A Global Safety of Life Service from Multiple GNSS Constellations (e.g. GPS + Compass)

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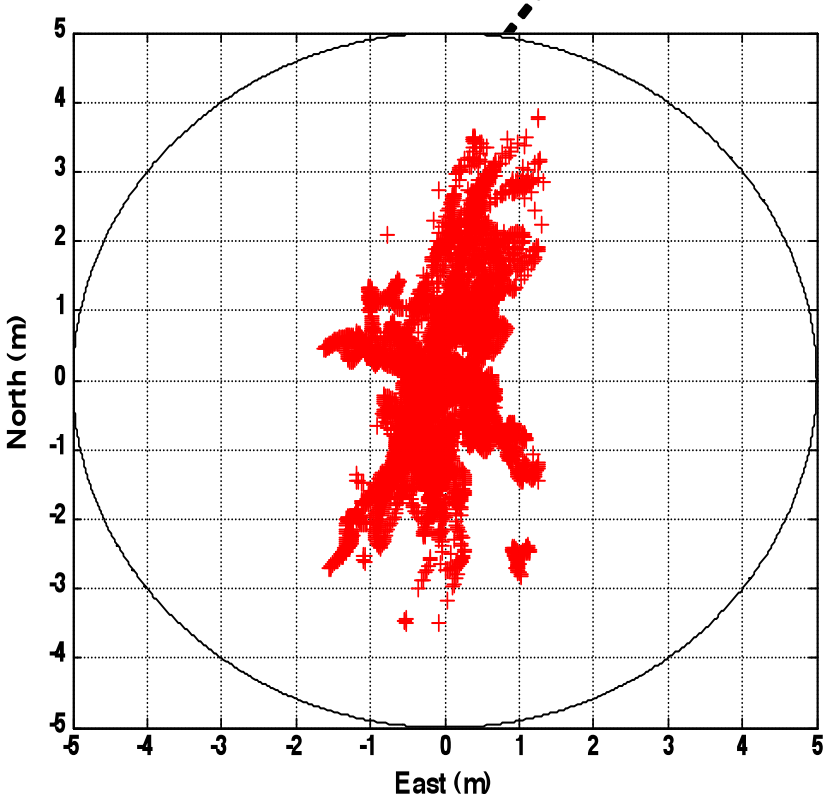
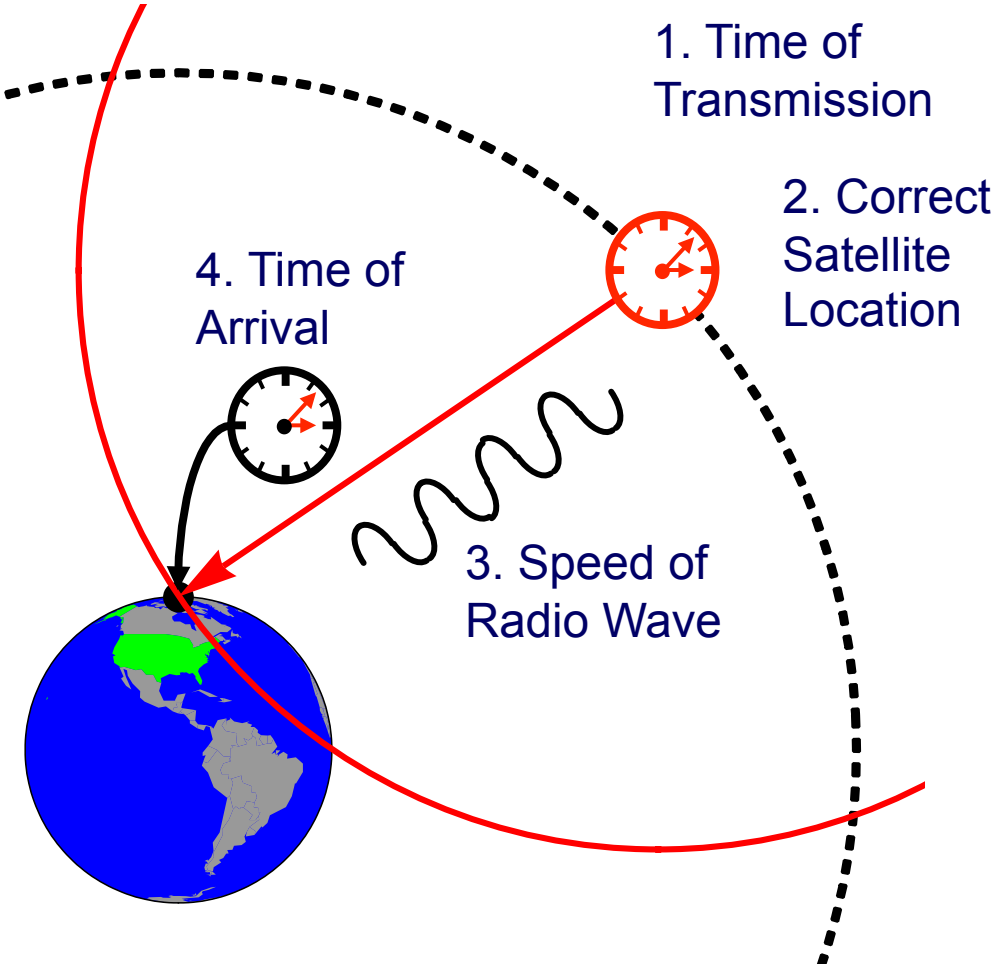
This briefing is NOT intended to convey a US Government position; rather, it is provided to facilitate a working-level discussion and exchange of ideas.

