivier Le Marchand PhD thesis

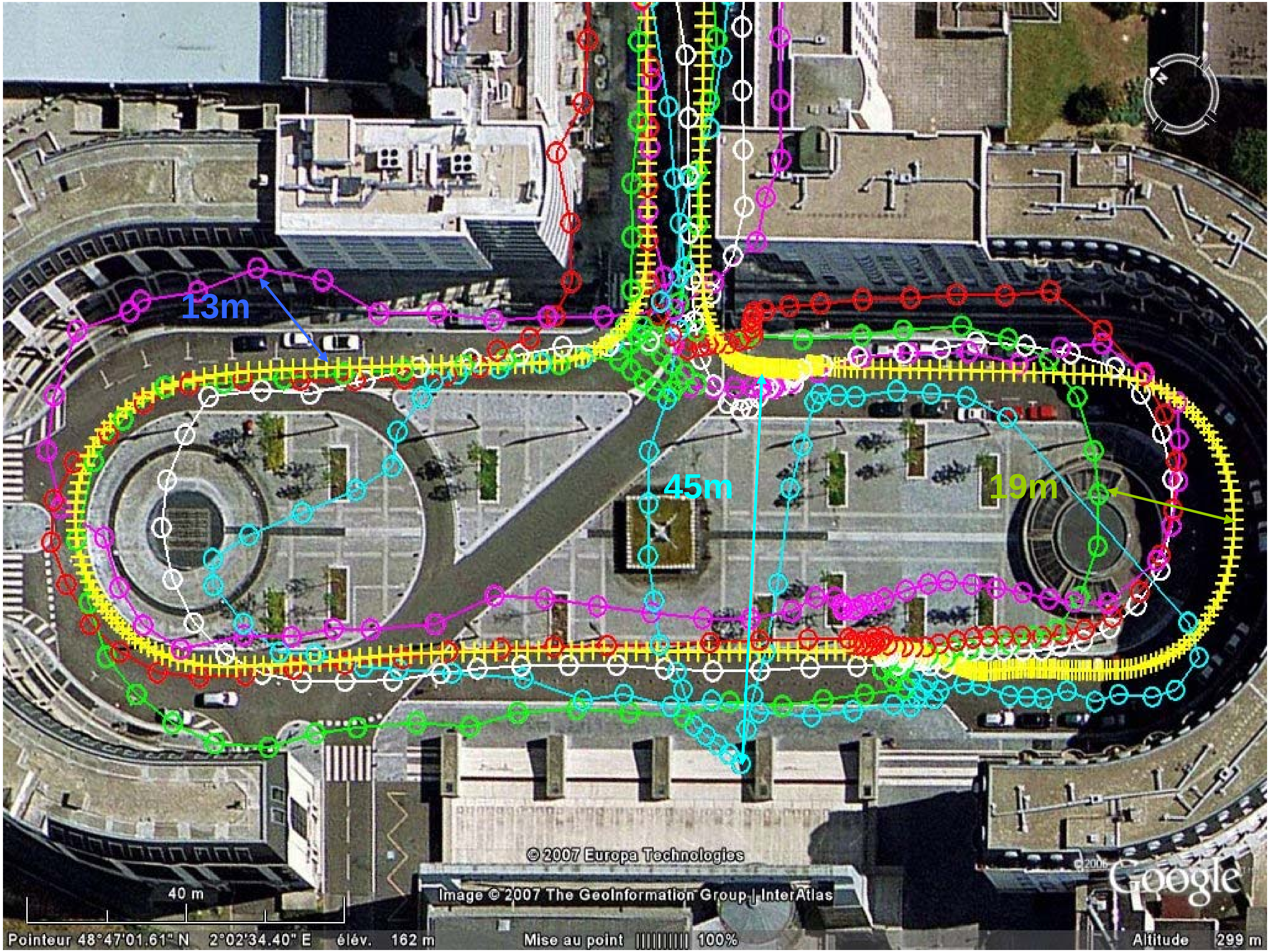
Co-supervisors:

