Collaborative All-Weather Sensing for Automated Vehicles

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UT San Antonio | April 20, 2018

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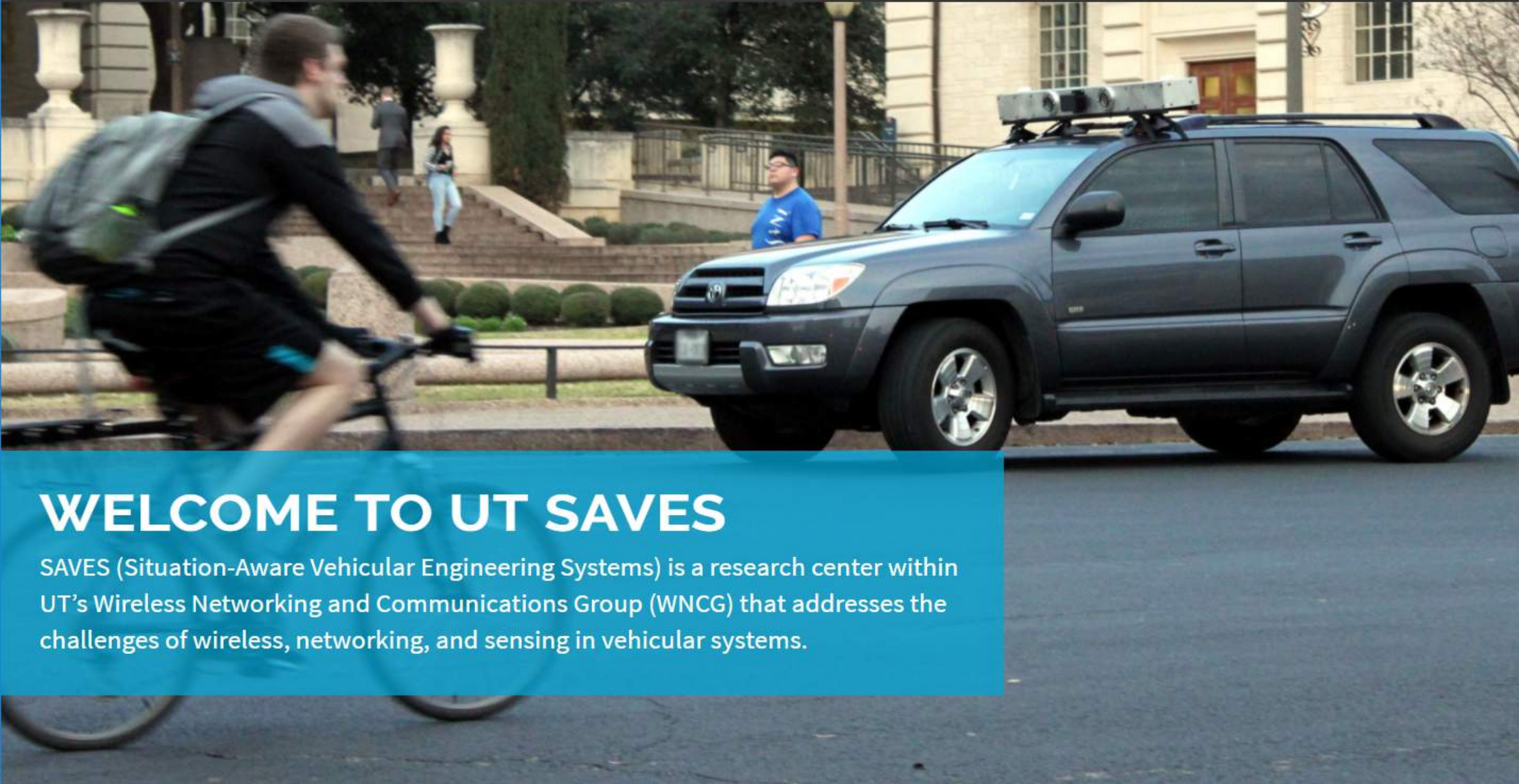

WELCOME TO UT SAVES

SAVES (Situation-Aware Vehicular Engineering Systems) is a research center within UT's Wireless Networking and Communications Group (WNCG) that addresses the challenges of wireless, networking, and sensing in vehicular systems.

UT SAVES: Situation-Aware Vehicular Engineering Systems

COMMUNICATION

Communicating high rate sensor data, using sensing to make communication more efficient

SENSING

Fusing sensor data, discovering the relevance of data to safety, traffic, management

ANALYTICS

Exchanging processed data, enhancing automated driving

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UT SAVES

TOYOTA InfoTechnology Center, U.S.A., Inc.

HUAWEI

FUJITSU

HONDA
Honda R&D Americas

AT&T

NXP

QUALCOMM®

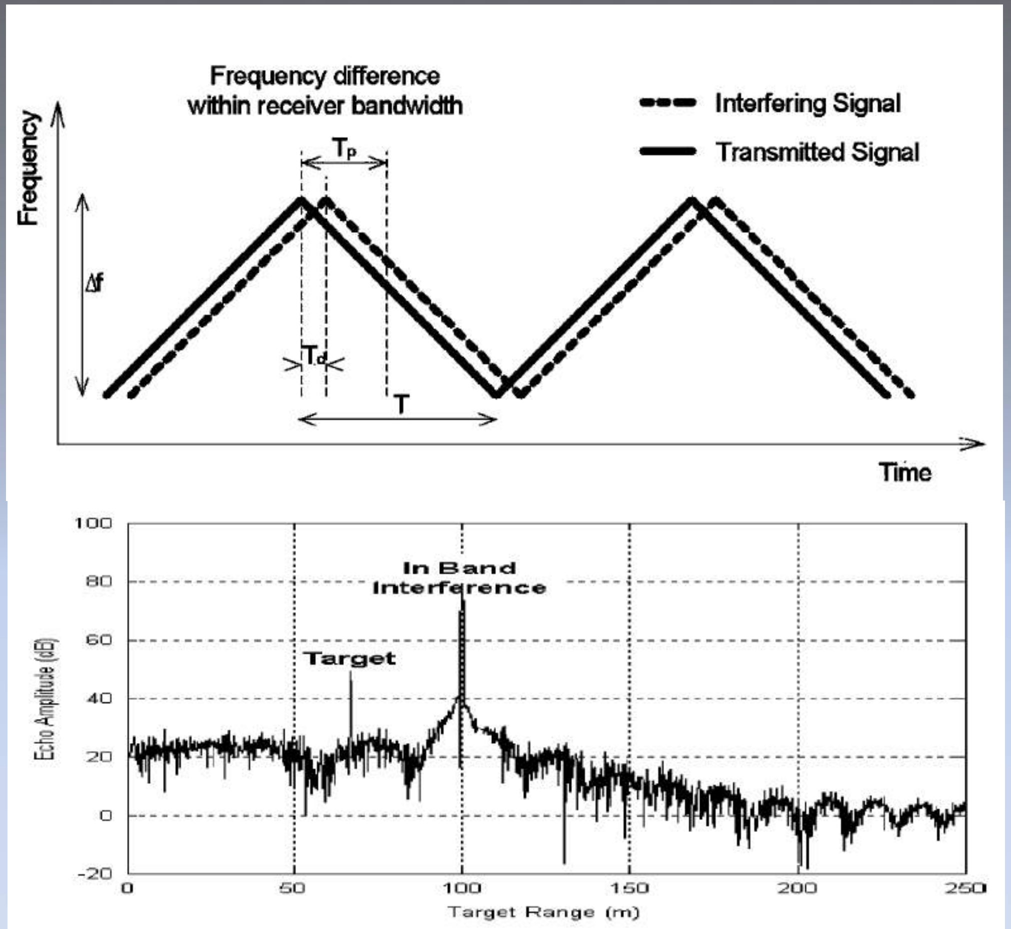
RNL Grand challenge:

Design automated systems that are both *robust* in the face of unusual natural or accidental events and *secure* against deliberate attack

Robustness and Security at Odds

Improved robustness can reduce security: After the Tesla update to Autopilot 8.x, radar can force automatic braking without cross-validation from camera

Robustness and Security at Odds



Booker, "Mutual interference of mm-wave radar systems." (2007)

The security of automotive radar systems against deliberate attack is weak because the standard FMCW waveform is trivially predictable

Robustness and Security in Unison

Having many subsystems with non-overlapping failure modes improves both robustness and security

Robust
&
Secure

Robust

&

Secure

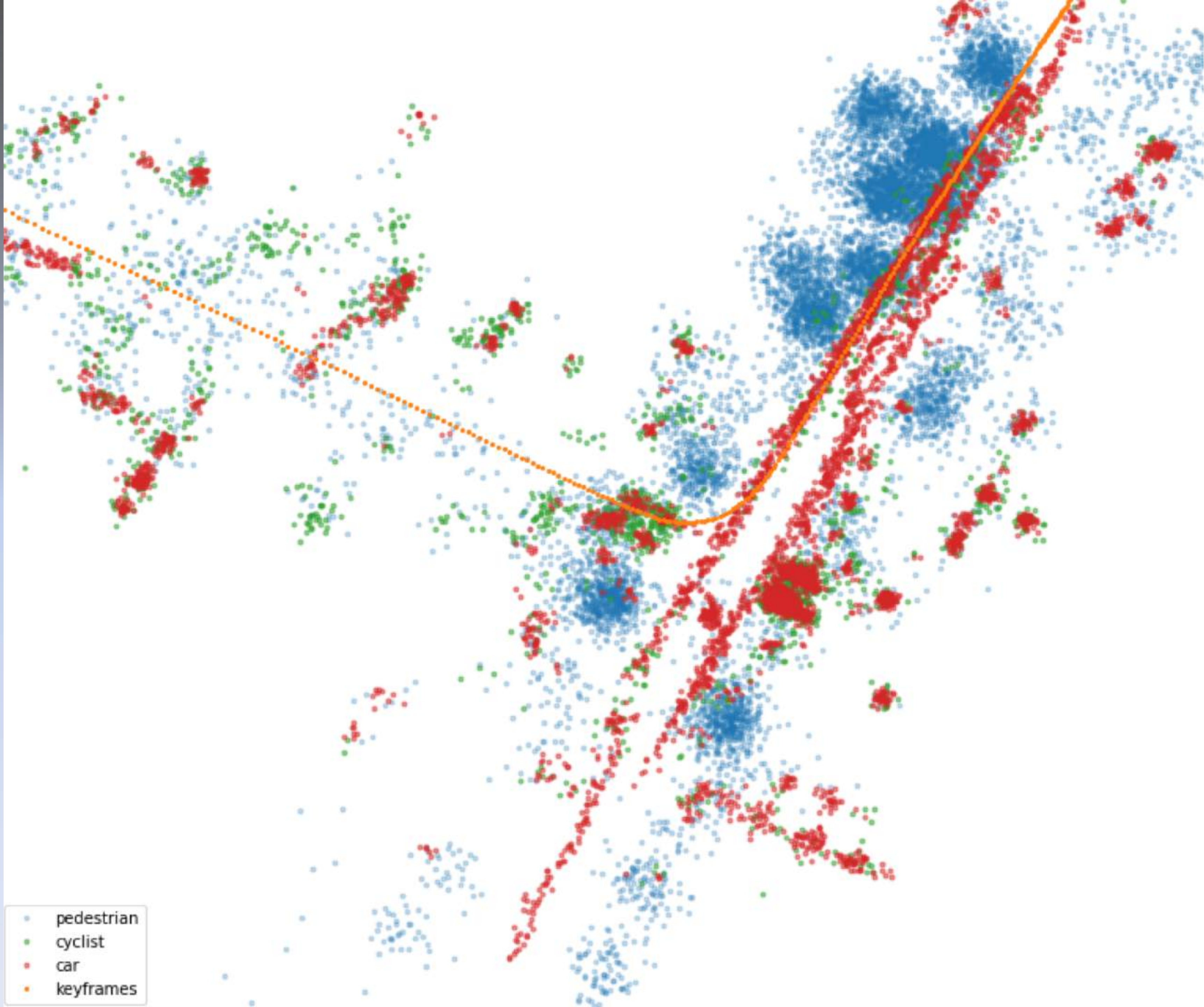
Robust perception:

