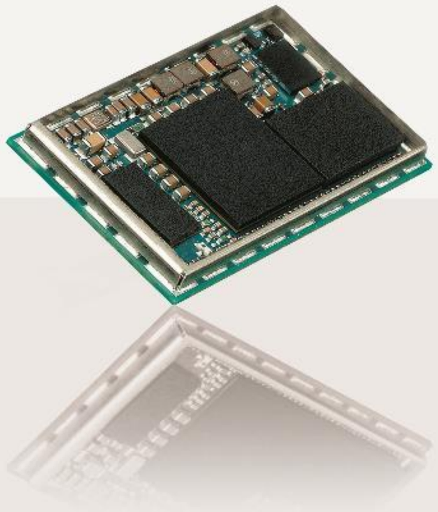
Real-Time Multipath Mitigation with Sensor-Aided Long Coherent Integration (SALI)

ION GNSS+ Sept. 2024, Baltimore, USA

Zhenlan Cheng

U-blox AG, Switzerland

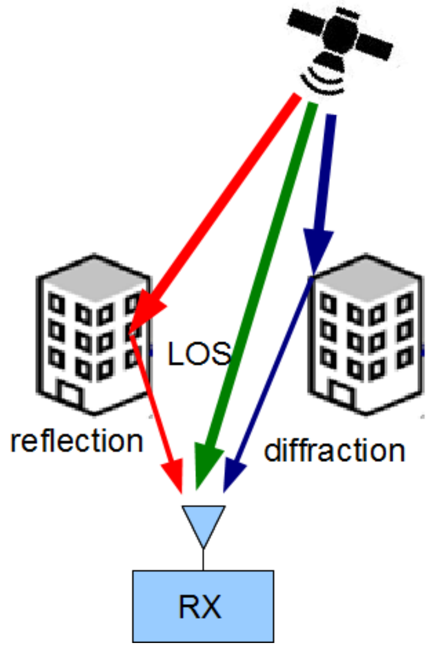
with Support of Positioning Engine (PE), Measurement Engine (ME) and Testing Teams



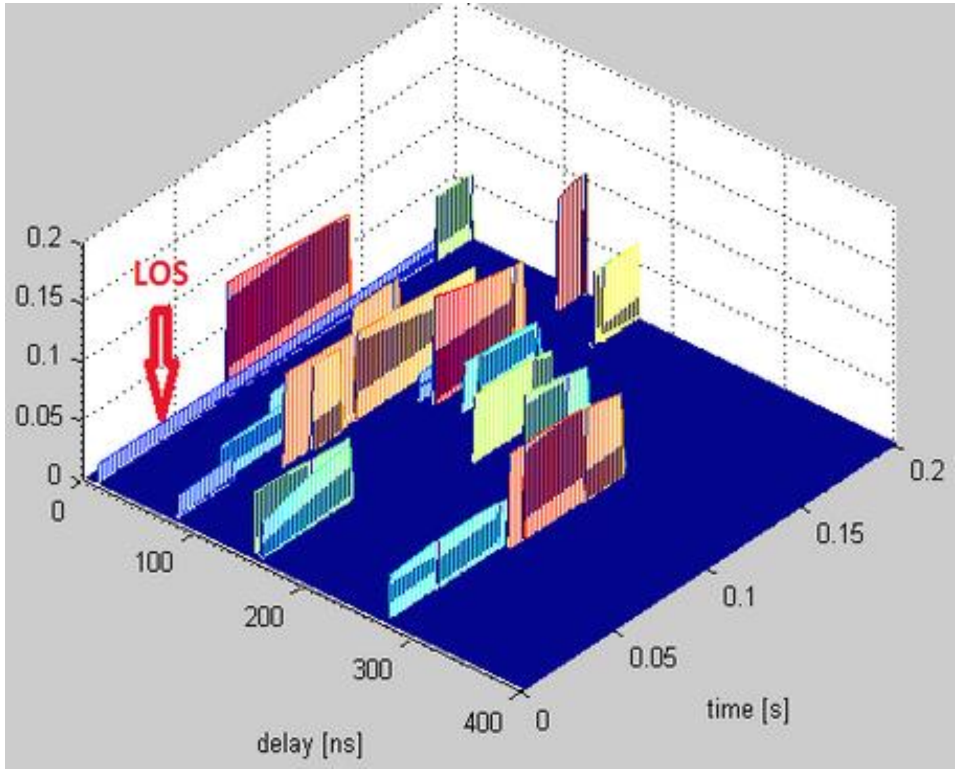
Outline

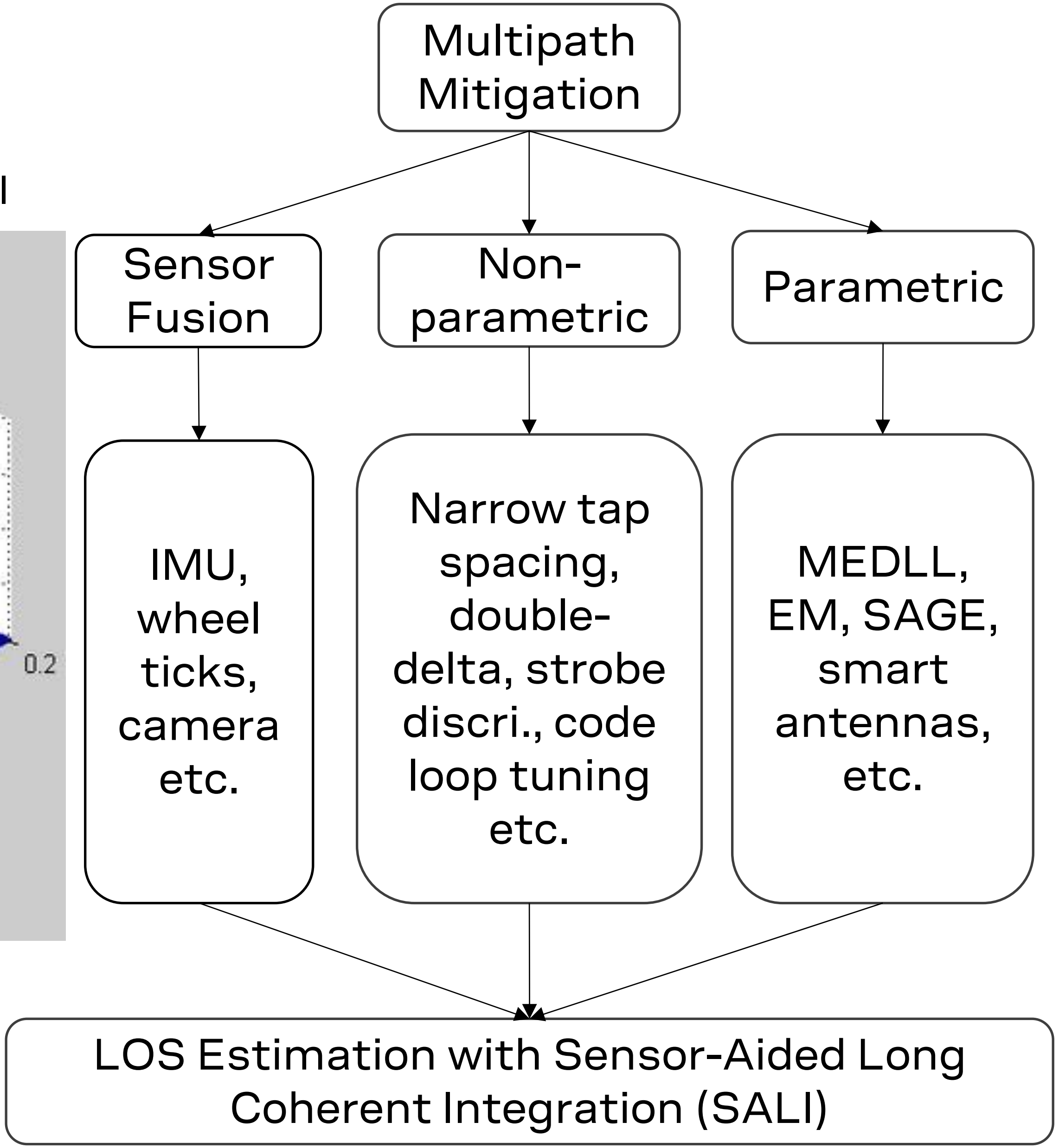
- Objectives
- LOS Estimation using **S**ensor-**A**ided **L**ong Coherent **I**ntegration (**SALI**)
- Testing
- Pseudo-range and Doppler Error Analysis
- Position Error and Integrity Analysis
- Visual Examples
- Computational and Memory Complexity
- Conclusions & Outlook

Multipath Effects



A time-variant multipath fading channel

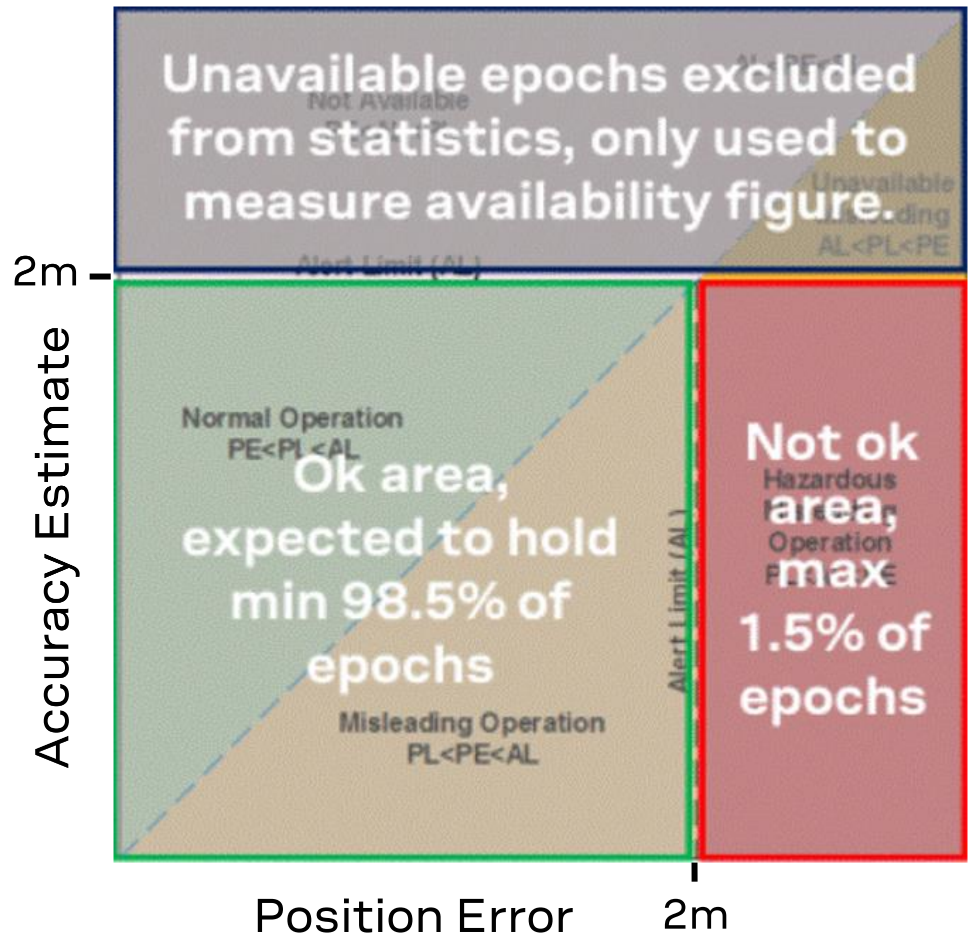




Objectives

- To quantify the benefits of extended coherent integration of ~1s for sensor fusion receivers.
  - To what extent can position accuracy, integrity, and availability be enhanced compared to a conventional sensor fusion receiver in various environments?
  - Can we achieve 2m accuracy anywhere?