F. Peyret (LCPC), J. Ibañez Guzman (Renault)

Issue

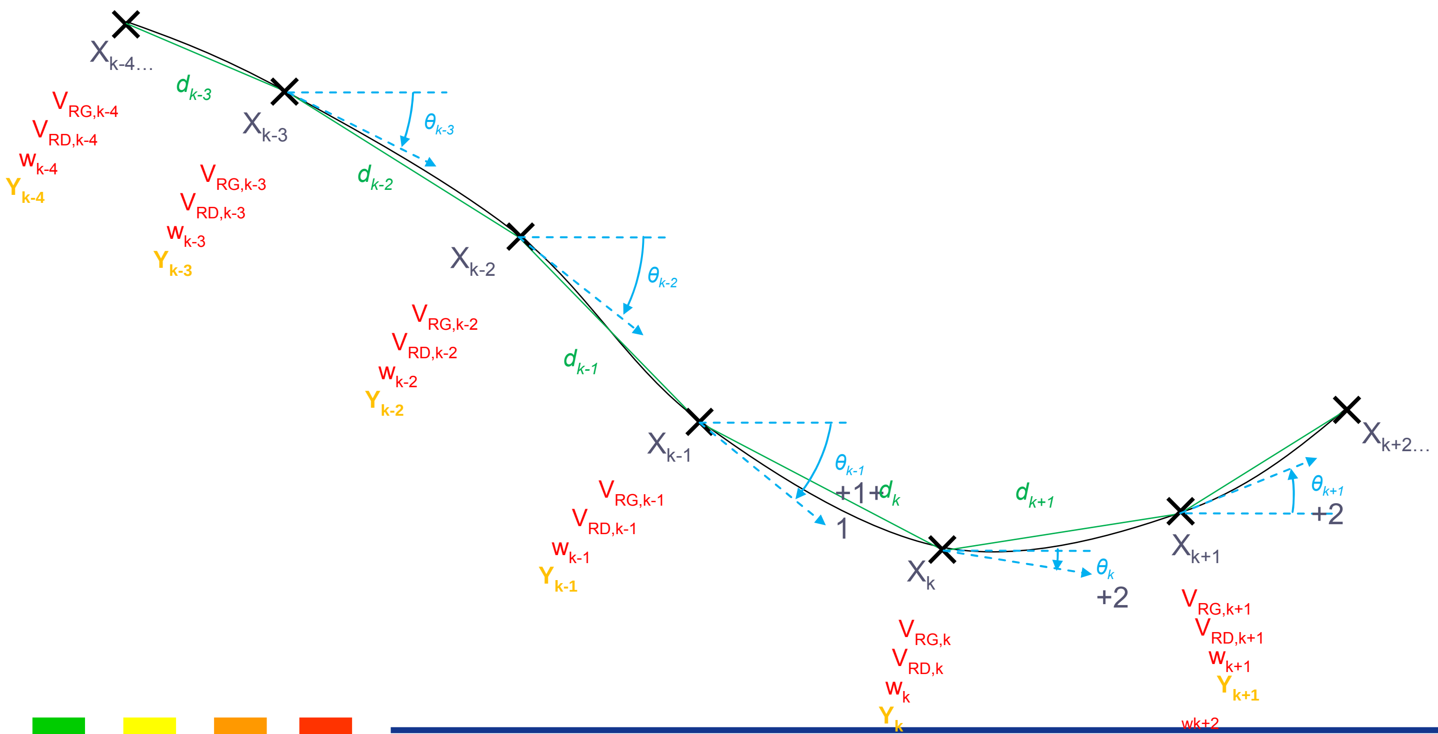
- Road vehicles in urban areas
- GPS alone provides little redundancy
  - Satellites outages
- Multipath is very frequent




