Assured PNT for the United States

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Positioning, Navigation, Timing(PNT) is an Essential Capability for Modern Societies

- Loss of capability could be disastrous
- GPS is the current U. S. provider.
  - Reliable, but vulnerable
    - Mainly, subject to interference because of weak signal
  - Believed to require a backup system
  - Can be the space component of an assured capability
- eloran proposed by USG and EU several times as a backup.
  - Terrestrial, low frequency system
    - Well tested and reliable
  - The terrestrial component of a complete system
- Neither eloran nor GPS is adequate alone

Limited Thinking Compounds Problem

- Compartmentalized ideas are likely to produce degraded capabilities.
- Options are thought to be:
  - GNSS
    - Long fielding time
    - Expensive
    - Vulnerable
  - Terrestrial system
    - Usually eloran
    - Less accurate PNT performance that GNSS
      - More survivable
      - Identified by USG Independent Assessment Team and Working Groups as the best domestic backup to GPS
- Both are now commodities that can work together

PNT performance for eloran and GPS

Performance	eloran	GPS
Position	20 m	4 m
Time	50 ns	8 ns
Jamming sensitivity	Low	High

Q: Which is adequate?
A: Neither

Future applications will require better time, and position, accuracy.

cyber attack and defeat
Precision farming
Driverless autos
Autonomous aircraft
Product location and delivery

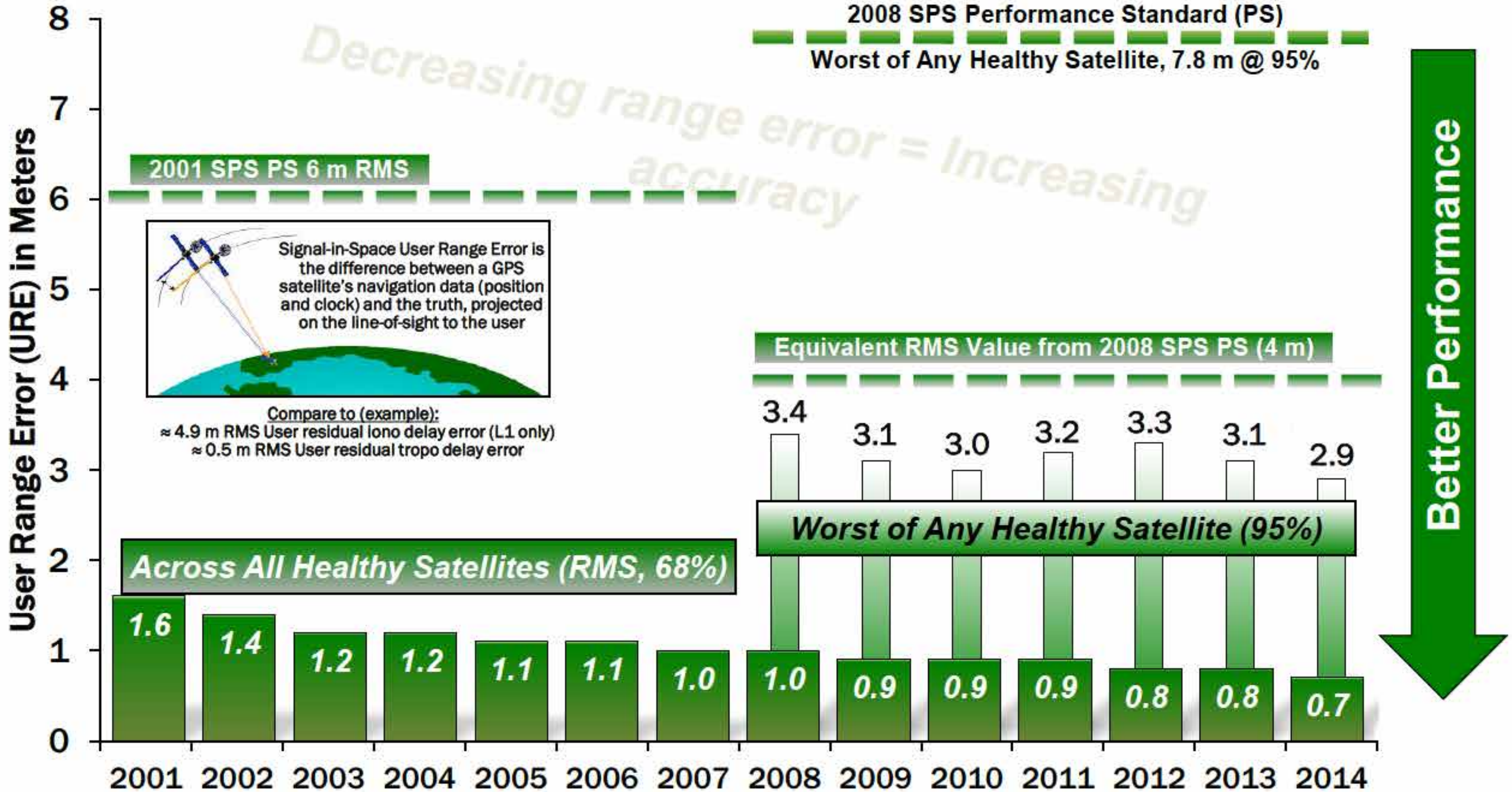
Application needs have always exceeded requirements

