THE UNIVERSITY OF TEXAS AT AUSTIN
RADIONAVIGATION LABORATORY

Robust and Secure Perception for Automated Vehicles

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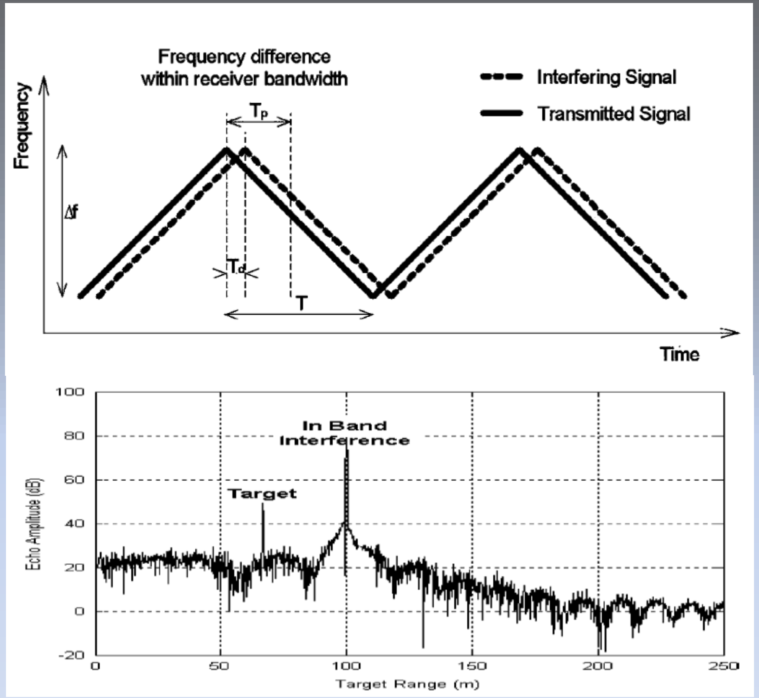
Grand challenge:

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 recent Tesla update to Autopilot 8.0, 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

Some form of precise GNSS will be required for poor-weather lane keeping in areas with few pre-mapped radar reflectors

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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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
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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**

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

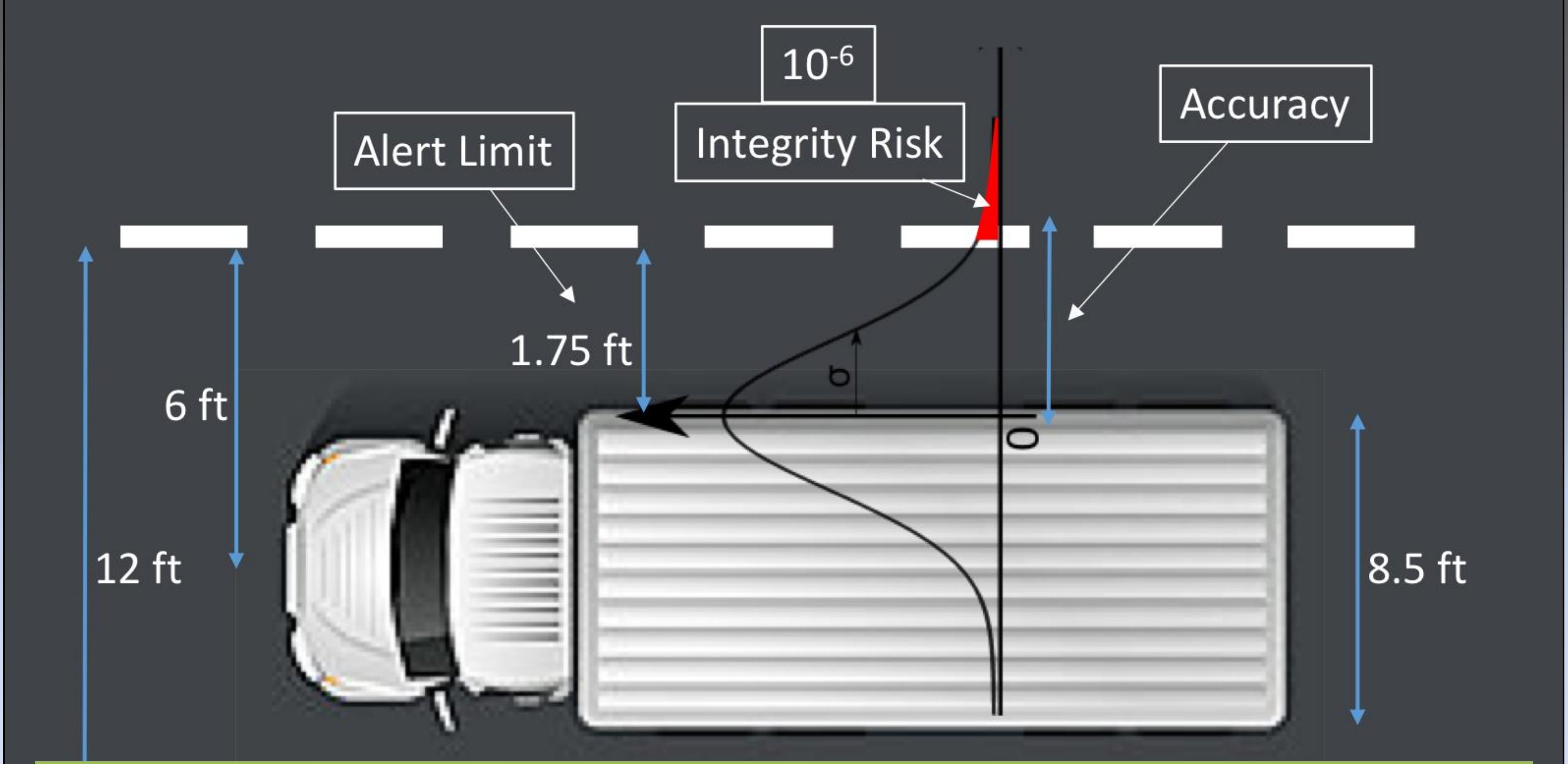
Current Affiliates:

Toyota, Honda, Qualcomm, AT&T, National Instruments, Fujitsu, Huawei

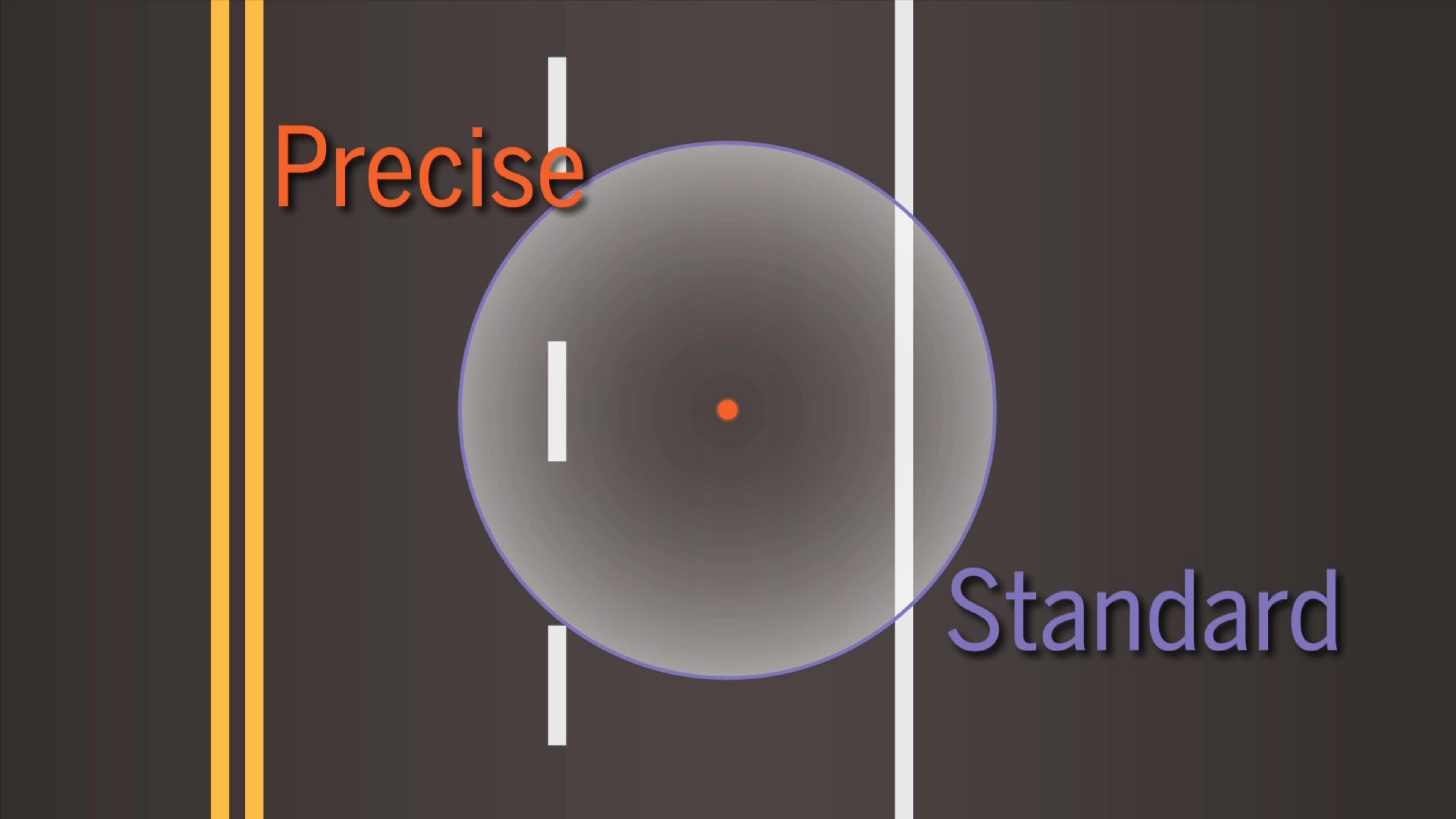
Q: What vehicle positioning techniques will suffice for urban areas?