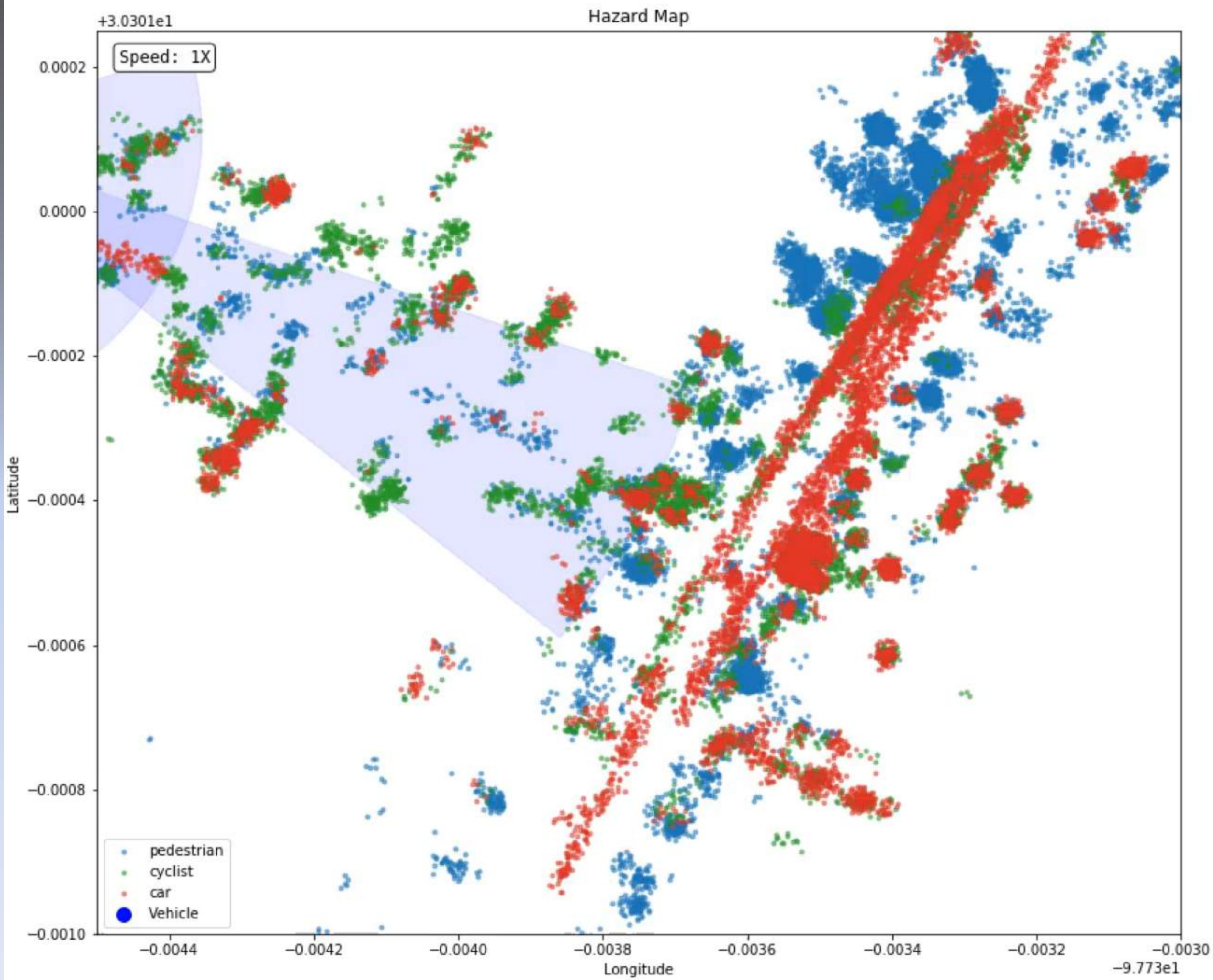
No blind spots

All environments

All weather conditions

Collaborative sensing reduces risk, increases perception robustness

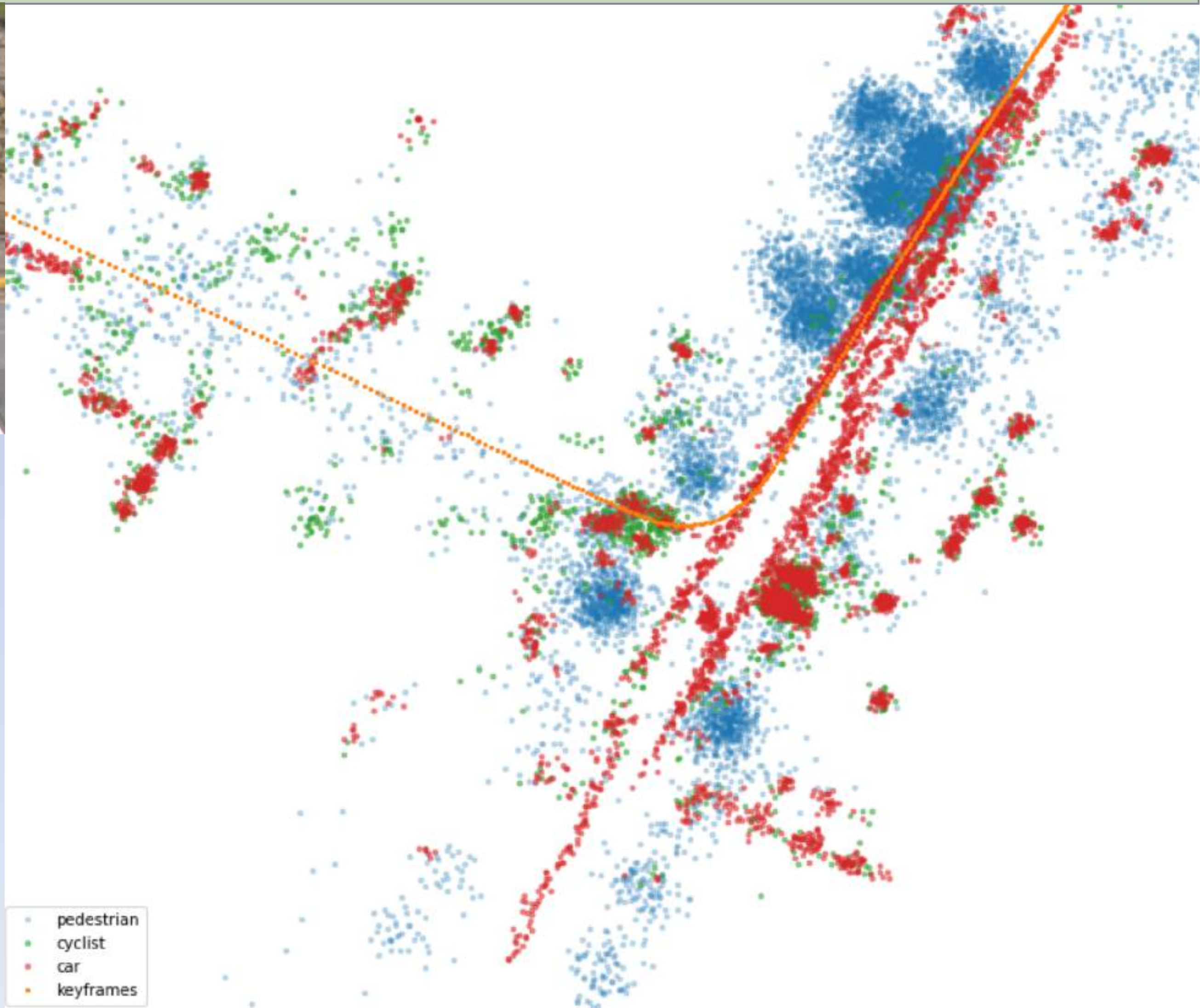



Hazard Map
+3.0301e1
Speed： 1X
0.0002
0.0000
−0.0002
−0.0004
−0.0006
−0.0008
−0.0010
Latitude
−0.0044
−0.0042
−0.0040
−0.0038
−0.0036
−0.0034
−0.0032
−0.0030
−9.773e1
Longitude
pedestrian
cyclist
car
Vehicle

Features	5G V2X requirements	LTE C-V2X	DSRC
Data rate	10 Mb/s @ 1000m 700 Mb/s @ 500m 1 Gb/s @ 50m	Up to 1 Gb/s	3-27 Mb/s
End-to-end Latency	20 ms , limited auto. 3 ms , full auto.	20-100 ms	2-100 ms
Reliability	90~99%, limited auto. 99~99.999%, full auto.	90% @ 450m*	90% @ 225m*
Range	Up to 1 km	Up to 1km (very large via infra.)	100 – 1000m
Tx Rate	50 messages/s	Up to 50 messages/s	Up to 20 messages/s

5G's high data rates and low latency enable multiple vehicles and infrastructure to function as a single sensing organism

System	4 Cameras, 77GHZ IF Radar, 77Ghz Delphi Automotive Radar, and GNSS Receiver		
Sensor	Raw	Processed	Interpreted
Image	PNG 3MP Mono Image - 1 MB	SIFT Image Features - 544kb	Detected Object, Sparse/Dense Reconstructions
Radar	77GHz FMCW (32 Channels at 80 Mhz) - 8.192 MB	Radar Tracks - 8192 b	Classified Detection and Maps
GNSS	Observables < 1KB	Position/Orientation - 100 B	Ionospheric, Local Multi-path Models
Per Frame Total	97.53 Mb	1.1Mb	1-1000Mb
10 FPS Total Rate	975.3 Mb/s	11 Mb/s	



Q: How to quantify reduction in risk for each level of data sharing (raw, processed, interpreted)?

Key insight so far on data sharing:

Share either raw data or fully semantically-labeled and located data. Sharing partially-processed data across heterogeneous platforms is less useful

Keys to collaborative all-weather sensing:

- Common reference frame (not just within *your* map)
- Sub-30-cm positioning within common frame
- Decimeter-accurate mapping capability
- Map-merging
- Quick-response and lifetime map maintenance
- Means of *quantifying* the benefit of collaboration

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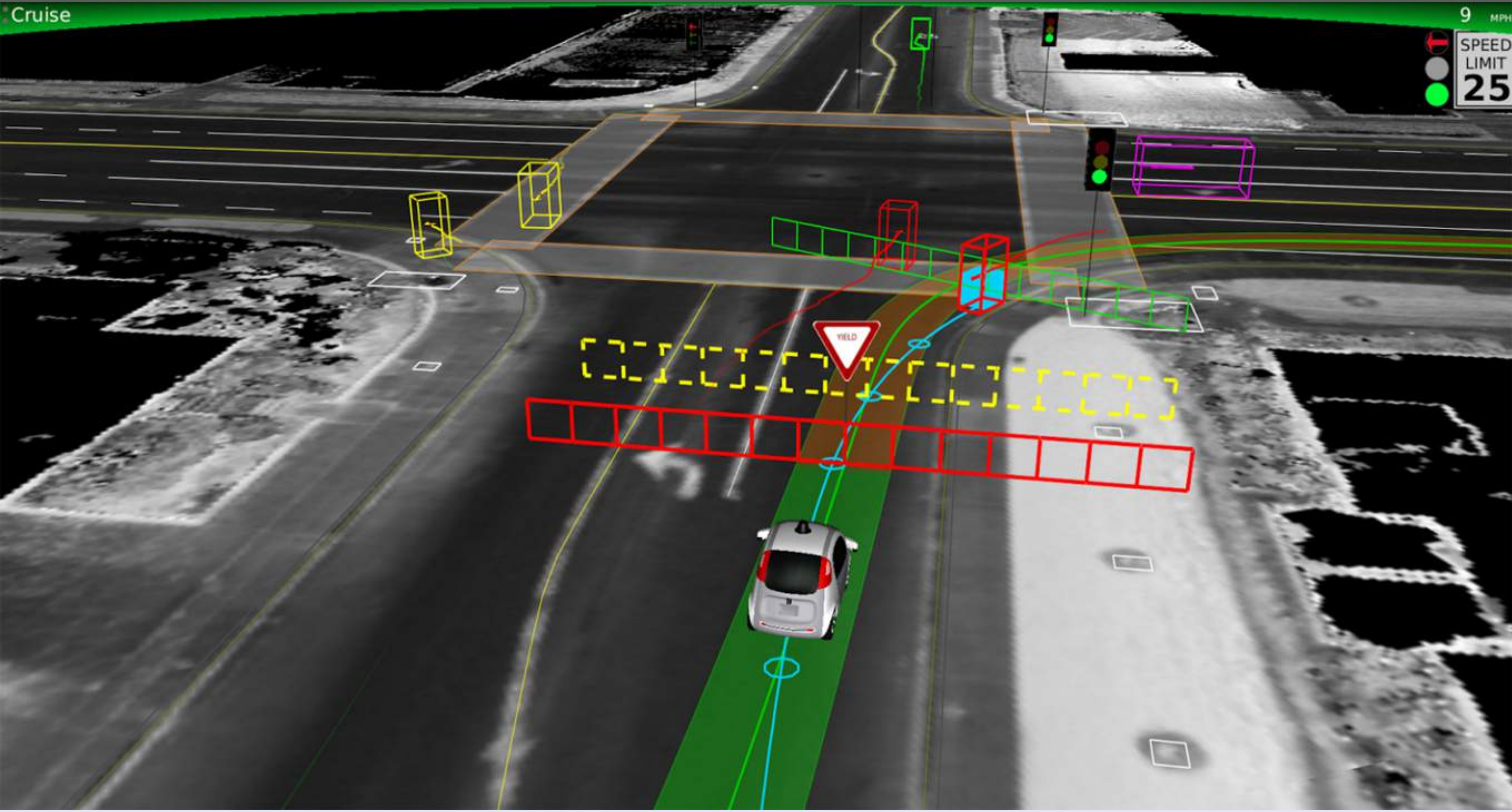
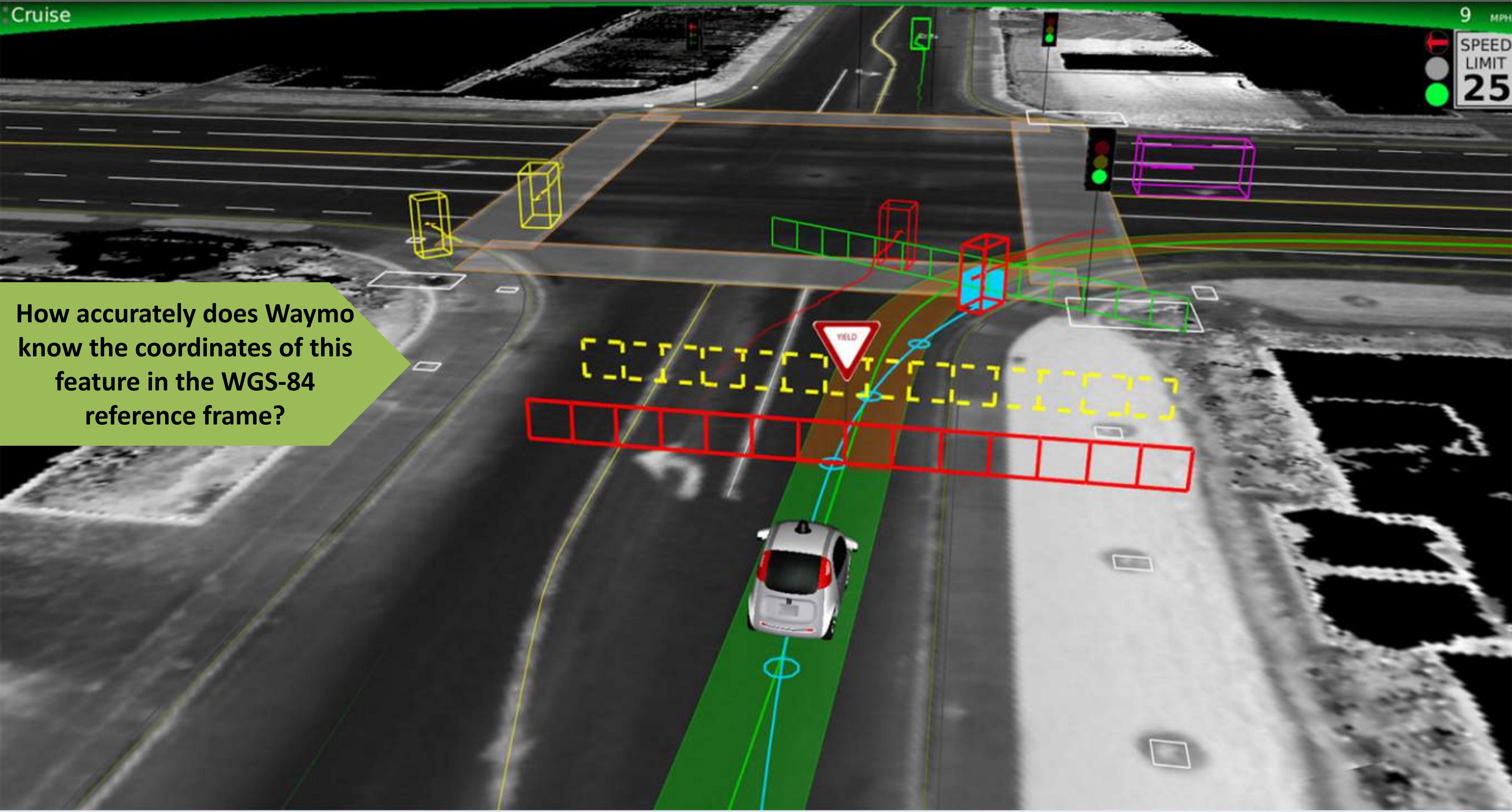


Cruise
9 MPH
SPEED LIMIT 25
YIELD



How accurately does Waymo know the coordinates of this feature in the WGS-84 reference frame?

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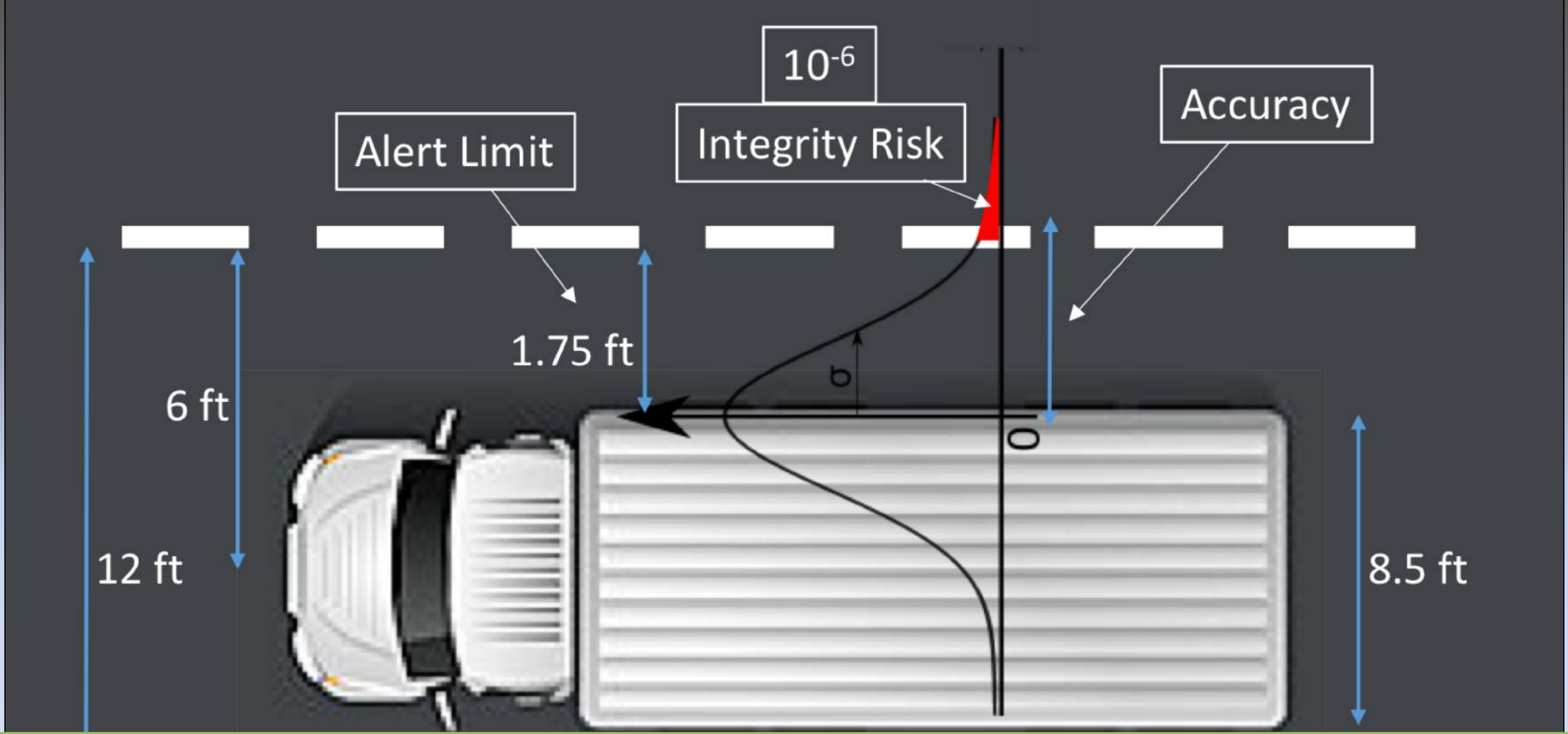

Q: What is required position accuracy for automated vehicles?

