Introduction to Advanced RAIM

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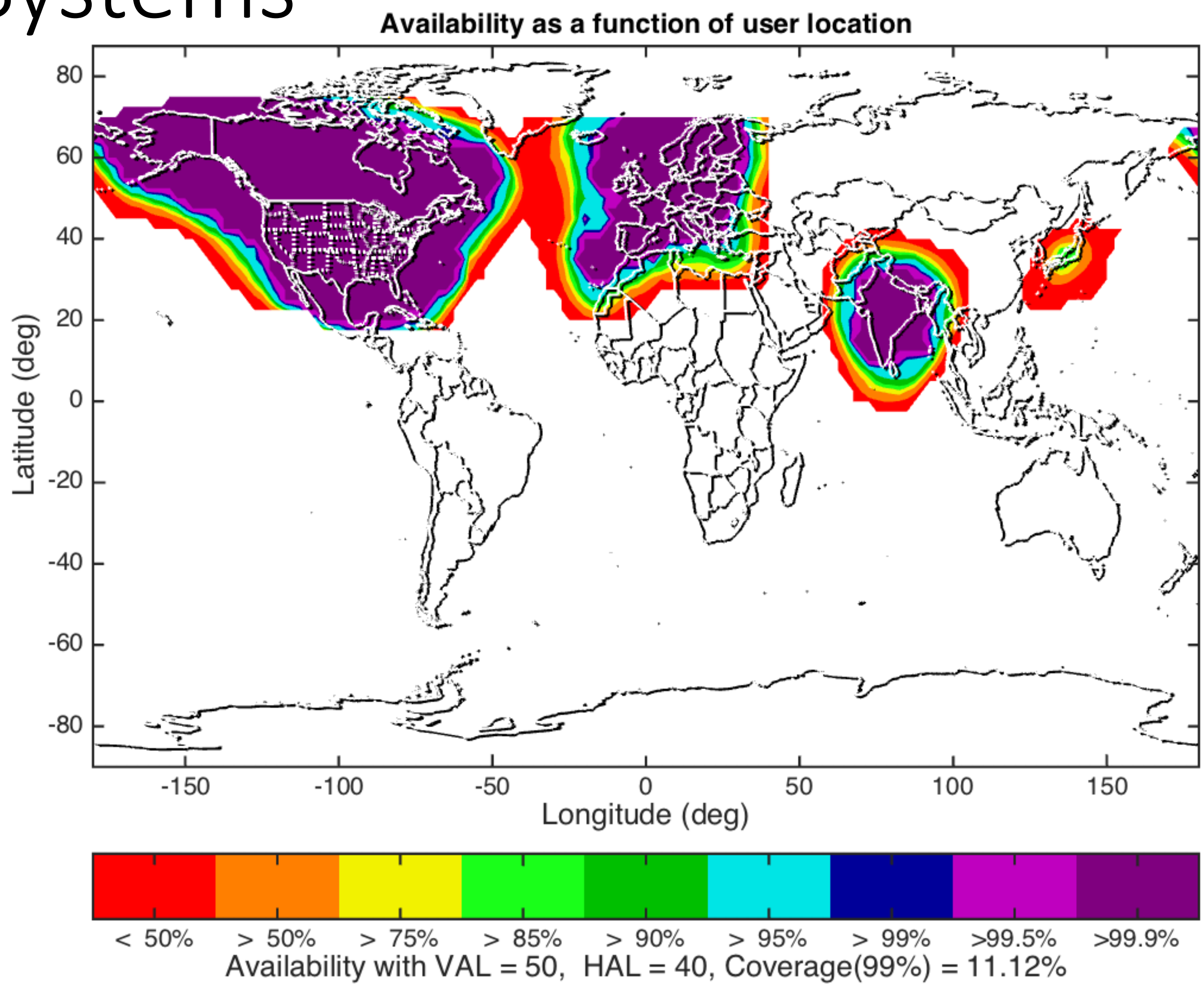
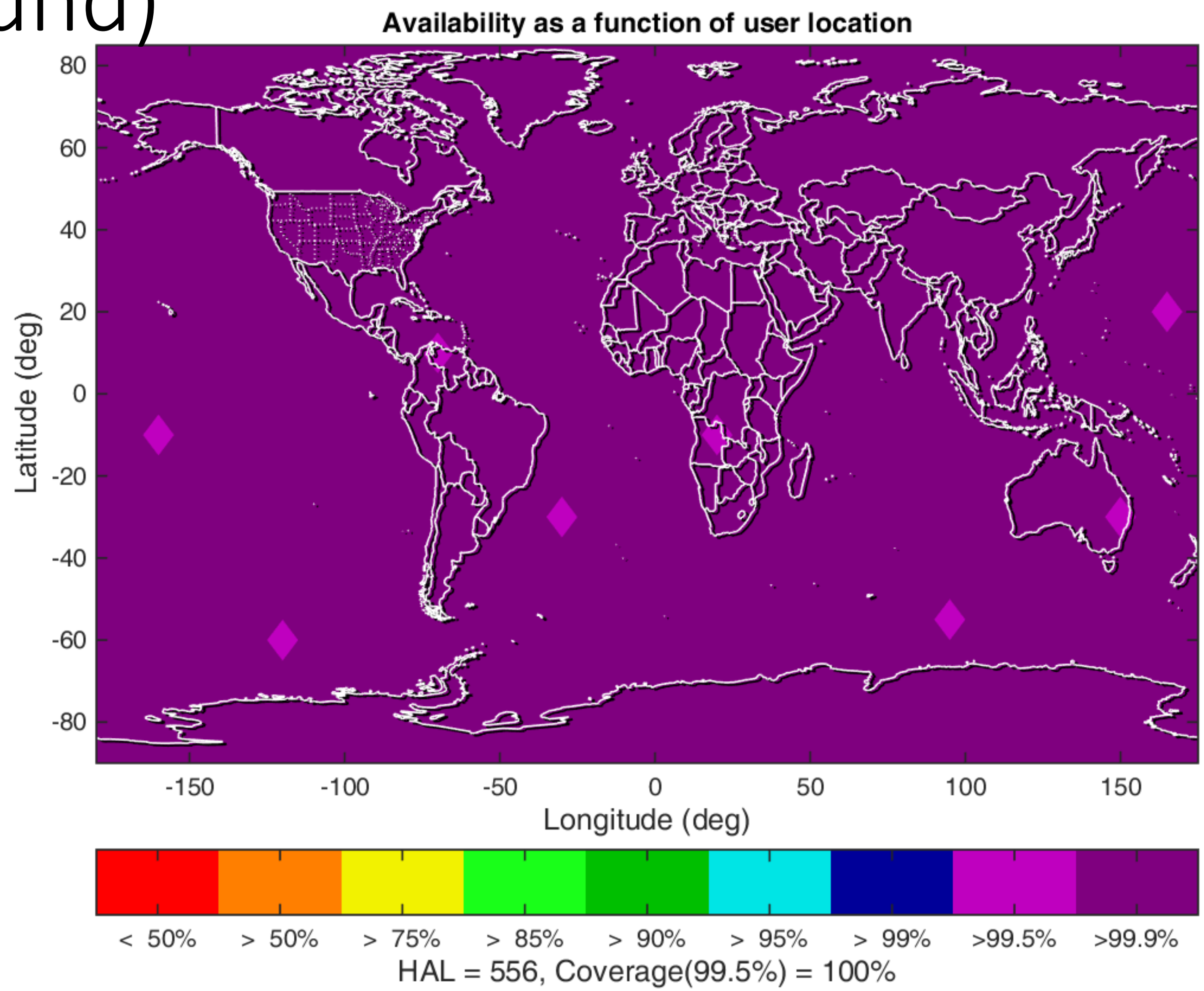
July 26, 2016

