Road to Seamless Positioning: Hybrid Positioning System Combining GPS and Television Signals

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GPS: Time and Position Reference

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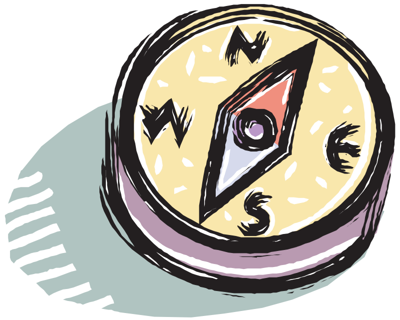

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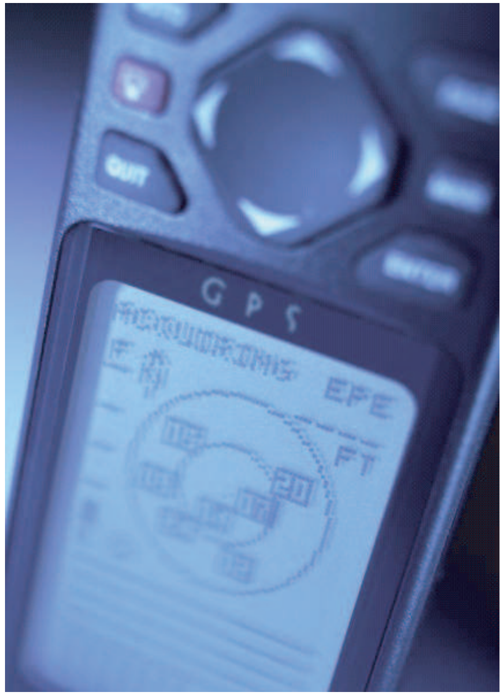


Time (1D)

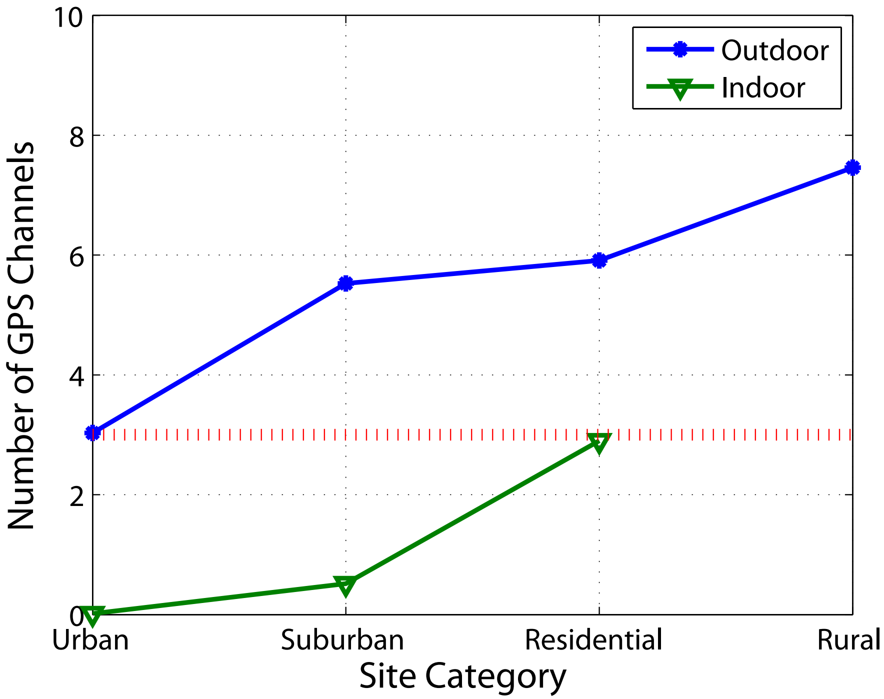
Position (3D)

Time & Position (4D)

(GPS: Global Positioning System)

Challenges for GPS in Urban/Indoor

Blocked skyview limits GPS availability in **urban/indoor** areas.



Measured number of GPS satellites at 39 Bay Area sites. However, benign urban/indoor areas usually allow better GPS reception.

GPS vs. Cell Phone

Positioning vs. Communication. Positioning (based on RF ranging) differs from communication in a few aspects which make positioning still challenging in urban/indoor areas where communication has been very successful.

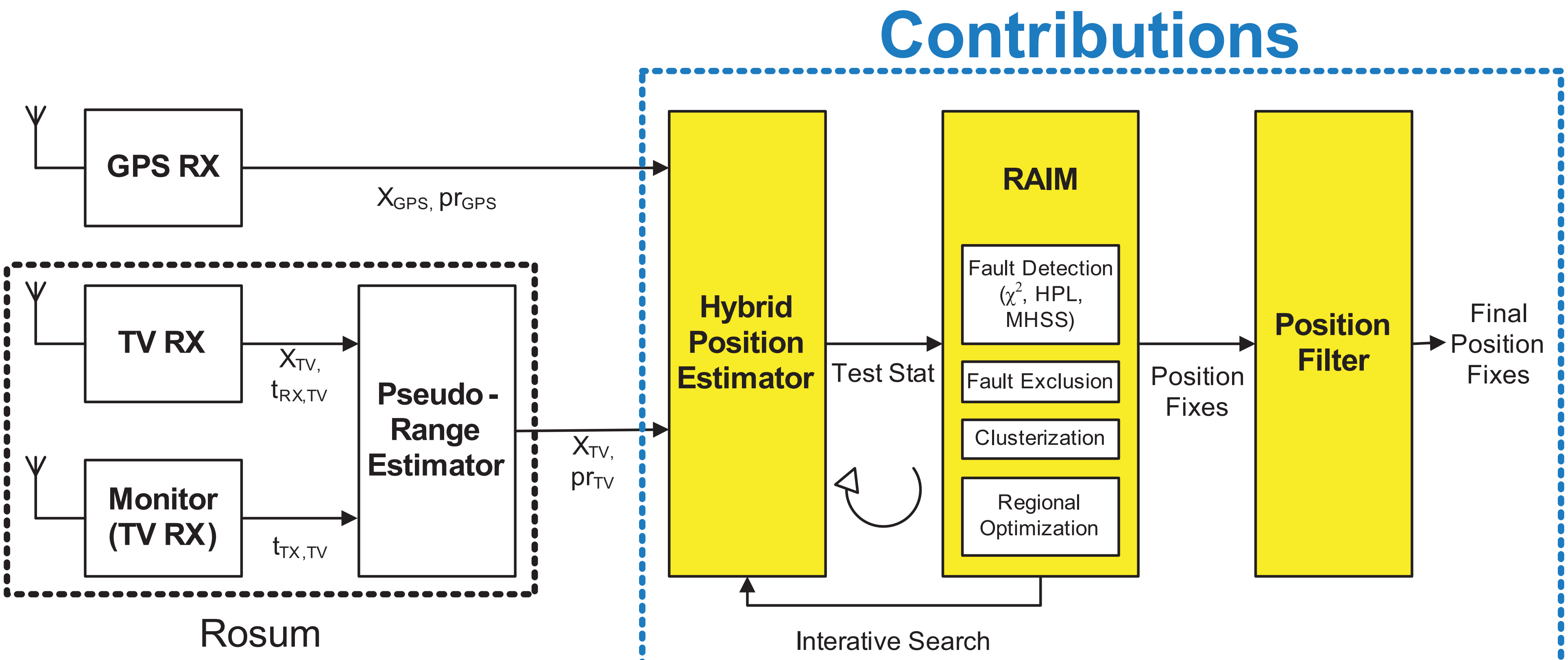
	Positioning	Communication
Goal	Position	Data or Voice
Measurement	Time of arrival (TOA)	Data bits
Required $\mathbf{N_{TX}}$	3	1
Redundancy	$\mathbf{N_{TX} > 3}$	Channel coding
Indirect Path	TOA error	Less sensitive

Contributions for Seamless Positioning

1. **Hybrid Positioning System Combining GPS and TV Signals**
    - Implemented a hybrid position estimator based on GPS pseudorange and TV pseudorange measurements.
    - Conducted extensive field tests at 39 Bay Area sites with a prototype.
2. **Multi-Fault Tolerant RAIM (Receiver Autonomous Integrity Monitoring)**
    - Proposed and implemented Multi-Fault Tolerant Iterative RAIM for protection against outlying terrestrial range measurements.
3. Interference Survey
    - Conducted a spectrum survey on GPS L1, Unified-S, and ISM 2.4 GHz bands, an joint effort with NASA and Clemson Univ.
4. Multipath Mitigation
    - Proposed Inverse Correlation Method optimized for multipath resolution.

Contribution I,II: Hybrid Positioning

Integration of GPS and TV opens door to seamless positioning.



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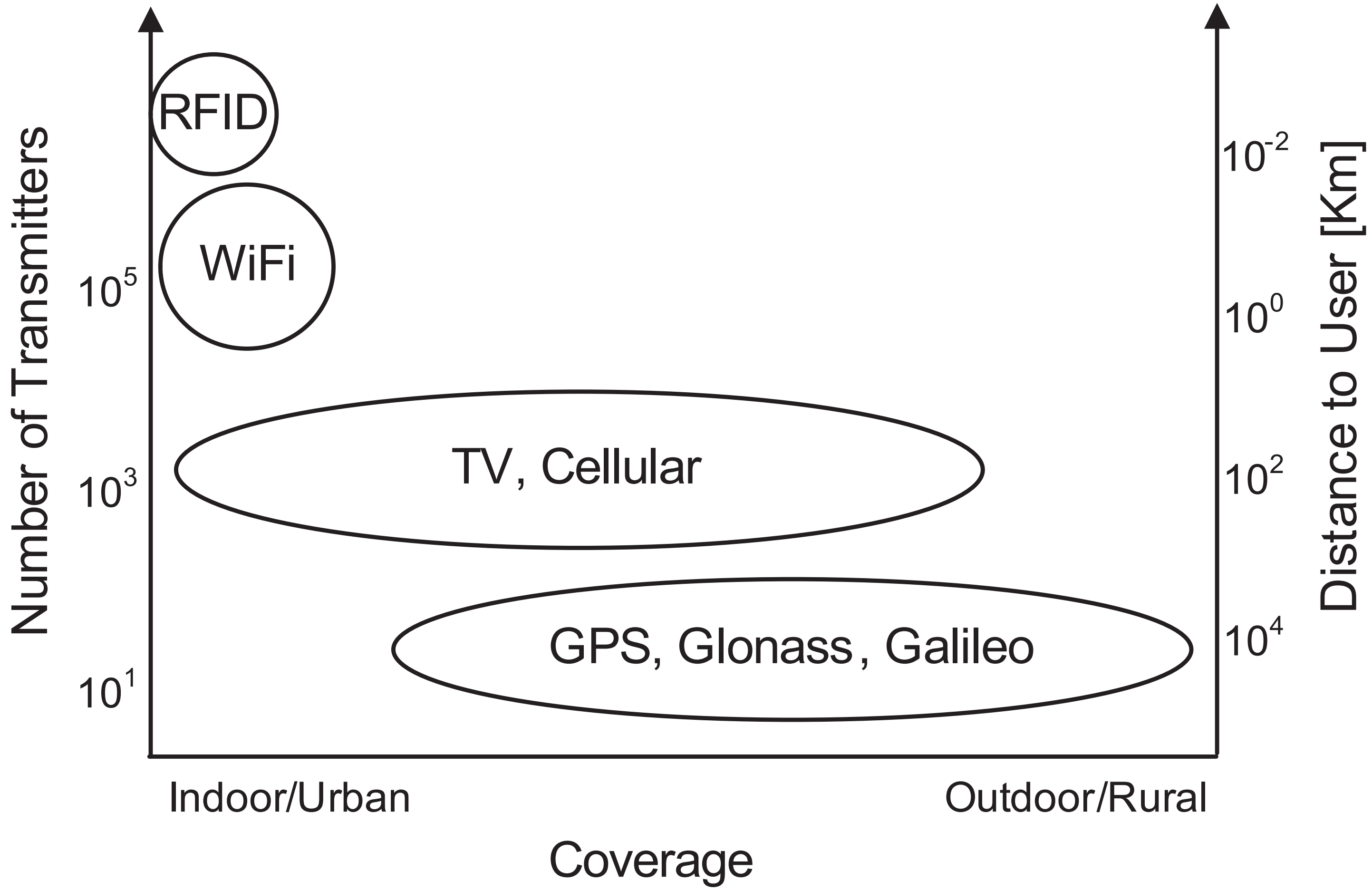
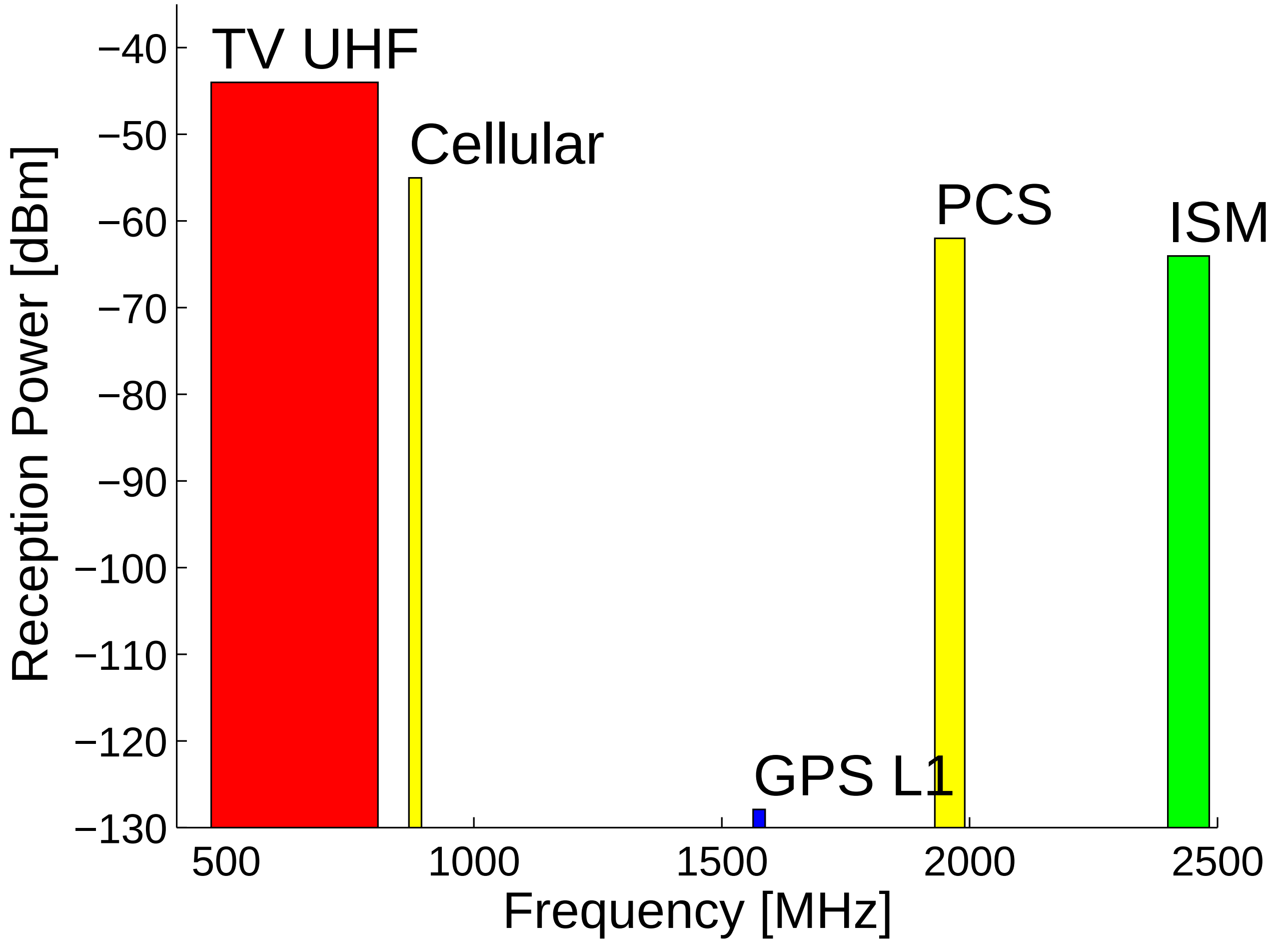
Search in Geographical Signal Space

Combining ranging sources for the **end-to-end coverage!**



Search in Spectral Signal Space (RX)

Signal power and bandwidth are the key factors in positioning.



Final Selection = GPS + TV

Pros and cons of candidate ranging sources (GPS and terrestrial communication systems).