A: None specified currently, maybe there never will be.

It doesn't make sense to cut-and-paste from FAA regulations:

Federalism and high death rate make automotive case unique

Emerging industry consensus: Horizontal position accuracy better than 30cm @ 95%

In low-visibility conditions, LIDAR and cameras will fail. If pre-mapped radar reflectors are too sparse, lane keeping may be compromised

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	**High Automation**	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
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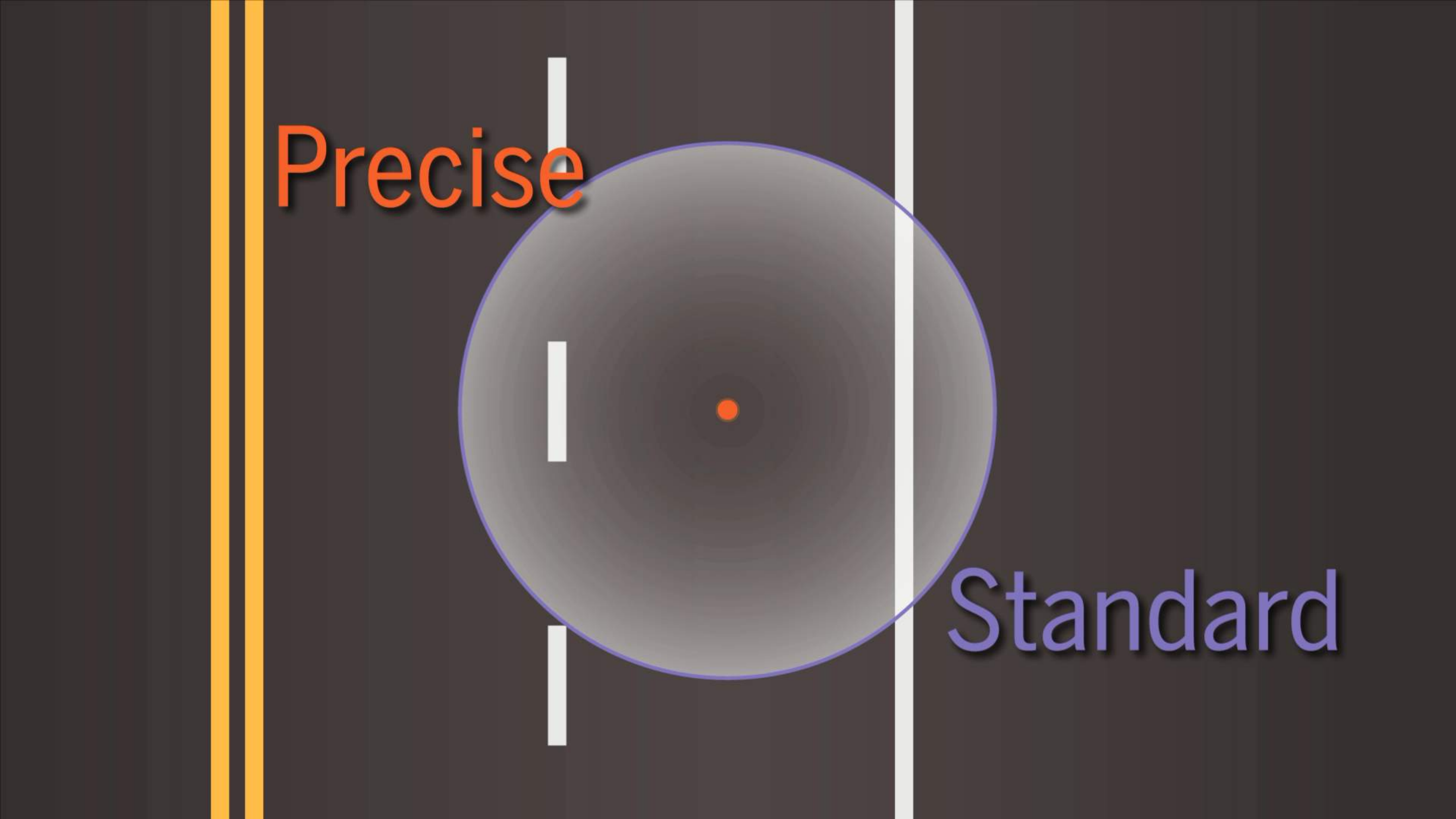
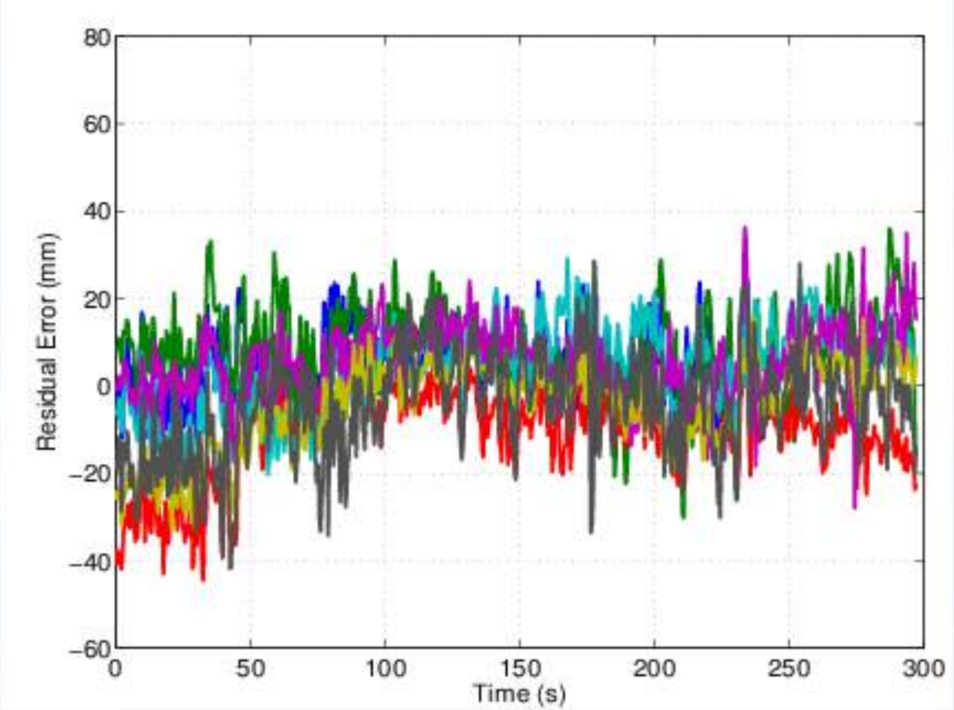
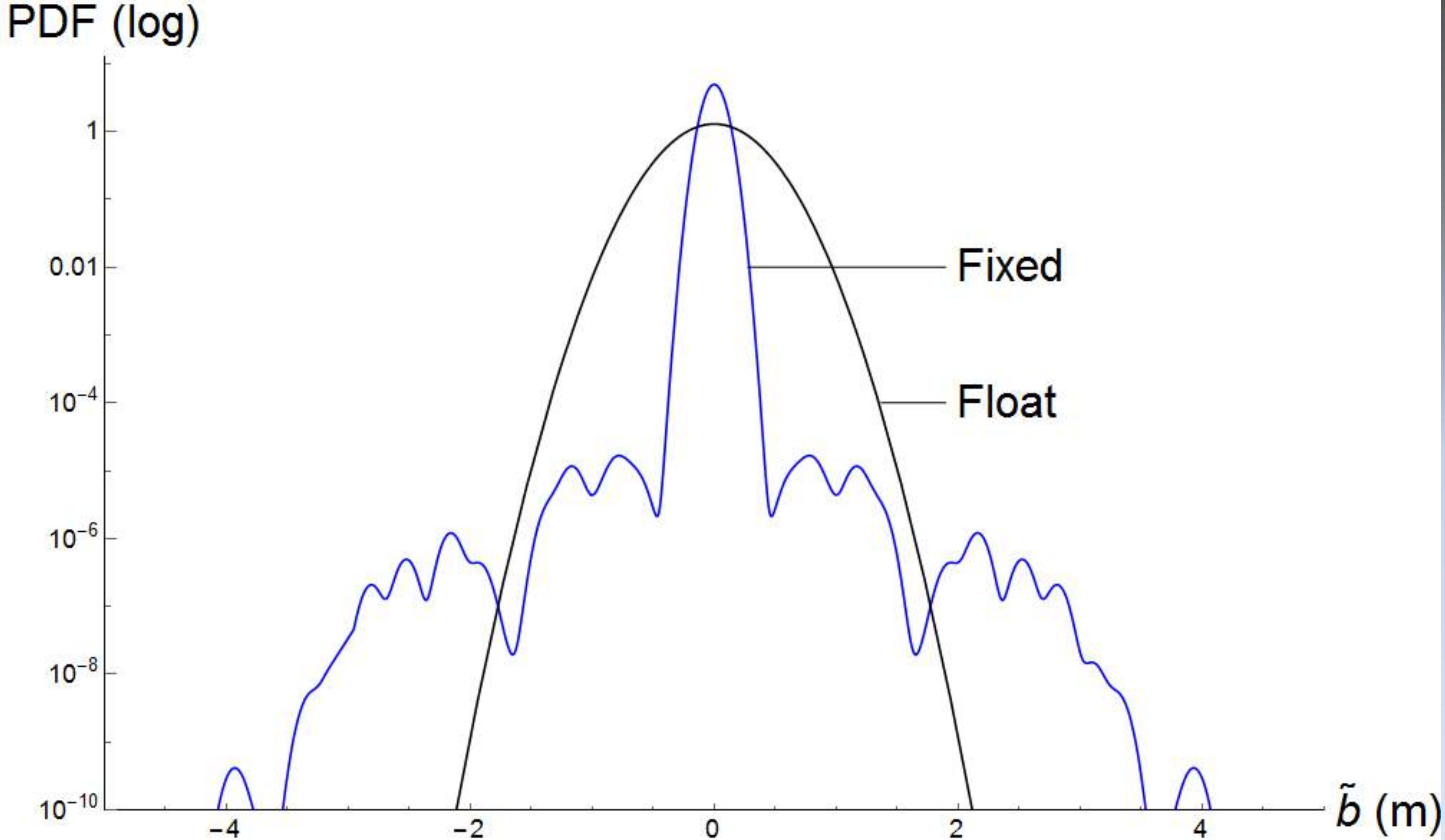
Call to robustness:

We should be designing for Level 6,
Continued operation under conditions in which a human couldn’t manage

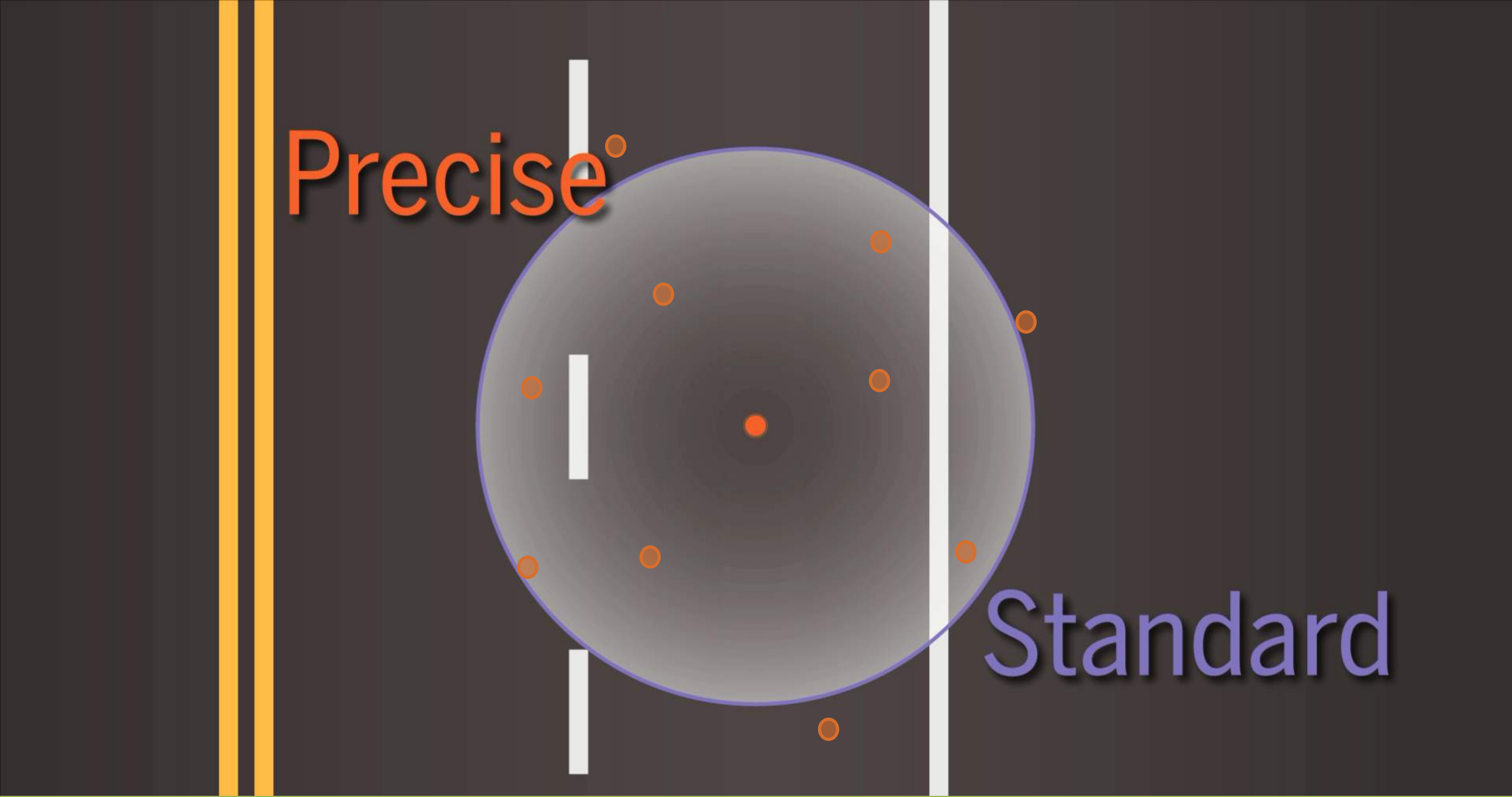

Precise
Standard



Dec. 2014: First successful RTK solution with a smartphone antenna.



Float solution does not enforce integer constraint. Fixed solution does, but may be wrong.