Satellite-based Augmentation Systems



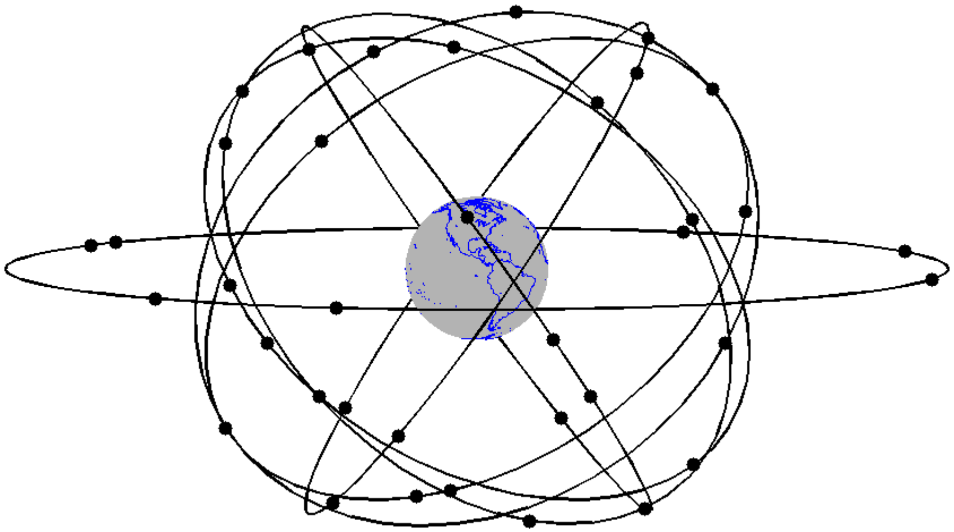
Credit: Todd Walter

Receiver Autonomous Integrity Monitoring (556 m Horizontal Error Bound)