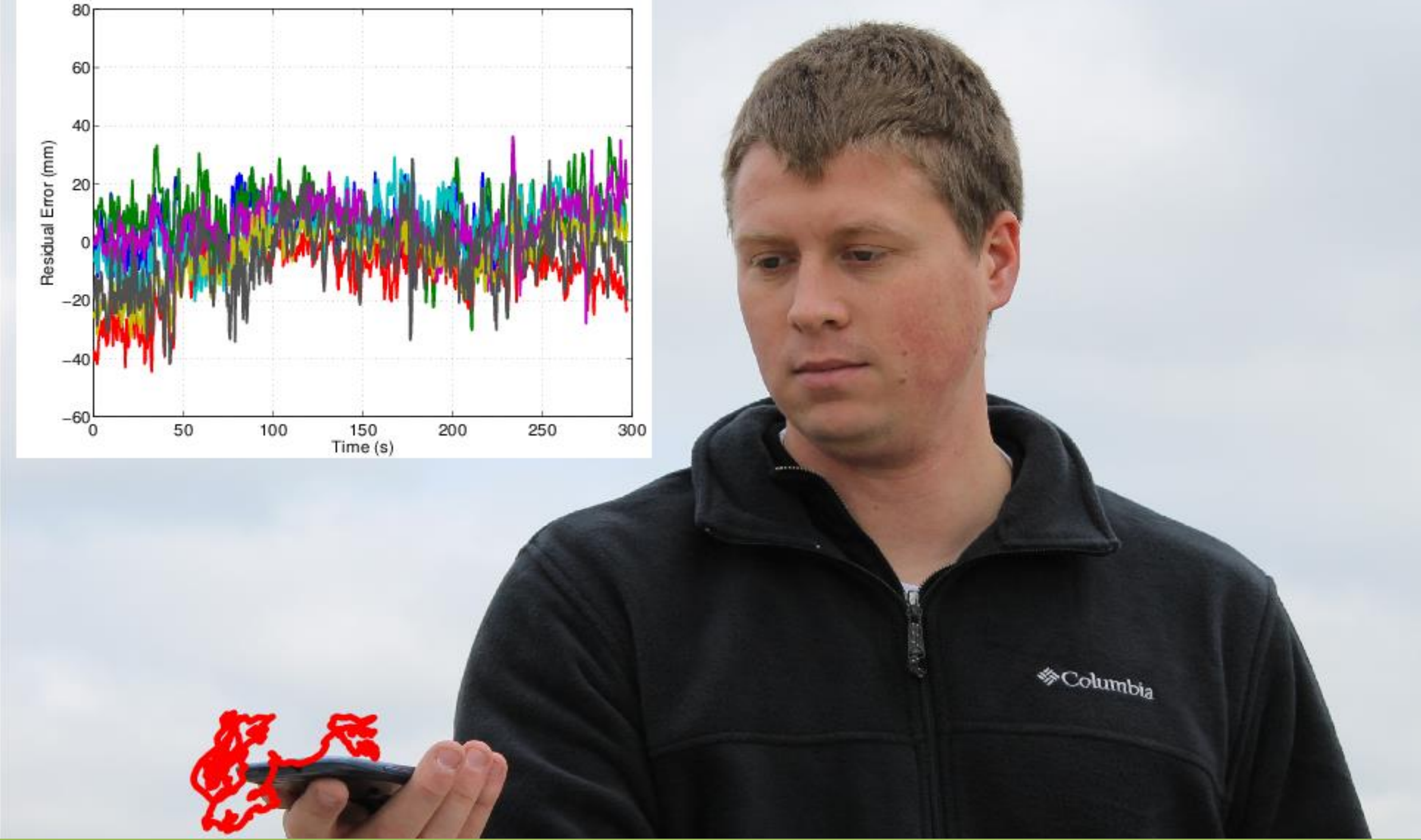
Light urban setting

Urban setting



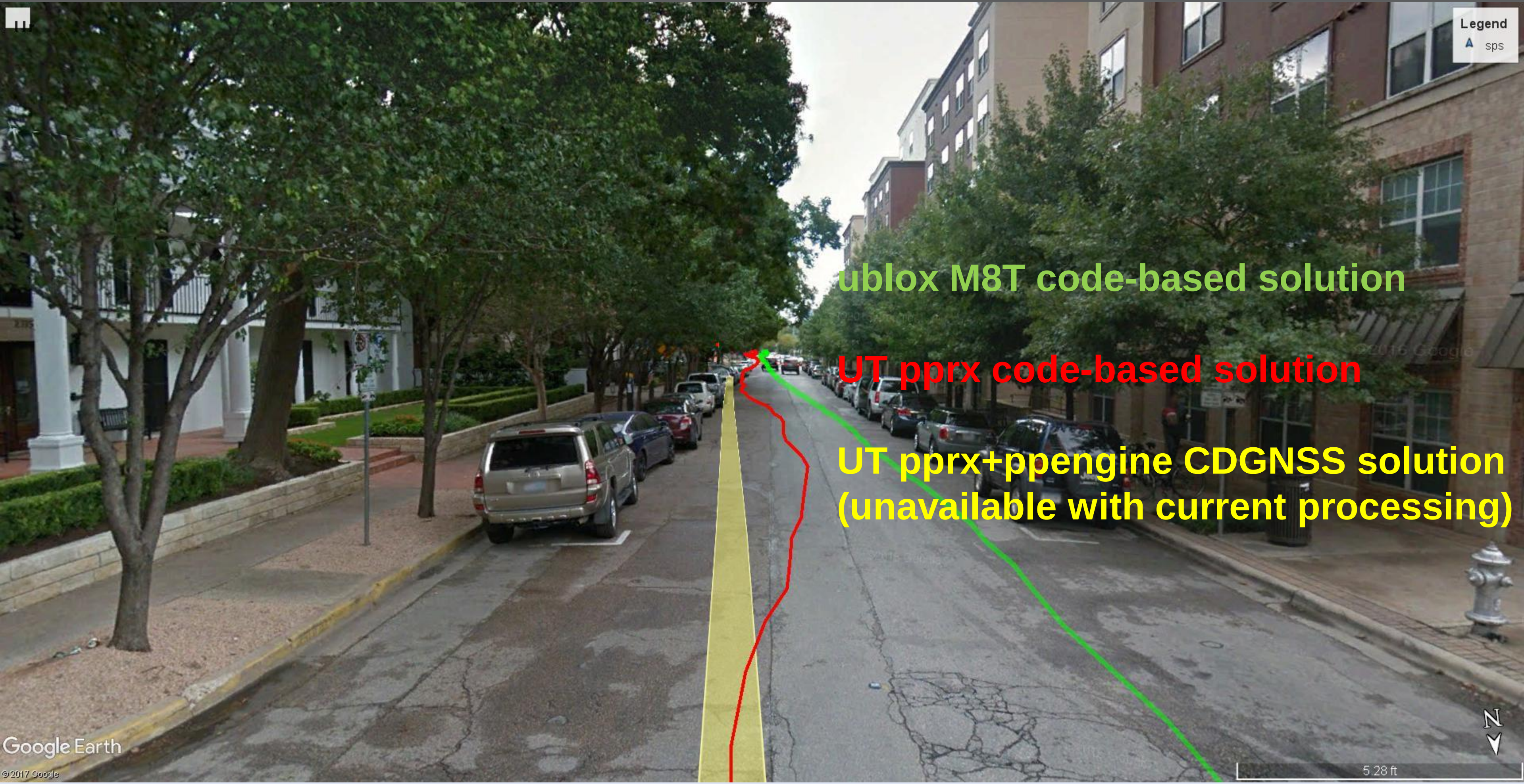
<u>Goal</u>: Lateral position accuracy better than 30cm @ 95%, under *all outdoor conditions*. Satisfies integrity risk less than 10^{-6} for 12-ft lane width (highway)


Precise
Standard

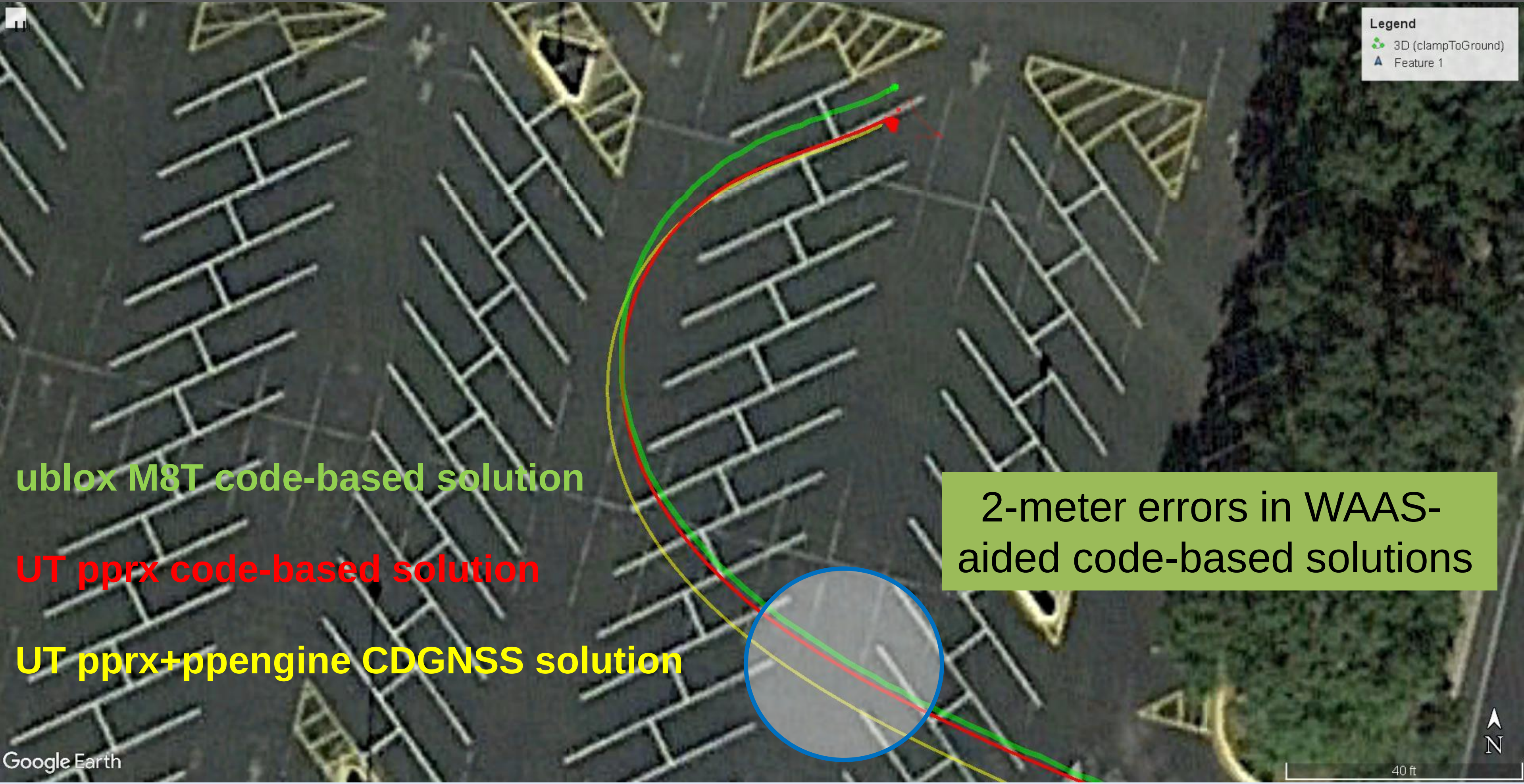


Dec. 2014: First successful RTK solution with a smartphone antenna. But this was a rooftop test. What about down on the streets?

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


Legend
sps
ublox M8T code-based solution
UT pprx code-based solution
UT pprx+ppengine CDGNSS solution
(unavailable with current processing)
Google Earth
© 2017 Google
5.28 ft
N

Q: How far can we push CDGNSS in urban areas?


