Using interval analysis in real-time for mobile robot integrity monitoring

Philippe Bonnifait

Heudiasyc UMR7253 CNRS

Université de Technologie de Compiègne

France

IPA 2012 UPPSALA

Localization Quality of Service

3 key attributes

Availability

- The percentage of time that the localizer is providing estimates respecting navigation requirements

Accuracy

- The statistical difference between the location estimate and the true value of the location.

Integrity

- A measure of the trust that can be put in the information from the localizer (i.e., likelihood of undetected failures).

heudiasyc

Integrity

Ability to associate to a result a reliable indication of confidence.

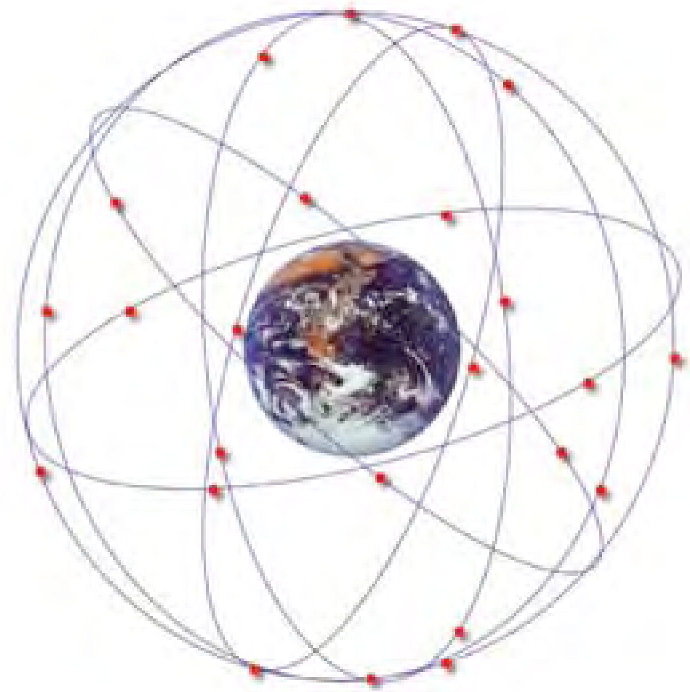
Civil aviation

- The indicator is a confidence domain
- Alert Limit: maximum tolerable error in the position solution
- Time to alert : maximum time between the occurrence of an alarm condition and its signaling
- Integrity risk: probability that the position error exceeds the alert limit without the user being informed during the time to alert

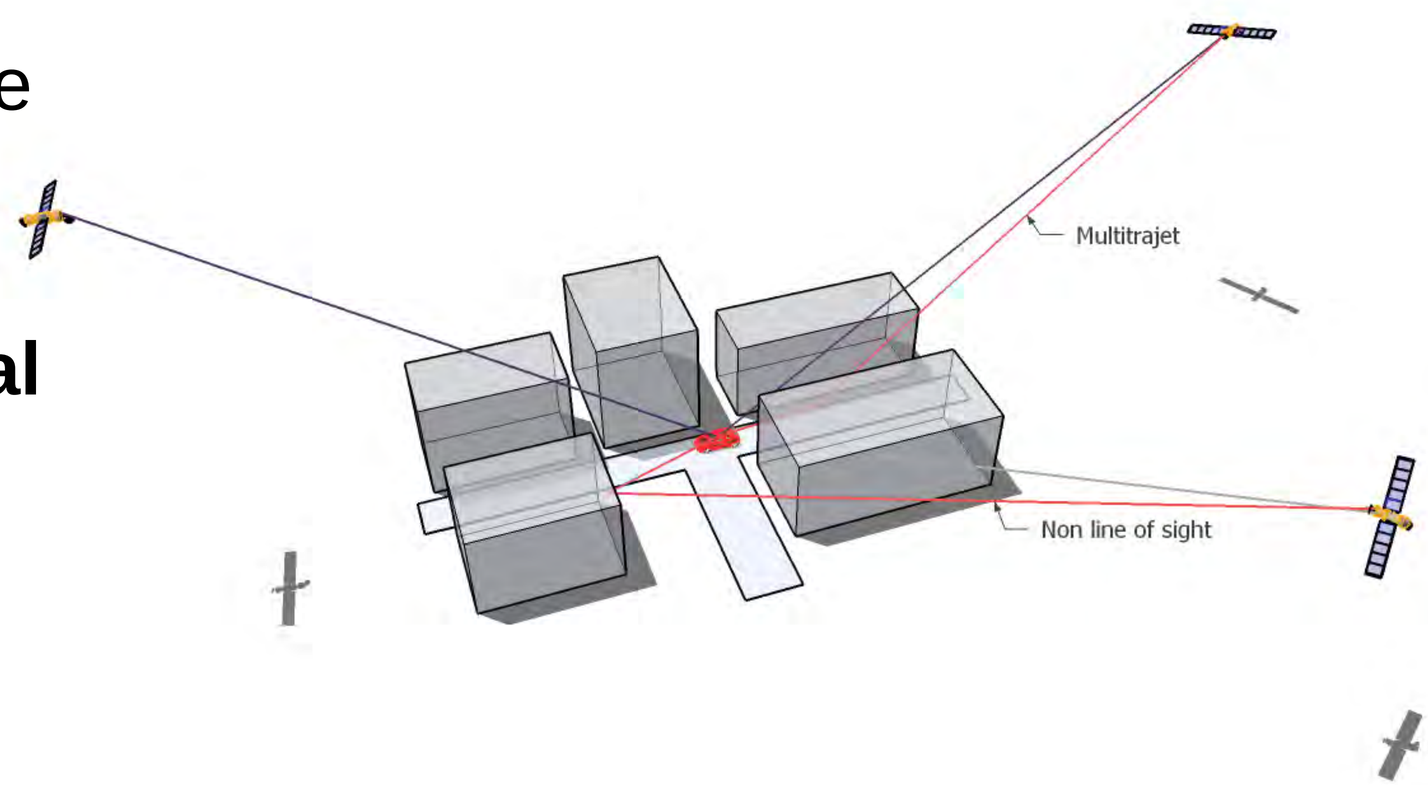
[RTCA/DO-229D]

heudiasyc

Localization uncertainty



- A localization system implements measures on exteroceptive landmarks.
- The design of a system (coverage, geometry, signals, landmarks...) is made in terms of quality of service objectives.
- In complex environment, the visibility of the landmarks and the quality of the measures can be severely degraded
- **The user must estimate in real time the confidence in the estimated position**.



heudiasyc

Localization uncertainty

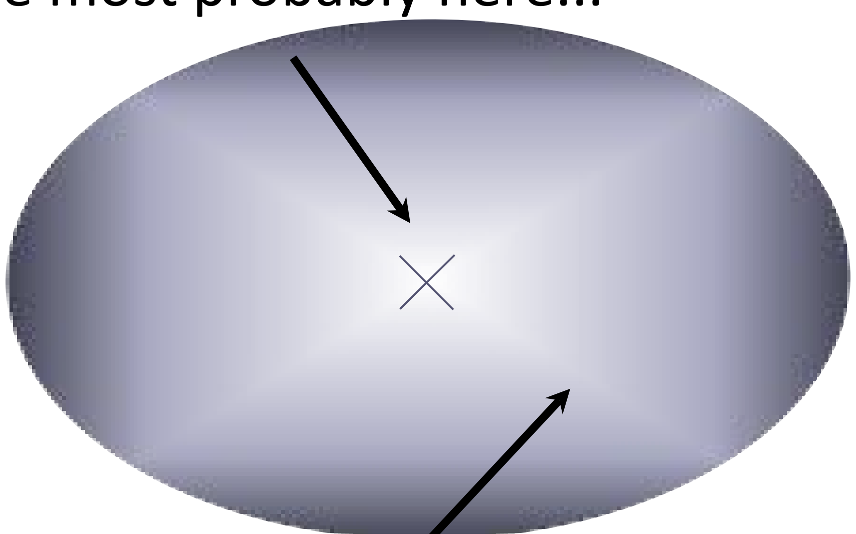
Knowledge of positioning uncertainty is necessary to decide if position information is relevant for the current application

Localization uncertainty is time and location dependent

- Geometrical configuration - Noise - Faults

Second order moments

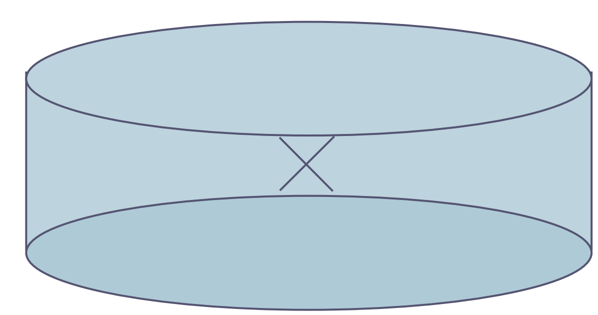
You are most probably here...



...and less probably here

Protection levels

You are somewhere inside this box

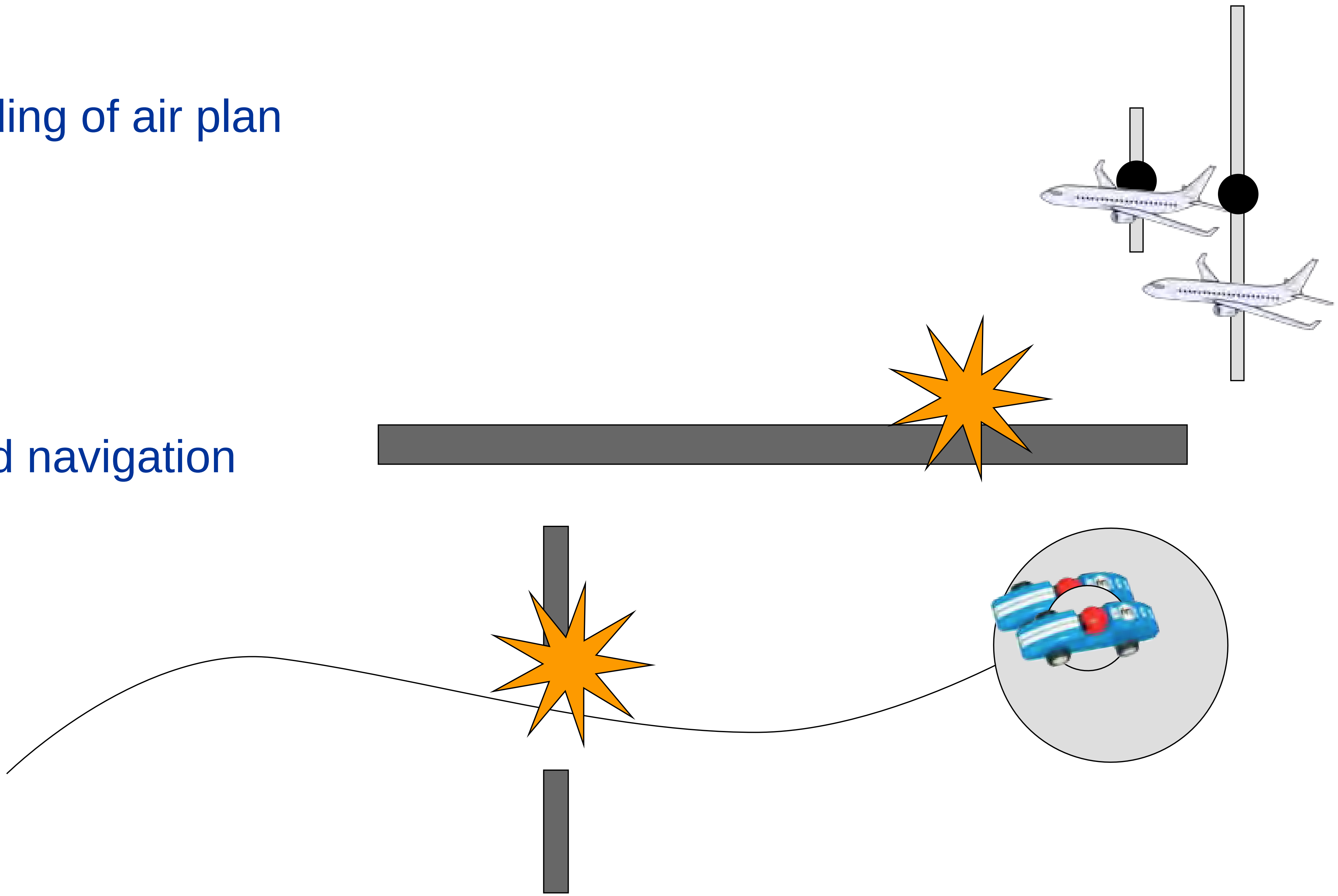


On the use of the confidence during navigation

Confidence must be compatible with navigation requirements

- Landing of air plan

- Road navigation

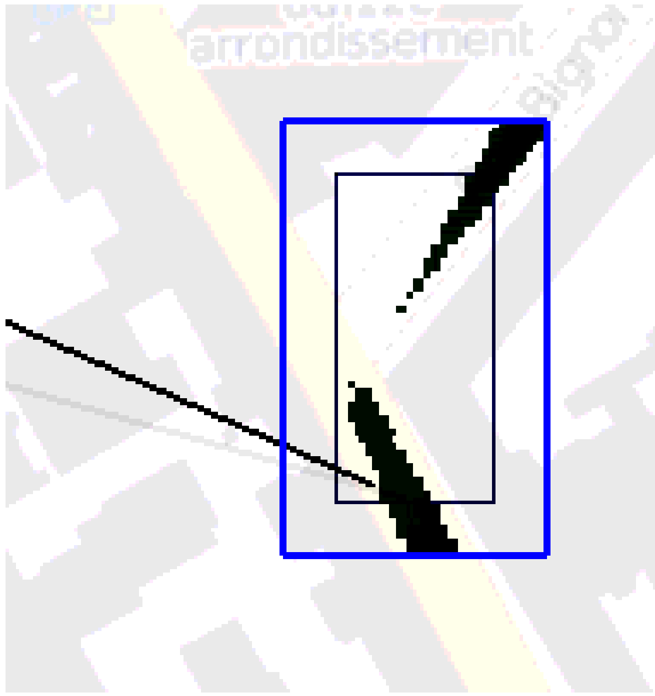


Bounded-error framework

A way to compute positioning confidence domains is to use interval analysis

The set of positions compatible with the measurements and constraints

- Arbitrary shaped solution set
- Disconnected sets in case of ambiguity
- With a integrity risk computed using the pdf of the noise



Outline

Sources of information

Location domain computation using set inversion

Adding maps for challenging environments

Robust set inversion

Risk computation

Confidence domain validation through real experiments

Fault detection and identification

Conclusion

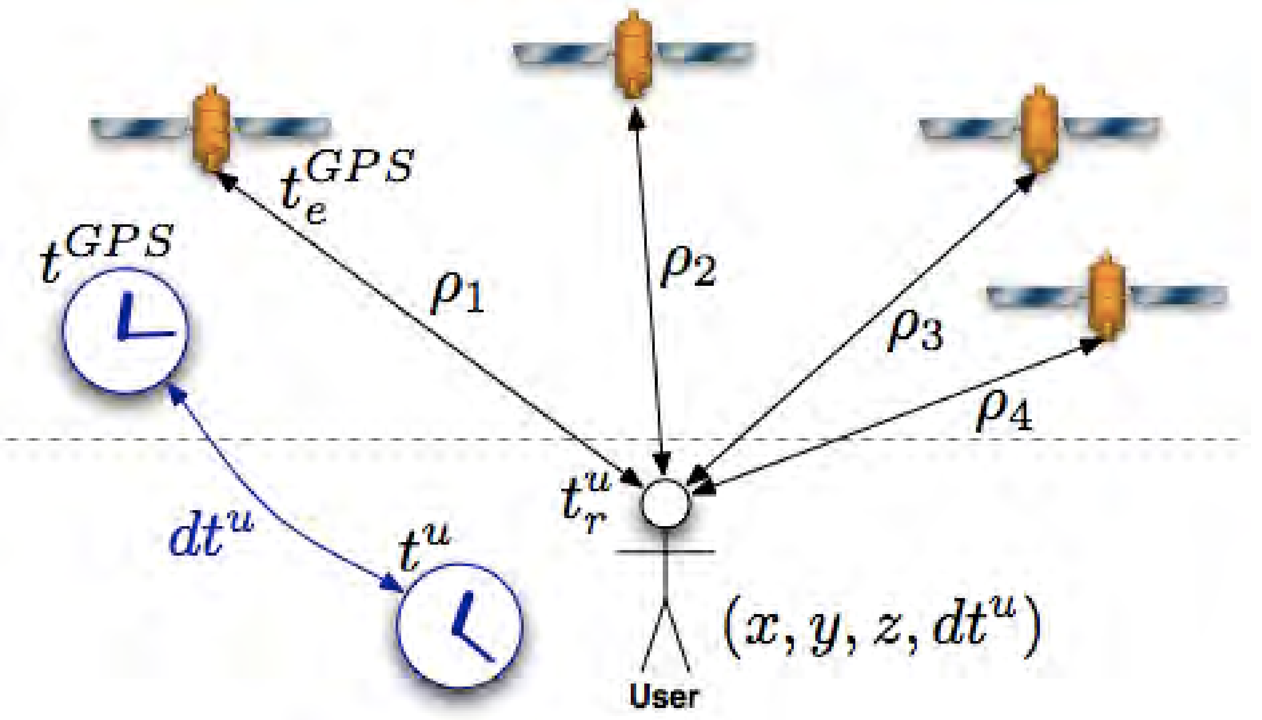
heudiasyc

Sources of information

Classical GPS positioning problem

-Receiver measures pseudo-ranges:
range + offset

-4 unknowns: x, y, z, dtu



-Pseudo-range observation model:

$$\begin{cases} \rho_1 & = \sqrt{(x - x_{s1})^2 + (y - y_{s1})^2 + (z - z_{s1})^2} + c \cdot dtu \\ \rho_2 & = \sqrt{(x - x_{s2})^2 + (y - y_{s2})^2 + (z - z_{s2})^2} + c \cdot dtu \\ & \dots \\ \rho_p & = \sqrt{(x - x_{sp})^2 + (y - y_{sp})^2 + (z - z_{sp})^2} + c \cdot dtu \end{cases}$$

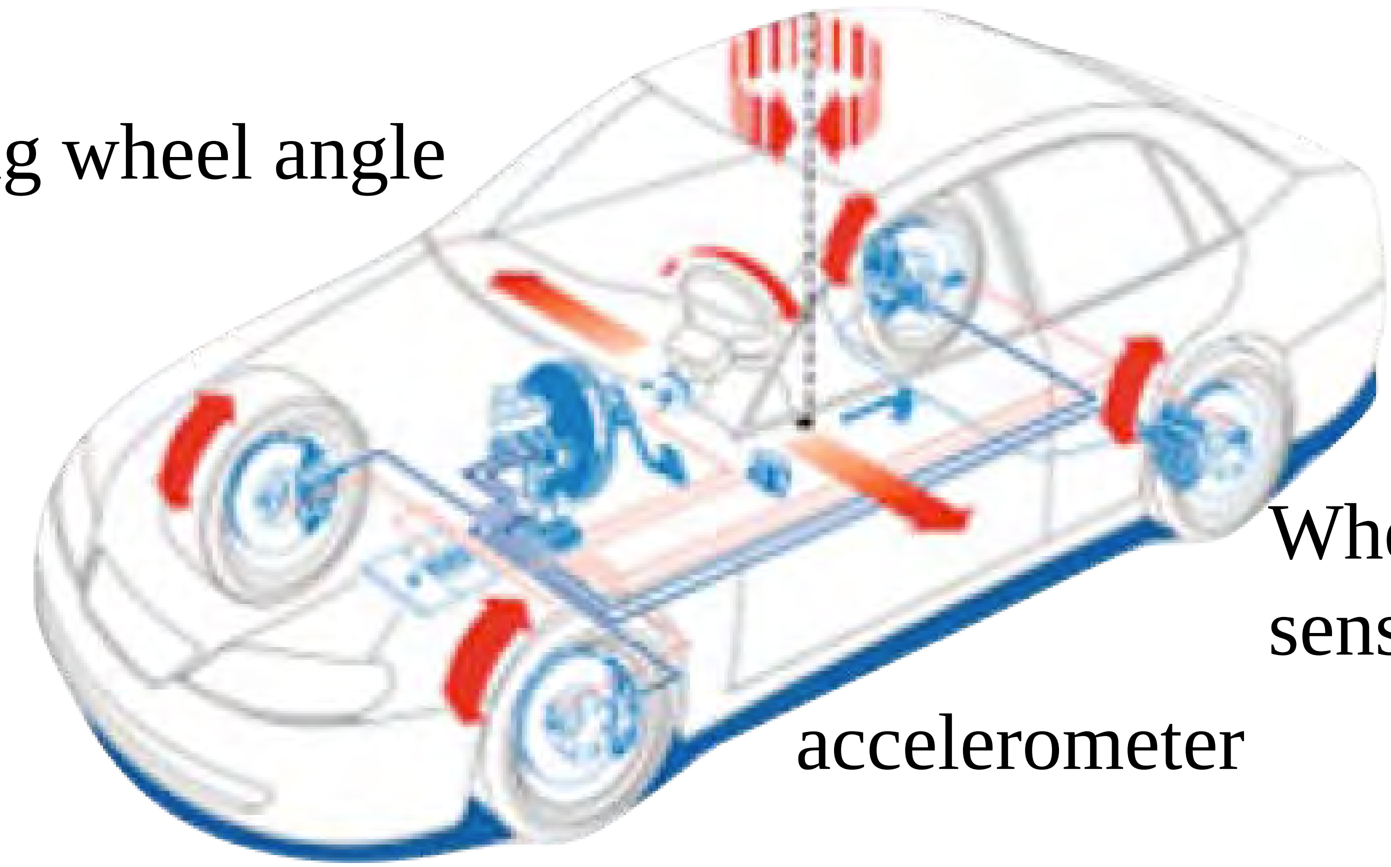
$x_{s_i}, y_{s_i}, z_{s_i}$ are satellite positions (broadcast)

ρ_i are corrected pseudoranges:

heudiasyc

Proprioceptive sensors

- Easily accessible via the CAN-bus of modern vehicles
- Used to determine the movement of the vehicle



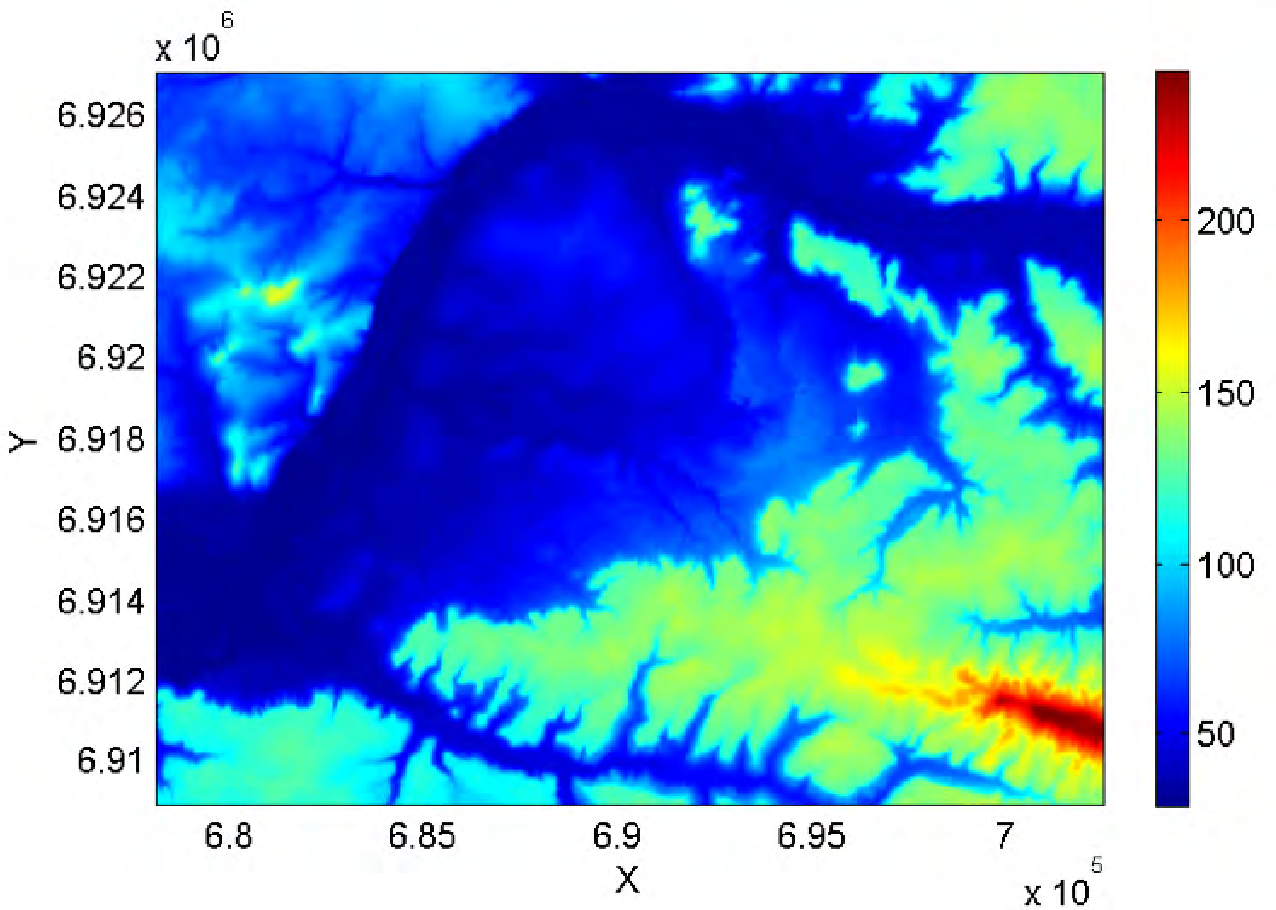
Digital Terrain Model

Digital representation of the altitude

- Square mesh (metric)
- pseudo-square (meridian-parallel)