Fortunately, performance has exceeded requirements

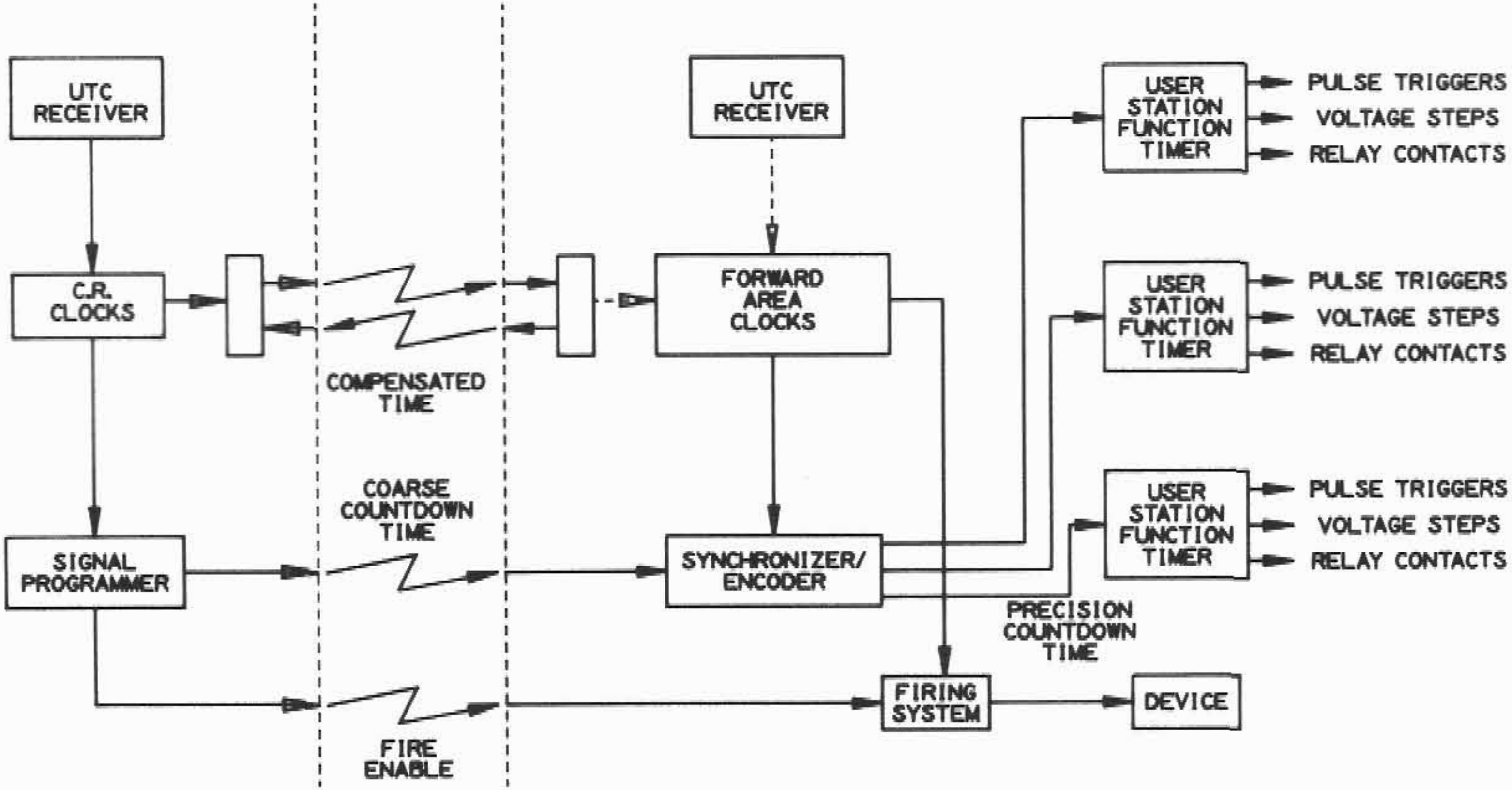
Accuracy: Civil Commitments

Standard Positioning Service (SPS) Performance Standard

Standard Positioning Service (SPS) Signal-in-Space Performance



System accuracy better than published standard



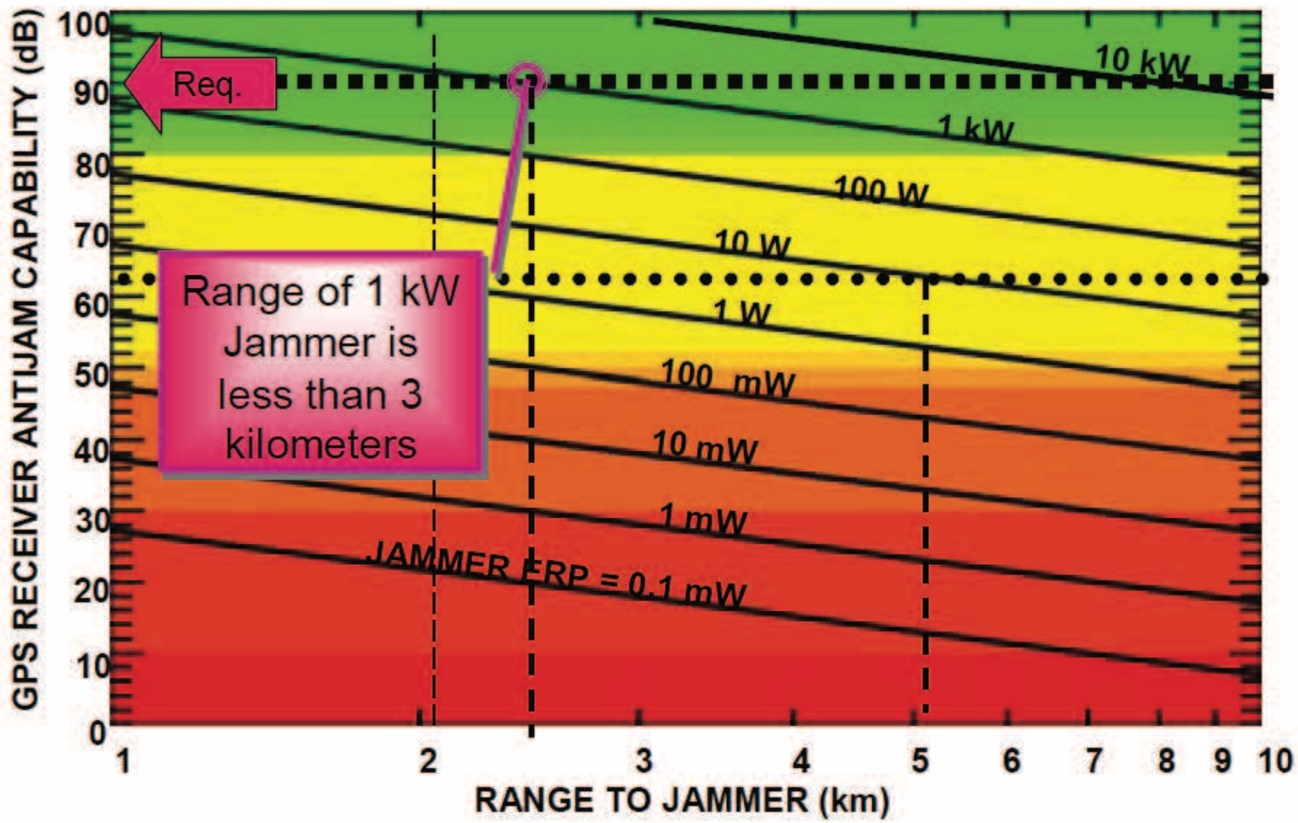
R. E. Partridge, Los Alamos, 1991.