13m
45m
19m
© 2007 Europa Technologies
Image © 2007 The GeoInformation Group | InterAtlas
Google
40 m
Pointeur 48°47'01.61" N 2°02'34.40" E élév. 162 m
Mise au point 100%
Altitude 299 m

Proposal

- To exploit the dead-reckoning sensors to elaborate data horizon on several epochs, in order to increase the redundancy (degree of freedom)



Problem formulation

- Algebraic manipulations

$$u_k = g\left(x_{k-m},\ldots,x_k\right)$$

- Constraints on the trajectory
  - for instance, constant speed, low variation altitude

$$\vec{0} = l\left(x_{k-n},\ldots,x_k\right)$$

Implementation

Stack data

$$\begin{cases} \vec{0} = l(x_{k-n,k}) \\ u_{k-n,k} = g(x_{k-n,k}) \\ y_{k-n,k} = h(x_{k-n,k}) \end{cases}$$

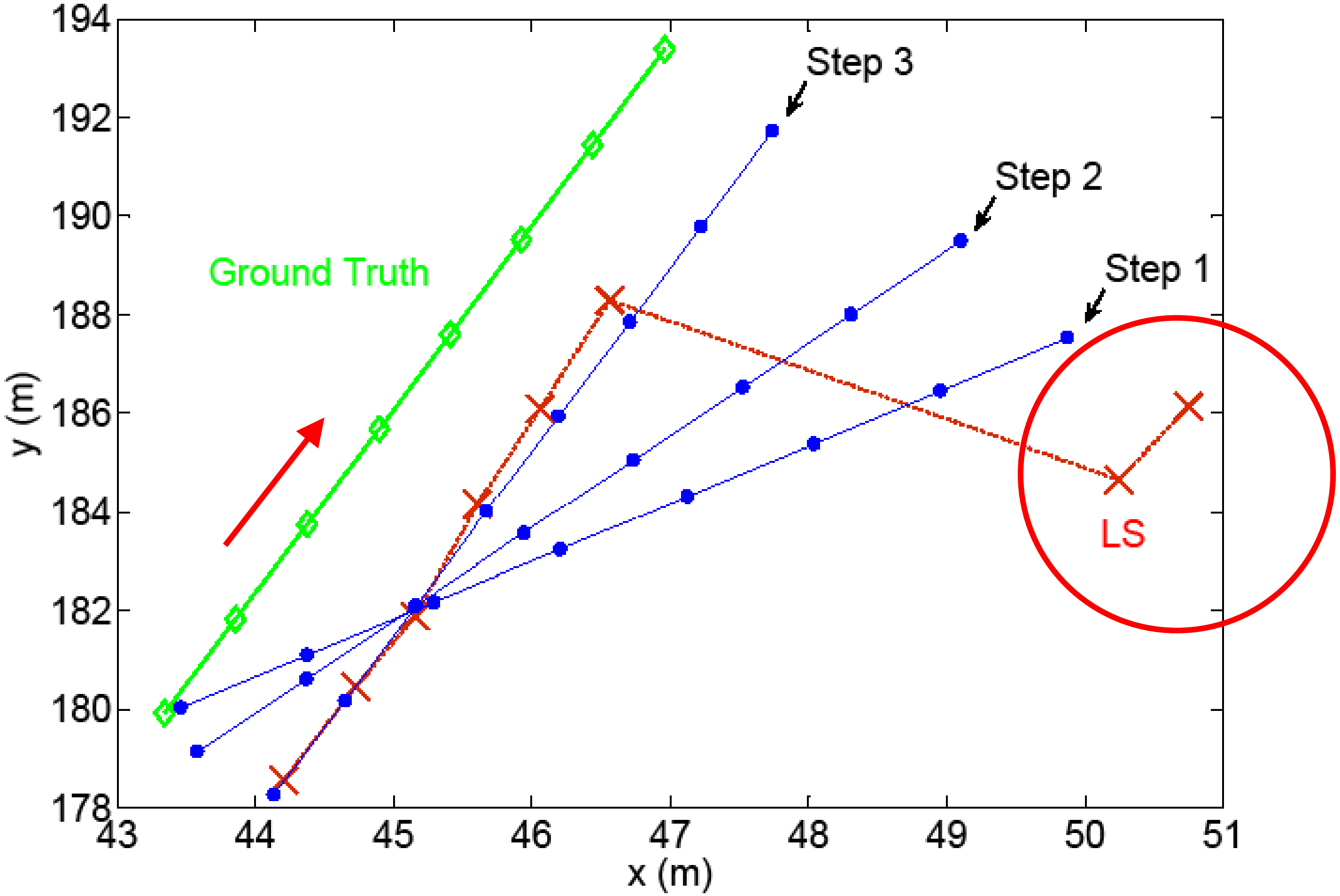
Linearization

$$\begin{bmatrix} \vec{0} \\ du_{k-n:k} \\ dy_{k-n:k} \end{bmatrix} = \begin{bmatrix} \frac{\partial l}{\partial x} \\ \frac{\partial g}{\partial x} \\ \frac{\partial h}{\partial x} \end{bmatrix}_{x_{k-n:k}} \cdot dx_{k-n:k}$$

1. Apply successive checks to detect and eliminate aberrant measurements

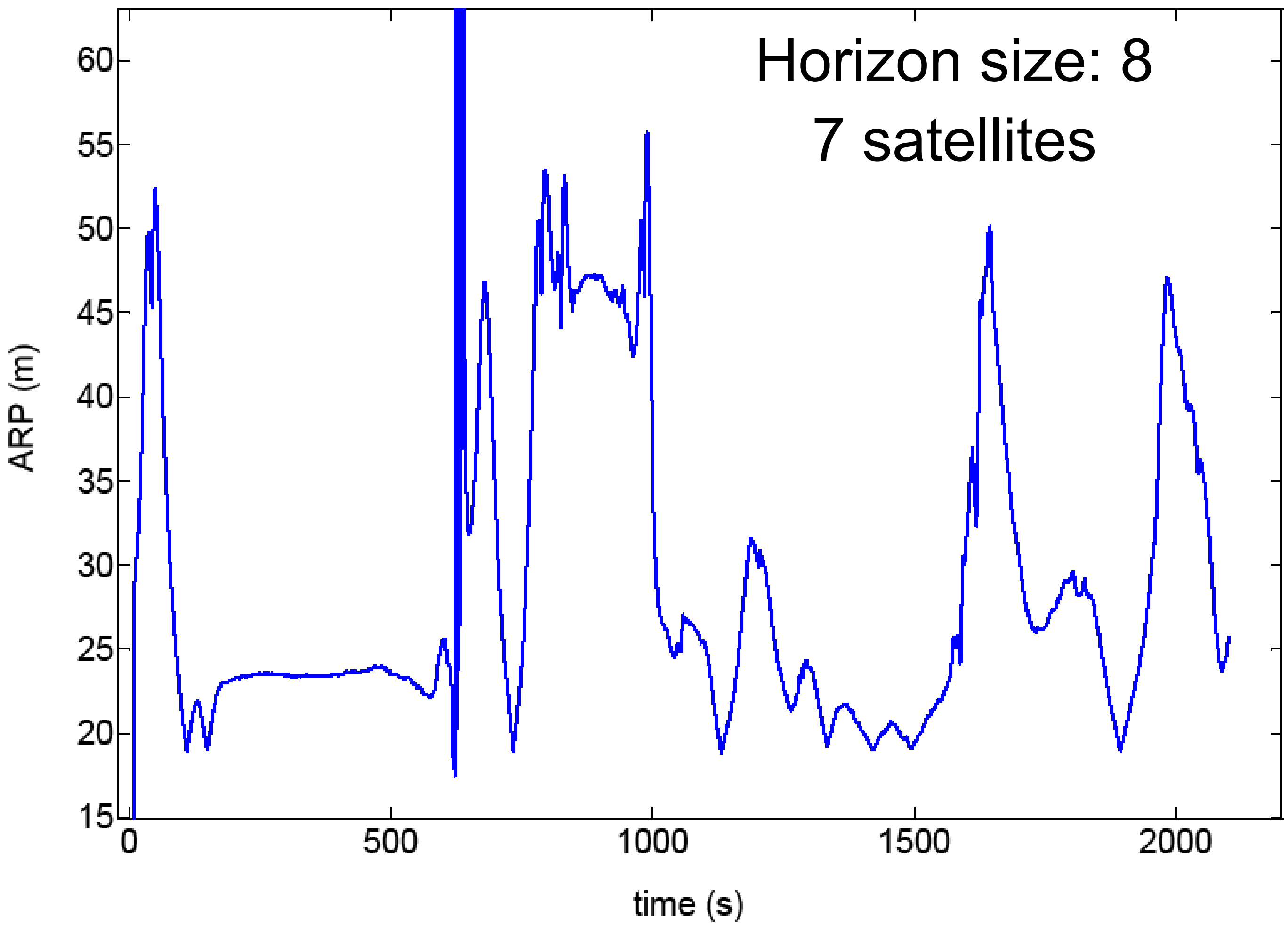
2. Estimate a location zone under assumption that no more than one fault remains