GPS Essential Ingredients & Normal Performance

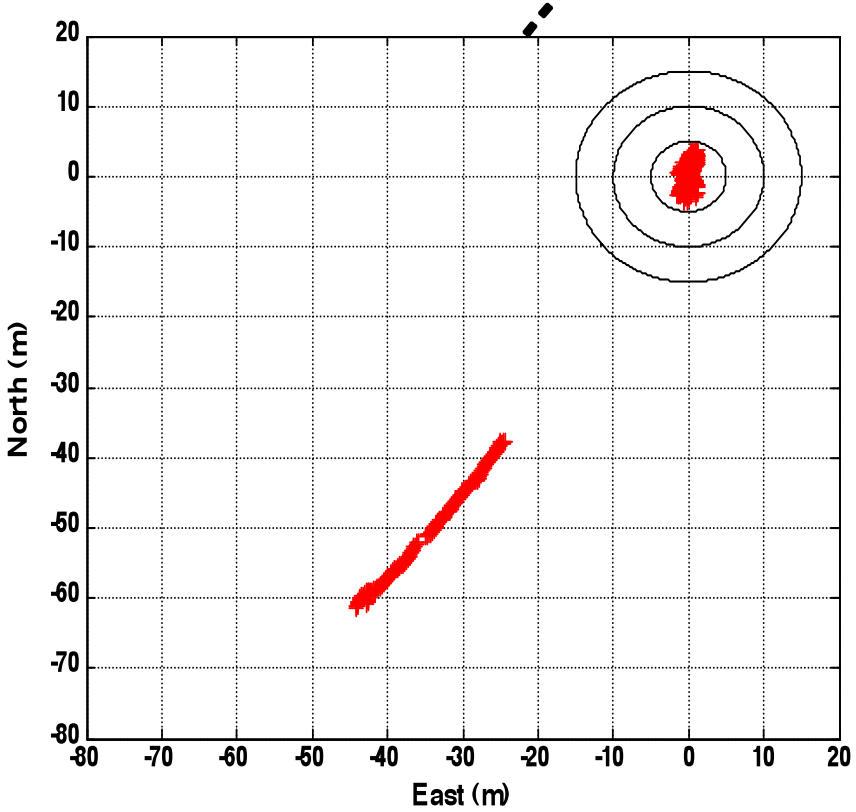


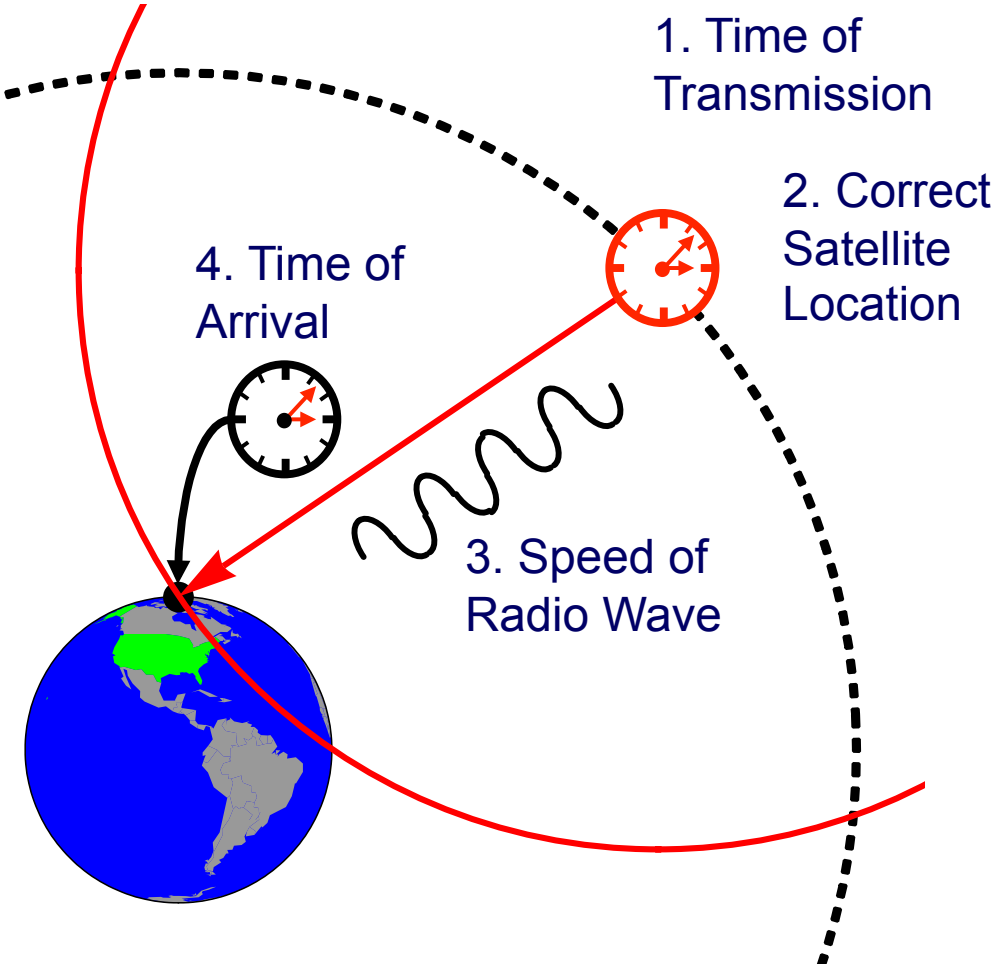


Our Canoe

But Every Once in a While

GPS Faults Occur Three Times a Year
Rare Normals Due to Space Weather

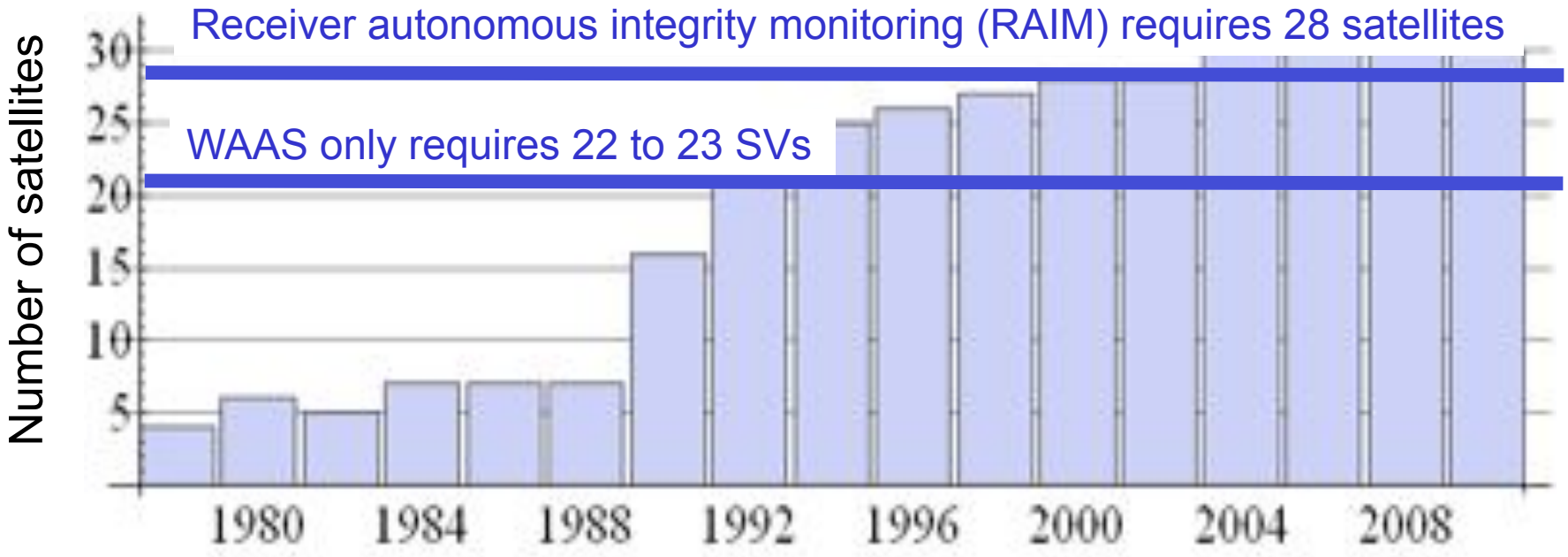




Today's Single Frequency Technology for Detection of GPS Faults

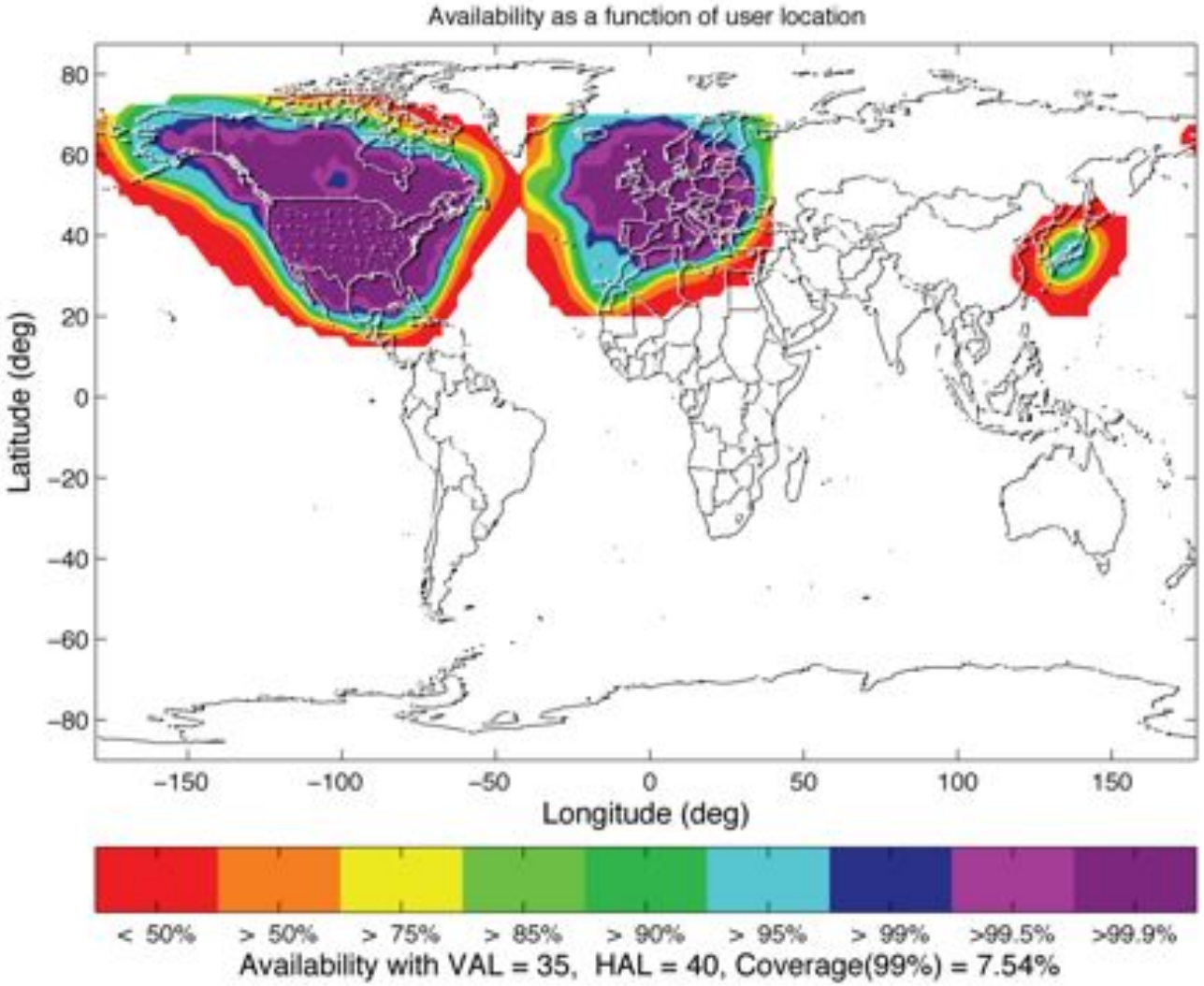
<table>
<tr><th colspan="3">Positioning & Fault Detection</th><th>Navigation</th><th>Surveillance</th></tr>
<tr><td rowspan="5"></td><td rowspan="4"></td><td rowspan="3"></td><td>En Route</td><td>5 nm</td></tr>
<tr><td rowspan="2">Terminal & LNAV</td><td rowspan="2">3 nm</td></tr>
<tr><td rowspan="3">RNP</td></tr>
<tr><td rowspan="3">GBAS
detect
10 (28) m
in 2 sec.
vertical &
horizontal
(23 sats)</td><td rowspan="2">SBAS
detect
35 m in
6 seconds
vertical &
horizontal
(22 sats)</td><td rowspan="2">RAIM
detect
200 m in
2 seconds
(28 sats)</td></tr>
<tr><td>LPV
LPV-200</td><td>Independent
parallel
approaches</td></tr>
<tr><td colspan="3"></td><td>Cat I &
Cat II/III</td><td>Independent
parallel
approaches</td></tr>
</table>

Compared to RAIM, SBAS Provides More Performance With Fewer MEO Satellites



- Each GEO is roughly equivalent to 2 or 3 satellites.
- SBAS compares satellites to ground truth
- RAIM compares satellites to satellites

Coverage of Space Based Augmentation Systems (WAAS, EGNOS & MSAS, from Dr. T. Walter)