Fig. 7. Simplified system schematic

Response to Vulnerability Issues

- Protected system should provide better, not poorer performance.
  - Integrated GNSS/eloran exceeds the capabilities of either system alone.
- System should enable a technology upgrade path to future improvements
  - Improved time and position accuracy.

Effect of 90 dB Capability



Jammers available on the internet for $100-$200.

Power approx. 2W

Izvestia, August 27, 2016

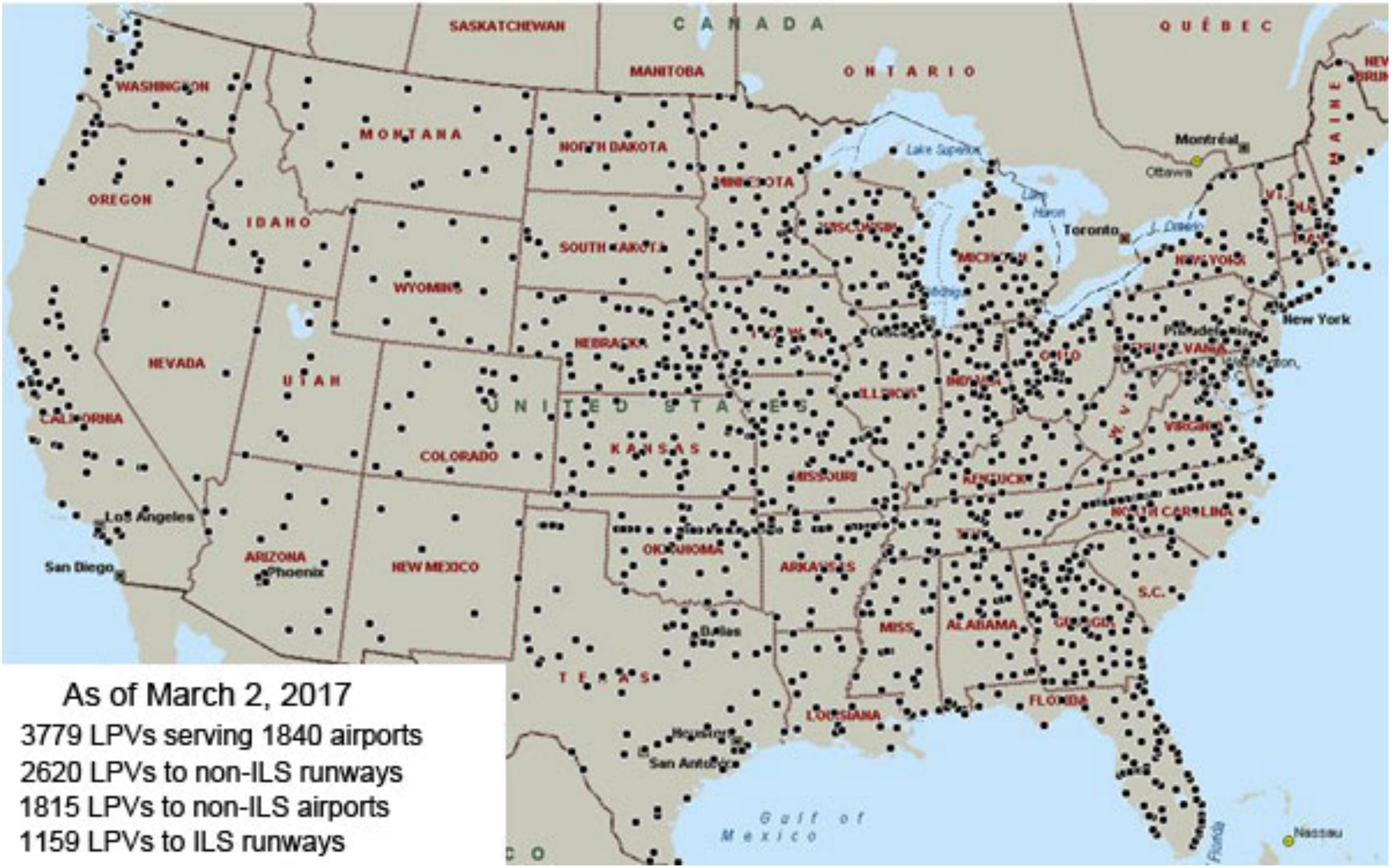
Korean Intentional High Power Jamming Incidents

[Source: The Central Radio Management Office, South Korea]

Dates	August 23-26, 2010 (4 Days)	March 4-14, 2011 (11 Days)	April 28 – May 13, 2012 (16 Days)
Jammer Locations	Kaesong	Kaesong, Mount Kumgang	Kaesong
Affected Areas	Gimpo, Paju, etc.	Gimpo, Paju, Gangwon	Gimpo, Paju
GPS Disruptions	181 cell towers 15 airplanes 1 battleship	145 cell towers 106 airplanes 10 ships	1,016 airplanes 254 ships

European Experience

- Spirent jammer detectors at 40 sites
  - Current data taken from 1 Feb. 2016 to 30 April 2017
- Results are impressive
  - 141,000 events, mostly in city centers(NYSE)
  - 17000 jammers
  - 300 jammers of related types(families)
- New, more effective jammers are emerging
- gnss-strike3.eu