FDE result



Effect of faulty pseudo-range

ARP (max{SLOPE} effect)

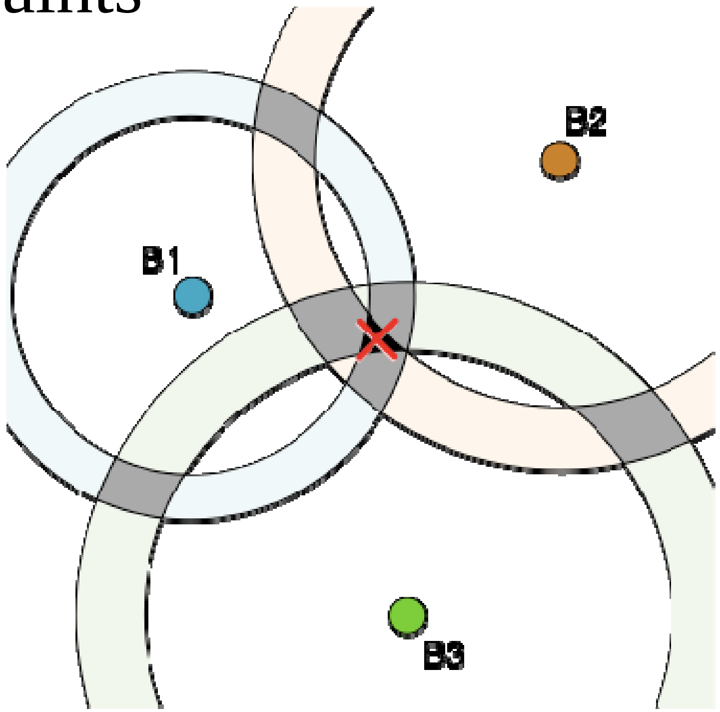


Part 4
A new strategy using bounded errors

Vincent Drevelle PhD thesis

Set-Membership Positioning

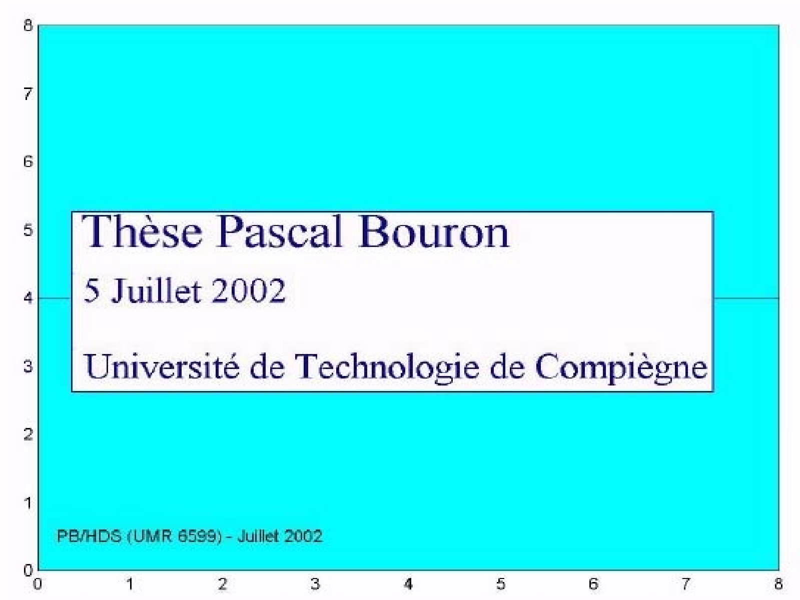
- Each measurement acts as a constraint on location