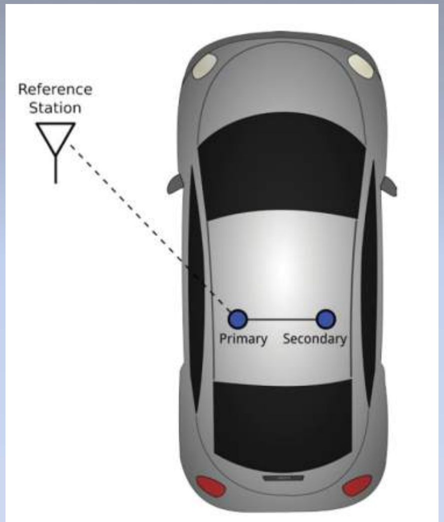


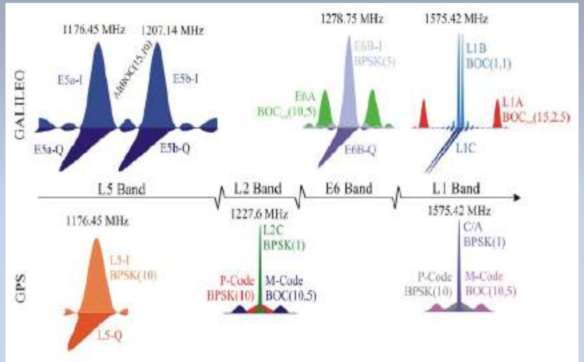
Safety-of-life applications require careful management of incorrect fixing probability

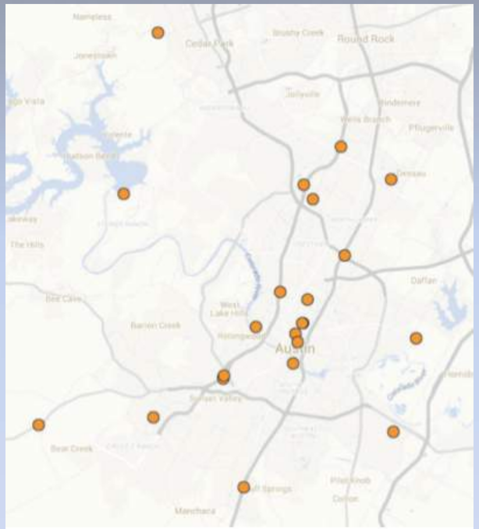
Light urban setting

Urban setting

Keys to Robust CDGNSS Positioning







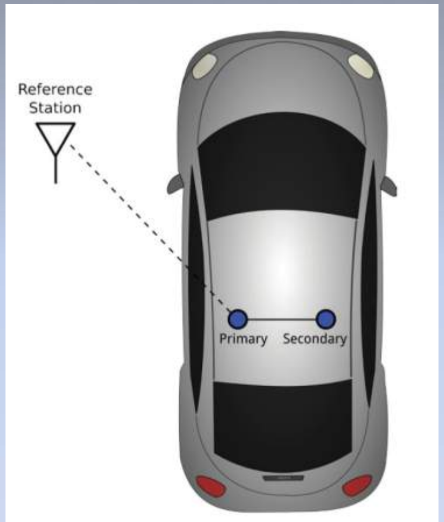
Multiple Rover Antennas

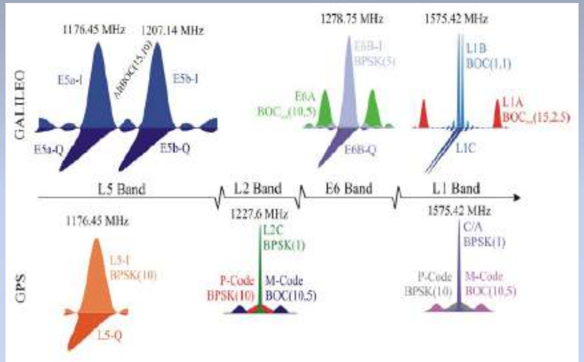
Multiple Frequencies

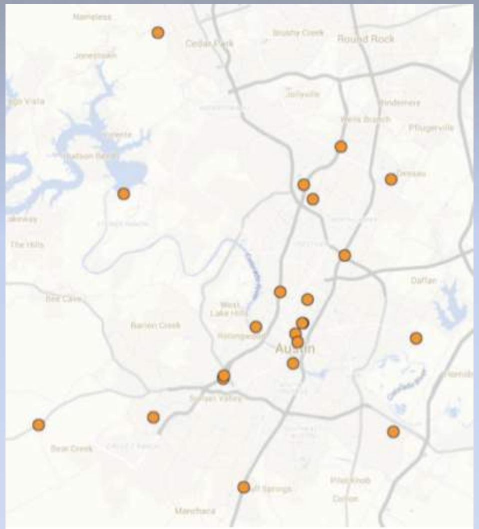
Dense Reference Network

Fusion with Vision/Radar

Keys to Robust CDGNSS Positioning







Multiple Rover Antennas

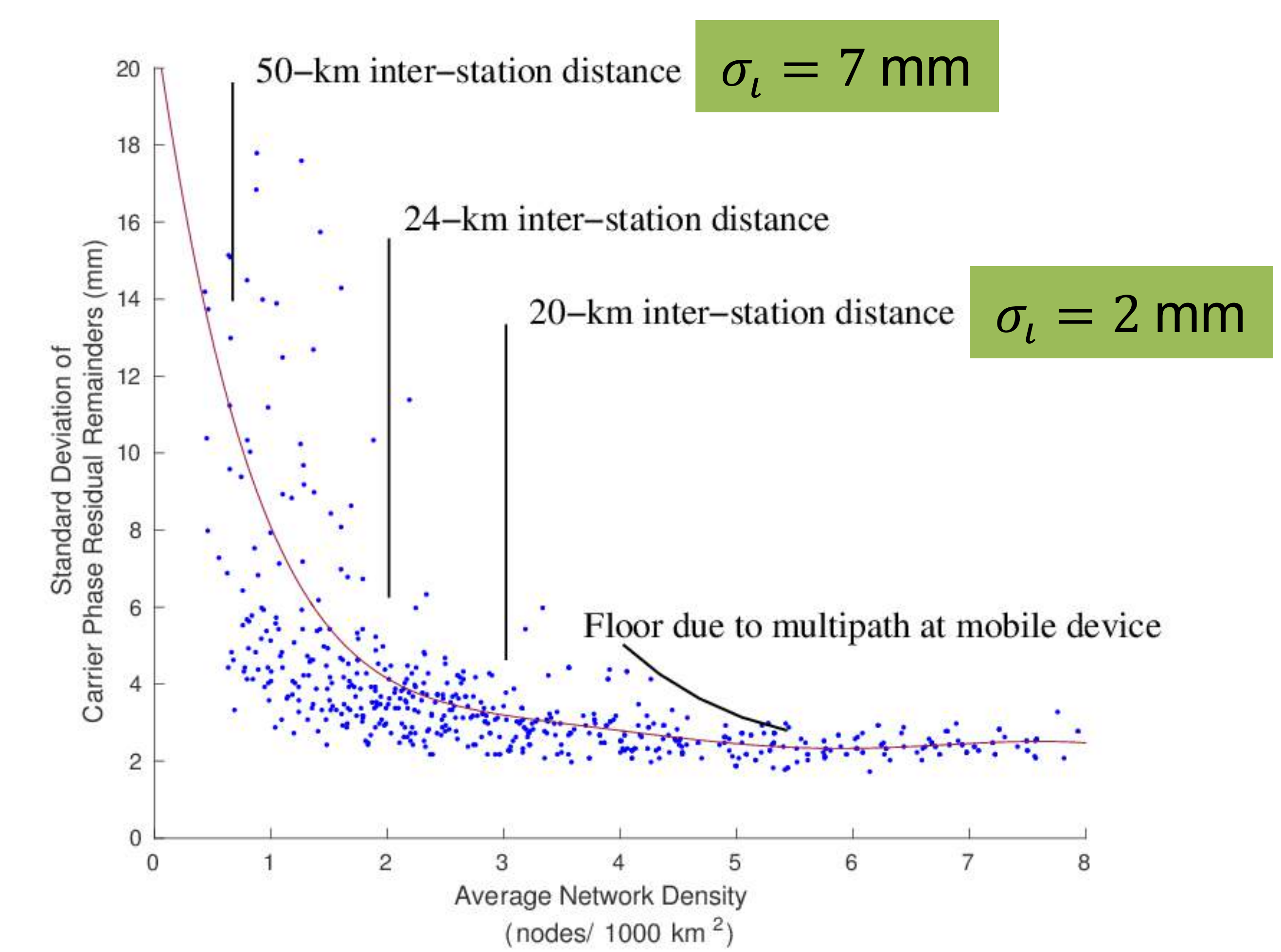
Multiple Frequencies

Dense Reference Network

Fusion with Vision/Radar

Don't waste valuable signals estimating atmospheric errors: you'll need them to combat your chief adversary: ***multipath***

Eliminate iono with a dense reference network



Corrections uncertainty is a highly nonlinear function of density. Culprit: medium-scale ionospheric irregularities. **Floor due to multipath at mobile device reached with < 20km distance between reference stations.**

Longhorn Dense Reference Network stations under test prior to deployment

UT SAVES Sensorium v2.0:
Stereo cameras, dual-antenna triple-frequency software-defined GNSS, industrial-grade IMU (8 deg/hr gyros), automotive radar, LTE connectivity

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Stereo cameras, dual-antenna triple-frequency software-defined GNSS, industrial-grade IMU (8 deg/hr gyros), automotive radar, LTE connectivity


Legend
sps
sps
Google Earth
Gray Buildings © 2008 Sanborn
200 ft
N

GRID: General Radionavigation Interfusion Device

Receiver time: 0 weeks 600.9 seconds   Build ID: 3442

GPS time: 1965 weeks 244541.6 seconds

GPS_L1_CA_PRIMARY

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	2	-1343.8	782989.6	21128343.1	42.5	63.0	36.0	6c
2	5	-1661.7	902836.6	19249040.5	48.3	36.0	64.5	6c
3	12	-3373.4	1987585.1	21709900.9	43.0	196.3	27.7	6c
4	20	1279.8	-865862.0	19194139.2	46.0	243.2	63.8	6c
5	25	-2022.9	1118935.8	20918316.9	44.9	238.8	40.3	6c
6	29	1979.6	-1258804.9	19582115.1	47.9	328.4	55.5	6c
7	13	2460.6	-1467509.0	21549244.8	43.1	131.4	29.8	6c
8	15	3374.3	-1960403.0	22036087.3	44.7	170.5	23.4	6c
9	21	1705.6	-991877.2	23621779.0	40.1	283.5	12.7	6c
10	--	---------	-----------	-----------	----	-----	-----	-
11	--	---------	-----------	-----------	----	-----	-----	-
12	--	---------	-----------	-----------	----	-----	-----	-

GPS_L1_CA_ALT1

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	2	-1343.7	750416.7	21128341.2	42.1	63.0	36.0	6c
2	5	-1661.5	868181.1	19249037.8	47.8	36.0	64.5	6c
3	12	-3373.0	1904292.2	21709899.1	47.1	196.3	27.7	6c
4	13	2460.6	-1467508.2	21549241.3	40.6	131.4	29.8	6c
5	15	3374.5	-1960402.4	22036083.3	44.3	170.5	23.4	6c
6	20	1279.5	-824962.7	19194137.8	46.7	243.2	63.8	6c
7	21	1706.3	-991877.4	23621778.4	38.0	283.5	12.7	6c
8	25	-2022.4	1075087.8	20918315.1	44.2	238.8	40.3	6c
9	29	1979.6	-1202363.9	19582114.2	47.6	328.4	55.5	6c
10	--	---------	-----------	-----------	----	-----	-----	-
11	--	---------	-----------	-----------	----	-----	-----	-
12	--	---------	-----------	-----------	----	-----	-----	-

GPS_L2_CLM_PRIMARY

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	5	-1294.3	676504.0	19249033.4	45.8	36.0	64.5	5
2	12	-2628.8	1483861.6	21709895.5	42.3	196.3	27.7	5
3	15	2628.9	-1527582.2	22036083.3	41.6	170.5	23.4	5
4	25	-1575.8	837730.5	20918313.7	44.1	238.8	40.3	5
5	29	1542.8	-936906.6	19582109.2	43.9	328.4	55.5	5
6	--	---------	-----------	-----------	----	-----	-----	-
7	--	---------	-----------	-----------	----	-----	-----	-

GPS_L2_CLM_ALT1

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	5	-1294.9	676504.9	19249046.9	47.0	36.0	64.5	5
2	12	-2628.7	1483862.2	21709908.7	40.8	196.3	27.7	5
3	15	2629.6	-1527582.8	22036097.8	39.3	170.5	23.4	5
4	25	-1575.8	837730.2	20918327.4	43.4	238.8	40.3	5
5	29	1542.8	-936906.8	19582123.4	45.1	328.4	55.5	5
6	--	---------	-----------	-----------	----	-----	-----	-
7	--	---------	-----------	-----------	----	-----	-----	-

SBAS_L1_I_PRIMARY

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	131	-48.3	18694.0	35836255.6	46.3	214.8	48.9	6
2	135	-47.1	17814.2	36620656.2	45.3	234.5	38.0	6
3	138	-51.2	20063.8	35565790.0	47.0	198.5	53.2	6
4	133	-123.7	63286.4	35482515.8	43.6	180.5	54.5	6

SBAS_L1_I_ALT1

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	131	-48.2	16607.2	35836250.2	44.9	214.8	48.9	6
2	133	-123.7	63883.1	35482512.3	43.0	180.5	54.5	6
3	135	-47.2	17609.8	36620658.0	46.4	234.5	38.0	6
4	138	-50.4	19992.2	35565787.8	47.0	198.5	53.2	6

GALILEO_E1_BC_PRIMARY

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	2	-2263.8	1273668.6	25887705.4	43.5	243.4	16.0	6
2	4	-2315.7	1278521.1	25606366.3	41.1	42.4	18.7	6
3	5	2388.4	-1424573.5	23410321.5	47.1	182.2	43.4	6
4	9	-85.4	-36855.5	20433681.7	46.6	86.8	61.4	6
5	11	-1293.4	709001.1	23734748.1	35.7	91.9	33.8	6
6	22	1853.0	-1067434.6	23014817.2	43.5	309.6	25.5	6
7	30	-720.2	259884.0	24451915.2	38.2	293.9	11.1	6
8	--	---------	-----------	-----------	----	-----	-----	-