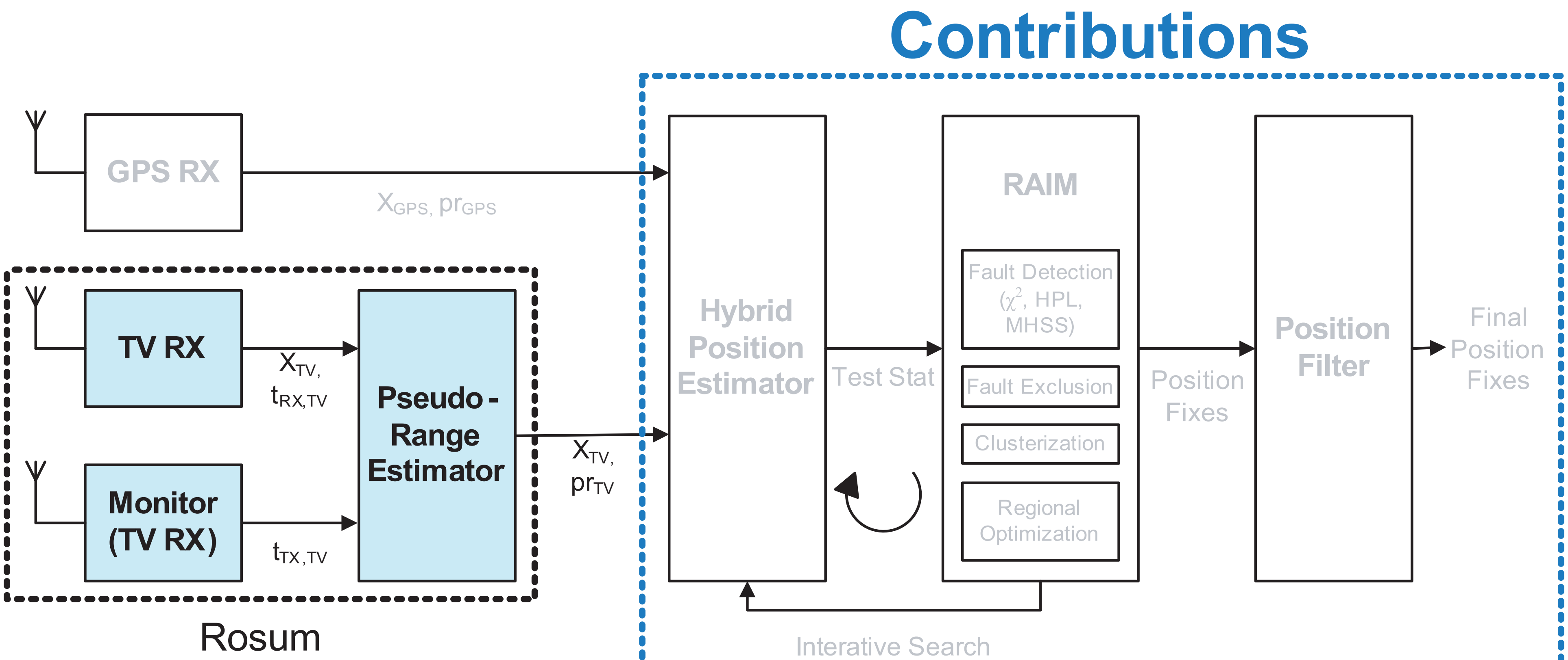
	GPS	TV	Cellular	WiFi	RFID
Distance (km) P_{RX} (dBm) BW (MHz) Ch BW (MHz)	**20,000** **-125** 24 2	< 100 -44 336 6	< 10 -55 25 1.25	< 0.5 -64 83.5 22	< 0.01
Near-Far Coverage Measurement	Mild Outdoor Range	None Out/In Range	**Severe** Out/In Range	High Indoor $\mathbf{P_{RX}}$	N/A **Proximity** Detection
Required Investment	None	**Clock monitoring**	None	**Periodic surveying**	**Installation**

TV channel allocations:

54–88 MHz (ch2–6), 174–216 MHz (ch7–13), and 470–806 MHz (ch14–69)

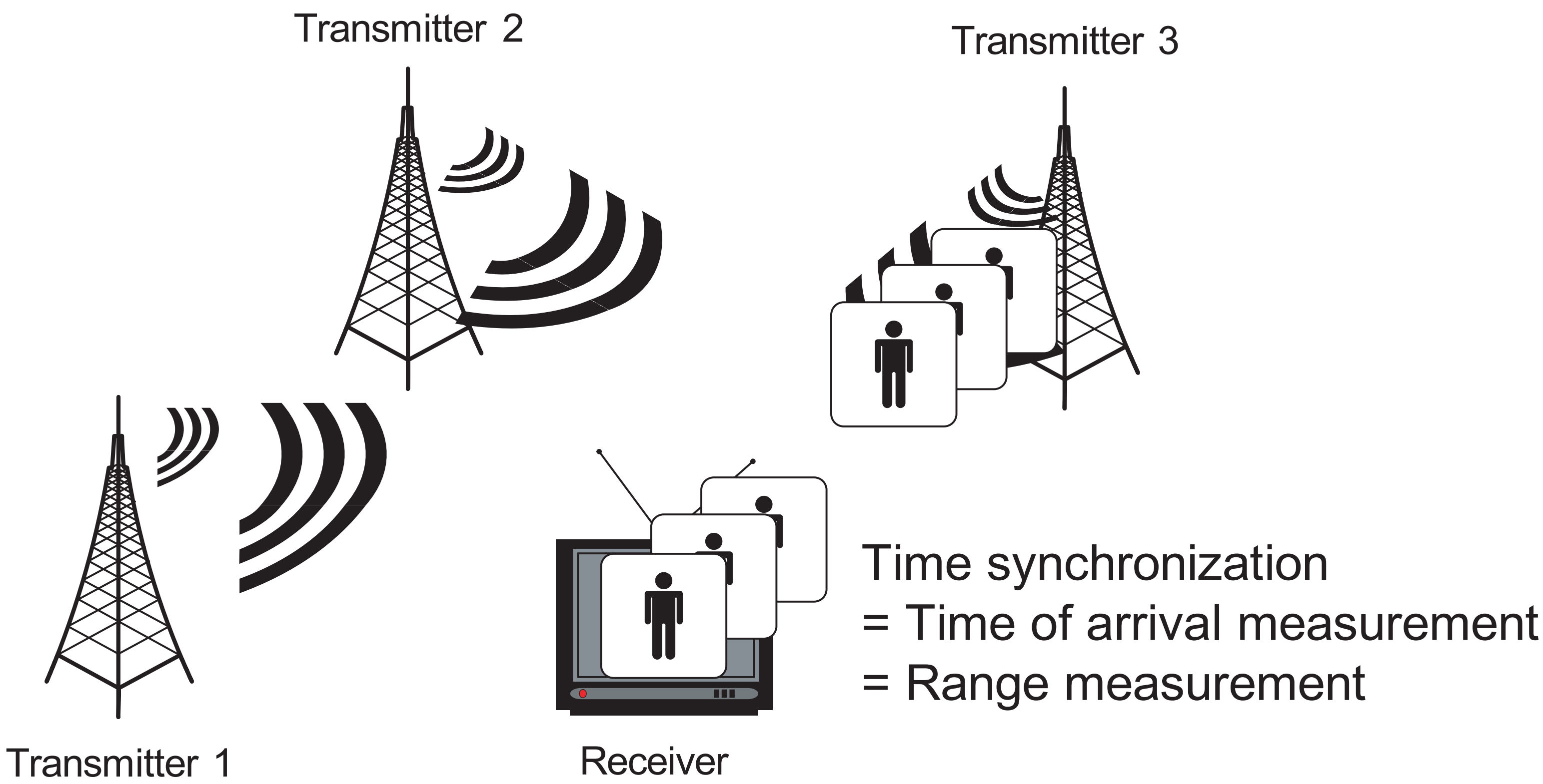
TV Positioning System

Pioneering works by Rabinowitz and Spilker (Rosum Corp. '00)



TV Towers

Time synchronization = Range (distance) measurement.



Network Synchronization

- GPS, CDMA Cellular $\longrightarrow$ synchronized networks

- TV, WiFi, GSM/TDMA cellular networks
  $\longrightarrow$ **Un**-synchronized networks

Absolute/Relative Positioning

- Absolute positioning

$$\rho_i^l = r_i^l + b^l + B_i + \epsilon_i^l$$

For GPS, $B_i \approx 0$ for all i, but for others, $B_i \neq 0$.

- Relative positioning (no TX clock bias B)

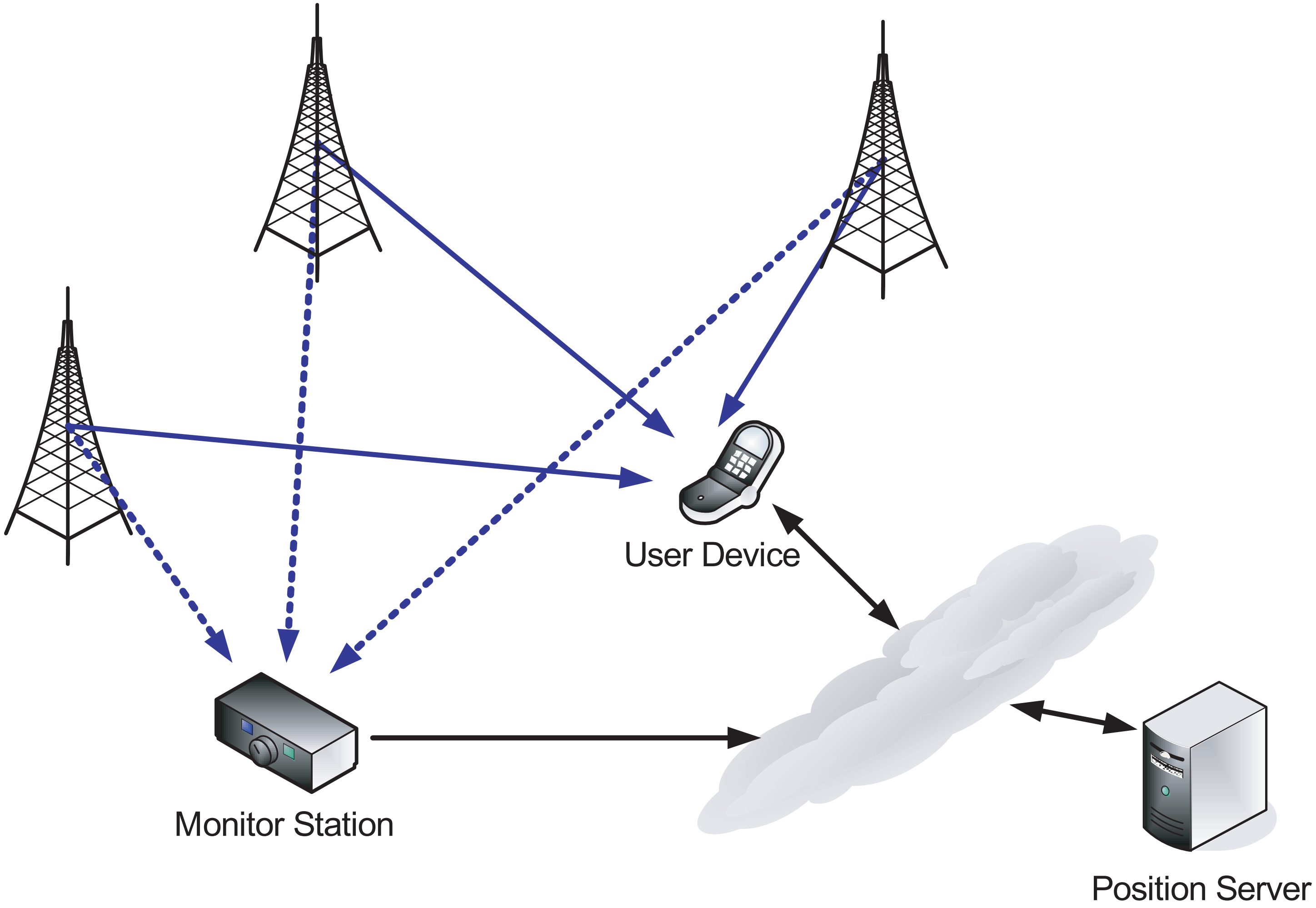
$$\Delta\rho_i^{l,m} = \Delta r_i^{l,m} + \Delta b^{l,m} + \Delta\epsilon_i^{l,m}$$

- Pseudo-absolute (with an installed reference receiver)

$$\rho_i = r_i + b + (B_i - \hat{B}_i) + \epsilon_i$$
$$\hat{B}_i = \rho_i^{ref} - (r_i^{ref} + \hat{b}^{ref})$$

TV Positioning System

A monitor (reference) station calibrates out transmitter clock biases.



TV Positioning Equation

- Construction of Pseudoranges

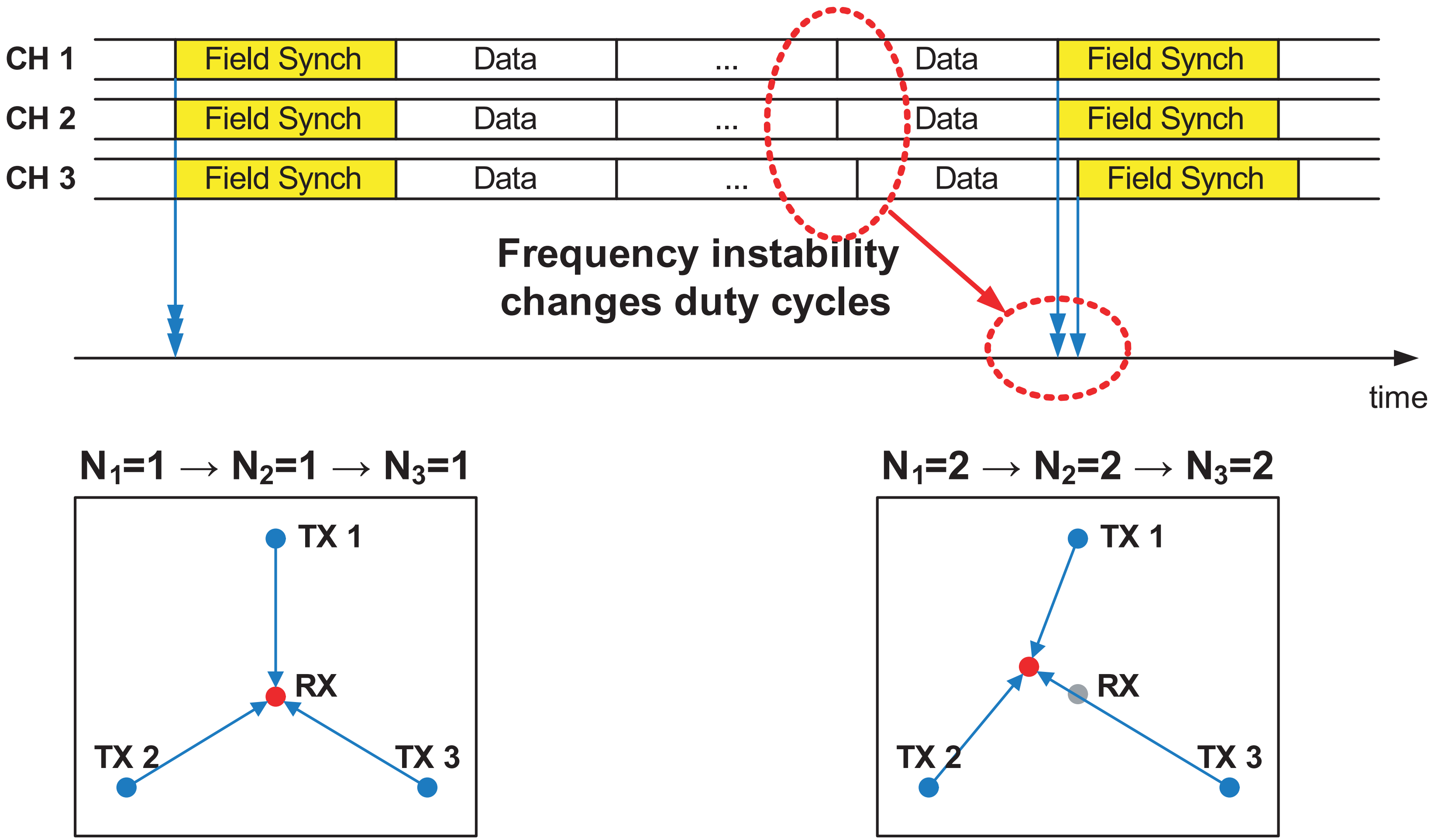
$$\begin{aligned}\rho_i &= \tilde{t}^{u}_{RX,i} - \tilde{t}^{ref}_{TX,i} \\ &= (t^{u}_{RX,i} - t^{u}_{TX,i}) + (b_u - b_{ref}) + N_i\lambda_i + (\epsilon^u_i - \epsilon^{ref}_i) \\ &= r_i + b + N_i\lambda_i + \epsilon_i\end{aligned}$$

where

$$\begin{aligned}\tilde{t}^{u}_{RX,i} &= \text{RX time at user} = t^{u}_{RX,i} + b_u + \epsilon^u_i \\ \tilde{t}^{ref}_{TX,i} &= \text{estimated TX time at reference} \\ &= t^{ref}_{TX,i} + b_{ref} + \epsilon^{ref}_i = (t^{u}_{TX,i} - N_i\lambda_i) + b_{ref} + \epsilon^{ref}_i \\ \lambda &= 24.2 \text{ ms} = 7254 \text{ Km}\end{aligned}$$