- Find the set of locations fulfilling all the constraints



Example:
Beacons with uncertain distance measurements

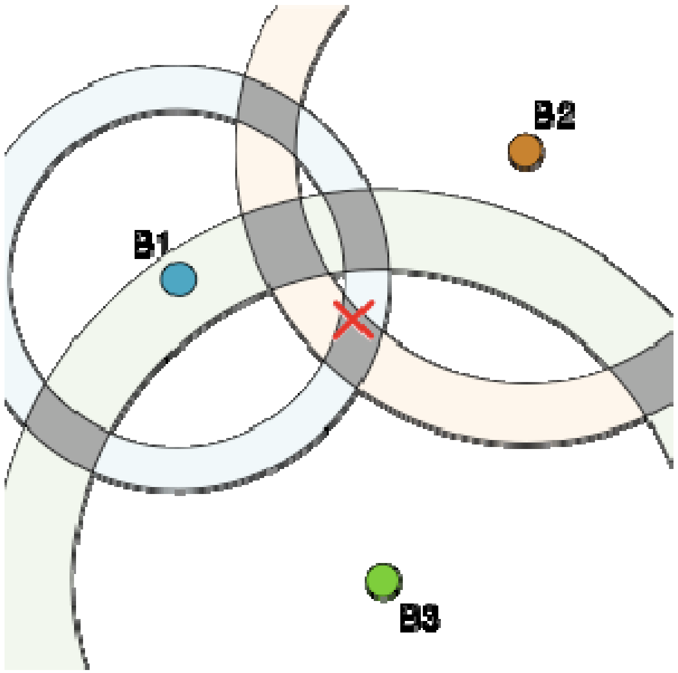
Set Inversion

- Approximation of a set between two subpavings
- Constraints Propagation
  - contraction of boxes using relationships between variables and parameters
  - limit the number of bisections