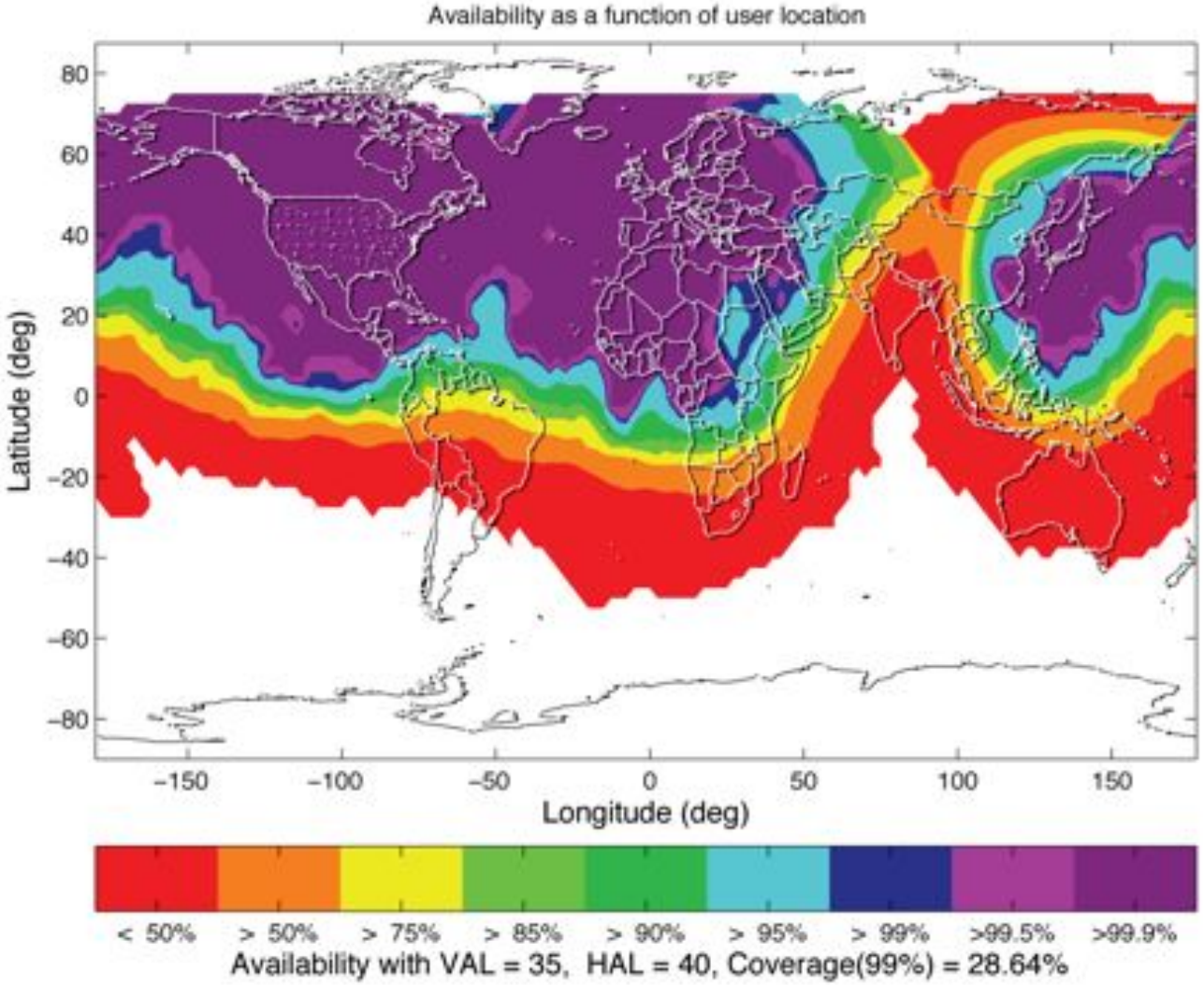
Utility of Dual Frequencies & Multiple Constellations

<table>
<tr><th colspan="2">Positioning & Fault Detection</th><th>Navigation</th><th>Surveillance</th></tr>
<tr><td rowspan="5">Dual freq GBAS detect 10 m in 2 sec. (23 sats)

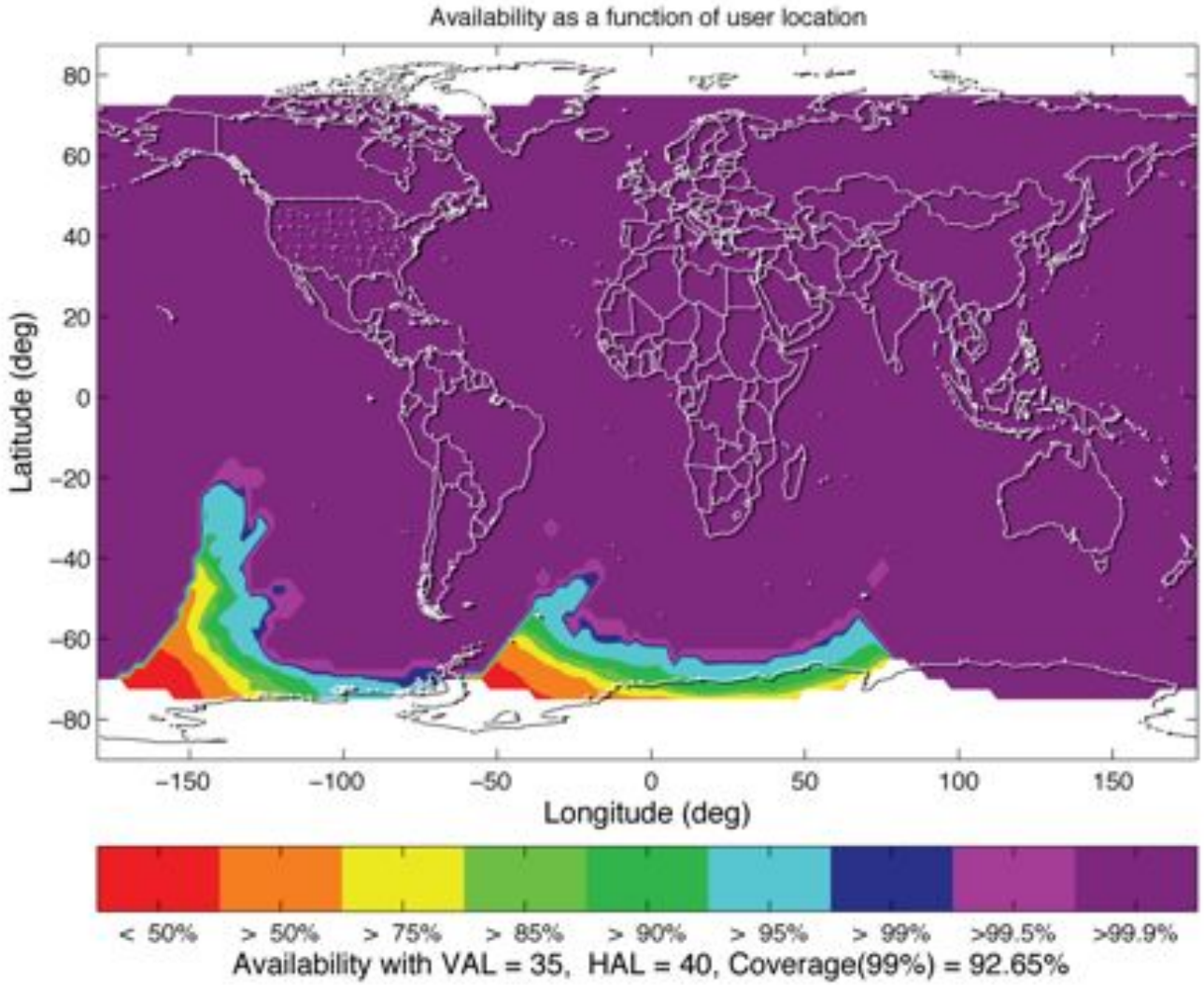
Hardened against RFI</td><td rowspan="4">Dual freq SBAS

Research & Development on Multi-constellation ARAIM</td><td>En Route</td><td>5 nm</td></tr>
<tr><td>Terminal & LNAV</td><td>3 nm</td></tr>
<tr><td>RNP</td><td>Dependent parallel approaches</td></tr>
<tr><td>LPV
LPV-200</td><td>Independent parallel approaches</td></tr>
<tr><td>Cat I & Cat II/III</td><td>Independent parallel approaches</td></tr>
</table>

Dual Frequency Coverage
(WAAS, EGNOS, MSAS, from Dr. T. Walter)