Frequency Instability Induced Range Error

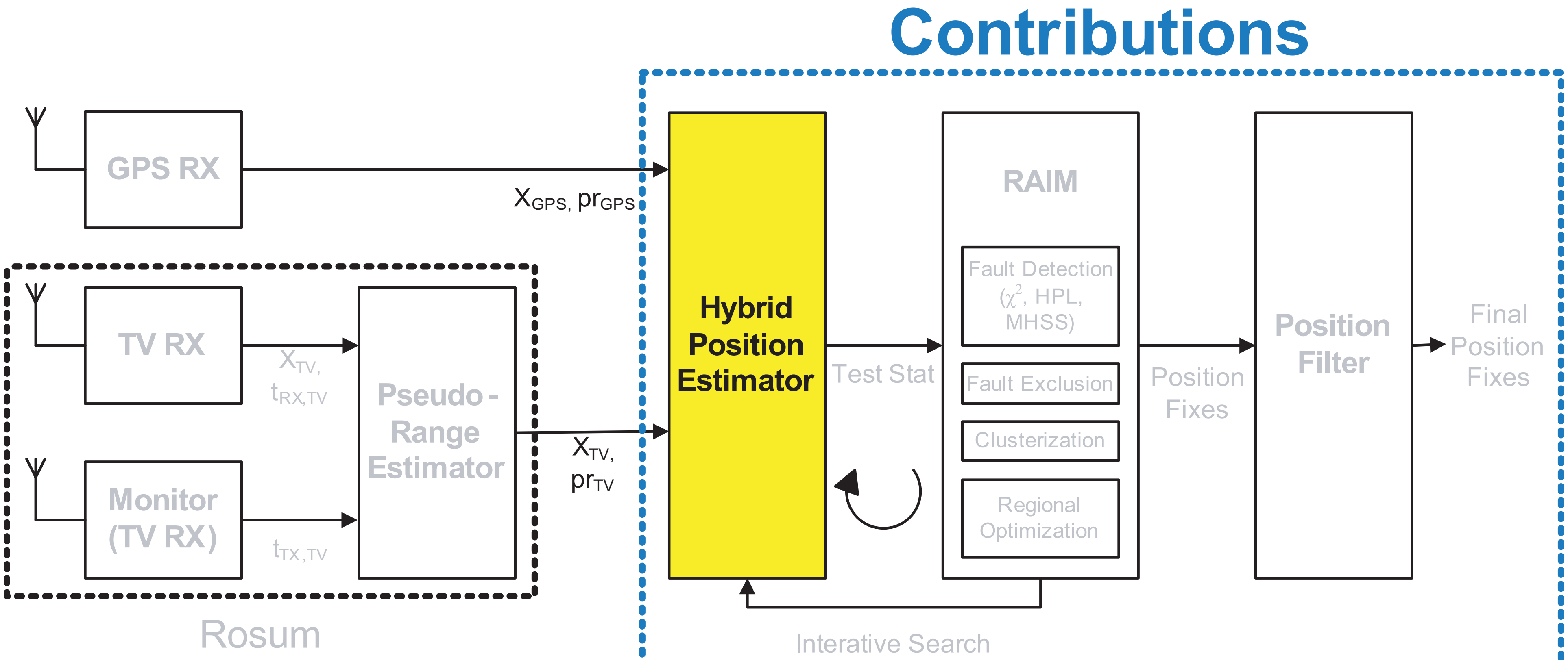
Integer ambiguity + Frequency instability → Range error → Position error



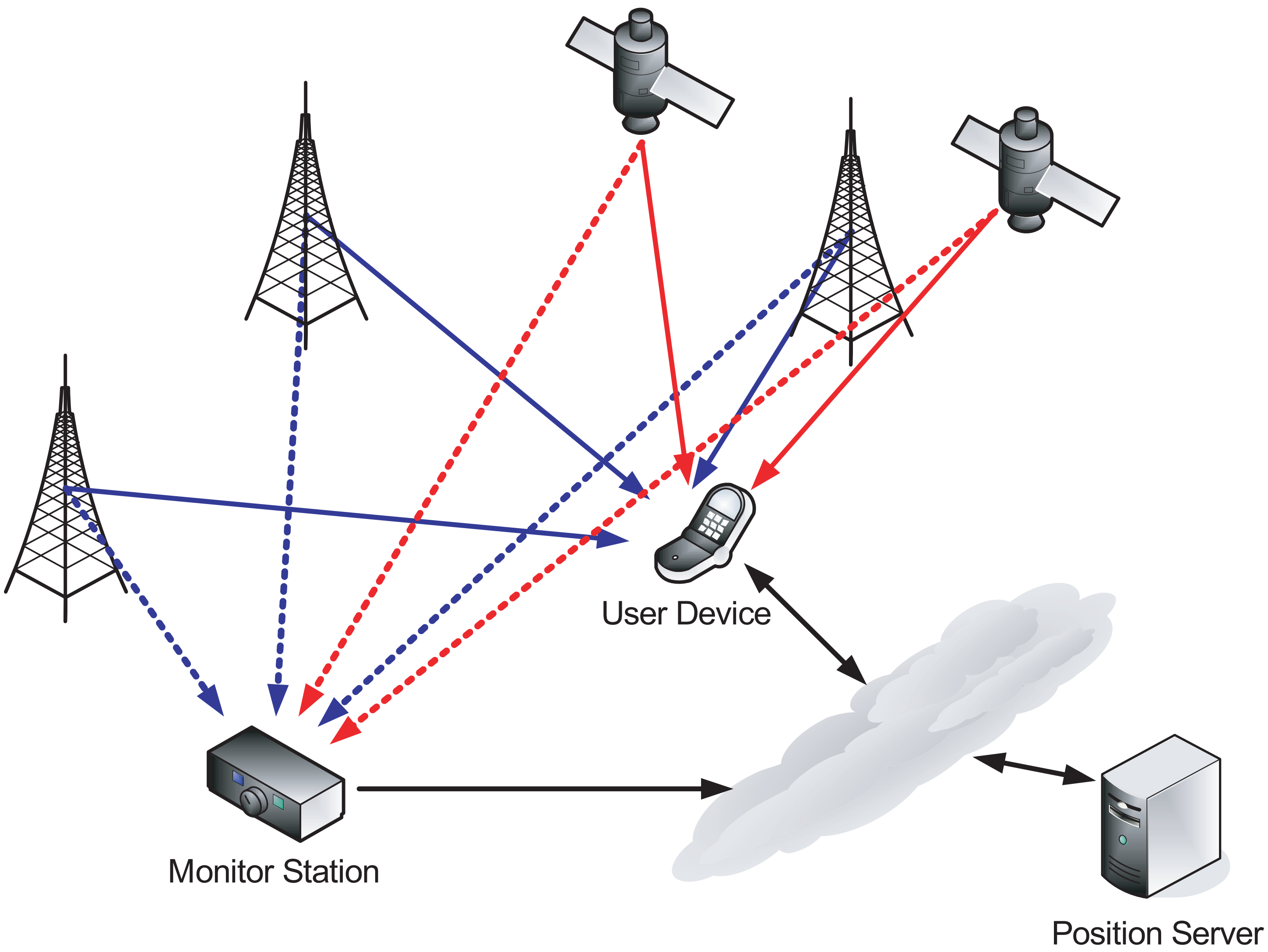
Contents

Contribution I: Hybrid Positioning System

Implemented Hybrid Positioning Estimator combining GPS/TV range measurements on a MATLAB platform and conducted field tests with its prototype.



Hybrid Positioning System



Hybrid Positioning Equations

- TV and GPS Pseudoranges

$$\text{TV: } \rho_{TV,i} = r_i + b_{TV} + \epsilon_{TV,i}$$

$$\text{GPS: } \rho_{GPS,j} = r_j + b_{GPS} + \epsilon_{GPS,j}$$

- Combined Pseudoranges after Differentiation

$$\text{Hybrid: } \delta\boldsymbol{\rho} = \boldsymbol{G}\delta\boldsymbol{x} + \boldsymbol{v}$$

where

$$\delta\boldsymbol{\rho} = [\delta\boldsymbol{\rho}_{TV}^T, \delta\boldsymbol{\rho}_{GPS}^T]^T$$

$$\delta\boldsymbol{x} = [\delta x, \delta y, \delta z, \delta b_{TV}, \delta b_{GPS}]^T$$

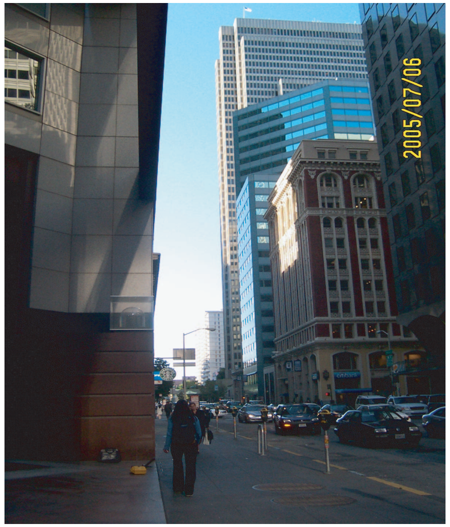
Extensive Field Tests at 37 (+2) Bay Area Sites

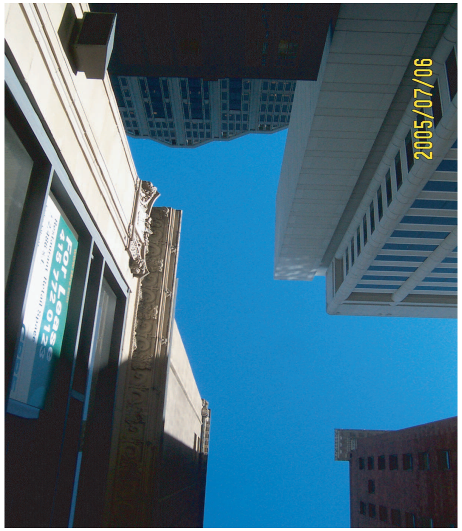
Constructed a prototype with a SiRF GPS RX and a Rosum TV RX with the help of Samra (Rosum) and conducted extensive field tests.

- Stationary tests of GPS and TV RXs
- 1 hour test per site
- 1 measurement per a minute
- Extreme urban indoor sites (2) removed due to the lack of sufficient measurements

Category	Location	Outdoor	Indoor
Urban	San Francisco downtown	6	4 (+2)
Suburban	Palo Alto downtown	4	5
Residential	Stanford graduate housing	8	5
Rural	Halfmoon Bay and Highway 280	5	N/A

Outdoor Test Sites

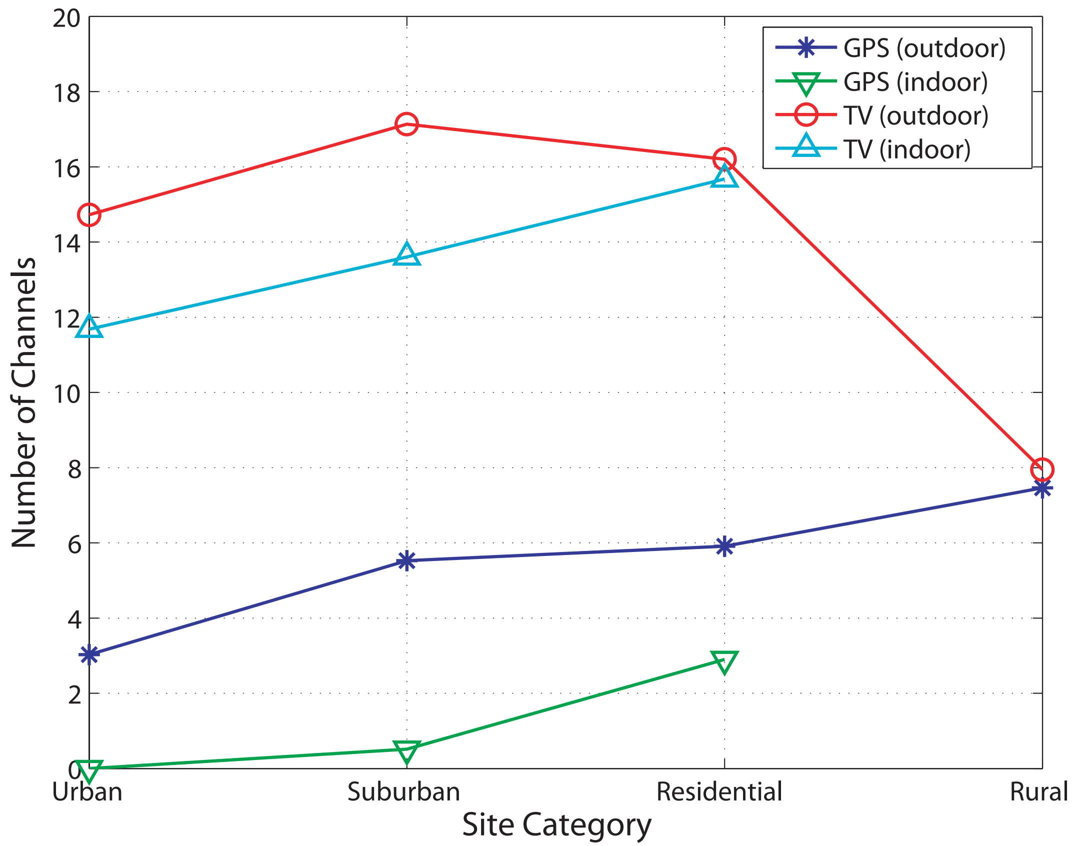


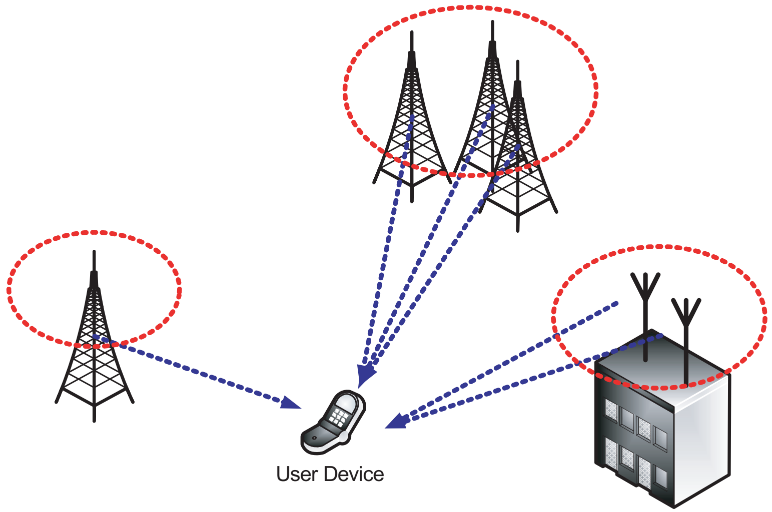


Indoor Test Sites

Number of Observed Channels

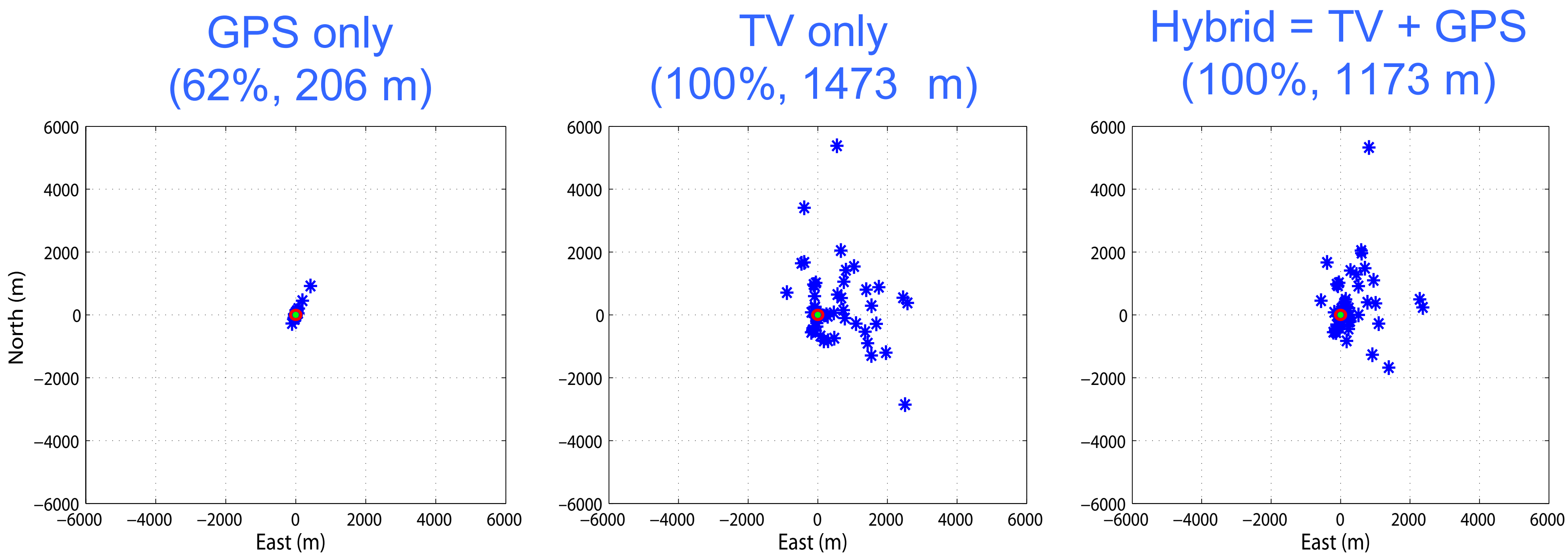
Many TV channels even in indoors but tend to be co-located: less favorable for geometry but good for cross-check.