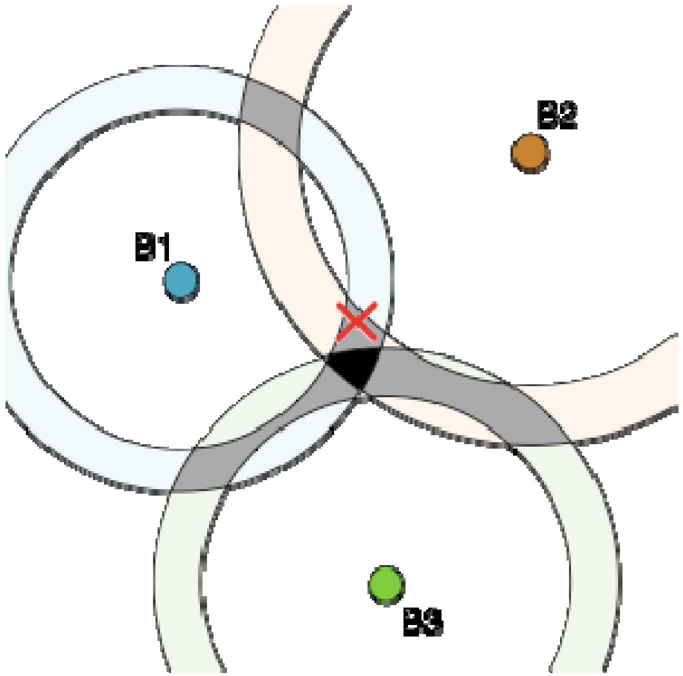


Influence of Outliers

No solution (empty set)

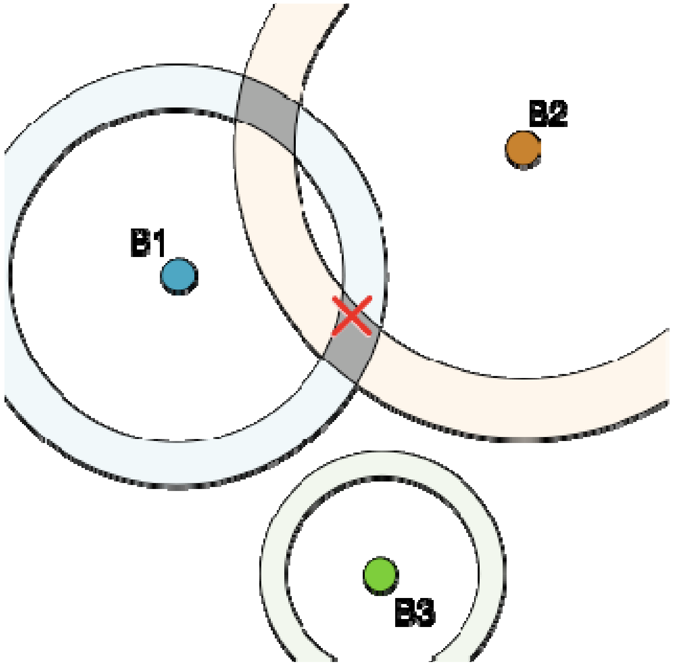


Misleading solution



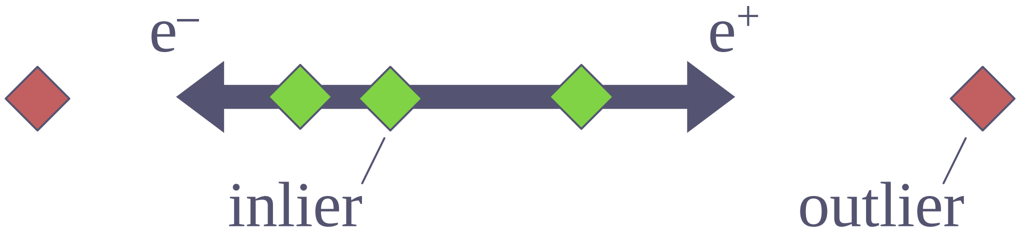
Robust Set Inversion

- q-relaxed intersection (Jaulin 2008)
  - Find the set fulfilling at least *m-q* constraints out of *m* constraints