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

```
==========   GRID: General Radionavigation Interfusion Device   ===============================================================================
 Receiver time:    0 weeks    600.9 seconds        Build ID:        3442
 GPS time:      1965 weeks 244541.6 seconds
---------------------------------------------------------------------------------------------------------------------------------------------
CH  TXID    Doppler        BCP            PR       C/N0    Az      El   Status      CH  TXID    Doppler        BCP            PR       C/N0    Az      El   Status
             (Hz)       (cycles)      (meters)  (dB-Hz)  (deg)  (deg)                            (Hz)       (cycles)      (meters)  (dB-Hz)  (deg)  (deg)
---------------------------- GPS_L1_CA_PRIMARY ----------------------------      ---------------------------- GPS_L1_CA_ALT1 ------------------------------
 1    2     -1343.8       782989.6   21128343.1  42.5    63.0    36.0    6c         1    2     -1343.7       750416.7   21128341.2  42.1    63.0    36.0    6c
 2    5     -1661.7       902836.6   19249040.5  48.3    36.0    64.5    6c         2    5     -1661.5       868181.1   19249037.8  47.8    36.0    64.5    6c
 3   12     -3373.4      1987585.1   21709900.9  43.0   196.3    27.7    6c         3   12     -3373.0      1904292.2   21709899.1  47.1   196.3    27.7    6c
 4   20      1279.8      -865862.0   19194139.2  46.0   243.2    63.8    6c         4   13      2460.6     -1467508.2   21549241.3  40.6   131.4    29.8    6c
 5   25     -2022.9      1118935.8   20918316.9  44.9   238.8    40.3    6c         5   15      3374.5     -1960402.4   22036083.3  44.3   170.5    23.4    6c
 6   29      1979.6     -1258804.9   19582115.1  47.9   328.4    55.5    6c         6   20      1279.5      -824962.7   19194137.8  46.7   243.2    63.8    6c
 7   13      2460.6     -1467509.0   21549244.8  43.1   131.4    29.8    6c         7   21      1706.3      -991877.4   23621778.4  38.0   283.5    12.7    6c
 8   15      3374.3     -1960403.0   22036087.3  44.7   170.5    23.4    6c         8   25     -2022.4      1075087.8   20918315.1  44.2   238.8    40.3    6c
 9   21      1705.6      -991877.2   23621779.0  40.1   283.5    12.7    6c         9   29      1979.6     -1202363.9   19582114.2  47.6   328.4    55.5    6c
10   --   ---------  ------------  -----------  ----   -----   -----    -         10   --   ---------  ------------  -----------  ----   -----   -----    -
11   --   ---------  ------------  -----------  ----   -----   -----    -         11   --   ---------  ------------  -----------  ----   -----   -----    -
12   --   ---------  ------------  -----------  ----   -----   -----    -         12   --   ---------  ------------  -----------  ----   -----   -----    -
---------------------------- GPS_L2_CLM_PRIMARY ---------------------------      ---------------------------- GPS_L2_CLM_ALT1 -----------------------------
 1    5     -1294.3       676504.0   19249033.4  45.8    36.0    64.5    5          1    5     -1294.9       676504.9   19249046.9  47.0    36.0    64.5    5
 2   12     -2628.8      1483861.6   21709895.5  42.3   196.3    27.7    5          2   12     -2628.7      1483862.2   21709908.7  40.8   196.3    27.7    5
 3   15      2628.9     -1527582.2   22036083.3  41.6   170.5    23.4    5          3   15      2629.6     -1527582.8   22036097.8  39.3   170.5    23.4    5
 4   25     -1575.8       837730.5   20918313.7  44.1   238.8    40.3    5          4   25     -1575.8       837730.2   20918327.4  43.4   238.8    40.3    5
 5   29      1542.8      -936906.6   19582109.2  43.9   328.4    55.5    5          5   29      1542.8      -936906.8   19582123.4  45.1   328.4    55.5    5
 6   --   ---------  ------------  -----------  ----   -----   -----    -          6   --   ---------  ------------  -----------  ----   -----   -----    -
 7   --   ---------  ------------  -----------  ----   -----   -----    -          7   --   ---------  ------------  -----------  ----   -----   -----    -
---------------------------- SBAS_L1_I_PRIMARY ----------------------------      ---------------------------- SBAS_L1_I_ALT1 ------------------------------
 1  131       -48.3        18694.0   35836255.6  46.3   214.8    48.9    6          1  131       -48.2        16607.2   35836250.2  44.9   214.8    48.9    6
 2  135       -47.1        17814.2   36620656.2  45.3   234.5    38.0    6          2  133      -123.7        63883.1   35482512.3  43.0   180.5    54.5    6
 3  138       -51.2        20063.8   35565790.0  47.0   198.5    53.2    6          3  135       -47.2        17609.8   36620658.0  46.4   234.5    38.0    6
 4  133      -123.7        63286.4   35482515.8  43.6   180.5    54.5    6          4  138       -50.4        19992.2   35565787.8  47.0   198.5    53.2    6
---------------------------- GALILEO_E1_BC_PRIMARY ------------------------      ---------------------------- GALILEO_E1_BC_ALT1 --------------------------
 1    2     -2263.8      1273668.6   25887705.4  43.5   243.4    16.0    6          1    2     -2263.8      1273668.1   25887704.4  41.5   243.4    16.0    6
 2    4     -2315.7      1278521.1   25606366.3  41.1    42.4    18.7    6          2    4     -2315.5      1278520.5   25606366.9  38.1    42.4    18.7    6
 3    5      2388.4     -1424573.5   23410321.5  47.1   182.2    43.4    6          3    5      2388.3     -1424573.5   23410318.5  45.6   182.2    43.4    6
 4    9       -85.4       -36855.5   20433681.7  46.6    86.8    61.4    6          4    9       -85.2       -36854.7   20433679.1  46.3    86.8    61.4    6
 5   11     -1293.4       709001.1   23734748.1  35.7    91.9    33.8    6          5   11     -1292.7       709000.6   23734746.2  42.7    91.9    33.8    6
 6   22      1853.0     -1067434.6   23014817.2  43.5   309.6    25.5    6          6   22      1853.0     -1067434.7   23014815.7  43.6   309.6    25.5    6
 7   30      -720.2       259884.0   24451915.2  38.2   293.9    11.1    6          7   30      -721.1       253501.6   24451916.3  31.3   293.9    11.1    6
 8   --   ---------  ------------  -----------  ----   -----   -----    -          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
=============================================================================================================================================
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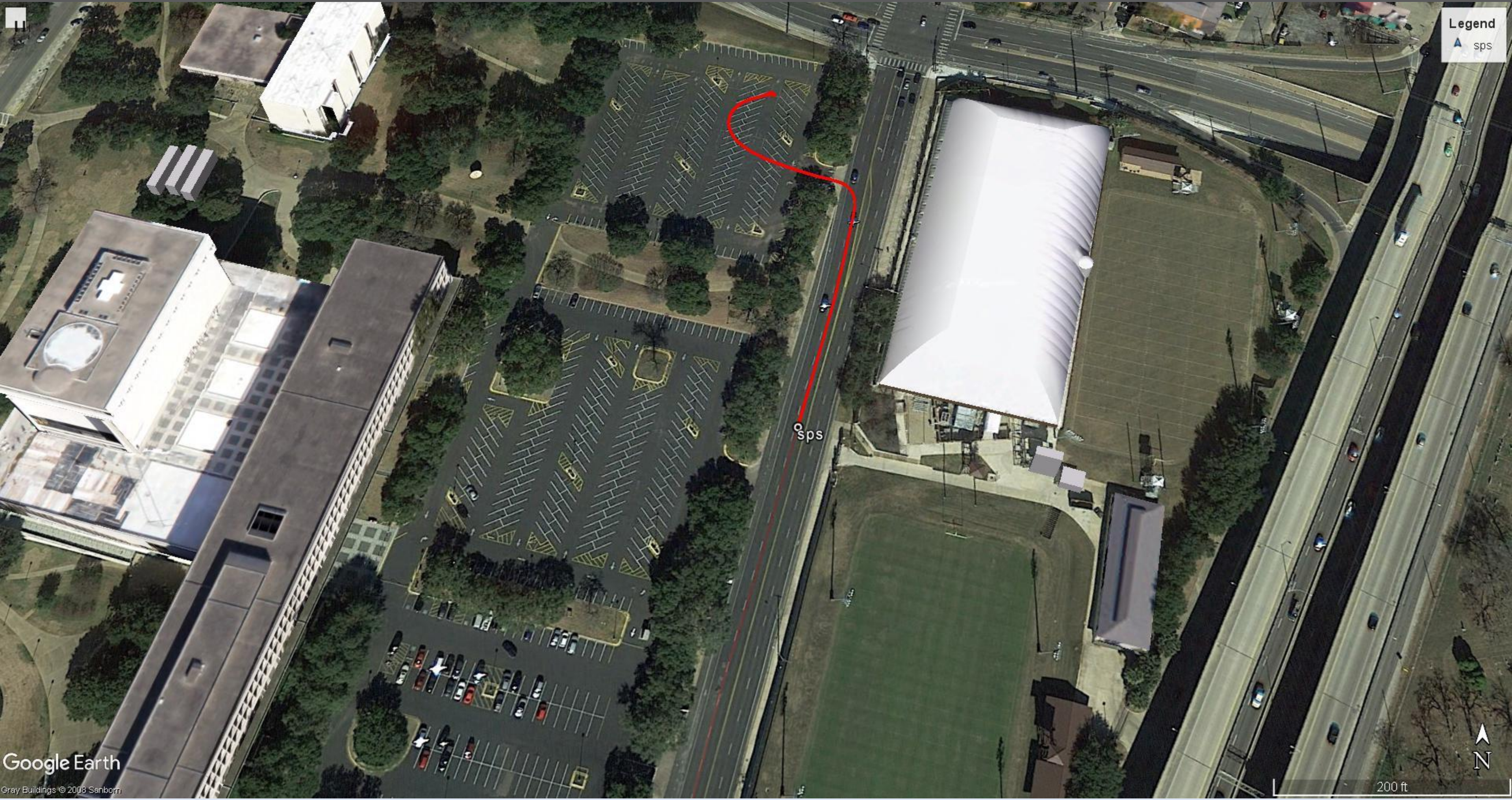
Legend
sps
sps
Google Earth
Gray Buildings © 2008 Sanborn
200 ft
N

========== 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

==========


Legend
sps
sps
Google Earth
100 ft
N

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==========   GRID: General Radionavigation Interfusion Device   ==============================================================
 Receiver time:    0 weeks   1417.3 seconds        Build ID:        3442
 GPS time:      1965 weeks 245358.0 seconds
------------------------------------------------------------------------------------------------------------------------------
CH  TXID    Doppler        BCP             PR       C/N0    Az      El    Status      CH  TXID    Doppler        BCP             PR       C/N0    Az      El    Status
             (Hz)       (cycles)       (meters)  (dB-Hz)  (deg)   (deg)                            (Hz)       (cycles)       (meters)  (dB-Hz)  (deg)   (deg)
---------------------------- GPS_L1_CA_PRIMARY ---------------------------        ---------------------------- GPS_L1_CA_ALT1 ----------------------------
 1    2     -1502.5         1796.9   21349029.9  34.9    69.1    32.7    6c-       1    2u    -1500.6           -0.0          0.0  32.8    69.1    32.7    5*-
 2    5     -2088.7      2432327.5   19540086.3  46.4    35.4    58.1    6         2    5     -2089.1      2397651.0   19540084.2  47.5    35.4    58.1    6c
 3   12     -3481.7      4804069.0   22245894.1  38.0   193.7    22.1    6-        3   12     -3460.2      4720823.9   22245893.5  39.2   193.7    22.1    6c-
 4   20       831.9     -1725295.4   19030594.6  45.2   255.8    68.5    6c        4   13      2157.8      -158734.5   21192915.1  39.4   125.6    34.2    6c-
 5   21      1638.5       -28325.3   23360131.6  31.7   288.2    16.0    6         5   15      3252.0      -211434.0   21524687.4  44.1   167.8    29.1    6c
 6   29      1590.0     -2727910.6   19302554.1  48.2   328.8    61.9    6c        6   20       830.3     -1684393.8   19030593.7  45.3   255.8    68.5    6c
 7   13      2154.0      -199744.1   21192915.7  42.6   125.6    34.2    6c-       7   21      1637.2        -1969.9   23360112.6  35.0   288.2    16.0    6-
 8   15      3251.9      -984558.6   21524689.7  44.5   167.8    29.1    6c        8   25     -2394.4        80956.3   21263970.7  39.4   232.3    36.0    6-
 9   25     -2394.9        43766.9   21263961.3  39.1   232.3    36.0    6c-       9   29      1589.2     -2671474.4   19302552.7  47.0   328.8    61.9    6c
10   --   ---------  -------------  -----------  ----   -----   -----    -        10   --   ---------  -------------  -----------  ----   -----   -----    -
11   --   ---------  -------------  -----------  ----   -----   -----    -        11   --   ---------  -------------  -----------  ----   -----   -----    -
12   --   ---------  -------------  -----------  ----   -----   -----    -        12   --   ---------  -------------  -----------  ----   -----   -----    -
---------------------------- GPS_L2_CLM_PRIMARY --------------------------        ---------------------------- GPS_L2_CLM_ALT1 ---------------------------
 1    5     -1627.5      1868306.2   19540079.4  43.7    35.4    58.1    5         1    5     -1627.7      1868352.8   19540093.3  45.5    35.4    58.1    5
 2   12     -2699.6      1229747.1   22245890.1  35.3   193.7    22.1    5-        2   12     -2696.8      3678573.9   22245905.6  32.9   193.7    22.1    5-
 3   15      2534.5      -691286.0   21524685.0  40.1   167.8    29.1    5         3   15      2535.2      -767188.6   21524697.9  38.4   167.8    29.1    5
 4   25     -1866.6        56404.7   21263964.2  39.1   232.3    36.0    5-        4   25     -1862.8        56405.8   21263977.6  40.4   232.3    36.0    5
 5   29      1239.2     -2081662.8   19302546.8  44.0   328.8    61.9    5         5   29      1238.4     -2081666.4   19302561.4  46.8   328.8    61.9    5
 6   --   ---------  -------------  -----------  ----   -----   -----    -         6   --   ---------  -------------  -----------  ----   -----   -----    -
 7   --   ---------  -------------  -----------  ----   -----   -----    -         7   --   ---------  -------------  -----------  ----   -----   -----    -
---------------------------- SBAS_L1_I_PRIMARY ---------------------------        ---------------------------- SBAS_L1_I_ALT1 ----------------------------
 1  131       -79.9        83280.1   35848512.2  42.8   214.7    48.9    6-        1  131       -78.7        83157.5   35848511.1  42.5   214.7    48.9    6
 2  135       -79.9         2192.5   36632248.7  43.2   234.5    38.0    6-        2  133      -153.5       193462.4   35507145.6  43.2   180.4    54.3    6
 3  138       -82.1        87685.0   35578702.9  45.0   198.5    53.2    6-        3  135       -77.0         7266.9   36632247.9  42.0   234.5    38.0    6-
 4  133      -154.3       192680.2   35507147.0  41.5   180.4    54.3    6-        4  138       -82.4        90012.3   35578701.3  44.7   198.5    53.2    6-
---------------------------- GALILEO_E1_BC_PRIMARY -----------------------        ---------------------------- GALILEO_E1_BC_ALT1 -------------------------
 1    2     -2336.9         1874.9   26248521.9  31.1   239.4    12.6    6*-       1    2u    -2349.4           -0.0          0.0  25.1   239.4    12.6    6-
 2    4u    -2587.6           -0.0          0.0  26.8    40.5    15.1    6-        2    4     -2600.8          523.5   25987073.1  35.5    40.5    15.1    6*-
 3    5      2131.4     -3254754.1   23062050.7  45.8   182.5    49.0    6         3    5      2129.1      -958996.8   23062049.0  46.4   182.5    49.0    6
 4    9      -524.3       141159.6   20481714.7  46.0    75.6    60.7    6         4    9      -524.5       142179.9   20481712.7  47.8    75.6    60.7    6
 5   11     -1487.4        28471.2   23952196.0  30.6    97.6    31.3    6-        5   11u    -1491.8           -0.0          0.0  28.8    97.6    31.3    5*-
 6   22      1795.4        -9356.3   22728390.7  43.3   313.0    28.9    6         6   22      1796.8        -8631.4   22728389.8  42.9   313.0    28.9    6
 7   --   ---------  -------------  -----------  ----   -----   -----    -         7   --   ---------  -------------  -----------  ----   -----   -----    -
 8   --   ---------  -------------  -----------  ----   -----   -----    -         8   --   ---------  -------------  -----------  ----   -----   -----    -
------------------------------ Navigation Data -------------------------------------------------------------------------------
 X:  -742657.04   Y: -5461987.51   Z:  3198259.26   deltRx:  -1294900.86
 Xvel:     -1.35   Yvel:     -4.50   Zvel:     -8.32   deltRxDot:     20.38
 Hsigma:   0.17   Vsigma:   0.37   NISratio: 1.17
==============================================================================================================================
```
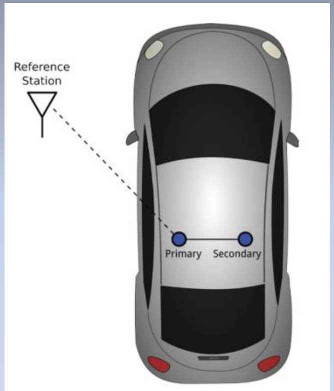
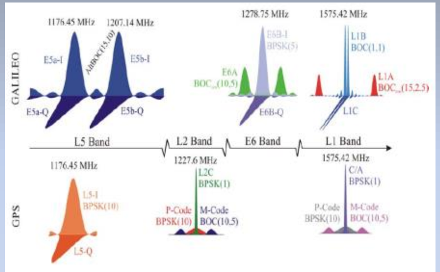
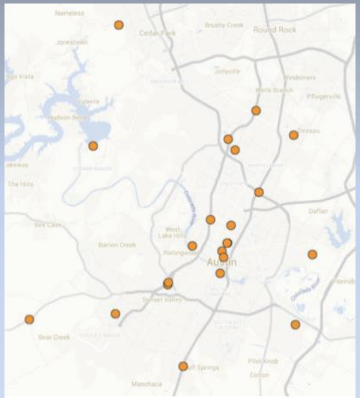