- To assess the practicality of implementing a real-time embedded receiver using standard GNSS chip architecture.
  - Robustness, CPU load, memory footprint, etc.?



Sensor-Aided Long Coherent Integration (SALI)

SALI

Received signal modeled as LOS + multipaths:

Max path index

Max time index in the observation window

AWGN

$$r(t) = \sum_{l=0}^{L} \sum_{k=0}^{K-1} h_l[k] e^{\jmath \phi_l[k]} x(t - kT - \tau_l[k]) + n(t).$$

Geometric delay

Geometric carrier phase

Stochastic complex amplitude

LOS hypothesis:

Doppler error hypothesis

Delay error hypothesis

$$s_0(t; f, \tau) = \sum_{k=0}^{K-1} e^{\jmath(\hat{\phi}_0[k] + 2\pi f k T)} x\left(t - kT - (\hat{\tau}_0[k] + \tau)\right)$$

Initial LOS phase estimate by IMU-aided velocity solution

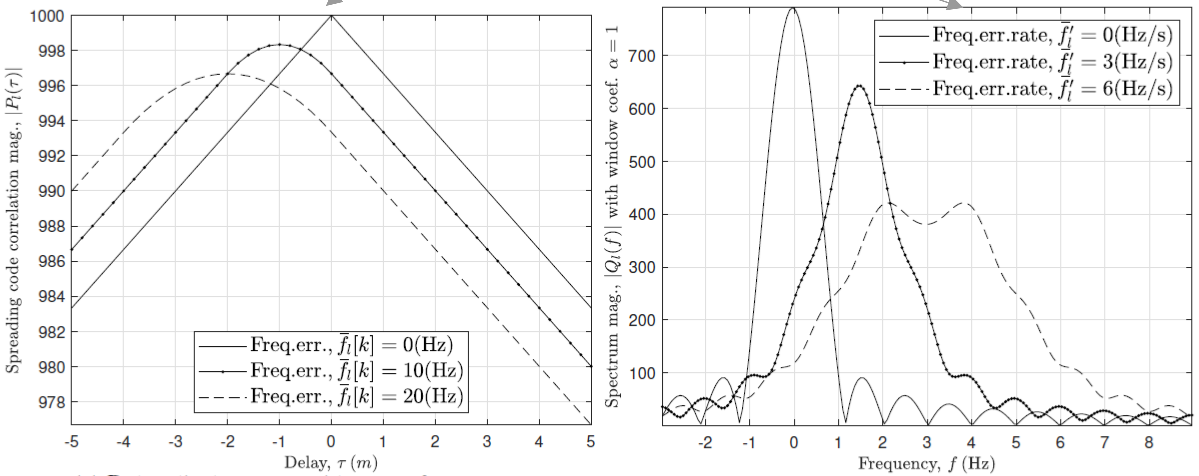
Initial LOS delay estimate by IMU-aided velocity solution

Maximum likelihood path detection and estimation based on the correlation with the LOS hypothesis — projecting the observation to the LOS sub-space.

Gaussian window for Gabor transform

$$R(f, \tau) = \int_{-\infty}^{\infty} W(t) r(t) s_0^*(t; f, \tau) \mathrm{d}t$$

$$\approx \sum_{l=0}^{L} P_l(\tau) Q_l(f) + \nu$$

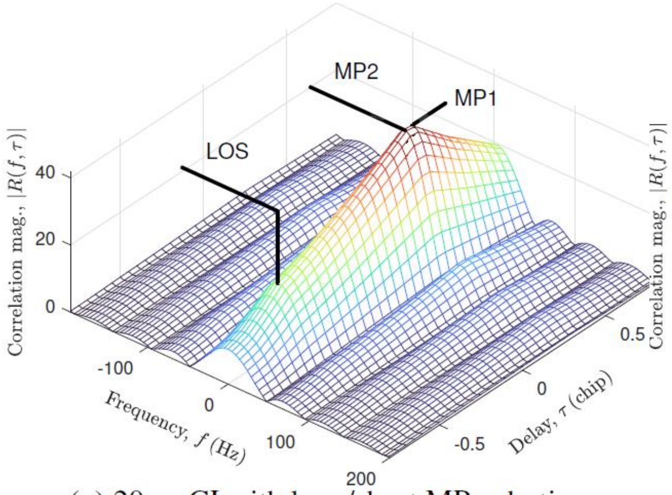


(a) Delay displacement with const. freq. errors **(b)** Frequency displacement with const. freq. error rates

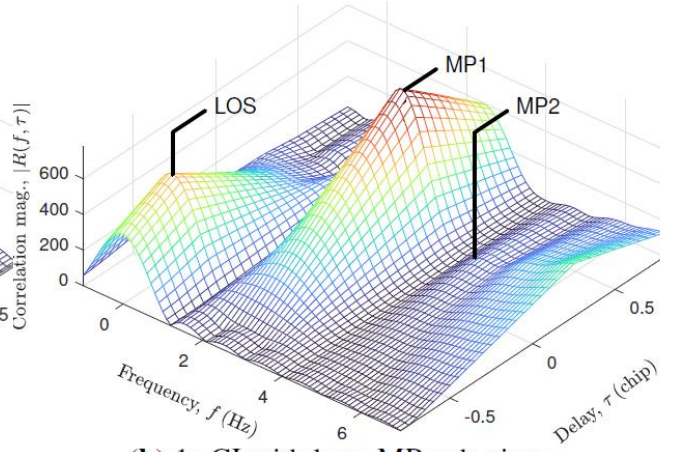
SALI-based LOS Detection

Implications of SALI:

1. High coherent integration gain for LOS by sensor-aided motion compensation
2. Path energy is confined within narrow Doppler bins — path separation in the frequency domain, facilitating delay estimation
3. Cross-correlation between multipath components and the LOS hypothesis suppresses the multipaths due to mismatching parameters
4. Long coherent integration suppresses time-variant multipaths with shorter life-time

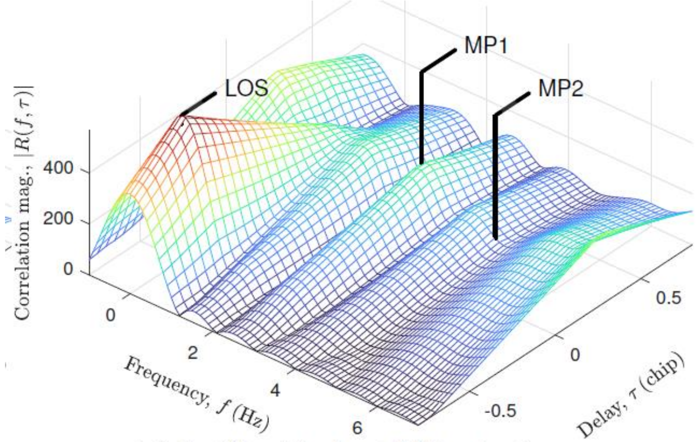


(a) 20ms CI with long/short MP coh. time



(b) 1s CI with long MP coh. time

Detect all paths in a small hypothesis window and select LOS with the shortest delay!