GALILEO_E1_BC_ALT1

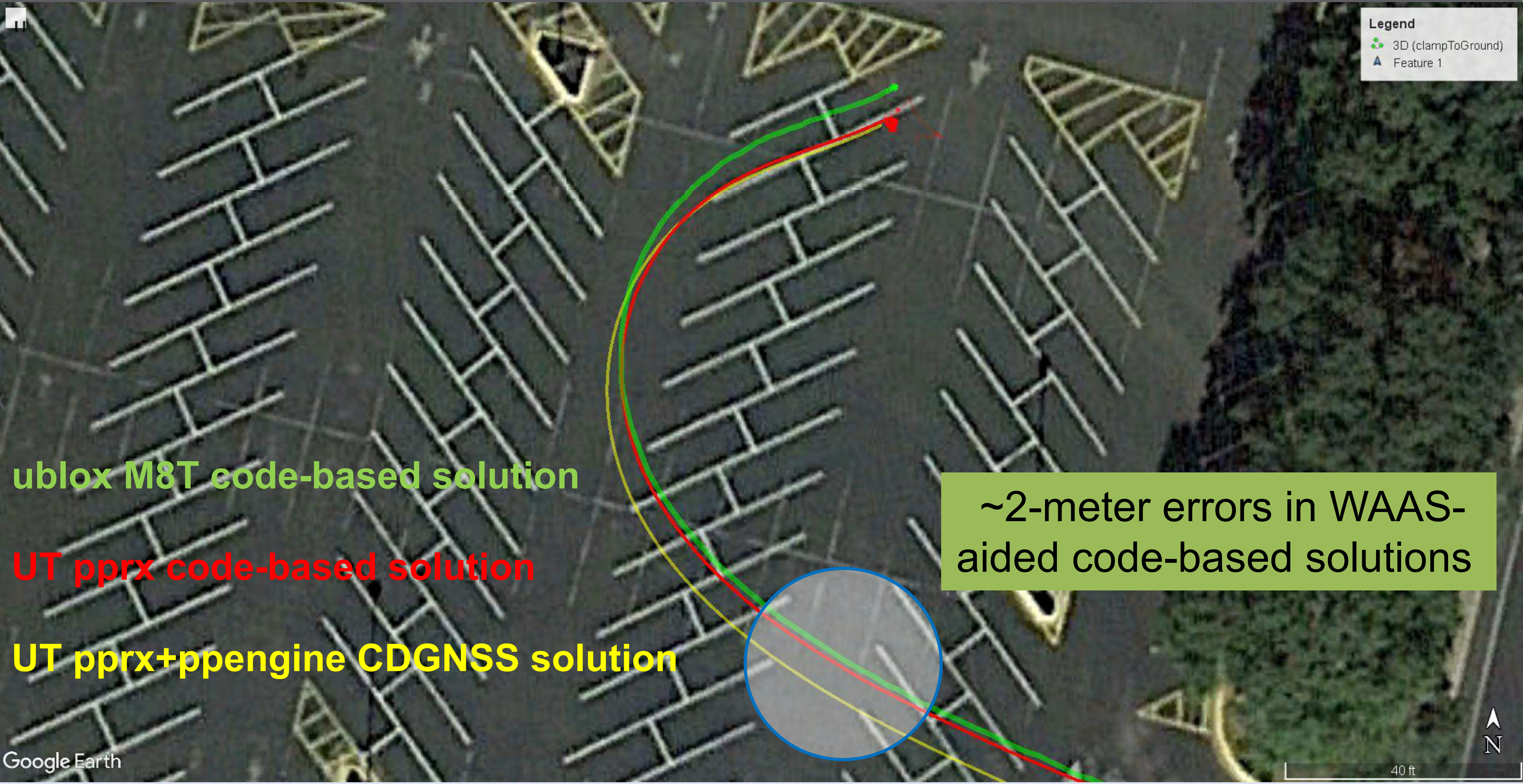
CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	2	-2263.8	1273668.1	25887704.4	41.5	243.4	16.0	6
2	4	-2315.5	1278520.5	25606366.9	38.1	42.4	18.7	6
3	5	2388.3	-1424573.5	23410318.5	45.6	182.2	43.4	6
4	9	-85.2	-36854.7	20433679.1	46.3	86.8	61.4	6
5	11	-1292.7	709000.6	23734746.2	42.7	91.9	33.8	6
6	22	1853.0	-1067434.7	23014815.7	43.6	309.6	25.5	6
7	30	-721.1	253501.6	24451916.3	31.3	293.9	11.1	6
8	--	---------	-----------	-----------	----	-----	-----	-

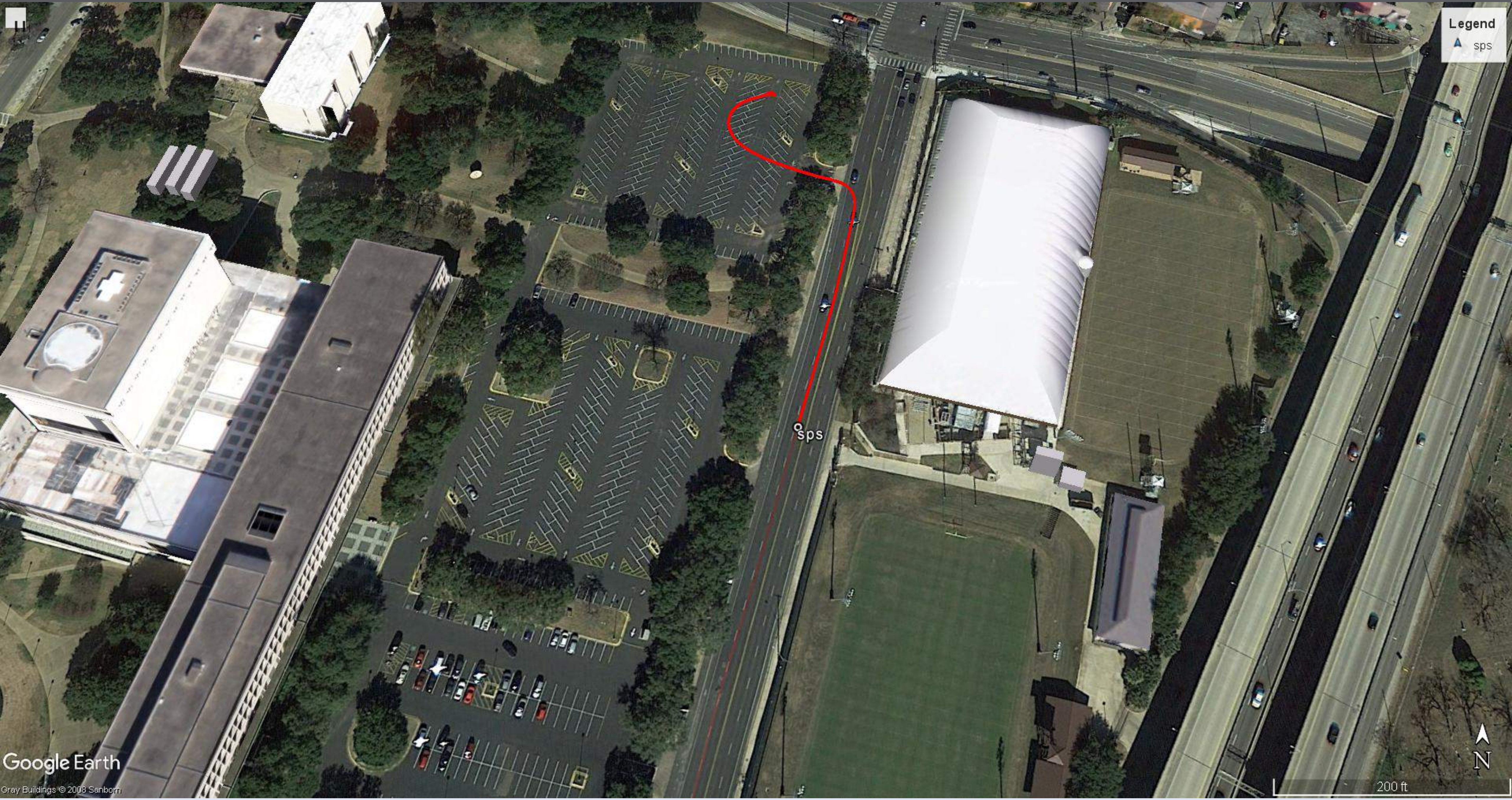
Navigation Data

X: -741194.13   Y: -5462362.04   Z: 3197959.42   deltRx: -1307489.33

Xvel: 0.01   Yvel: 0.05   Zvel: 0.03   deltRxDot: 9.12

Hsigma: 0.13   Vsigma: 0.24   NISratio: 0.58


Legend
3D (clampToGround)
Feature 1
ublox M8T code-based solution
UT pprx code-based solution
UT pprx+ppengine CDGNSS solution
~2-meter errors in WAAS-aided code-based solutions
Google Earth
40 ft
N


Legend
sps
sps
Google Earth
Gray Buildings © 2008 Sanborn
200 ft
N

GRID: General Radionavigation Interfusion Device

Receiver time: 0 weeks 808.9 seconds   Build ID: 3442
GPS time: 1965 weeks 244749.6 seconds

GPS_L1_CA_PRIMARY

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	2	-1411.8	1067034.9	21182394.7	38.7	64.6	35.1	6c
2	5	-1797.7	1260713.4	19317141.4	47.5	35.7	62.9	6c
3	12	-3367.3	2692235.3	21843992.4	45.1	195.6	26.3	6c
4	20	1175.4	-1120164.0	19145747.6	45.8	246.0	65.1	6c
5	25	-2099.7	1550124.1	21000369.4	45.2	237.1	39.2	6c
6	29	1867.6	-1660452.7	19505684.8	48.4	328.6	57.1	6c
7	13	2400.9	-1972222.9	21453201.3	44.3	130.0	30.9	6c
8	15	3382.0	-2660123.9	21902933.8	43.0	169.8	24.9	6c
9	21	1689.6	-1344771.3	23554629.3	36.3	284.7	13.5	6c
10	--	---------	-----------	-----------	----	-----	-----	-
11	--	---------	-----------	-----------	----	-----	-----	-
12	--	---------	-----------	-----------	----	-----	-----	-

GPS_L1_CA_ALT1

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	2	-1411.9	1034458.1	21182392.7	42.8	64.6	35.1	6c
2	5	-1797.6	1226055.7	19317139.5	47.3	35.7	62.9	6c
3	12	-3367.3	2608946.6	21843990.9	46.3	195.6	26.3	6c
4	13	2400.6	-1972221.7	21453198.4	44.0	130.0	30.9	6c
5	15	3381.4	-2660121.3	21902931.9	42.9	169.8	24.9	6c
6	20	1175.4	-1079262.6	19145746.6	45.9	246.0	65.1	6c
7	21	1689.3	-1344770.5	23554625.4	38.9	284.7	13.5	6c
8	25	-2099.7	1506280.9	21000369.0	43.5	237.1	39.2	6c
9	29	1867.4	-1604012.7	19505683.7	47.4	328.6	57.1	6c
10	--	---------	-----------	-----------	----	-----	-----	-
11	--	---------	-----------	-----------	----	-----	-----	-
12	--	---------	-----------	-----------	----	-----	-----	-

GPS_L2_CLM_PRIMARY

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	5	-1400.5	955369.0	19317134.2	44.6	35.7	62.9	5
2	12	-2623.4	2032937.6	21843989.2	40.9	195.6	26.3	5
3	15	2635.2	-2072818.9	21902929.4	42.5	169.8	24.9	5
4	25	-1636.7	1173721.9	21000366.0	43.6	237.1	39.2	5
5	29	1455.6	-1249878.9	19505677.4	44.3	328.6	57.1	5
6	--	---------	-----------	-----------	----	-----	-----	-
7	--	---------	-----------	-----------	----	-----	-----	-

GPS_L2_CLM_ALT1

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	5	-1400.6	955368.1	19317148.6	46.2	35.7	62.9	5
2	12	-2623.6	2032942.5	21844002.6	39.3	195.6	26.3	5
3	15	2634.6	-2072817.1	21902943.1	36.8	169.8	24.9	5
4	25	-1635.5	1173724.5	21000381.7	42.1	237.1	39.2	5
5	29	1455.3	-1249879.9	19505692.2	45.5	328.6	57.1	5
6	--	---------	-----------	-----------	----	-----	-----	-
7	--	---------	-----------	-----------	----	-----	-----	-

SBAS_L1_I_PRIMARY

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	131	-31.1	29454.0	35838301.7	44.9	214.8	48.9	6
2	135	-29.5	28389.9	36622656.7	44.4	234.5	38.0	6
3	138	-35.7	31305.0	35567928.7	45.9	198.5	53.2	6
4	133	-111.7	89853.9	35487570.7	41.6	180.5	54.5	6

SBAS_L1_I_ALT1

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	131	-31.5	27370.7	35838299.8	46.6	214.8	48.9	6
2	133	-111.6	90453.2	35487568.2	42.7	180.5	54.5	6
3	135	-30.8	28091.5	36622656.3	43.6	234.5	38.0	6
4	138	-35.3	31236.5	35567927.3	46.1	198.5	53.2	6

GALILEO_E1_BC_PRIMARY

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	2	-2264.4	22113.6	25977868.1	40.2	242.4	15.1	6
2	4	-2435.1	1768875.7	25699679.3	37.1	41.9	17.8	6
3	5	2353.4	-1915162.6	23316965.4	46.2	182.3	44.8	6
4	9	-210.3	-7189.5	20439326.8	45.4	83.9	61.4	6
5	11	-1353.5	983158.7	23786918.0	40.6	93.3	33.2	6
6	22	1823.6	-1451091.4	22941807.0	43.1	310.5	26.3	6
7	30u	-841.4	-0.0	0.0	33.8	292.7	10.8	3*
8	--	---------	-----------	-----------	----	-----	-----	-

GALILEO_E1_BC_ALT1

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	2u	-2263.0	-0.0	0.0	38.0	242.4	15.1	6
2	4	-2436.5	1768867.4	25699677.0	39.5	41.9	17.8	6
3	5	2353.3	-1915159.4	23316963.6	46.3	182.3	44.8	6
4	9	-209.9	-7190.1	20439324.3	47.6	83.9	61.4	6
5	11	-1354.9	983155.5	23786915.8	42.0	93.3	33.2	6
6	22u	1823.5	-0.0	0.0	42.9	310.5	26.3	6
7	30	-823.2	414142.6	24482483.6	35.3	292.7	10.8	6-
8	--	---------	-----------	-----------	----	-----	-----	-

Navigation Data

X: -741265.91 Y: -5462527.36 Z: 3197665.65 deltRx: -1305247.97
Xvel: -3.79 Yvel: -4.74 Zvel: -8.84 deltRxDot: 12.67
Hsigma: 0.14 Vsigma: 0.26 NISratio: 0.55


ublox M8T code-based solution
UT pprx code-based solution
UT pprx+ppengine CDGNSS solution
Legend
3D (clampToGround)
Feature 1
ROAD WORK AHEAD
UTILITY WORK AHEAD
Google Earth
© 2017 Google
N
6.79 ft

========== GRID: General Radionavigation Interfusion Device ==========

Receiver time: 0 weeks 1549.5 seconds Build ID: 3442

GPS time: 1965 weeks 245490.2 seconds

GPS_L1_CA_PRIMARY

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	2	-1508.0	5114.7	21386653.8	23.7	70.1	32.2	6*-
2	5	-2128.4	2710023.4	19592933.6	37.7	35.5	57.1	6-
3	12	-3501.8	5266210.1	22333835.3	43.5	193.2	21.1	6
4	20	760.0	-52583.6	19010570.6	45.8	258.3	69.2	6c
5	21	1654.5	-20464.9	23318629.9	30.3	289.0	16.5	6-
6	29	1542.1	-79927.5	19262956.9	48.1	328.8	62.9	6c
7	13	2087.7	-2931.5	21139720.6	30.3	124.6	34.9	6c-
8	15	3196.2	-14098.1	21443910.9	45.9	167.3	30.0	6c
9	25	-2461.3	72206.9	21325190.9	44.2	231.3	35.2	6c
10	--	---------	-----------	-----------	----	-----	-----	-
11	--	---------	-----------	-----------	----	-----	-----	-
12	--	---------	-----------	-----------	----	-----	-----	-

GPS_L1_CA_ALT1

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	2	-1499.3	2100.4	21386657.0	29.0	70.1	32.2	6c-
2	5	-2129.7	98338.8	19592932.1	34.9	35.5	57.1	6c-
3	12	-3501.4	169184.3	22333830.7	47.0	193.2	21.1	6c
4	13	2095.0	-7118.1	21139717.3	25.2	124.6	34.9	6*-
5	15	3194.9	-71481.5	21443942.6	45.5	167.3	30.0	6c
6	20	762.4	-1789628.1	19010573.5	44.4	258.3	69.2	6c
7	21	1658.3	-20443.4	23318623.3	28.7	289.0	16.5	6-
8	25u	-2469.5	-0.0	0.0	42.4	231.3	35.2	2*
9	29	1542.8	-79929.6	19262955.7	48.0	328.8	62.9	6c
10	--	---------	-----------	-----------	----	-----	-----	-
11	--	---------	-----------	-----------	----	-----	-----	-
12	--	---------	-----------	-----------	----	-----	-----	-

GPS_L2_CLM_PRIMARY

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	5	-1662.9	2084701.1	19592928.9	33.5	35.5	57.1	5-
2	12	-2727.2	300930.9	22333832.7	40.1	193.2	21.1	5
3	15	2491.2	-1022026.5	21443920.9	41.7	167.3	30.0	5
4	25	-1917.8	50535.7	21325187.2	44.0	231.3	35.2	5
5	29	1202.0	-63509.9	19262949.9	45.0	328.8	62.9	5
6	--	---------	-----------	-----------	----	-----	-----	-
7	--	---------	-----------	-----------	----	-----	-----	-