As of March 2, 2017

3779 LPVs serving 1840 airports

2620 LPVs to non-ILS runways

1815 LPVs to non-ILS airports

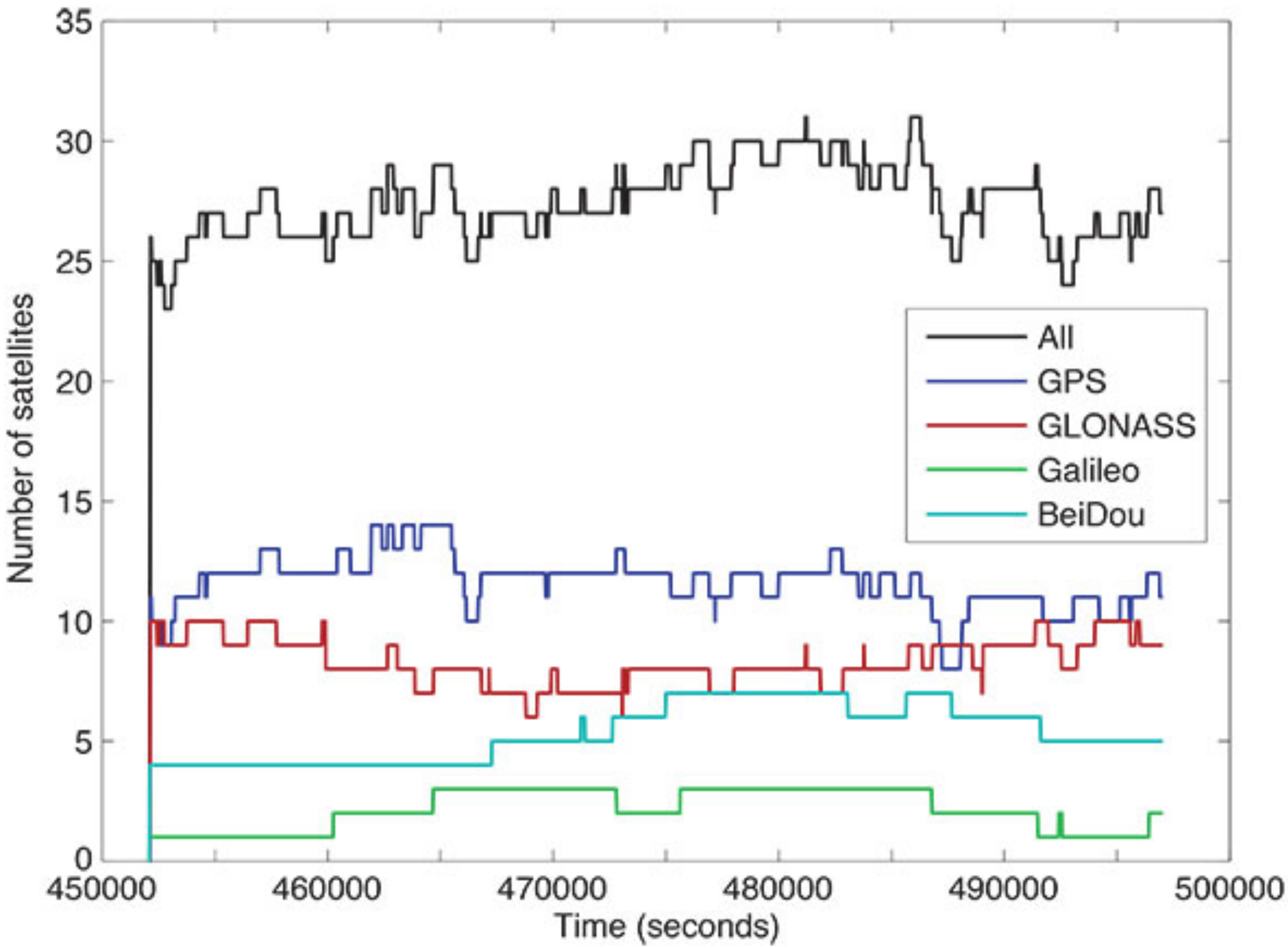
1159 LPVs to ILS runways

Features of a Protected GNSS System

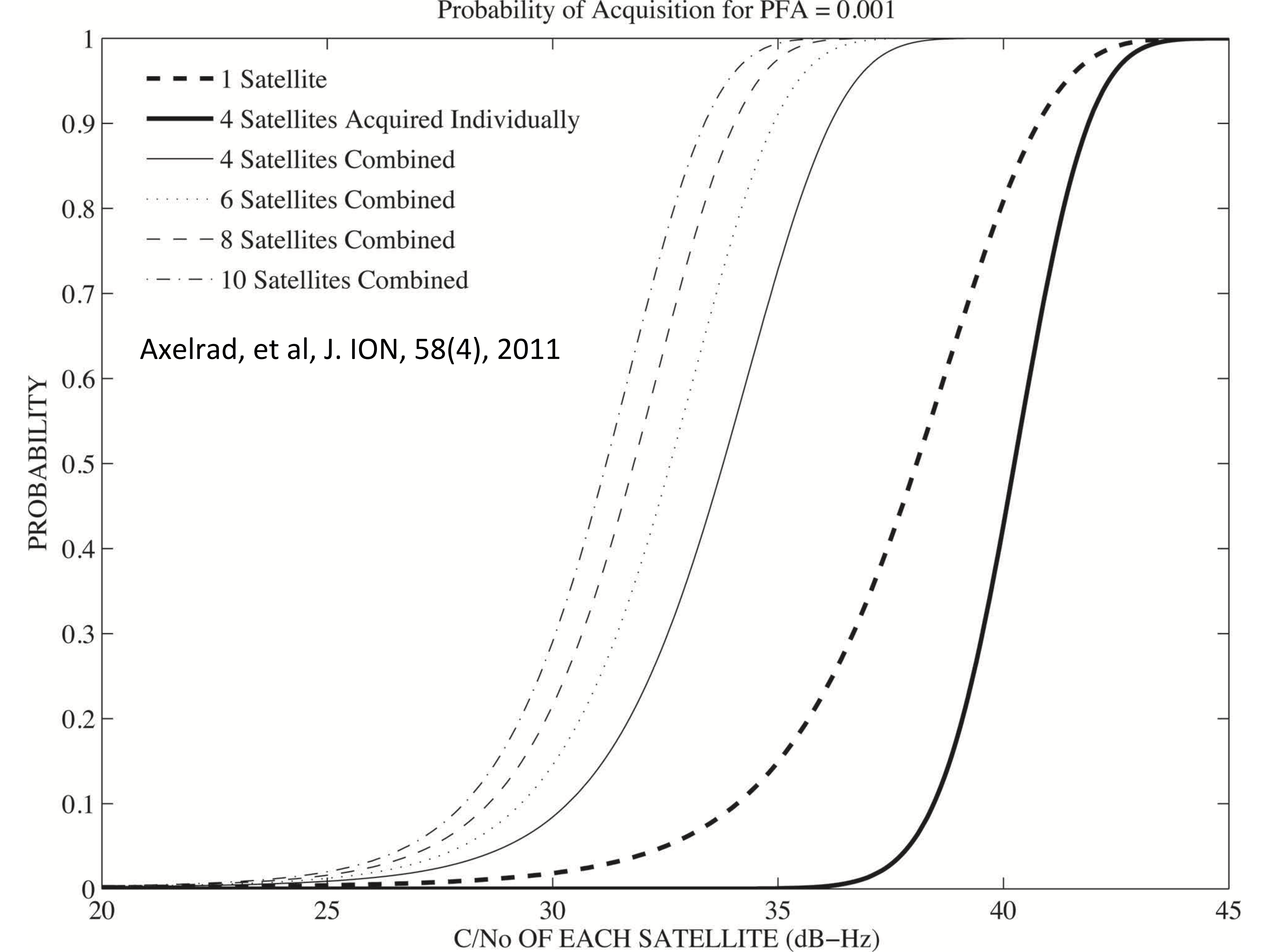
- For increased AJ:
- Coherent detection of all satellites in view
- High chipping rate(10 MHz for P,L5 codes)
- External source of navigation message to allow extended correlation time.
- For improved accuracy:
  - Short ephemeris and clock update times.