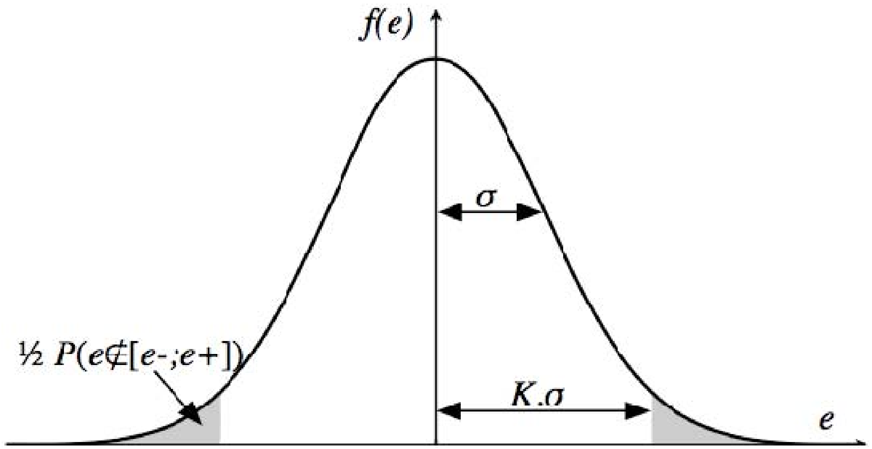


Noise Model

- Minimalist model: 2 error bounds $[e^{-},e^{+}]$



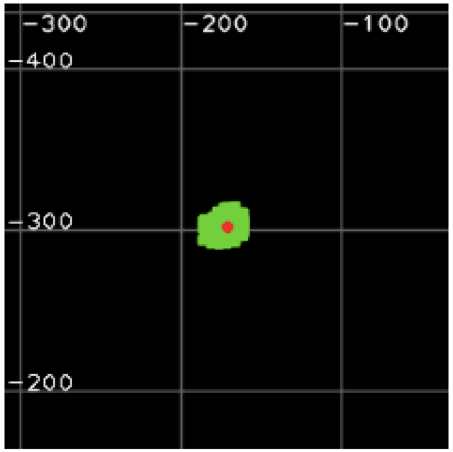
- SBAS provides 2nd order information
  - Overbounding Gaussians
  - [–Kσ,+Kσ] bounds
  - K is computed w.r.t. a chosen confidence *p*



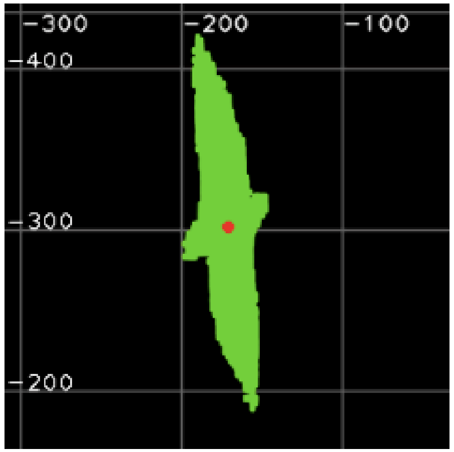
Experimental Results

- Septentrio PolaRx receiver
- Ground truth: post processed DGPS with local base
- 6 satellites used
- EGNOS SBAS corrections and error parameters

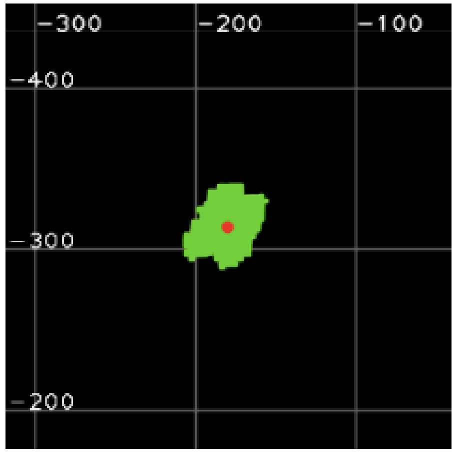
Horizontal Location Zone



non robust
GPS only



1-relaxed robust
GPS only



1-relaxed robust
GPS + DEM

±6-sigma measurement error bounds

Conclusion

- Managing noise, faults, and localization uncertainties is crucial for many IV applications
- Two strategies have been presented
  - FDE based on residuals + HPL/HUL computation
  - Q-relaxed set-membership approach
- In urban areas, GPS provides little redundancy and suffers from several multipaths
  - data horizon on several epochs using dead-reckoning sensors