GPS_L2_CLM_ALT1

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	5	-1647.4	2084716.7	19592941.4	32.5	35.5	57.1	5-
2	12	-2728.7	319924.5	22333849.6	39.3	193.2	21.1	5
3	15	2490.8	-58254.0	21443945.9	39.6	167.3	30.0	5
4	25	-1919.3	52446.8	21325201.4	44.6	231.3	35.2	5
5	29	1202.3	-2243821.6	19262968.2	46.4	328.8	62.9	5
6	--	---------	-----------	-----------	----	-----	-----	-
7	--	---------	-----------	-----------	----	-----	-----	-

SBAS_L1_I_PRIMARY

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	131	-101.7	96240.4	35850985.0	47.6	214.7	48.9	6
2	135u	-102.5	-0.0	0.0	47.2	234.5	38.0	5*
3	138	-104.9	101022.9	35581241.8	46.4	198.5	53.2	6
4	133	-177.9	215809.6	35511549.0	43.0	180.4	54.3	6

SBAS_L1_I_ALT1

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	131	-102.3	9597.8	35850984.1	47.2	214.7	48.9	6
2	133	-176.4	216591.5	35511547.2	44.7	180.4	54.3	6
3	135u	-100.7	-0.0	0.0	46.3	234.5	38.0	5*
4	138	-104.3	103353.0	35581240.2	47.3	198.5	53.2	6

GALILEO_E1_BC_PRIMARY

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	2u	-2375.4	-0.0	0.0	32.5	238.7	12.0	6-
2	4u	-2617.3	-0.0	0.0	23.8	40.3	14.4	6-
3	5	2064.2	-3530759.0	23009528.7	47.8	182.6	49.9	6
4	9	-546.7	213965.5	20495571.9	22.0	73.9	60.4	6-
5	11u	-1519.9	-0.0	0.0	22.8	98.5	30.9	2*
6	22	1813.1	-20734.5	22682700.4	42.4	313.6	29.4	6
7	--	---------	-----------	-----------	----	-----	-----	-
8	--	---------	-----------	-----------	----	-----	-----	-

GALILEO_E1_BC_ALT1

CH	TXID	Doppler (Hz)	BCP (cycles)	PR (meters)	C/N0 (dB-Hz)	Az (deg)	El (deg)	Status
1	2u	-2381.0	-0.0	0.0	35.0	238.7	12.0	6-
2	4u	-2609.2	-0.0	0.0	27.1	40.3	14.4	6*-
3	5	2064.1	-1235002.0	23009527.0	47.3	182.6	49.9	6
4	9u	-520.8	-0.0	0.0	24.3	73.9	60.4	2*
5	11u	-1509.1	-0.0	0.0	21.9	98.5	30.9	2*
6	22u	1568.6	-0.0	0.0	25.3	313.6	29.4	2*
7	--	---------	-----------	-----------	----	-----	-----	-
8	--	---------	-----------	-----------	----	-----	-----	-

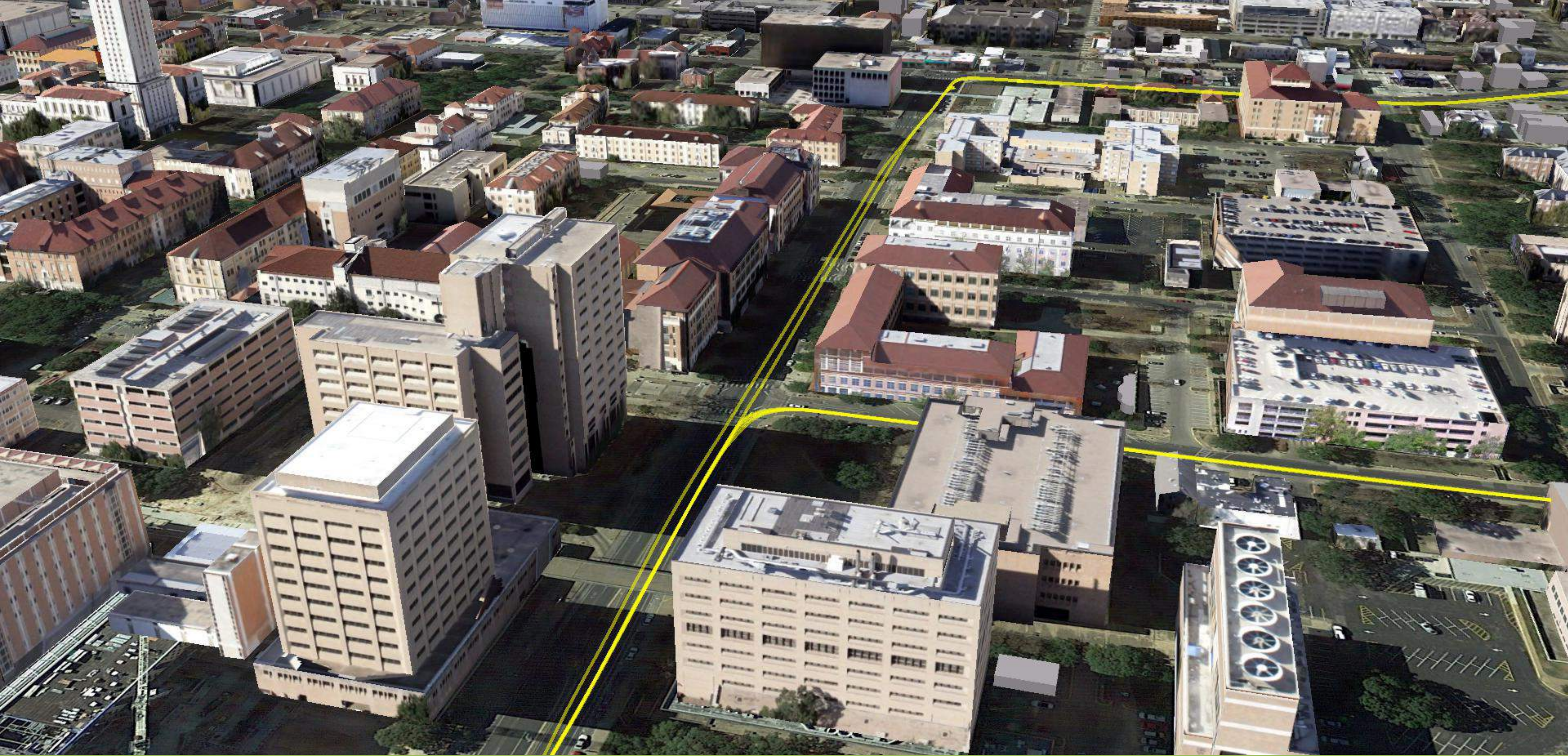
Navigation Data

X: -742773.32 Y: -5462185.82 Z: 3197876.79 deltRx: -1292173.77

Xvel: -0.52 Yvel: -1.67 Zvel: -2.89 deltRxDot: 21.28

Hsigma: 0.23 Vsigma: 0.42 NISratio: 1.02

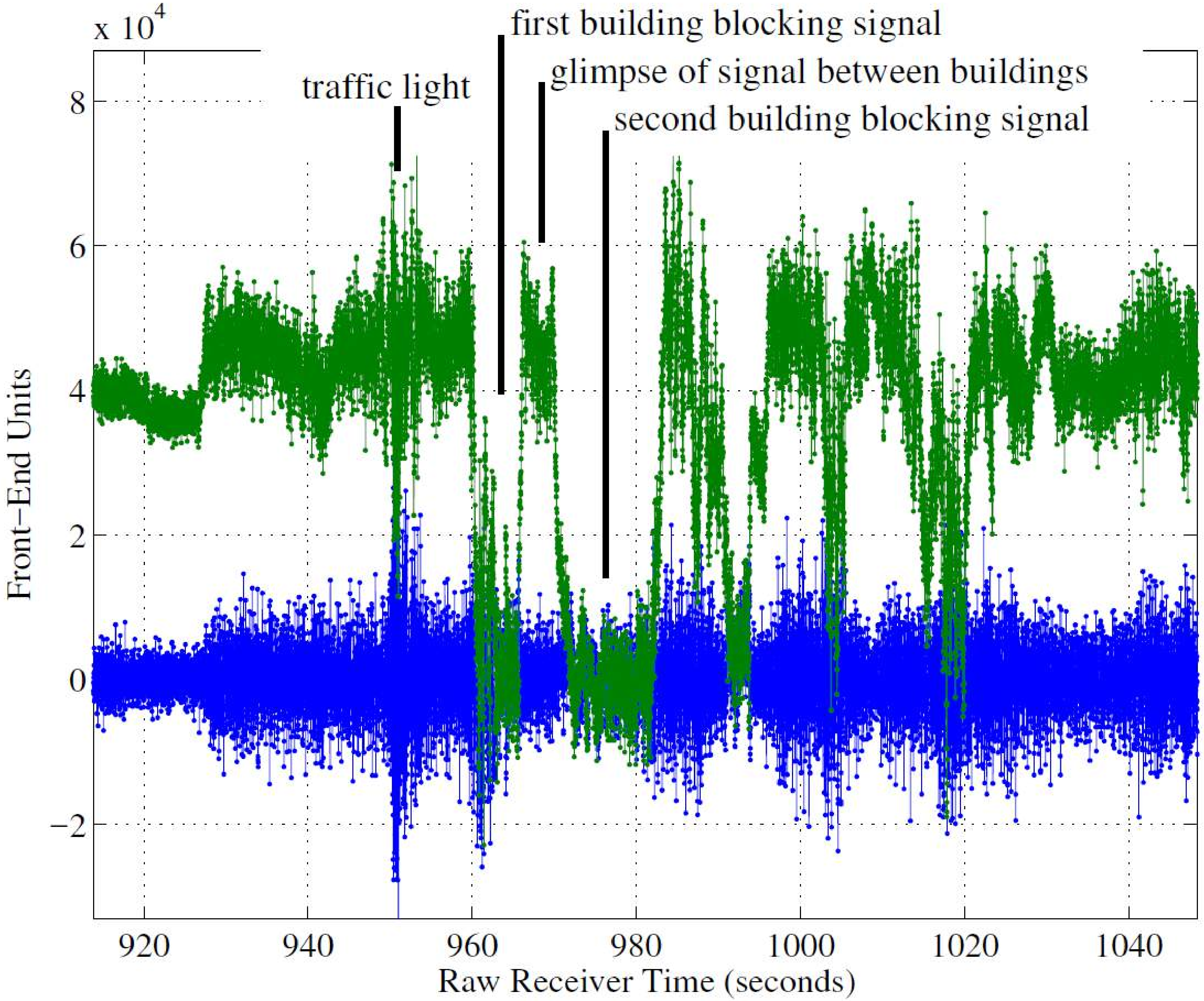
January 2018 test of single-antenna stand-alone precise GNSS in moderate urban environment without aiding, inertial or otherwise



Dean Keaton corridor:
Two bridges, overhanging trees, tall buildings on both sides of street

Dean Keaton corridor:
Two bridges, overhanging trees, tall buildings on both sides of street

Carrier tracking must be fast and opportunistic but avoid frequency unlock



Promising results:

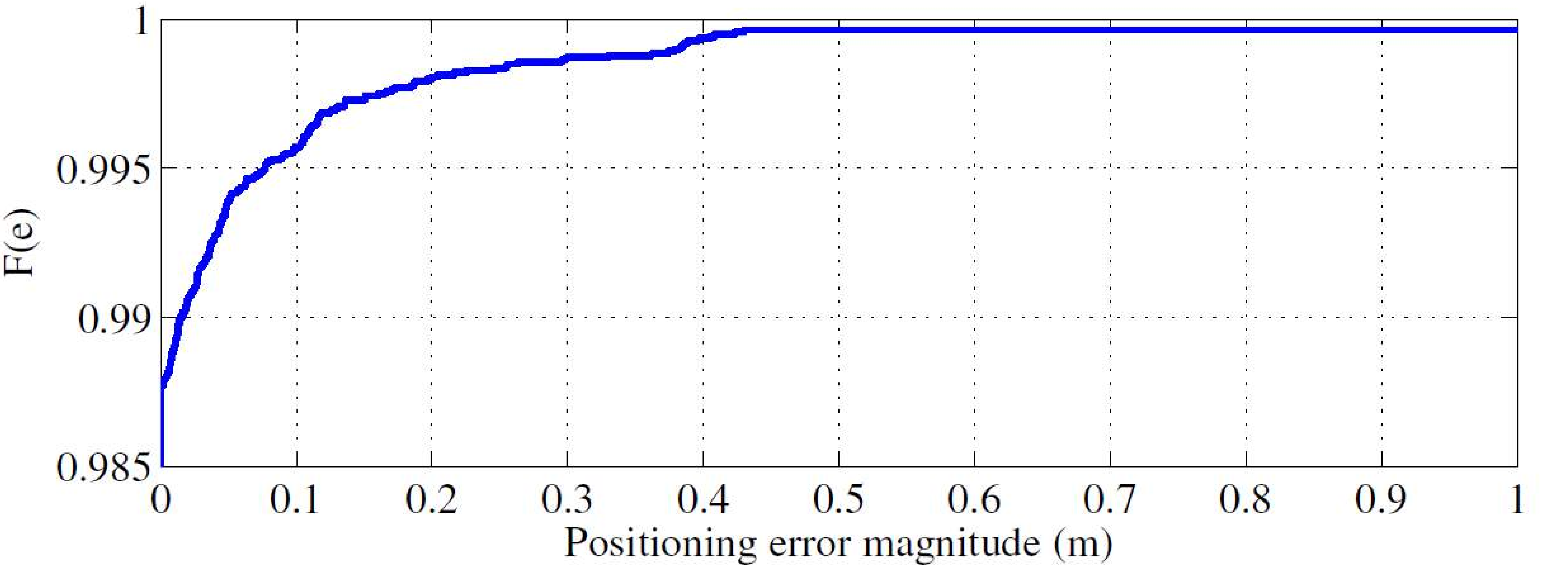
90% availability of validated solutions in 1 hour of driving

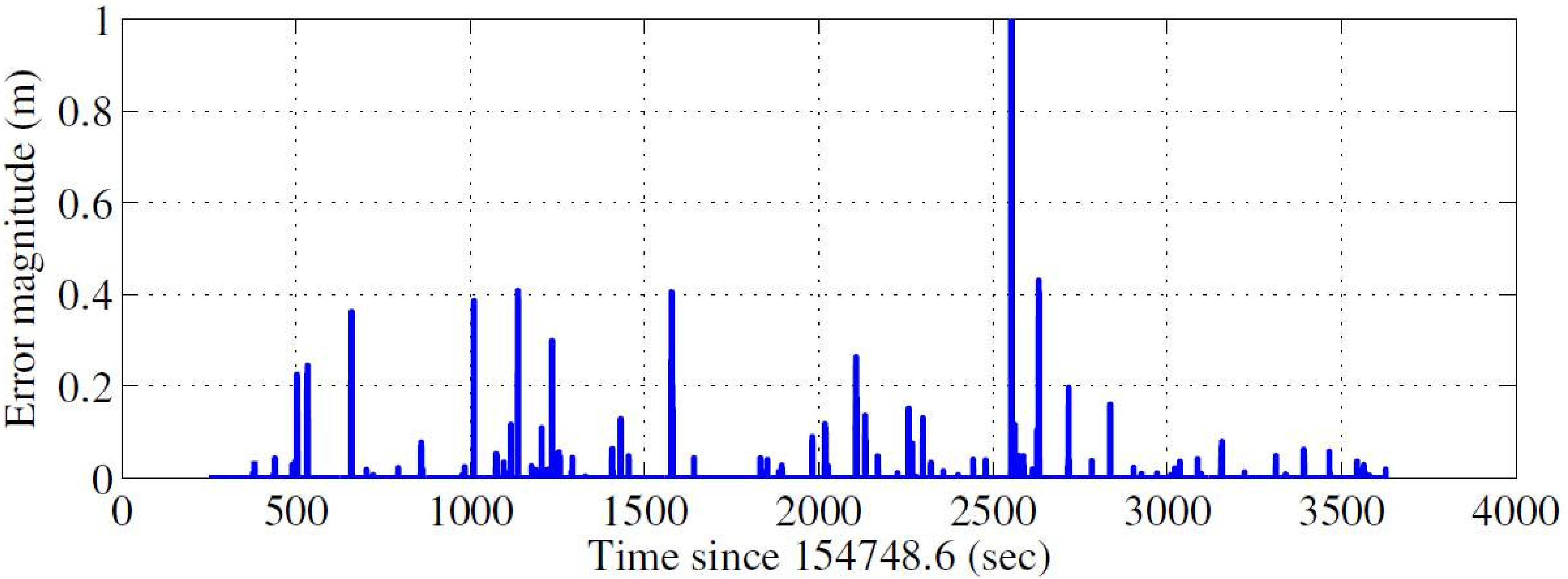
Validated solutions accurate to 10 cm for >99.5% of testable epochs

Still not good enough:

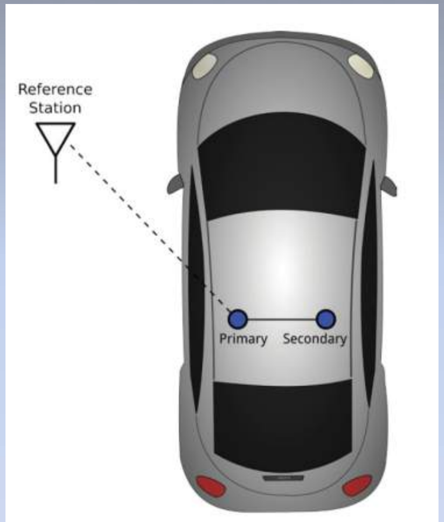
Need 100% avail.