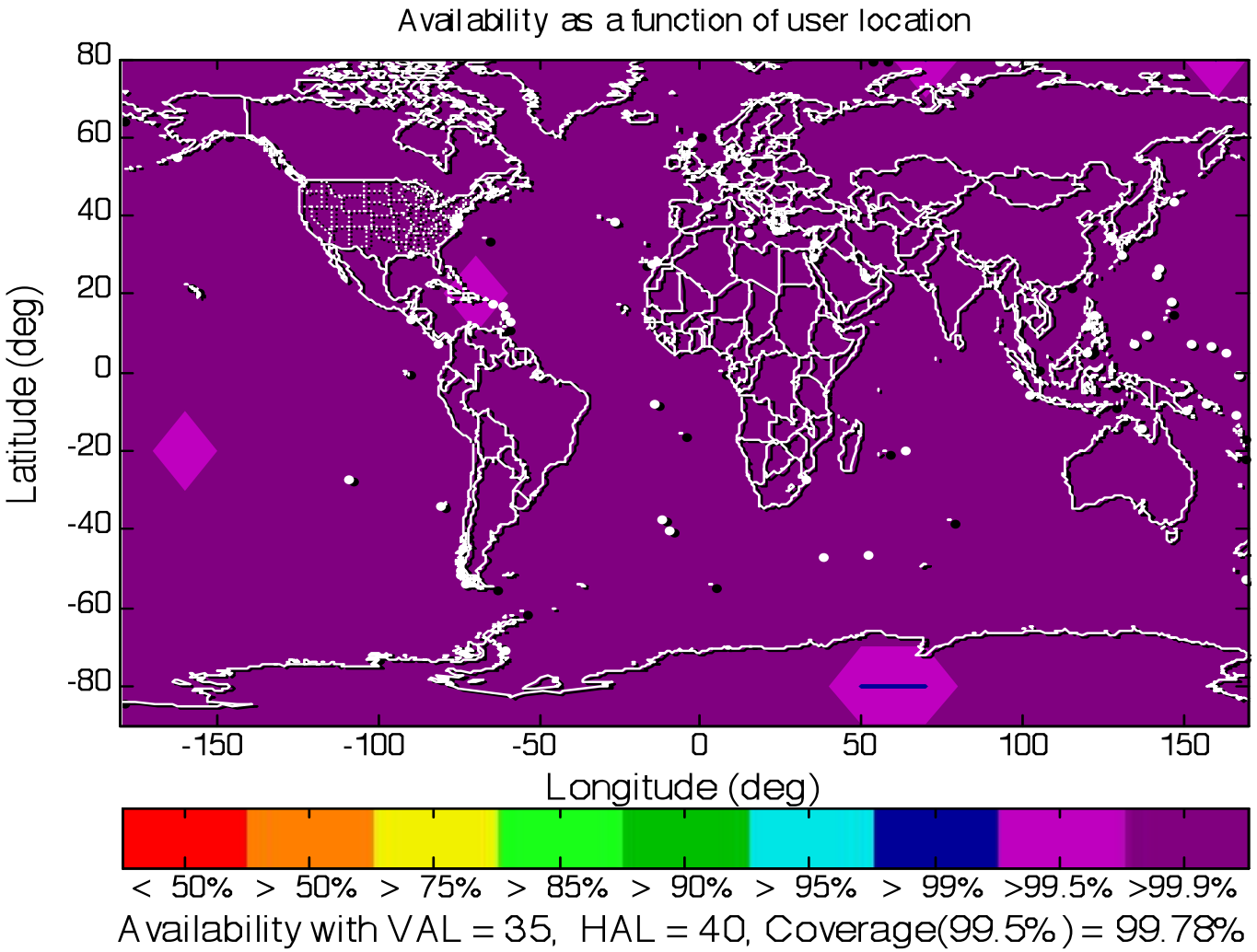
Dual Frequency, Dual GNSS, Expanded Networks (from Dr. T. Walter)



But it will cost $200M to add the 2nd string of reference receivers to WAAS. (and what if we add the wrong string?)

Data capacity could also be an issue.

Dual Frequency Advanced RAIM With 27 GPS + 27 Other GNSS (from Dr. J. Blanch)



Allow other constellations.

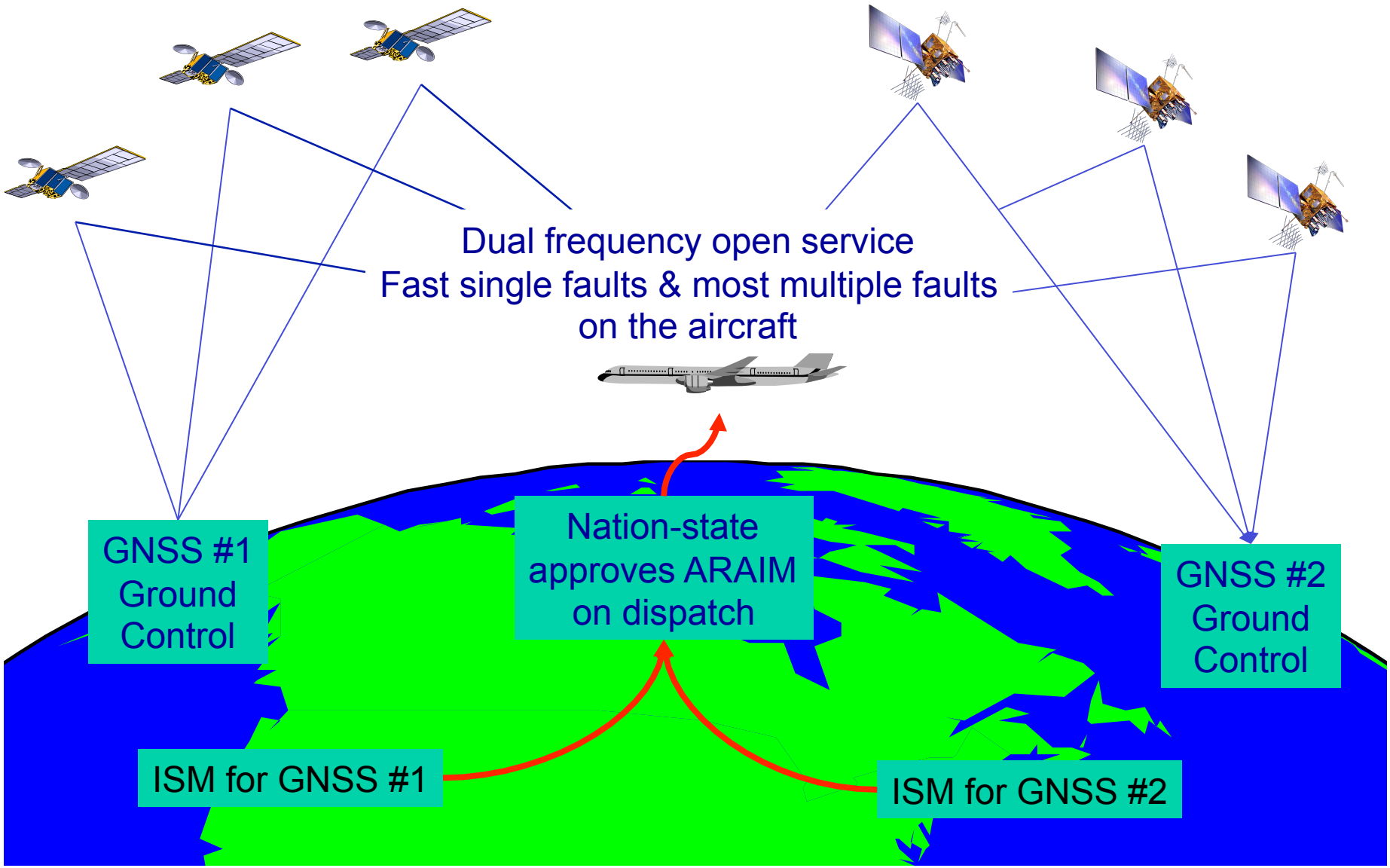
Robust to weak constellations ?