Examples :

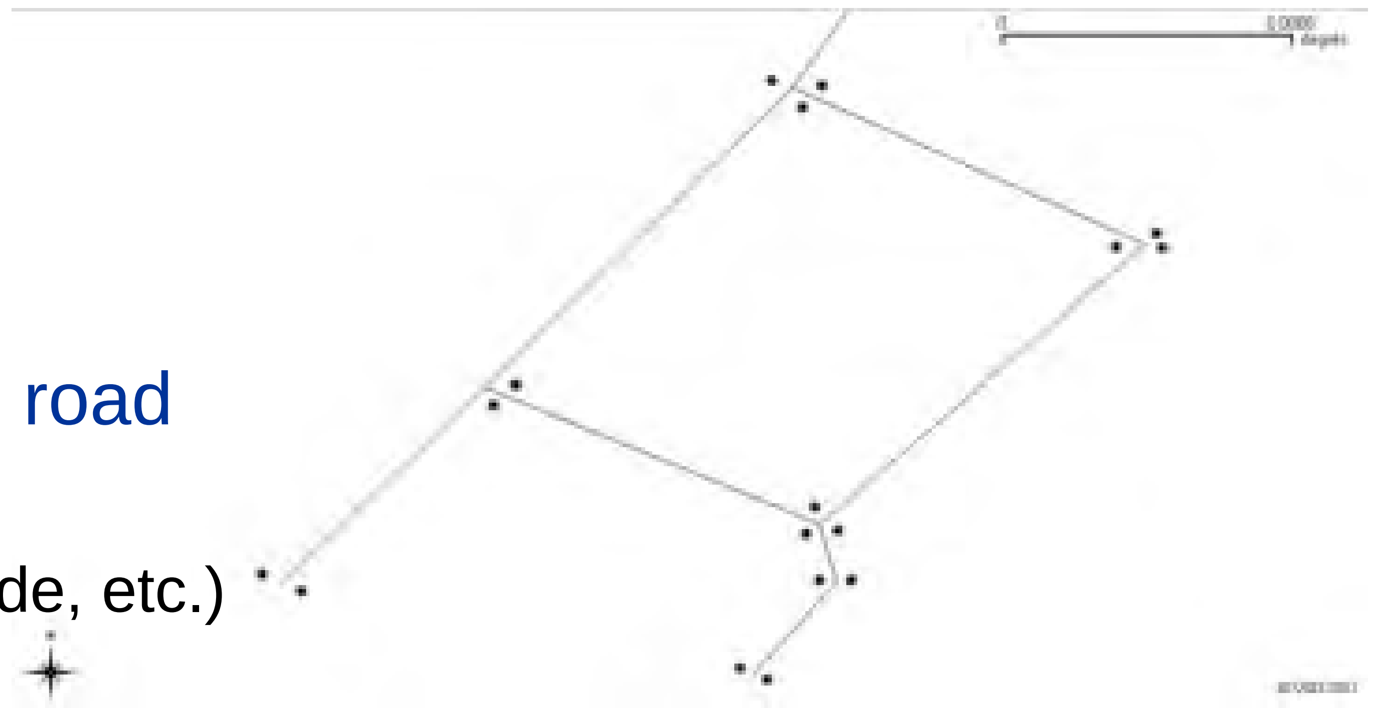
- SRTM-3 (NASA) : World
  - Mesh 90 m / ±14 m alti
- MNT BD Topo (IGN) : France
  - Mesh 25 m / ±1 m alti



Map

Linear representation

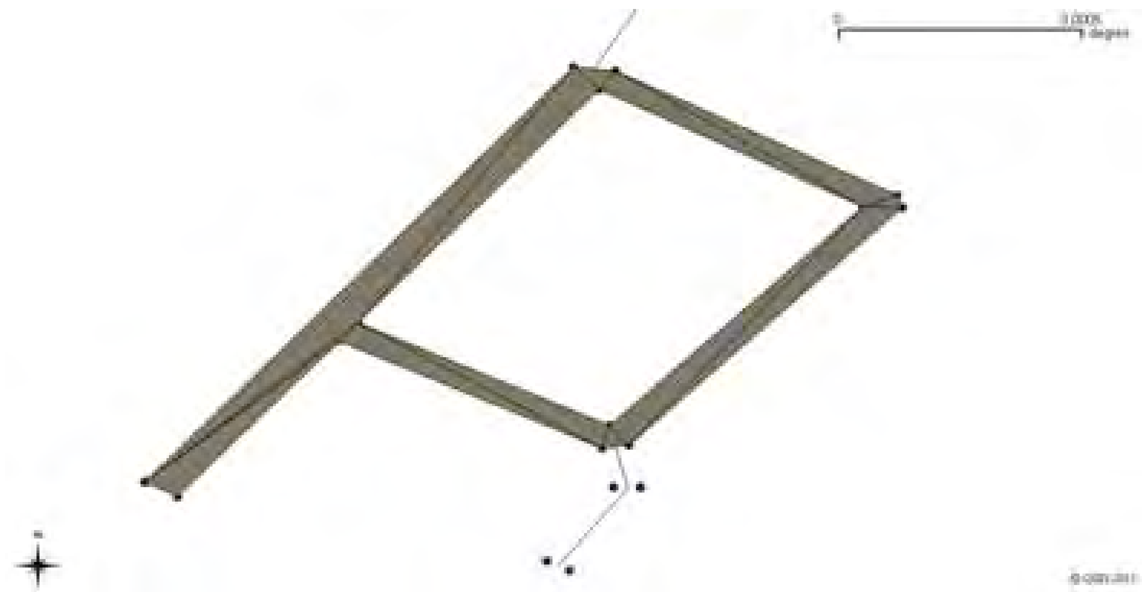
- Poly-lines describing the road network
  - attributes (speed limit, altitude, etc.)



[Betaille et al, 2008] Making an enhanced map for lane location based services

Surface

- Surface Describing the drivable space
  - 3D points
  - Triangular facets



- *[Paparoditis et al, 2000] Surface reconstruction in urban areas from multiple views of aerial digital frame cameras*

heudiasyc

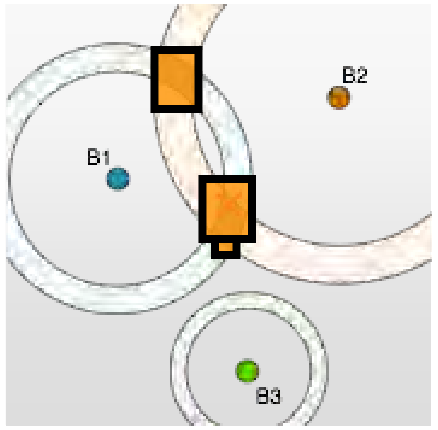
3D facets of the drivable space

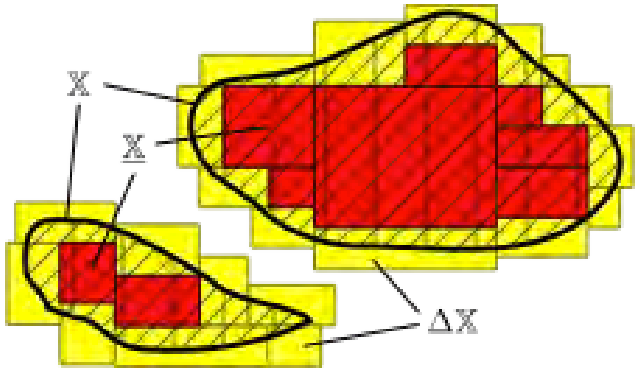
Produced by the French Institut Géographique National

- Photogrammetry from aerial photographs
- Precision of vertices
    - 5 cm planar / 20 cm altitude

heudiasyc

Location domain computation using set inversion





Bounded-error GPS positioning

Bounded-error framework

- Measurements = Intervals
- Intervals are assumed to include the true value with a given probability

Positioning is a Constraint Satisfaction Problem

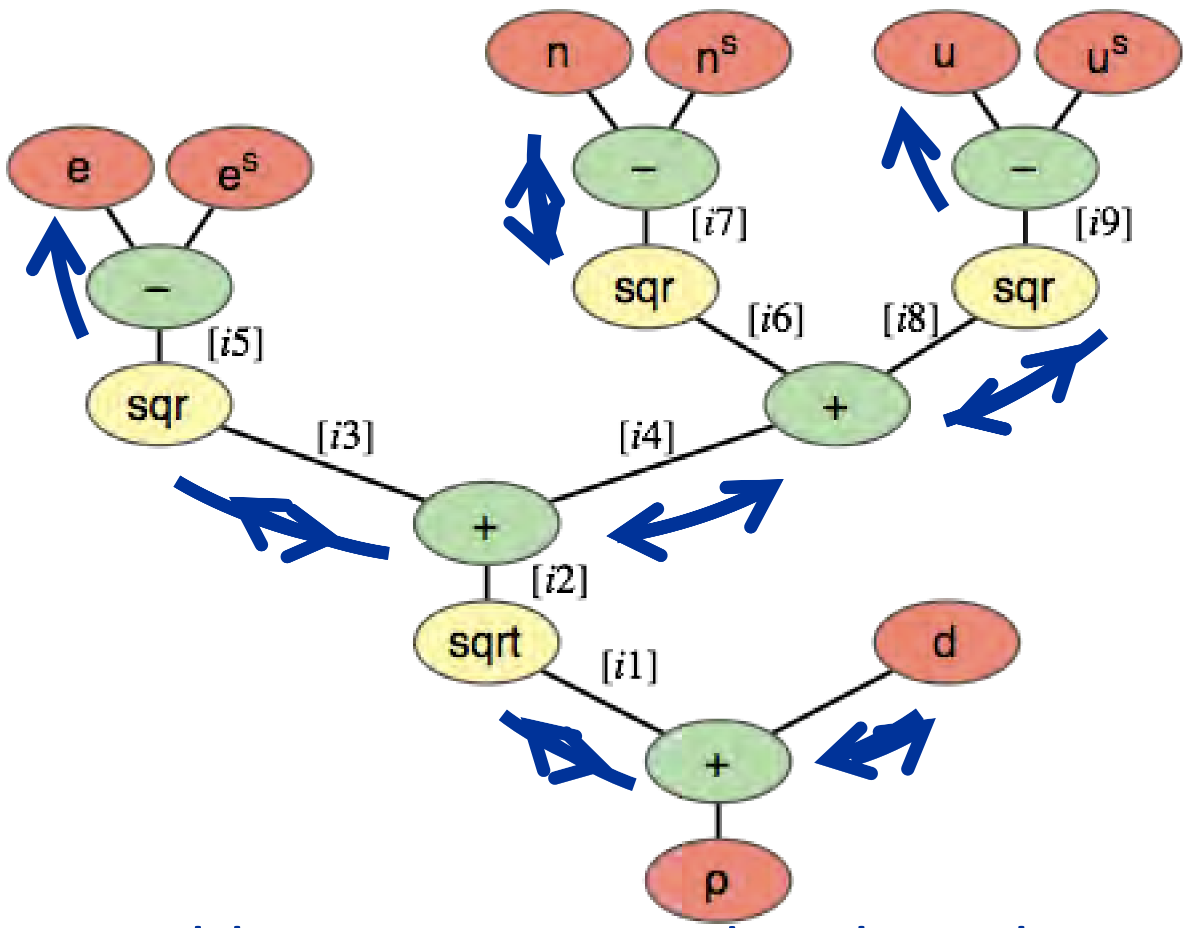
- Measurements = Constraints on position
- Position = Intersection of constraints

Pseudorange constraint

Each measurement is a constraint on position

$$[\rho_i] = \sqrt{([e]-[e_i^s])^2 + ([n]-[n_i^s])^2 + ([u]-[u_i^s])^2} + [d]$$

Prior position box is contracted with « fall - climb » constraint propagation



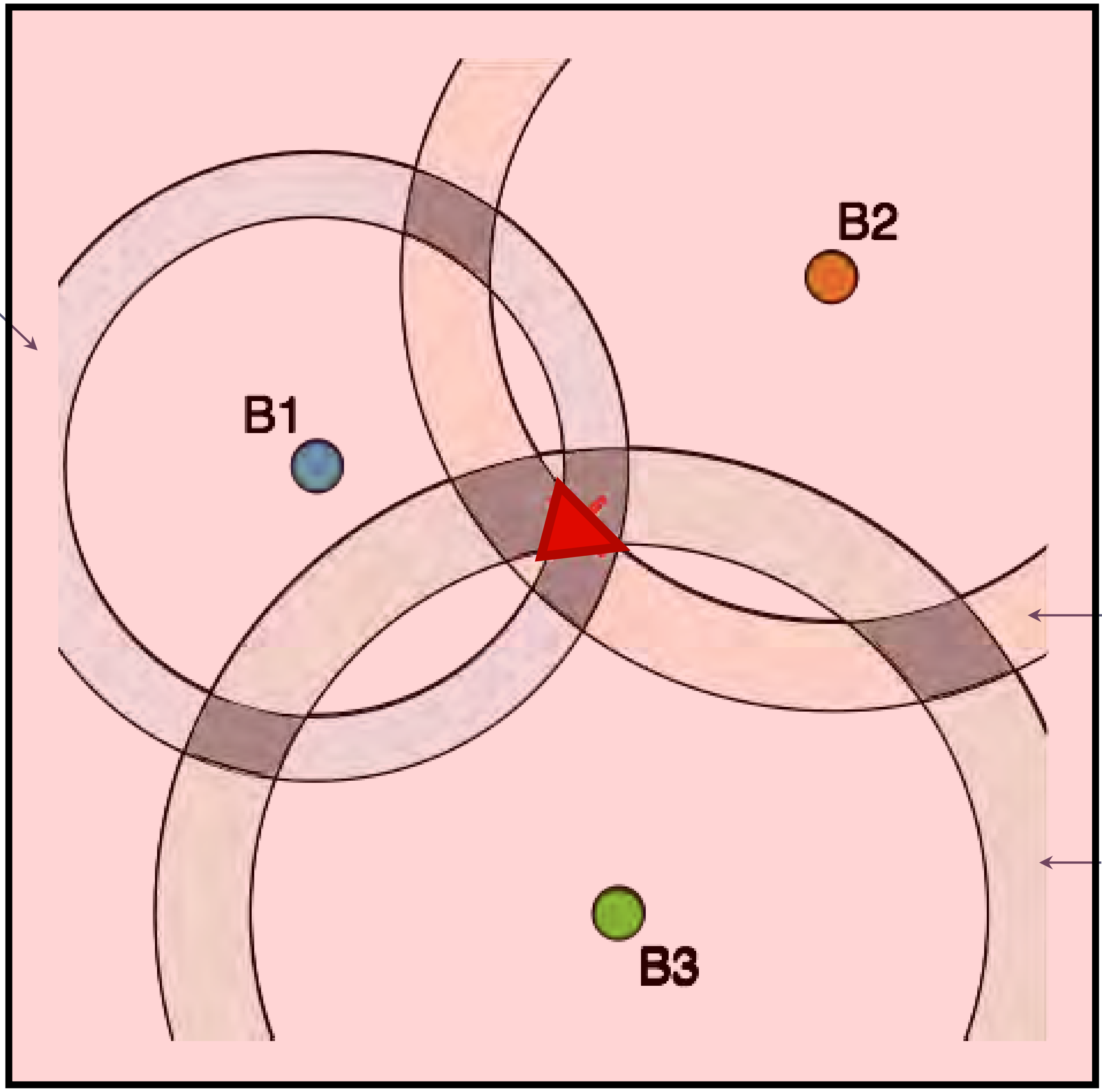
The domains of the variables are narrowed without losing solution

Contraction is successively applied with each pseudo-range, until a fixed point

Illustrative example

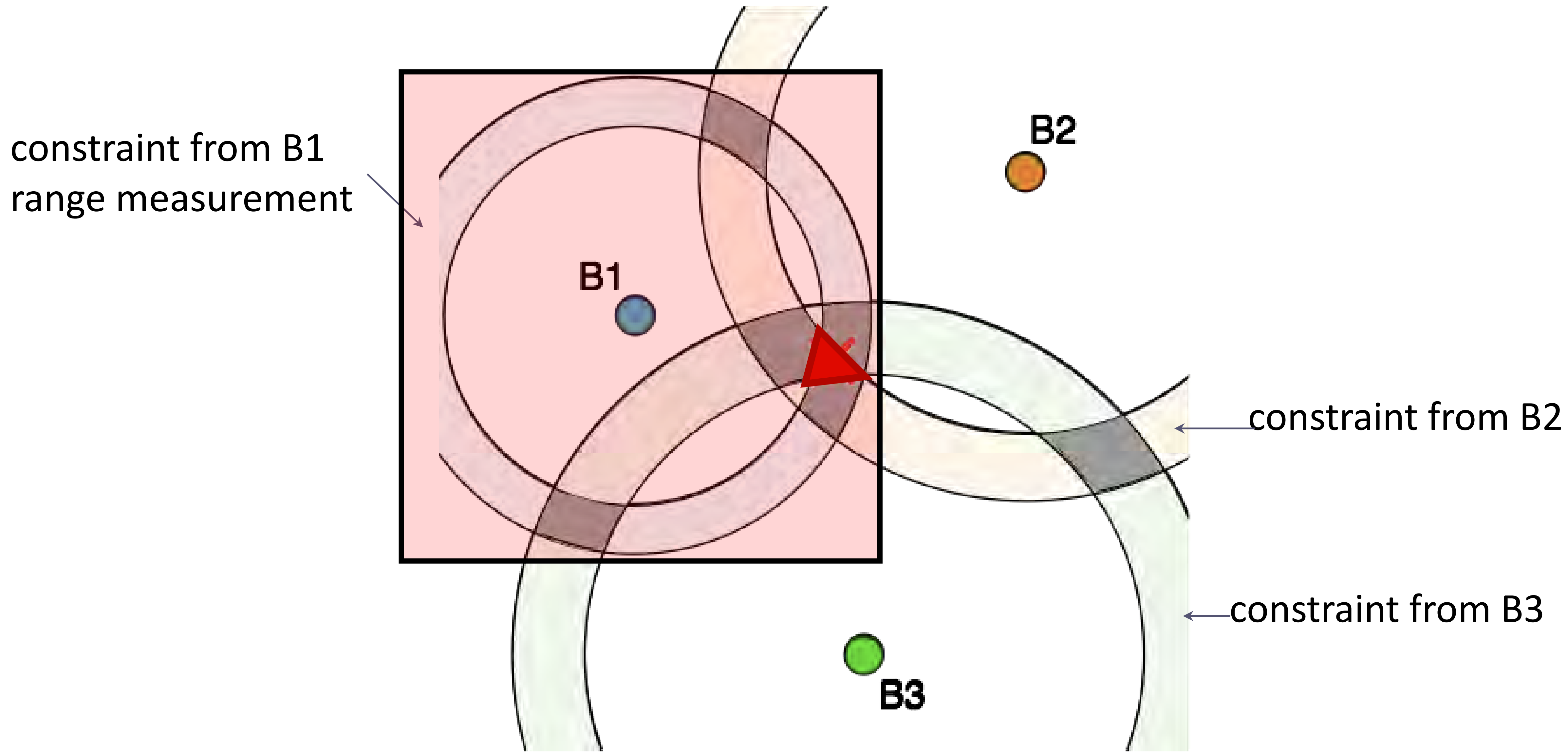
prior position box

constraint from B1
range measurement



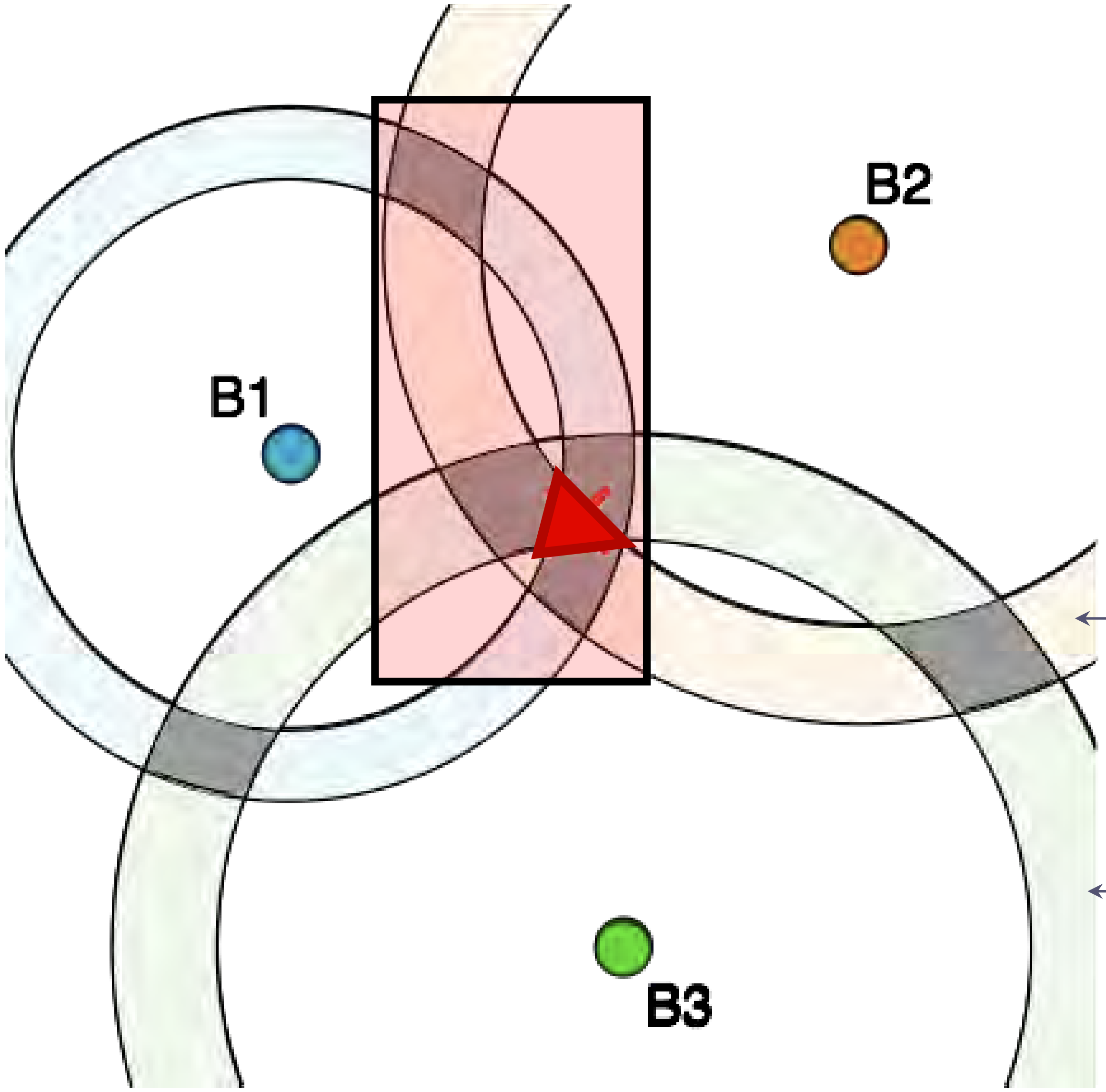
constraint from B2

constraint from B3



constraint from B1
range measurement
B2
B1
constraint from B2
constraint from B3
B3