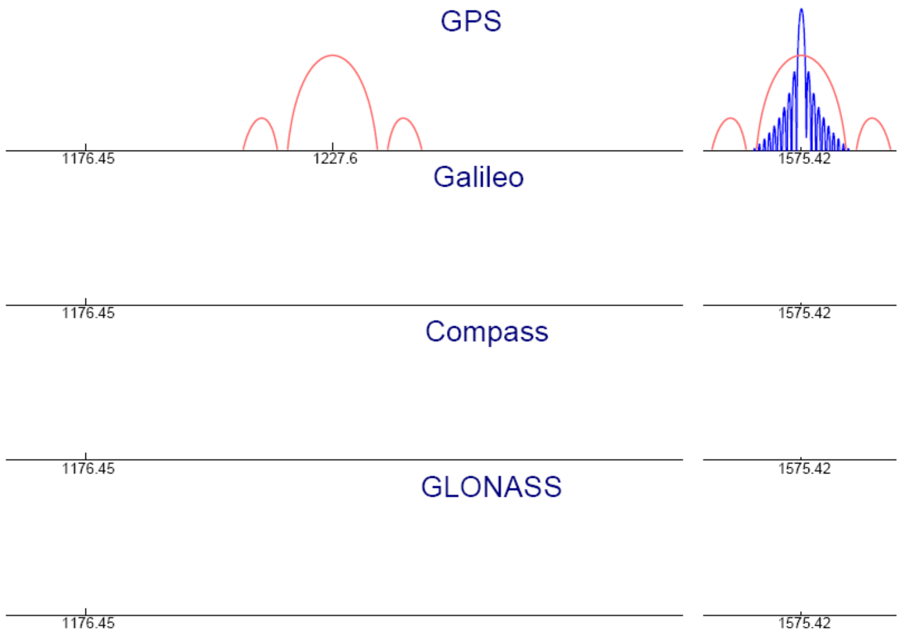


Signals used by aviation in 2016

constellations

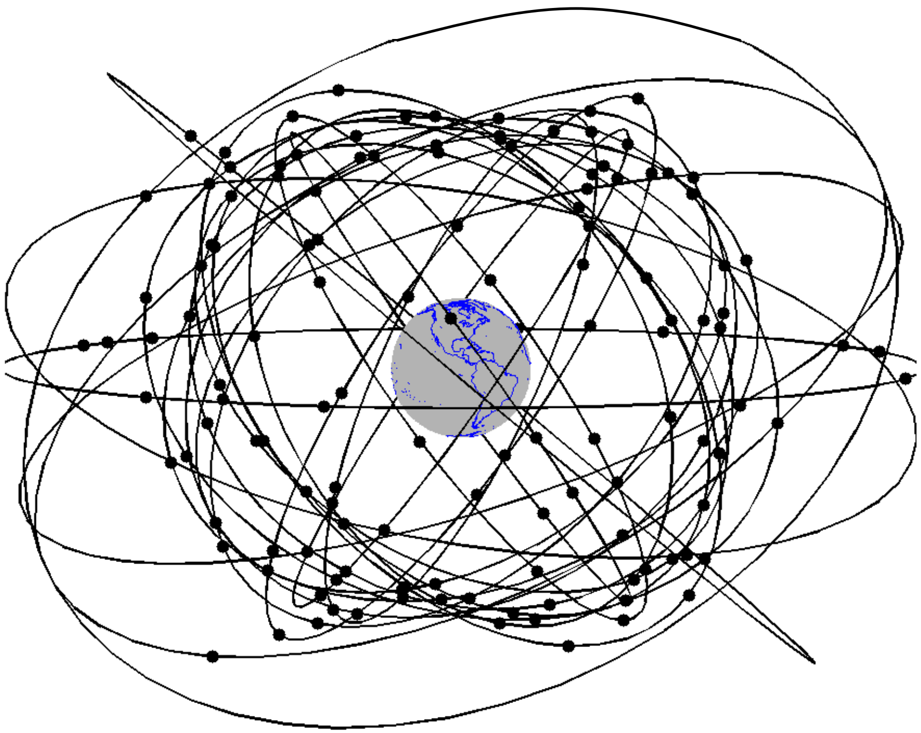


signals

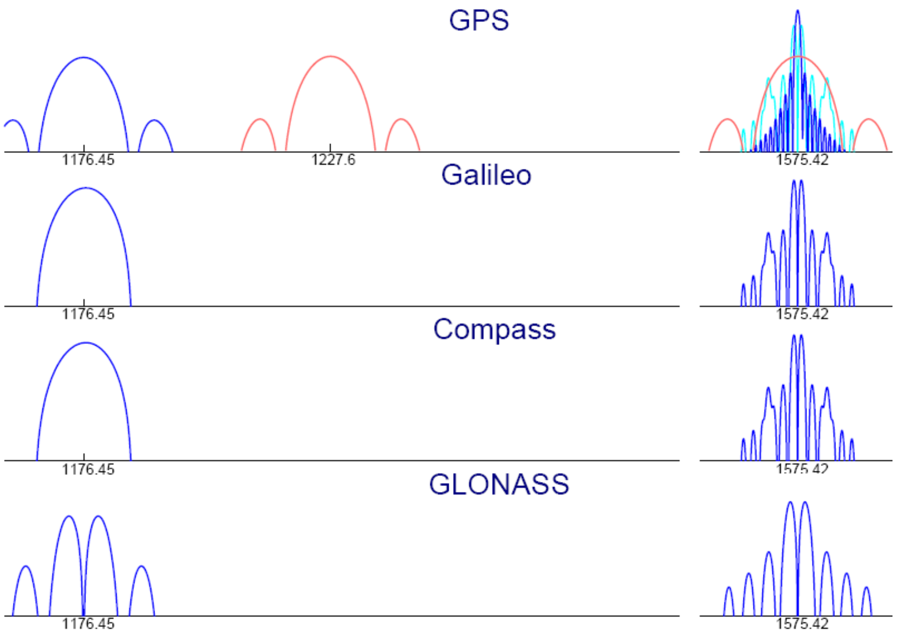


Signals that may be used by aviation users in 2025

constellations



signals



+ better clocks and orbit determination

Best use of multi-constellation multi-frequency for aviation?

If RAIM could be extended to vertical navigation:

- Worldwide coverage of the most stringent operations
- Arctic Navigation
- No need for GEO satellites
- No real time ground monitoring network

What do we want?

- Accuracy
- Integrity
- Continuity

$$std\left(\hat{x}_v \quad x_v\right) \quad 1.8 \text{ m}$$

$$P\left(\left|\hat{x}_v - x\right| > \text{Alert Limit \& no alert}\right) \leq 10^{-7}$$

$$P\left(\text{alert}\right) \leq 8 \times 10^{-6}$$

What do we fear?