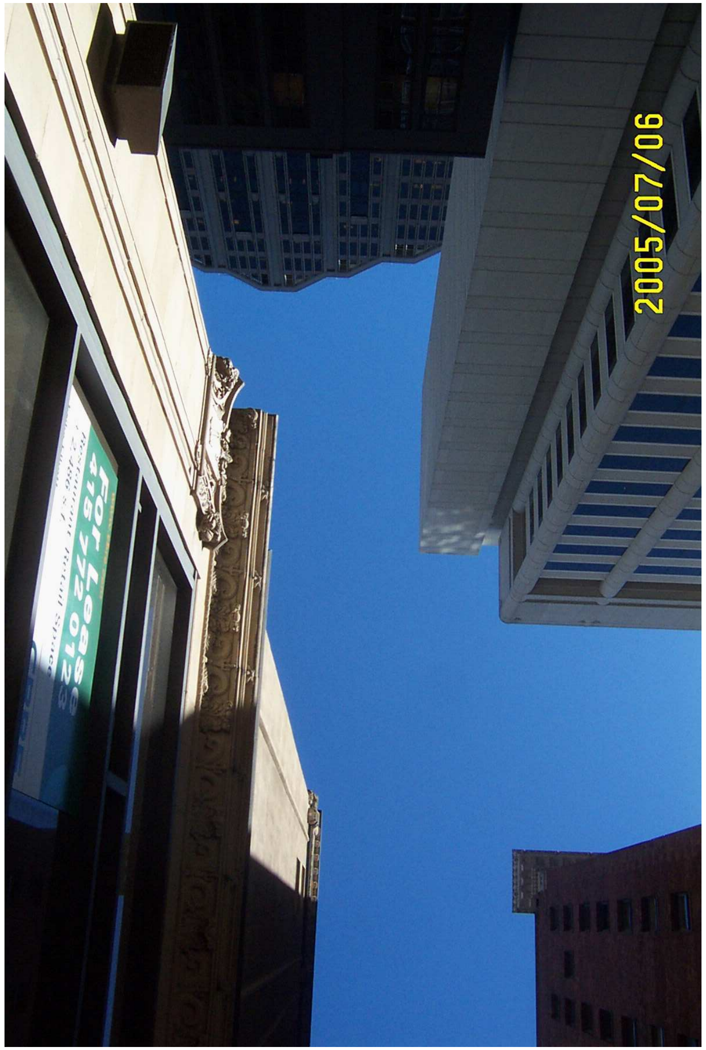


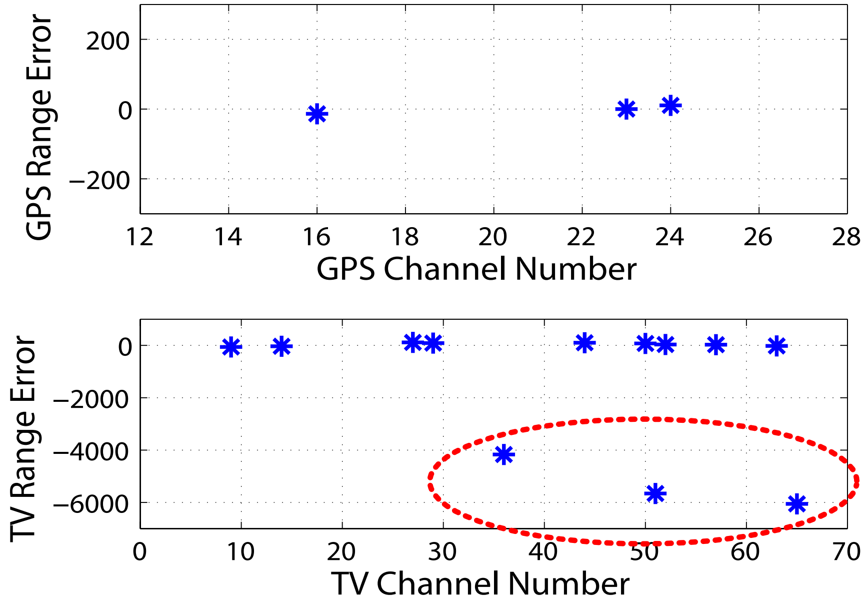
Hybrid Position Fixes! (Urban Canyon)

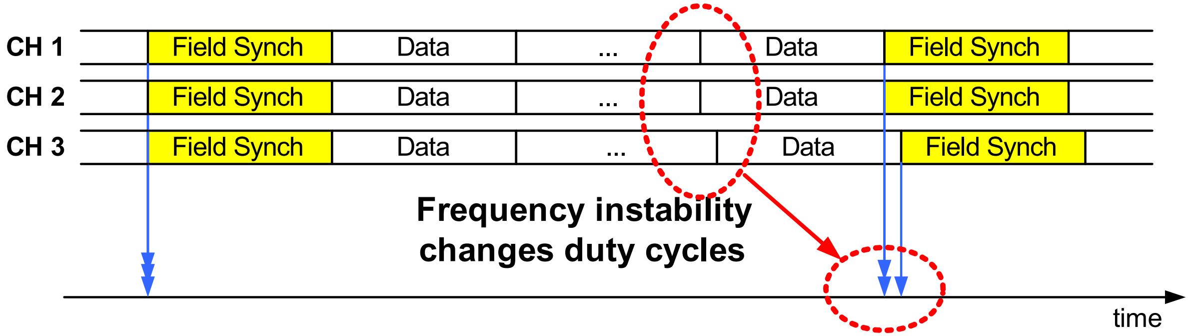
- Epoch by epoch position estimation.
- GPS, TV, Hybrid (GPS+TV) fixes on an urban canyon at San Francisco downtown.



Frequency Instability Induced Range Error







Contents

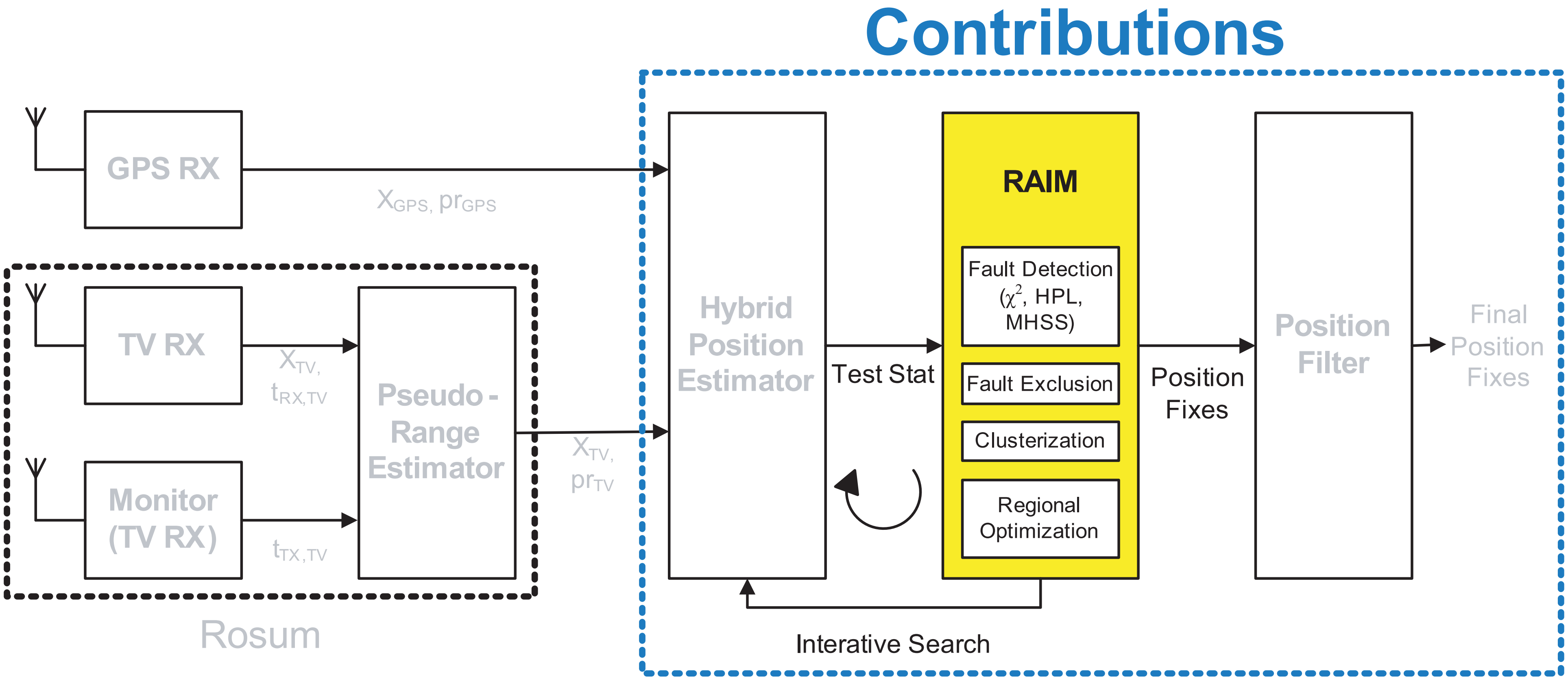
1. Search for a Solution for Urban/Indoor Areas

2. Hybrid Positioning System Combining GPS and TV Signals

3. **Multi-Fault Tolerant RAIM (Receiver Autonomous Integrity Monitoring)**

Contribution II: Multi-Fault Tolerant RAIM

Implemented Multi-fault tolerant iterative RAIM algorithms to detect and exclude outlying range measurements from integrated signals, in particular from TV pseudoranges.



Candidate RAIM Algorithms (Fault Detection)

- χ^2 test

$$||w||^2 < \chi^2_{\mathsf{th}}(P_{\mathsf{FA}}, k)$$

- HPL (Horizontal Protection Level) test (Brown '94)

$$\mathsf{HPL} = \Delta_{\mathsf{max}} \cdot \mathsf{pbiasB} < \mathsf{HAL}$$

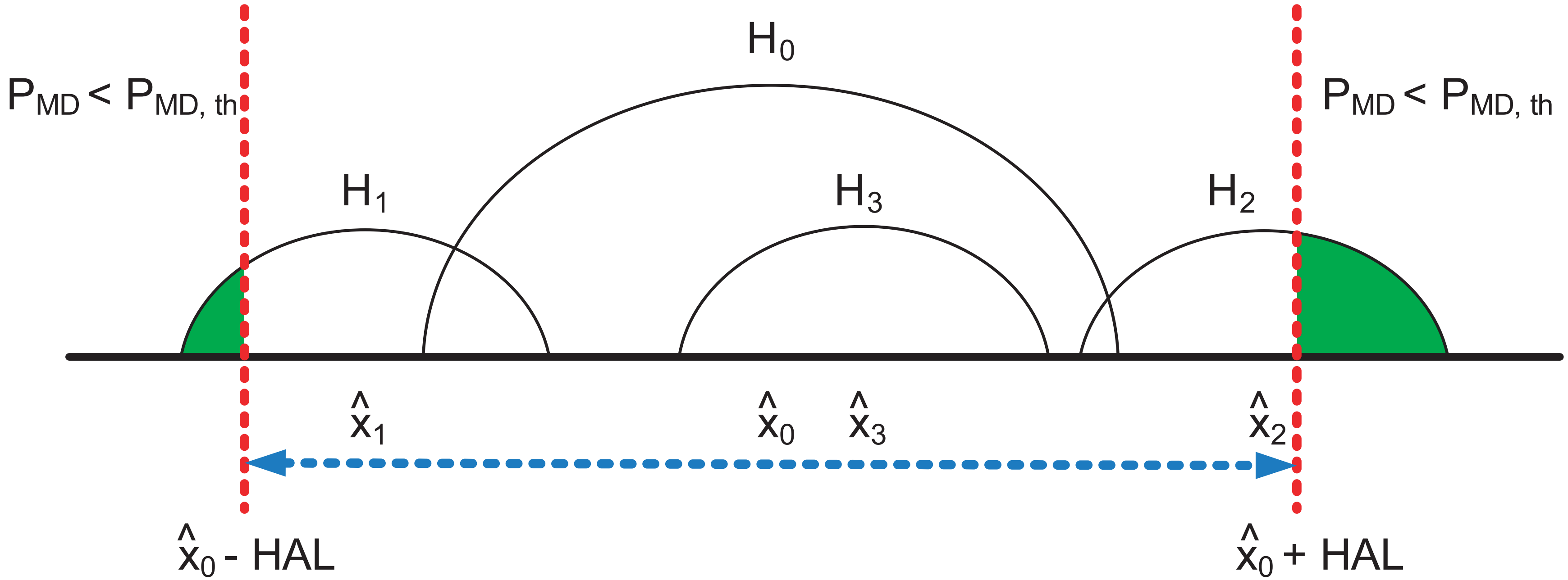
- MHSS (Multi-Hypothesis Solution Separation) test (Pervan '98) (H_i : a bias in ρ_i) and $X|H_i \sim N(\hat{x}_i, \sigma^2_{x,i})$

$$P_{\mathsf{MD},i} = \mathsf{Pr}\{||X - \hat{x}_0|| > \mathsf{HAL}|H_i\}$$

$$P_{\mathsf{MD}} = \sum_{i=0}^{n} P_{\mathsf{MD},i} \cdot \mathsf{P}(H_i) < P_{\mathsf{MD,th}}$$

MHSS (Multi-Hypothesis Solution Separation) Test

Construct hypotheses (H_i : a bias in ρ_i and $X|H_i \sim N(\hat{x}_i, \sigma^2_{x,i})$). Then, validates the initial position estimate ($\hat{x}_0$) based on $P_{\mathsf{MD},i} = \mathsf{Pr}\{||X - \hat{x}_0|| > \mathsf{HAL}|H_i\}$ and $P_{\mathsf{MD}} = \sum_{i=0}^{n} P_{\mathsf{MD},i} \cdot \mathsf{P}(H_i) < P_{\mathsf{MD,th}}$.



