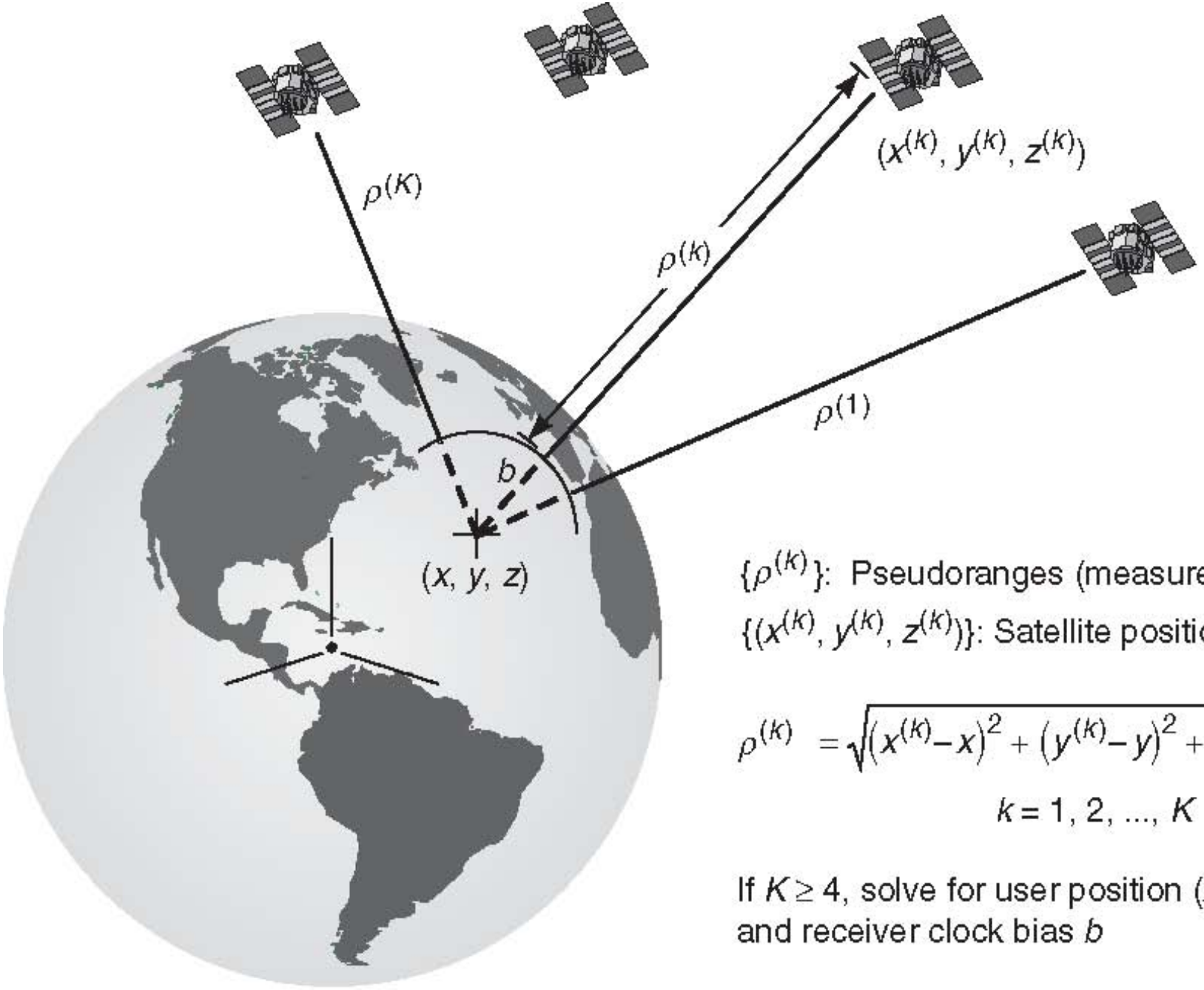
Thank you for inviting me to Calgary

On Location at Stanford University

by Per Enge (with the help of many)
May 29, 2009

With Gratitude to the Federal Aviation Administration



$\{\rho^{(k)}\}$: Pseudoranges (measurements)

$\{(x^{(k)}, y^{(k)}, z^{(k)})\}$: Satellite positions (known)

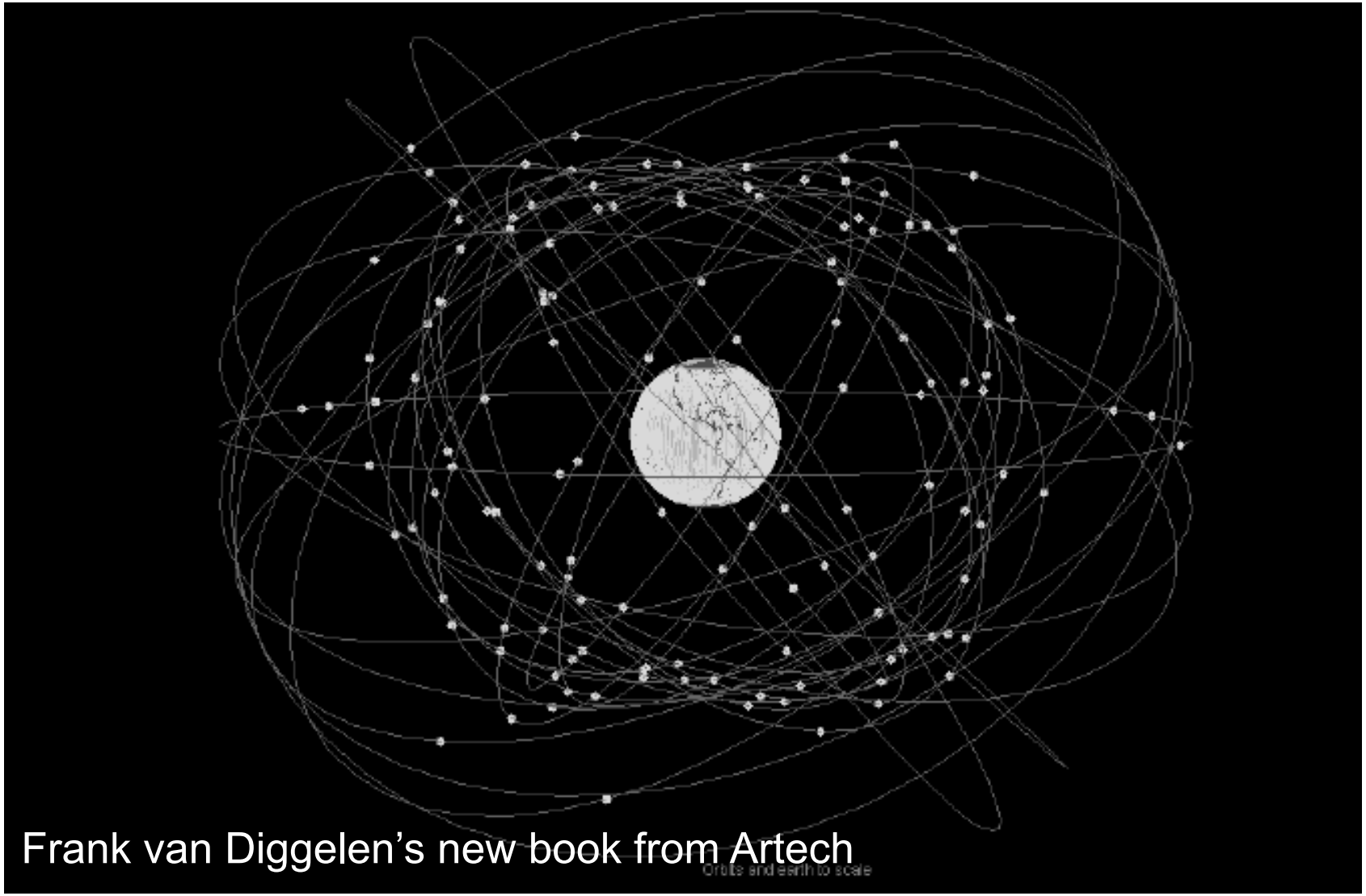
$$\rho^{(k)} = \sqrt{(x^{(k)}-x)^2 + (y^{(k)}-y)^2 + (z^{(k)}-z)^2} - b$$

$$k = 1, 2, \ldots, K$$

If $K \geq 4$, solve for user position (x, y, z), and receiver clock bias b

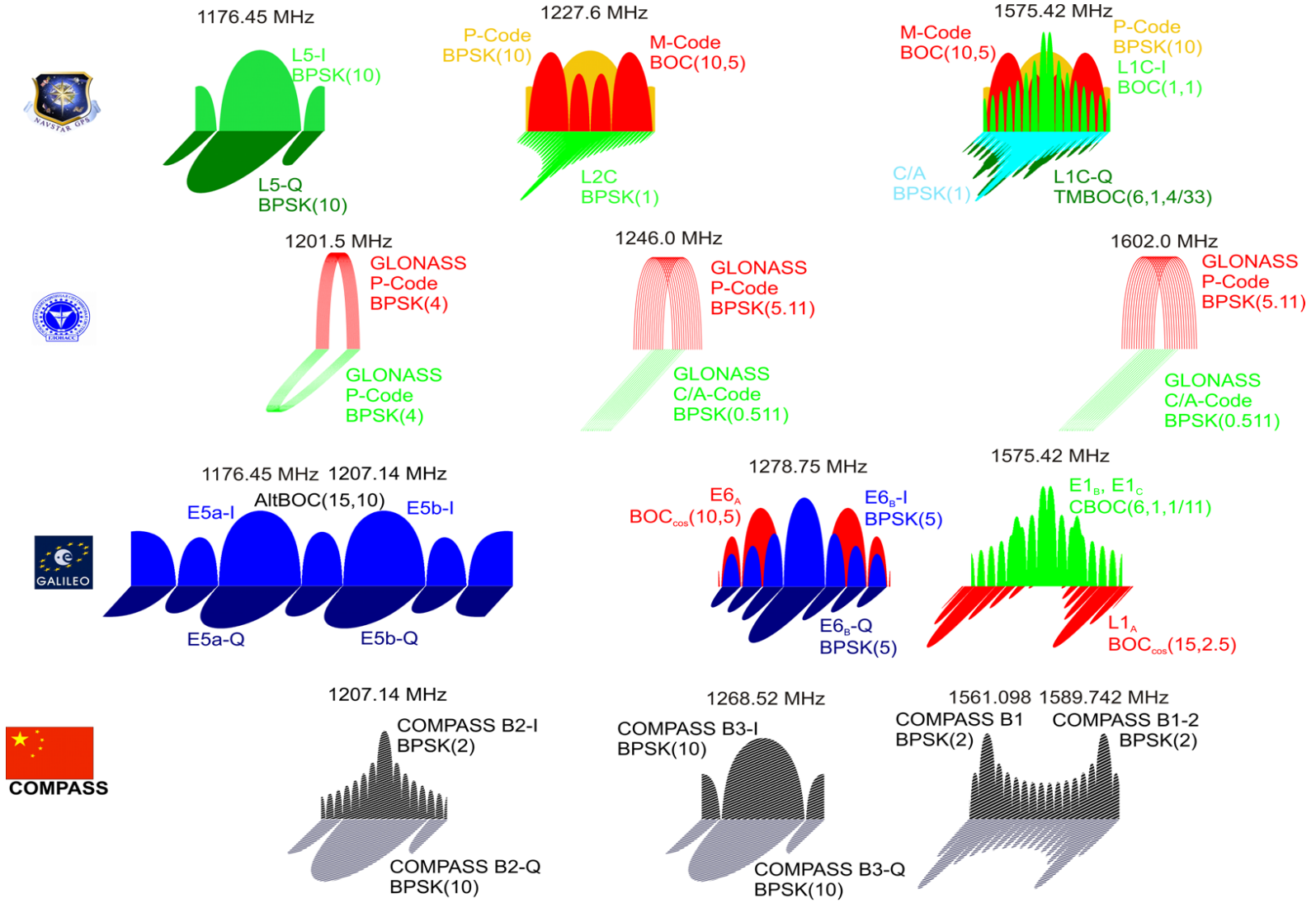
from Misra and Enge, 2006

GPS + Galileo + Compass + GLONASS
134 Navigation Satellites?