- Faults
- Nominal conditions

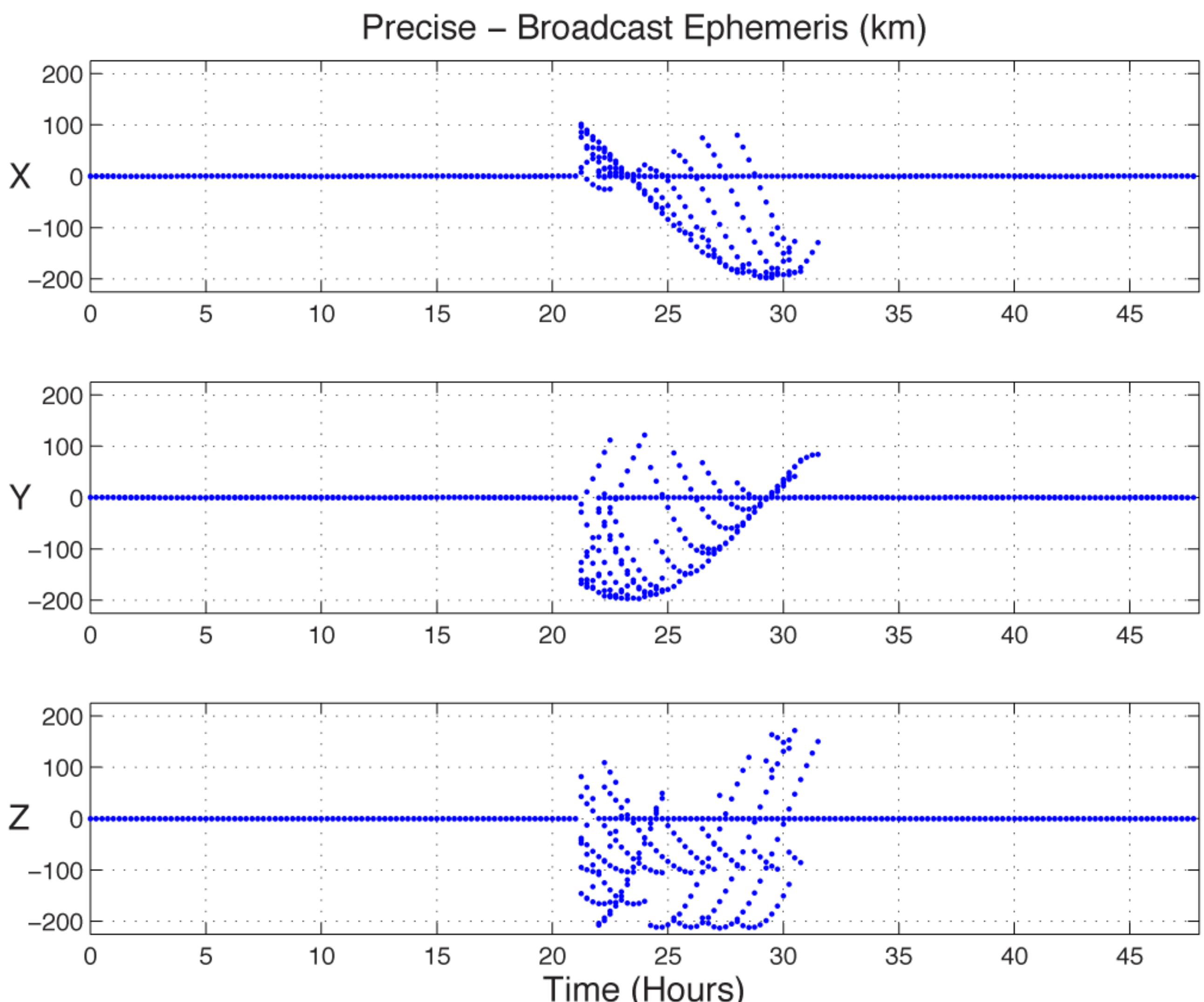
Threat Model

Threat model

	Nominal	Narrow fault	Wide fault
Clock and Ephemeris	Orbit/clock estimation and prediction and broadcast limits	Includes clock runoffs, bad ephemeris, unflagged manoeuvres	Erroneous EOPP, inadequate manned ops, ground-inherent failures
Signal Deformation	Nominal differences in signals due to RF components, filters, and antennas waveform distortion	Failures in satellite payload signal generation components. Faulted signal model as described in ICAO	N/A
Code-Carrier Incoherence	e.g. incoherence observed in IIF L5 signal or GEO L1 signals	e.g. incoherence observed in IIF L5 signal or GEO L1 signals	N/A
Interfrequency Biases	Delay differences in satellite payload signal paths	Delay differences in satellite payload signal paths TBC	N/A
Satellite Antenna Bias	Look-angle dependent biases caused at satellite antennas	Look-angle dependent biases caused at satellite antennas	N/A
Ionosphere	N/A	Scintillation	Multiple scintillations at solar storms
Troposphere	Nominal troposphere error (after applying SBAS MOPS model for tropo correction)	N/A	N/A
Receiver Noise and Multipath	Nominal noise and multipath terms in airborne model (TBC Gailleo BOC(1,1) and L5/E5a))	e.g.: receiver tracking failure or multipath from onboard reflector. TBC	e.g.: receiver tracking multiple failure or multipath from onboard reflector. TBC

From: Working Group C, ARAIM Technical Subgroup, Interim Report, Issue 1.0, December 19, 2012
http://ec.europa.eu/enterprise/newsroom/cf/_getdocument.cfm?doc_id=7793
http://www.gps.gov/policy/cooperation/europe/2013/working-group-c/ARAIM-report-1.0.pdf

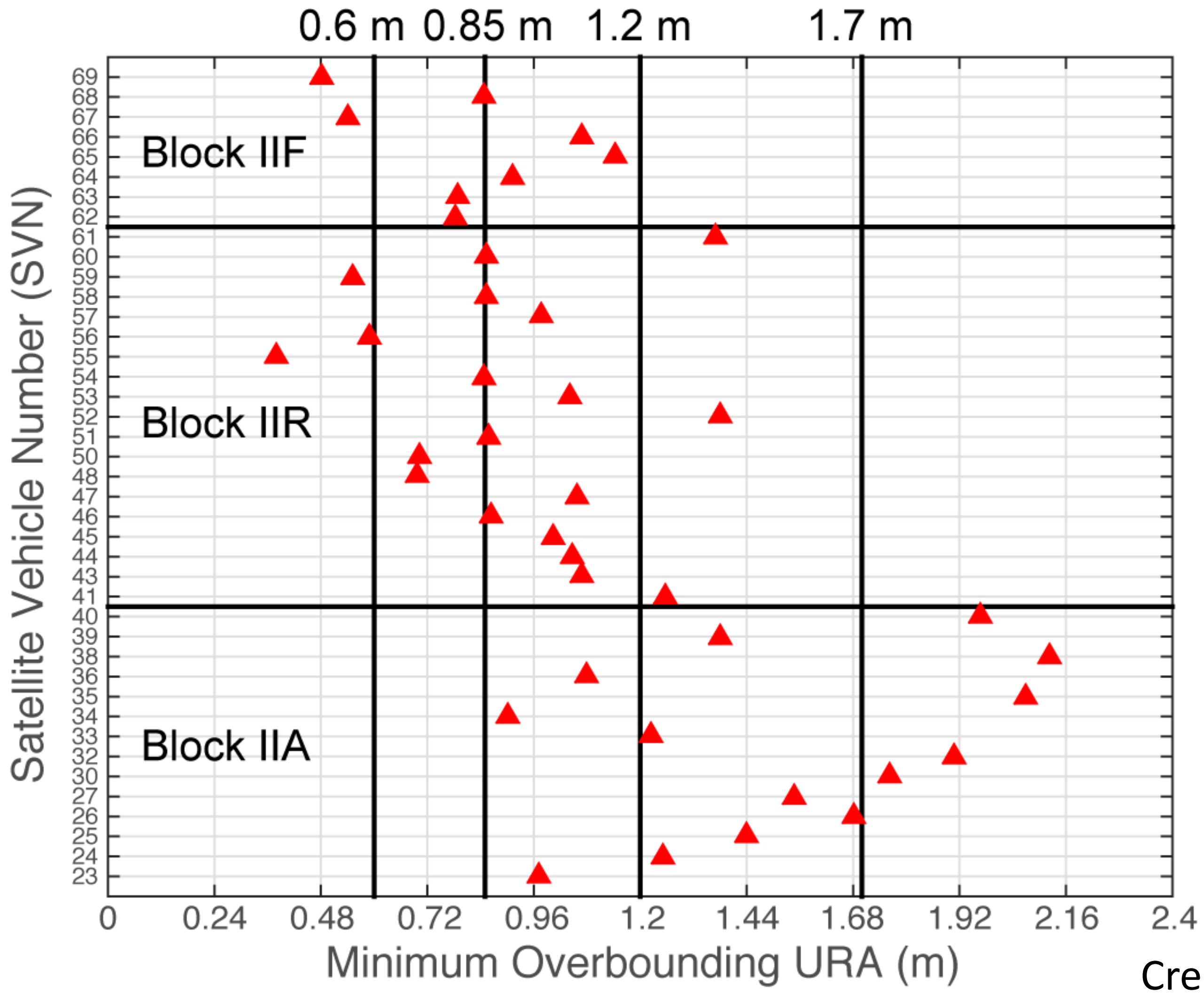
GLONASS constellation wide fault



April 1-2, 2014

Credit: Todd Walter

GPS Service history: Nominal clock and ephemeris errors (2009-2014)