Keys to Robust CDGNSS Positioning







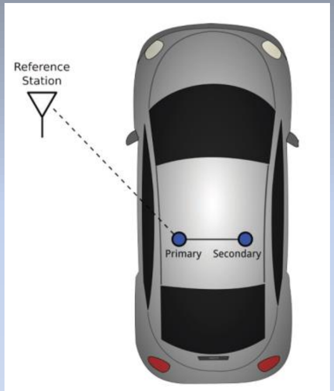
Multiple Rover Antennas

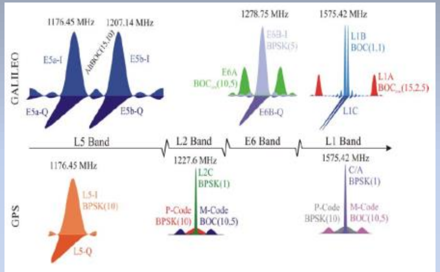
Multiple Frequencies

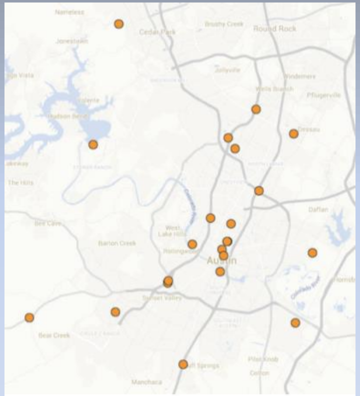
Dense Reference Network

Fusion with Vision/Radar

Keys to Robust CDGNSS Positioning







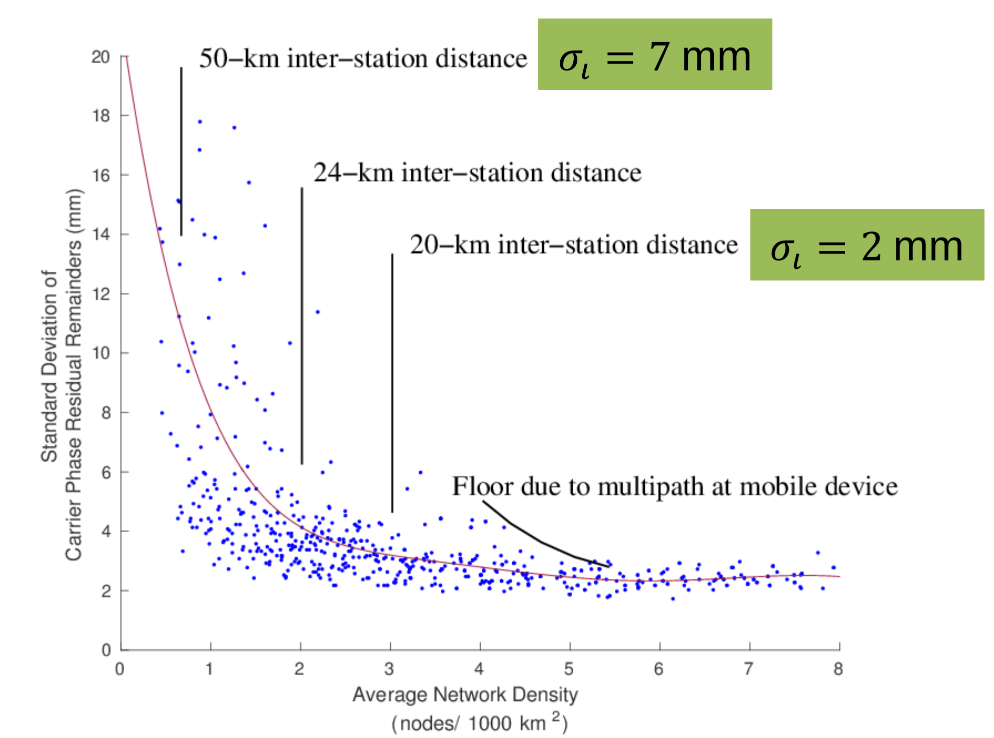
Multiple Rover Antennas

Multiple Frequencies

Dense Reference Network

Fusion with Vision/Radar

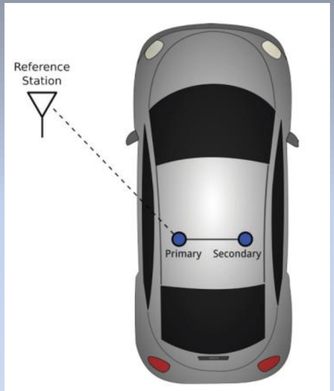
Completely eliminate ionospheric and tropospheric errors as a factor



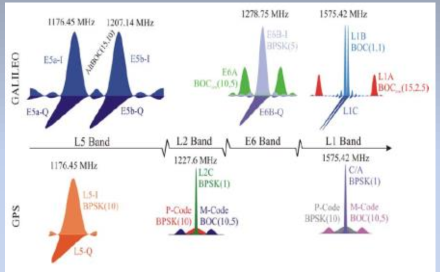
Corrections uncertainty is a highly nonlinear function of density. Culprit: medium-scale ionospheric irregularities. **Floor due to multipath at mobile device reached with < 20km inter-station distance.**