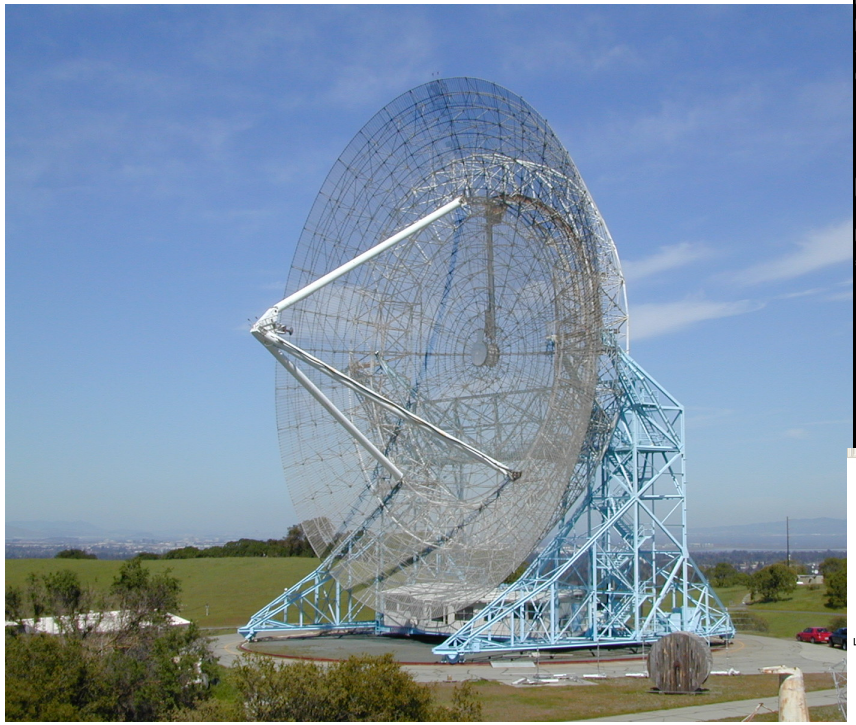


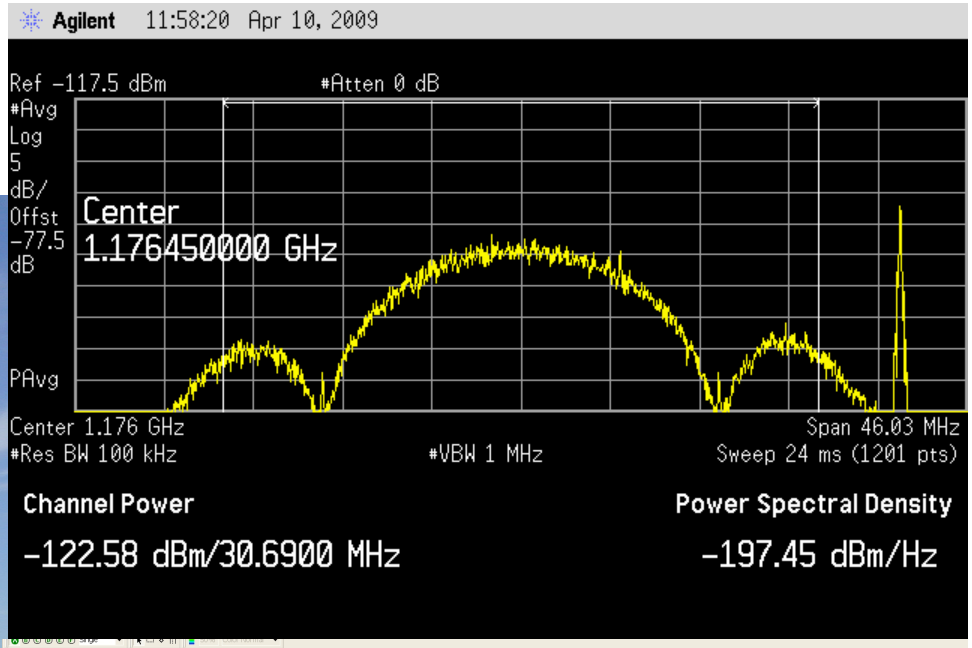
Frank van Diggelen's new book from Artech

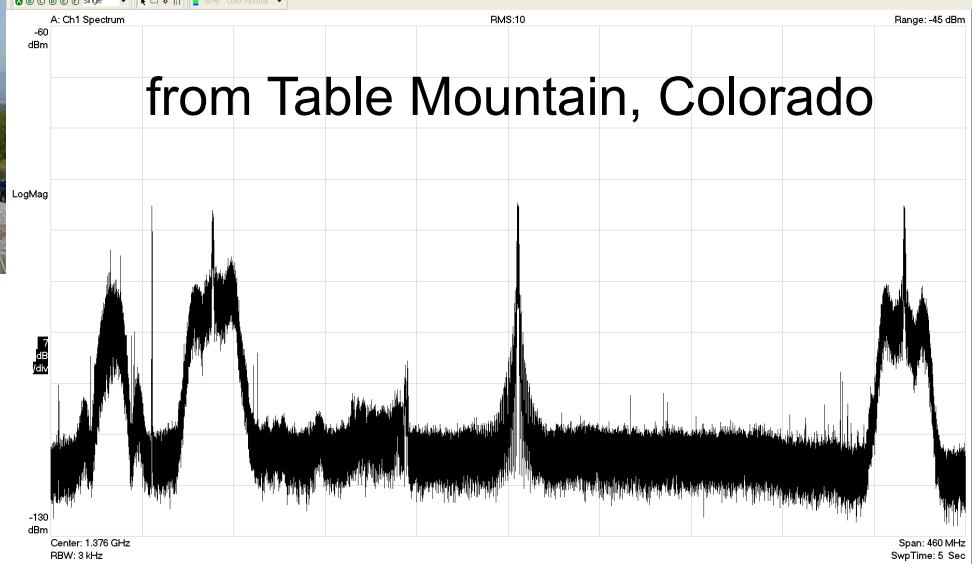
Future GNSS Signals



April 10, 2009 at 04:58 Pacific Time





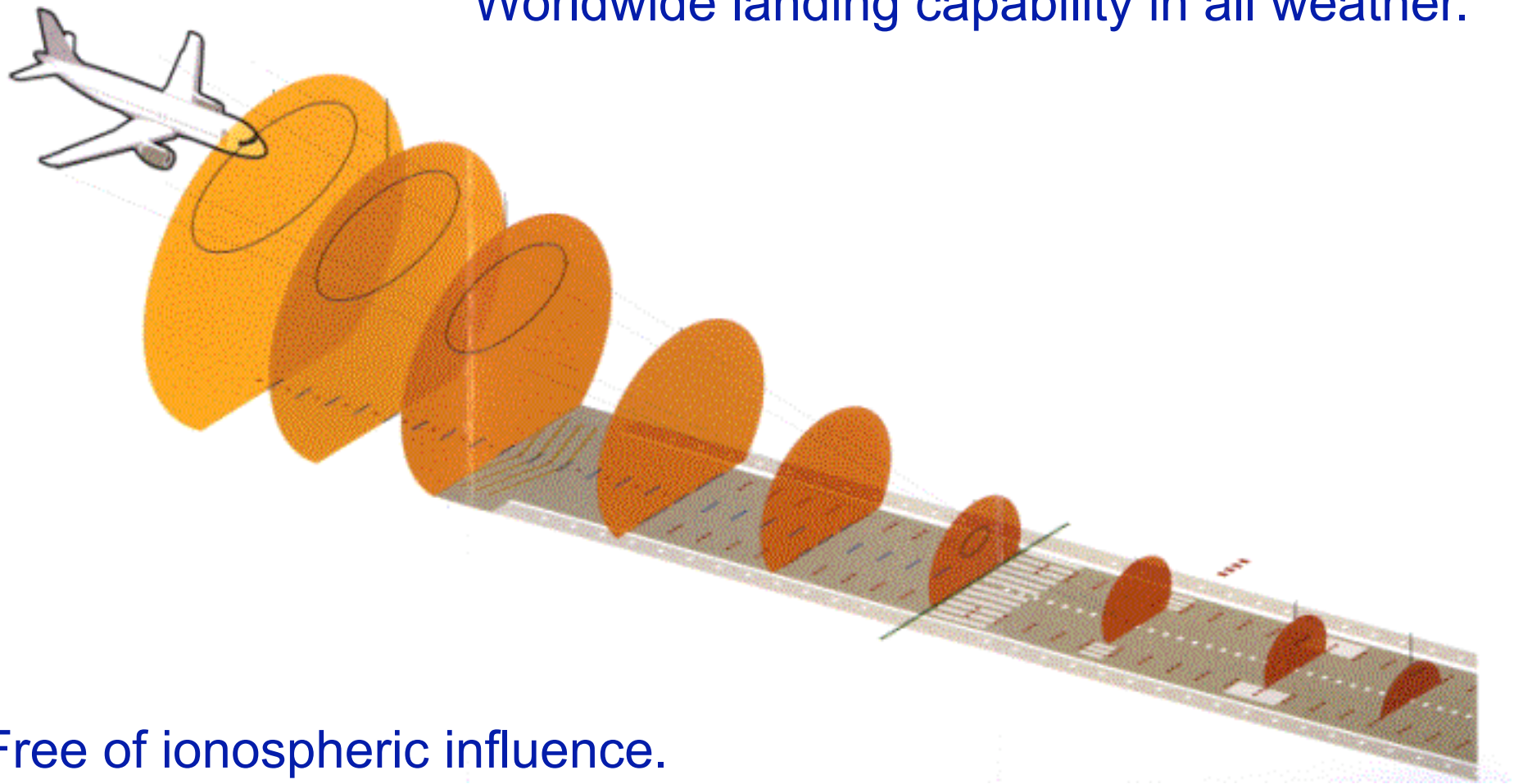


Outline

- Approach & Landing of Civil Aircraft
- Gravimetry Using Cold Atoms
- Geo-security