URA = 1m

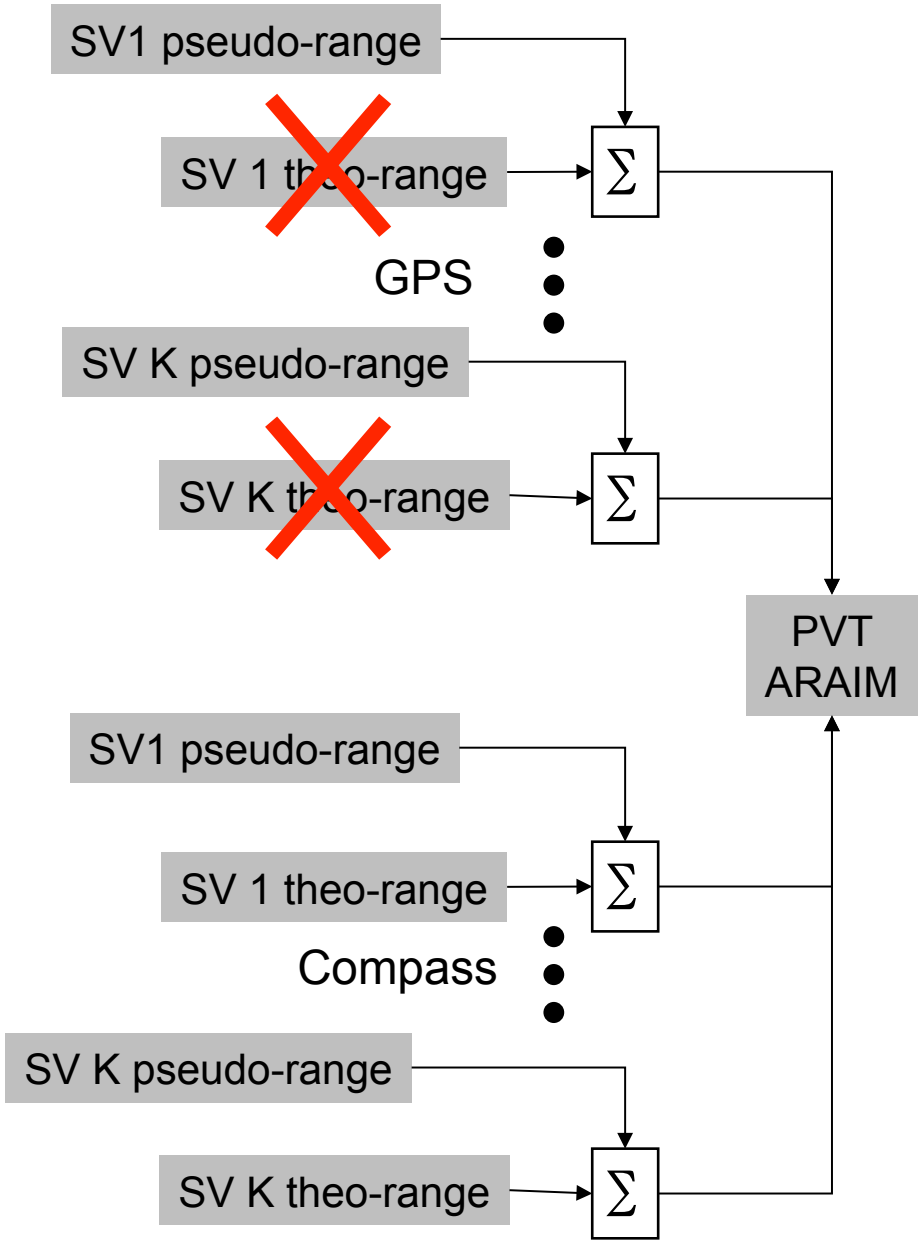
$P_{sat}=10^{-3}$

$P_{const} = 10^{-6}$

Receiver Autonomous Integrity Monitoring (RAIM) + Integrity Support Message (ISM)



ARAIM Challenge



Common cause for SV theo-range faults have been posited:

- Earth orientation parameters
- Bad clock rotates ephemeris
- Widespread URA optimism