Credit: Todd Walter

Mapping the threat model into the Integrity Support Message

	Nominal	Narrow fault	Wide fault
Clock and Ephemeris	Orbit/clock estimation and prediction and broadcast limits	Includes clock runoffs, bad ephemeris, unflagged manoeuvres	Erroneous EOPP, inadequate manned ops, ground-inherent failures
Signal Deformation	Nominal differences in signals due to RF components, filters, and antennas waveform distortion $\sigma_{URA,i}$	Failures in satellite payload signal generation components. Faulted signal model as described in ICAO	N/A
Code-Carrier Incoherence	e.g. incoherence observed in IIF L5 signal or GEO L1 signals	e.g. incoherence observed in IIF L5 signal or GEO L1 signals	N/A
Interfrequency Biases	Delay differences in satellite payload signal paths $b_{nom,i}$	Delay differences in satellite payload signal paths TBC $P_{sat,i}$	N/A $P_{const,j}$
Satellite Antenna Bias	Look-angle dependent biases caused at satellite antennas	Look-angle dependent biases caused at satellite antennas	N/A
Ionosphere	N/A	Scintillation	Multiple scintillations at solar storms
Troposphere	Nominal troposphere error (after applying SBAS MOPS model for tropo correction) $\sigma_{tropo,i}$	N/A	N/A
Receiver Noise and Multipath	Nominal noise and multipath terms in airborne model (TBC Gailleo BOC(1,1) and E5/E5a) $\sigma_{airborne,i}$	e.g.: receiver tracking failure or multipath from onboard reflector. TBC	e.g.: receiver tracking multiple failure or multipath from onboard reflector. TBC

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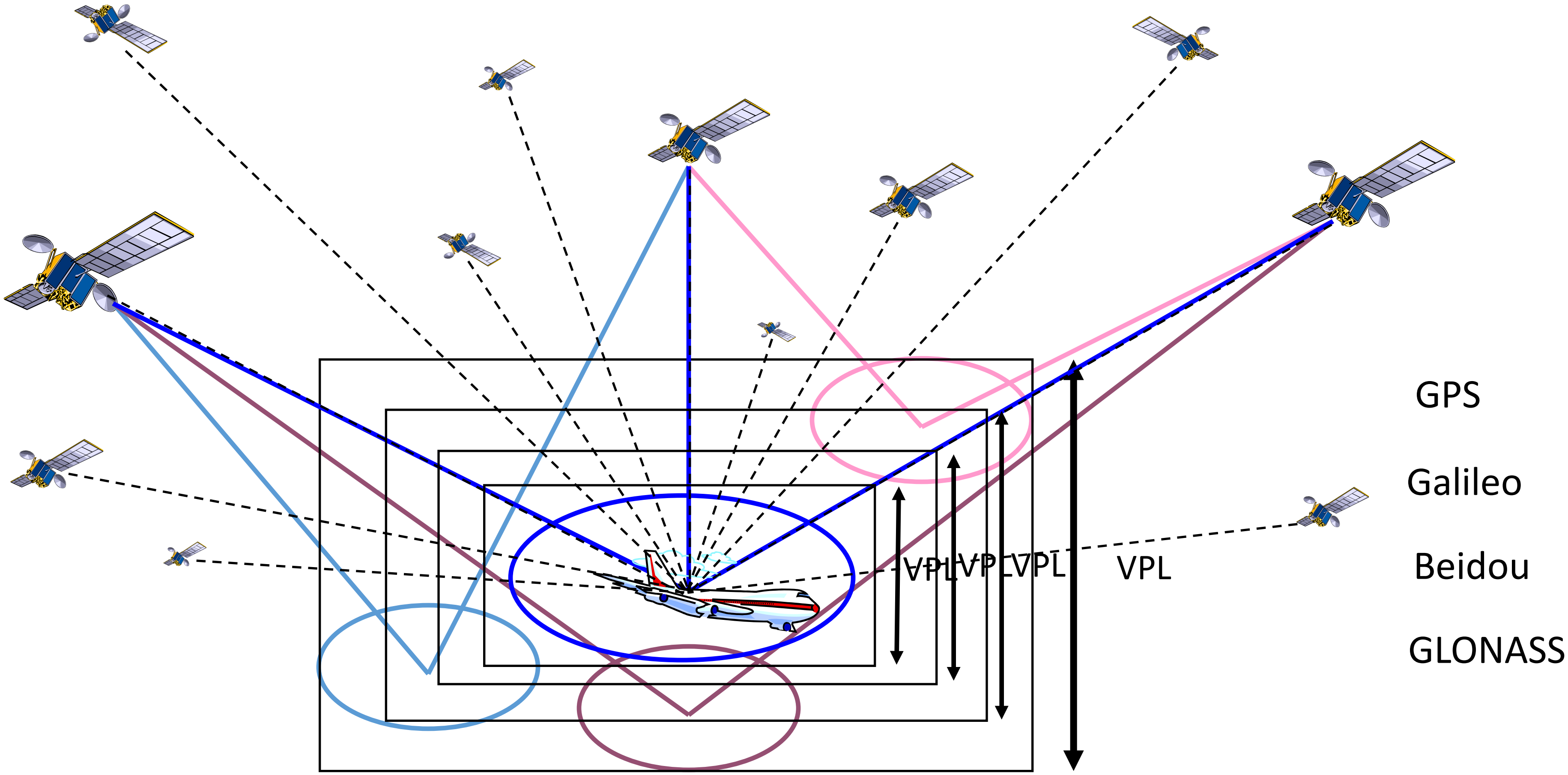
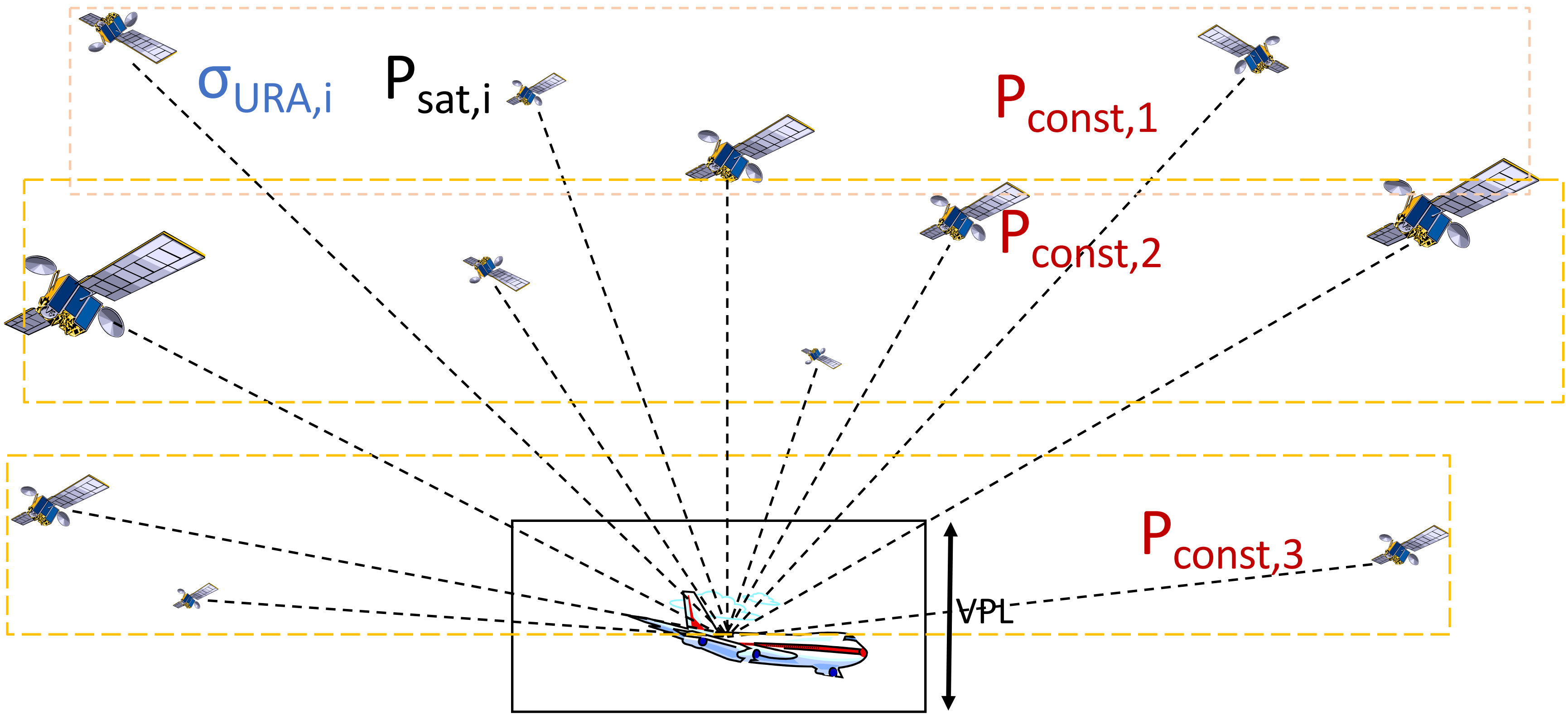
Solution Separation Algorithm