Candidate RAIM Algorithm (Fault Exclusion)

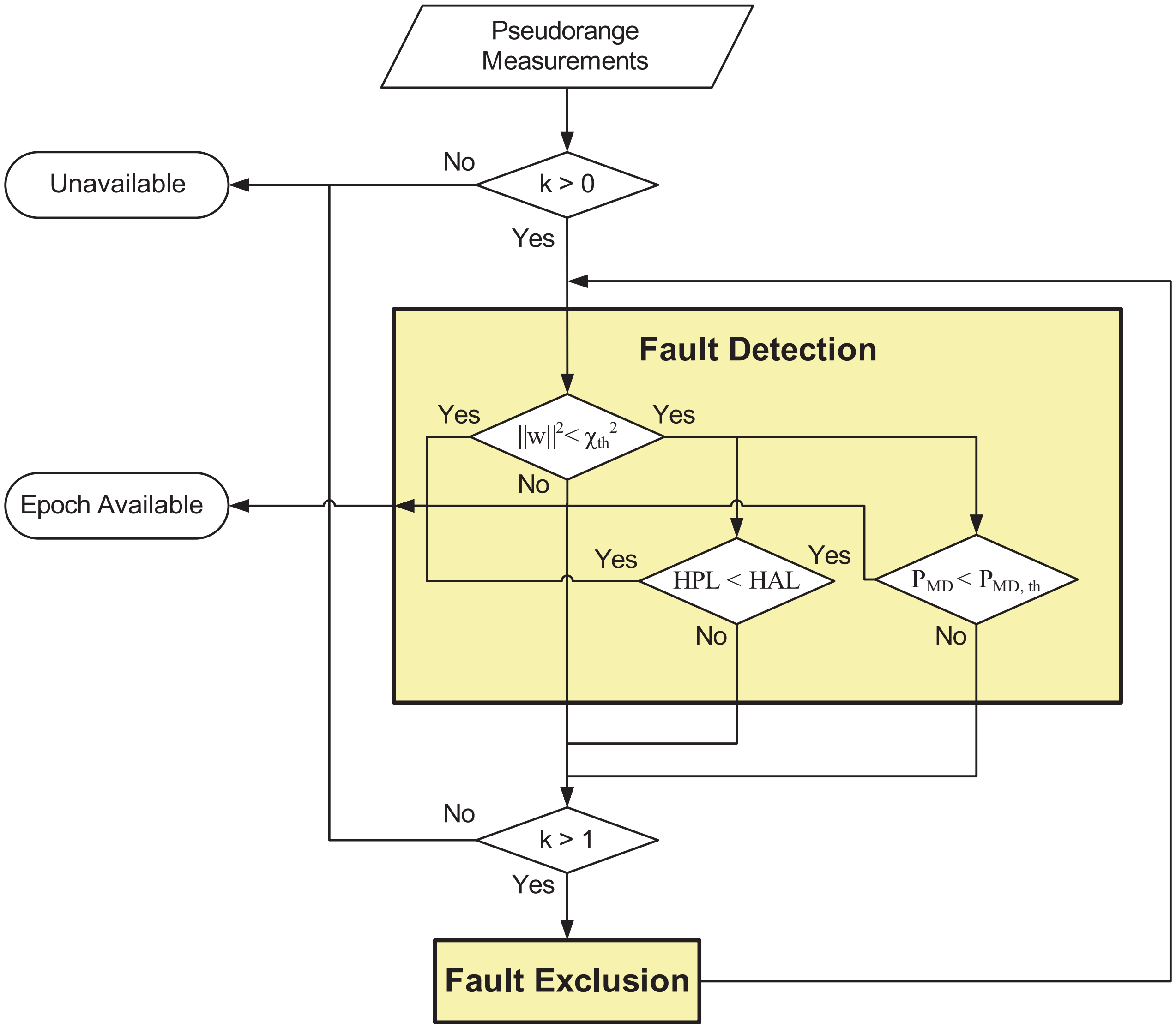
- Maximum likelihood test (Sturza '88)
  minimizing the distance, $||p - \hat{p}_i||$, between the parity vector $p = Pw$ and its reconstruction $\hat{p}_i$ based on H_i

$$i^* = \arg\min_i ||p - \hat{p}_i|| = \arg\max_i \frac{(p^T P_i)^2}{(P^T P)_{ii}}$$

  where P is a parity transformation matrix, spanning the null space of G. $PG = 0$ and $PP^T = I$.

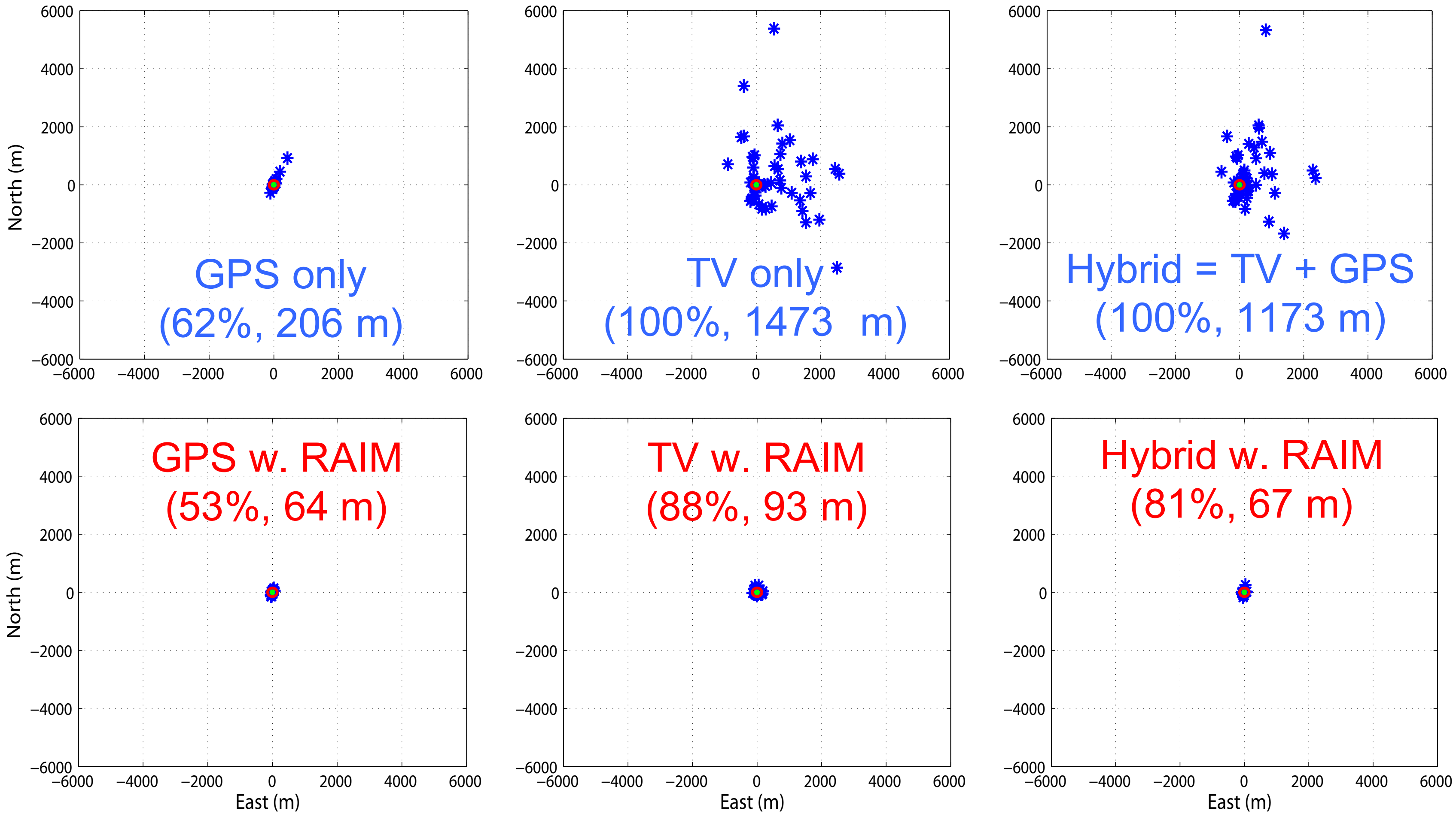
- Iteration of fault detection and exclusion steps until all outliers are removed.

Iterative RAIM Implementation



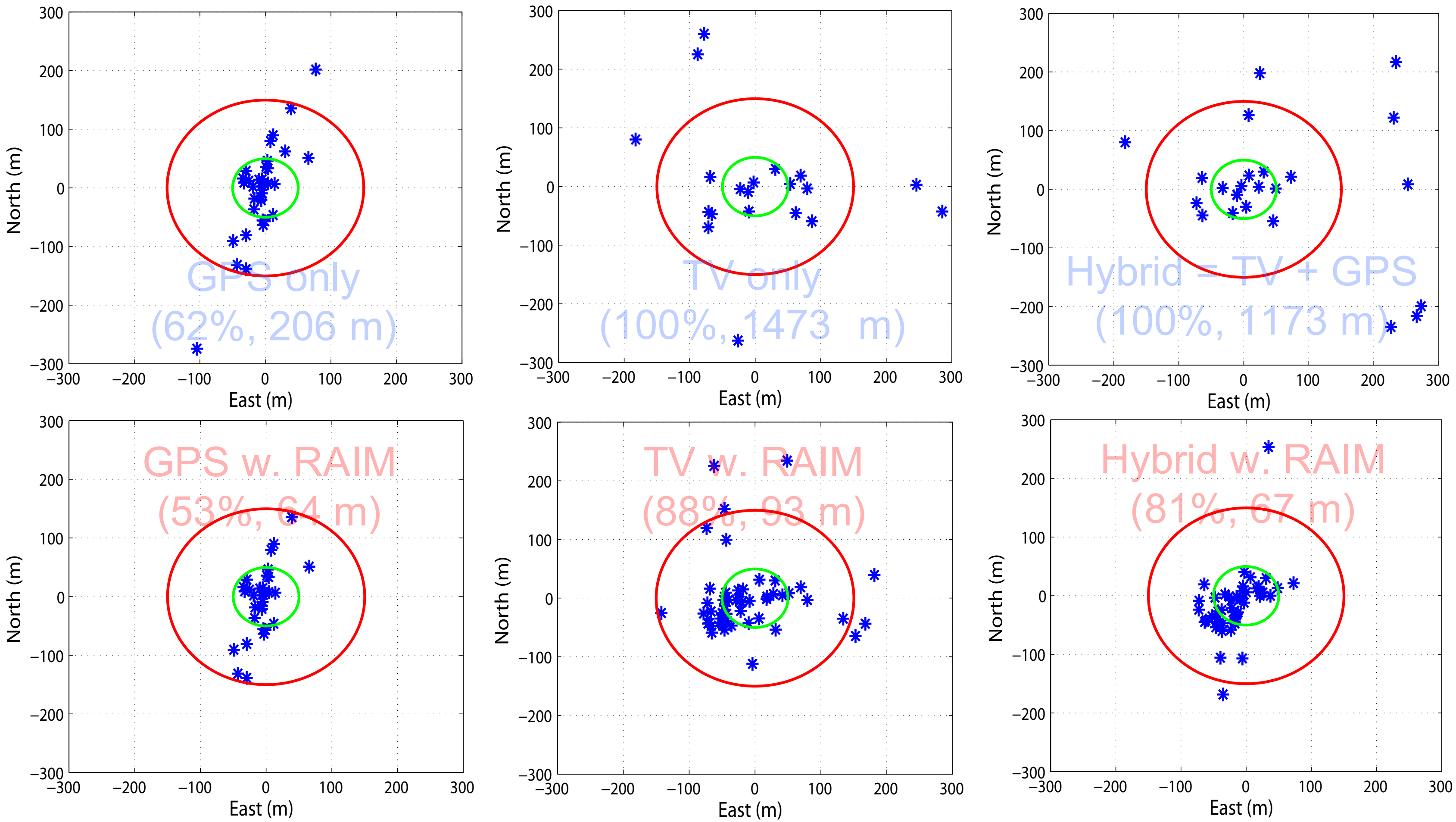
Position Fixes at the Urban Canyon

Availability and accuracy trade-off.



Position Fixes at the Urban Canyon (zoomed)

Availability and accuracy trade-off.



Search for a Best RAIM in Two Goals

- Two Goals: Availability and Accuracy

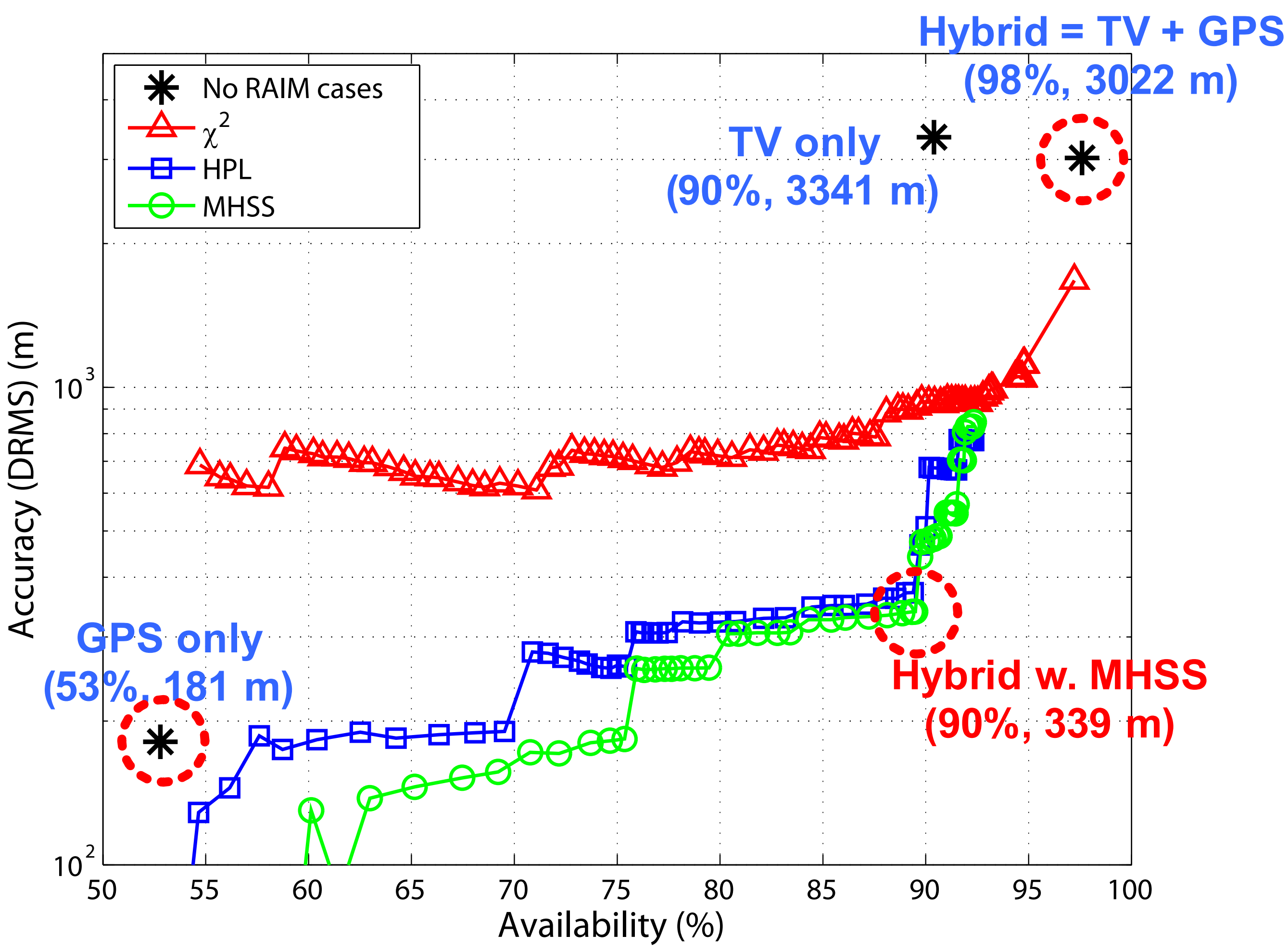
$$\text{Availability} = \frac{\text{number of available epochs}}{\text{number of total epochs}}$$

$$\text{Accuracy} = \text{DRMS (distance root mean squared) (m)}$$

- Calculate average availability and accuracy from all sites for given RAIM parameters.
  - For χ^2 test, adjust $P_{\text{FA}} = 0$–0.999.
  - For HPL and MHSS, adjust HAL= 10^1–10^5 (m) with fixed $P_{\text{FA}} = 10^{-3}$ and $P_{\text{MD}} = 10^{-2}$.