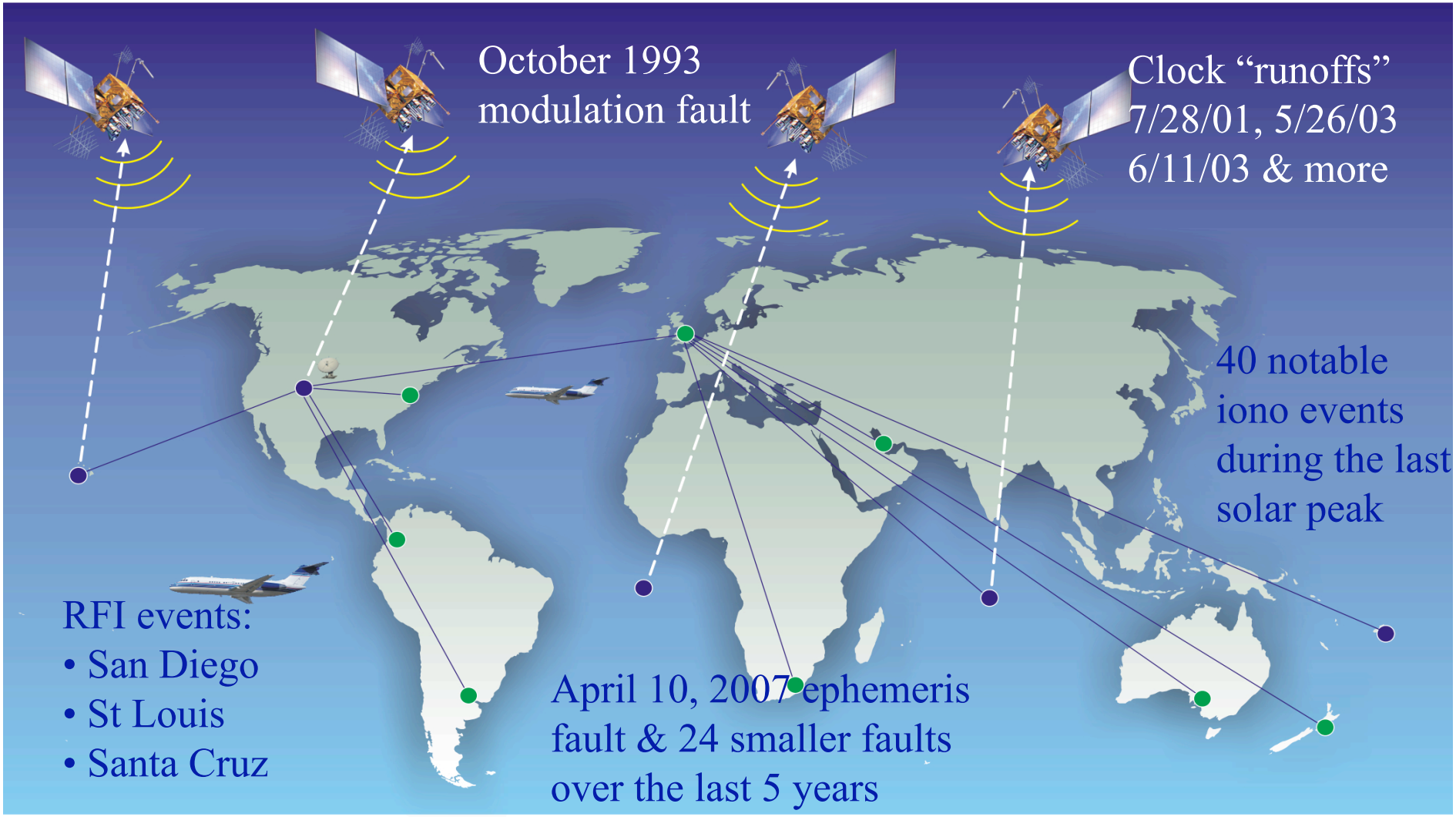
Approach & Landing

Worldwide approach capability with no airport equipment.
Worldwide landing capability in all weather.

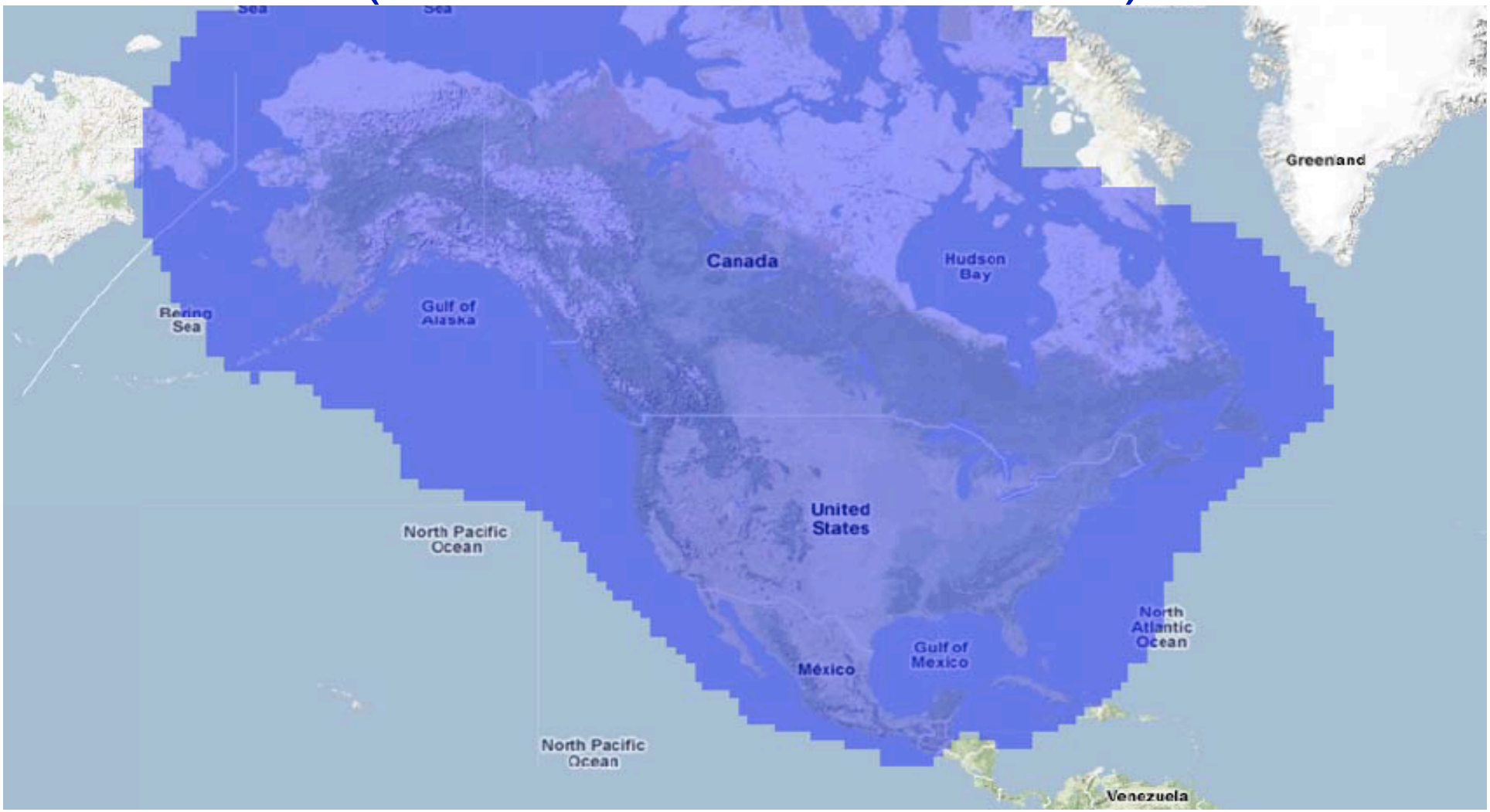


Free of ionospheric influence.
Robust against RFI (scheduled, accidental or malevolent).

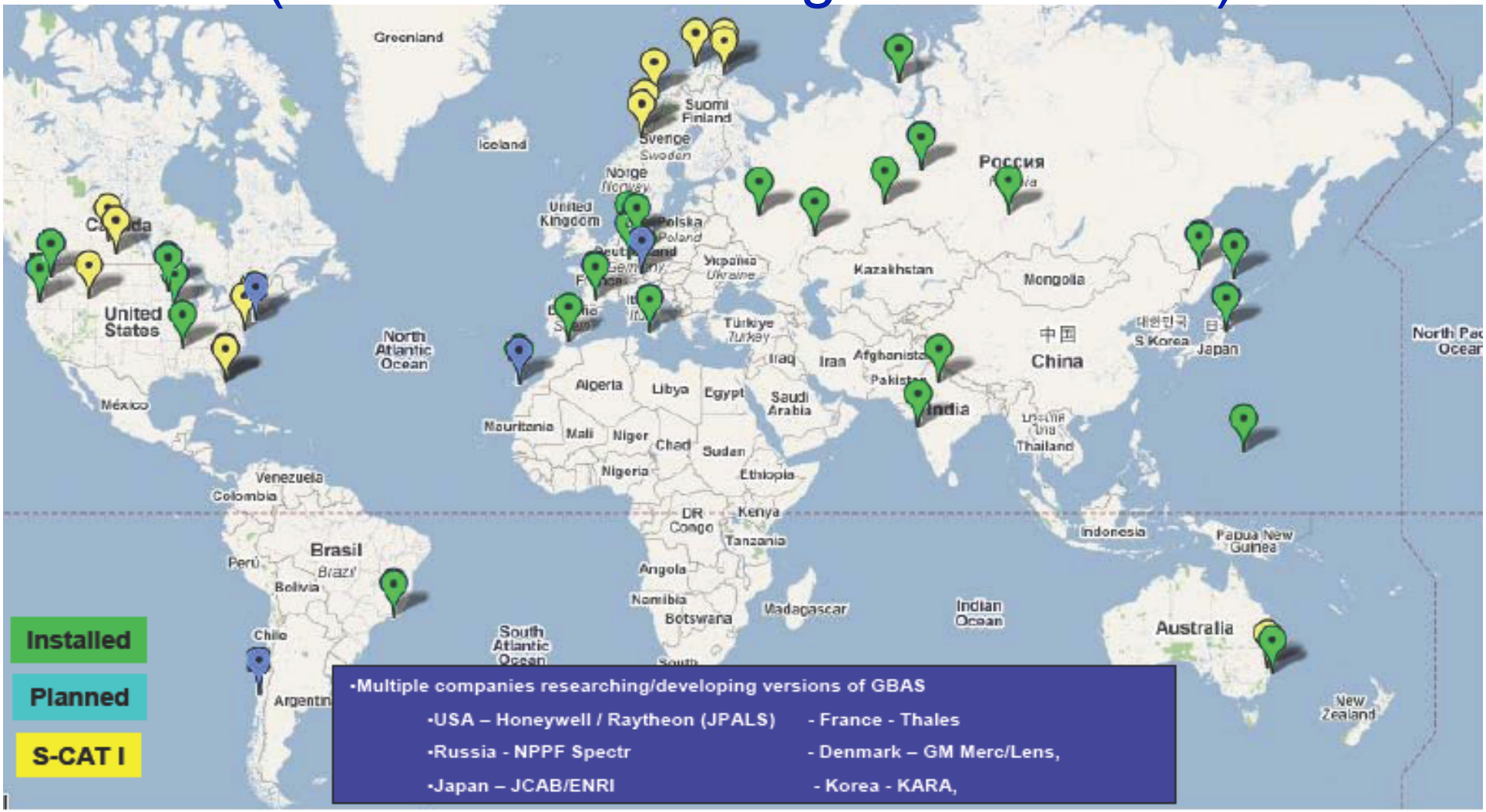
Safety: Faults & “Rare Normal” Events



LPV-200 Coverage on February 27, 2009 (from the FAATC live feed)