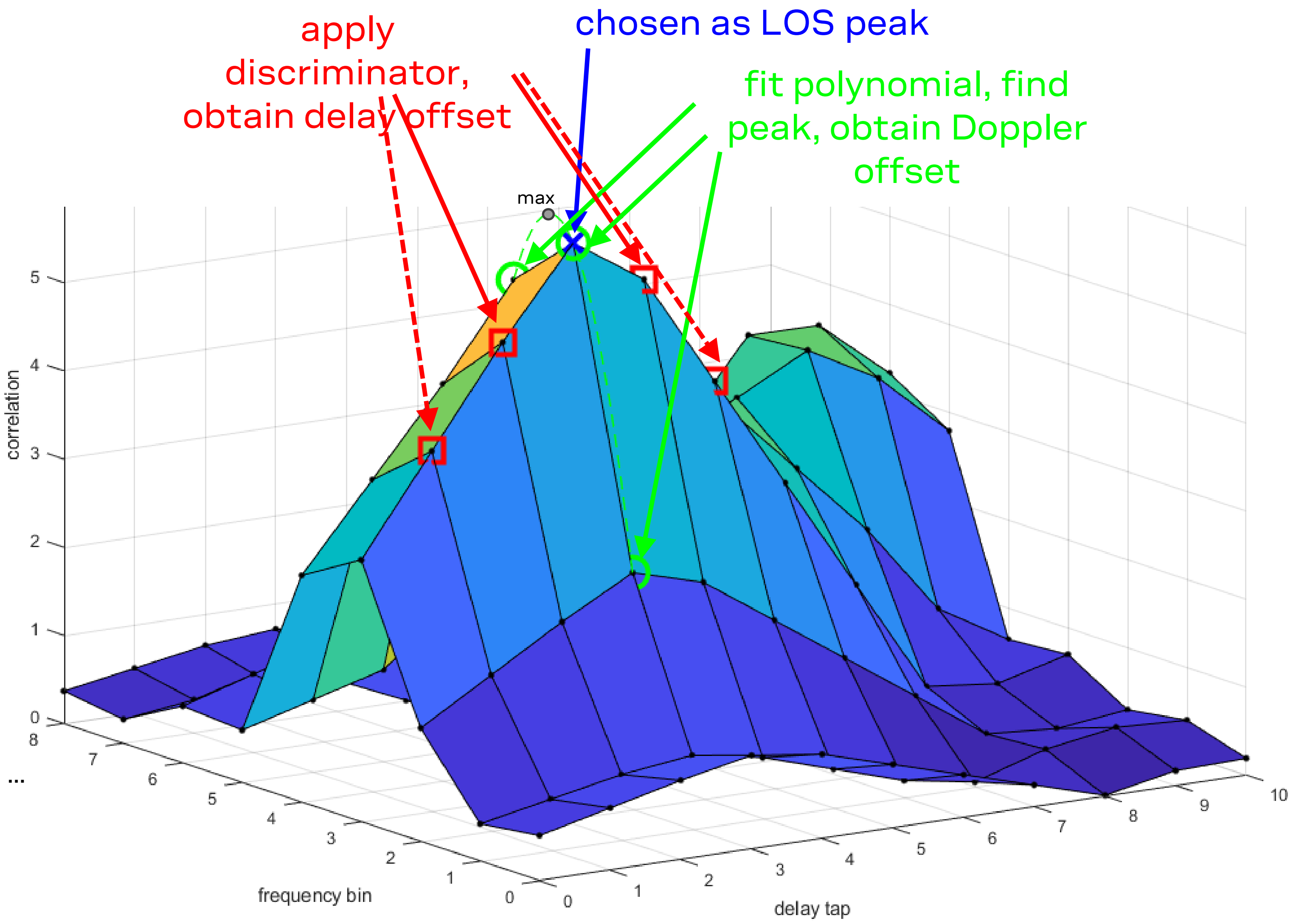


(c) 1s CI with short MP coh. time

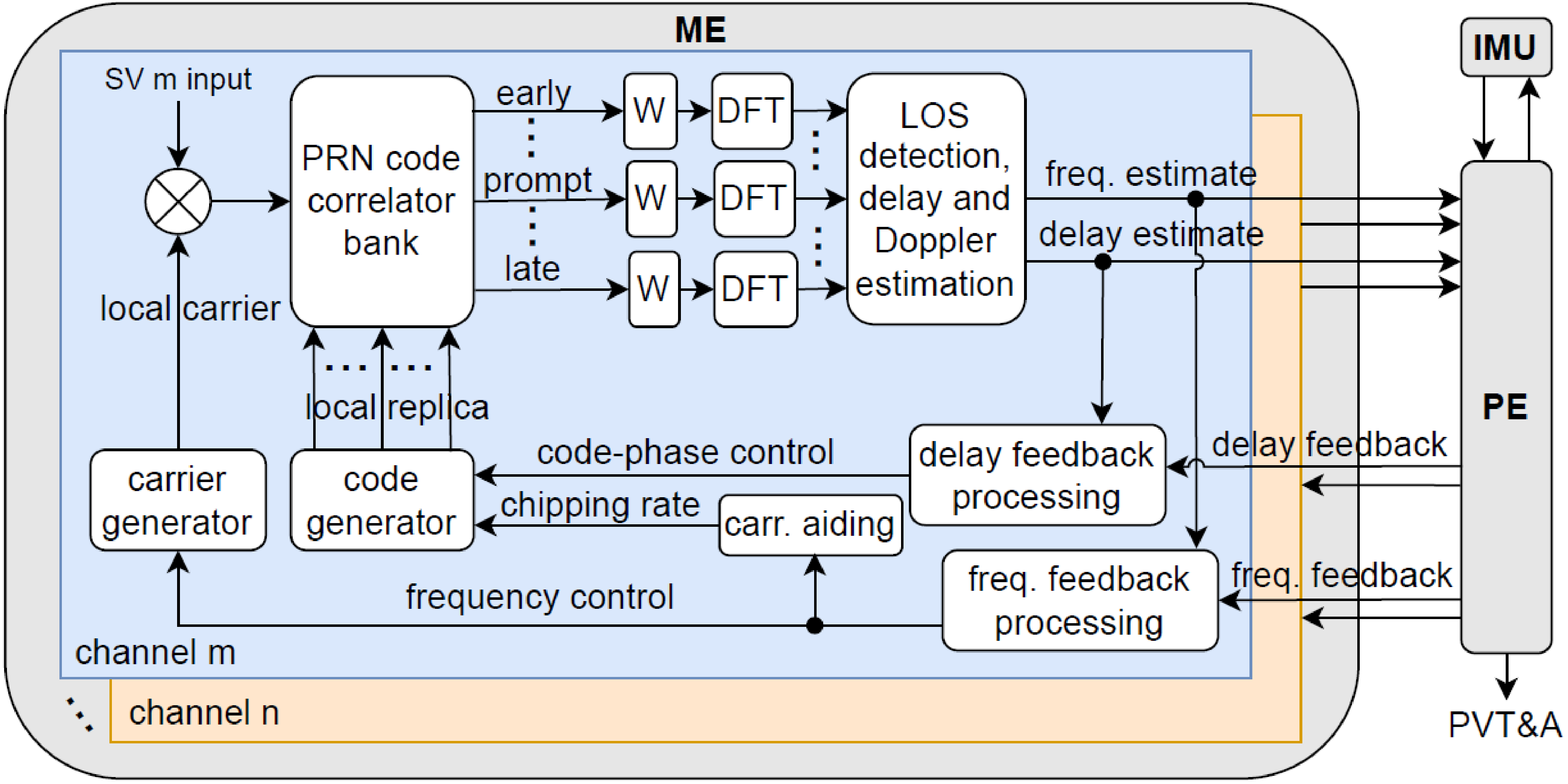
SALI-based LOS Estimation

Delay-Doppler interpolation across discrete taps and frequency bins:

- Parabolic interpolator of frequency bins for final Doppler estimates
- Multipath-mitigating interpolators for delay taps, mimicking double-delta DLL without requiring code loop iterations.



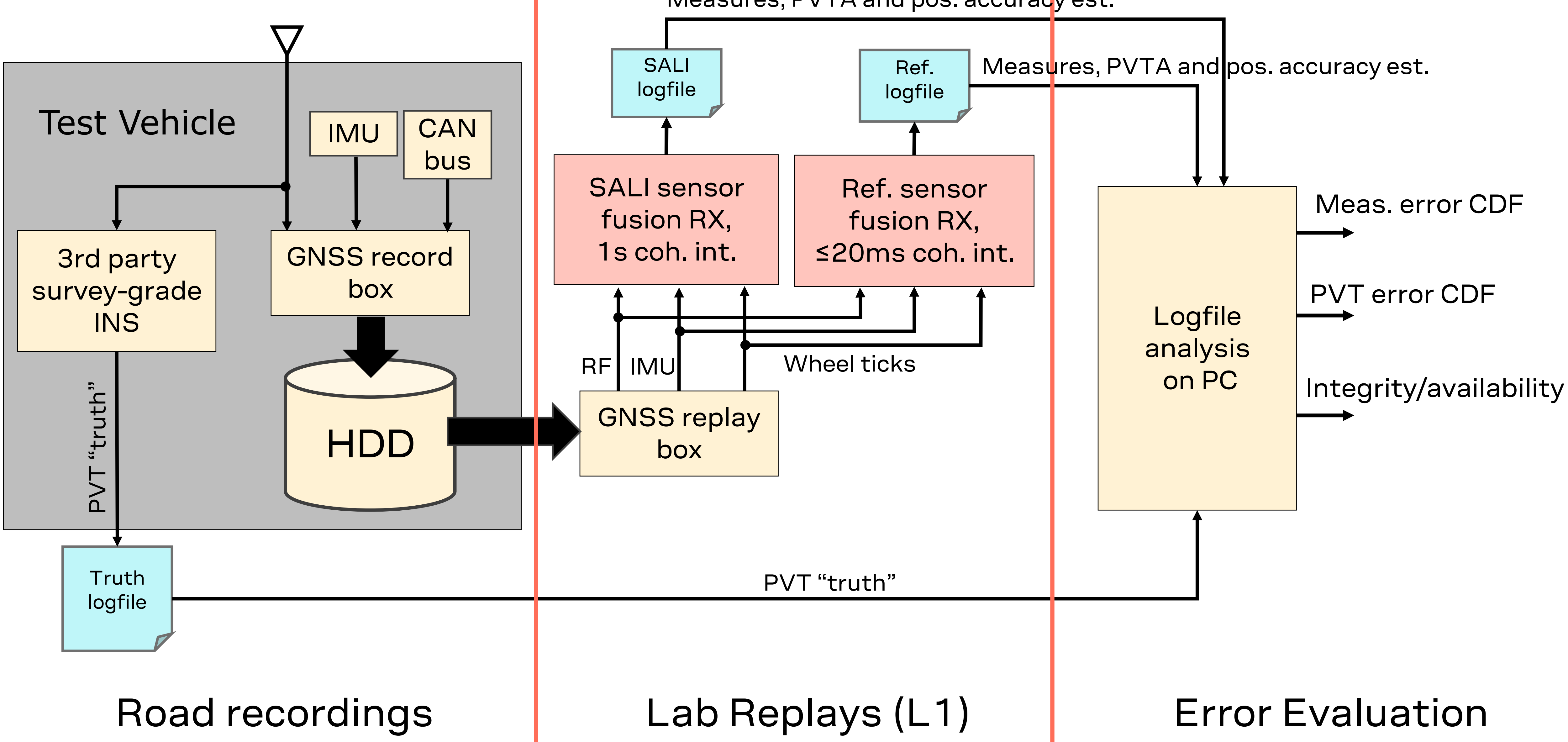
A SALI-based Sensor Fusion Receiver



A generic receiver architecture with conventional hardware accelerators.