constraint from B1 range measurement

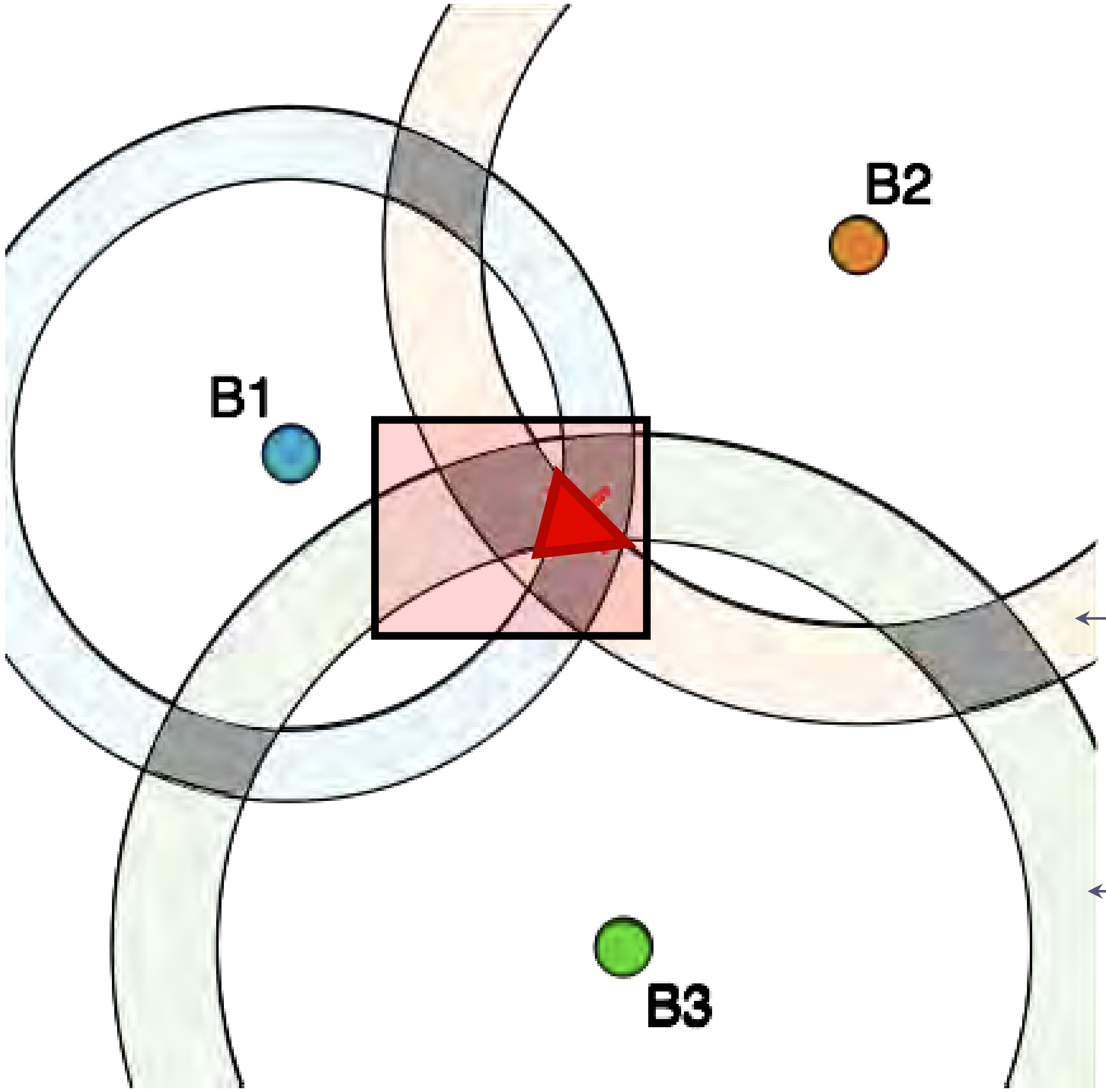


constraint from B2

constraint from B3

heudiasyc

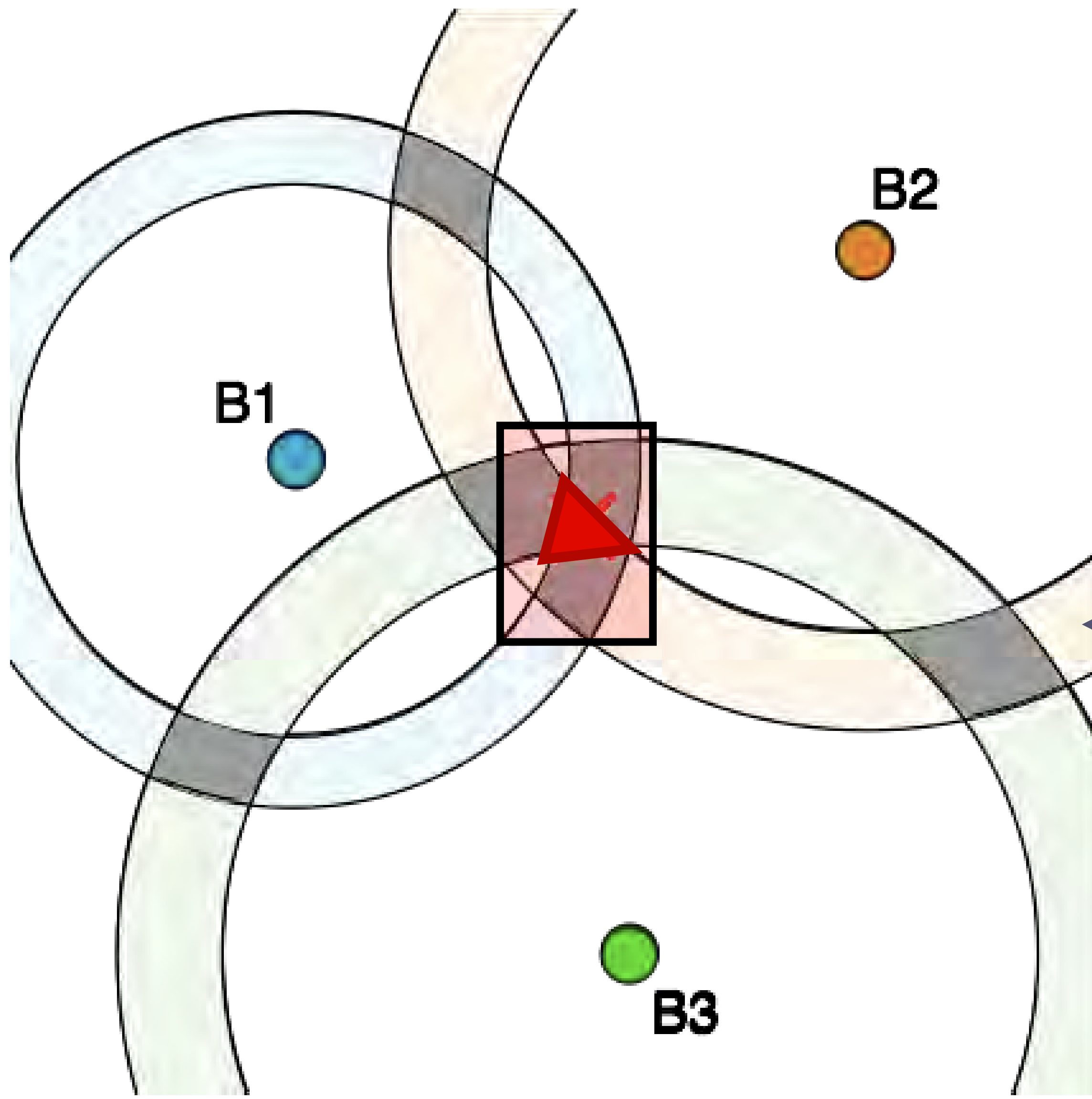
constraint from B1
range measurement



constraint from B2

constraint from B3

constraint from B1
range measurement

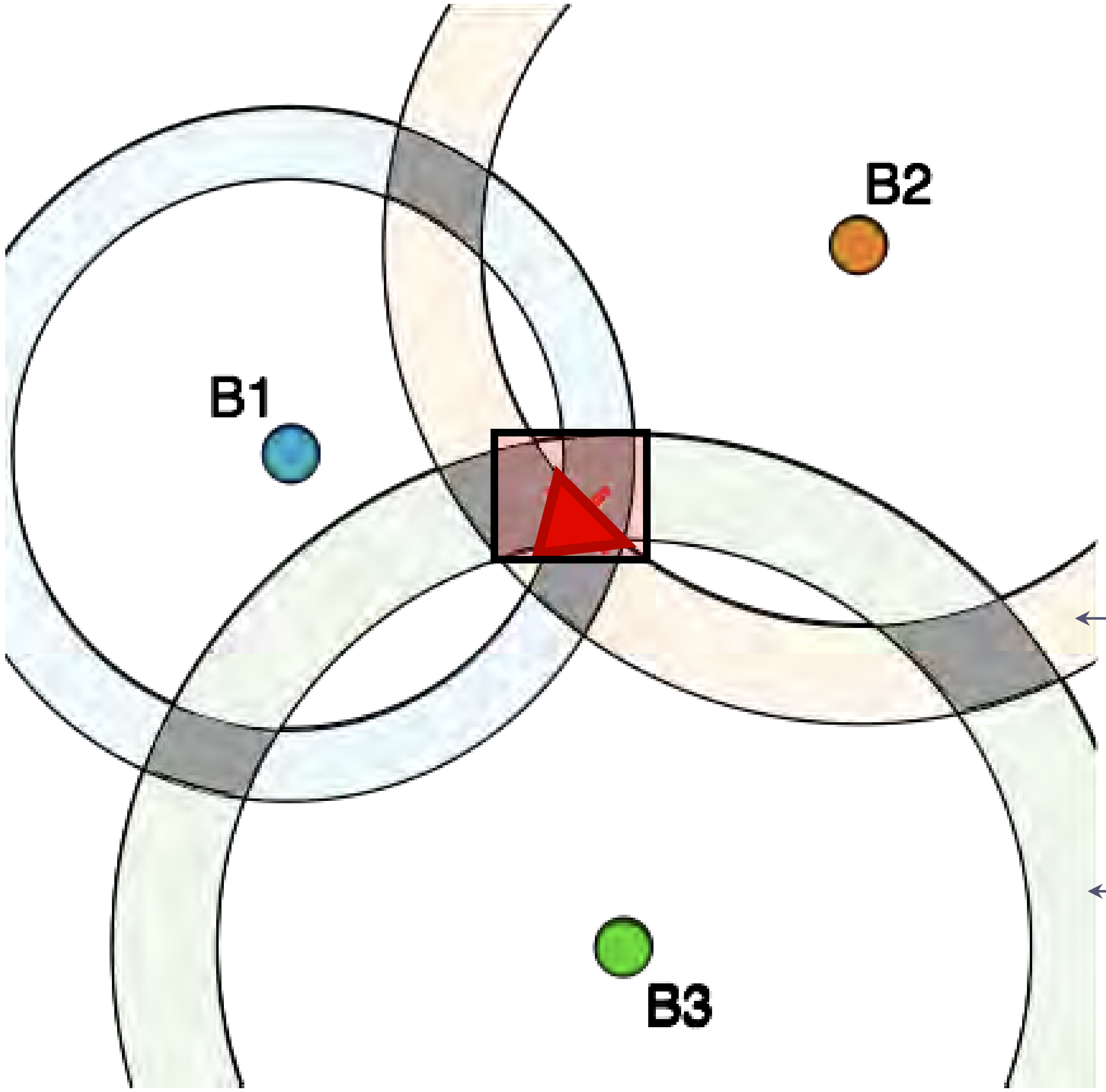


constraint from B2

constraint from B3

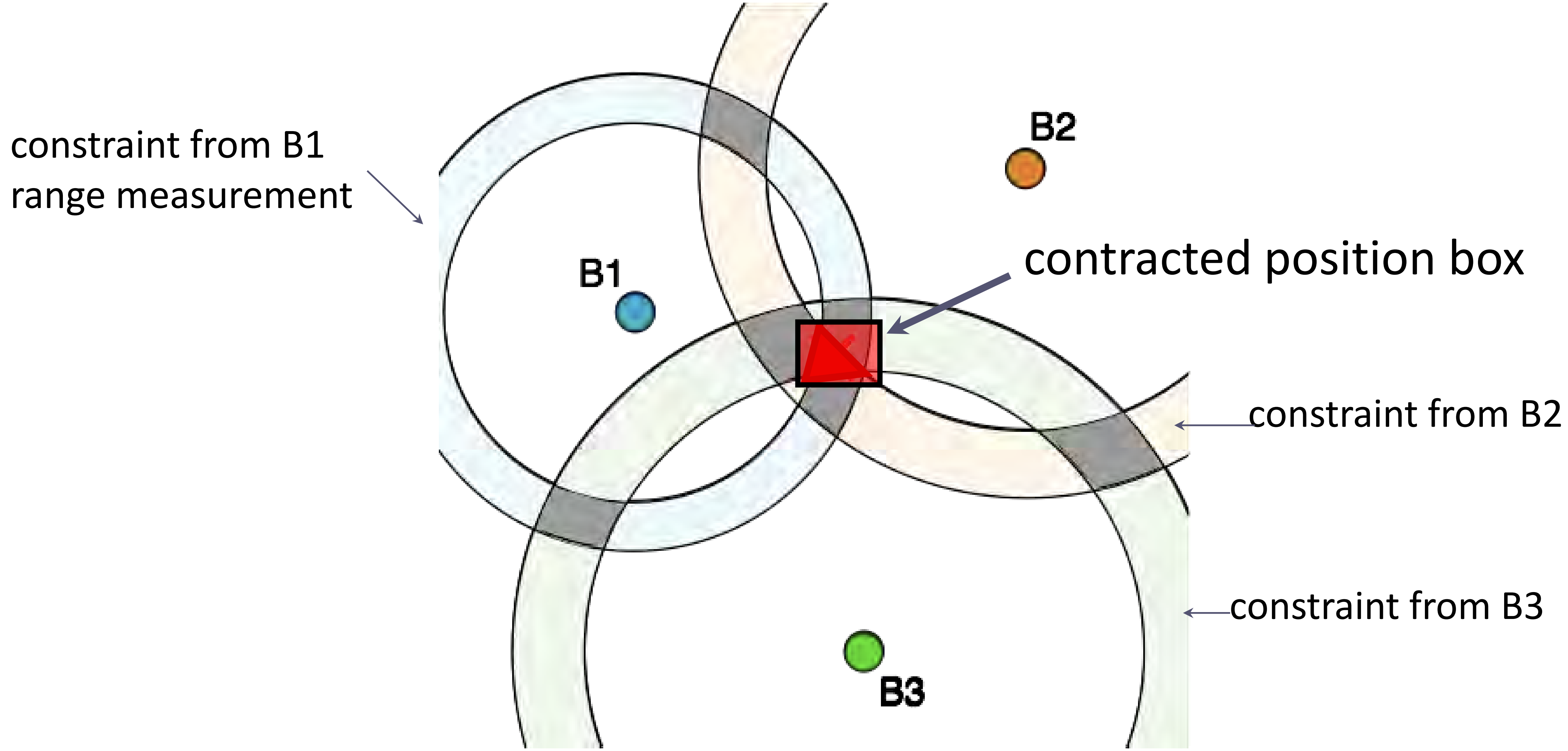
heudiasyc

constraint from B1
range measurement



constraint from B2

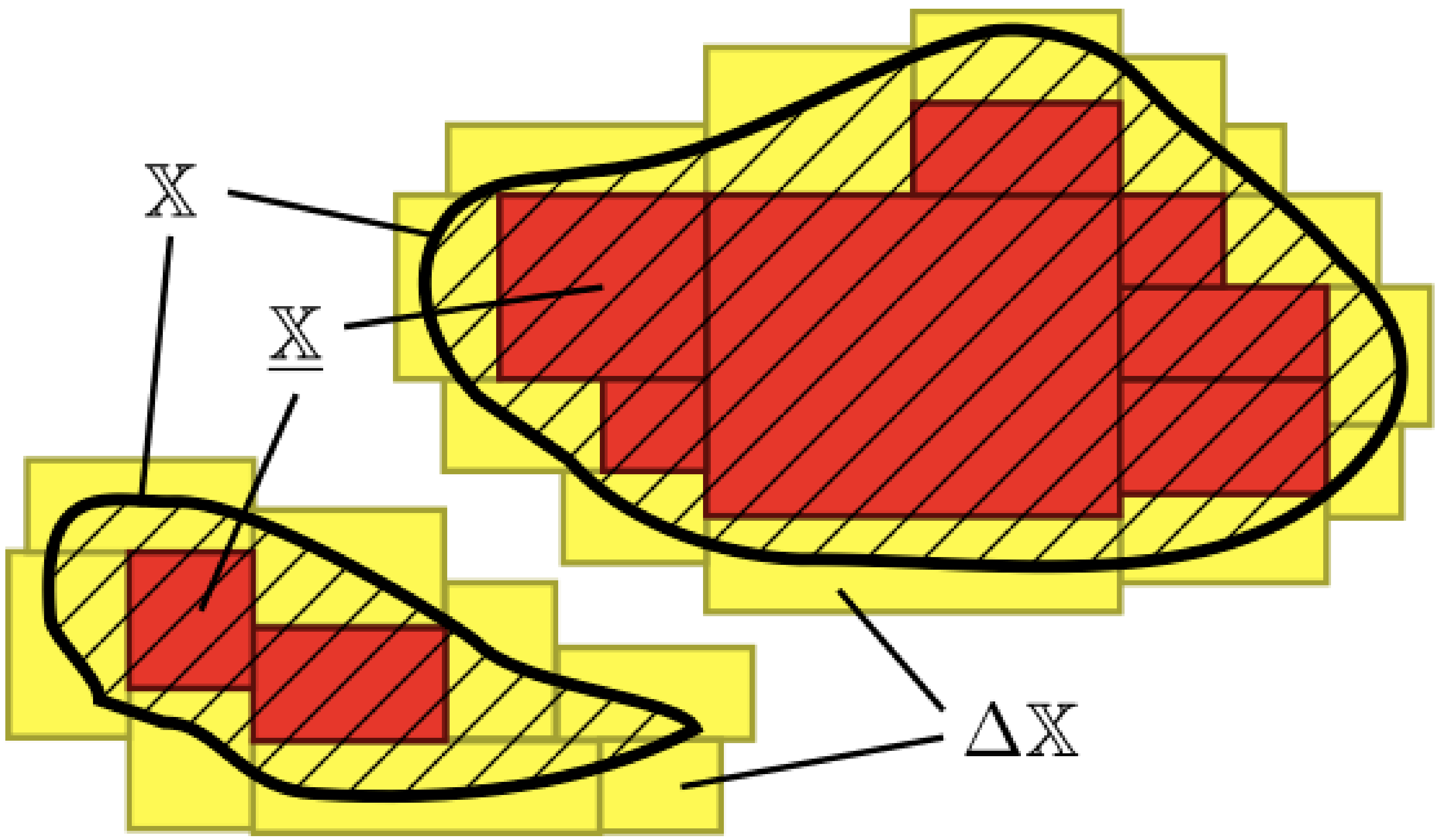
constraint from B3


constraint from B1
range measurement
B2
B1
contracted position box
constraint from B2
constraint from B3
B3

Refining the solution set: Subpavings

Boxes only provide a rough approximation

Better approximation of arbitrary sets: subpavings



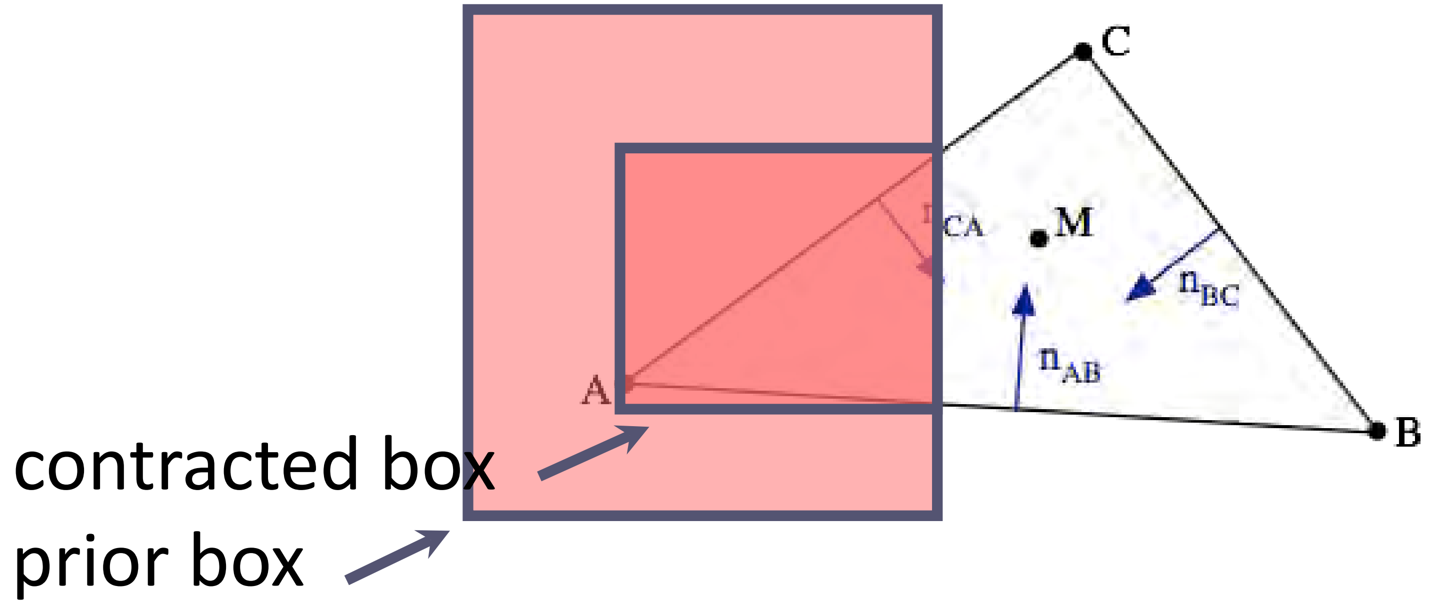
Adding maps for challenging environments

Map: 3D facets constraint

Bounded error framework allows taking into account surface constraint

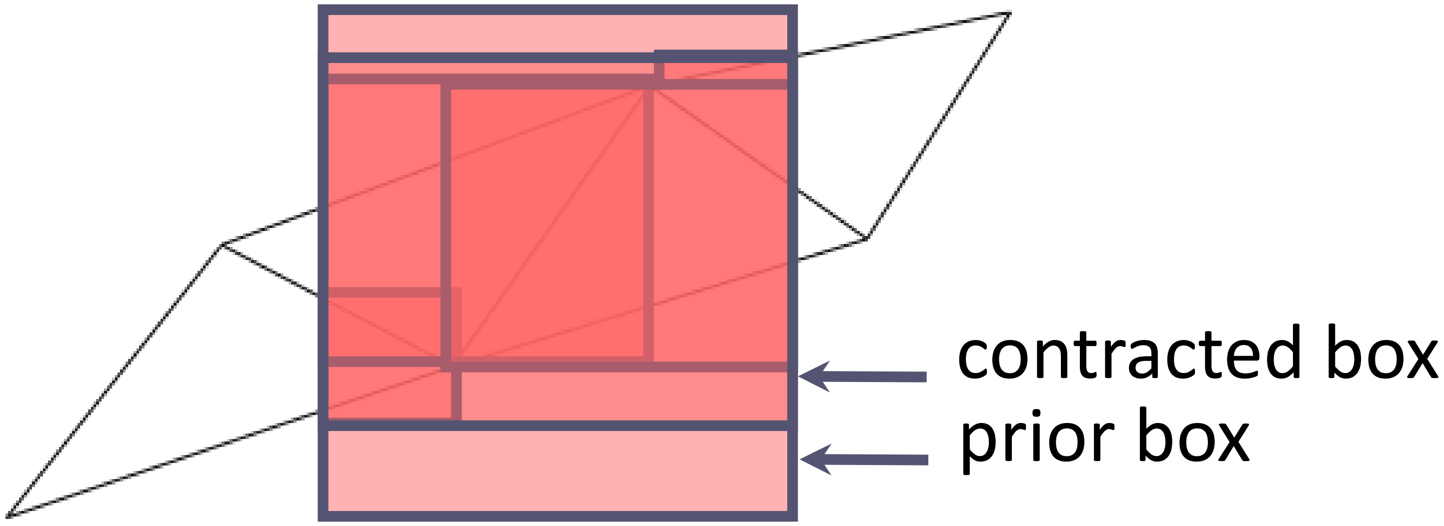
1 facet constraint

- Vertices coordinates are boxes (uncertainty)
- Facet plane constraint
- 3 facet edges constraints