Longhorn Dense Reference Network stations under test prior to deployment

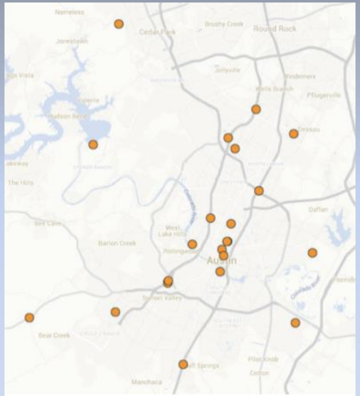
Keys to Robust CDGNSS Positioning



Multiple Rover Antennas



Multiple Frequencies



Dense Reference Network

Fusion with Vision/Radar

Goal: Decimeter-accurate visual and radar features

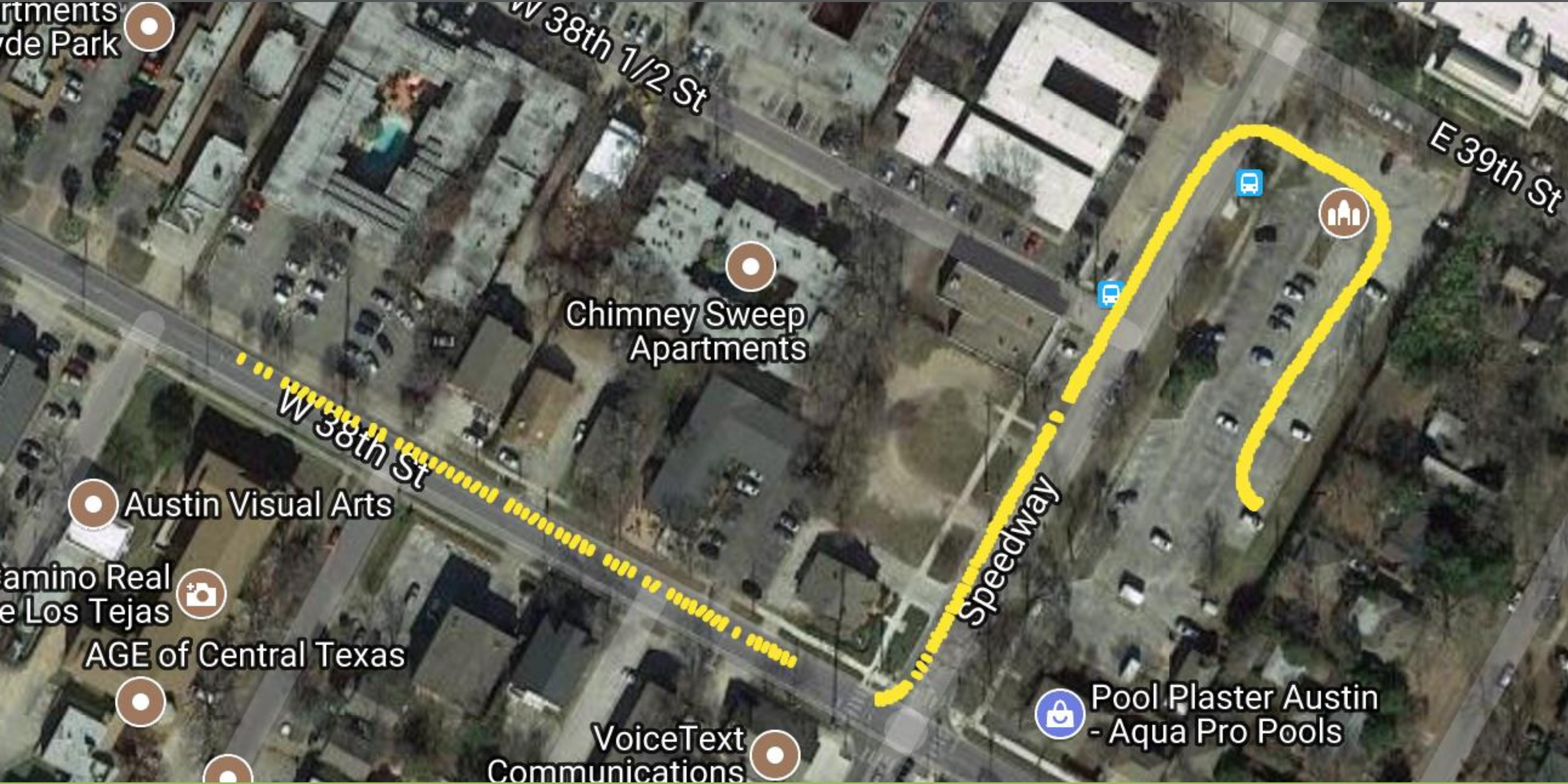
GNSS-INS provides initial pose and global reference

Merges globally-referenced maps from multiple sessions

Cooperative fleet refinement of map

GEOSLAM: Global Electro-Optical SLAM

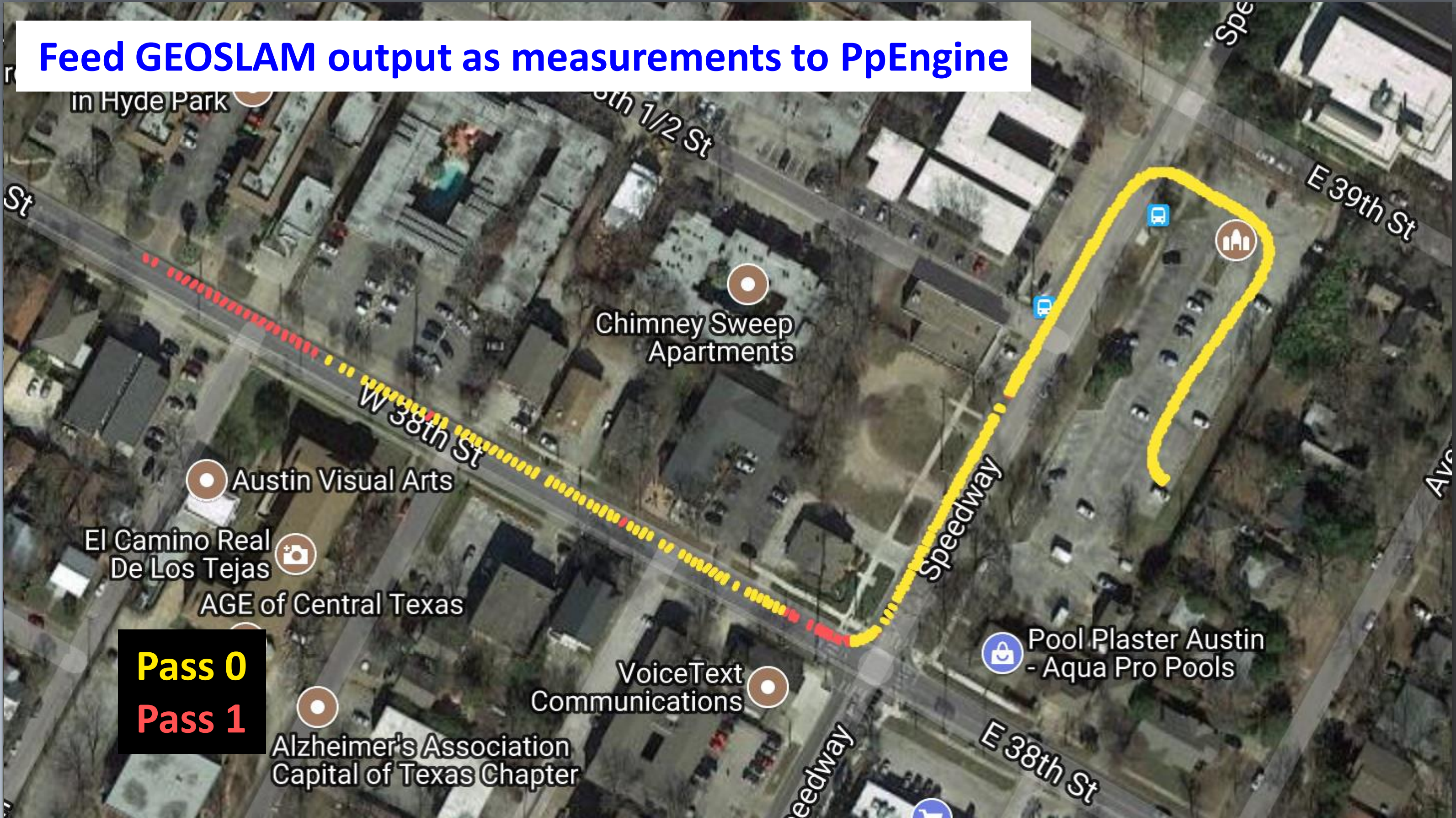
Cooperative mapping at decimeter accuracy for all-weather localization

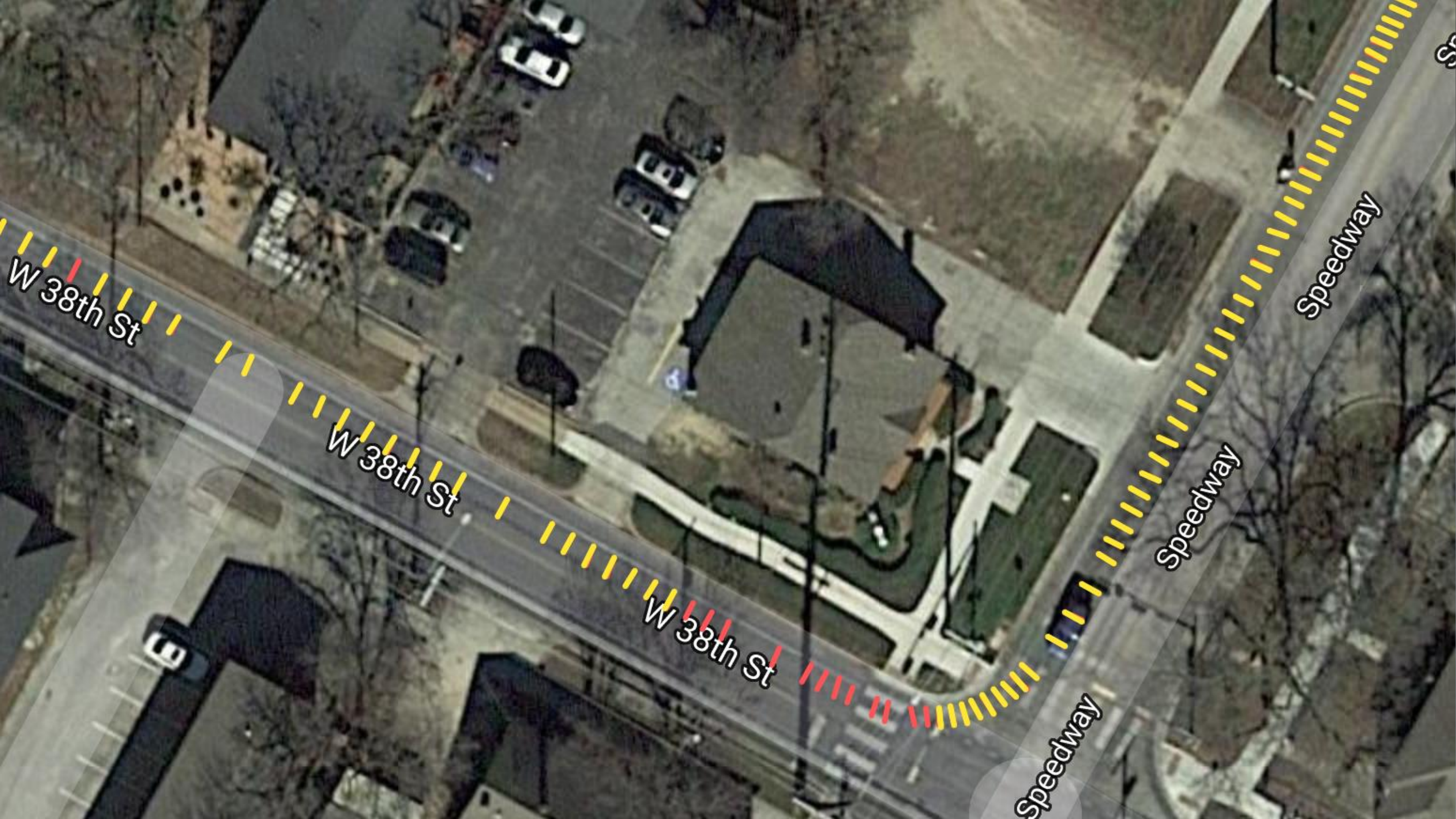


CDGNSS solutions are high-confidence 5-cm accurate, but not continuously available