Blanch et al "Advanced RAIM user Algorithm Description: Integrity Support Message Processing, Fault Detection, Exclusion, and Protection Level Calculation," *Proceedings of the 25th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS 2012)*, Nashville, TN, September 2012

Advanced RAIM concept



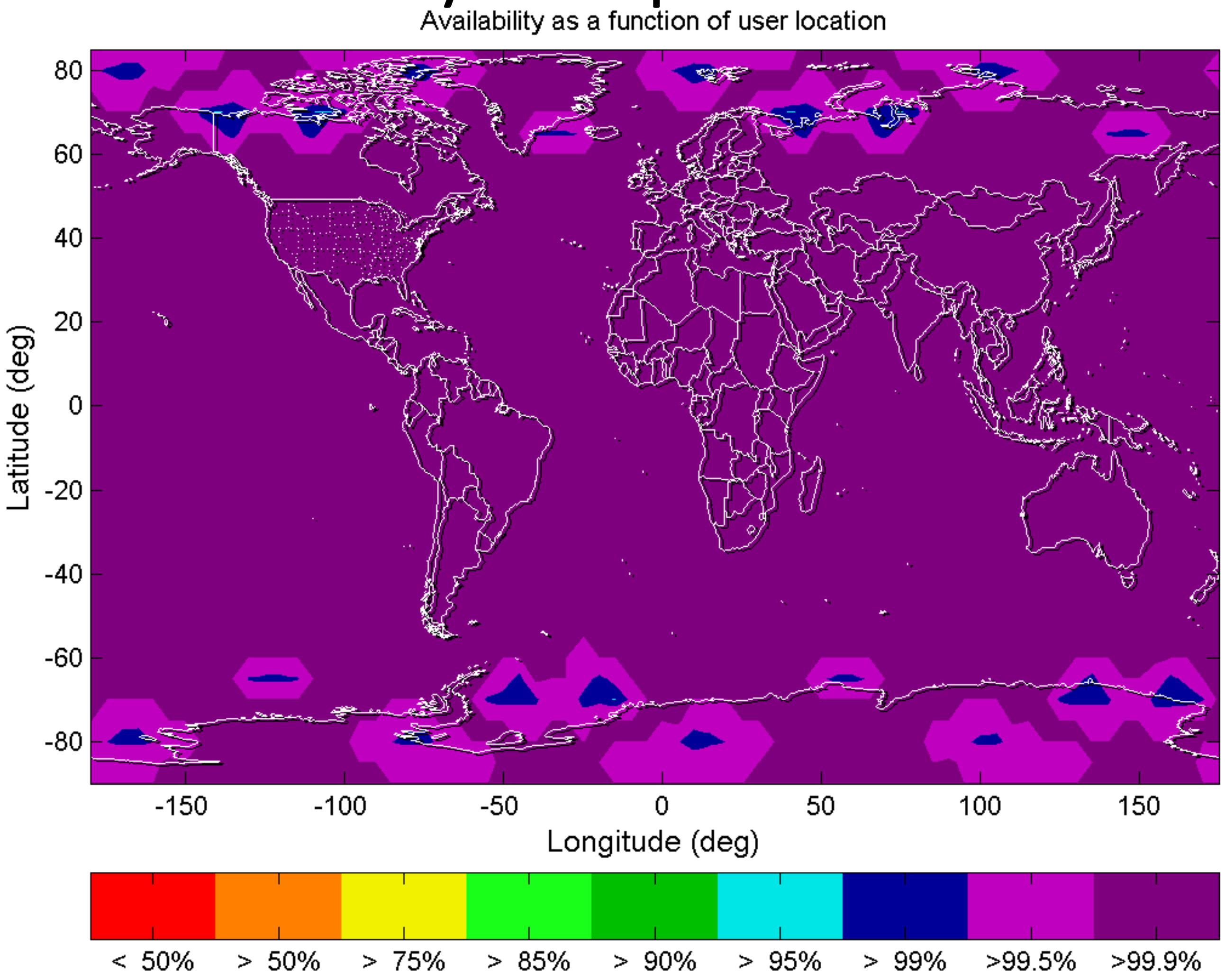
Integrity Support Message : $\sigma_{URA,i}$ $P_{sat,i}$ $P_{const,j}$