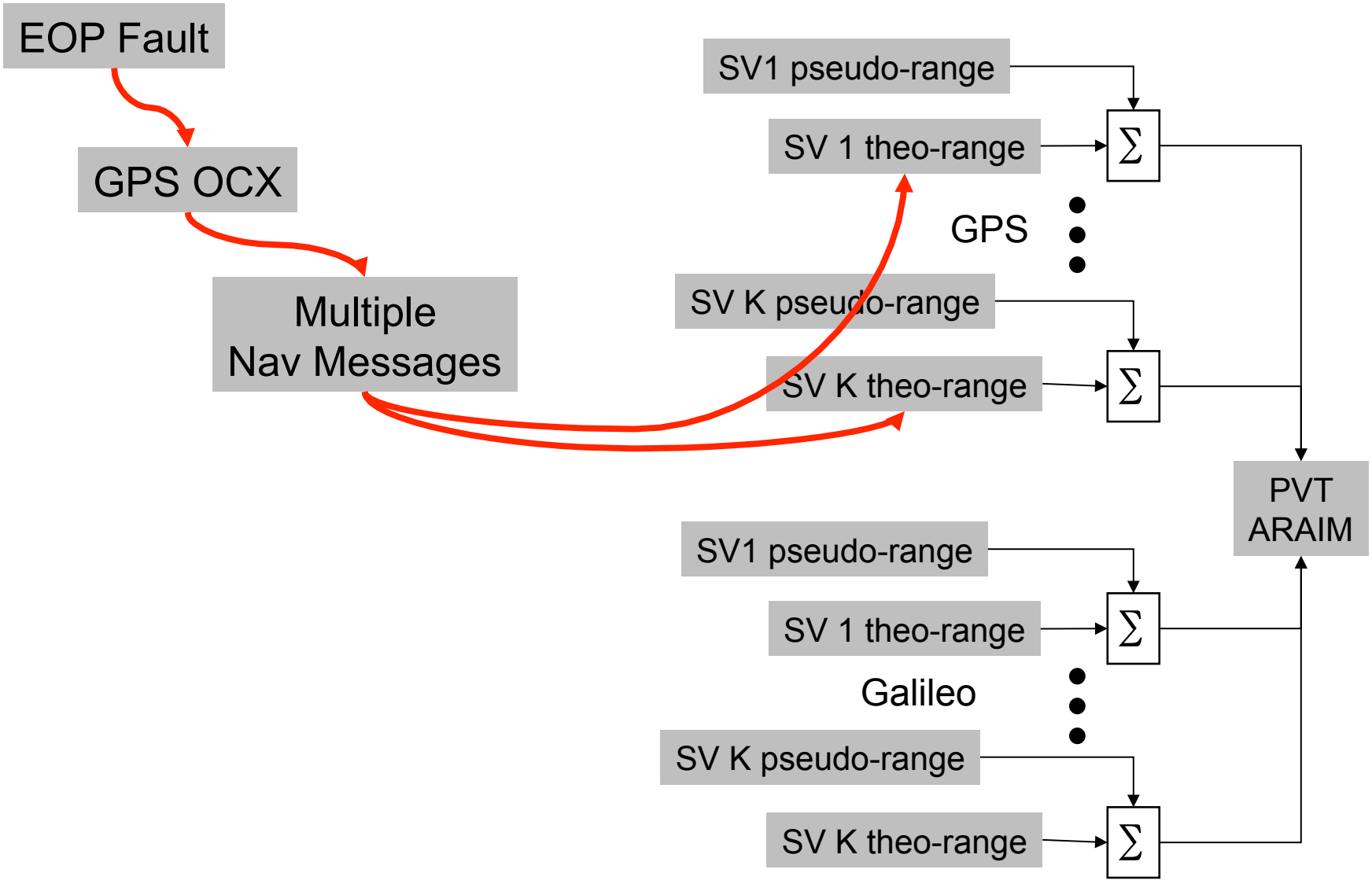
Seeking Something Sublime

- Aviation wants to use the new GNSS
- Availability & continuity
- Aviation does not want the downside
  - if a GNSS constellation becomes weaker
  - if a GNSS constellation has a spate of faults
- Aviation does want the upside
  - if integrity performance improves
  - e.g. clocks are added or URA reduced
  - e.g. GPS performance has improved dramatically in the last ten years
  - LPV-100 from space

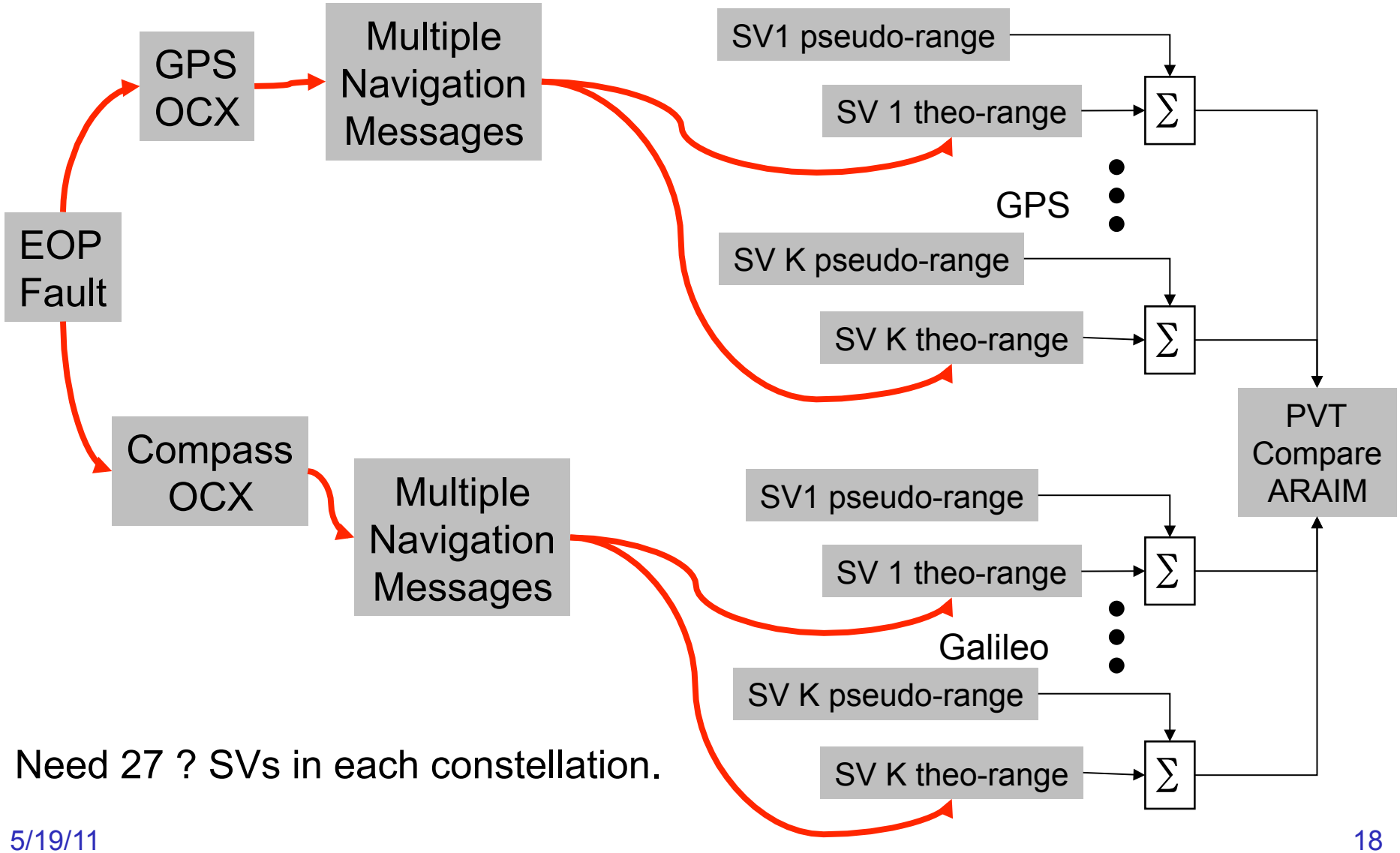
ARAIM + SBAS Mixtures

	Air & ground responsibilities	Update rate	# SVs (?)	Risk (of proof)
I	ARAIM Ground: priors & URAs	hourly	27 + 27	High ! EOP + Level D
II	ARAIM + constellation cross check Ground: priors & URAs	hourly	30 + ?	Medium EOP common cause
III	ARAIM Ground: priors & URAs Ground: level B GNSS nav. messages	hourly	27 + 27	Low Must build a global network with level B
IV	Regional SBAS for primary GNSS ARAIM for secondary GNSS	real time	18 + 18?	Low, availability penalty for high URAs for secondary GNSS
V	Regional SBAS for primary Global civil network: priors & URAs	real time	15 + 15?	Low, availability credit from low URAs

I. Prove that multi-satellite navigation message faults cannot cause HMI since the last ISM.

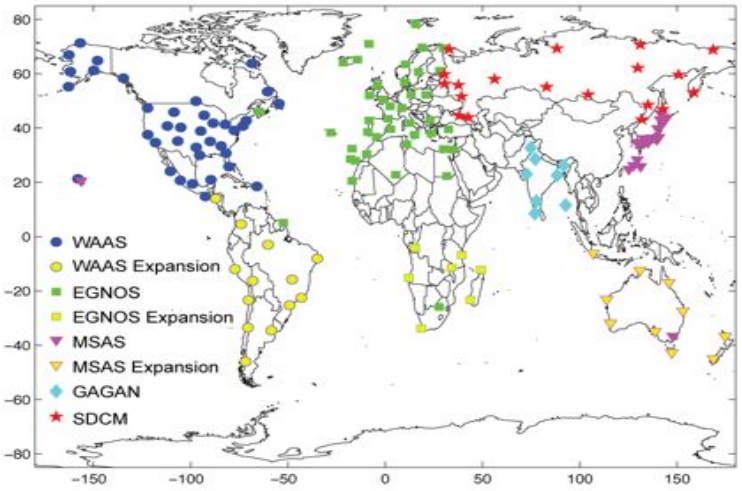


II. Believe that multi-SV failures are independent from one constellation to another



Need 27 ? SVs in each constellation.