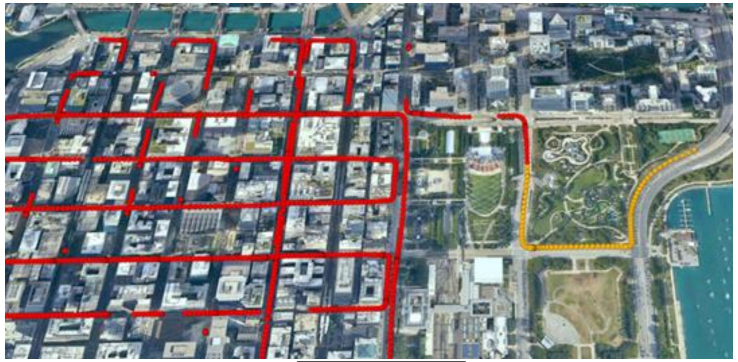
Testing

Test Procedure



Test Environment Classification

Thalwil (Switzerland)



Chicago

Detroit

Environment	Description **(manual classification)**
Open-sky	Rather clear 360 degrees sky view, not obstructed by large buildings, trees, mountains, etc.
Foliage	Trees present on **both sides of the road** and reasonably **close to street**. Trees were **leafed** (March - October). Mild-urban and deep-urban classes have higher priority than 'foliated' in case both co-exist
Suburban Suburban	Sky view is obstructed partially up to about **45 degrees** elevation, by either buildings, trees, mountains, etc.
Deep urban Deep urban	Sky view is obstructed partially up to about **60 degrees** elevation, by either buildings, trees, mountains, etc., or zenith part of the sky is obstructed, but lower elevation sky view is clear (e.g. gallery, or first level of two-level road).

Test Environments & Signals

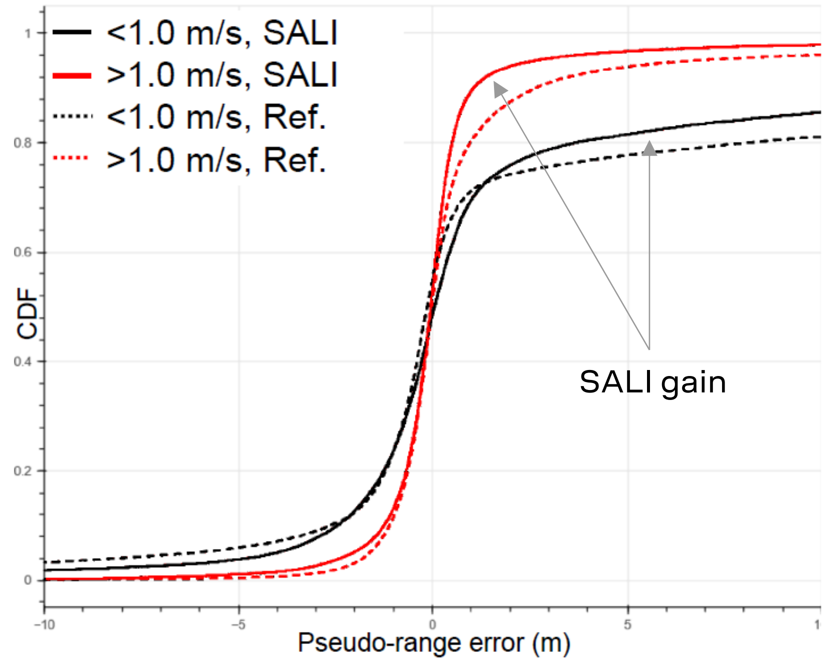
Open sky | Foliage | Suburban | Deep urban

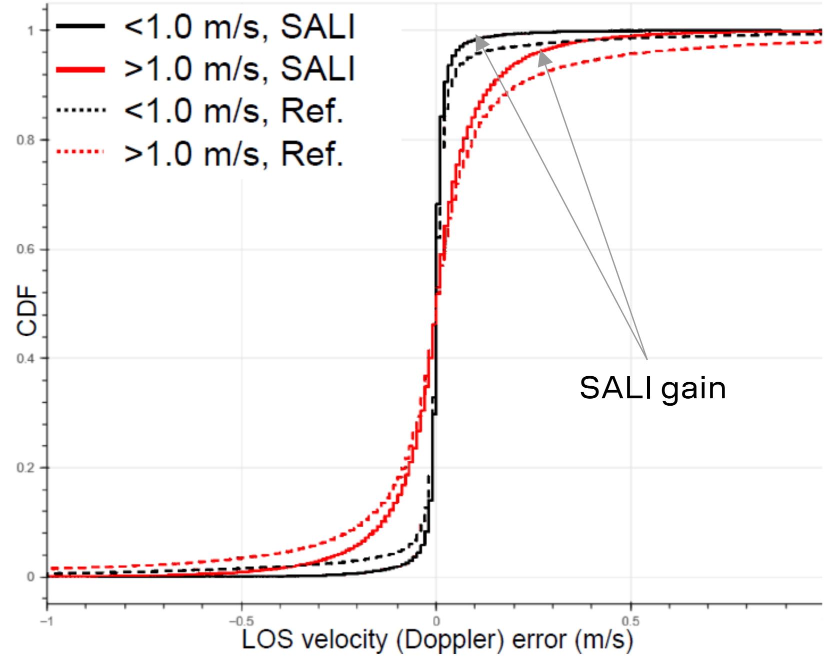
- Test locations: Thalwil, Zurich, Munich, Hannover, Frankfurt, New York City (NYC), Detroit, Chicago, Hakone, etc.
- Test signals: GAL E1 and BDS B1C

Pseudo-range and Doppler Error Analysis

High vs. Low Speeds

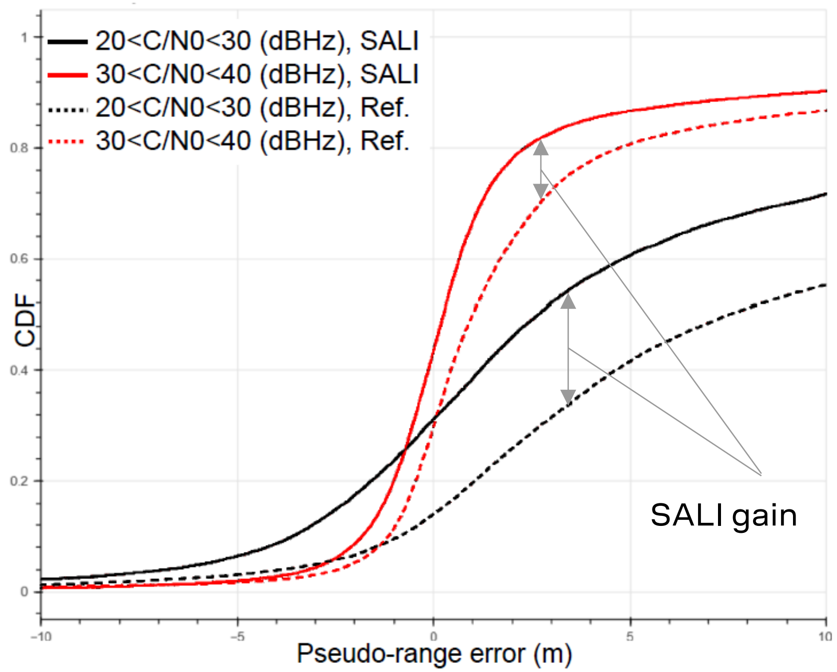
- High speeds benefit pseudo-range measurements.
- Low speeds benefit Doppler measurements.
- SALI improves both pseudo-range and Doppler measurements in both speed categories.
- SALI provides higher gain in the high-speed category.