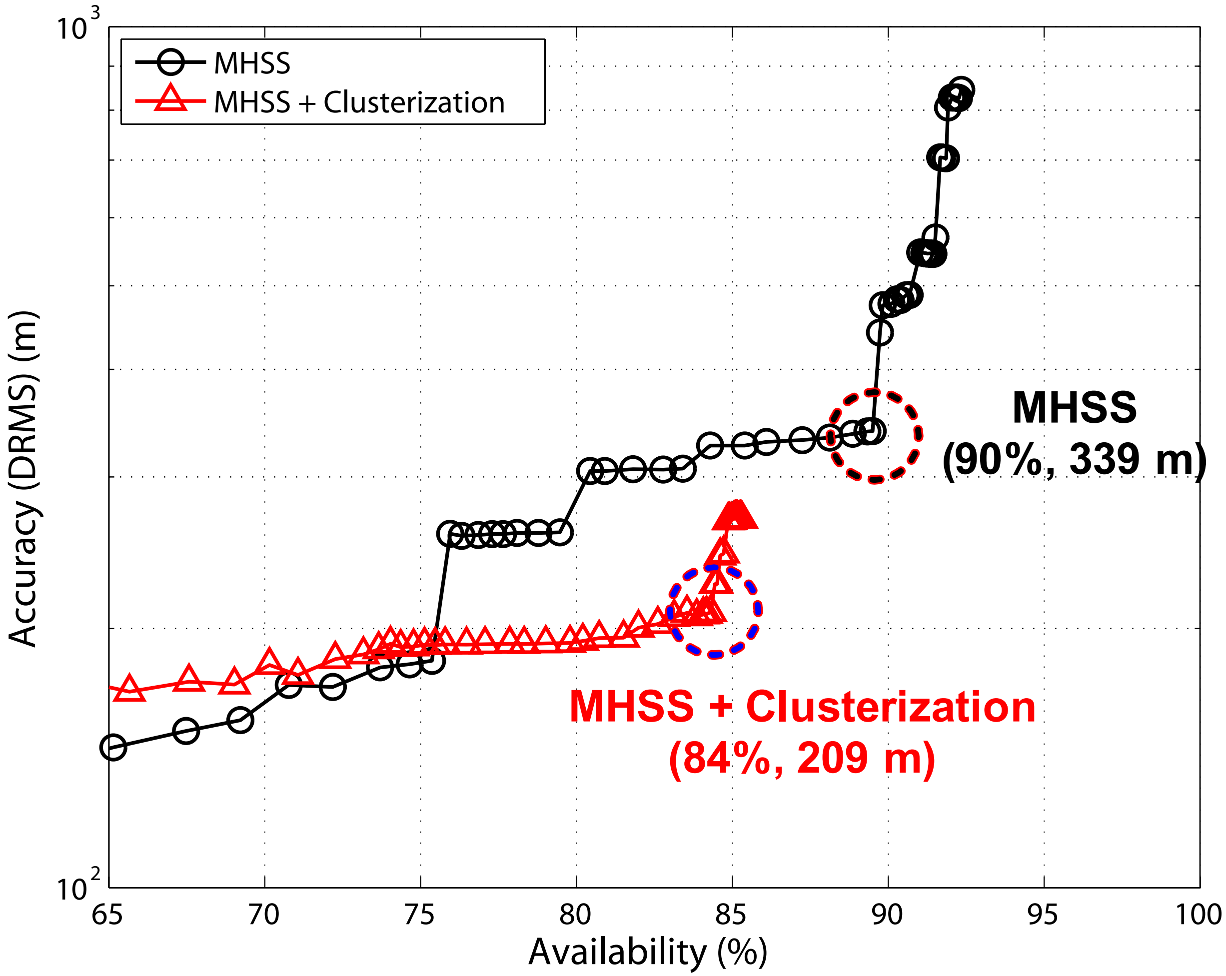
Availability and Accuracy Trade-Off

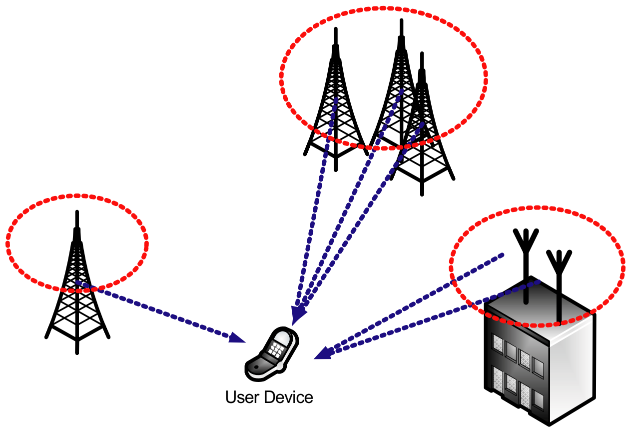
Each point is an average from 37 sites for given RAIM parameters.



Trade-off Curve after Clusterization

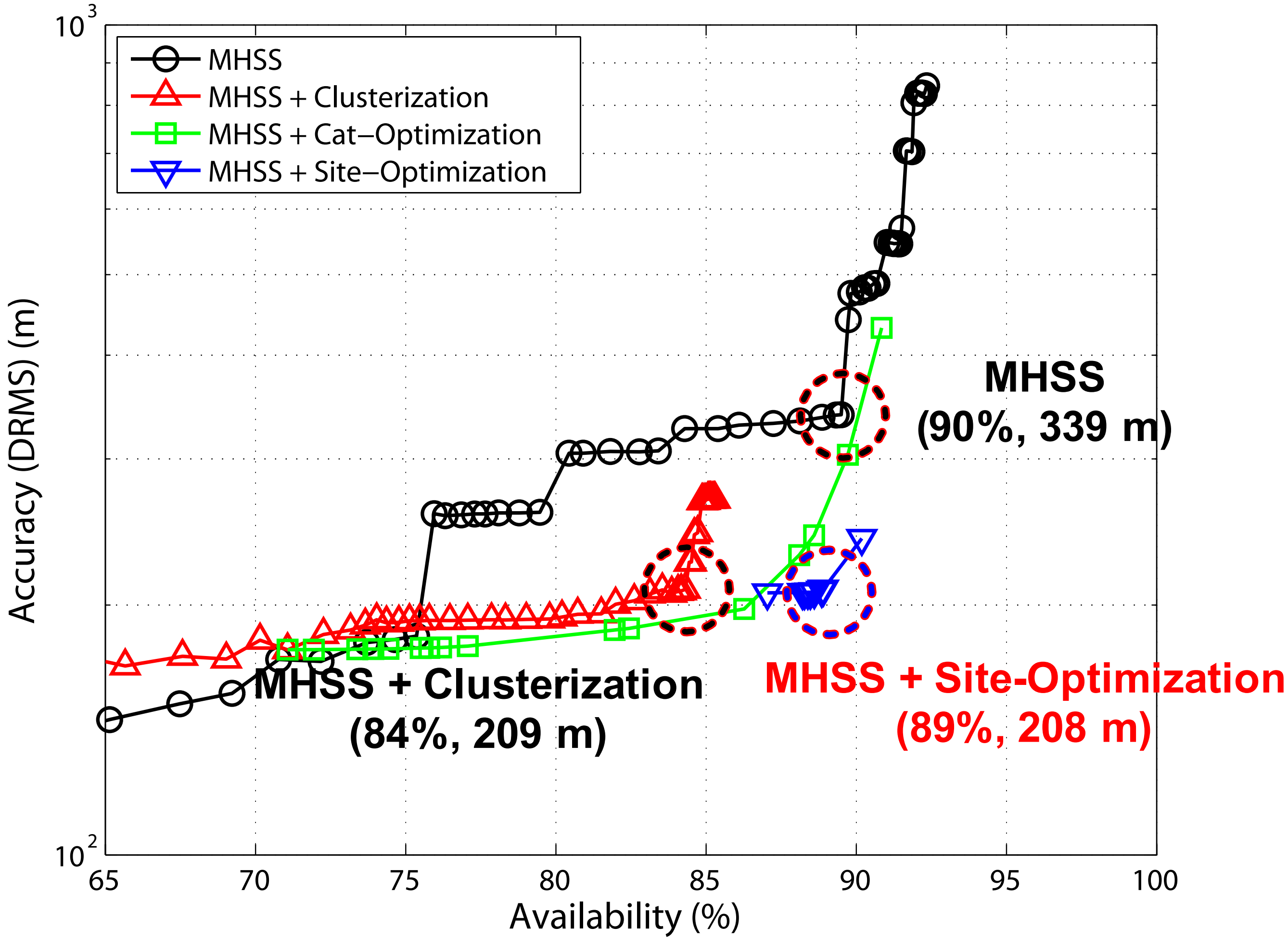
Improves accuracy (339 m to 209 m) at the expense of availability (90% to 84%).





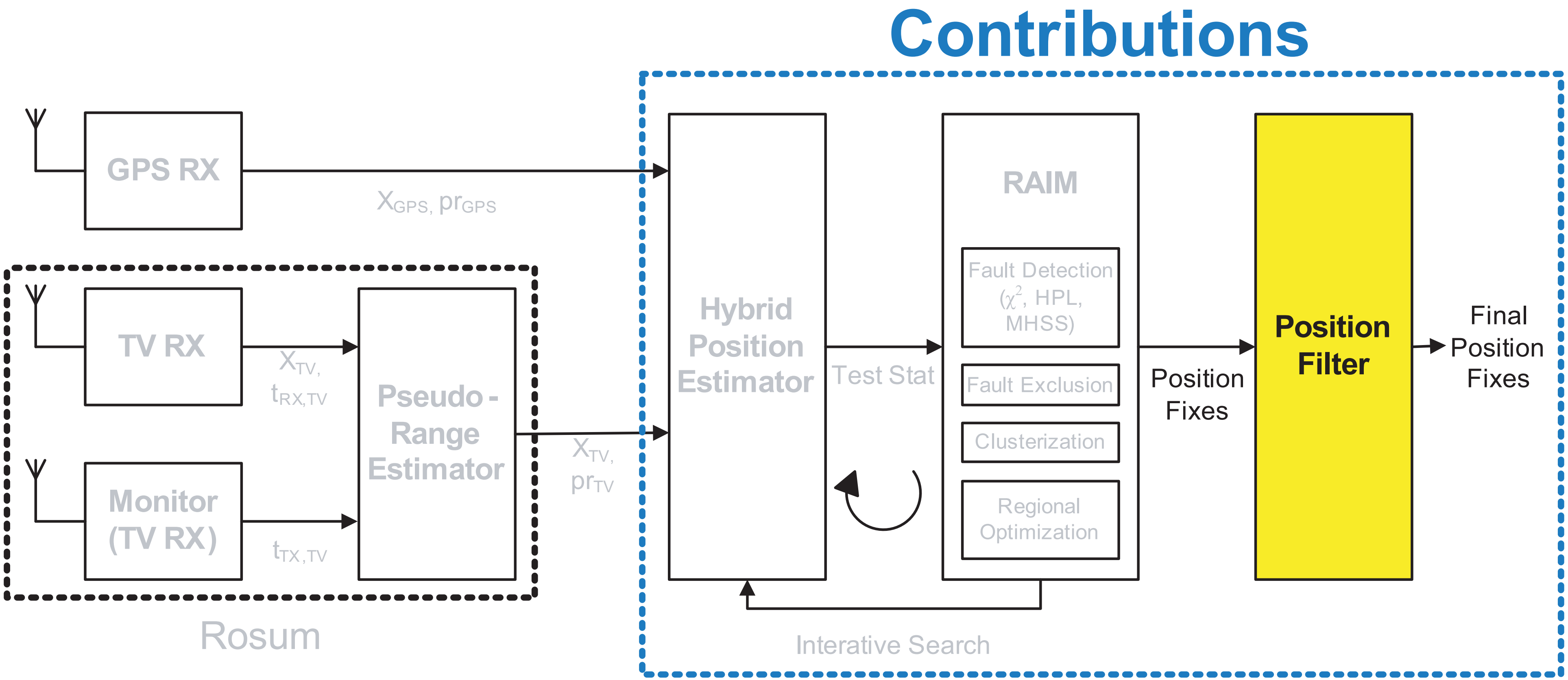
Trade-off Curve after Regional Optimization

Optimize RAIM parameters for each categorical region or site.



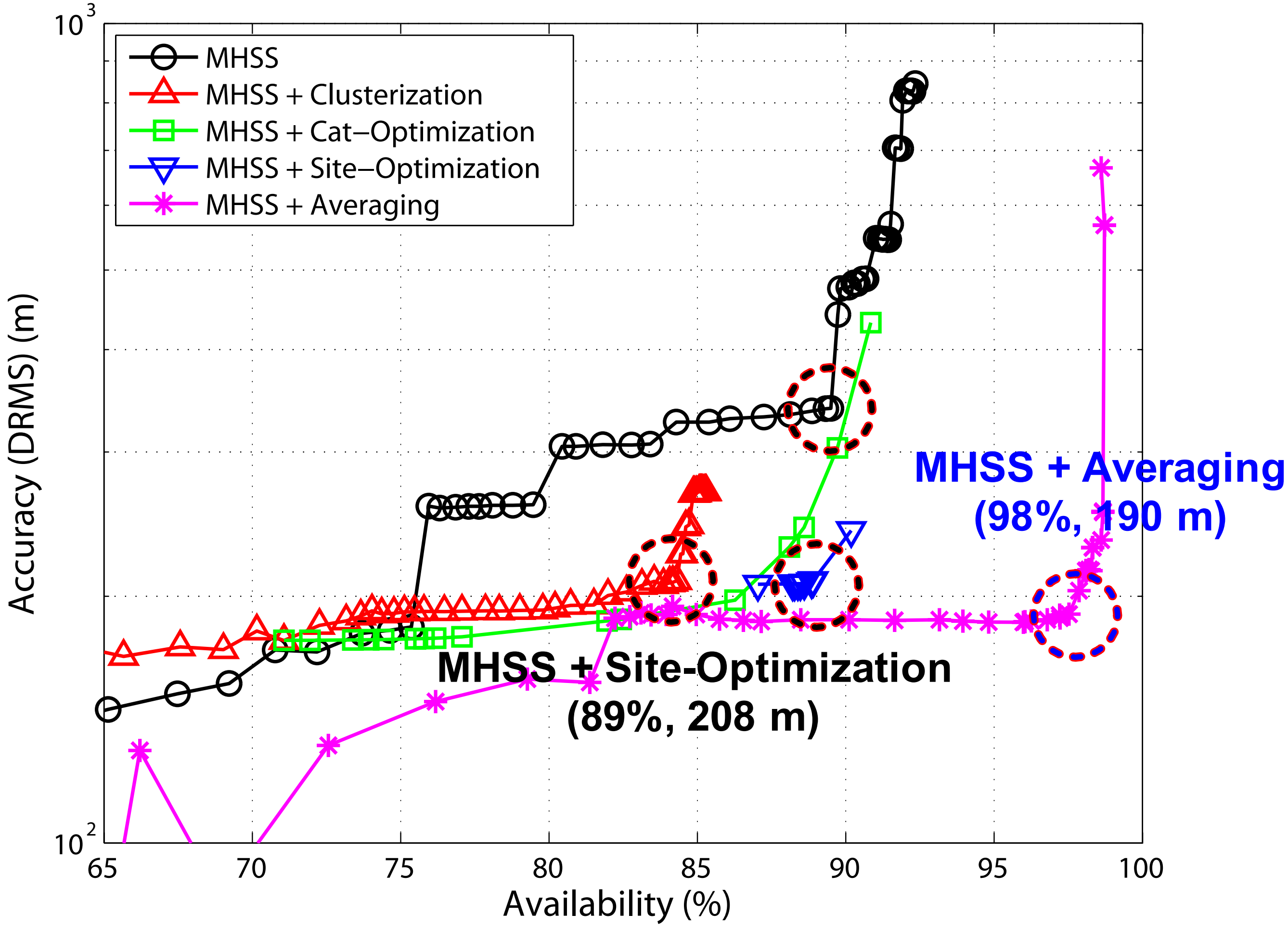
Position Domain Filtering

A solution for the last 10% availability.



Trade-off Curve after Averaging Position Fixes

Averaging (sliding window of 5 epochs) can fill the gap between fixes.