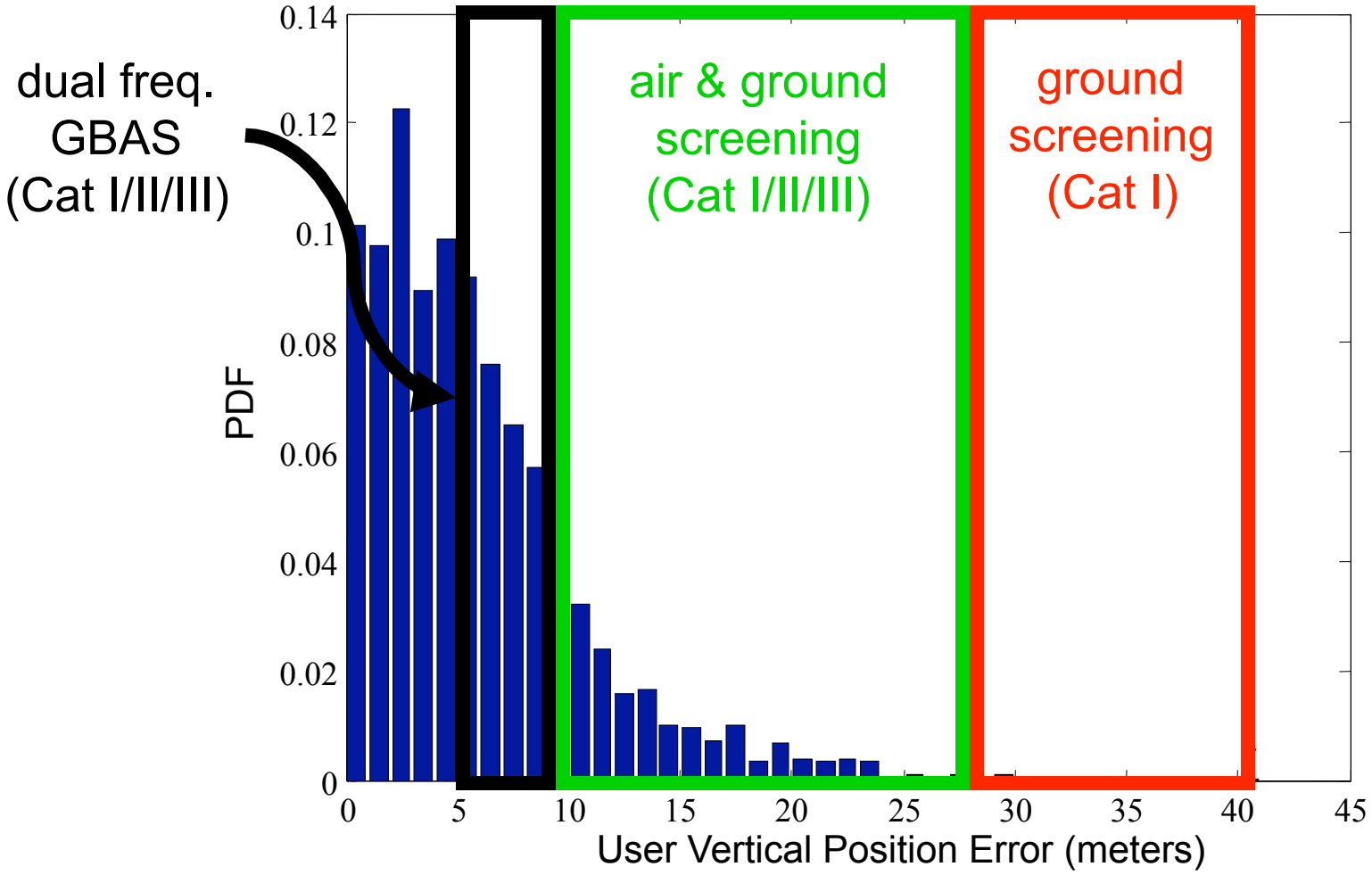


Near Term GBAS Installations (from Carlos Rodriguez to RTCA)