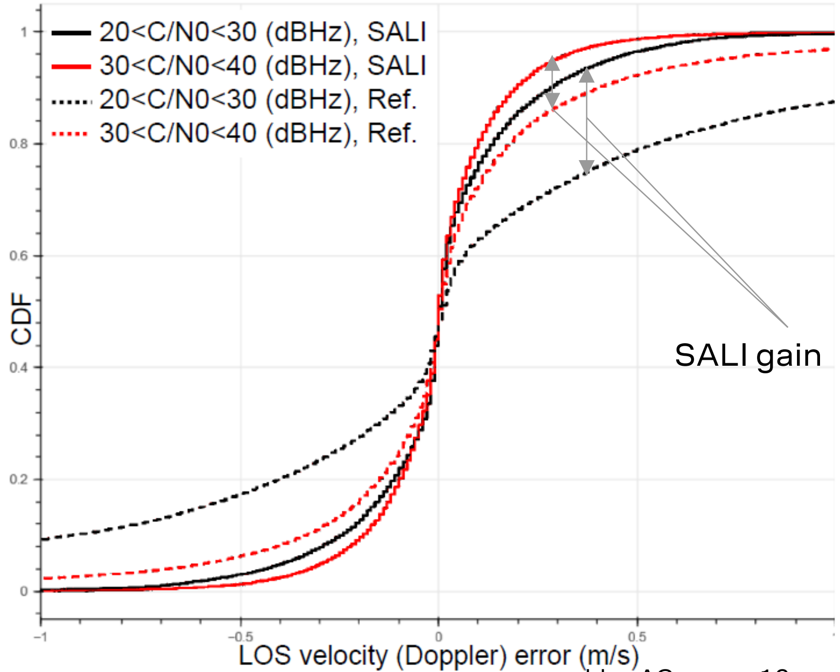




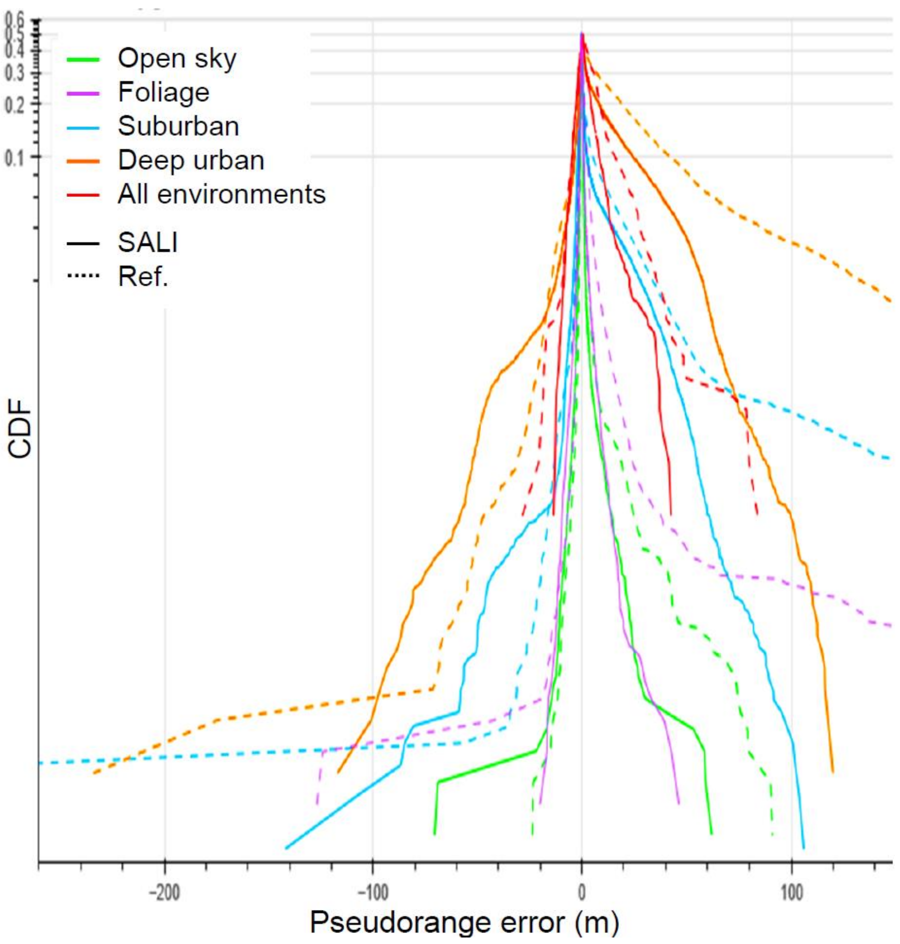
High vs. Low C/N0 Values

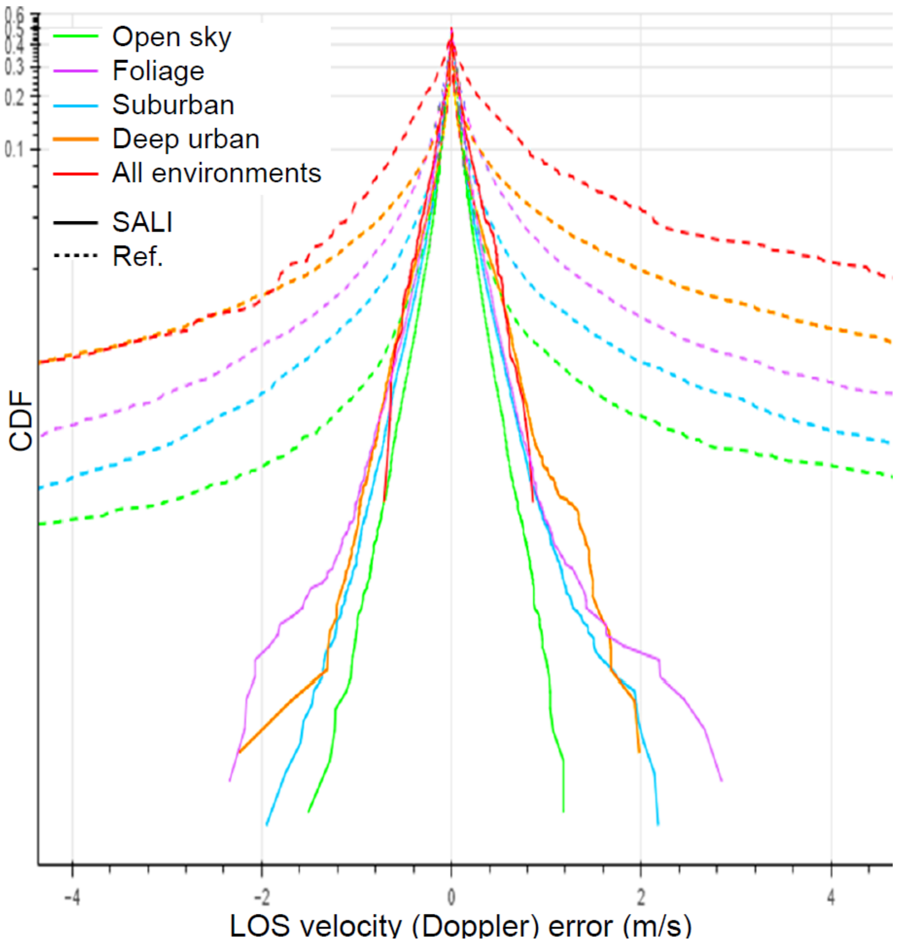
- SALI improves both pseudo-range and Doppler measurements in both C/N0 categories.
- SALI provides higher gain for low C/N0 values with prominent multipath effects.
- SALI provides higher gain for the Doppler estimation.





Different Environments



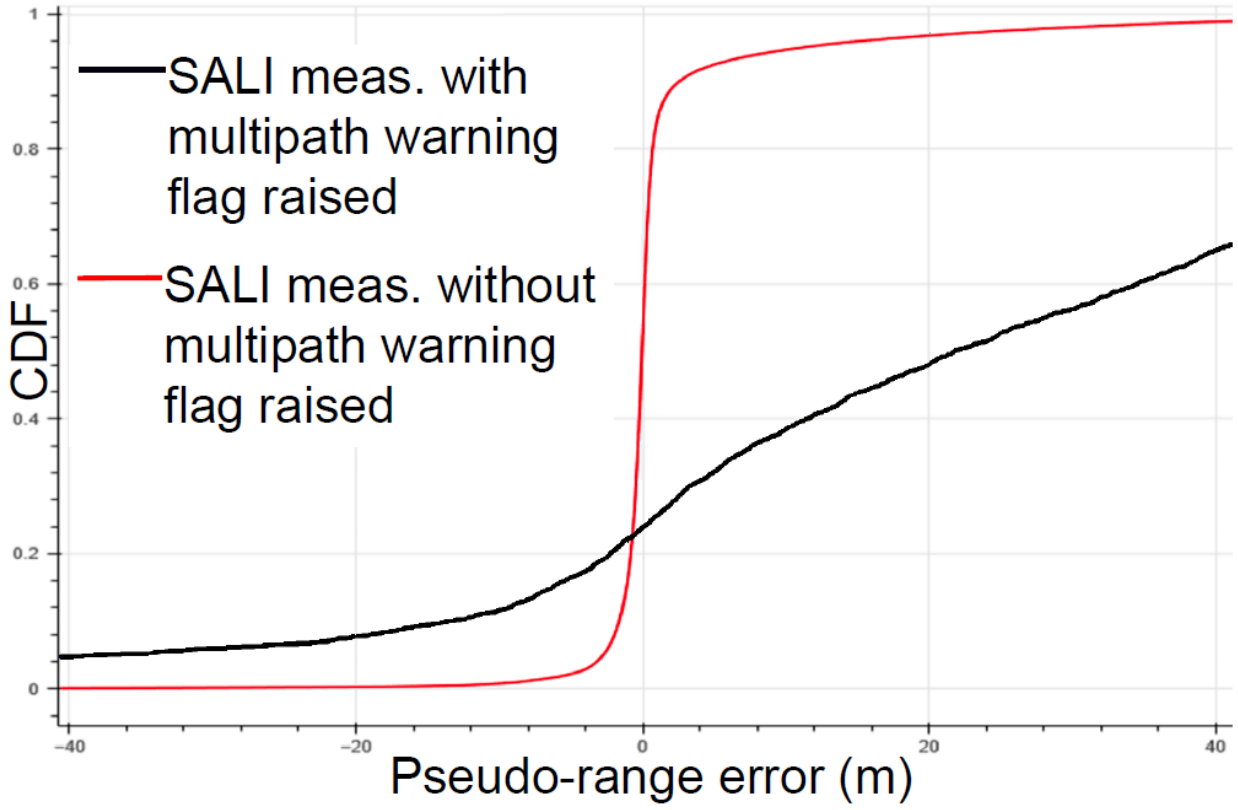


- CDF mountain plots aggregating all epochs of a specific environment type from all test drives
- Less bias in SALI measurements (multipaths suppressed)
- Much lower tail probabilities, especially with Doppler errors, advantageous for recurrent sensor calibration

Multipath/NLOS Indicator

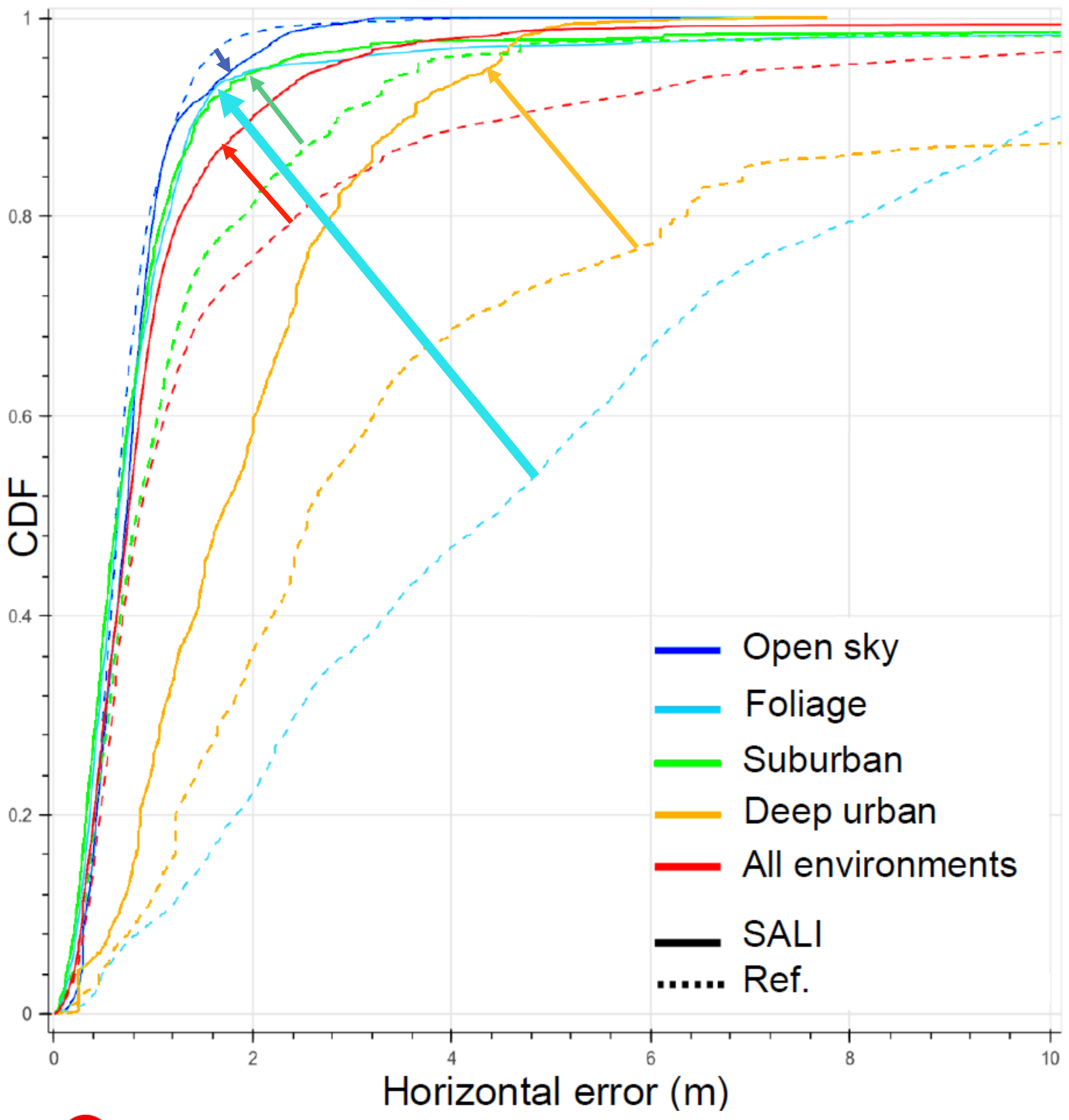
NLOS exclusion is crucial in deep urban:

- A multipath warning flag based on the Euclidean distance of the observed LOS correlation result and the expected correlation values.
- A NLOS flag is raised when the LOS path cannot be detected.