Integrity Support Message

	Parameter	Description	Value	Size (bits)
Data Header	ISM_WN	ISM Week Number	[0, 1, … 1023]	10
Data Header	ISM_TOW	ISM Time of Week (hours)	[0, 1, … 167]	8
Data Header	ANSP ID	Service Provider Identification	[0, 1, … 255]	8
Data Header	Criticality	Usable for Precise/Vertical?	[0, 1]	1
	Total Header = 27 bits			
Per Constellation Parameters	$Mask_i$	32 bits indicating whether an SV is valid for ARAIM (1) or not (0)	$[m_1, m_2, \dots m_{32}]$	32
Per Constellation Parameters	$P_{const,i}$	Probability of constellation fault at a given time	$[10^{-8}, 10^{-5}, 10^{-4}, 10^{-3}]$	2
Per Constellation Parameters	$P_{sat,j}$	Probability of satellite fault at a given time	$[10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}]$	2
Per Constellation Parameters	$\alpha_{URA,j}$	Multiplier of the URA for integrity	[1, 1.25, 1.5, 2, 2.5, 3, 5, 10]	3
Per Constellation Parameters	$\alpha_{URE,j}$	Multiplier of the URA for continuity & accuracy	[0.25, 0.5, 0.75, 1, 1.25, 1.5, 2, 4]	3
Per Constellation Parameters	$b_{nom,j}$	Nominal bias term in meters	[0.0:0.25: 2.5,, 3, 4, 5, 7.5, 10]	4
	Total Core = 46 bits x 4 Constellations = 184 bits			

Would fit in one SBAS message (250 bits), or in one GPS CNAV message (300 bits)

Multi-constellation L1-L5 ARAIM availability map



VAL = 35, HAL = 40, EMT_{th} = 15, σ_{acc} = 1.87, Coverage(99.5%) = 98.79%

GPS 24 – Galileo 24

URA = 1 m

$P_{const} = 10^{-4}$

Vertical ARAIM: L1-L5 performance

LPV-200

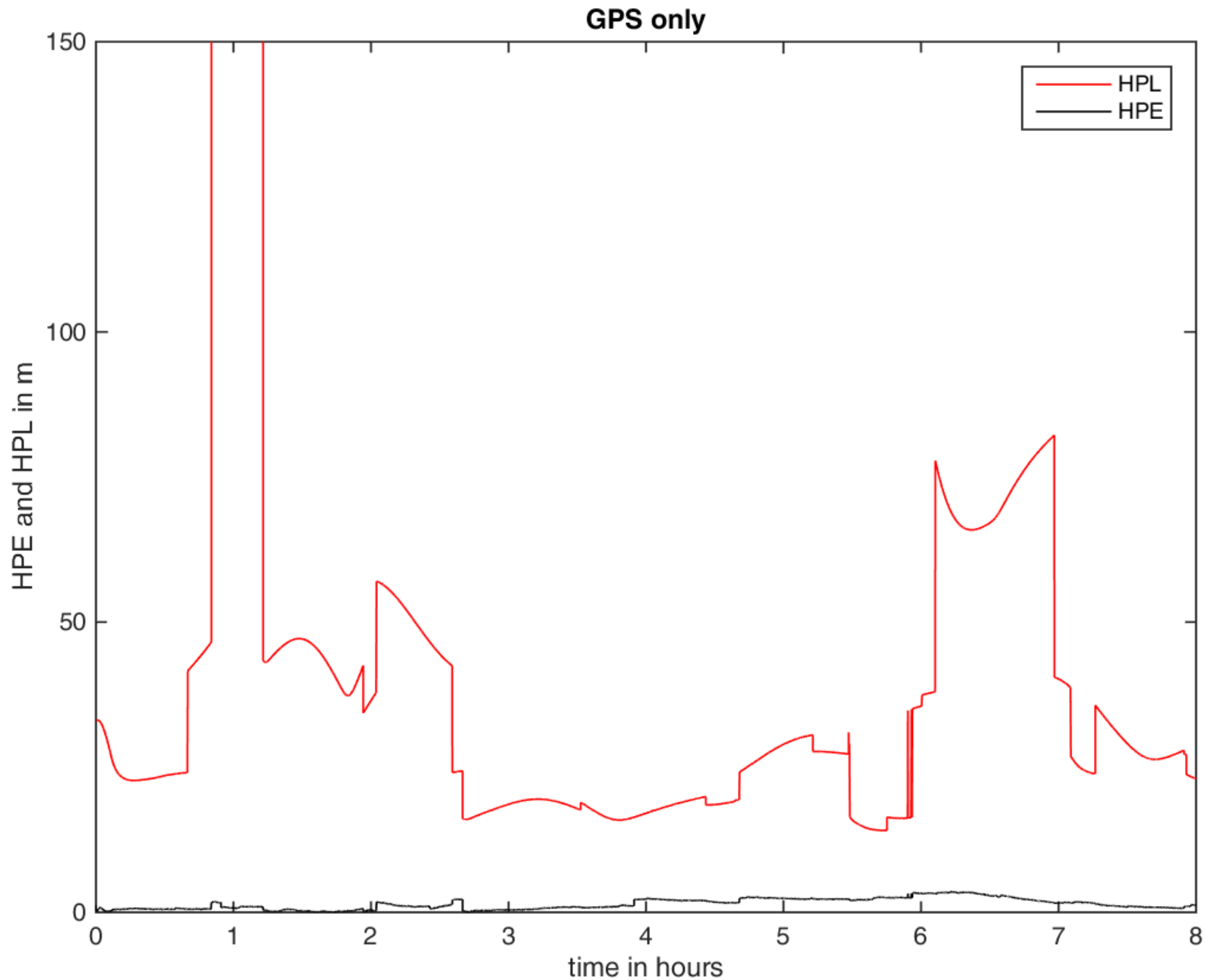
Constellation/URA	.5 m	.75 m	1 m	1.5 m	2 m
Depleted (GPS 23 – GAL 23)	88.1	86.1	81.3	38.1	0
Baseline (GPS 24 – GAL 24)	100	100	98.8	88.2	3
Optimistic (GPS 27 – GAL 27)	100	100	99.8	94.9	21.8