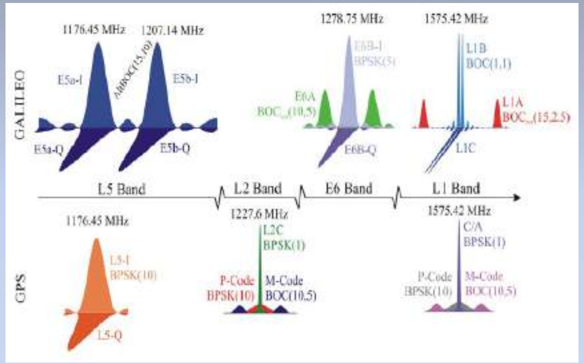
Even 0.2% errors greater than 30 cm is unacceptable

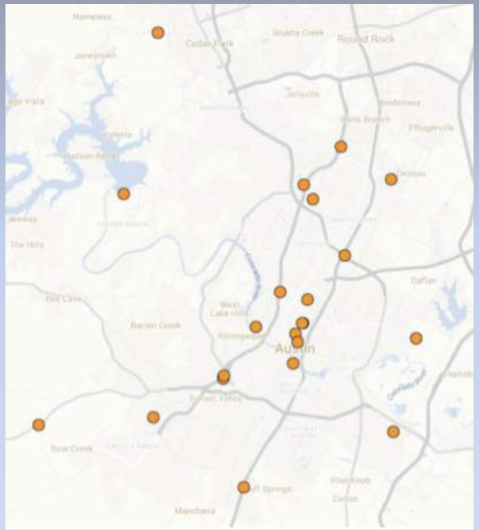




Keys to Robust CDGNSS Positioning







Multiple Rover Antennas

Multiple Frequencies

Dense Reference Network

Fusion with Vision/Radar

Goal: Decimeter-accurate visual and radar features

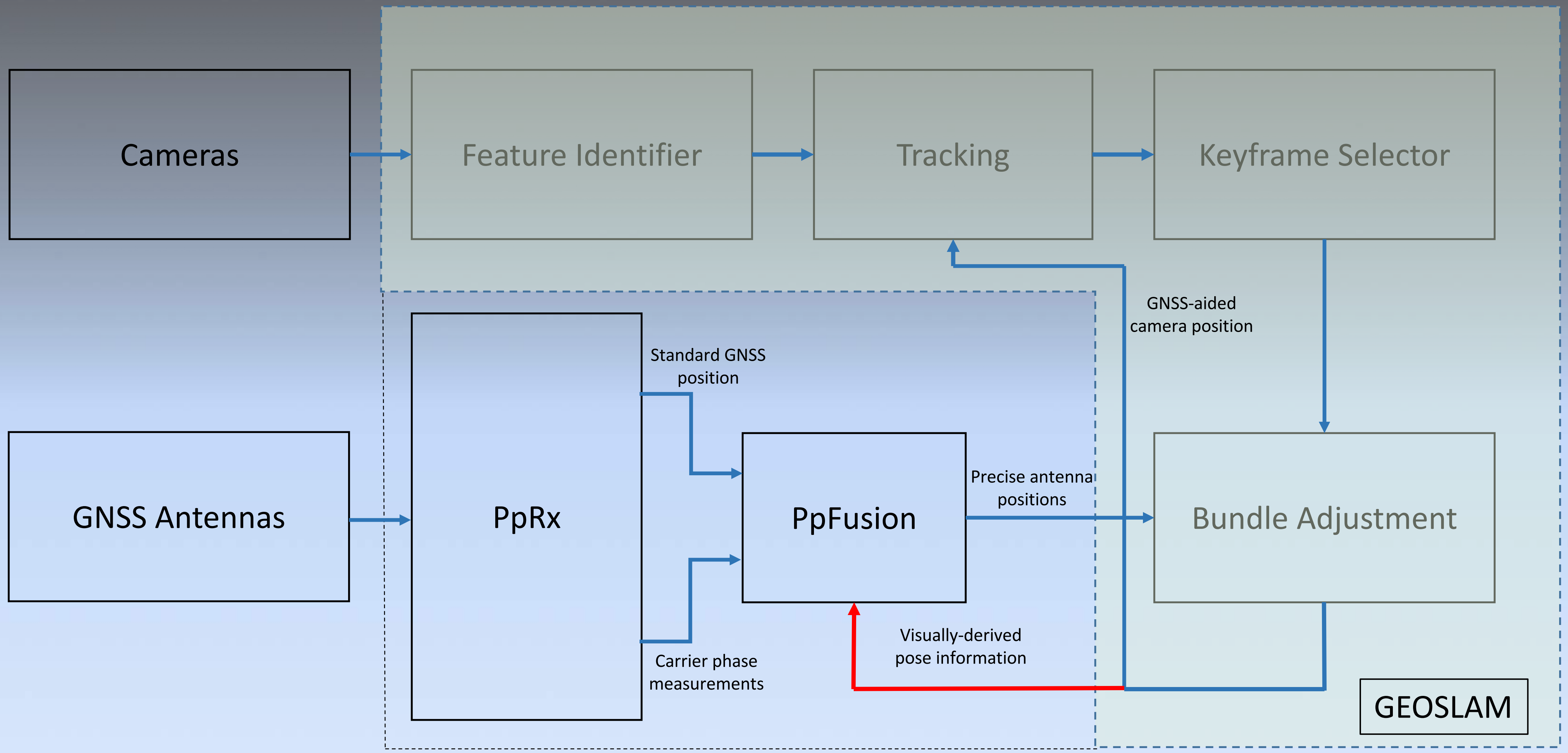
GNSS-INS provides initial pose and global reference

Merges globally-referenced maps from multiple sessions

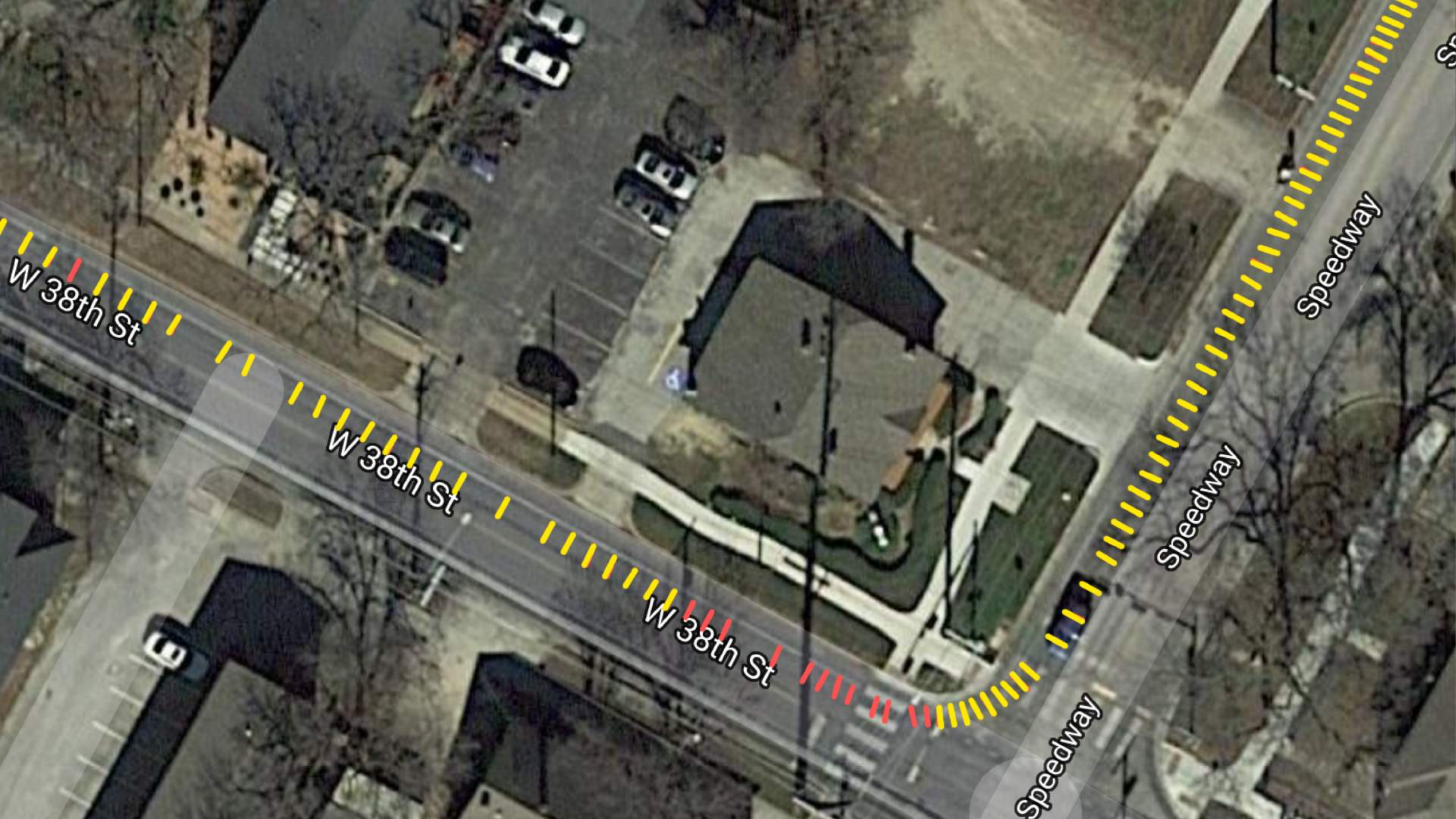
Cooperative fleet refinement of map

GEOSLAM: Global Electro-Optical SLAM

Cooperative mapping at decimeter accuracy for all-weather localization



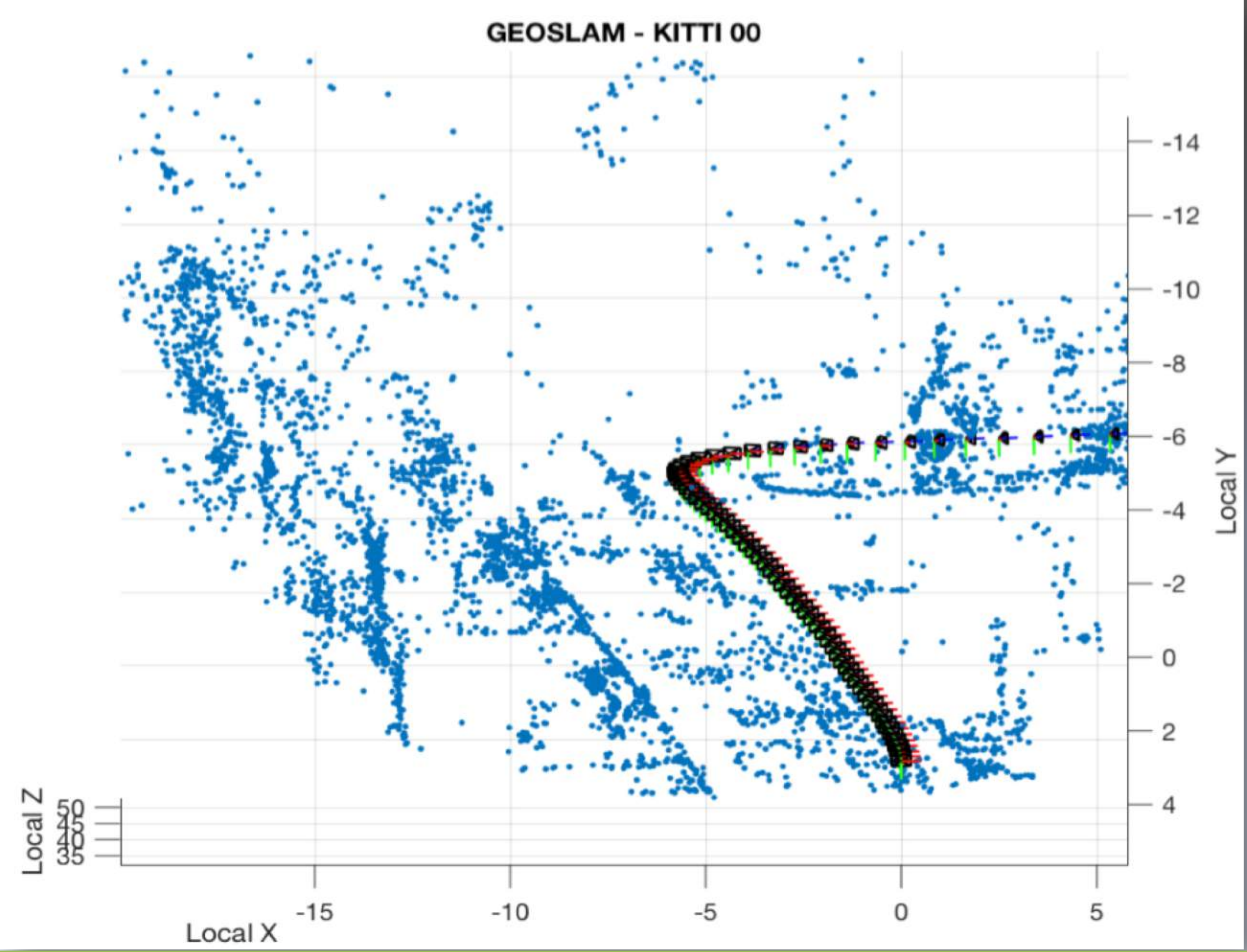
Tightly-coupled CDGNSS-Vision system


W 38th St
W 38th St
W 38th St
Speedway
Speedway
Speedway


W 38th St
W 38th St
W 38th St

Keys to collaborative all-weather sensing:

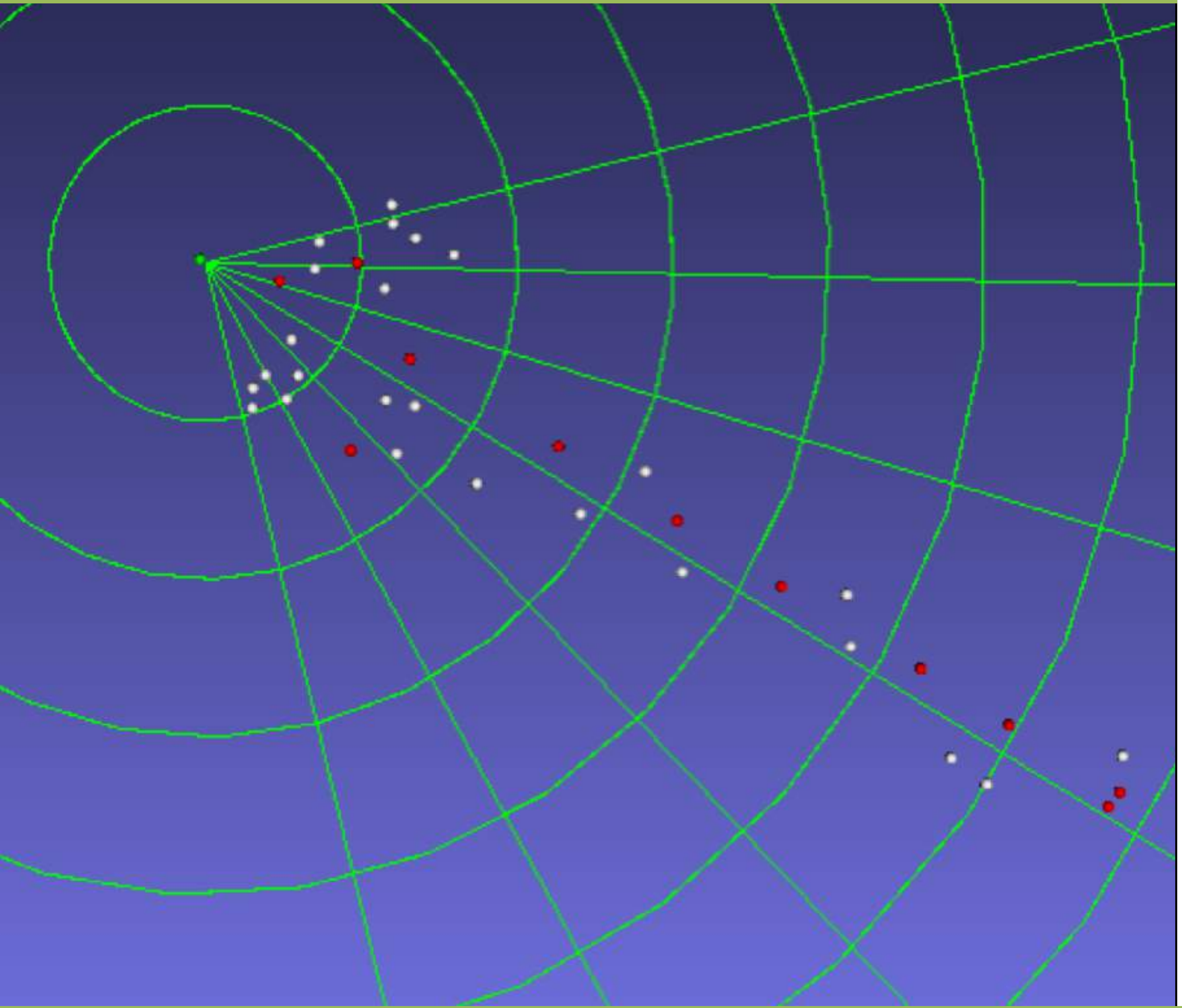
- Common reference frame (not just within *your* map)
- Sub-30-cm positioning within common frame
- <u>Decimeter-accurate mapping capability</u>
- Map-merging
- Quick-response and lifetime map maintenance
- Means of *quantifying* the benefit of collaboration

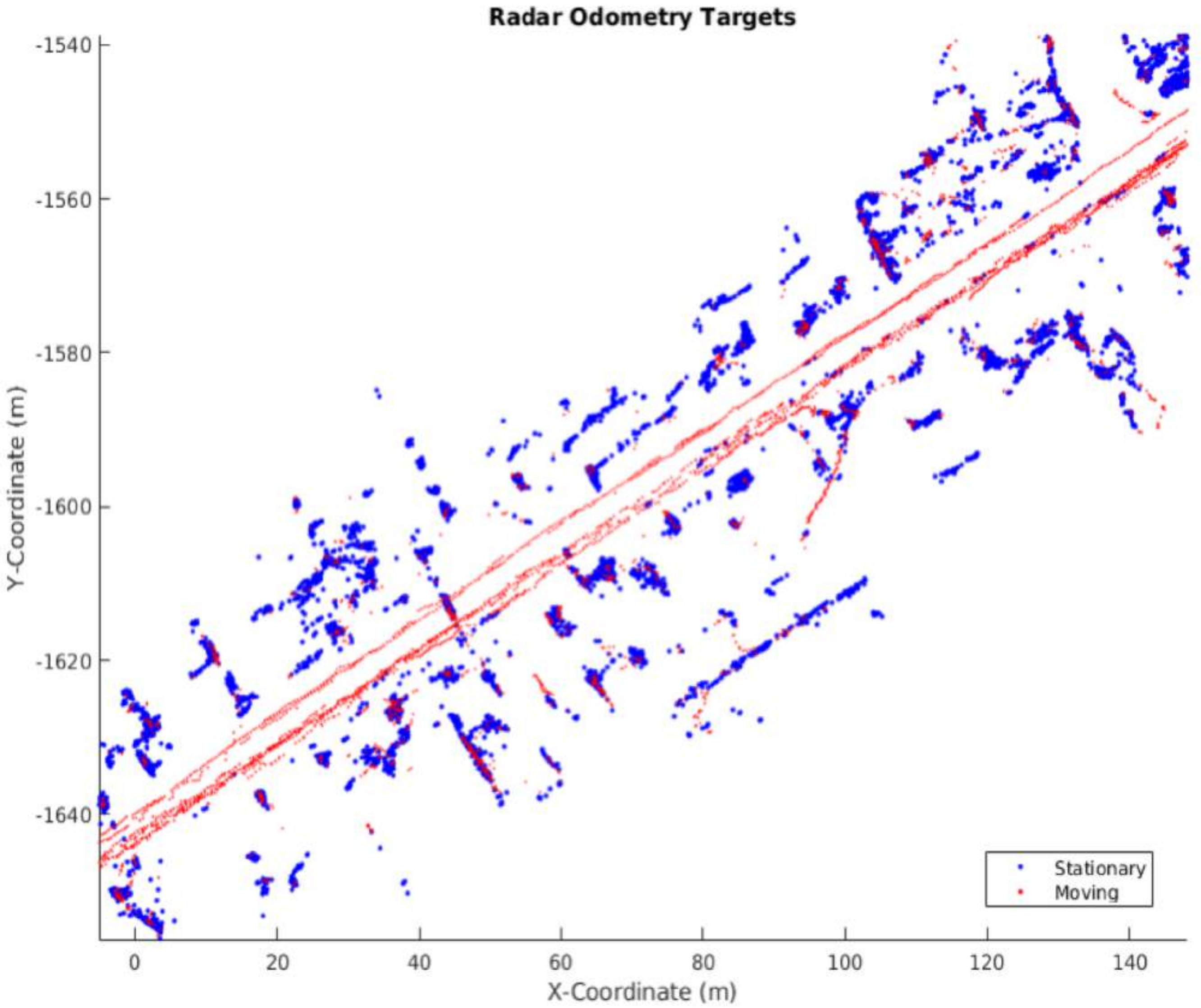


3D Map from GEOSLAM test on KITTI data set

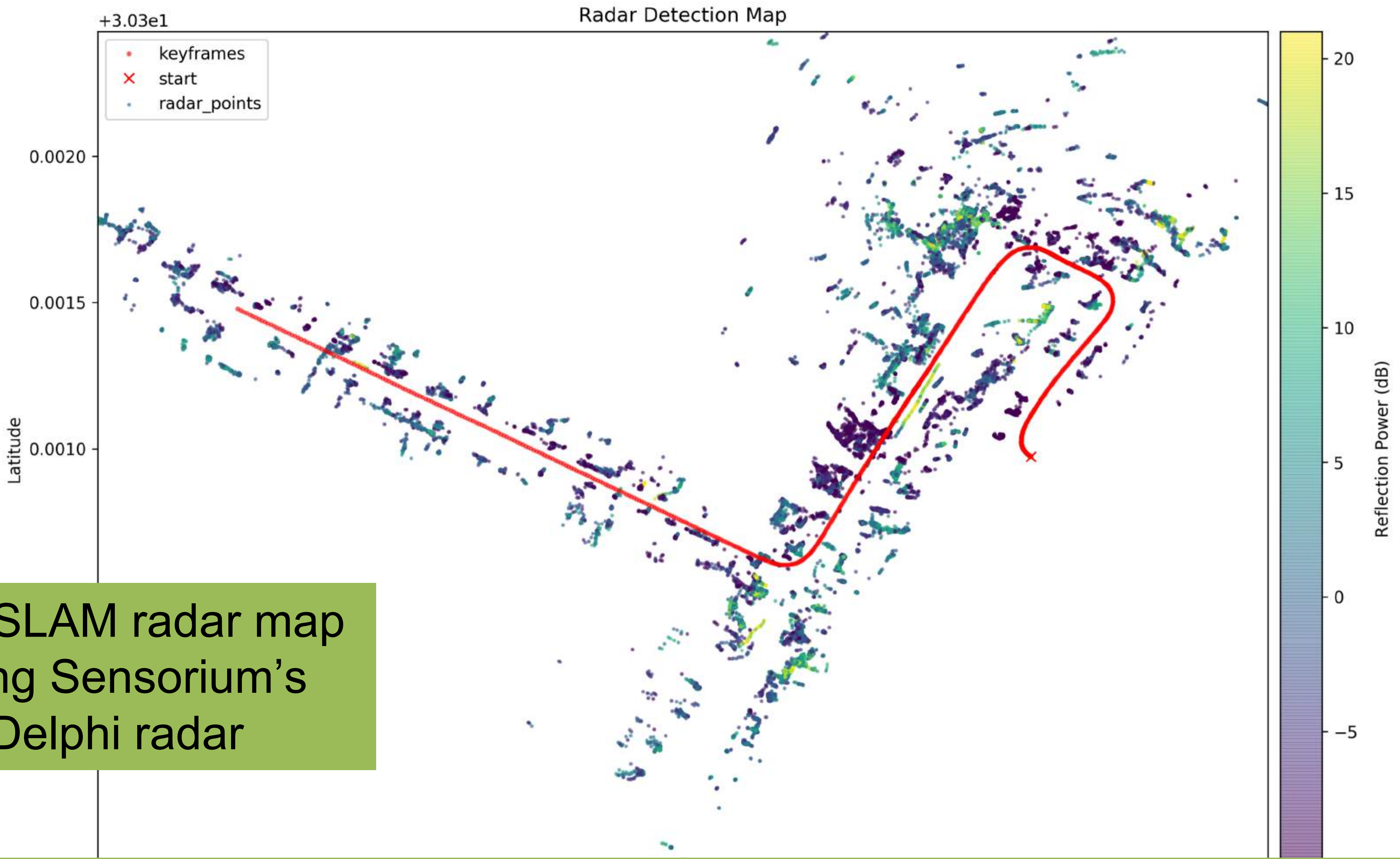
Map of 3D camera image features is a means to an end: it can’t be relied on when visibility poor, but when visibility good, it can be used (jointly with GNSS) to obtain highly accurate vehicle pose _with which a radar map can be built**_**

Sensorium radar data: Delphi unit





A radar map is useful in all weather conditions.
Our conjecture: In urban areas rich with radar reflectors, a radar map together with GNSS will be sufficient for 30 cm @ 95% accuracy



GEOSLAM radar map using Sensorium's Delphi radar

Goal: 30-cm all-environment positioning

Keys to collaborative all-weather sensing:

- Common reference frame (not just within *your* map)
- Sub-30-cm positioning within common frame
- Decimeter-accurate mapping capability
- <u>Map-merging</u>
- Quick-response and lifetime map maintenance
- Means of *quantifying* the benefit of collaboration

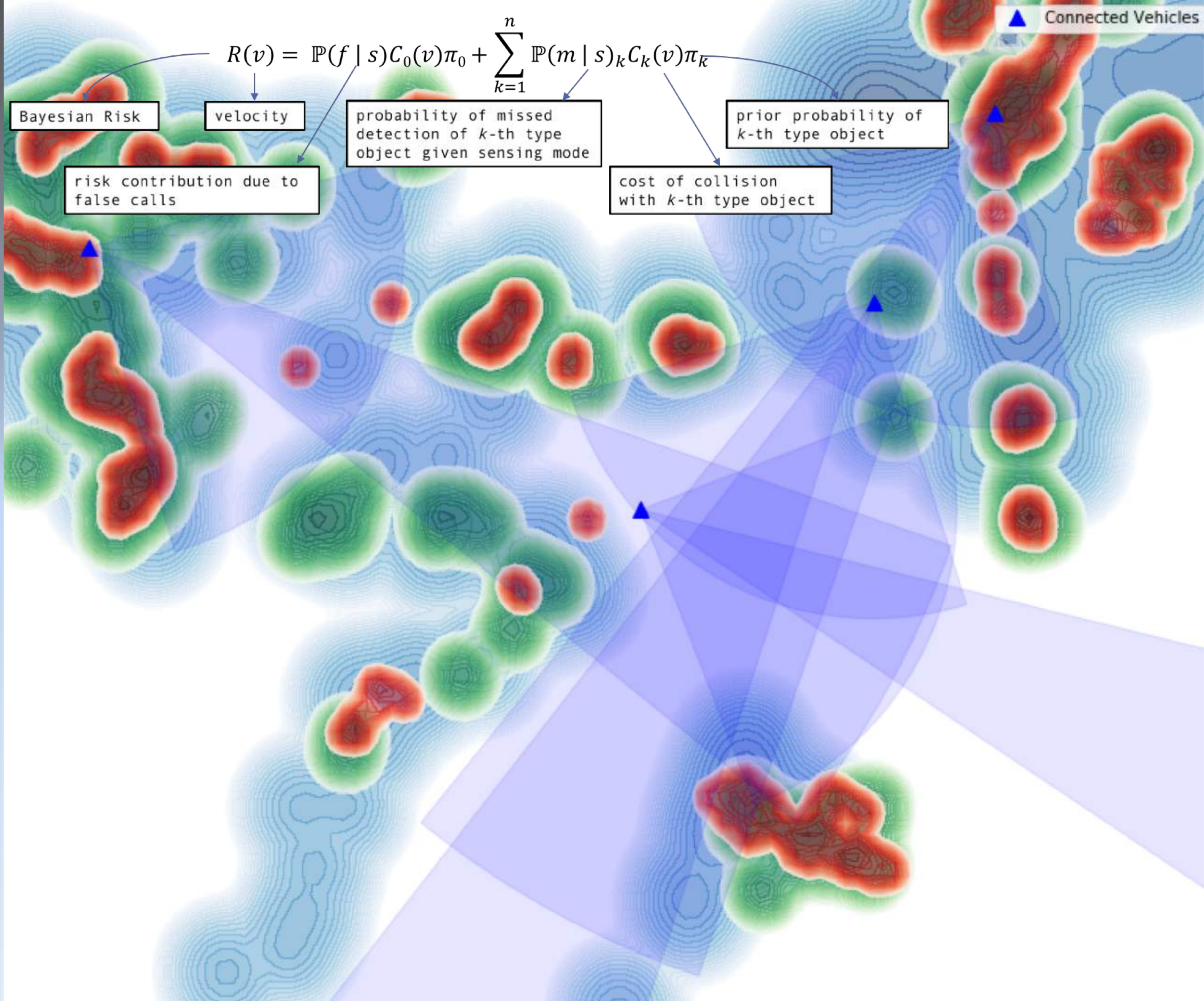
Keys to collaborative all-weather sensing:

- Common reference frame (not just within *your* map)
- Sub-30-cm positioning within common frame
- Decimeter-accurate mapping capability
- Map-merging
- <u>Quick-response and lifetime map maintenance</u>
- Means of *quantifying* the benefit of collaboration

Keys to collaborative all-weather sensing:

- Common reference frame (not just within *your* map)
- Sub-30-cm positioning within common frame
- Decimeter-accurate mapping capability
- Map-merging
- Quick-response and lifetime map maintenance
- Means of *quantifying* the benefit of collaboration

We take a Bayesian approach to risk evaluation



Occupancy distributions for pedestrians, cyclists, and vehicles indicate risk of hazardous interactions. As multiple vehicles share sensor data, the risk is reduced

Resulting 3D model has mm-level resolution and sub-cm absolute accuracy
Research goal: Multi-UAV fully-automated collaborative high-resolution mapping

UT SAVES


DE L'OUEST