Drivable space constraint

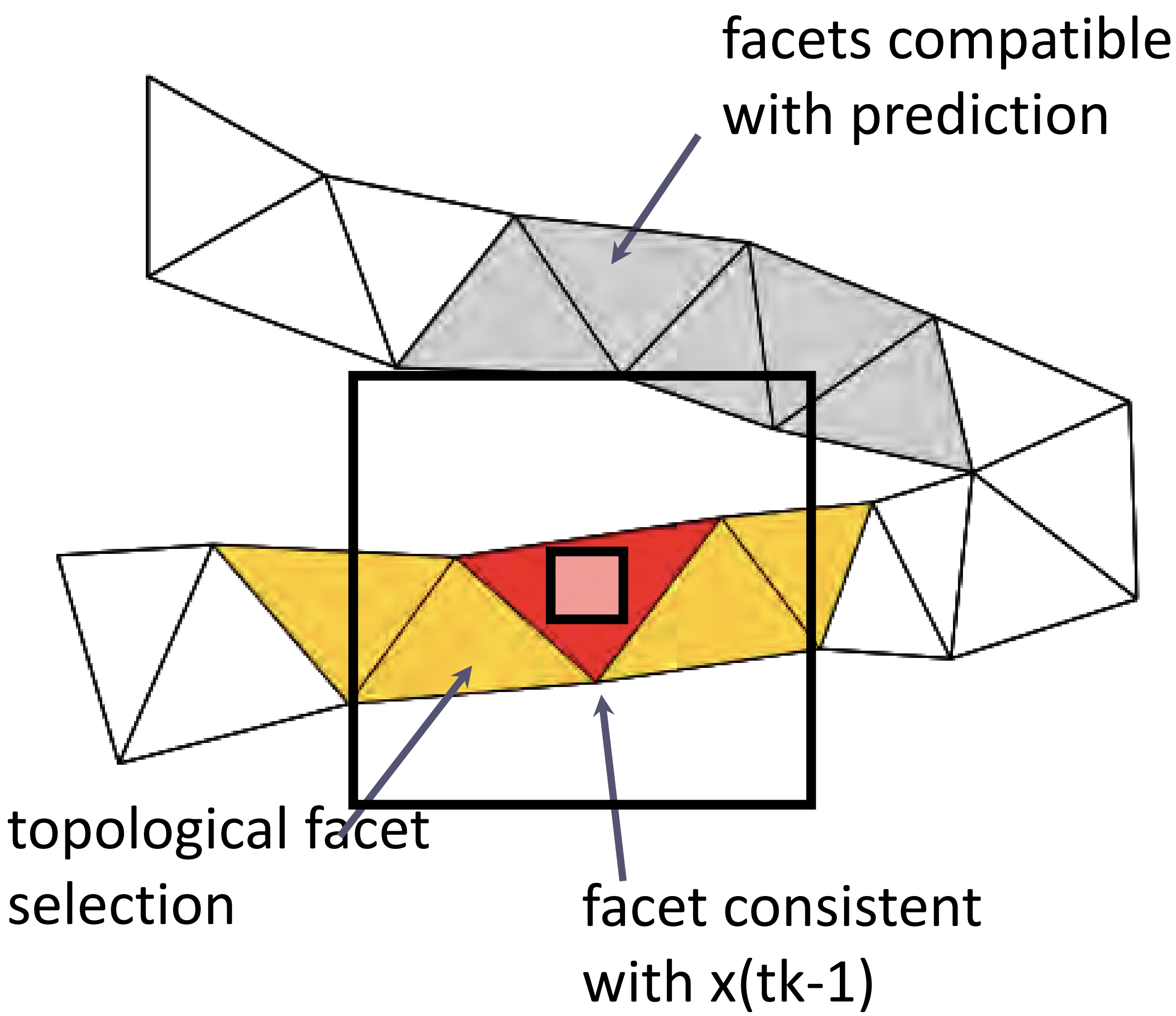
- Union of facet constraints



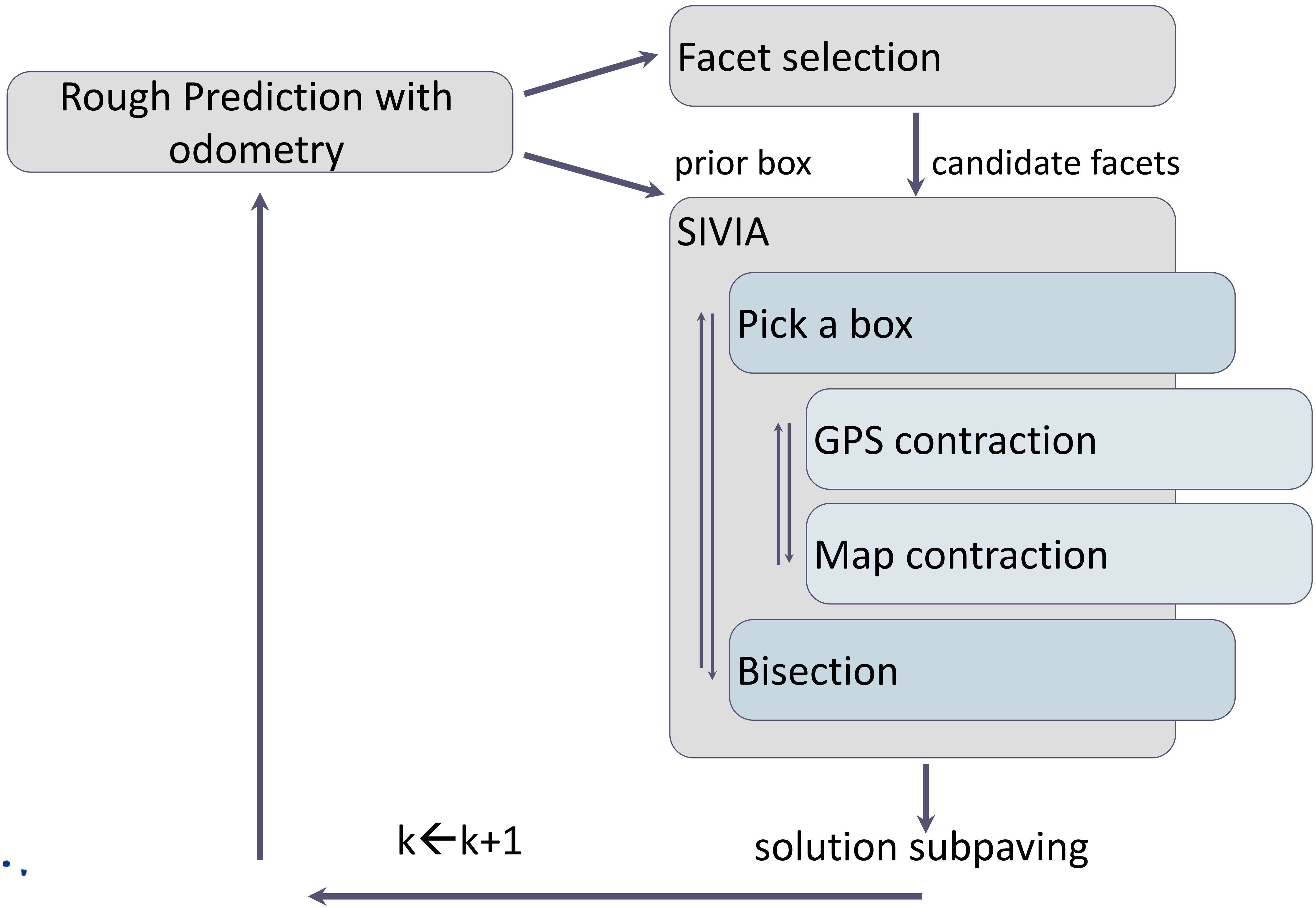
Facet selection (map matching)

Use topology to mark eligible neighbors from previous epoch facets set.

- Speeds up computation
- Limits ambiguous solutions in poor GPS conditions and dense road networks



Positioning algorithm

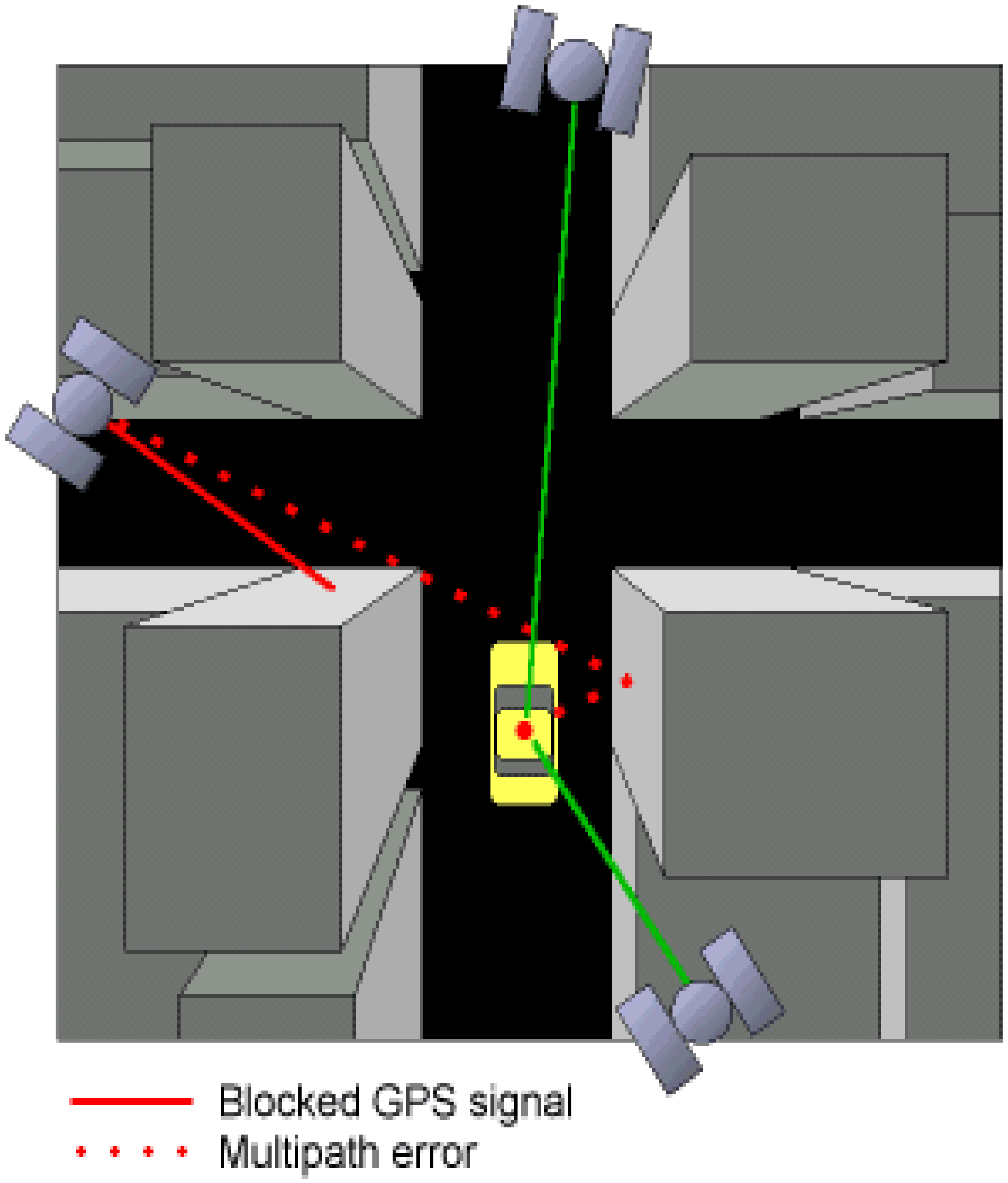


Integrity monitoring

Integrity risk

The risk is due to GPS pseudo-range outliers

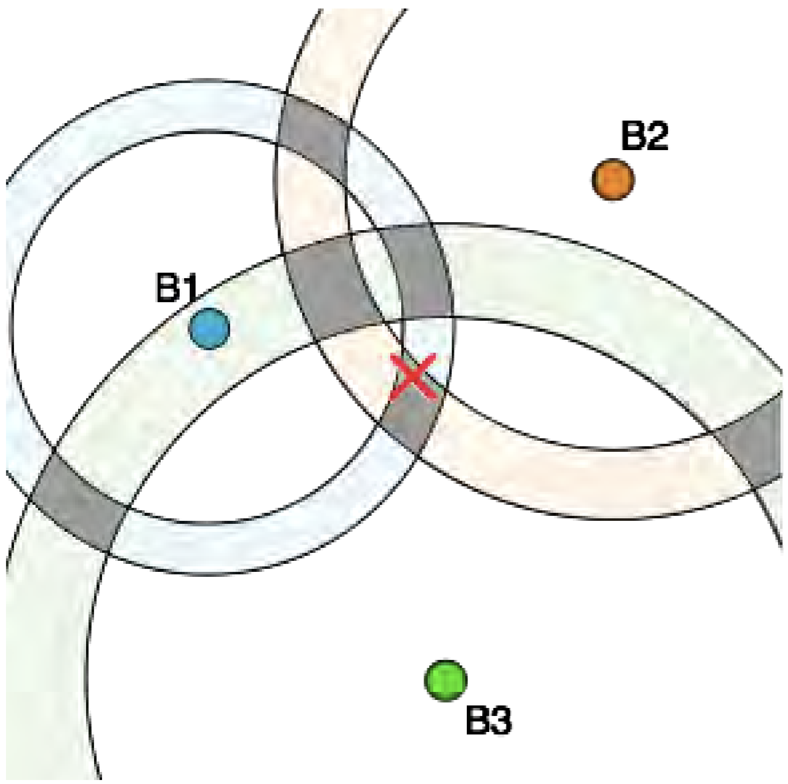
- e.g. NLOS multi-path
- Measurements that don't respect the bounded error model



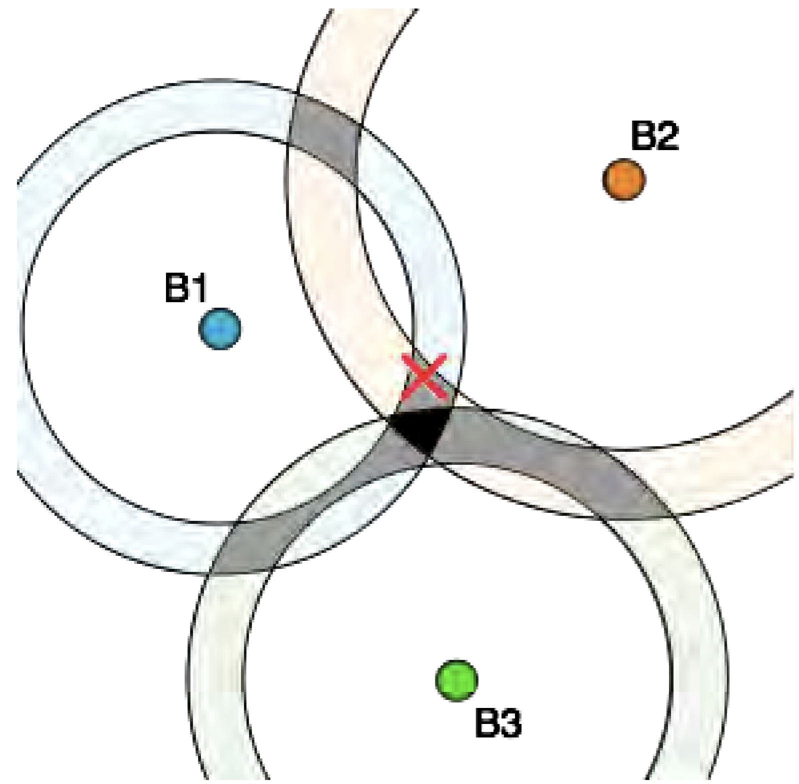
heudiasyc

Consequences of erroneous measurements

No solution



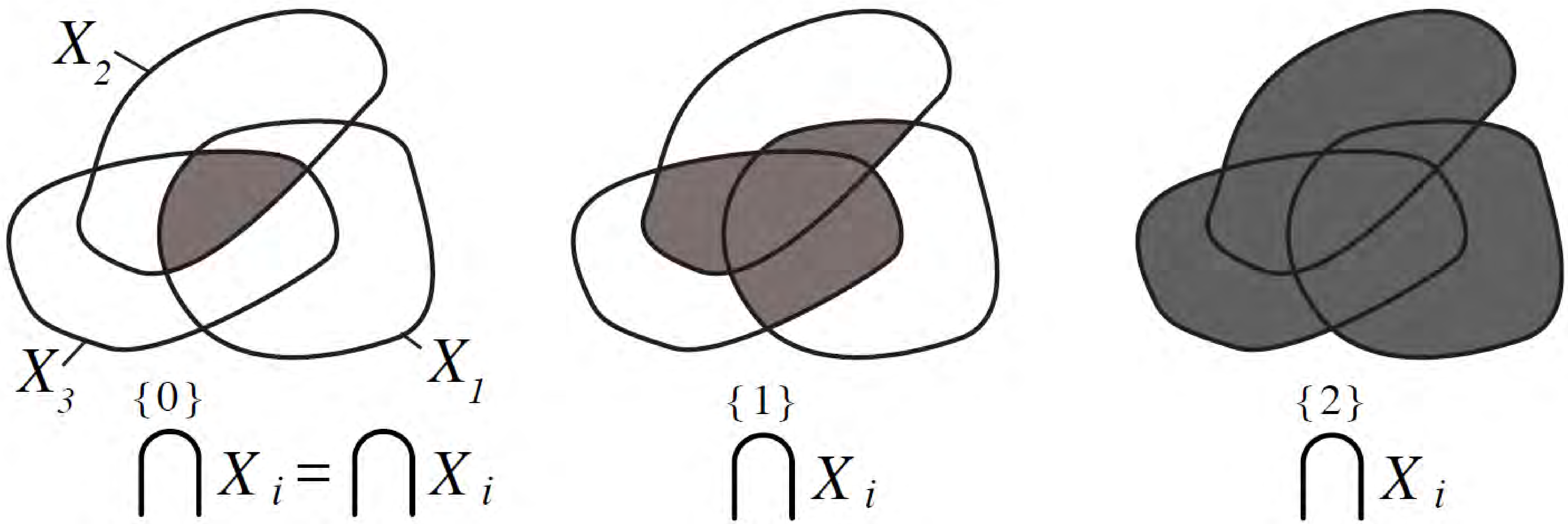
Misleading solution



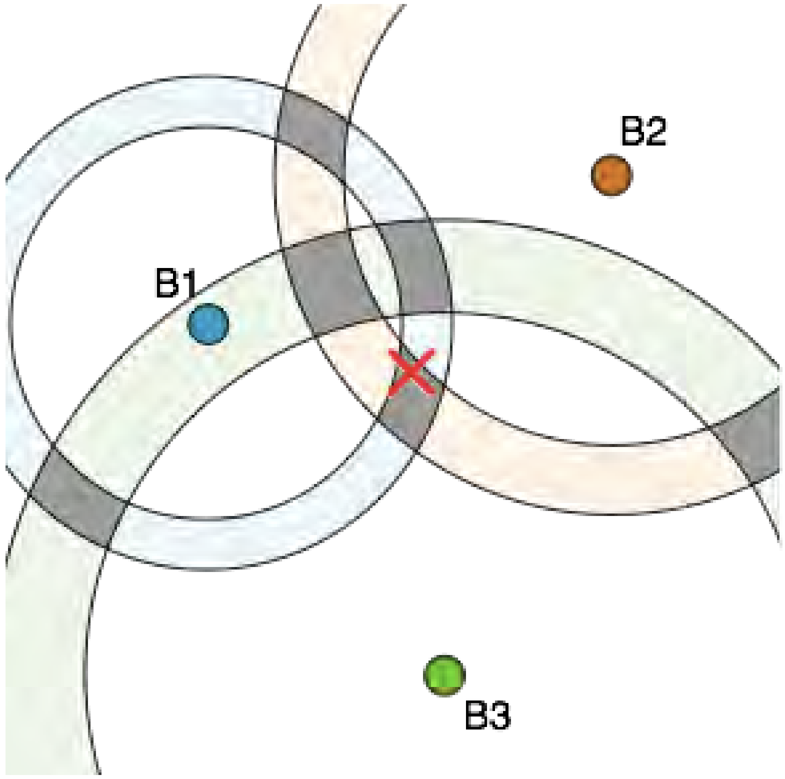
Intersection of all the constraints is not robust