LPV-250

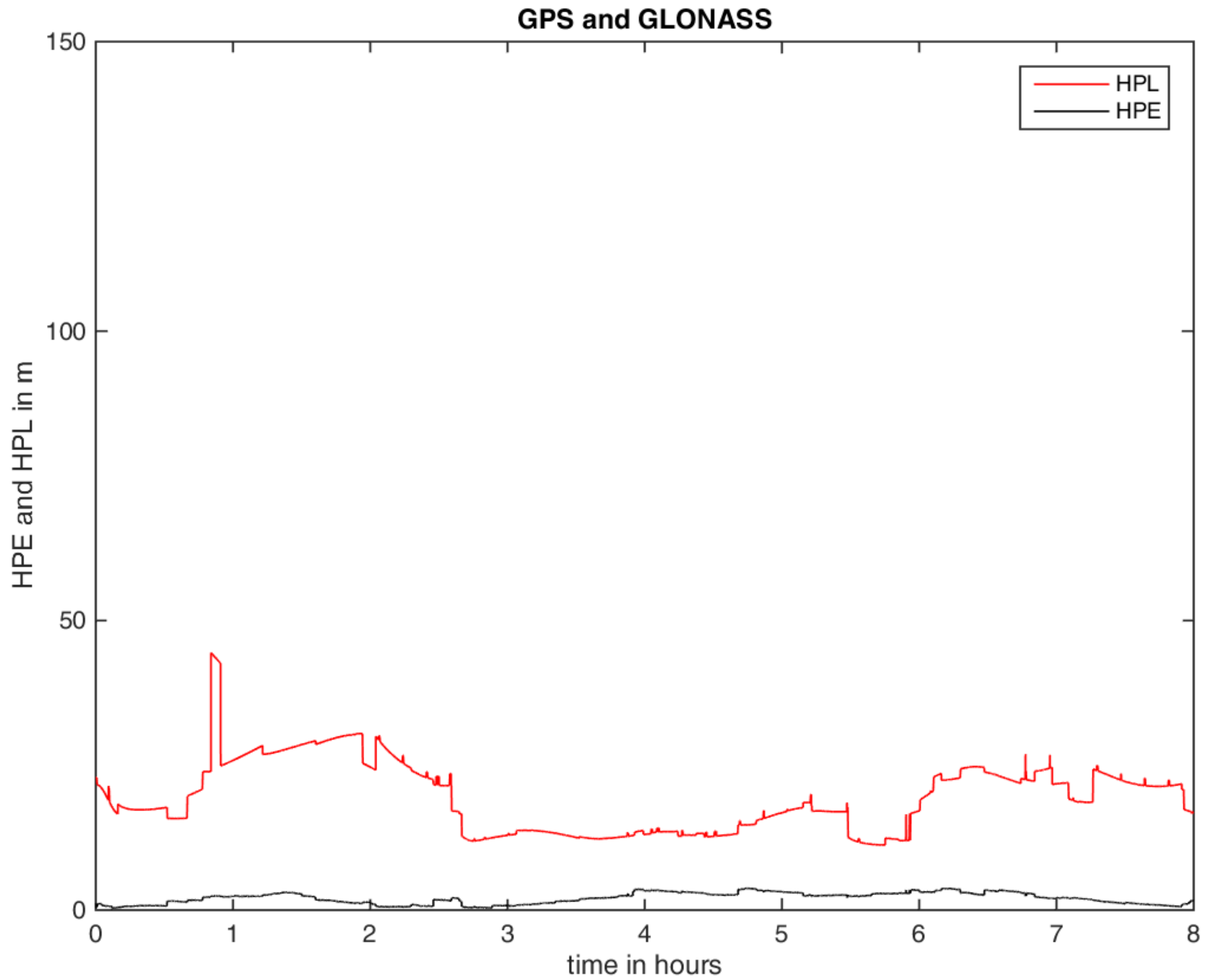
Constellation/URA	.5 m	.75 m	1 m	1.5 m	2 m
Depleted (GPS 23 – GAL 23)	94.0	91.8	87.7	75.0	35.4
Baseline (GPS 24 – GAL 24)	100	100	100	99.0	89.5
Optimistic (GPS 27 – GAL 27)	100	100	100	100	93.85

Constellation wide fault is mitigated by the residuals check: $P_{const} = 10^{-4}$

Horizontal ARAIM with GPS only (matches current RAIM performance)



Horizontal ARAIM with GPS and GLONASS



Summary

- Advanced RAIM is a natural and very promising method to exploit multi-constellation GNSS.

- It will improve dramatically horizontal performance and may provide vertical guidance

- Advanced RAIM is conceptually simple (at the user level)

- Challenges remain for the determination of the Integrity Support Message

Reports and publications

- Working Group C, ARAIM Technical Subgroup, Interim Report, Issue 1.0, December 19, 2012. Available at:

http://ec.europa.eu/enterprise/newsroom/cf/_getdocument.cfm?doc_id=7793

http://www.gps.gov/policy/cooperation/europe/2013/working-groupc/ARAIM-report-1.0.pdf

- GPS-Galileo Working Group C ARAIM Technical Subgroup Milestone 2 Report, February 11, 2015. Available at:

http://www.gps.gov/policy/cooperation/europe/2015/working-group-c/

http://ec.europa.eu/growth/tools-databases/newsroom/cf/itemdetail.cfm?item_id=8191

Other publications:

- Walter, Todd, Blanch, Juan, "Characterization of GNSS Clock and Ephemeris Errors to Support ARAIM," *Proceedings of the ION 2015 Pacific PNT Meeting*, Honolulu, Hawaii, April 2015, pp. 920-931.
- Blanch, J., Walter, T., Enge, P., Kropp, V.,"A Simple Position Estimator that Improves Advanced RAIM Performance," *IEEE Transactions on Aerospace and Electronic Systems* Vol. 51, No. 3, July 2015.
- Blanch, J., Walter, T., Enge, P., Lee, Y., Pervan, B., Rippl, M., Spletter, A., Kropp, V., "Baseline Advanced RAIM User Algorithm and Possible Improvements," *IEEE Transactions on Aerospace and Electronic Systems*, Volume 51, No. 1, January 2015.
- Blanch, J., Walter, T., and Enge, P.,"Results on the Optimal Detection Statistic for Integrity Monitoring," *Proceedings of the Institute of Navigation International Technical Meeting 2013*, San Diego, January 2013. Submitted to NAVIGATION.
- Phelts, R.E., Blanch, J., Walter, T., Enge, P., "The Effect of Nominal Signal Deformation Biases on ARAIM Users," Proceedings of the 2014 International Technical Meeting of The Institute of Navigation, San Diego, California, January 2014, pp. 56-67.