Coherent Detection

- Locks on to all satellites in view simultaneously
- Usually, initial fix is inaccurate
  - Assumes coarse grid
  - First fix errors as large as 200 meters.
- Starting with eloran position reduces initial error to eloran resolution
- Gives jam protection
  - N(signals per sat)XN(sat)



Escher, Stanisak, Bestmann, GPS World, May 2016


Probability of Acquisition for PFA = 0.001
1 Satellite
4 Satellites Acquired Individually
4 Satellites Combined
6 Satellites Combined
8 Satellites Combined
10 Satellites Combined
Axelrad, et al, J. ION, 58(4), 2011
PROBABILITY
C/No OF EACH SATELLITE (dB−Hz)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
20
25
30
35
40
45


BS Position
True MS Position
Estimated MS Position
Esteves, Sahmoudi, Ries
Inside GNSS, 2014

Eloran Signaling

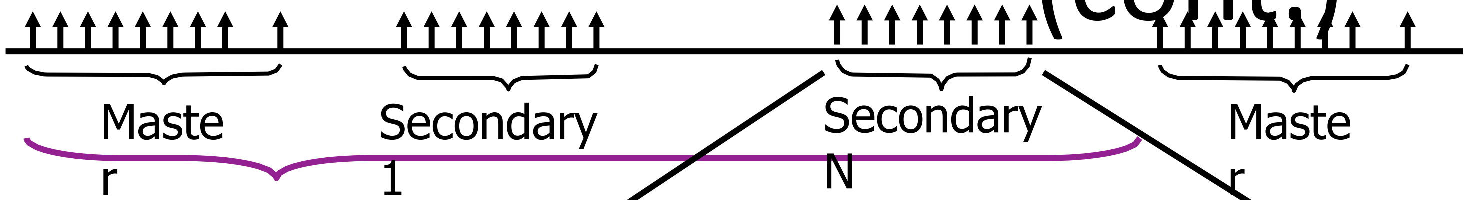
- Enables essential features
- “The ability to carry communication on LORAN would be of immense use to navigation.”
  - –Lo and Enge, 2002.

Eloran signaling

- 9th pulse modulation to transmit GPS nav message and precision ephemeris and time.
- Liang 9thIFM modulation gives 128 bits per GRI
- North American loran chain used GRI between 0.0499 and 0.0999 seconds
  - Raw bit rate is 1280 bits per second
  - 250 bps demonstrated in WAAS tests in Alaska
- Possible 4000 bps
  - Peterson, Schue, Boyer, Betz, USCG, March 2000.

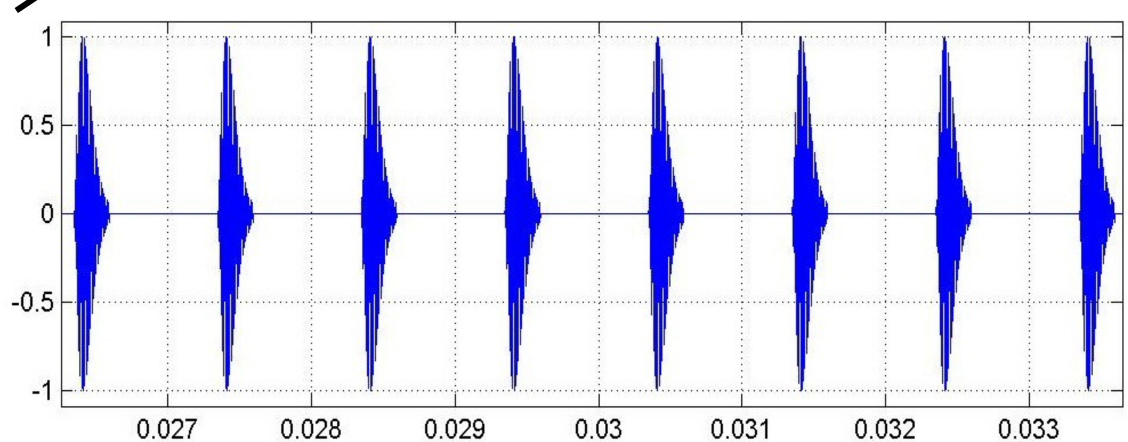
eLoran Signal Structure (cont.)

eLoran Signal Structure (cont.)