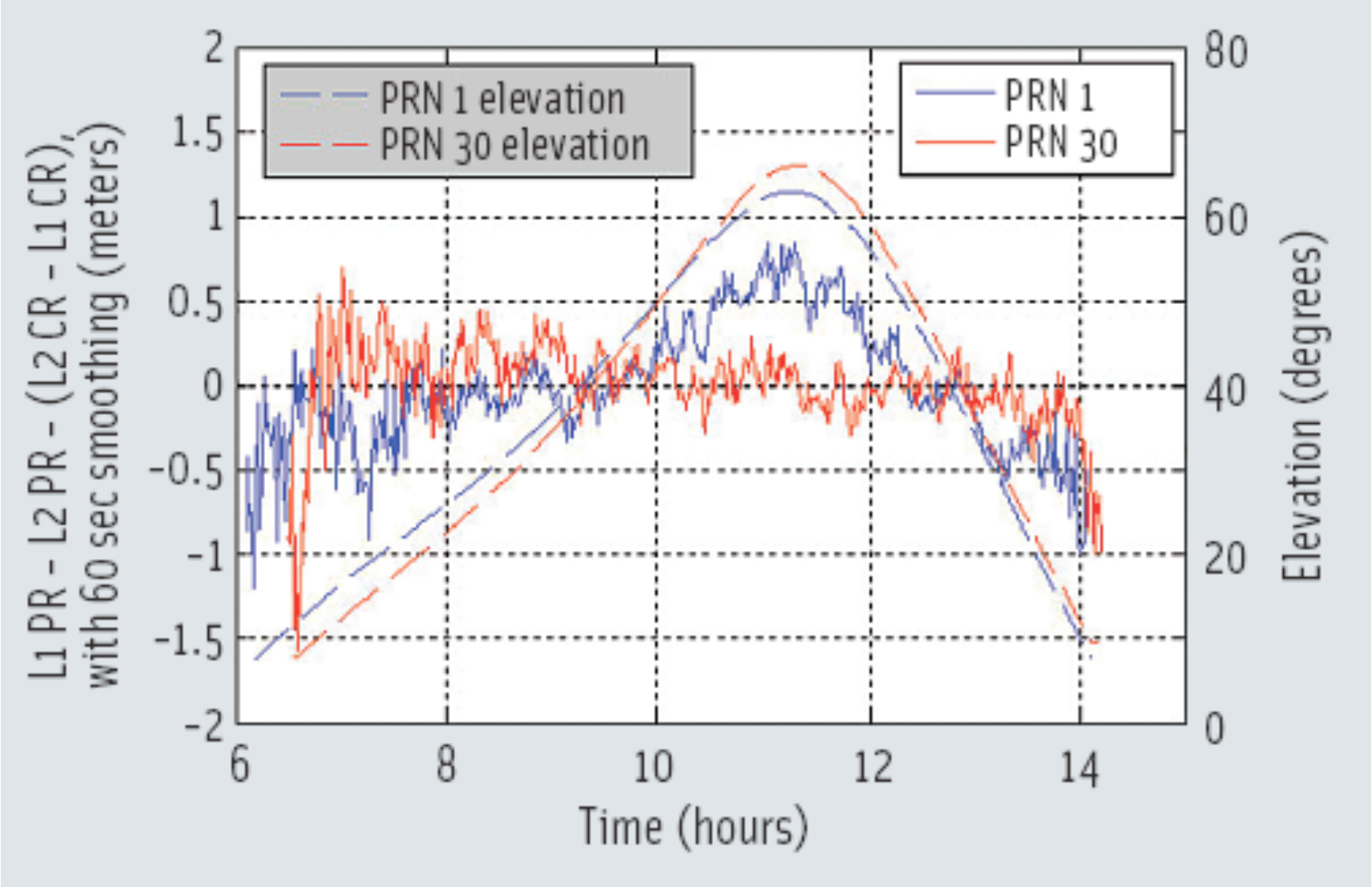


over 1000 aircraft orders include GBAS avionics

Truncation of the Error Tail



PRN 1 Bias on L1



Evolution of GNSS-Based Safety

2010 2020 2030

L1 Only
- RAIM
- SBAS
- GBAS

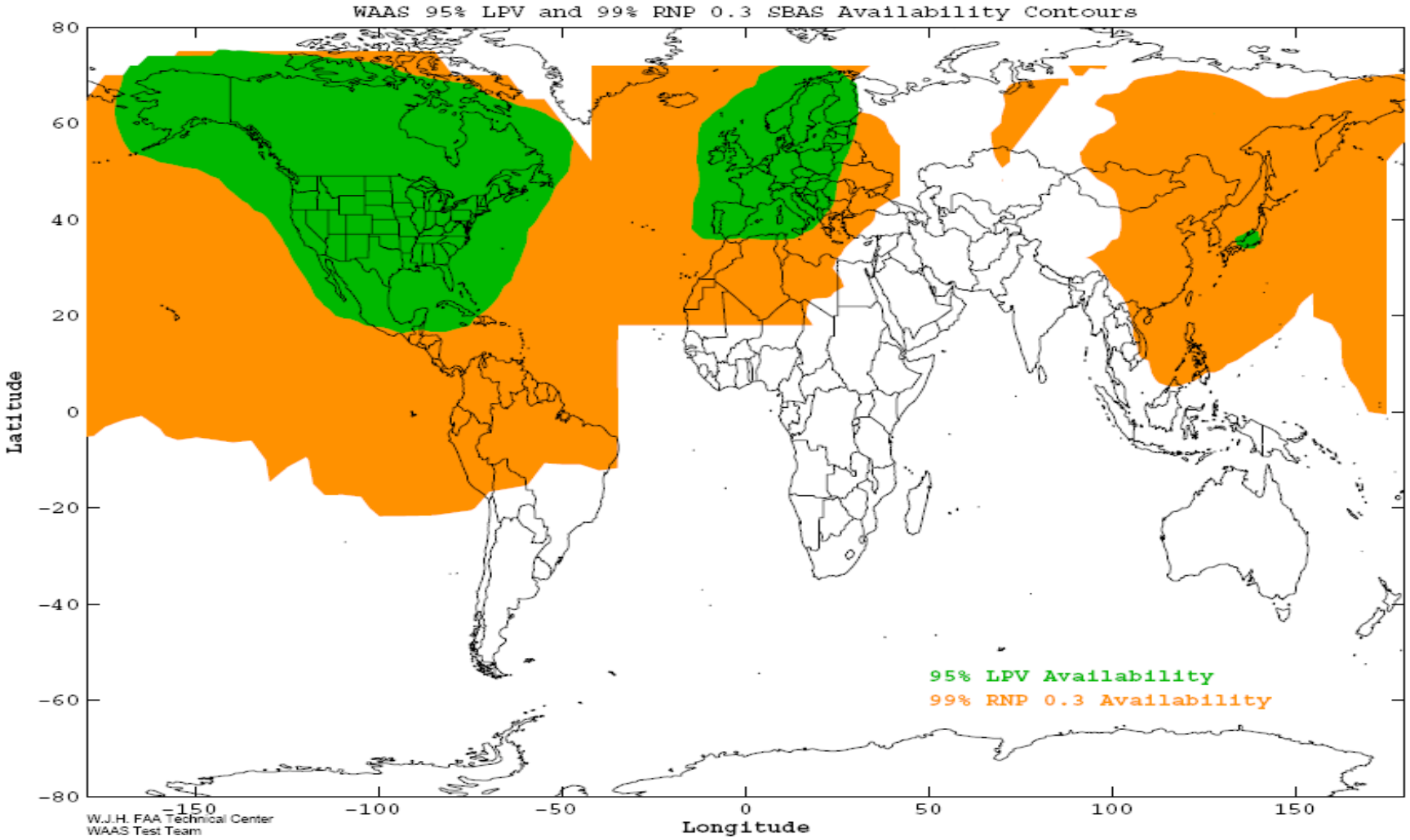
Dual freq. SBAS & GBAS
- 24 SVs Minimum
- 10^{-4} from GNSS

Dual freq. ARAIM
- Open service
- GPS: 30+ Slots
- Multi-constellation
- 10^{-4} from GNSS

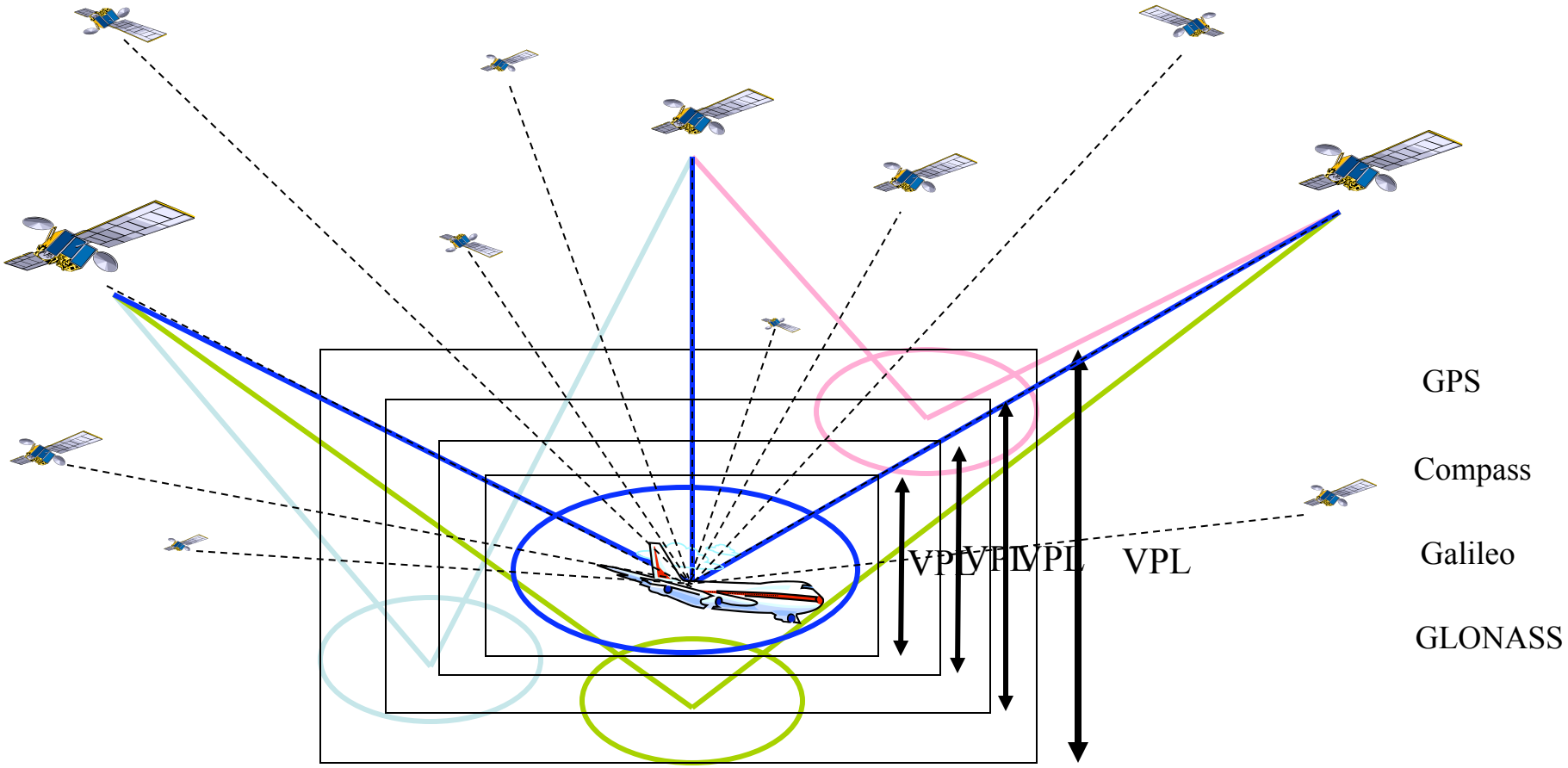
GNSS Integrity Within
- GPS IIIC (1^{st} 14) ++, or
- GNSS Safety of Life
- 24 SVs (GPS alone)
- 10^{-7} from GNSS

Civil security (DoS & spoofing)

Dual Frequency WAAS
Convert Orange to Green



System Definition
ARAIM for 2020



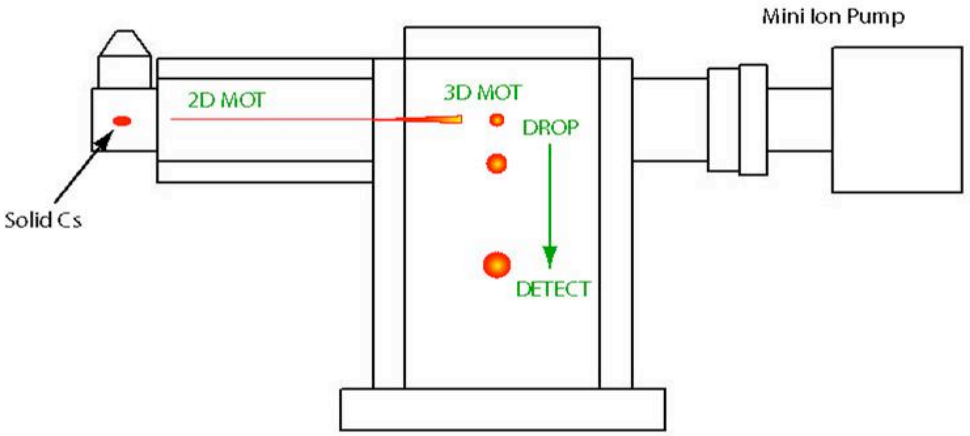
Trade Between Constellation Strength & Multiplicity of Ground Monitors (from Juan Blanch)

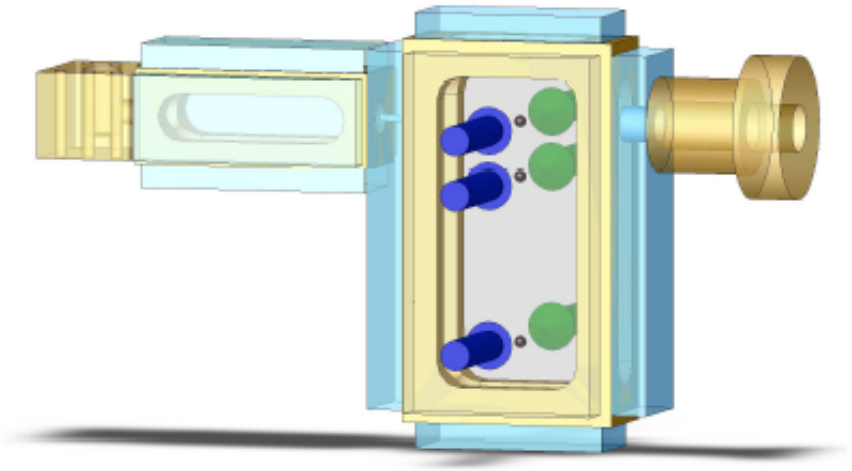
Civil monitoring is a trade between:

- Constellation size
- Robustness to SV failures
- Network size (URA bounding)

ARAIM 99.5% coverage	24-1	24	27-1	27	30-1	30
No Real Time Monitoring	3.7%	27.5%	9.56%	87.9%	79.8%	99.6%
8 stations	50.8%	88.3%	71.5%	96.7%	98.7%	100%
38 stations	71.2%	98.9%	90.0%	100%	99.9%	100%

Stanford Atom-based Inertial Sensors
5 m/hour Versus 500 m/hour
(from Stanford's Mark Kasevich)