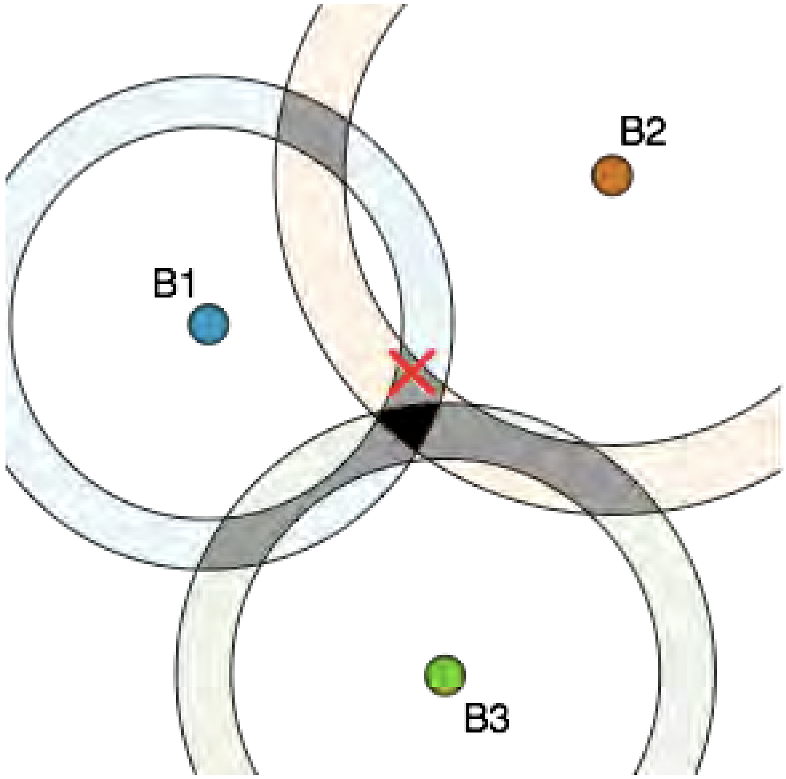
heudiasyc

q-relaxed Intersection



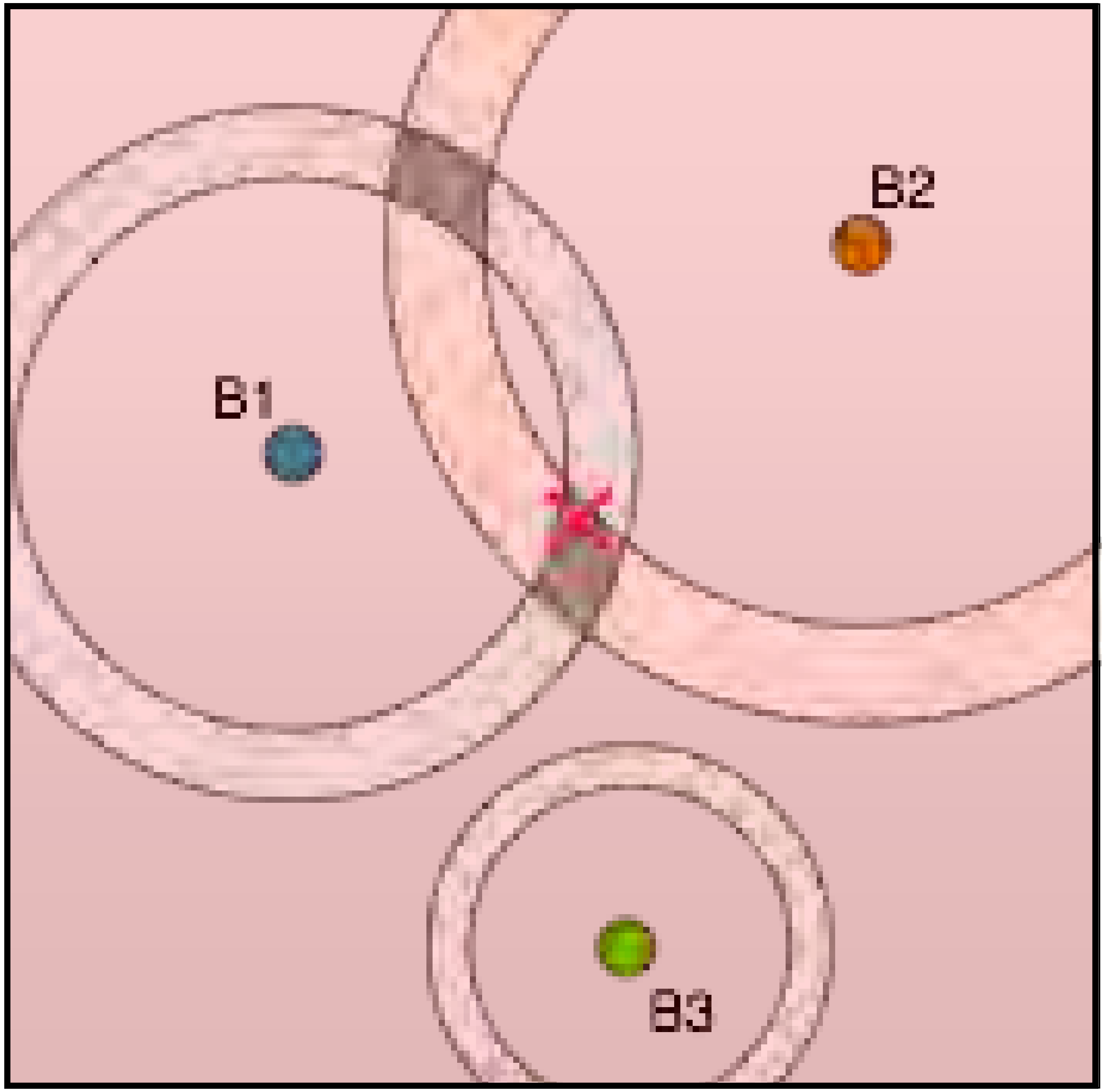
Robustness to wrong measurements

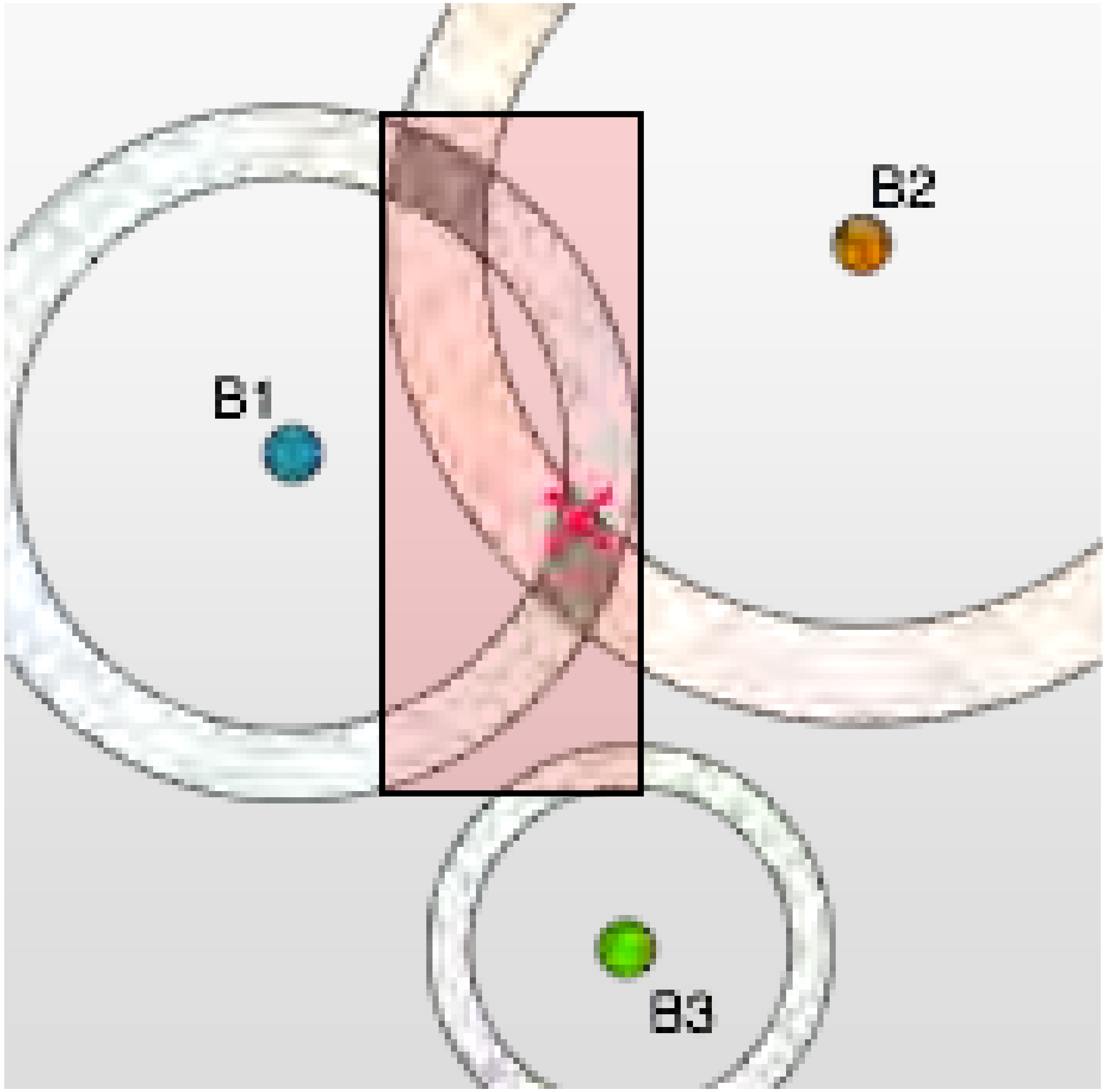




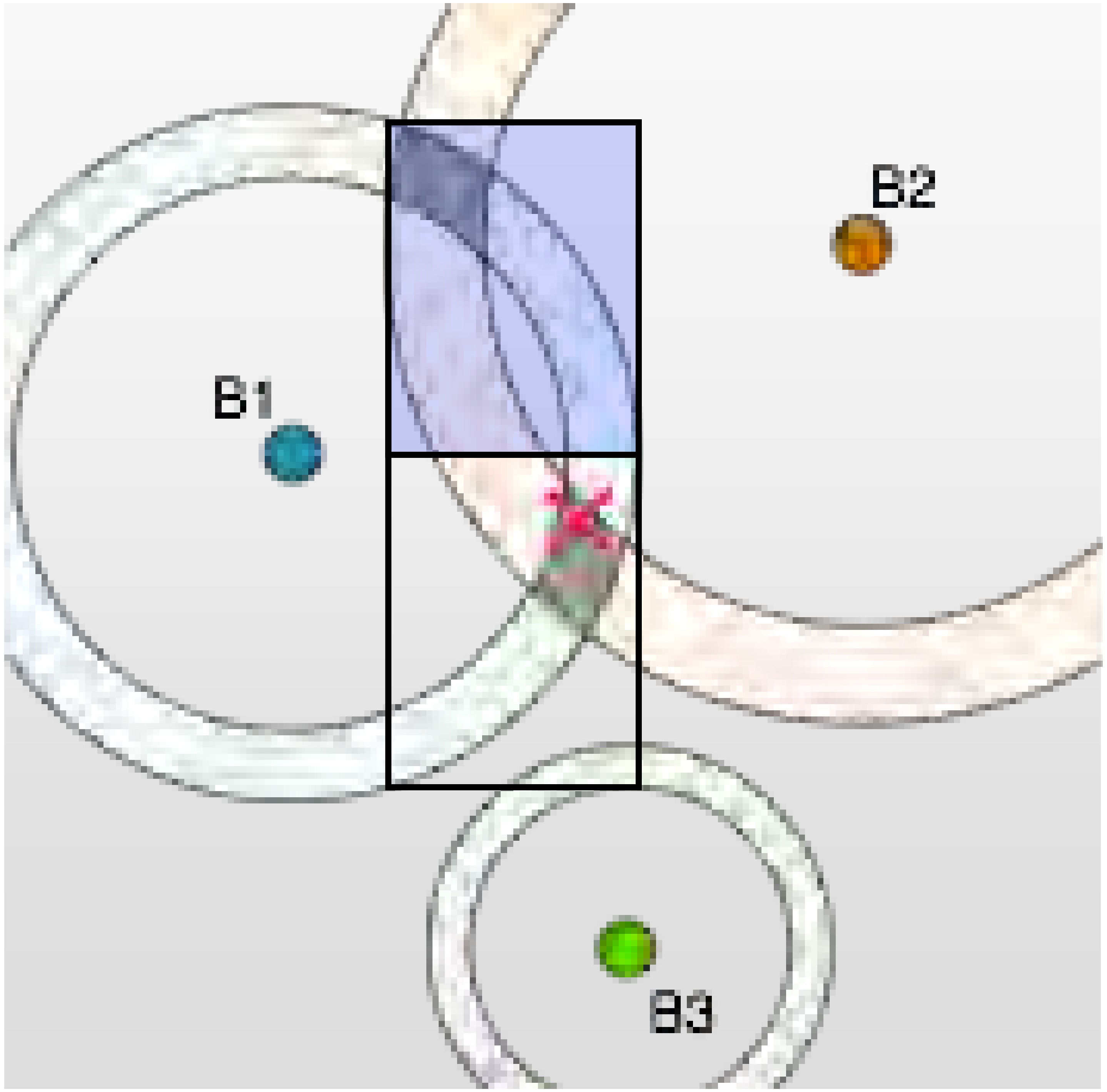
Robustness : Intersection of at least m-q constraints.
-> q-relaxed intersection