Lines drawn between independent CDGNSS solutions from each of Sensorium's two antennas

GEOSLAM ⇌ PpEngine

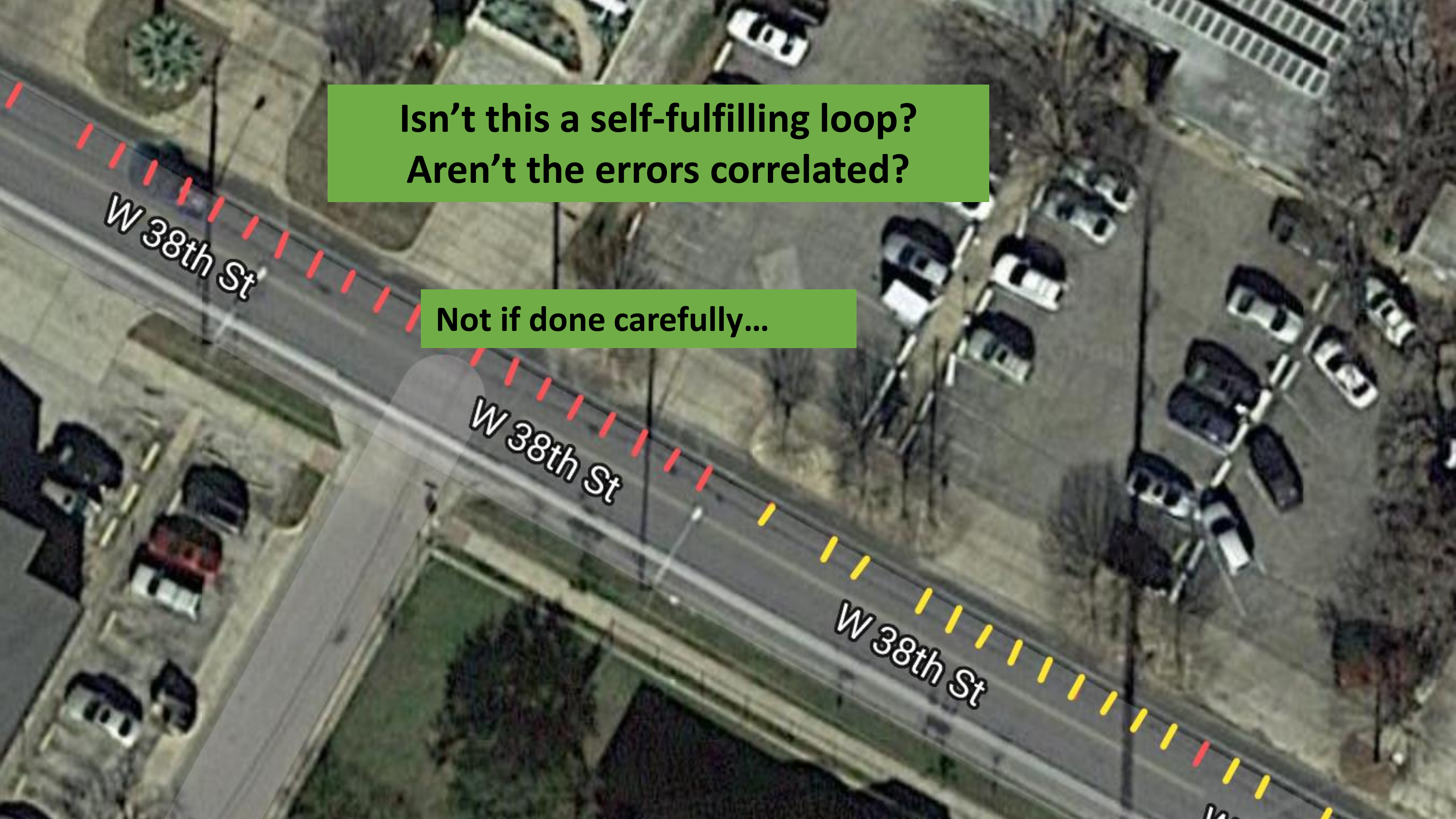




W 38th St
W 38th St
W 38th St
Speedway
Speedway
Speedway

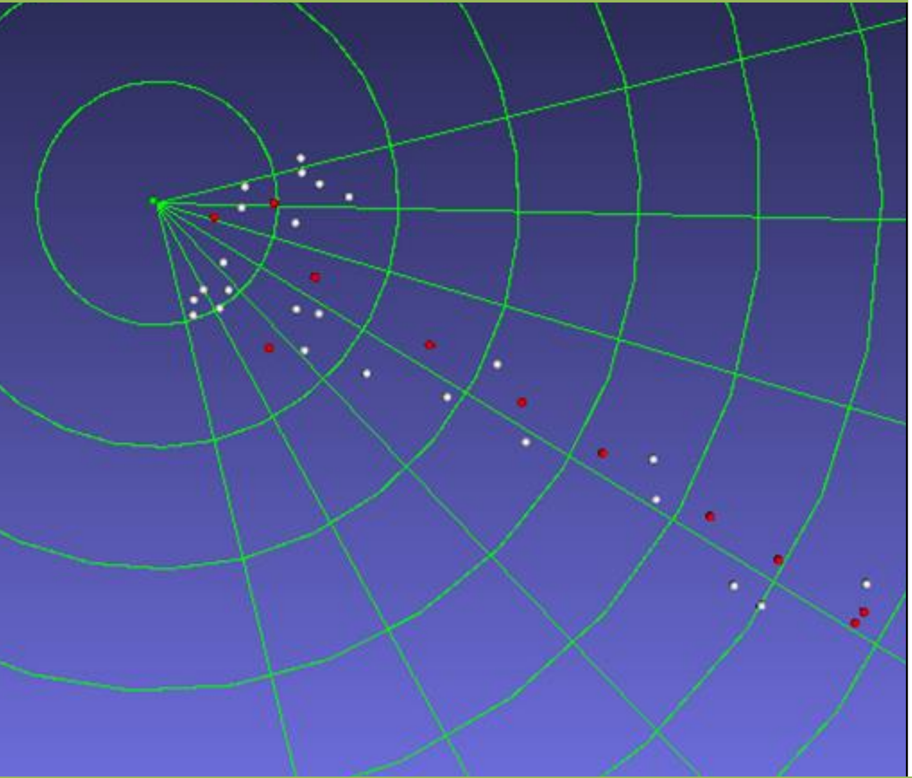
Isn’t this a self-fulfilling loop?
Aren’t the errors correlated?

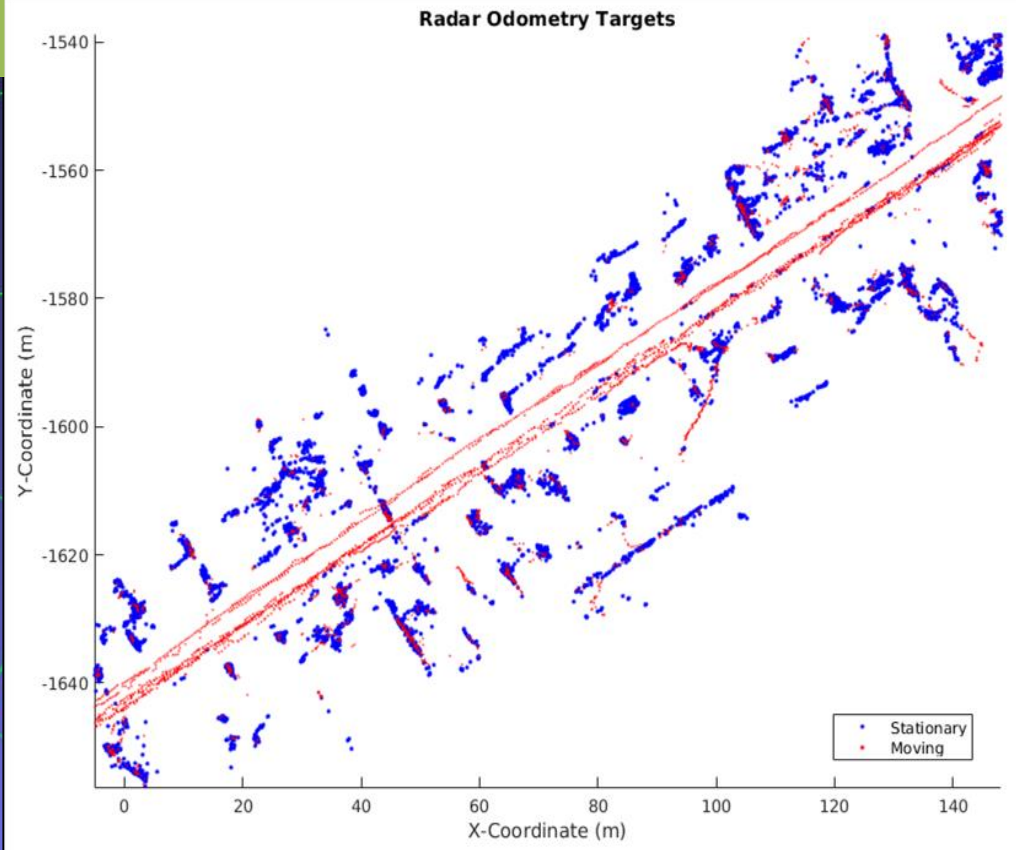
Not if done carefully…



Map of 3D camera image features is 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 *<u>with which a radar map can be built</u>*