Position Error and Integrity Analysis

Positioning Performance



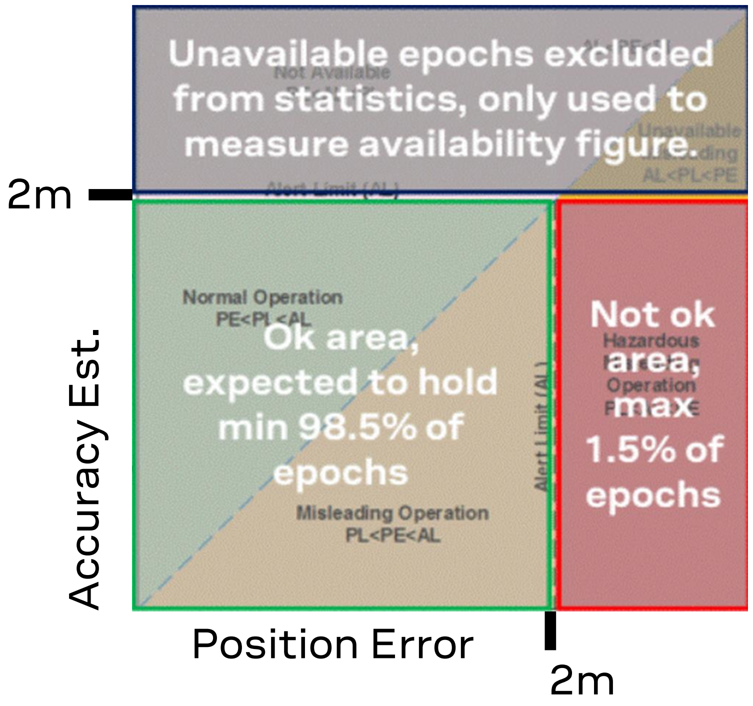
- SALI-based sensor fusion RX with ~1s coherent integration compared to conventional sensor fusion RX with ≤20ms coherent integration
- Significantly improved position accuracy in all multipath environments
- No benefits (slight degradation) in open sky.
- Most improvements in the foliage environment.

Positioning Performance

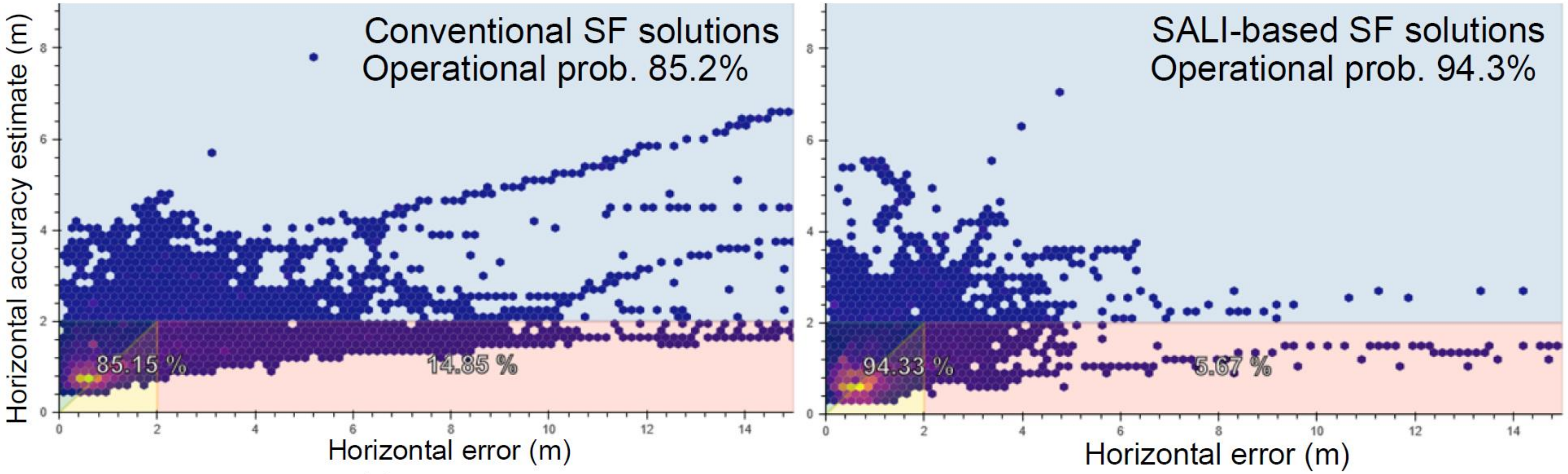
Table 1: Position error, unavailability and integrity statistics across all test drives

	P68 (m)		P95 (m)		P2m (%)		Unavailability (%)		HMI (%)	
	Ref.	SALI(±)	Ref.	SALI(±)	Ref.	SALI(±)	Ref.	SALI(±)	Ref.	SALI(±)
Open sky	0.8	→ 0.9(+0.1)	1.5	→ 1.8(+0.3)	99	→ 96(−3)	0.0	→ 0.3(+0.3)	1.5	→ 3.8(+2.3)
Foliage	6.1	→ 0.9(**-5.2**)	14.5	→ 2.1(**-12.4**)	22	→ 95(**+73**)	6.8	→ 0.2(**-6.6**)	76.2	→ 5.3(**-70.9**)
Suburban	1.2	→ 0.9(−0.3)	3.7	→ 2.1(−1.6)	82	→ 95(+13)	20.3	→ 7.7(−12.6)	8.3	→ 2.6(−5.7)
Deep urban	3.3	→ 2.1(−1.2)	15.0	→ 4.2(−10.8)	42	→ 63(+21)	52.1	→ 44.5(−7.6)	34.7	→ 25.3(−9.4)
All environments	1.4	→ 1.0(**-0.4**)	7.1	→ 2.7(**-4.4**)	76	→ 90(**+14**)	16.9	→ 10.7(**-6.2**)	14.9	→ 5.7(**-9.2**)

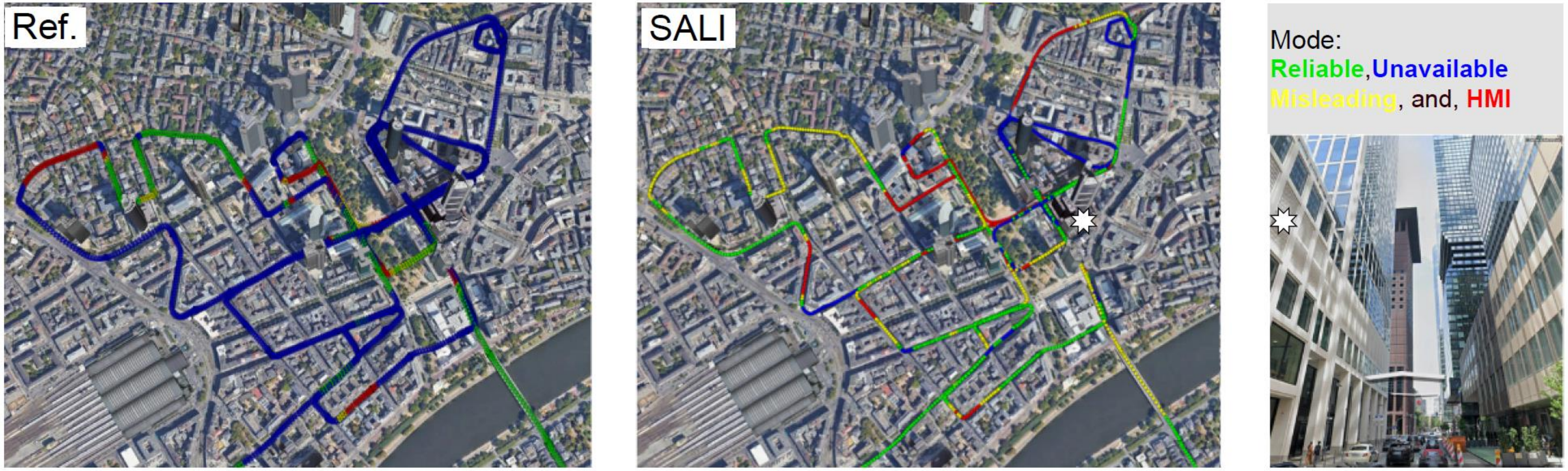
- **p68** [m] = horizontal position error 68th percentile
- **p95** [m] = horizontal position error 95th percentile
- **p2m** [%] = **P**(horizontal position error ≤ 2 m)
- **Unavailability** = **P**(accuracy estimate > 2 m)
- **HMI rate = P**(accuracy estimate ≤ 2m & position error > 2m)
  - **H**azardously **M**isleading **I**nformation



Positioning Performance



(a) Integrity diagrams across all test drives, SALI v.s. ref.