1-relaxed intersection

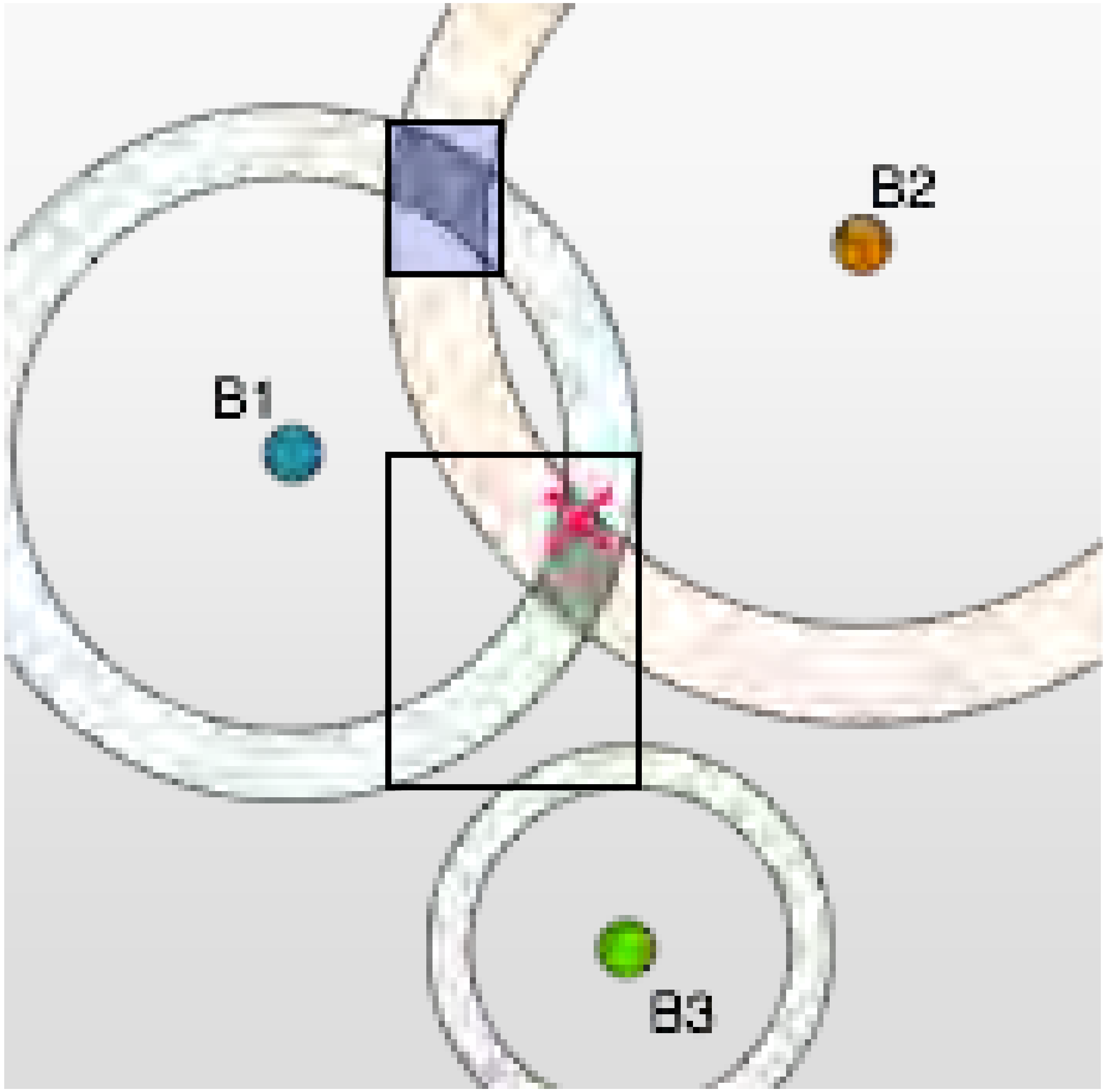


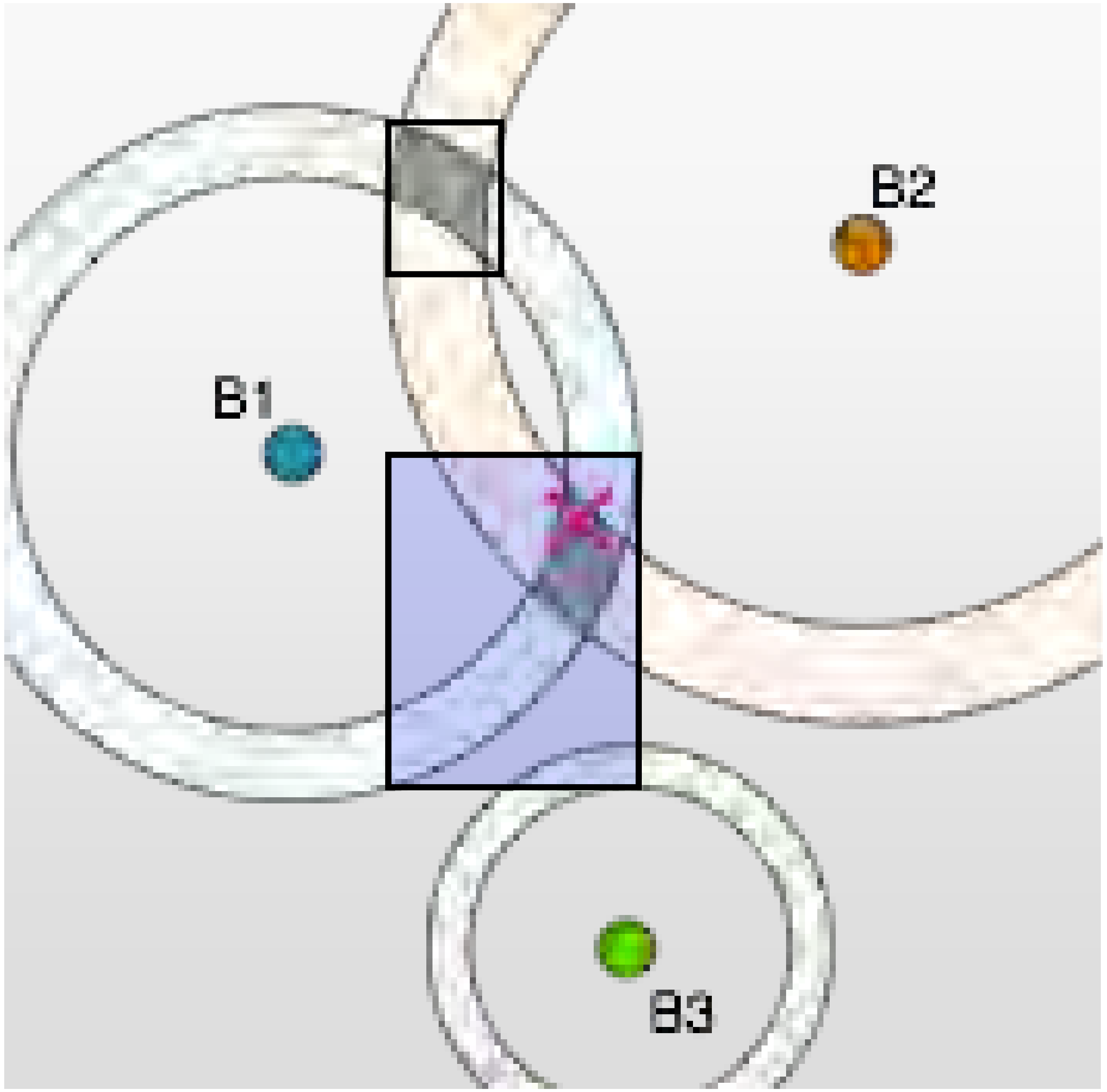


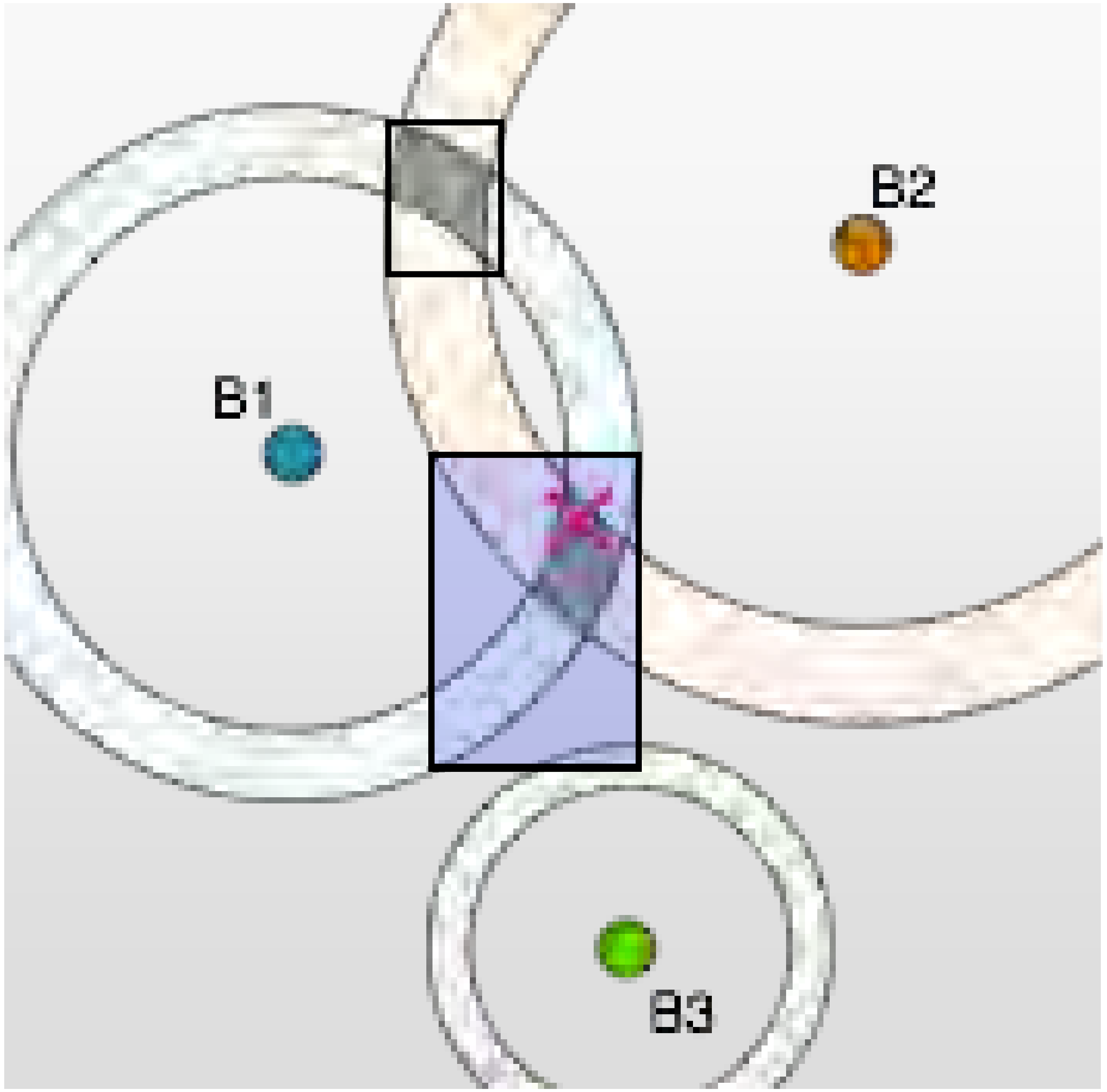
heudiasyc



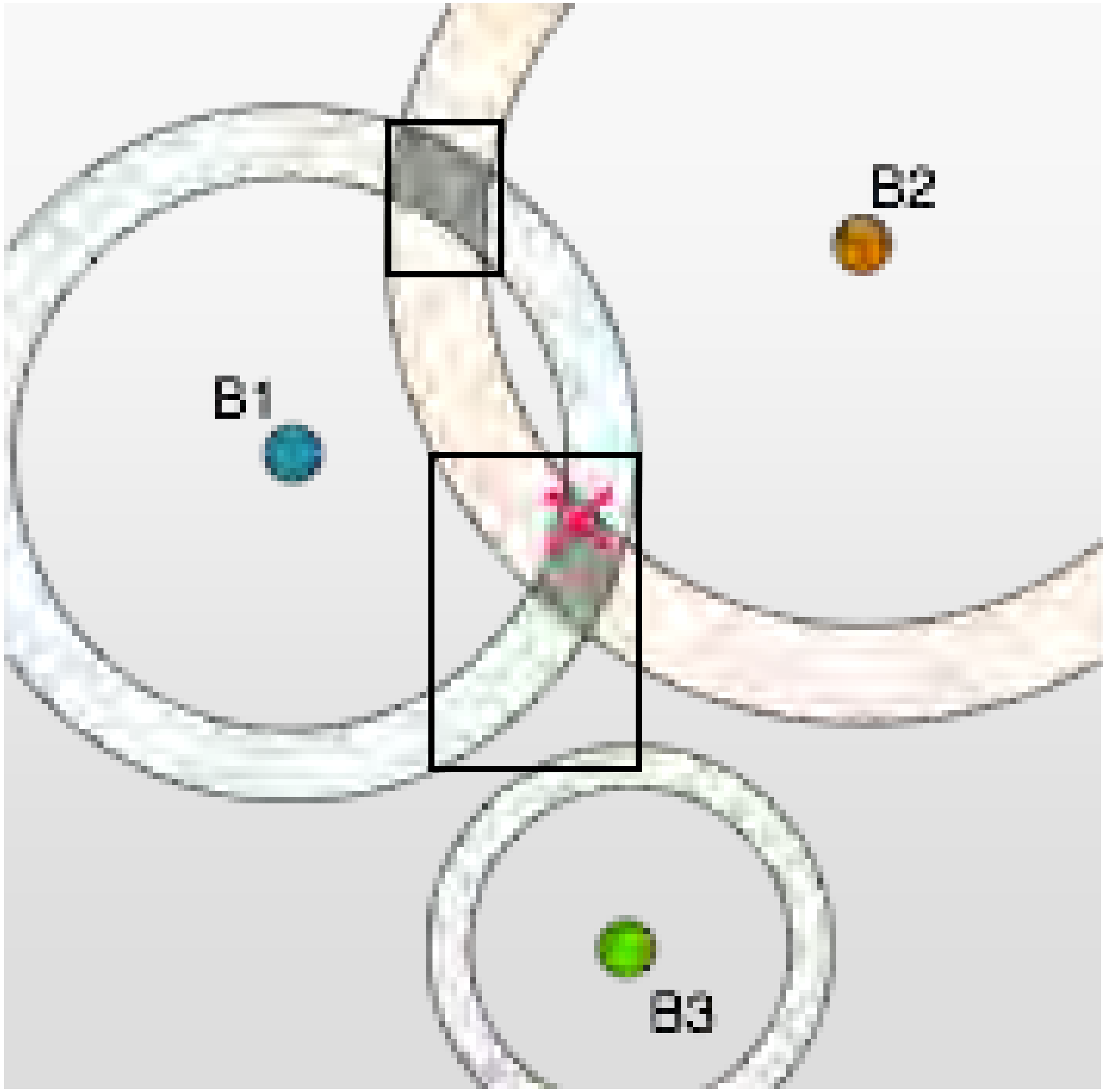
heudiasyc

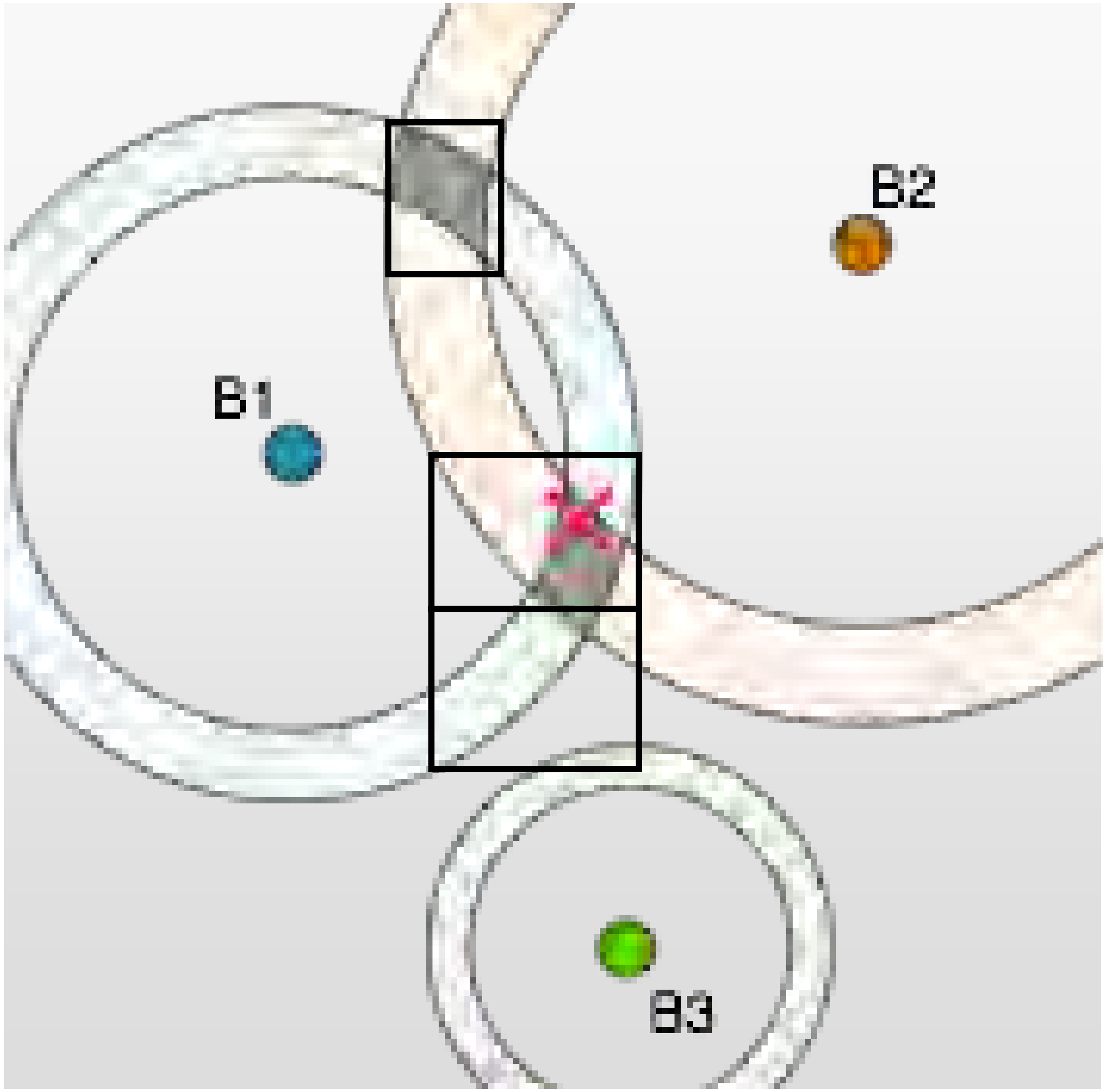

B2
B1
B3

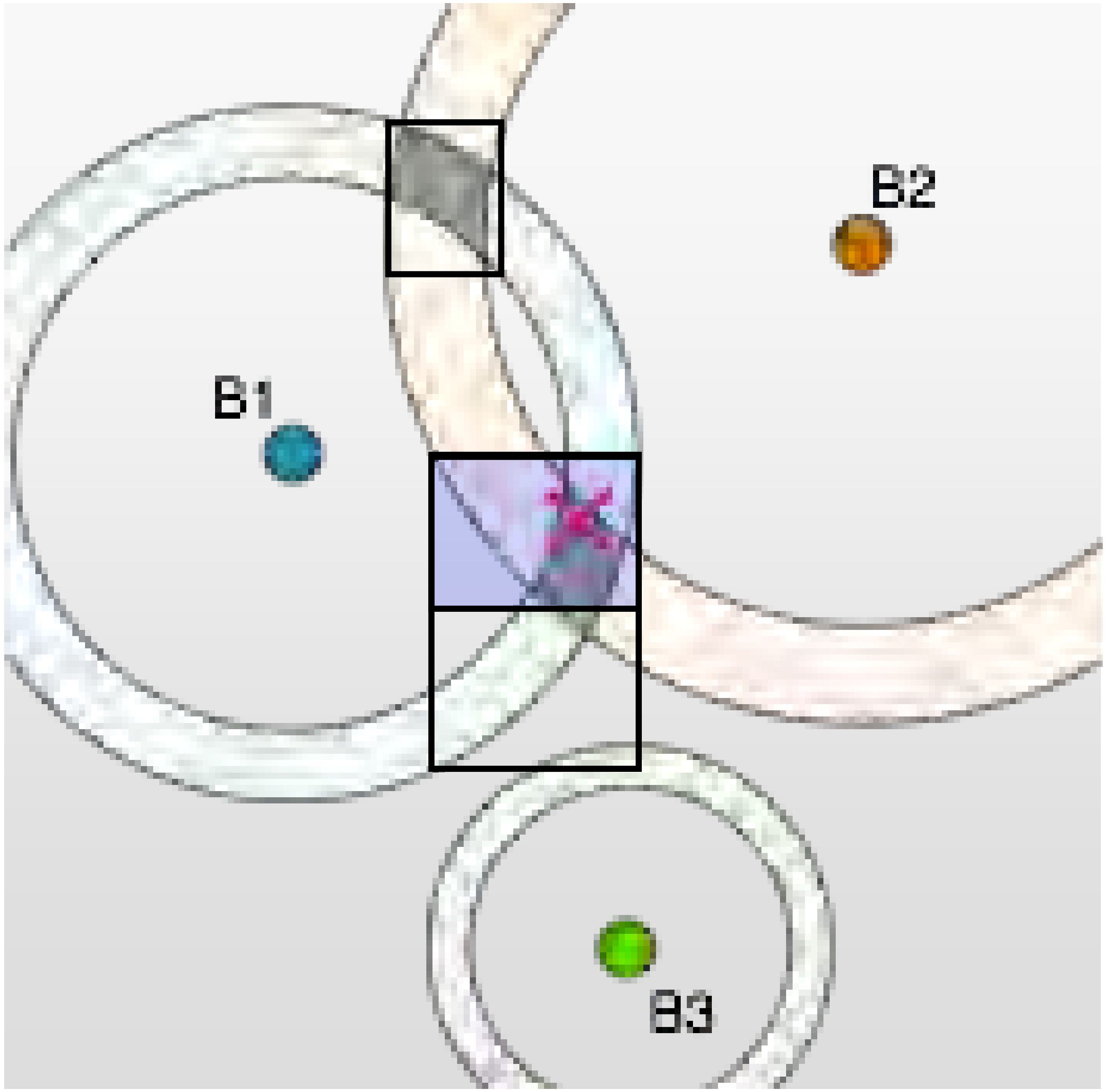

B2
B1
B3



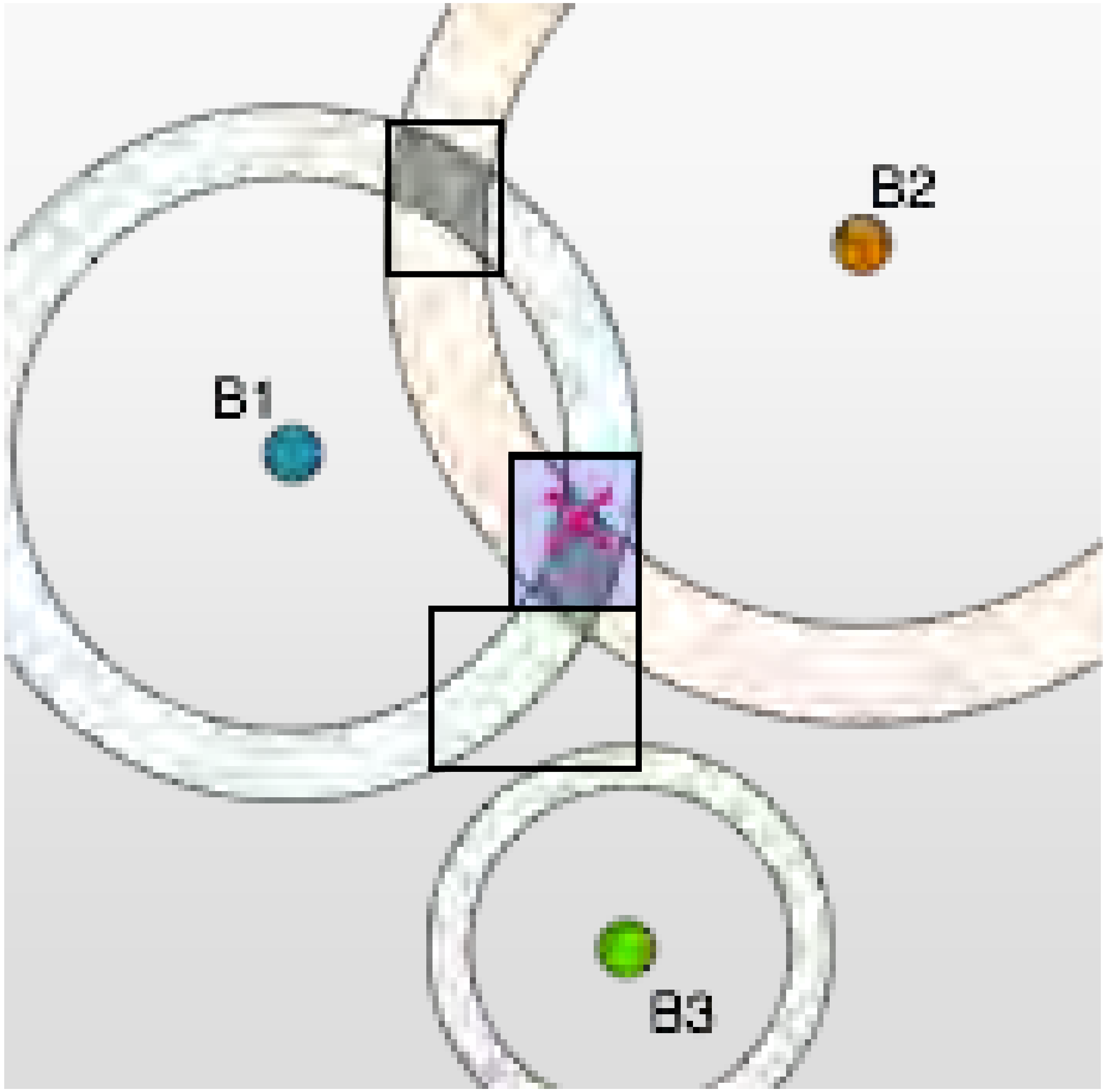
heudiasyc


B2
B1
B3

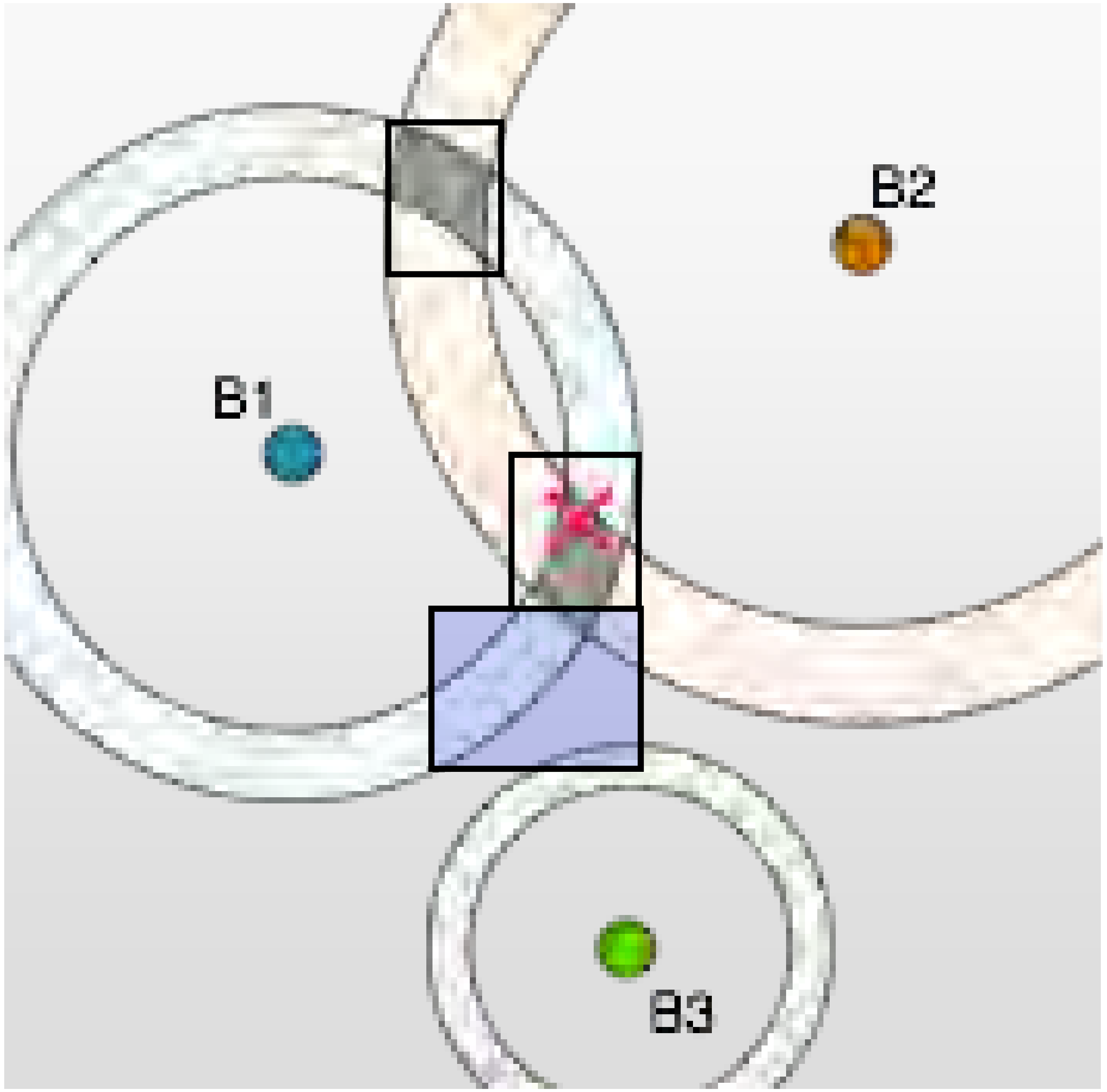

B2
B1
B3

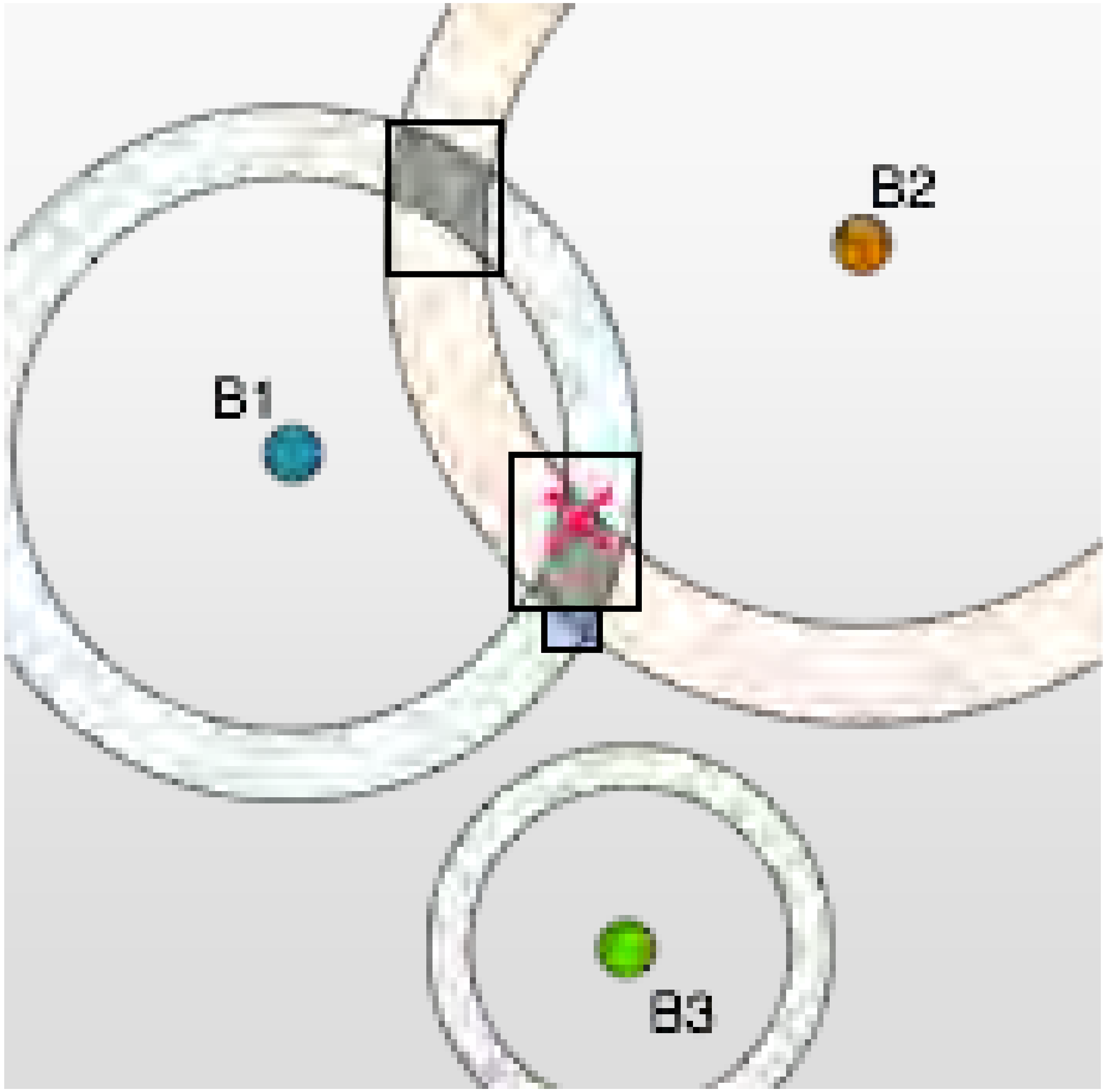


heudiasyc

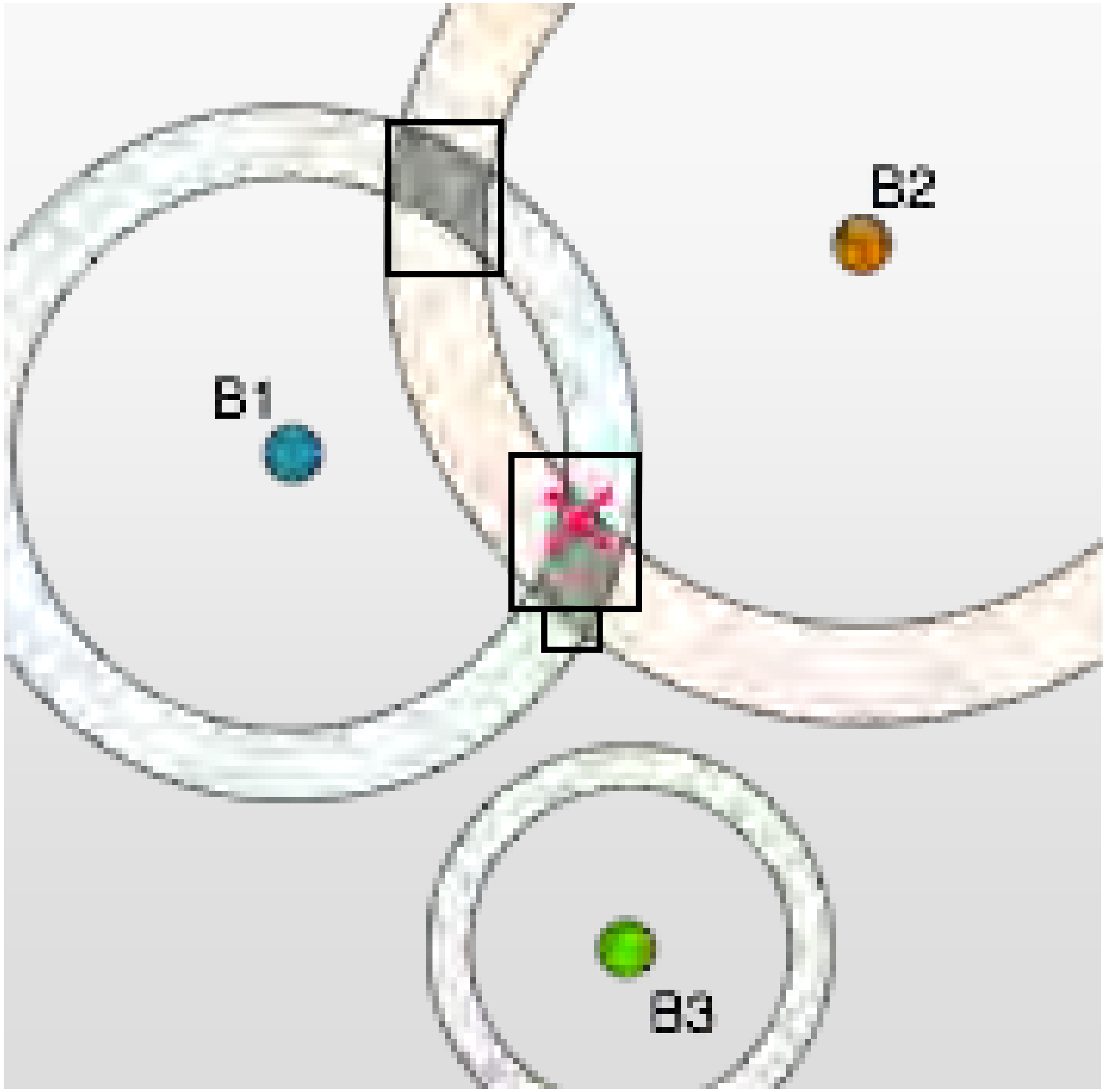


heudiasyc

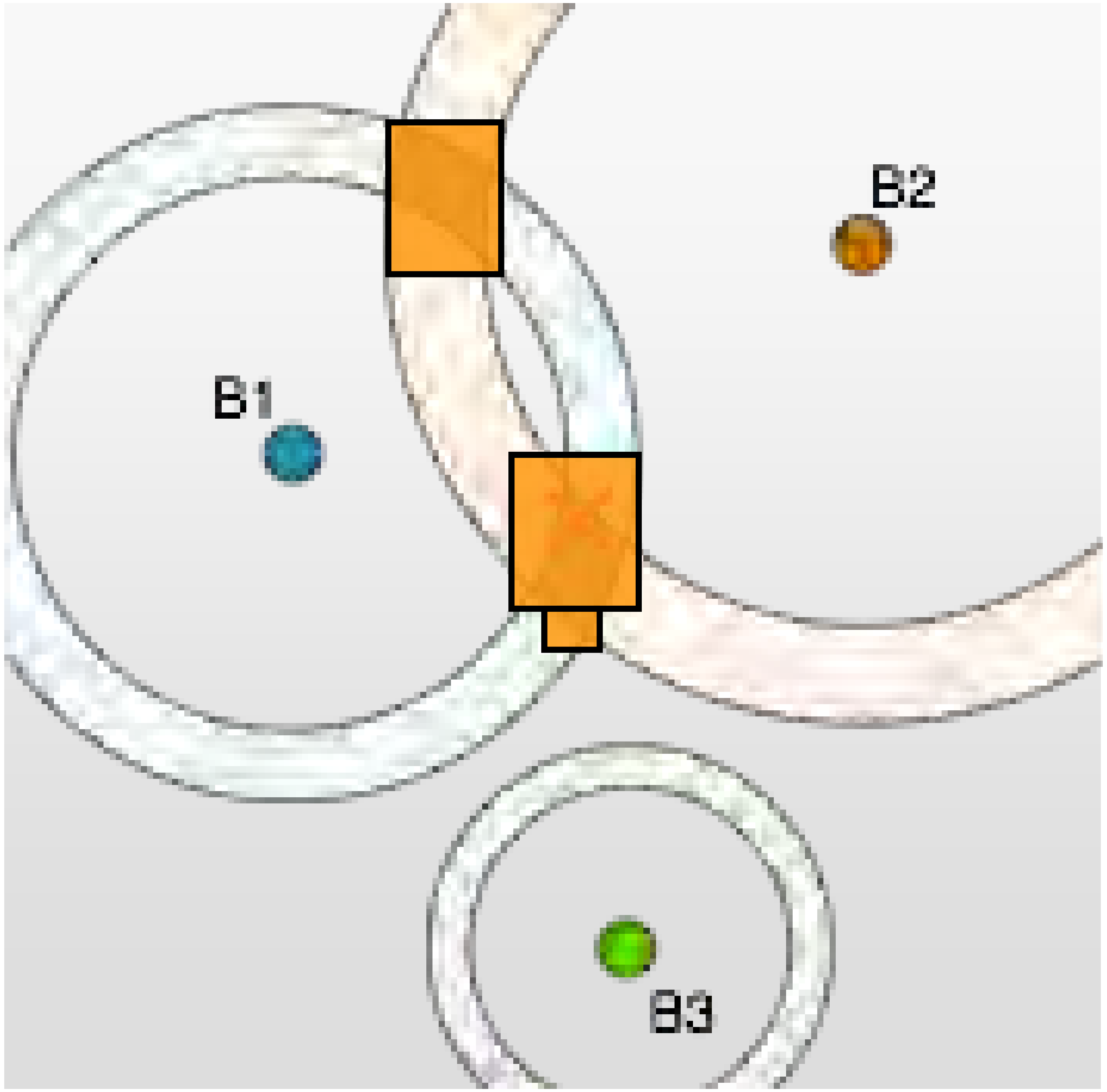

B2
B1
B3



heudiasyc



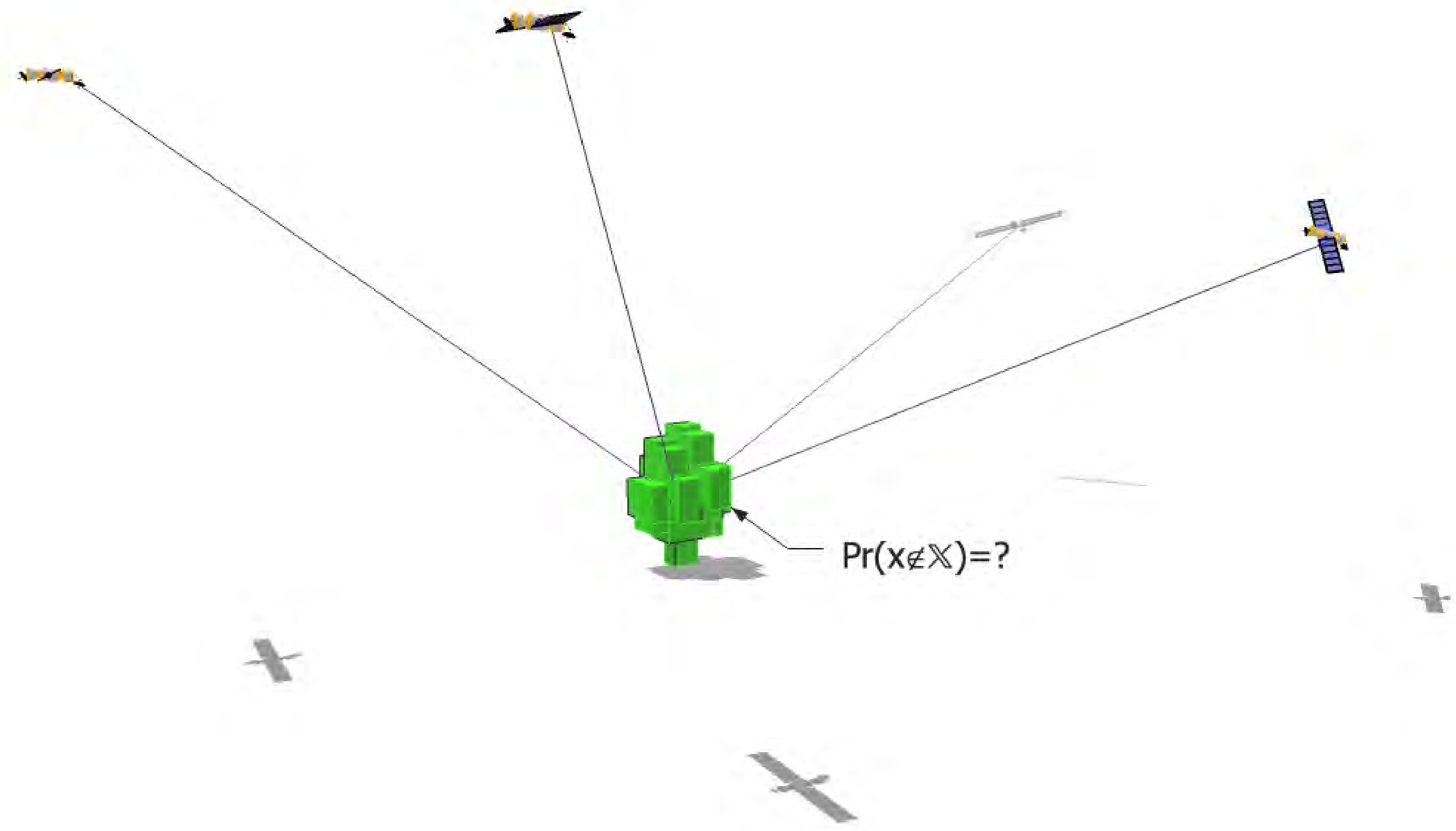
heudiasyc


B2
B1
B3

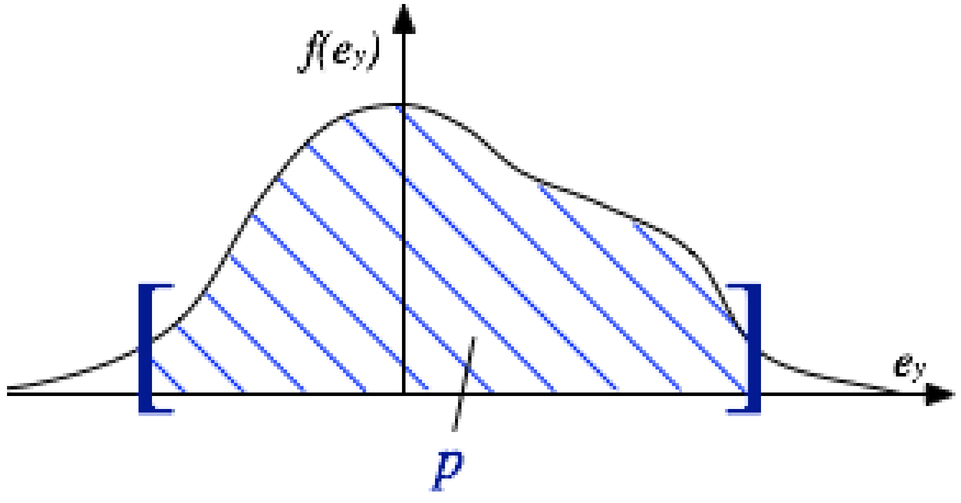
Risk computation

Confidence domain characterization

How to compute a risk associated with a computed domain?



knowing that the noise has not a bounded support?

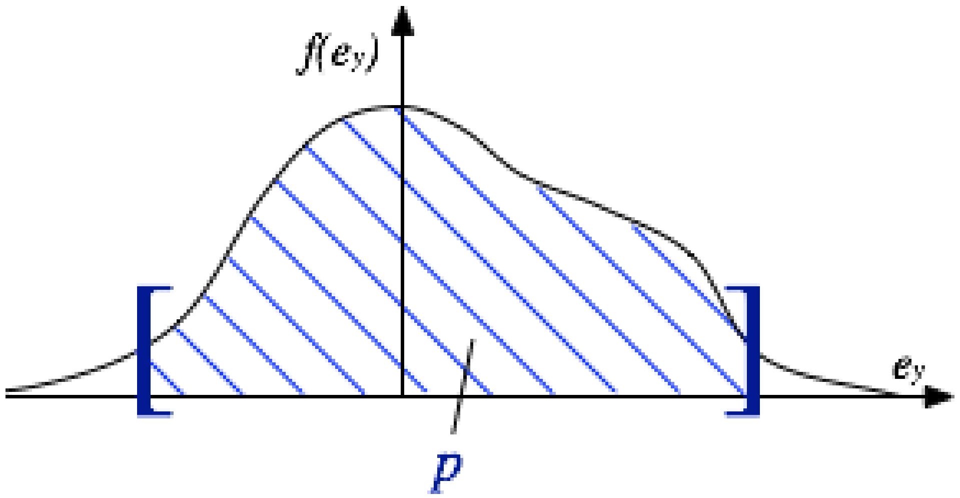


Risk computation

One measurement

Probability of having the measurement inside the bounds

$$p = \Pr(y \in [y_{meas}]) = \int_{\underline{e_y}}^{\overline{e_y}} f_{e_y}(\alpha) d\alpha.$$



"m" measurements

Probability of having *m* measurement inside the bounds

Independence assumption of measurement noise

$$\Pr(n_{ok} = m) = p^m.$$

heudiasyc

Risk computation using robust set inversion

The result is guaranteed as long as there are “m-q” intervals including the true value (i.e. no more than *q* outliers)

Probability of having *k* good measurements

Number of measurements

$$\Pr(n_{ok} = k) = \binom{m}{k} p^k (1-p)^{m-k}$$

$$\binom{m}{k} = \frac{m!}{k!\,(m-k)!}.$$

probability of belonging to the interval measurement

Probability of having at least *m-q* good measurements

$$\Pr(n_{ok} \geq m-q) = \sum_{k=m-q}^{m} \binom{m}{k} p^k (1-p)^{m-k}.$$

heudiasyc

Risk computation using robust set inversion

Computed solution set $\overline{\mathbb{X}}$

As long as the assumptions hold, we have $\mathbb{X} \subset \overline{\mathbb{X}}$.

So $n_{ok} \geq m - q \implies x \in \mathbb{X} \implies x \in \overline{\mathbb{X}}$

$$\Pr(x \in \overline{\mathbb{X}}) \geq \Pr(x \in \mathbb{X}) \geq \Pr(n_{ok} \geq m - q)$$

$$r = \Pr(x \notin \overline{\mathbb{X}}) \leq \Pr(x \notin \mathbb{X}) \leq 1 - \Pr(n_{ok} \geq m - q)$$