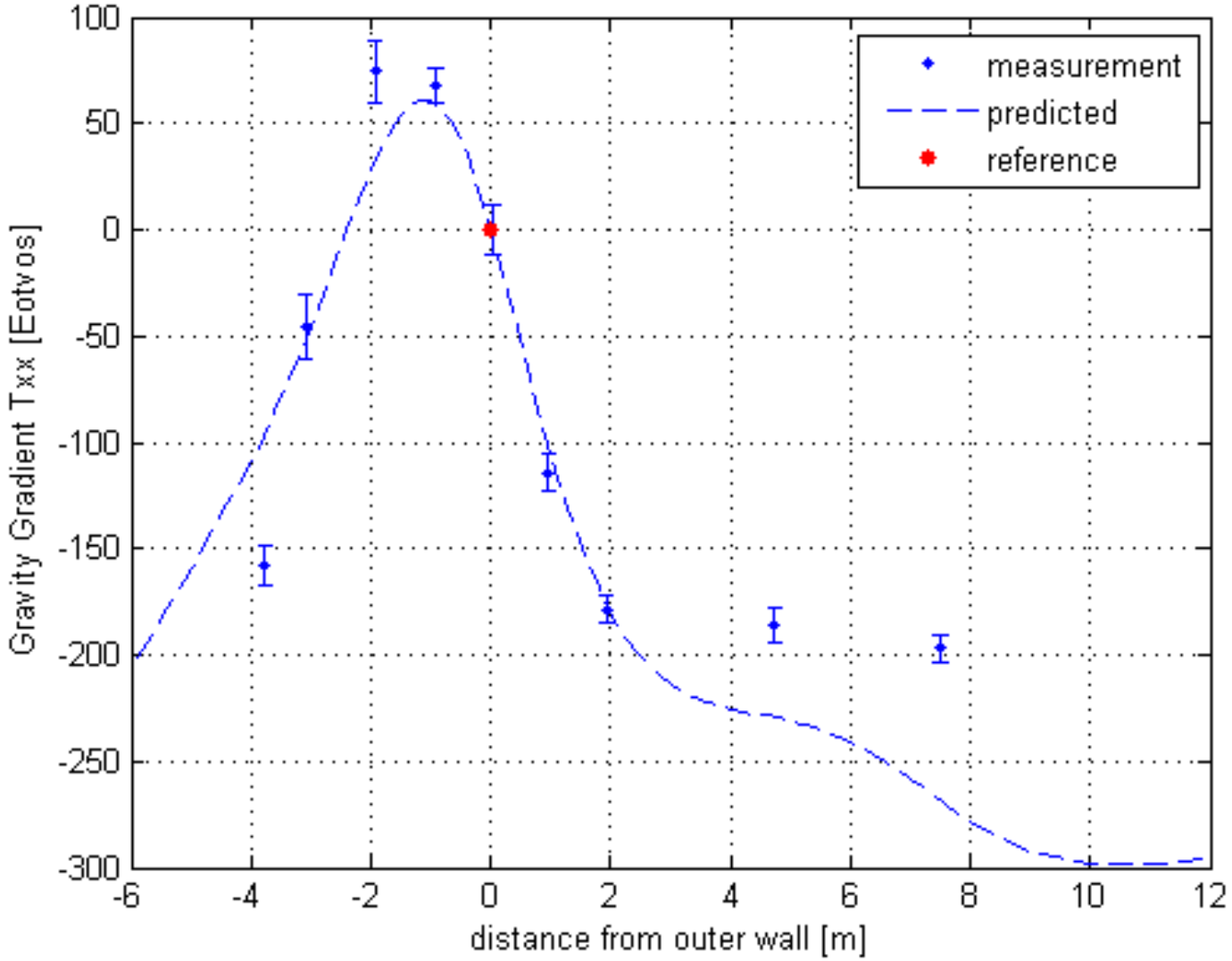
Cesium atoms are proof masses.

Pulses of laser light measure relative motion between atoms and case.

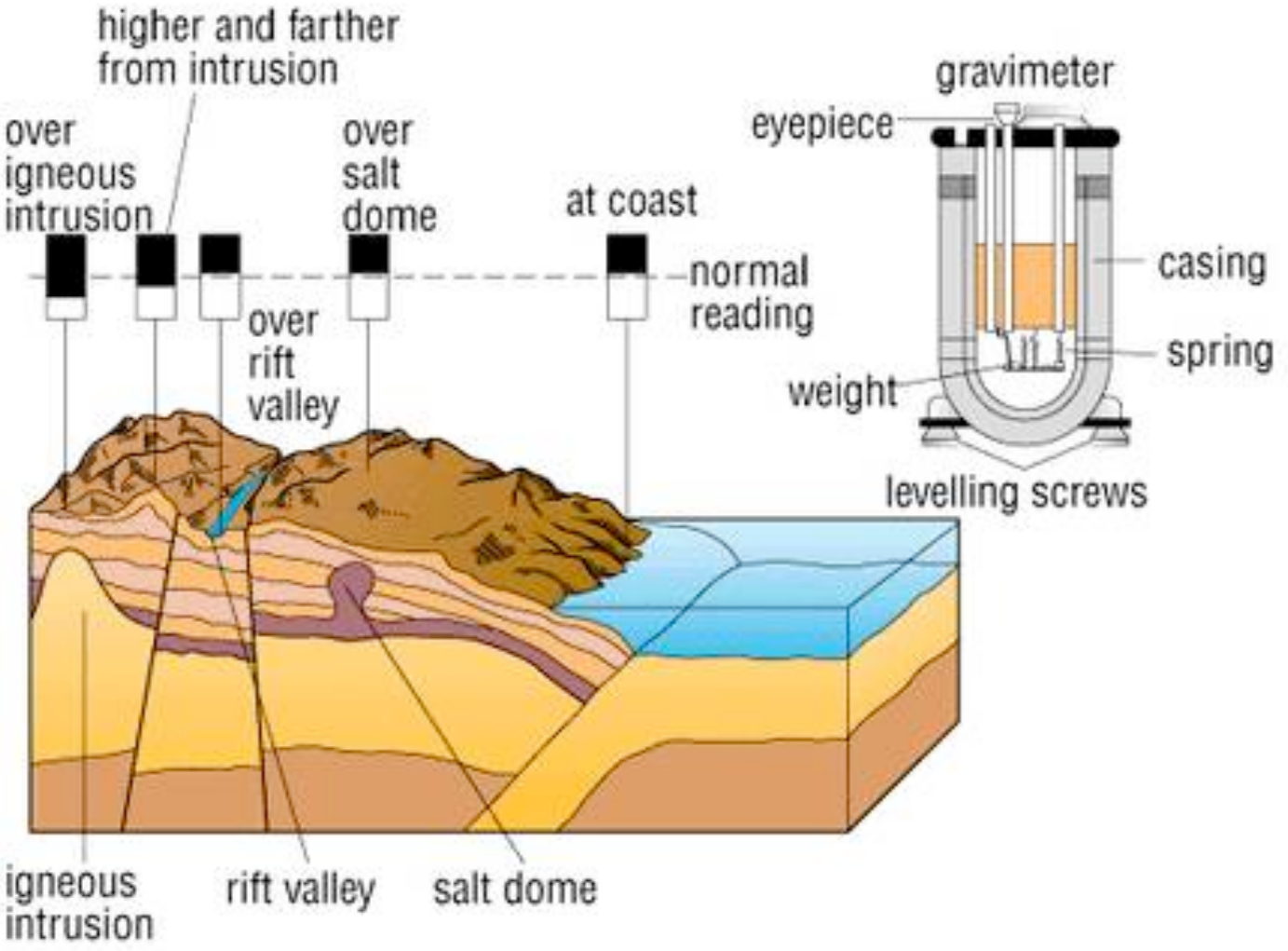
Mobile Gravity Gradient Survey (from Mark Kasevich)

RTK from Trimble

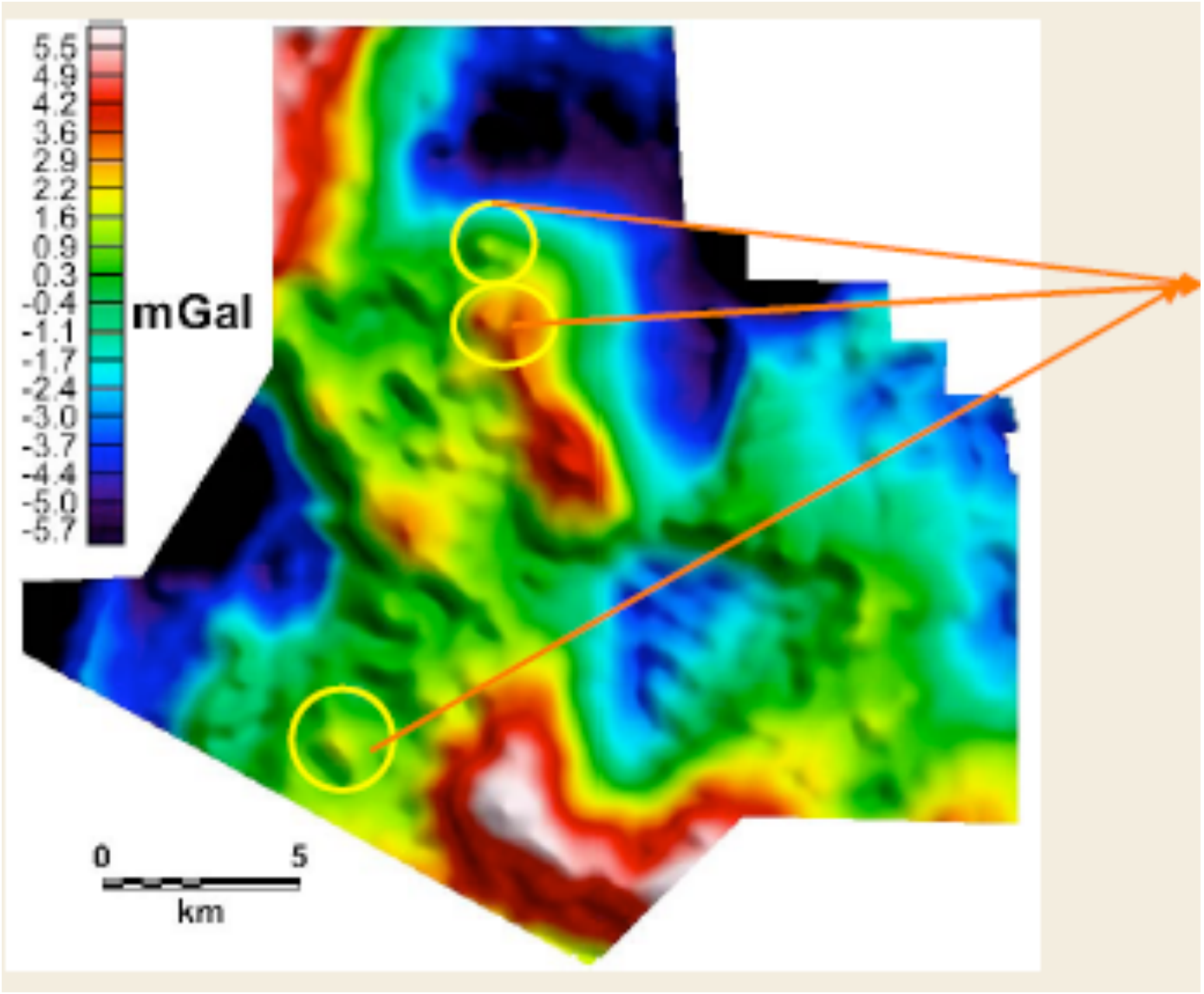
Gravity Gradient Survey of End Station III (from Mark Kasevich & Jeff Fixler)



Gravity Meter
(from Helicon Publishing)



Airborne Gravimetry (from M. Dransfield, FUGRO)