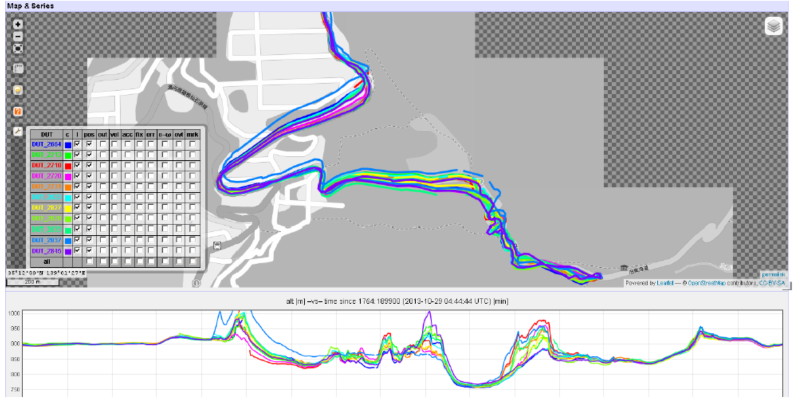


(b) Road test example: Downtown Frankfurt am Main, SALI v.s. ref.

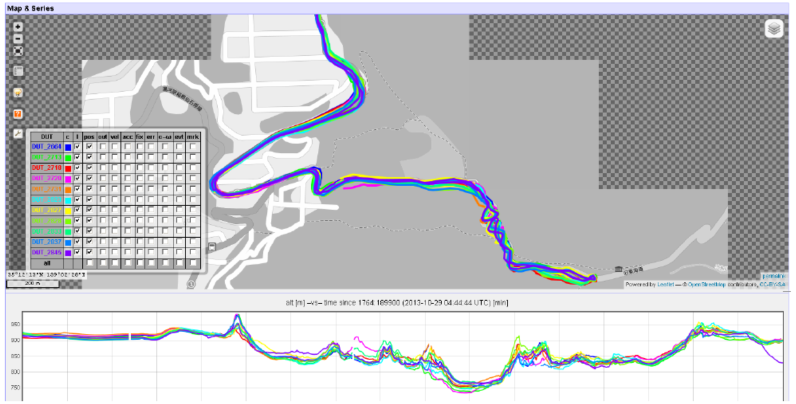
What if no Sensor-aiding?