$$r \leq 1 - \sum_{k=m-q}^{m} \binom{m}{k} p^k (1-p)^{m-k}.$$

heudiasyc

[Jaulin 2011] Set-membership localization with probabilistic errors

Bounds determination for a given risk

In practice, we need to solve the inverse problem

The maximum risk "r_{max}" is specified, the bound have to be found

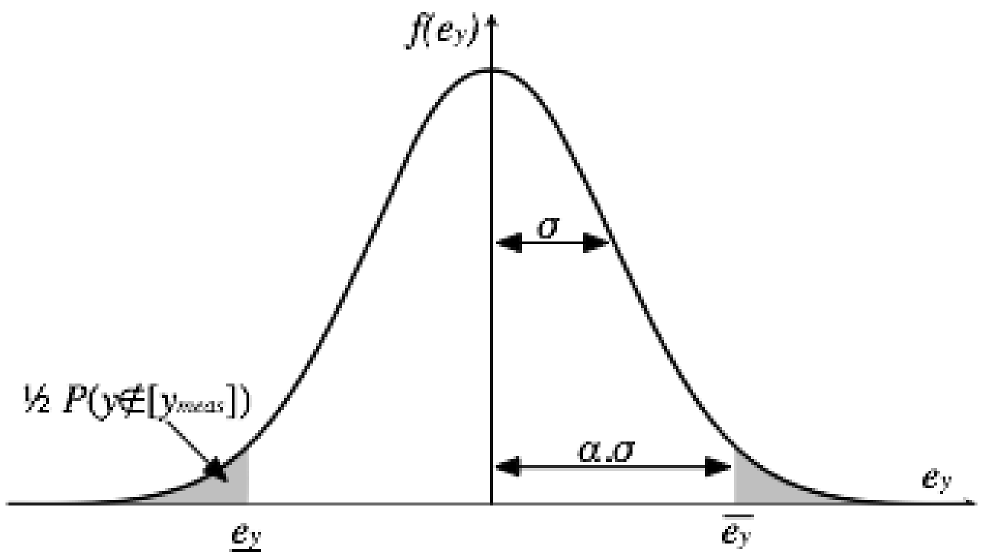
p can be computed by inverting the equation

$$r_{max} = 1 - \sum_{k=m-q}^{m} \binom{m}{k} p^k (1-p)^{m-k}$$

If the pdf of the noise is known

- Gaussian case

$$\alpha = -\Phi^{-1}\left(\frac{1-p}{2}\right)$$



$$[y_{meas}] = [y_{meas} - \alpha\sigma_y, y_{meas} + \alpha\sigma_y]$$

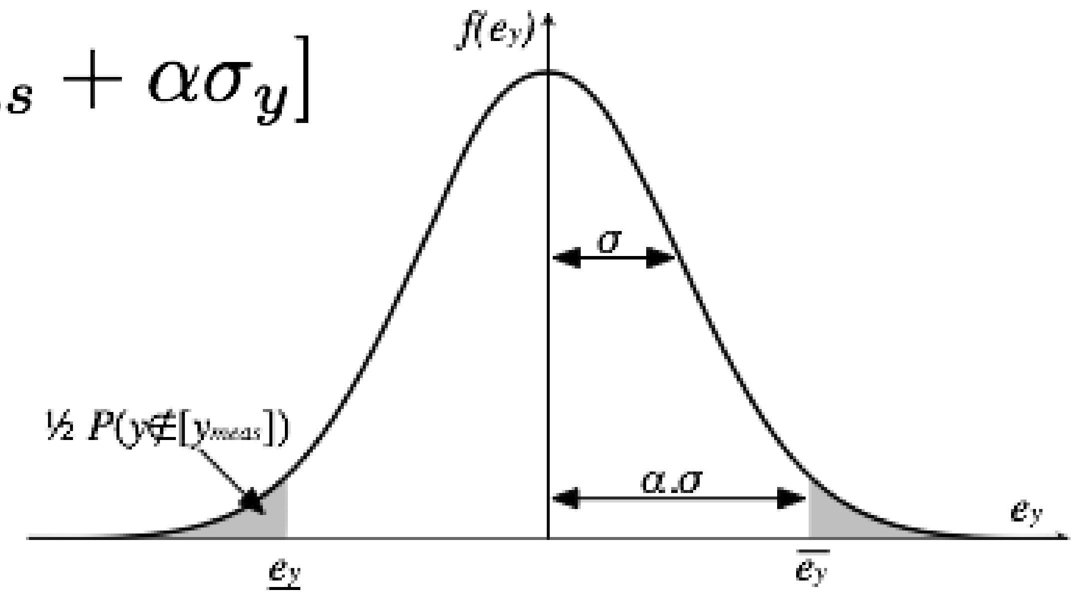
In practice, GPS provides over-bounding Gaussians

Bounds determination before set inversion

Algorithm input: Chosen risk

- Count the number of available measurements,
- compute a confidence interval for every measurement,
- Use over-bounding Gaussians

$$[y_{meas}] = [y_{meas} - \alpha\sigma_y, y_{meas} + \alpha\sigma_y]$$



- determine the bounds on every measurement

Bounds can be computed in advance

Example with $r = 10^{-7}$

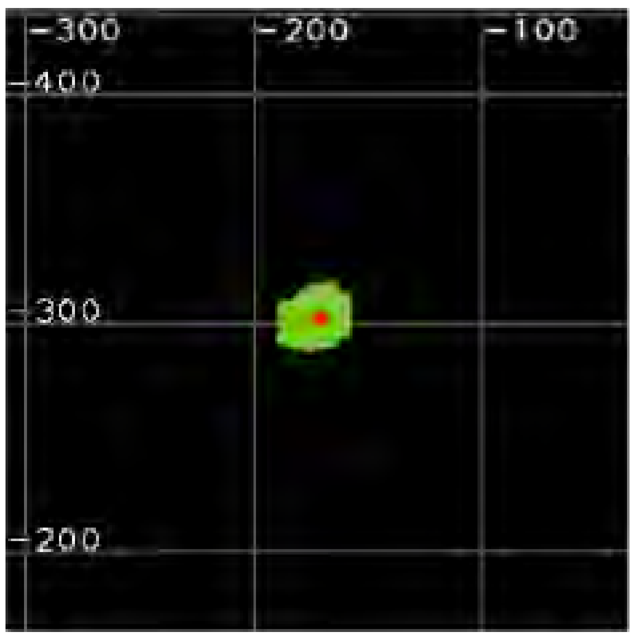
Risk "1-p" for each interval

	$m=4$	$m=5$	$m=6$	$m=7$
$q=0$	$2.5 \cdot 10^{-8}$	$2 \cdot 10^{-8}$	$1.66 \cdot 10^{-8}$	$1.42 \cdot 10^{-8}$
$q=1$	$* \ 1.29 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$	$8.16 \cdot 10^{-5}$	$6.90 \cdot 10^{-5}$
$q=2$	$* \ 2.93 \cdot 10^{-3}$	$* \ 2.16 \cdot 10^{-3}$	$2.71 \cdot 10^{-3}$	$1.42 \cdot 10^{-3}$

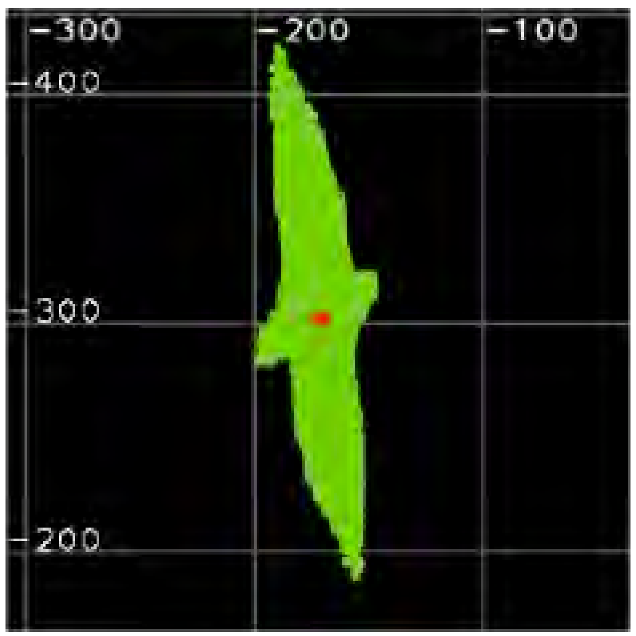
Number of standard deviations for Gaussian pdf

	$m=4$	$m=5$	$m=6$	$m=7$
$q=0$	5.57	5.61	5.64	5.67
$q=1$	3.83	3.89	3.94	3.98
$q=2$	2.98	3.07	3.14	3.19

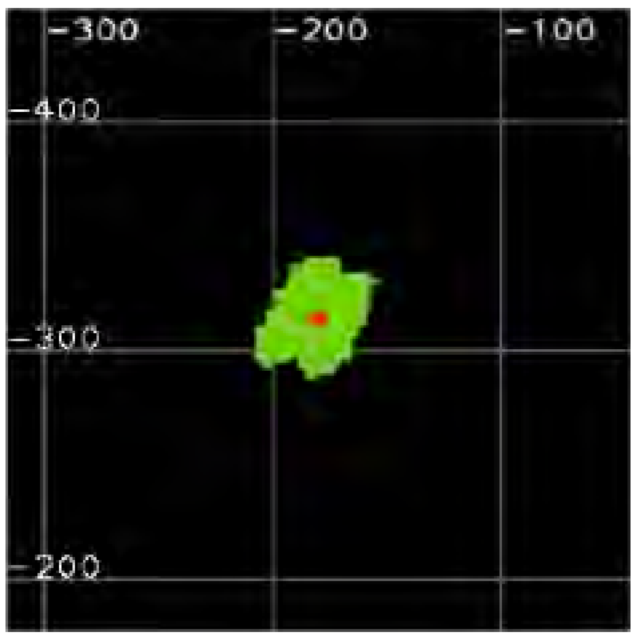
DTM reduces uncertainty introduced by q-relaxation



non robust
GPS only



robust 1-relaxed
GPS only



robust 1-relaxed
GPS + DTM

Validation

Are the computed location domains relevant?

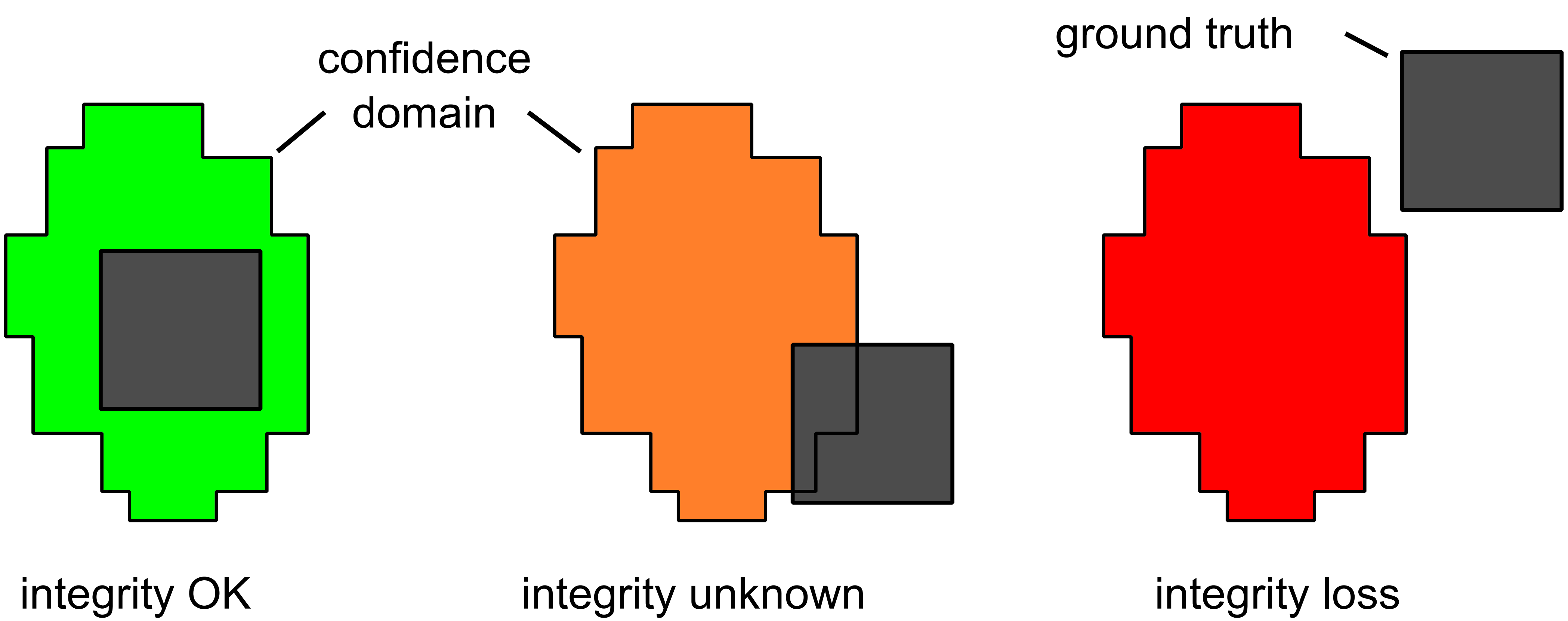
Evaluation methodology

Goal: to test the method with different risk settings

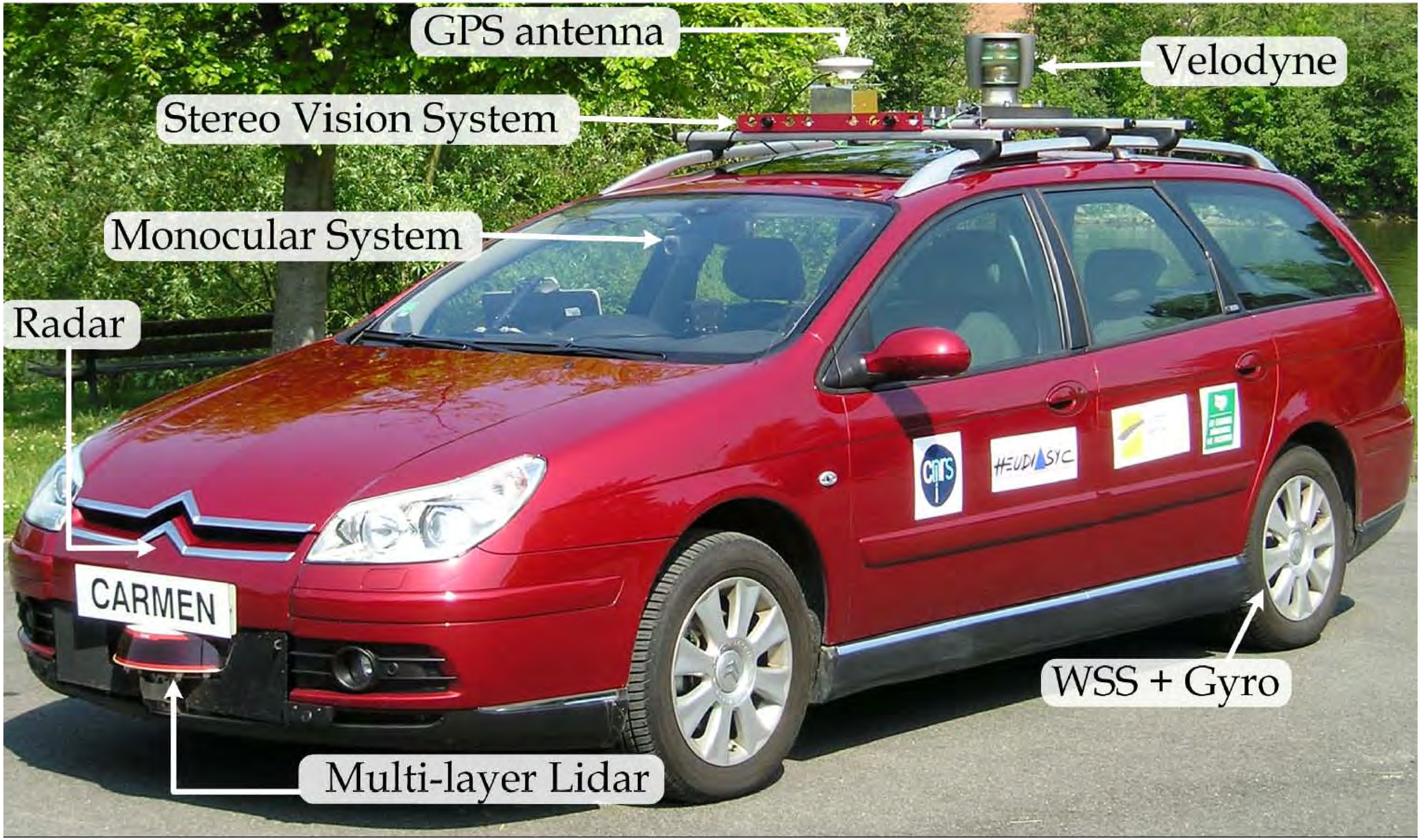
Availability

- bounding box of the sub-paving
- its radius is compared with a 10-meter Alarm Limit (HAL)