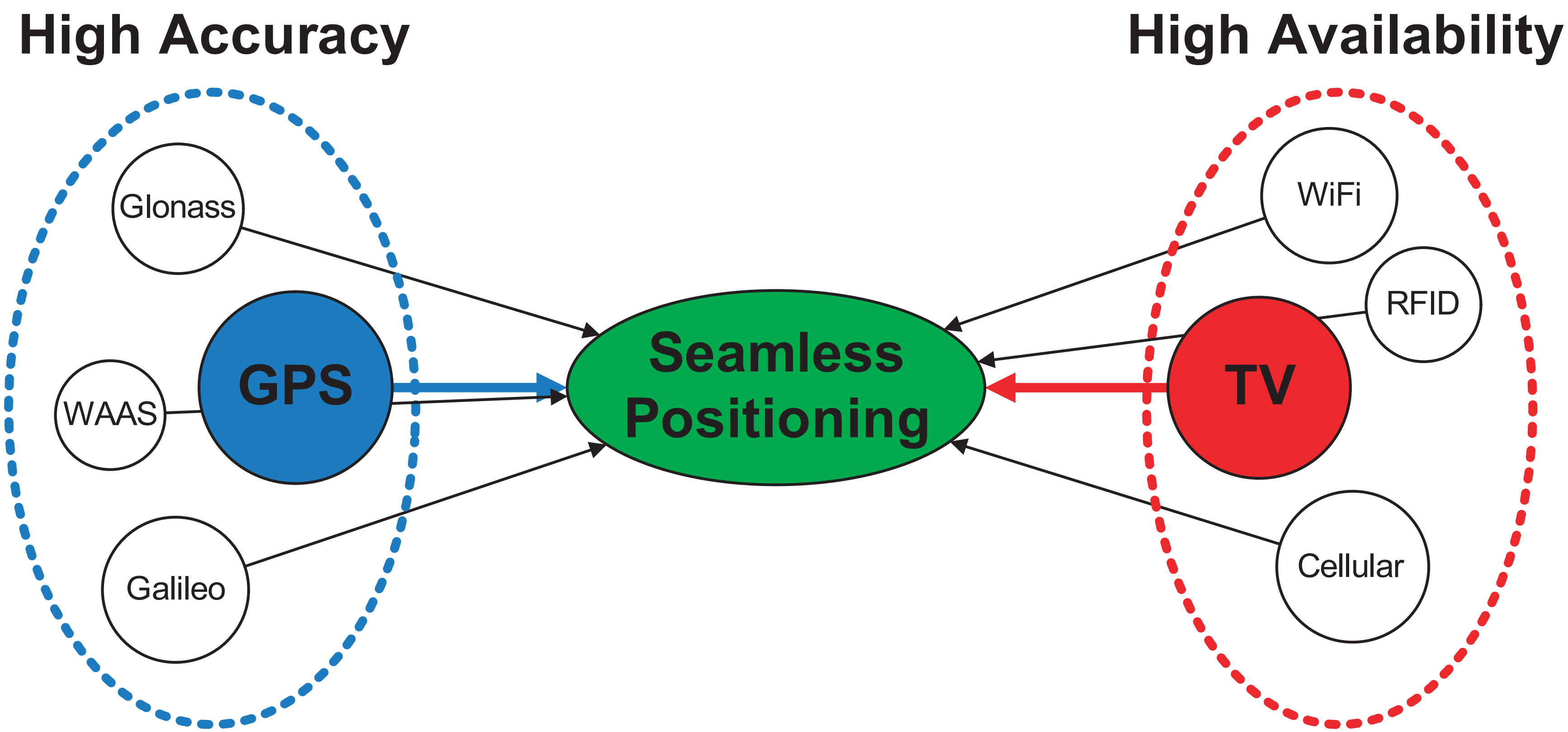


Availability & Accuracy Summary

Processing Method		Availability (%)	CEP (m)	DRMS (m)
GPS only		53	17	181
Hybrid	No RAIM	98	215	3022
	MHSS	90	83	339
	MHSS+Site-Optimization	89	73	208
	MHSS+Averaging	**98**	63	190

Processing Method		Outdoor			Indoor		
		%	CEP	DRMS	%	CEP	DRMS
GPS only		87	18	247	18	15	69
Hybrid	No RAIM	99	31	1269	96	400	4082
	MHSS	96	17	38	83	149	478
	MHSS+Site-Optimization	96	17	36	82	129	292
	MHSS+Averaging	**99.6**	14	26	**95**	111	268

Road to Seamless Positioning



(WAAS: Wide Area Augmentation System)

Summary

- Hybrid positioning (combining space and land-based signals) is the road to seamless positioning.
- Implemented **Matlab-based Hybrid Positioning System** using GPS/TV measurements.
- **Extensive field tests** of a prototype demonstrated the enhanced availability by the integration of TV and GPS.
- **Iterative RAIM** (MHSS) for Multi-Fault Tolerance required for signal integration. (+ Clusterization, Regional Optimization)
- Performance on continuous fixes (averaging):
  for outdoor sites, **99.6**%, 14 m (CEP) and 26 m (DRMS);
  for indoor sites, **95.4**%, 111 m (CEP) and 268 m (DRMS).

Recommendations for Infrastructural Investments

Still need a solution for extreme sites (2 zero-availability urban indoor sites)—high multipath and low observability.

- **Receiver: Utilization of data segment**
  only 0.3% of TV signals are used for range measurement. The rest 99.7% of TV signals can provide a higher SNR for survival in extreme sites.

- **Monitor: Better clock monitoring**
  parallel RF tuners at a monitor station, dedicated to each channel, can provide better transmitter clock monitoring.

- **Network: TV towers synchronized to GPS or Loran**
  a frequency/time/position reference to urban/indoor users.
  In particular, **TV+Loran can be a backup system in case of GPS outage**.

Publications

1. J. Do, M. Rabinowitz, and P. Enge, "Multi-Fault Tolerant RAIM Algorithm for Hybrid GPS/TV Positioning," to be appeared on ION National Technical Meeting Proceeding, San Diego, January 2007

2. J. Do, M. Rabinowitz, and P. Enge, "Robustness of TOA and TDOA Positioning," submitted to IEEE AESS, January 2007

3. J. Do, M. Rabinowitz, and P. Enge, "Performance of Hybrid Positioning System Combining GPS and Television Signals," IEEE/ION Position Location and Navigation Symposium 2006, pp 556 - 564, San Diego, April 2006

4. J. Do, M. Rabinowitz, and P. Enge, "Performance of TOA and TDOA in a Non-homogeneous Transmitter Network Combining GPS and Terrestrial Signals," ION National Technical Meeting Proceeding, pp 642 - 649, Monterey, January 2006

5. J. Do, M. Rabinowitz, and P. Enge, "Linear Time-of-Arrival Estimation in a Multipath Environment by Inverse Correlation Method," ION Annual Meeting Proceeding, pp 720 - 725, Cambridge, June 2005

6. J. Do, D. Akos, and P. Enge, "L and S Bands Spectrum Survey in the San Francisco Bay Area," IEEE Position Location and Navigation Symposium 2004, pp 566 - 572, Monterey, April 2004

7. P. Enge, D. Akos, J. Do, J. Simoneau, L. P. Wilson, and V. Seetharam, "Measurements of Man-Made Spectrum Noise Floor," National Aeronautics and Space Administration, CR-2004-213551, November 2004

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- Former and current GPS labmates, friends...
- My family: My mother. My wife, Younju. Two sons, Wonho (for master) and Wonyoung (for Ph.D.)

Thank You

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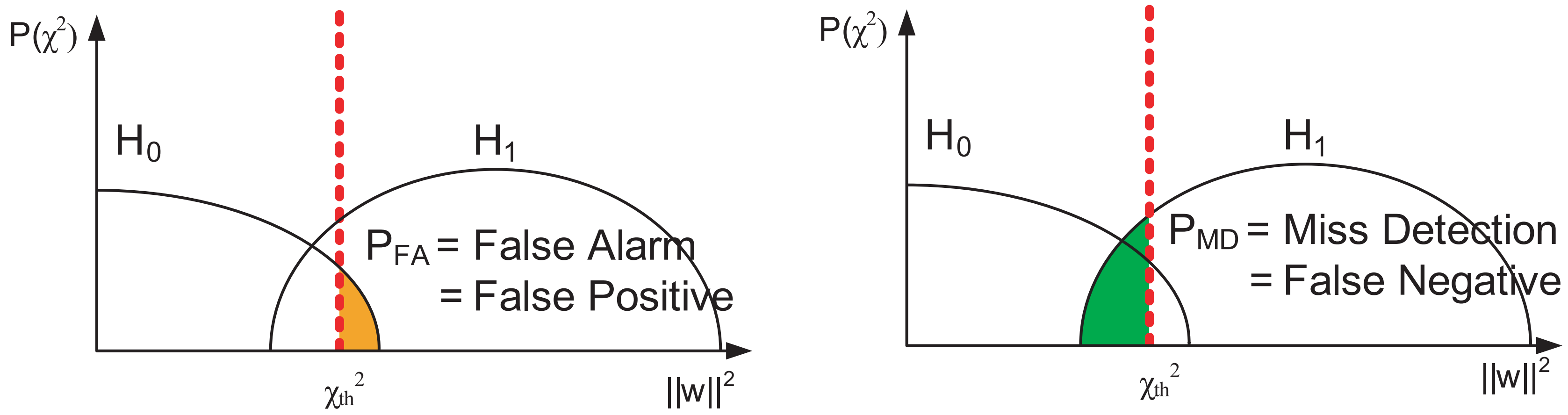
Thank you all for your attention!

χ^2 Test

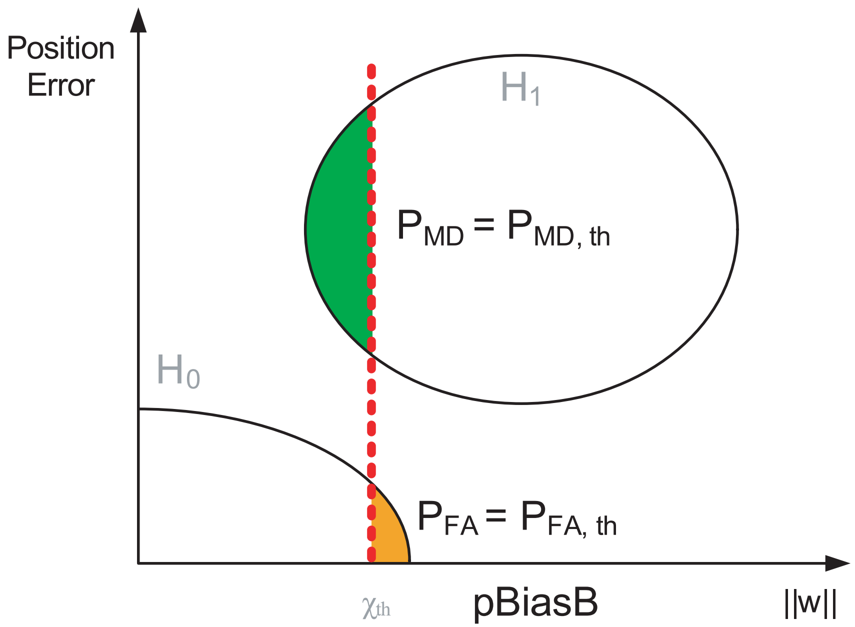
A widely used test for verification of Gaussian distribution of a given data set.

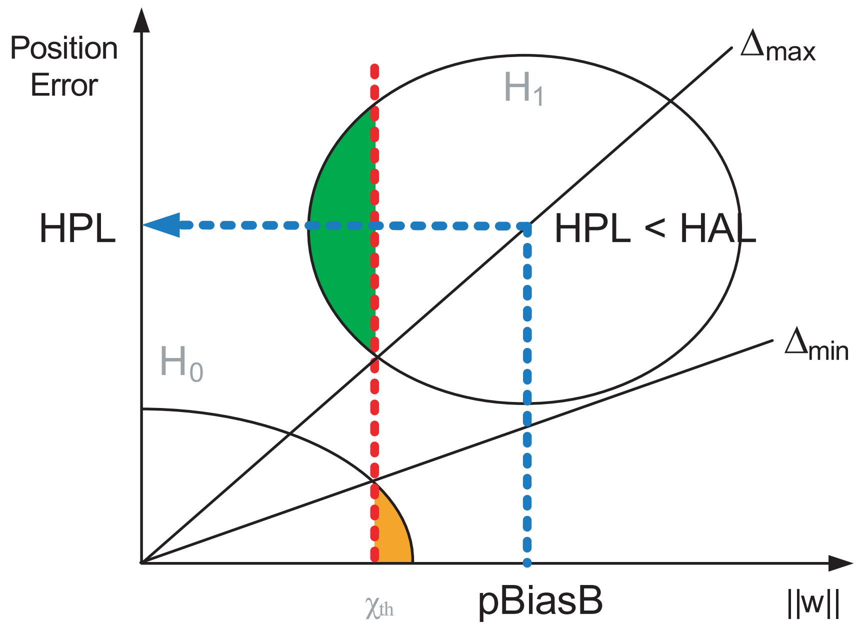
$$||w||^2 < \chi^2_{\mathsf{th}}(P_{\mathsf{FA}}, k)$$



HPL (Horizontal Protection Level) Test

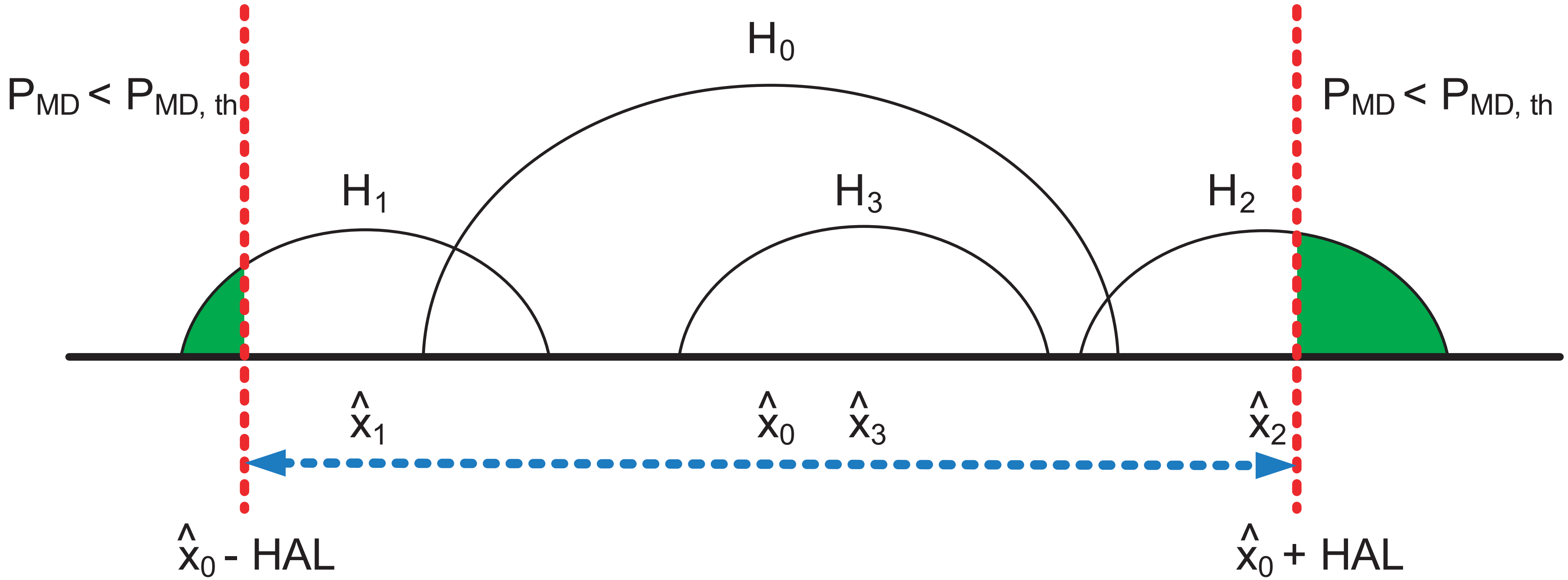
Projects the worst case horizontal position error based on the worst case geometry ($\Delta_{\text{max}} = \max_i \sqrt{\frac{\sum_{j=1}^{2}(G^{\dagger}_{ji})}{(P^T P)_{ii}}}$) and the worst case measurement error (pbiasB $= \{\beta | P_{\text{MD}} = F^{\text{non-central}}_{\chi^2}(\chi^2_{\text{th}}; k, \beta^2)\}$).