Group Repetition Interval

Standard Group of 8 Pulses with 1-ms Spacing



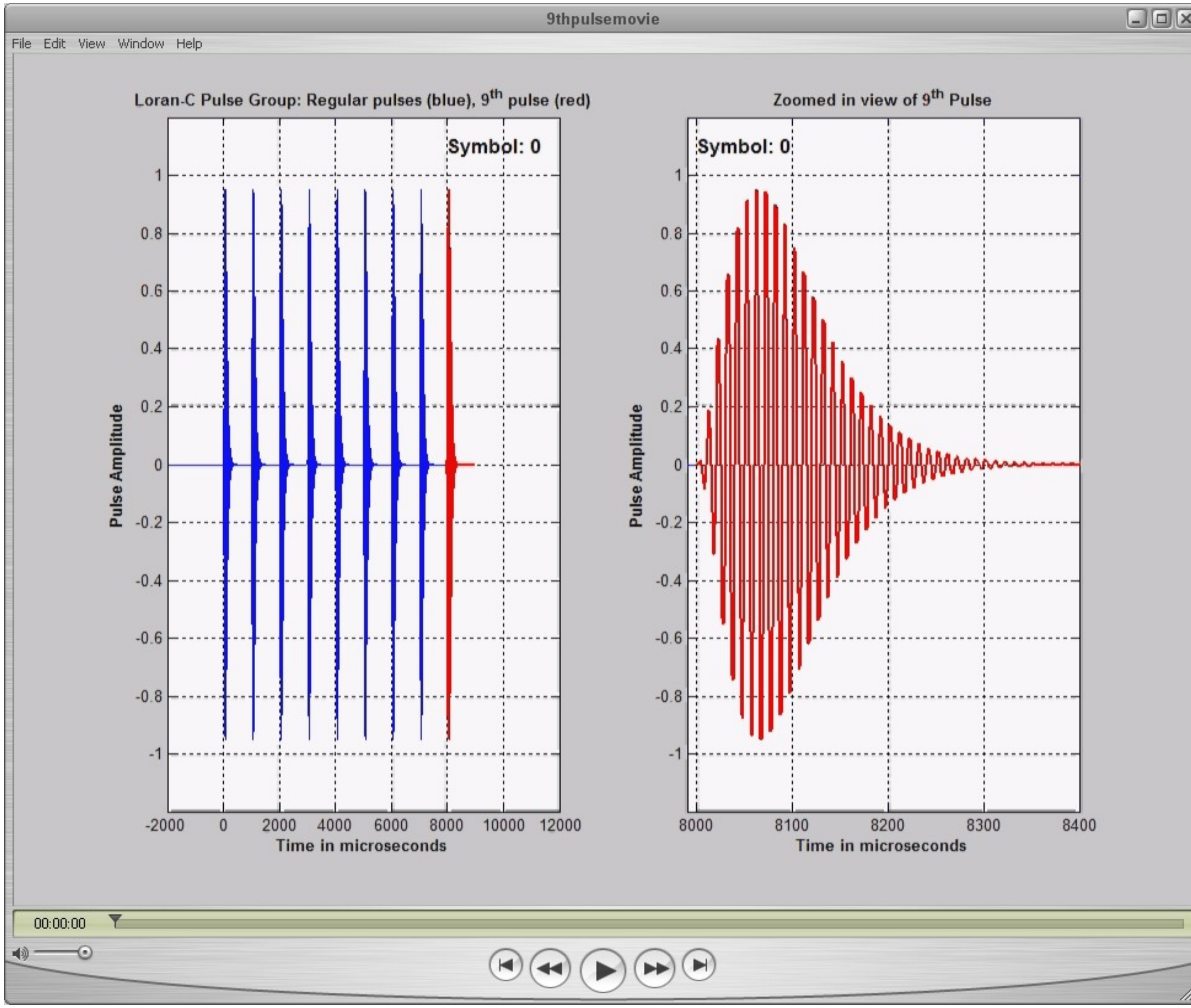
Washington DC Metropolitan Area
Leesburg, Virginia