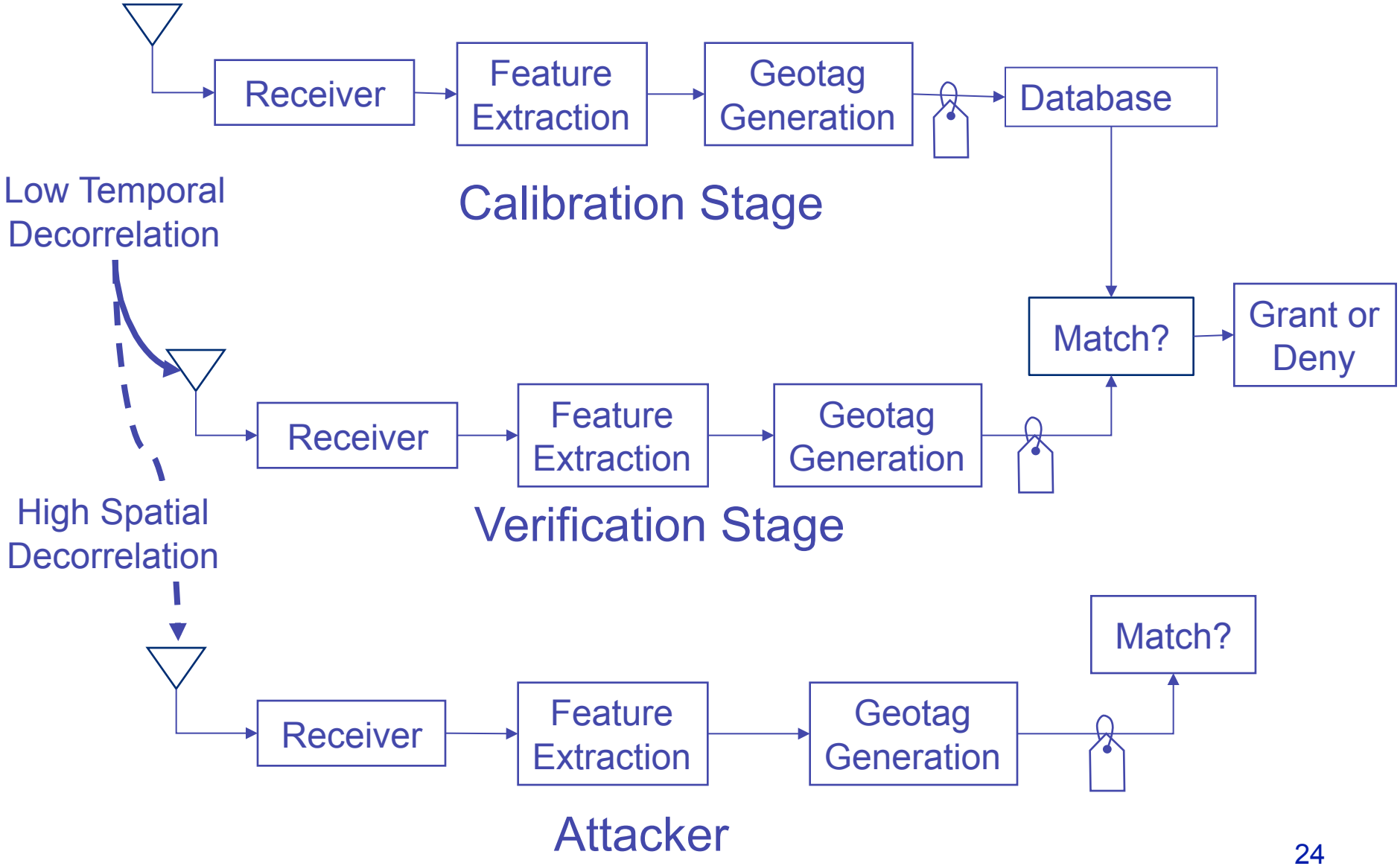
Airborne Gravimetry

- Atom gravimeter to measure gravity field at 10^{-6} level
- High performance GPS or laser to decouple platform motion
- Overfly region of interest
- Water table monitoring
- Homeland security
- Resource discovery & management (oil/mineral)

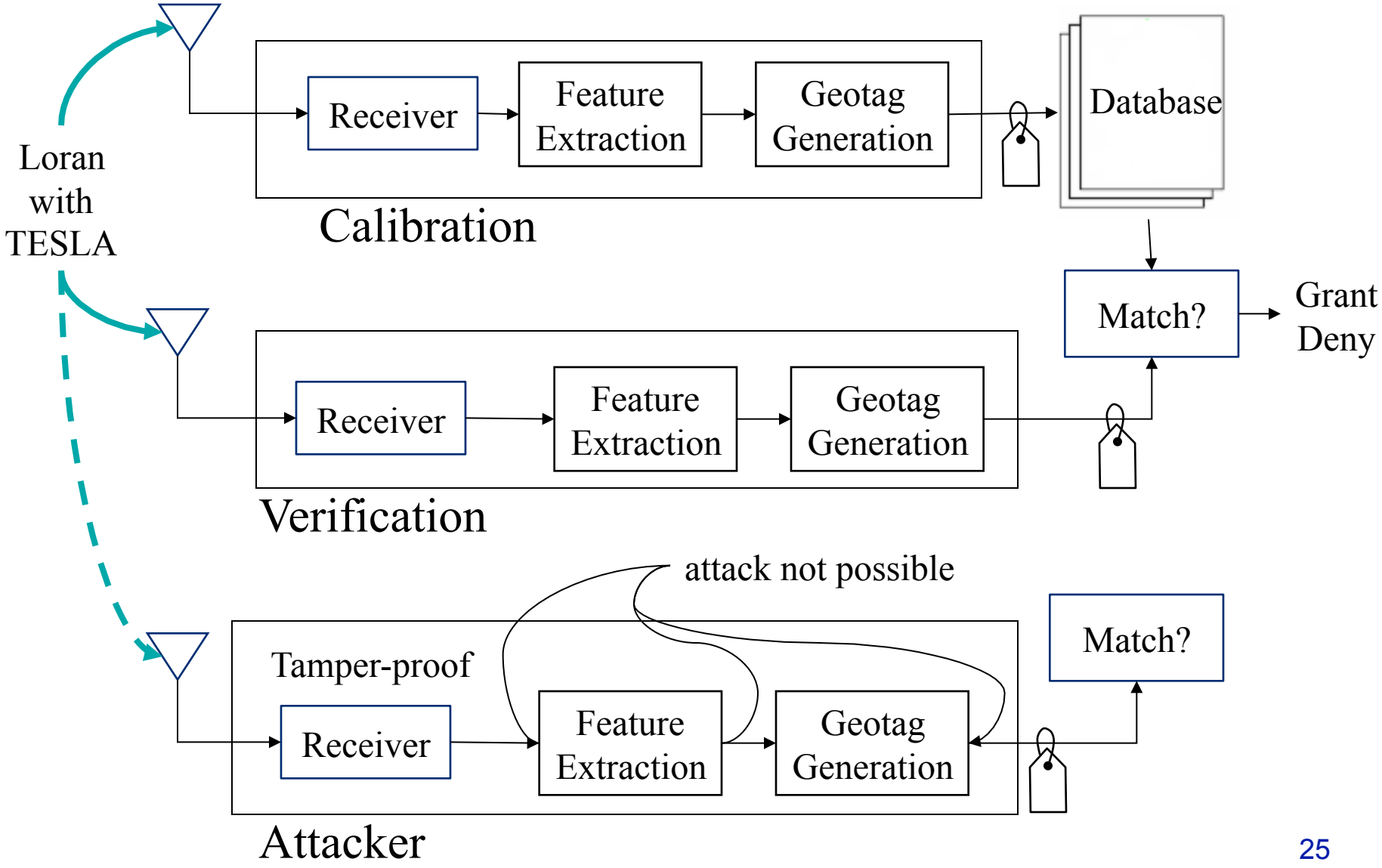
Reference System Requirements

- Blimp dynamics
  - equivalence principal
  - remove blimp acceleration from gravity measurements
  - mm accuracy for 100 second
- Terrain to estimate nominal gravity
  - accuracy to fraction of feature size
  - sub meter position
- X band
- Visual

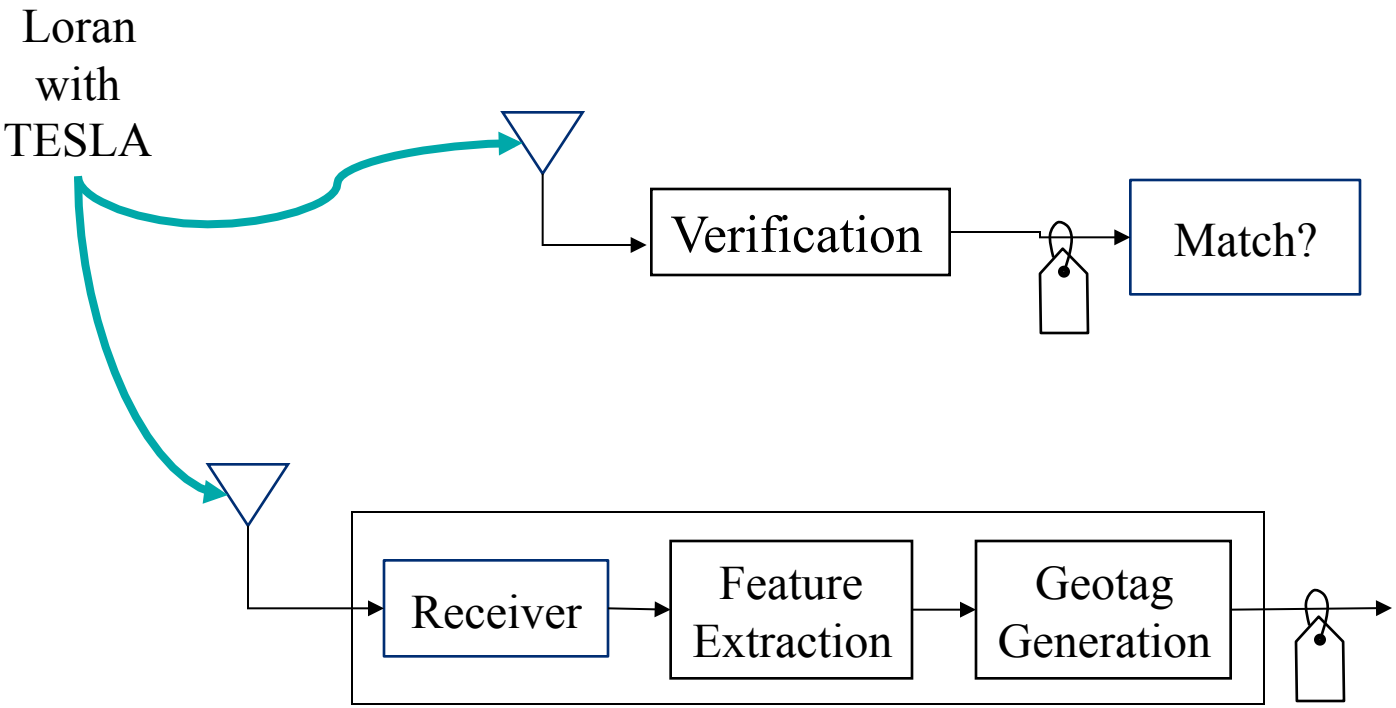
Geo-encryption (from Stanford's Di Qiu)