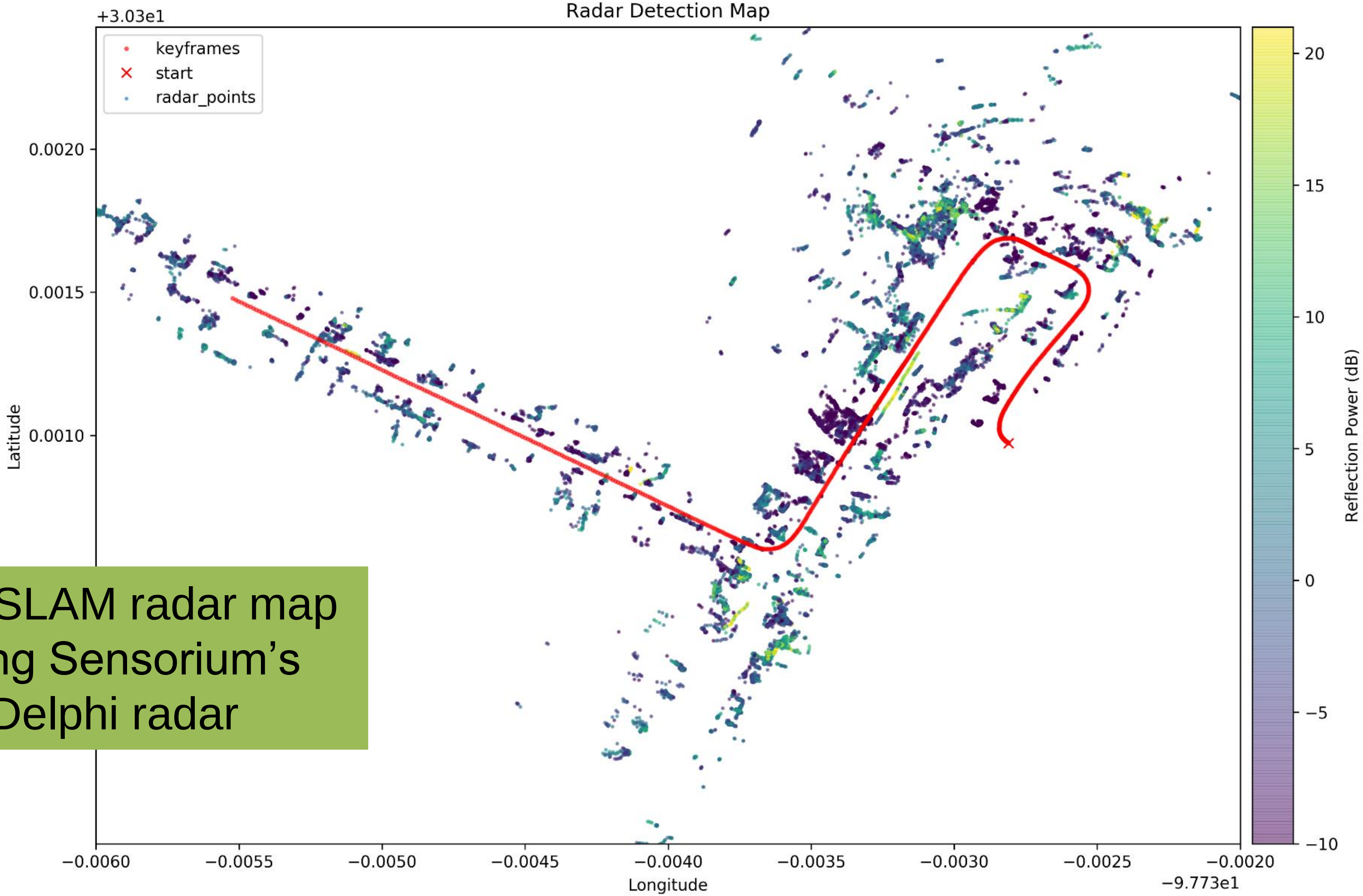
Sensorium radar data: Delphi unit





A radar map is useful in all weather conditions.

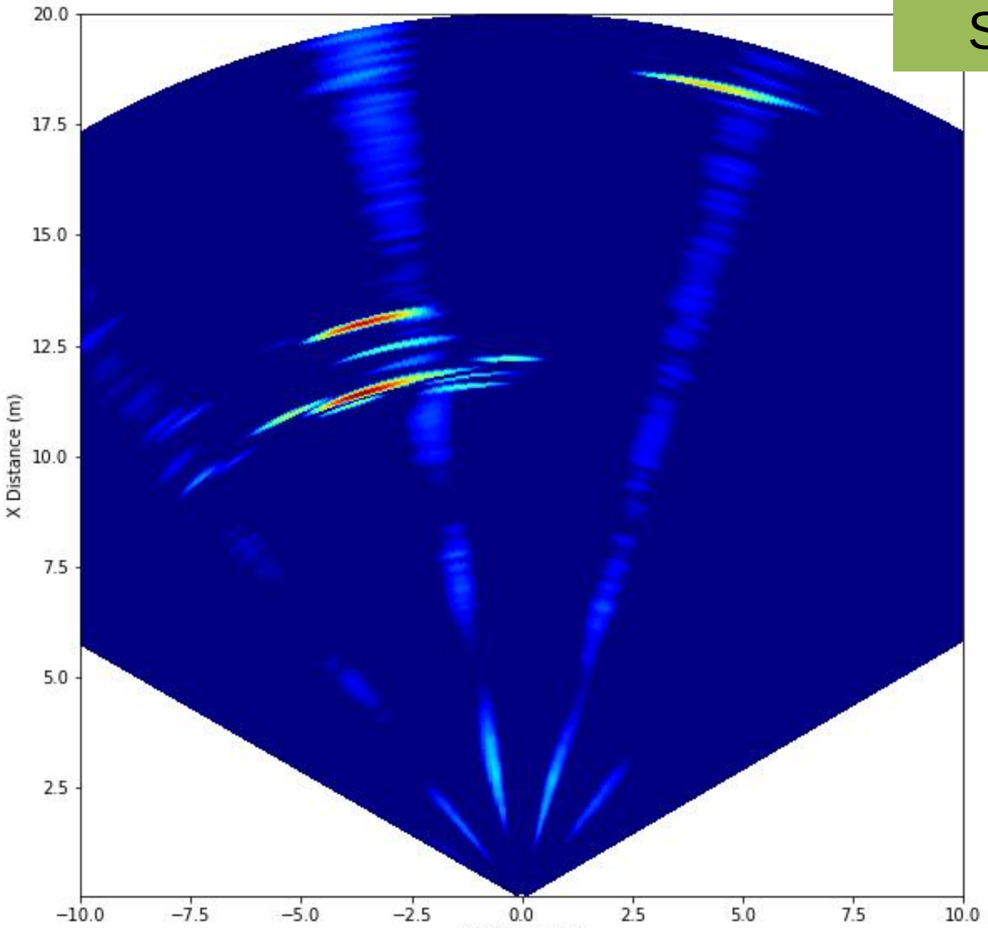
Our conjecture: In urban areas rich with radar reflectors, a radar map together with GNSS will be sufficient for 30 cm @ 95% accuracy



GEOSLAM radar map using Sensorium's Delphi radar


Frame: 0
Radar Target Velocity (m/s)
4
3
2
1
0
−1
−2
−3
−4

Sensorium radar data: Raw-data unit



New experimental radar allows us to create our own waveforms and access the raw returns (not just processed tracking points) to create more informative radar maps

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Robust

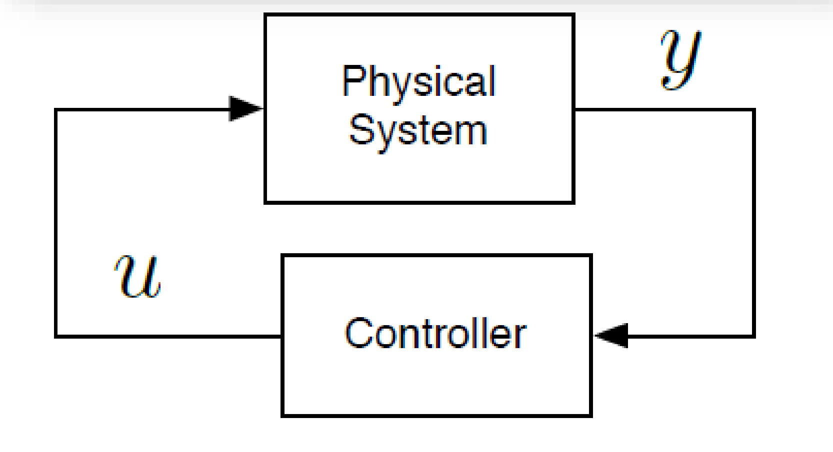
&

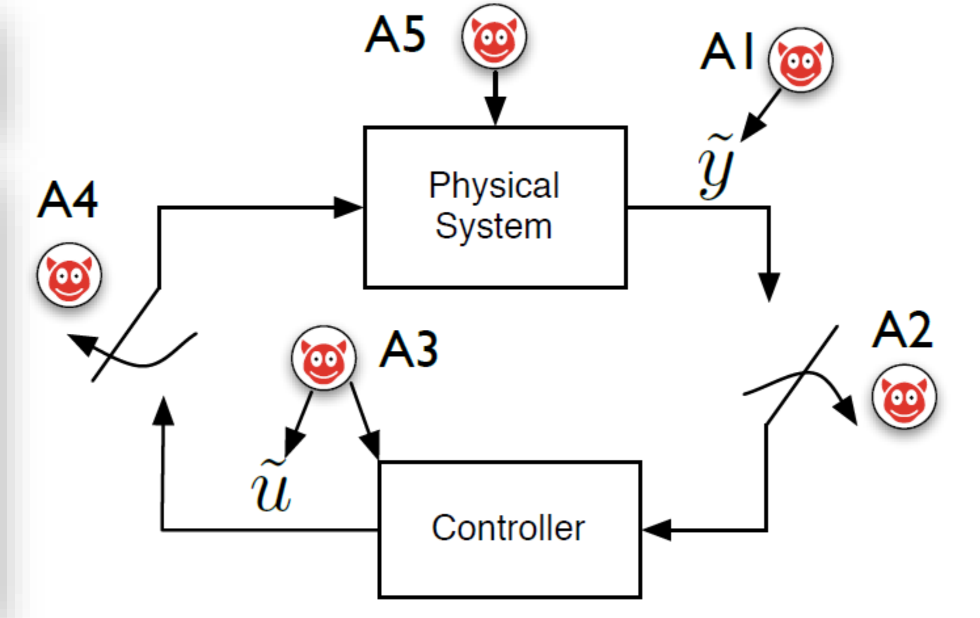
Secure

General Automated Control System Security

Secure Control: Towards Survivable Cyber-Physical Systems*

Alvaro A. Cárdenas Saurabh Amin Shankar Sastry
University of California, Berkeley 2008

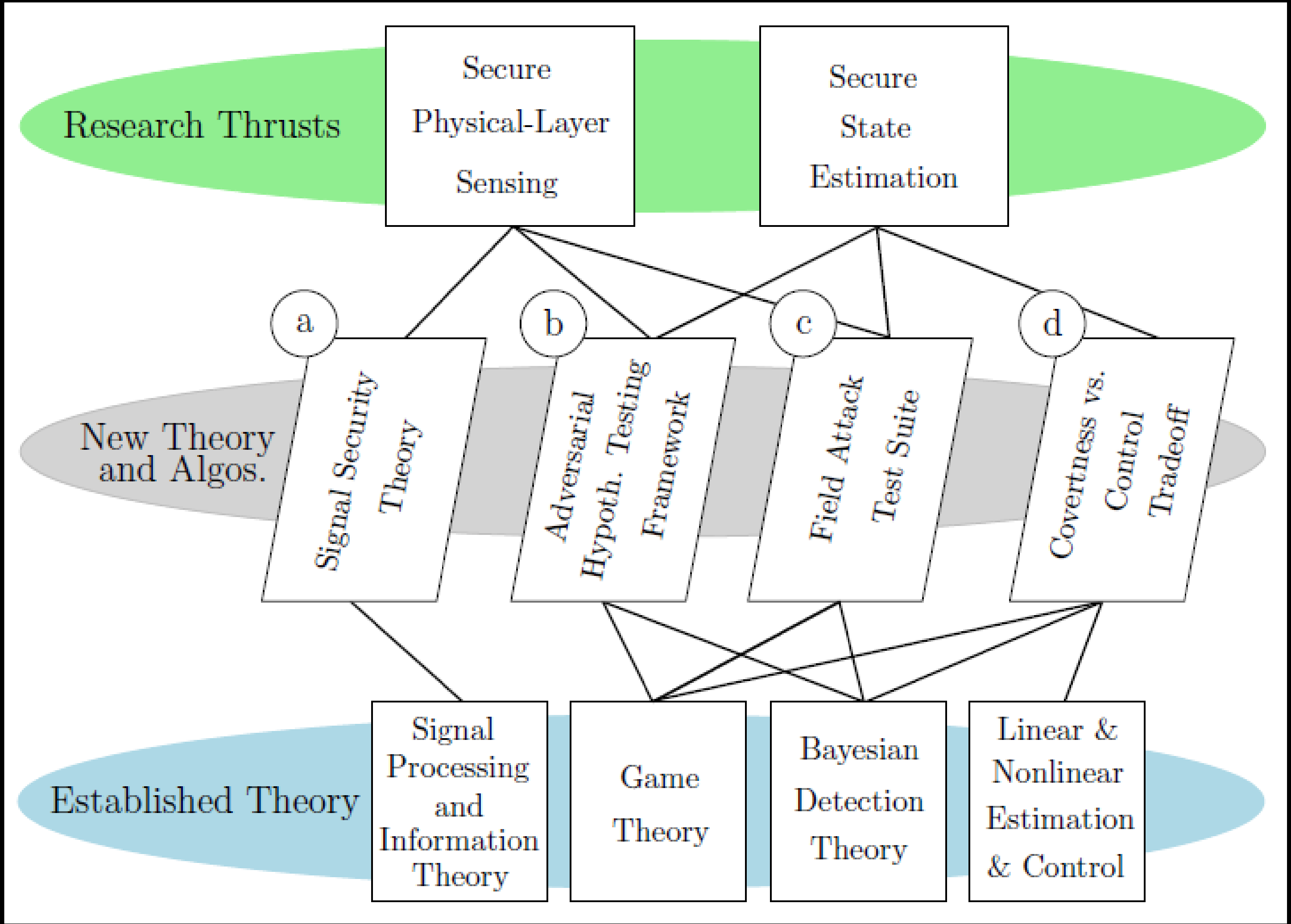




The general secure control problem envisions arbitrary manipulation of y (e.g, deception and DoS attacks) and u (e.g., actuator attacks)