III. Use SBAS monitoring network & ISM to replace the navigation message



GPS OCX

SV1 pseudo-range

SV 1 theo-range

GPS

SV K pseudo-range

SV K theo-range

Σ

Σ

PVT ARAIM

Compass OCX

SV1 pseudo-range

SV 1 theo-range

Compass

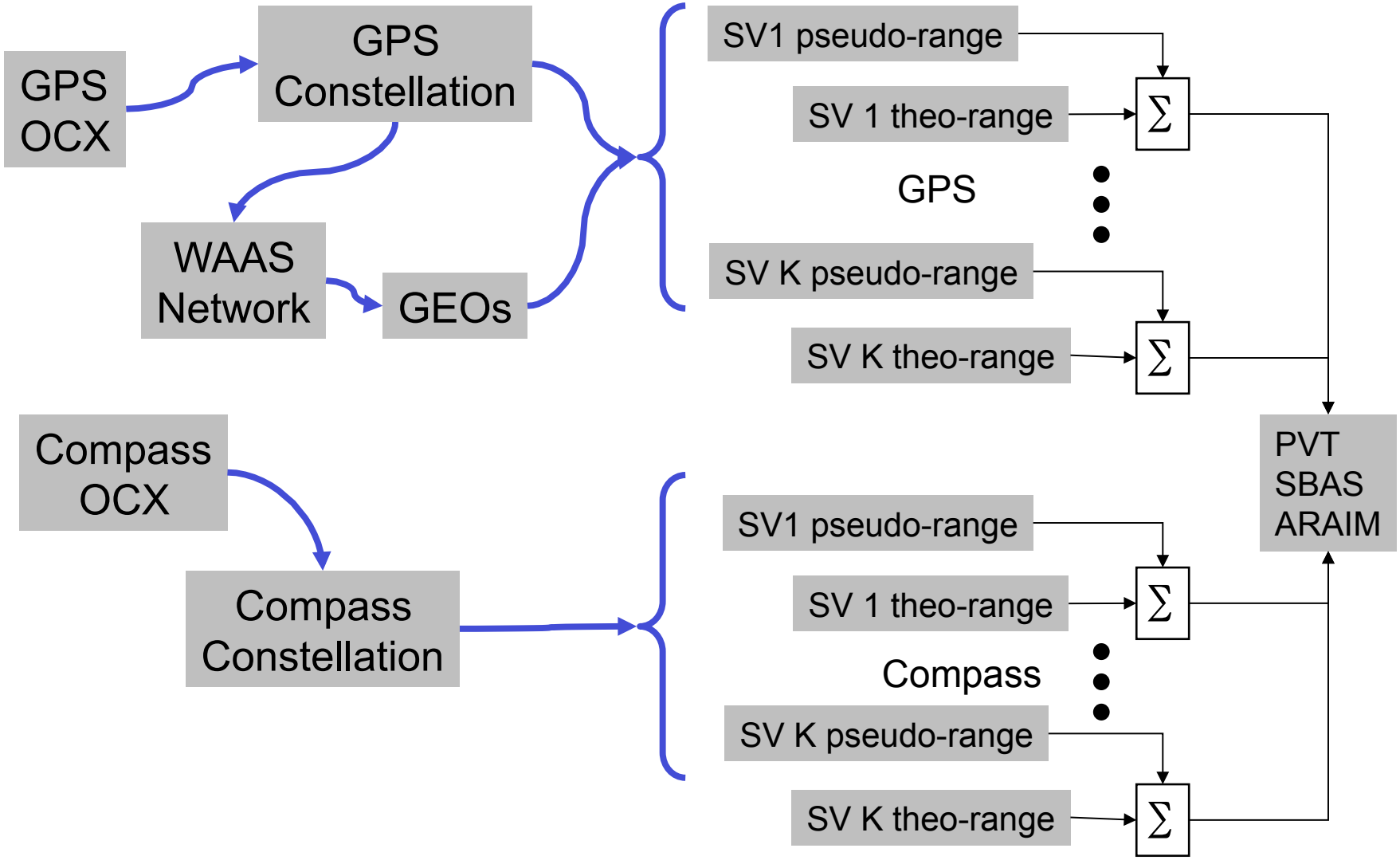
SV K pseudo-range

SV K theo-range

Σ

Σ

IV. Use SBAS to monitor one constellation and use ARAIM to accept SVs from other constellations.



V. Need Global Network to Reduce the URAs

GPS 27 + GNSS 27

less accuracy (URA) →

Less constellation reliability ↓

Less satellite reliability ↓

P_{sat}/URA	.5 m	1 m	1.5m	2 m	3 m	3.5 m	4 m	
10^{-5}	100%	100%	100%	100%	100%	42.9%	3.4%	
10^{-4}	100%	100%	100%	100%	100%	0	0	$P_{const} < 10^{-8}$
10^{-3}	100%	100%	100%	99.6%	6.6%	0	0	
10^{-5}	100%	100%	95.0%	51.5%	0	0	0	
10^{-4}	100%	100%	95.0%	51.5%	0	0	GPS?	$P_{const} = 10^{-6}$
10^{-3}	100%	100%	95.0%	51.3%	0	0	0	
10^{-5}	100%	98.5%	79.2%	0.1%	0	0	0	
10^{-4}	100%	98.5%	79.2%	0.1%	0	0	GPS?	$P_{const} = 10^{-4}$
10^{-3}	100%	98.5%	79.2%	0.1%	0	0	0	

P_{sat} = Prob. of satellite fault
P_{const} = Prob.of constellation fault

b = 0.75 m

Summary:
Safety from Frequency & Geometric Diversity

- GPS + SBAS works
  - Over 70,000 aircraft installations
  - No known integrity failures
  - Hundreds of engineer-years to build
- Frequency diversity obviates iono storms & most RFI
- Multi-constellation requires something sublime
  - Geometric diversity from new GNSS
  - With 30 year equipment lifetimes, aviation cannot afford to be brittle.
  - Need elegant integration of SBAS and ARAIM