Corporate Headquarters
Chesapeake, Virginia

EMEA Operations
Bertem, Belgium

9th Pulse Demo

9th Pulse Demo



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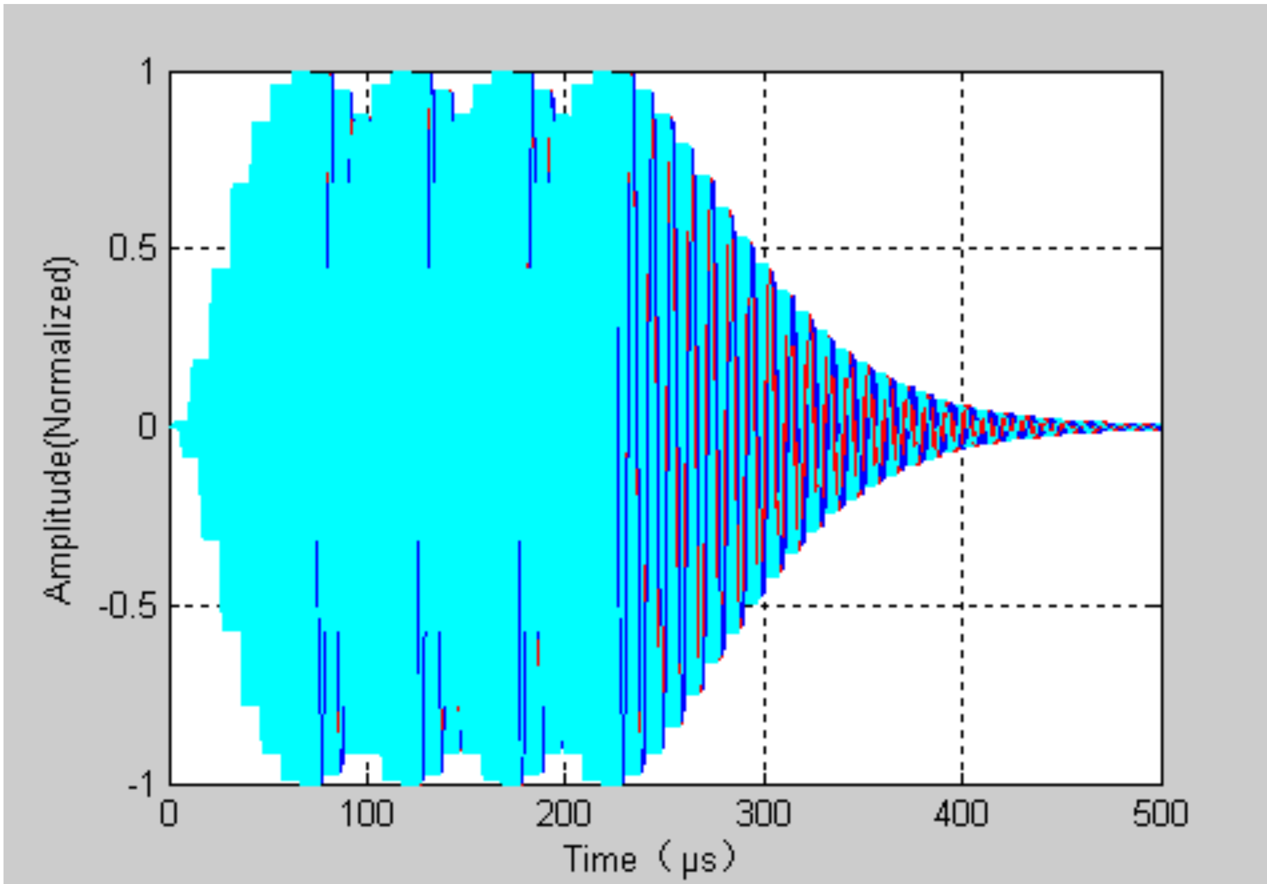
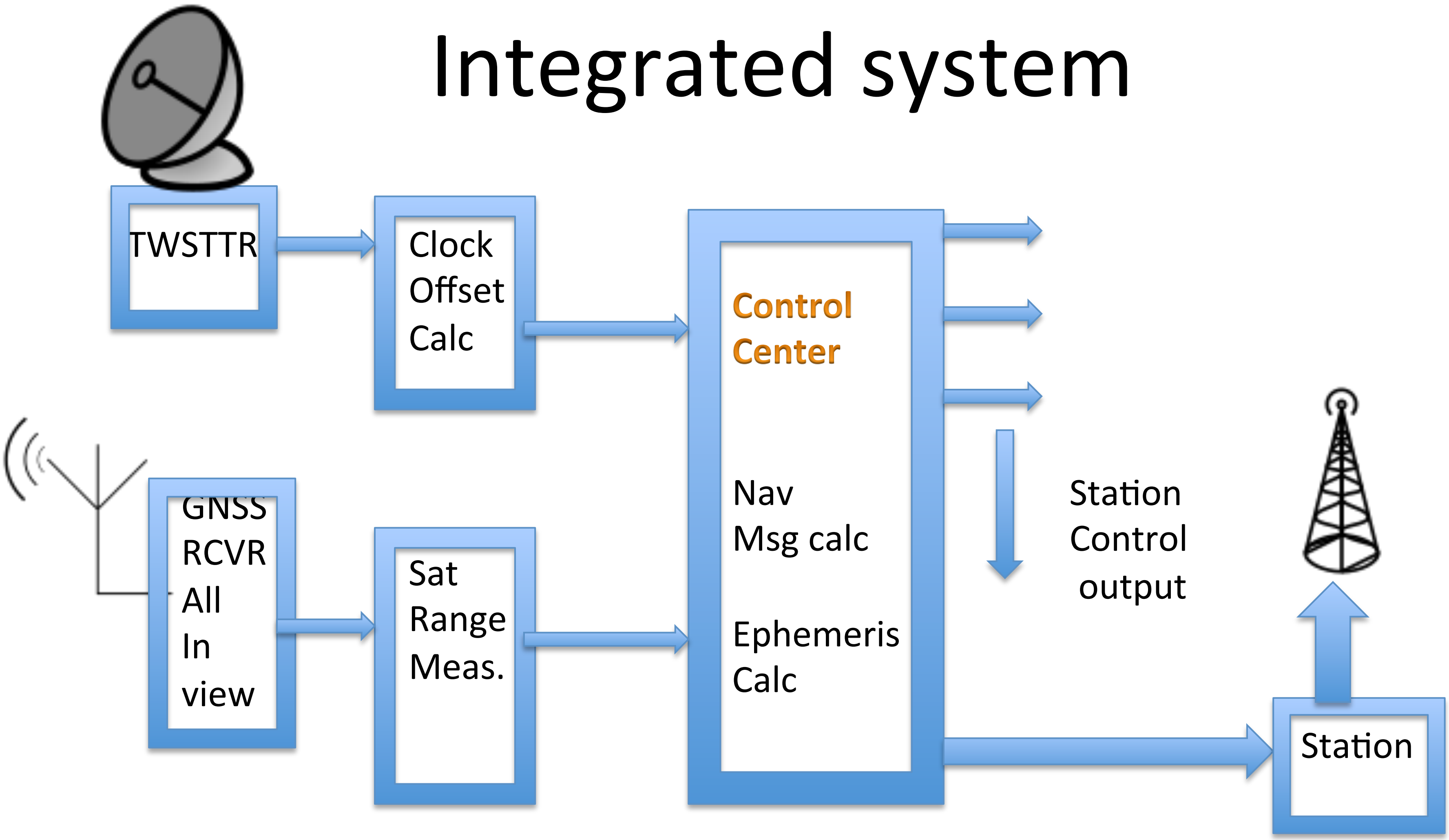