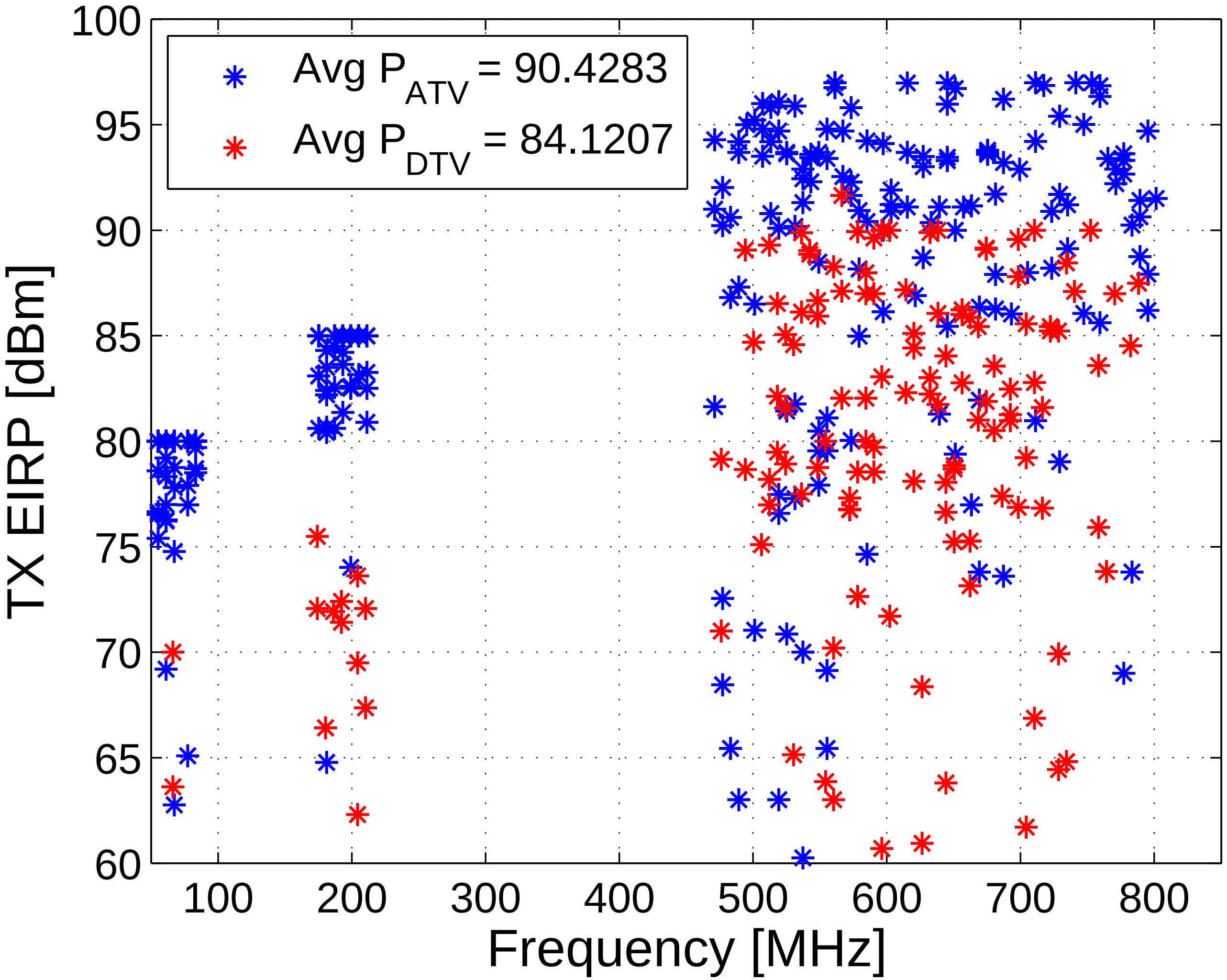


MHSS (Multi-Hypothesis Solution Separation) Test

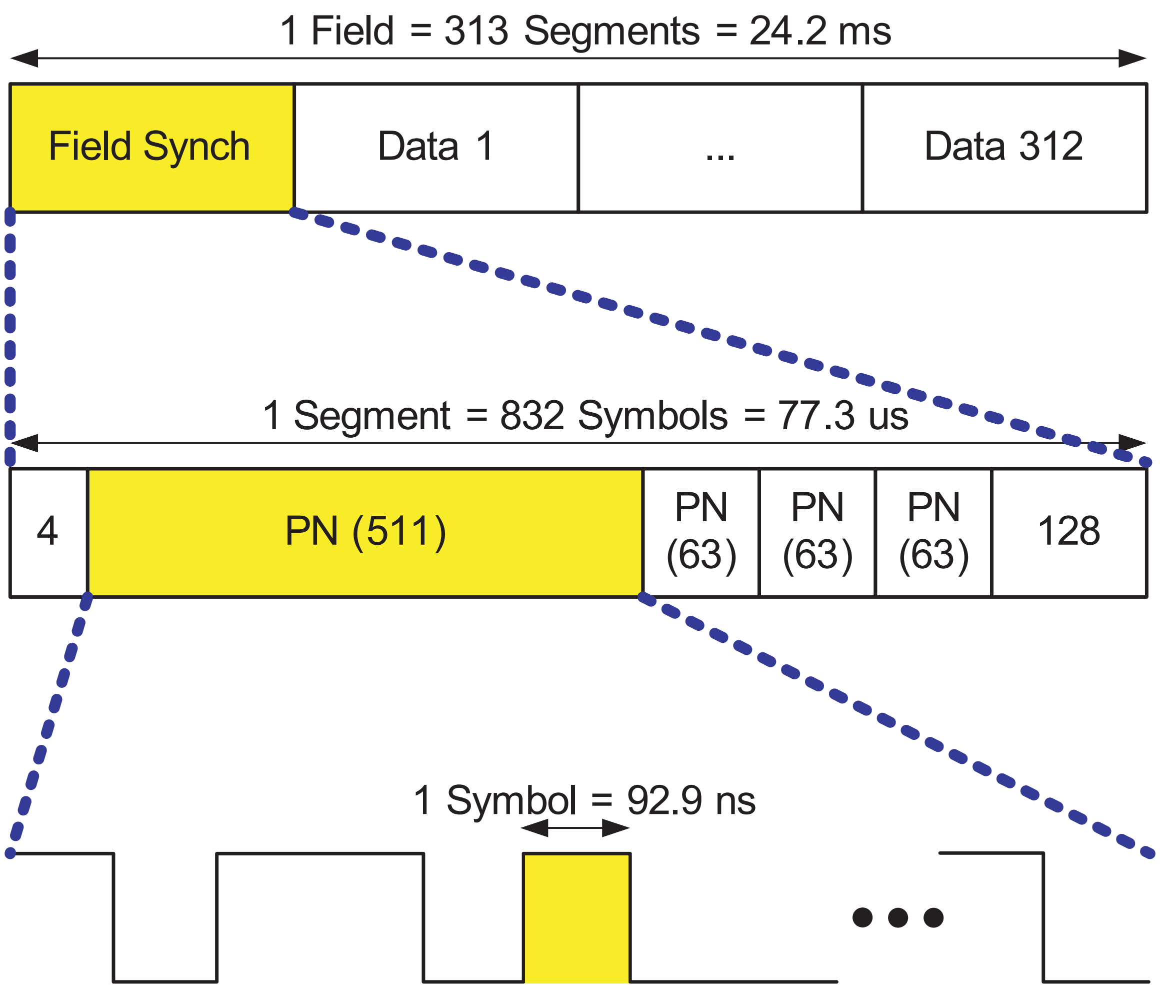
Construct hypotheses (H_i : a bias in ρ_i and $X|H_i \sim N(\hat{x}_i, \sigma^2_{x,i})$). Then, validates the initial position estimate ($\hat{x}_0$) based on $P_{\text{MD},i} = \text{Pr}\{||X - \hat{x}_0|| > \text{HAL}|H_i\}$ and $P_{\text{MD}} = \sum_{i=0}^{n} P_{\text{MD},i} \cdot \text{P}(H_i) < P_{\text{MD,th}}$.



TV Stations (364 in US = 229(A)+ 135(D))



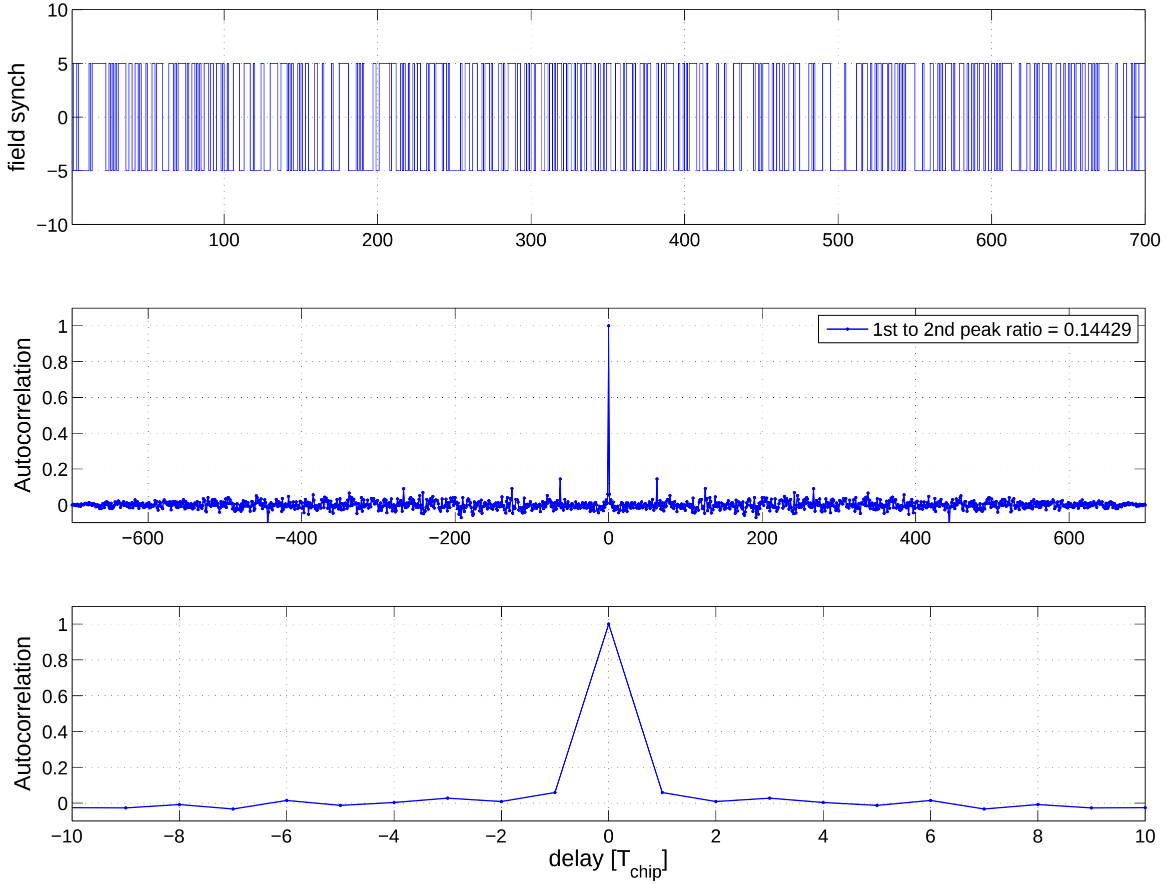
Digital TV (ATSC) Signal Structure



(PN: pseudo random sequence)

Autocorrelation of Field Synch Segment

Quite similar to GPS signal processing.

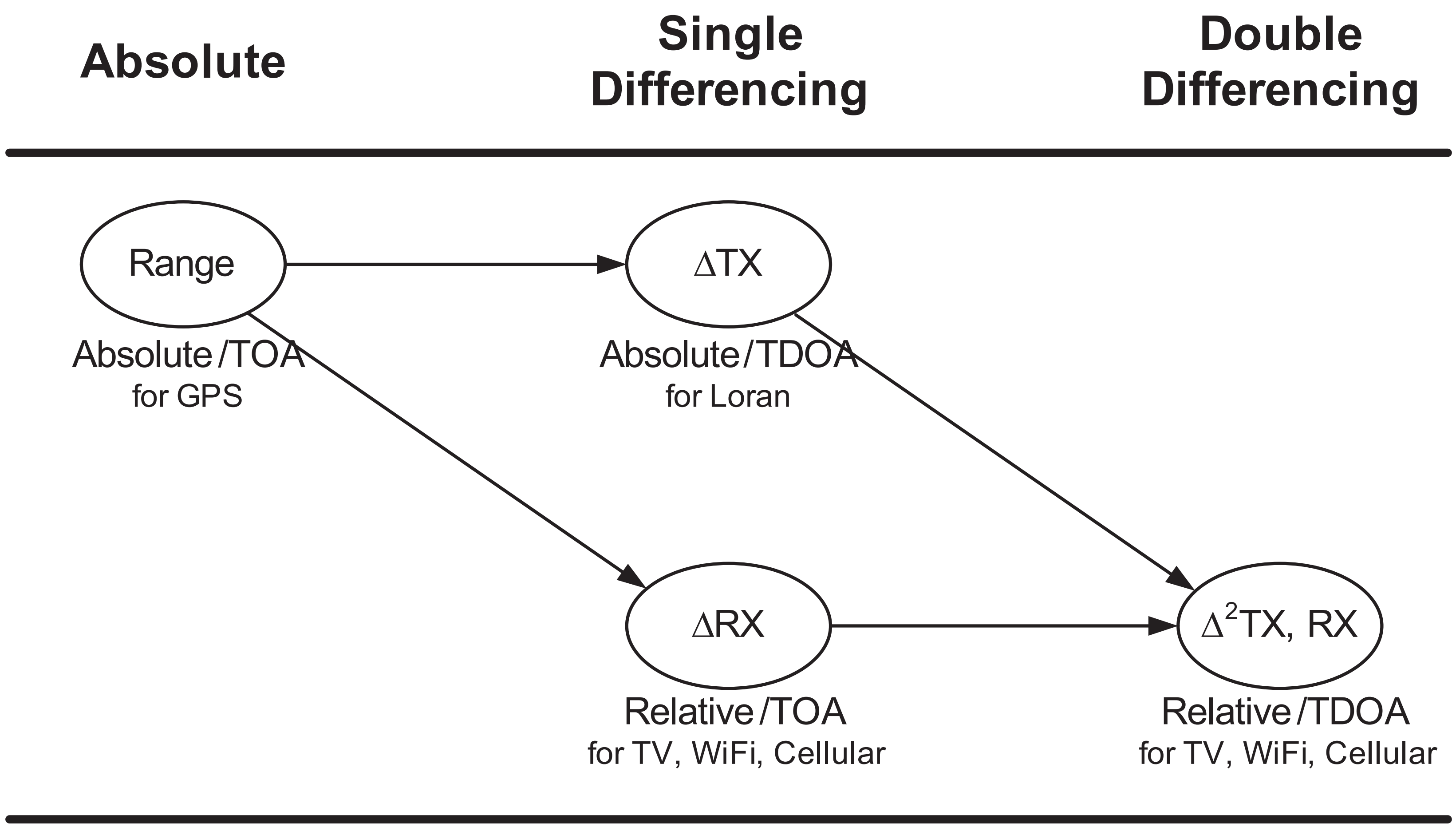


Candidate Positioning Sources

Signal specification for candidate ranging sources (GNSS and terrestrial communication systems)

	GPS	TV	Cellular	WiFi	RFID	INS
Distance (km)	20,000	< 100	< 10	< 0.5	< 0.01	N/A
P_{TX} (dBm)	55	84	50	30	TBD	N/A
P_{RX} (dBm)	-125	-44	-55	-64	TBD	N/A
Frequency (MHz)	1563–1587	470–806	869-894	2400–2484	TBD	N/A
Bandwidth (MHz)	24	336	25	83.5	TBD	N/A
Channel Bandwidth (MHz)	2	6	1.25	22	TBD	N/A
Multiple Access	CDMA	FDMA	CDMA	FDMA	TBD	N/A
Near-Far Problem	Mild	None	Severe	Severe	TBD	N/A
Network Synchronization	Synch	Asynch	Synch	Asynch	TBD	N/A
Positioning	3D	2D	2D	2D	2D	3D
Coverage	Global	National	National	Indoors	Proximity	N/A
Measurement	Range	Range	Range	Signal strength	Signal strength	Acceleration
Continuous Operation	Yes	Yes	Yes	Yes	Yes	No
Clock Stability	Good	Medium	Good	Bad	N/A	N/A
Multipath	Mild	Severe	Severe	Severe	N/A	N/A
Requirement	None	Clock Monitoring	None	Periodic surveying	Installation	None

Absolute/Relative and TOA/TDOA (cont'd)



Television Standards

- Analog Television
  - NTSC (National Television Systems Committee)
  - PAL (Phase Alternating Line)
  - SECAM (Color Sequential with Memory)

- Digital Television (supporting MPEG-2 standard)
  - ATSC (Advanced Television Systems Committee) in US, using VSB + 8/16 ASK
  - DVB (Digital Video Broadcasting) in Europe, using COFDM + 16/64 QAM
  - ISDB (Integrated Services Digital Broadcasting) in Japan, using COFDM + 16/64 QAM