The UT Radionavigation Lab's Focus:

Sensor attacks: **attacks on sensors by manipulation of the physical fields (e.g., electromagnetic, acoustic, pressure, etc.) they measure – especially against navigation, timing, and collision avoidance system sensors**


Research Thrusts
Secure Physical-Layer Sensing
Secure State Estimation
New Theory and Algos.
a
Signal Security Theory
b
Adversarial Hypoth. Testing Framework
c
Field Attack Test Suite
d
Covertness vs. Control Tradeoff
Established Theory
Signal Processing and Information Theory
Game Theory
Bayesian Detection Theory
Linear & Nonlinear Estimation & Control

Useful Concepts and Approaches

Defenders should seek to minimize, and attackers max., *integrity risk*

Analysis must encompass full defender-attacker closed-loop dynamics

Full analysis of complex differential games may be intractable, but useful results may arise from only "one level of gaming."

Useful Concepts and Approaches

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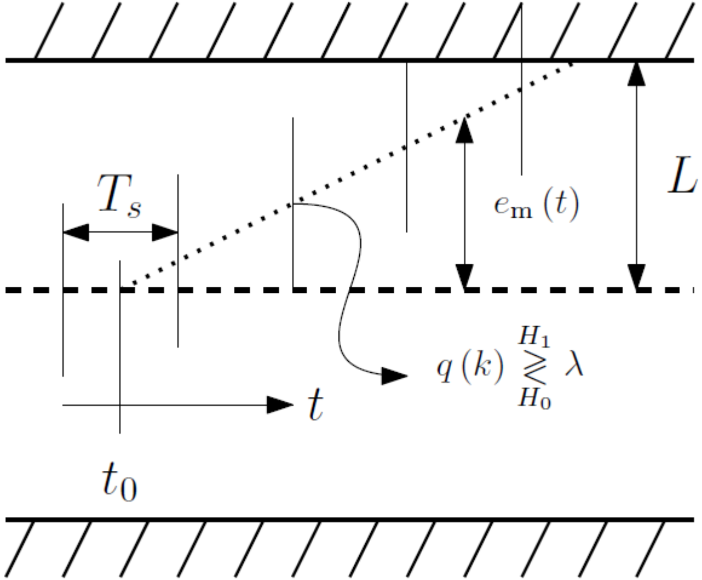
White Rose of Drachs: 65-meter, $80M research laboratory in the Mediterranean



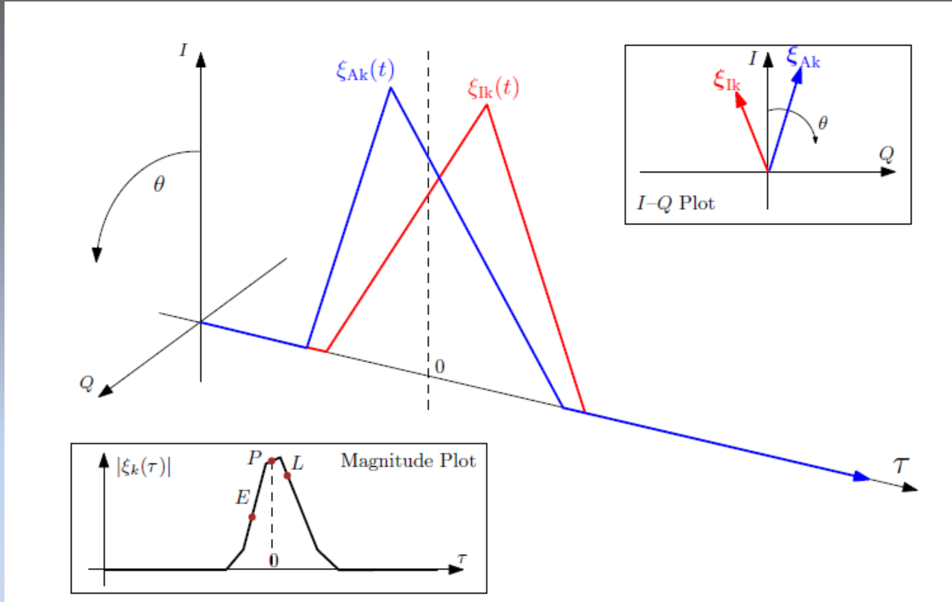
Goal is not just to maximize P_D for a fixed P_F, nor to minimize time-to-detect for a fixed P_F and P_D. For vehicle security, goal should be to minimize *integrity risk* for a given false alarm rate

Bhatti & Humphreys, "Hostile control of ships via false GPS signals: Demonstration and Detection," *Navigation, Aug. 2017*

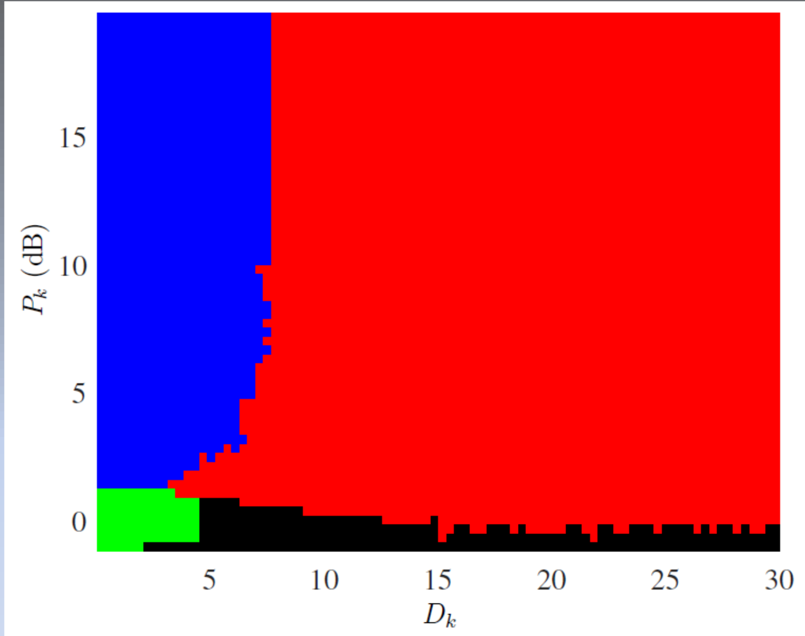
<u>Generalization of notion of integrity risk</u>:
The cost of deciding for hypothesis i depends not only on which hypothesis is true, but more precisely on the parameters of the attack: not all attacks are equally costly.

Use $C[i, \theta]$ to model cost, not C_{ij}

The Power-Distortion GNSS Spoofing Defense



Authentic (blue) and spoofing (red) signals interact in the correlation domain. To eliminate interaction, spoofer must either null or overpower the authentic signals. Nulling difficult: requires accurate knowledge of length of and fading along signal path.



We have determined the optimum decision regions for a combined power and distortion hypothesis test to indicate clean (green), multipath (black), spoofing (red), or jamming (blue). Costs are expressed as fnc. of spoofing power, delay, and phase.

Wesson et al.,“Receiver-Autonomous GNSS Signal Authentication via Power and Distortion Monitoring,” 2017, accepted.

Useful Concepts and Approaches

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Full analysis of complex differential games may be intractable, but useful results may arise from only "one level of gaming."

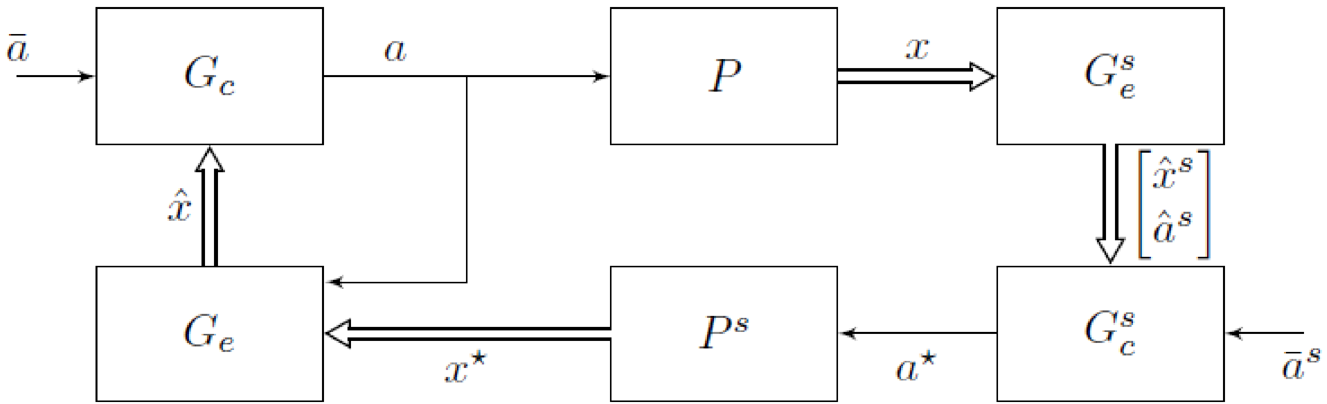

Figure 4: Block diagram of the closed-loop UAV-spoofer system showing the interconnections between the UAV controller G_c, plant P, and estimator G_e; and the spoofer controller G_c^s, plant P^s and estimator G_e^s. The spoofer plant P^s embodies the double integrator dynamics that generate $x^\star$ from $a^\star$. Thick lines represent vector data paths.

A.J. Kerns, D.P. Shepard, J.A. Bhatti, T.E. Humphreys, "Unmanned aircraft capture and control via GPS spoofing," Journal of Field Robotics, 2014

Analysis of interplay between defender and attacker must consider full closed-loop system including: (1) vehicle dynamics (including state estimation and control), (2) defender's detection strategy, (3) predictability of defender's control actions, and (4) attacker's state estimation system

Useful Concepts and Approaches

Defenders should seek to minimize, and attackers max., *integrity risk*

Analysis must encompass full defender-attacker closed-loop dynamics

<u>**Full analysis of complex differential games may be intractable, but useful results may arise from only "one level of gaming."**</u>

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DE L'OUEST