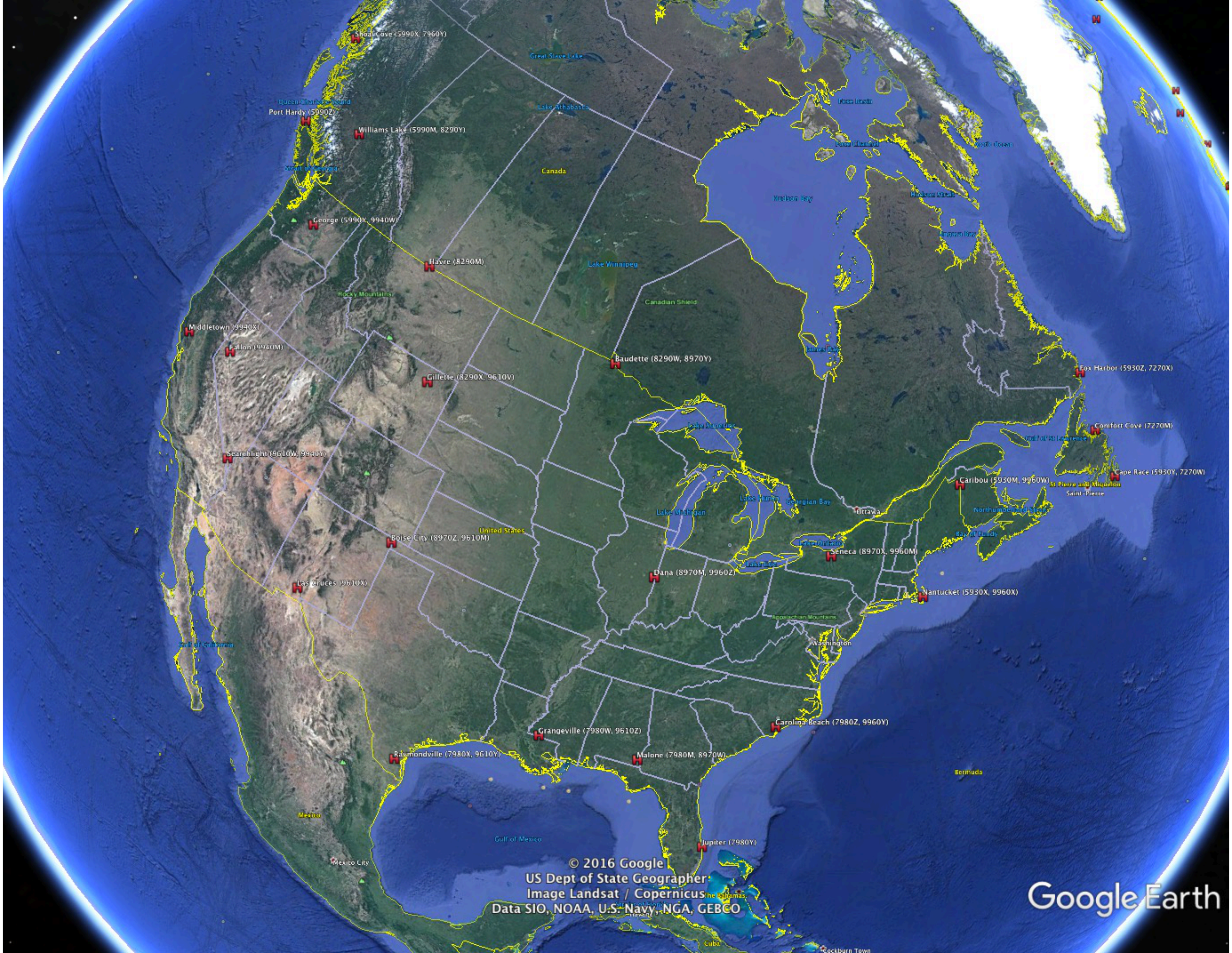
1
0.5
0
-0.5
-1
Amplitude(Normalized)
0
100
200
300
400
500
Time（μs）

System structure

- Key eloran stations have TWSTTR and track all satellites in view over region of coverage.
  - New ephemeris every 3 minutes.
- Tracking results used to construct nav message transmission and precision ephemeris
  - TWSTTR gives time within 1 ns of UTC to measure satellite clock bias
- Assume 2 seconds to transmit nav message, clock bias, and ephemeris for all satellites in view from North America(or other region).
  - Number of order 15. 30 seconds to complete.

Integrated system





Shoal Cove (5990X, 7960Y)
Port Hardy (5990Z)
Williams Lake (5990M, 8290Y)
George (5990Y, 9940W)
Havre (8290M)
Middletown (9940X)
Fallon (9940M)
Gillette (8290X, 9610V)
Baudette (8290W, 8970Y)
Searchlight (9610W, 9940Y)
Boise City (8970Z, 9610M)
Las Cruces (9610X)
Dana (8970M, 9960Z)
Seneca (8970X, 9960M)
Nantucket (5930X, 9960X)
Fox Harbor (5930Z, 7270X)
Comfort Cove (7270M)
Cape Race (5930Y, 7270W)
Caribou (5930M, 9960W)
Carolina Beach (7980Z, 9960Y)
Grangeville (7980W, 9610Z)
Raymondville (7980X, 9610Y)
Malone (7980M, 8970W)
Jupiter (7980Y)
Great Slave Lake
Lake Athabasca
Canada
Lake Winnipeg
Canadian Shield
Rocky Mountains
Hudson Bay
James Bay
Lake Superior
Lake Michigan
Lake Huron
Georgian Bay
Lake Ontario
Lake Erie
Ottawa
Washington
Appalachian Mountains
Gulf of St Lawrence
St Pierre and Miquelon
Saint-Pierre
Northumberland Strait
Bay of Fundy
United States
Gulf of California
Mexico
Mexico City
Gulf of Mexico
Bermuda
The Bahamas
Cuba
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Image Landsat / Copernicus
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google Earth

Signaling Improves Accuracy

- Current ephemerides of all satellites in view calculated and transmitted every 3 minutes.
- Used to reduce position errors.
- 15 minute ephemeris shown to reduce errors below 1 m.
  - 3 minutes should reduce error to 10 cm.
- Time error less than 1 ns

Ultratight coupling

- Ultratight coupling of GPS/INS has given jam resistance as high as 65 dB.
- Replace INS with eloran carrier phase measurement.(Dynamic differential tracking, DDT.
- GNSS/INS/eloran form a **Resilience Triad**

Extended correlation time raises jam resistance

- UTCoupled INS can be used to maintain track during integration time
- Measurement of eloran phase changes should make possible an INS emulator for the tracking loop.
  - Likely to be more accurate than MEMS.
  - May need vertical channel
- 90-100 dB jamming protection possible.

Total Protection

- 16 dB from coherent detection
- 10 second correlation time gives 80 dB
- Total 96 dB exceeds DSB recommendation
- 100-110 dB possible with UTC
  - Receiver will operate properly within 1 km of a kilowatt jammer.

Spoofing is eliminated as a threat

- Only the ephemeris transmitted by an eloran station is valid
  - Ephemerides recalculated every three minutes
- GNSS and eloran solutions must agree within system error.
- False signals will be ignored, or treated as a jammer.

Implications

- Reduces impact of GPS III launch delays
- Continue with IIF satellites
  - No GPS III or OCX
  - Substantial reduction in cost
- No SAASM card for receivers
  - Possible CSAC replacement for additional accuracy.

An Added Benefit

- Jammer resistance effectively raises the satellite signal.
  - Also works for weak signals
  - Makes effective satellite power the same as a kilowatt at range of one kilometer.
- Enables indoor navigation.

The Way Ahead

- R&D verification
  - 2+ eloran stations
  - Receiver prototype.
    - Dynamic differential, or INS
  - Vulnerability testing
- System construction and production receiver design
- Coast Guard is logical manager.

Questions

- Is anyone in charge?
  - If so, who, and by what authority?