Integrity validation of the solution



Experimental vehicle: Carmen

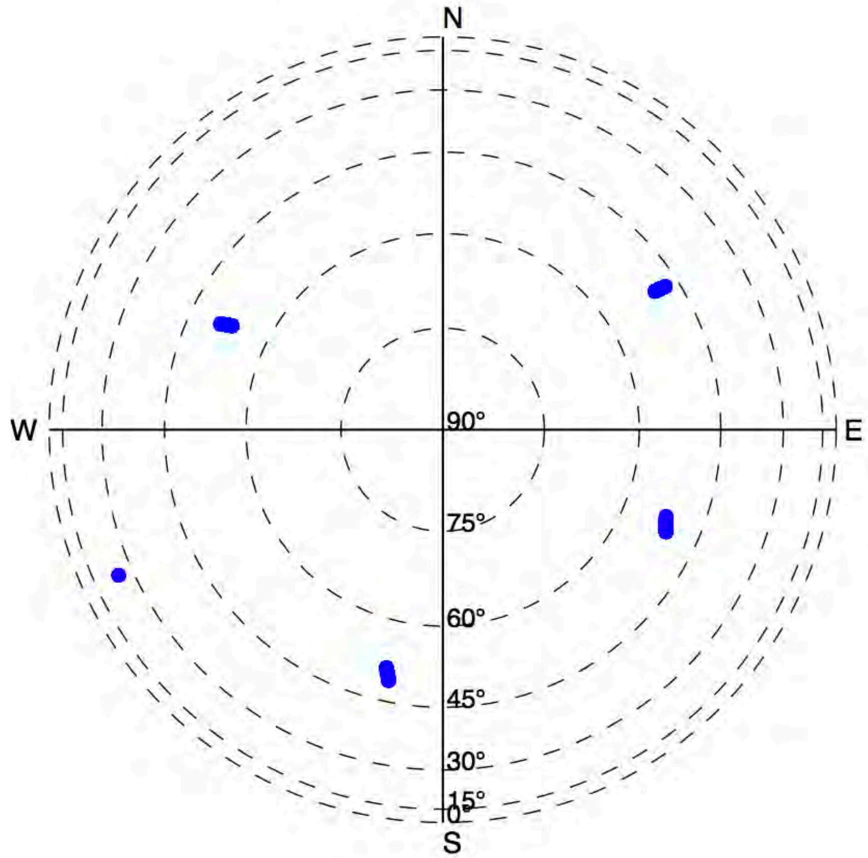


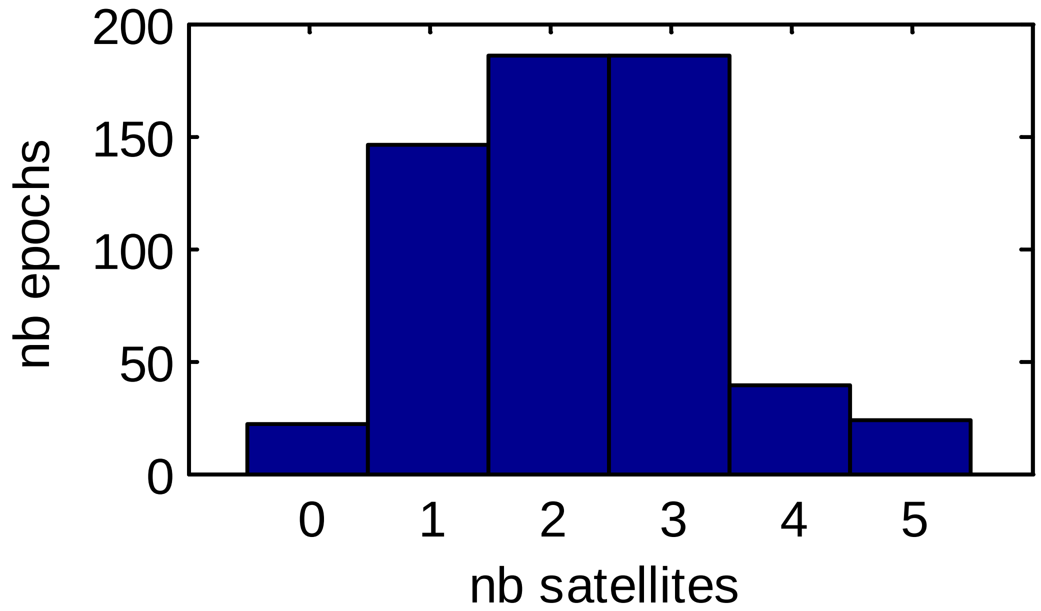
heudiasyc

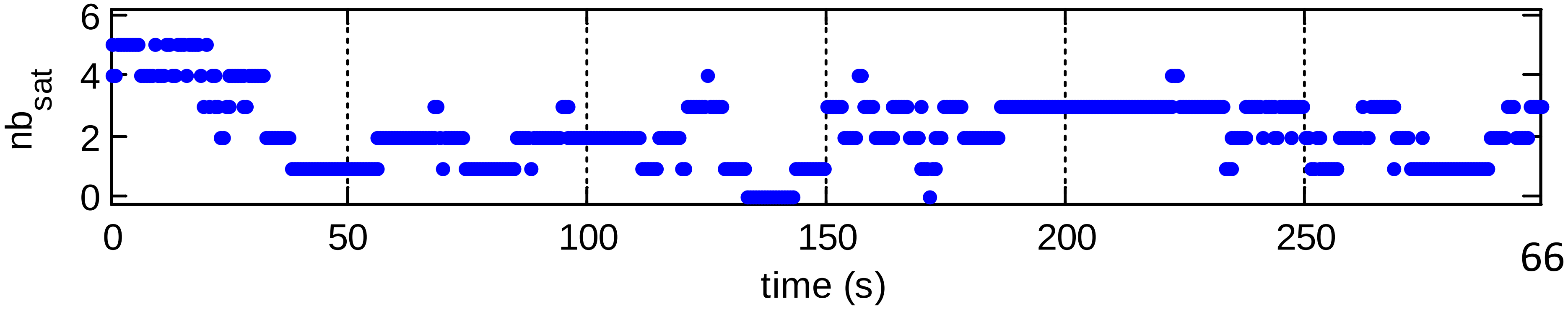
Experiment

-12th arrondissement in Paris

-Septentrio PolaRx, SNR threshold of 35dBHz





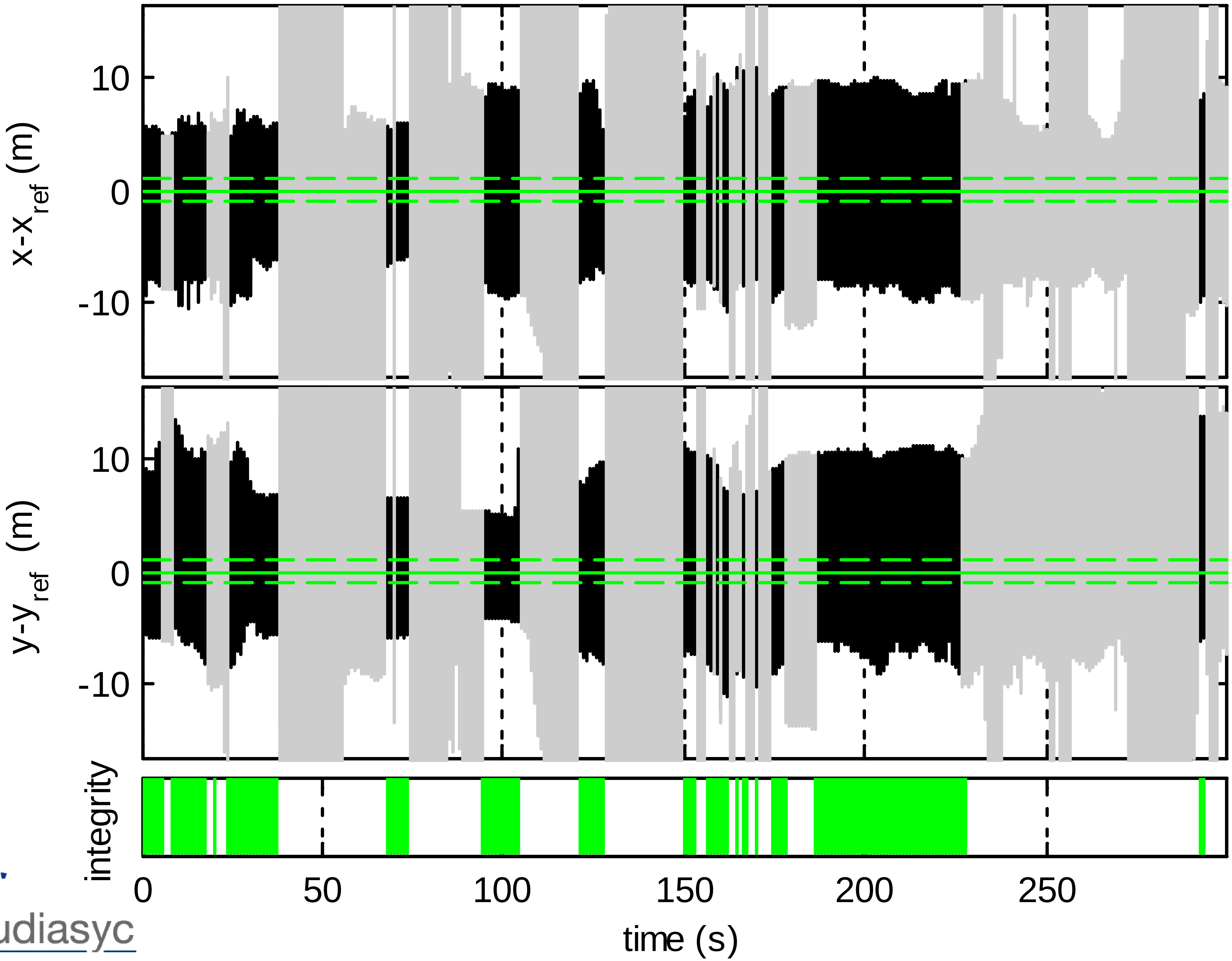


heudiasyc

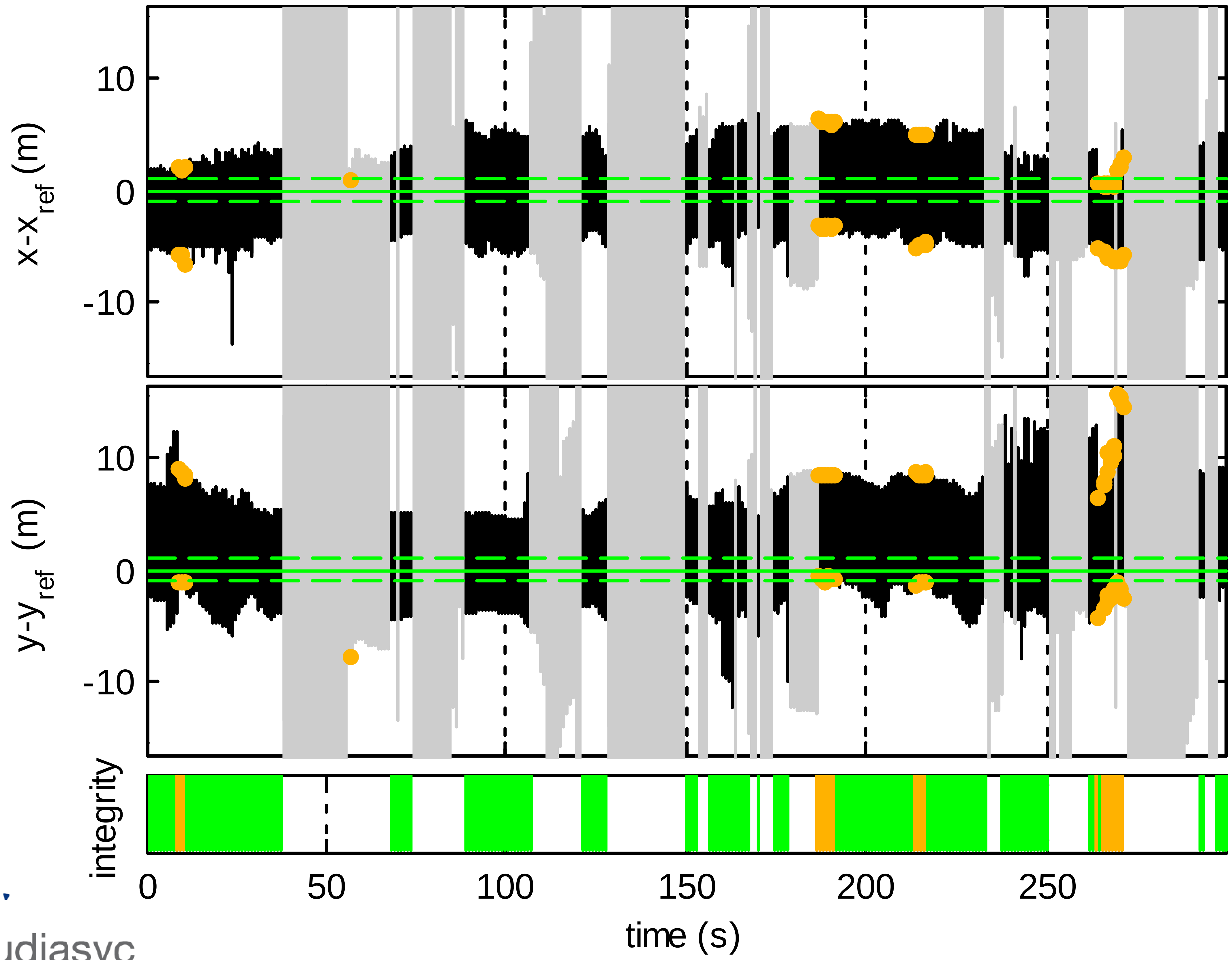

Rue Pleyel
Rue Dugommier
Rue de Charenton
Boulevard de Bercy
Boulevard de Bercy
Métro 6
Square Jean Morin
Le Dugommier

heudiasyc

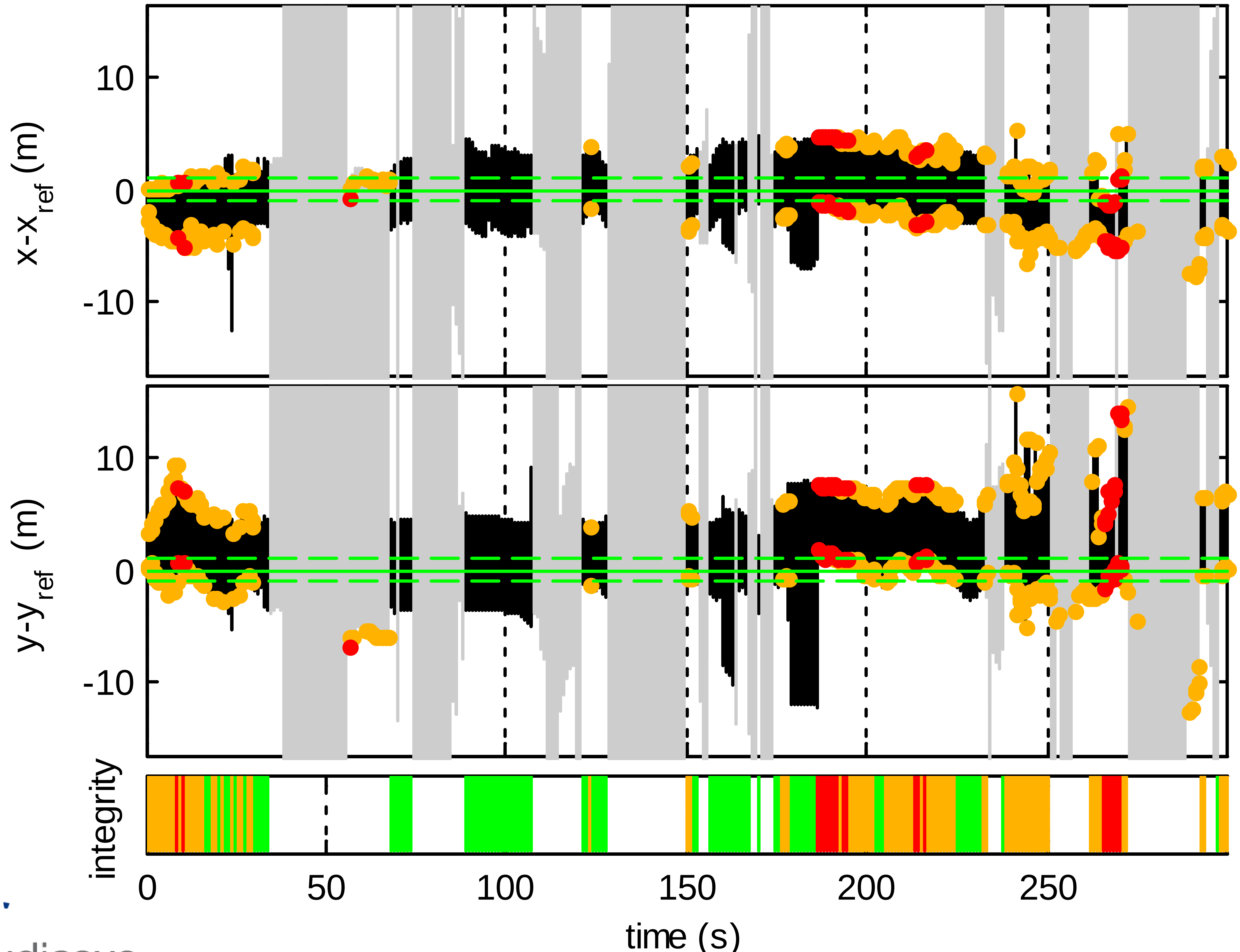
Results with r=0.01%



Results with r=10%



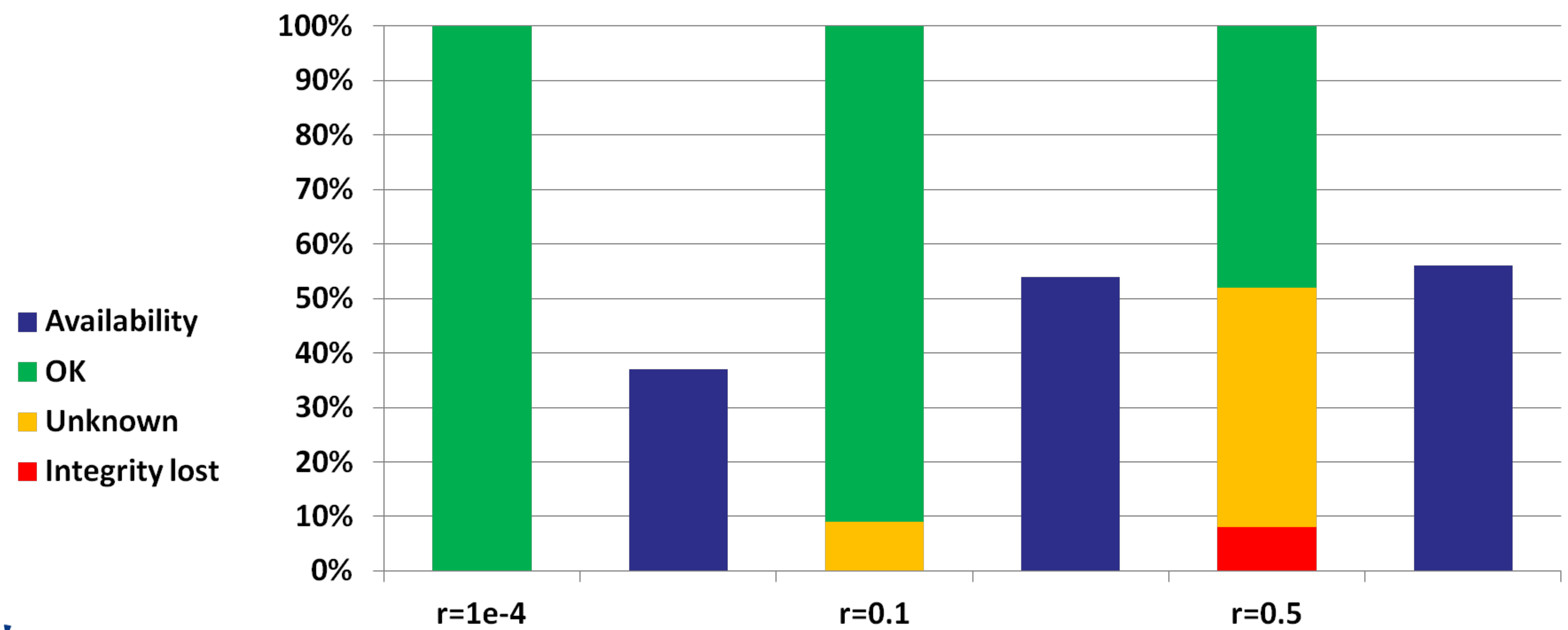
Results with r=50%



heudiasyc

Availability and integrity statistics

Integrity risk	r=0.01%	r=10%	r=50%
Availability	37%	54%	56%
Integrity OK	100%	91%	48%
Integrity unknown	0%	9%	44%
Integrity lost	0%	0%	8%



heudiasyc

Fault detection and identification

Fault detection and identification

Fault detection

-A fault is detected if there is no solution that fulfills all the constraints

Fault exclusion & identification

-Measurements whose constraint is not satisfied by any of the solution boxes are implicitly excluded

-They can easily be identified

heudiasyc

Results in Compiègne

robust 1-relaxed GPS + DTM

- Fault = drift of the satellite clock

heudiasyc

Real experiment in Paris

heudiasyc

Conclusion

Bounded-error solver for tightly coupling GPS pseudo-ranges and 3D map

Navigable maps provide pertinent information to assist localization process

Basic ideas

- We guarantee the computation
- But the computed domains are not guaranteed
- The method can protect against several outliers but the number has to be fixed in advance.

Real experiments to check if a risk computed using over-bounding Gaussians corresponds to reality

- Tests have been done with high risks to be statistically significant
- We have proposed a methodology to deal with ground truth uncertainty
- Results show that the confidence associated with the solution domain is consistent with reality.

Thank you for your attention!

Associated publications

- Drevelle, V. and Bonnifait, P. “iGPS: Global Positioning in Urban Canyons with Road Surface Maps”, IEEE Intelligent Transportation Systems Magazine, July 2012
- Fouque, C. and Bonnifait, Ph. "Matching Raw GPS Measurements on a Navigable Map Without Computing a Global Position”, IEEE Transactions on Intelligent Transportation Systems, June 2012
- Fouque, C. and Bonnifait, Ph. “Multi-Hypothesis Map-Matching on 3D Navigable Maps using Raw GPS Measurements”, IEEE ITSC 10
- Drevelle, V. and Bonnifait, P. (2011) A set-membership approach for high integrity height-aided satellite positioning. GPS Solutions
- Drevelle, V. and Bonnifait, P. (2011) Global Positioning in Urban Areas with 3-D Maps. 2011 IEEE Intelligent Vehicles Symposium, Baden-Baden
- Drevelle, V. and Bonnifait, P. (2010) Robust Positioning Using Relaxed Constraint-Propagation. IROS 2010, Taipei Taïwan