Tamper-proof Hardware & Self-Authenticating Signal



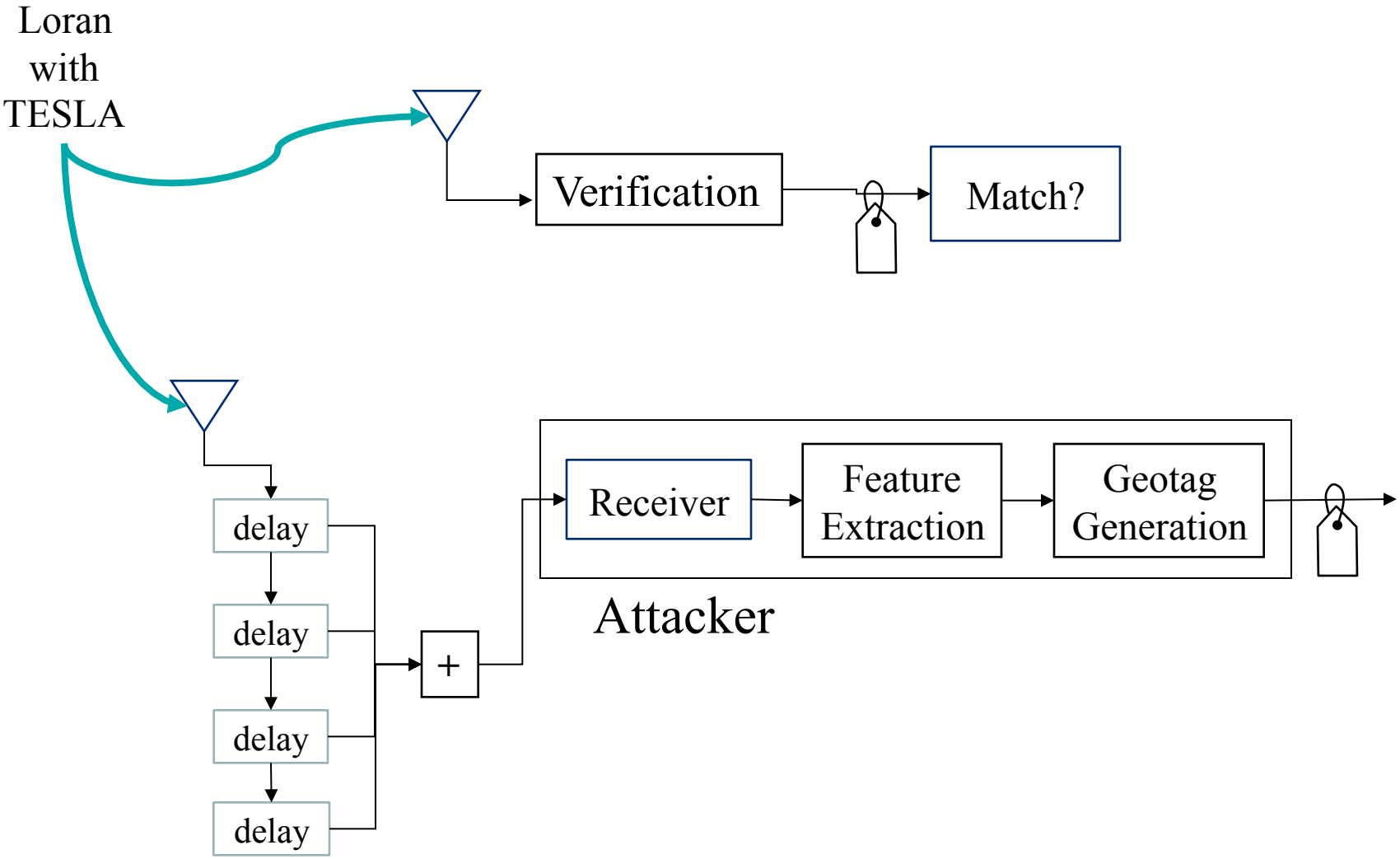
Parking Lot Attack



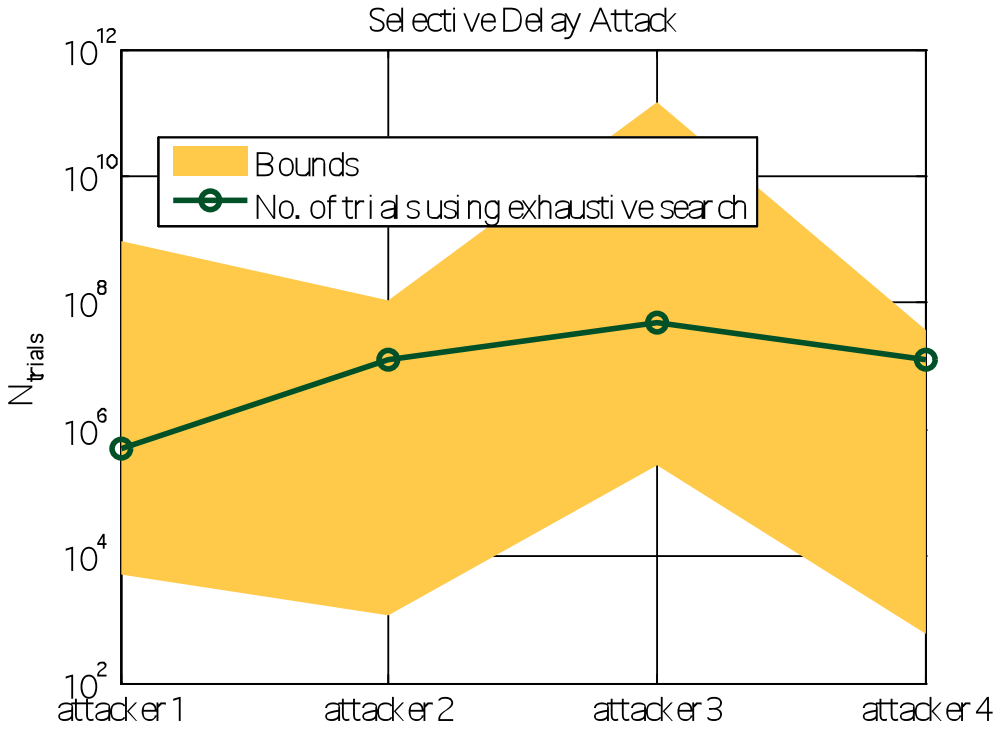
Attacker

- nearby
- hopes that his received data falls within geo-fence
- efficacy improves with proximity

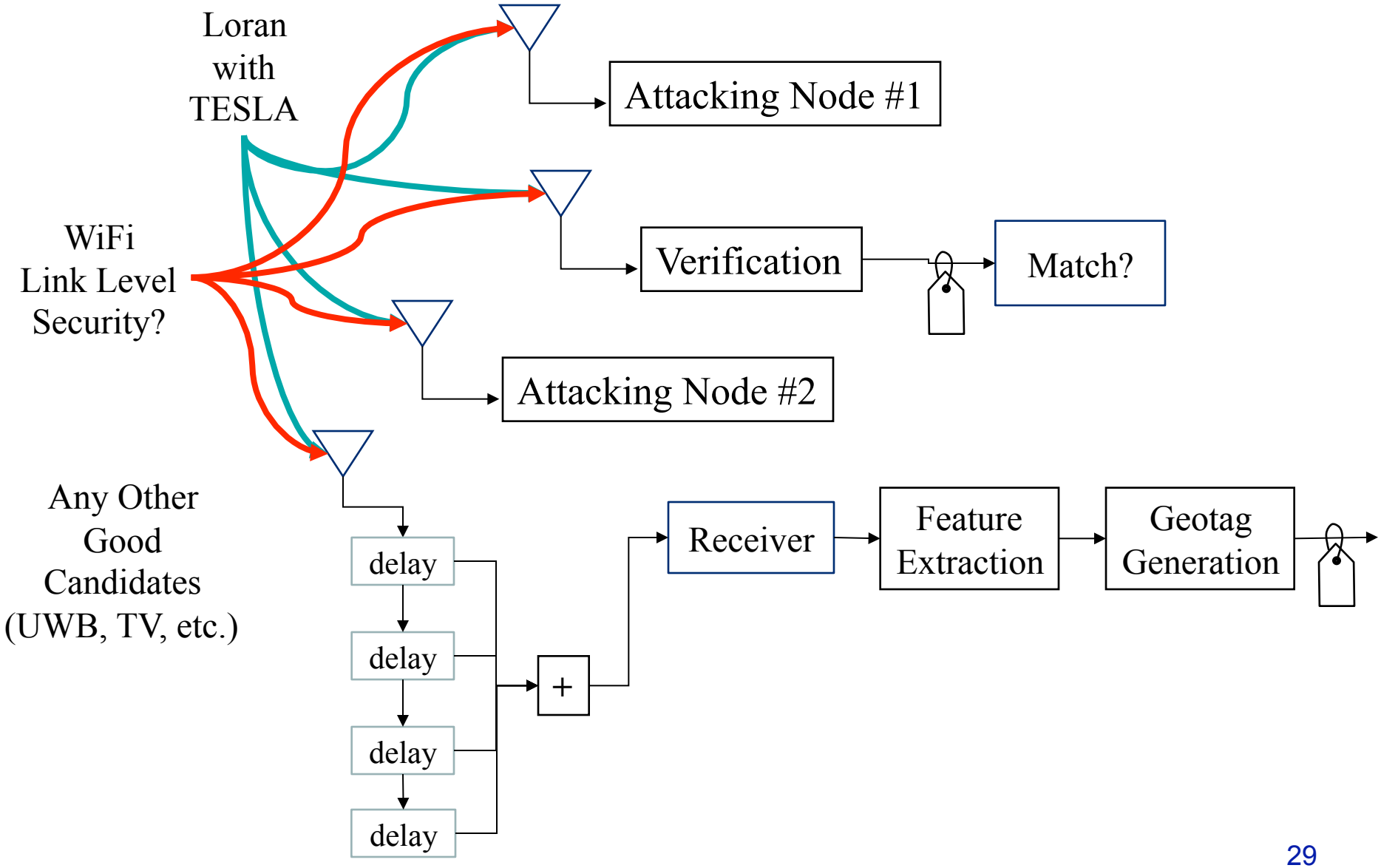
Smart Parking Lot Attack



Smart Parking Lot Attack



Multiplicity of Signal Characteristics



Conclusions

- Potential utility provided by new PNT technology is stunning.
- International cooperation is needed to fully realize these benefits.