100ms coherent integration without sensor-aided motion wipe-off

- Stand-alone receiver (no IMU at all), Hakone, Japan

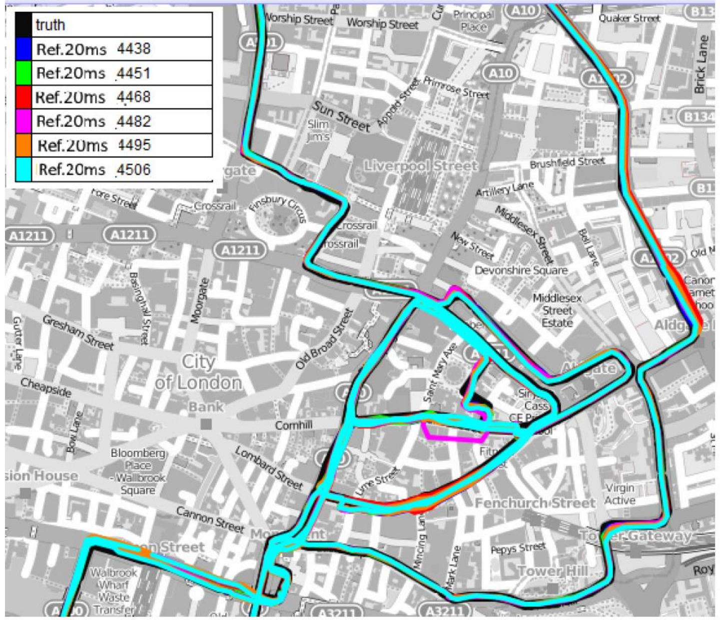


(a) ≤20ms coherent integration

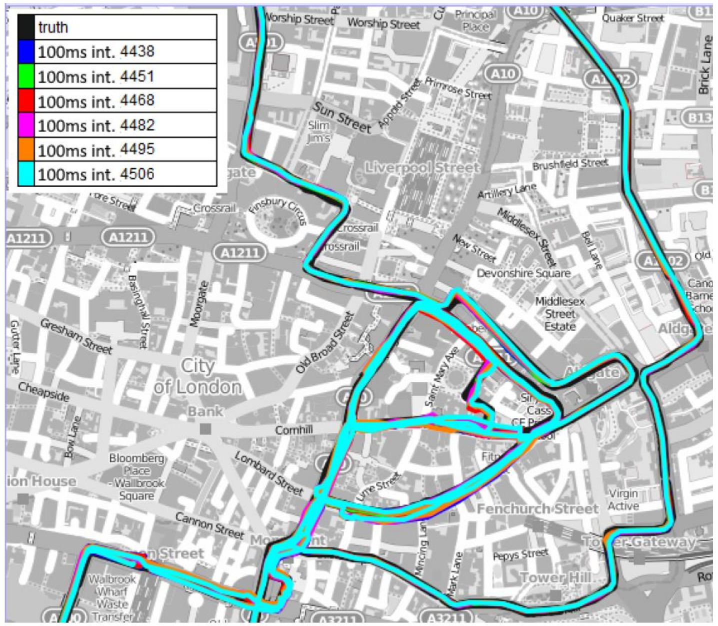


(b) 100ms coherent integration

- Sensor fusion receiver (IMU only used by PE), London



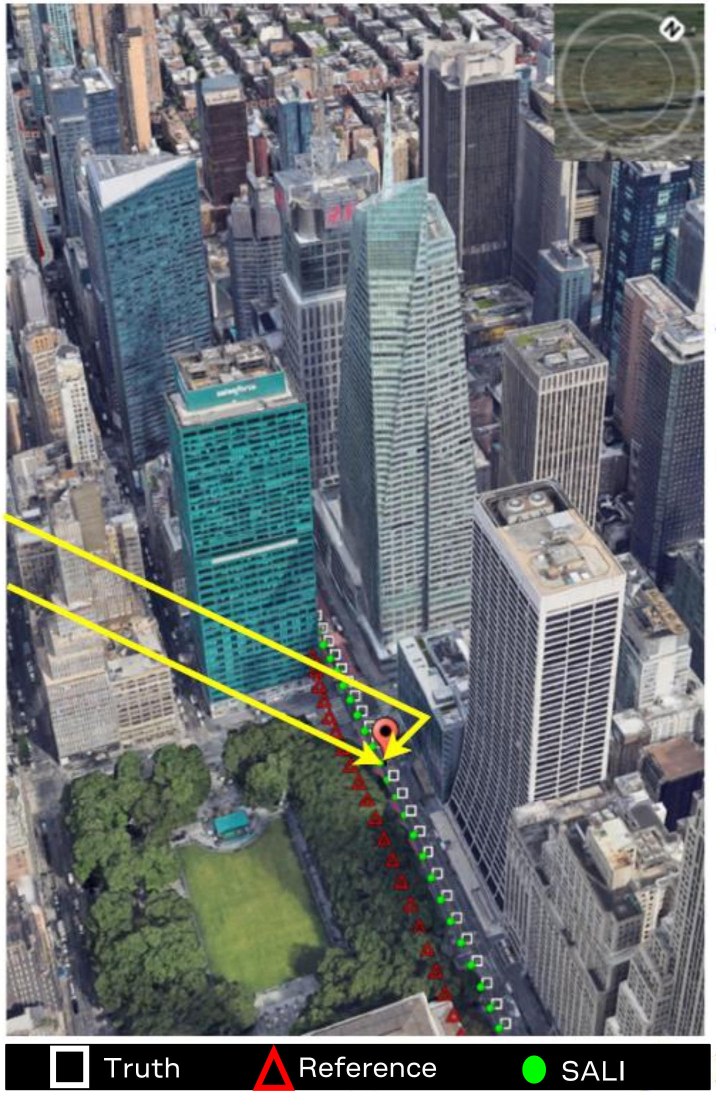
(a) ≤20ms coherent integration

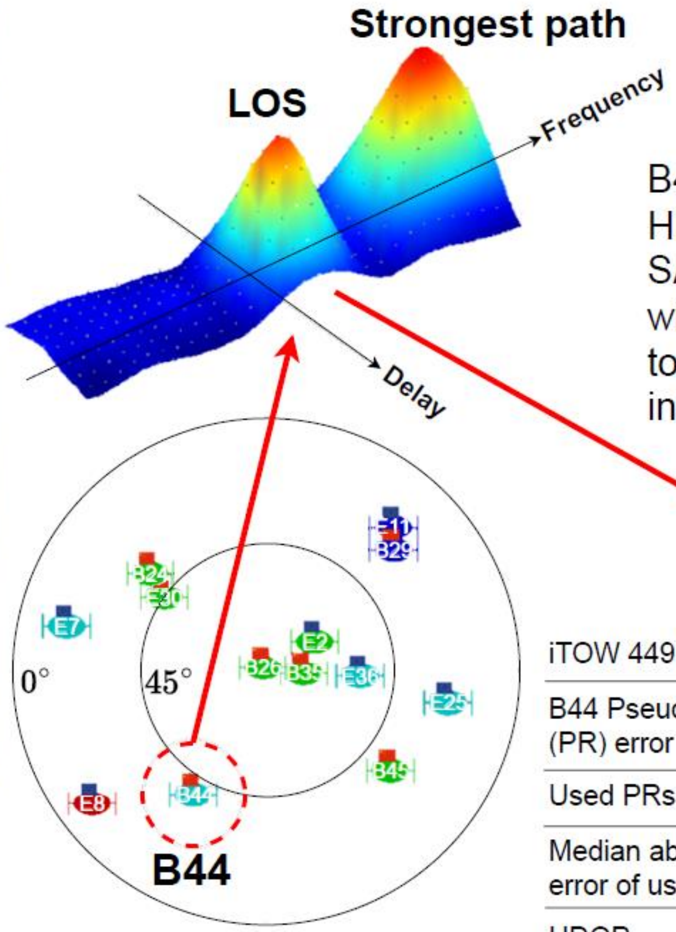


(b) 100ms coherent integration

Visual Examples

Multipaths in New York City



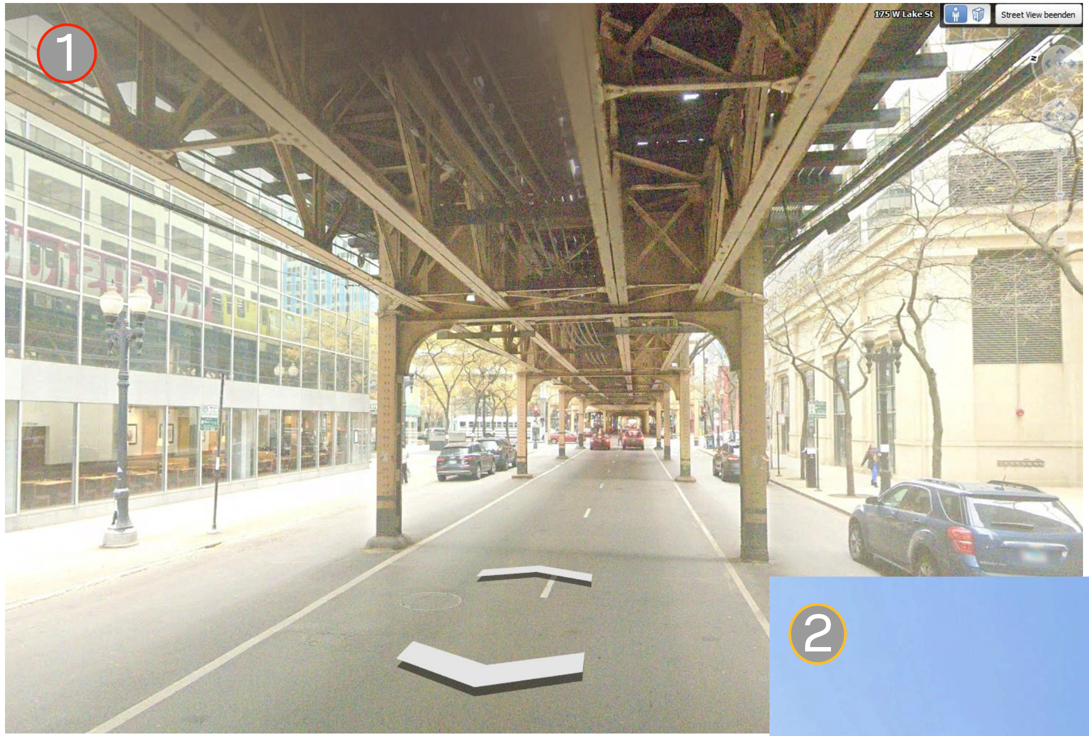


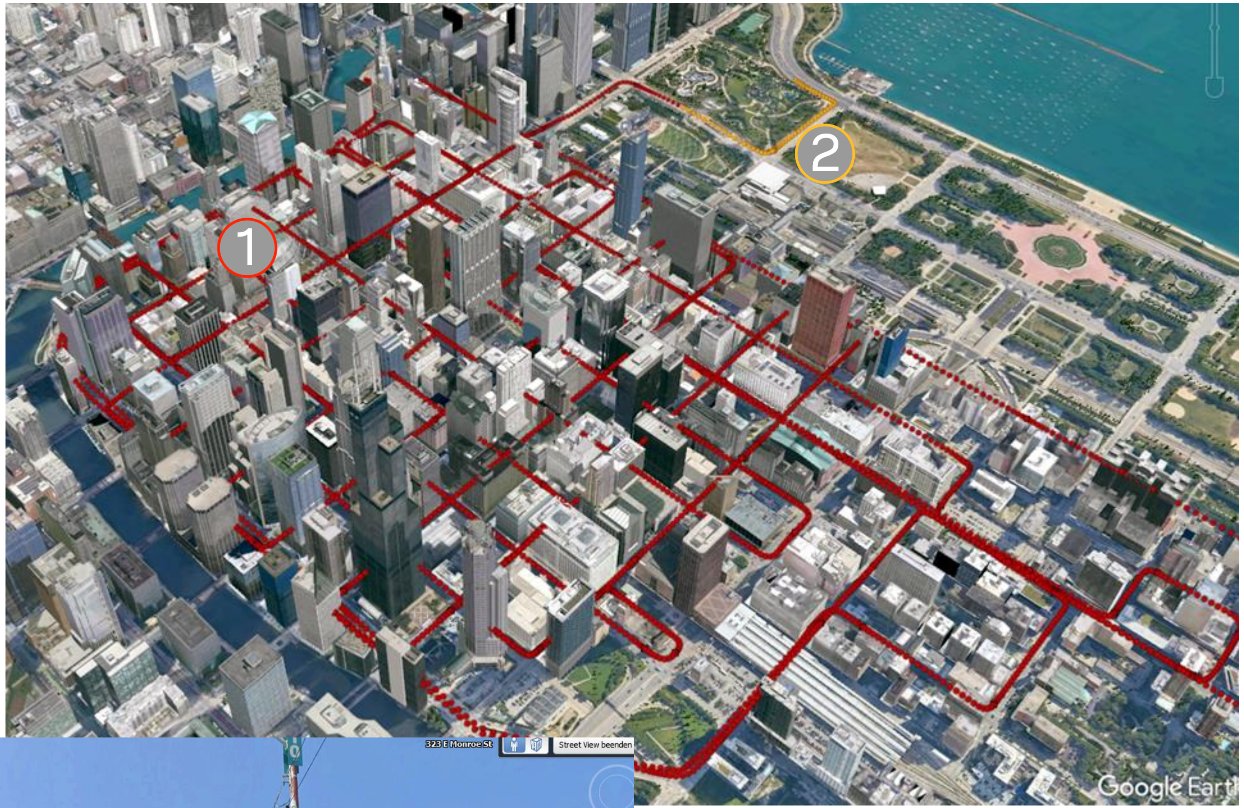
B44 stabilizes the HDOP, is used in SALI receiver, while ruled out due to large PR error in the ref. receiver.

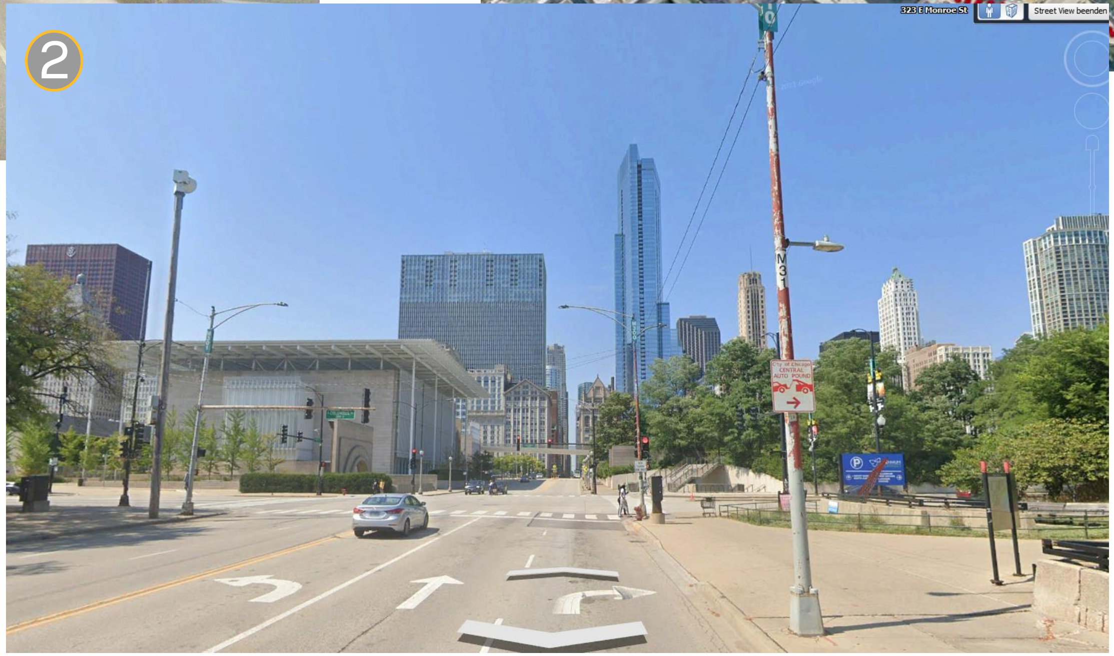
iTOW 449189	Ref.	SALI
B44 Pseudorange (PR) error	7.7m	0.8m
Used PRs	6	5
Median absolute error of used PRs	1.4m	1.3m
HDOP	4.1	3.4

NYC, B44 B1C tracking, SALI v.s. ref.

Chicago Downtown



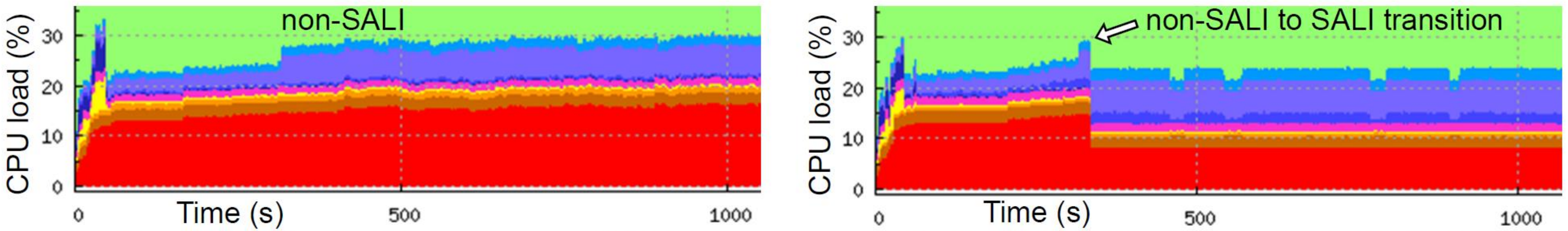




Computational & Memory Complexity

CPU-Load & Memory Size

- ~25% CPU-load reduction because high-rate carrier/code tracking loops are discontinued.
- No special hardware accelerators needed.
- Memory footprint increases linearly with the integration length and number of channels.



(a) Total CPU load of the reference SF RX   **(b)** Total CPU load of the SALI SF RX

Figure 12: CPU load comparison on ARM Cortex M3

Conclusions & Outlook

Conclusions

We have demonstrated that sensor-aided long coherent integration (SALI) using E1 and B1C signals significantly reduces multipath errors in mobile GNSS applications, providing a remarkable improvement over conventional sensor fusion receivers.

- Measurement and position accuracy improve in all challenging environments
- Much higher availability and integrity (lower HMI)
- Foliage and suburban improve most
  - ➢ Circular Error Probable at 95% = 2.1m
- Deep urban improvement
  - ➢ Circular Error Probable at 95% 15m → 4.2m
  - ➢ Percentile of 2m errors: 42% → 63%
- CPU load 25% down
- Open-sky slightly worse

Outlook

- SALI will benefit L5 wideband signals too.
- SALI will benefit Anti-jam & anti-spoof applications.
- SALI will benefit high-rate (100Hz) PVT output.
- Sub-meter accuracy using SALI for L1L5 in challenging environments.