USNO GPS OPS

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GPS Timekeeping Function

Twofold:

Navigation Service

- Navigation Timekeeping:
  critical for navigation mission, needed for orbit determination/ prediction and internal satellite clock synchronization, not intended for timing applications.

- Metrological Timekeeping:
  not critical for navigation, but needed to provide a UTC timing services (time dissemination) to support communication systems, banking, power grid management, etc…

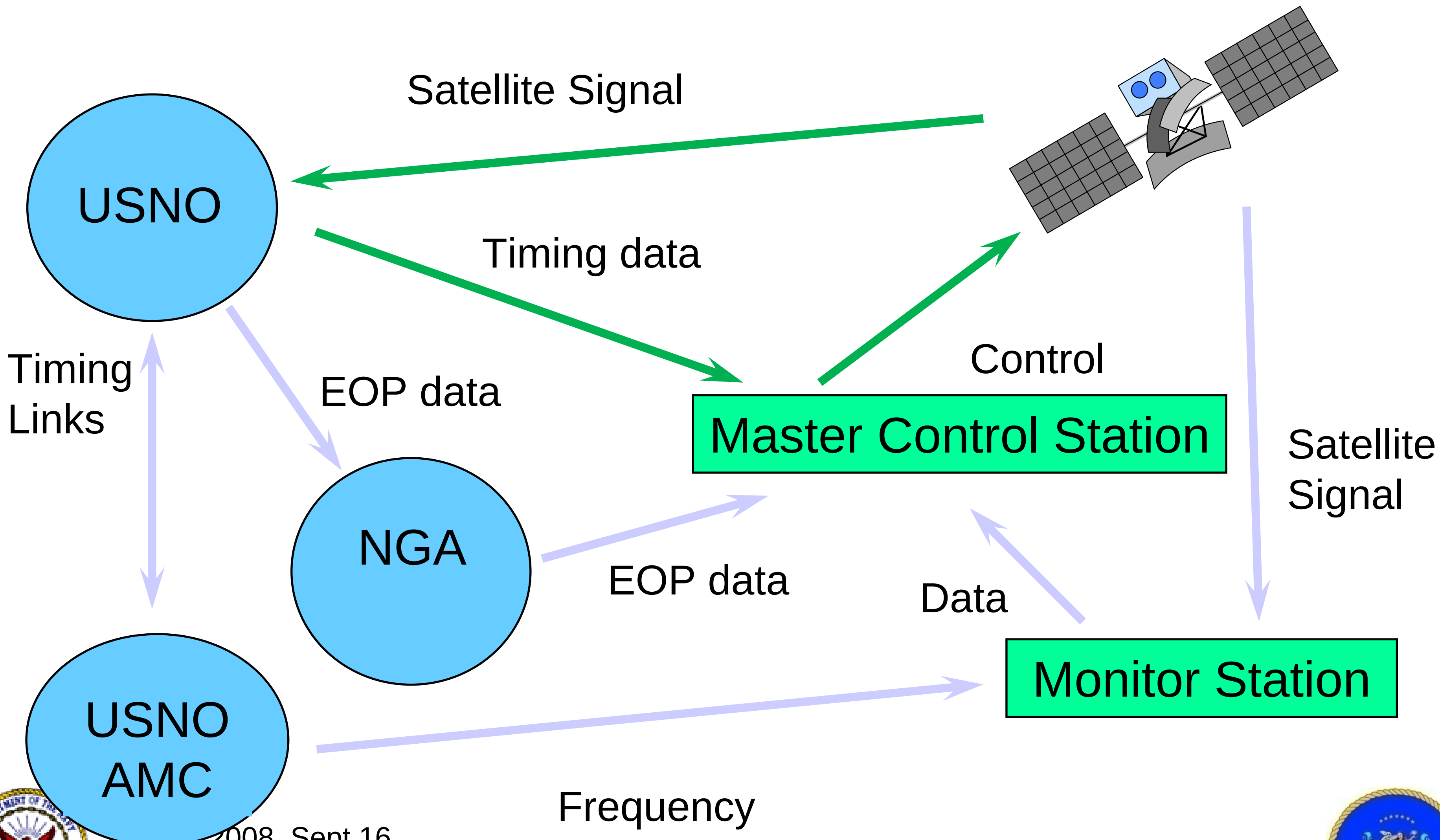
Timing Service

GPS Time Keeping

- **GPS Time**
  - an internal navigation time scale (paper clock)
  - Created from a weighted average of all GPS SV and monitor station clocks of which USNO and AMC contributes ~ 10 %
  - specified to be kept to within 1 us modulo 1 second of UTC (USNO) (Changes to 40 ns (2 sigma) for GPS III). In practice it has been kept to within +/- 25 ns (mod 1s) for the past decade. GPS time does not implement leap seconds
  - typically only used as part of the navigation solution

- **UTC Time** obtained from GPS by adding the integral number of leap seconds and fine UTC correction information contained in the GPS navigation data

USNO Contribution to GPS



Present USNO GPS Time Monitor Station Operations

- As part of USNO role as PTTI manager and keepers of the DOD Master Clock USNO serves as the time reference for the GPS system
- USNO uses Precise Positioning receivers with a UTC(USNO) reference to monitor GPS time from each GPS satellite
- USNO provides an average offset between GPS time and UTC(USNO) to the GPS Control Segment on a daily basis via secure internet
- GPS Control Segment uses this offset to steer GPS Time to UTC(USNO)
- GPS Broadcasts Correction of UTC offset

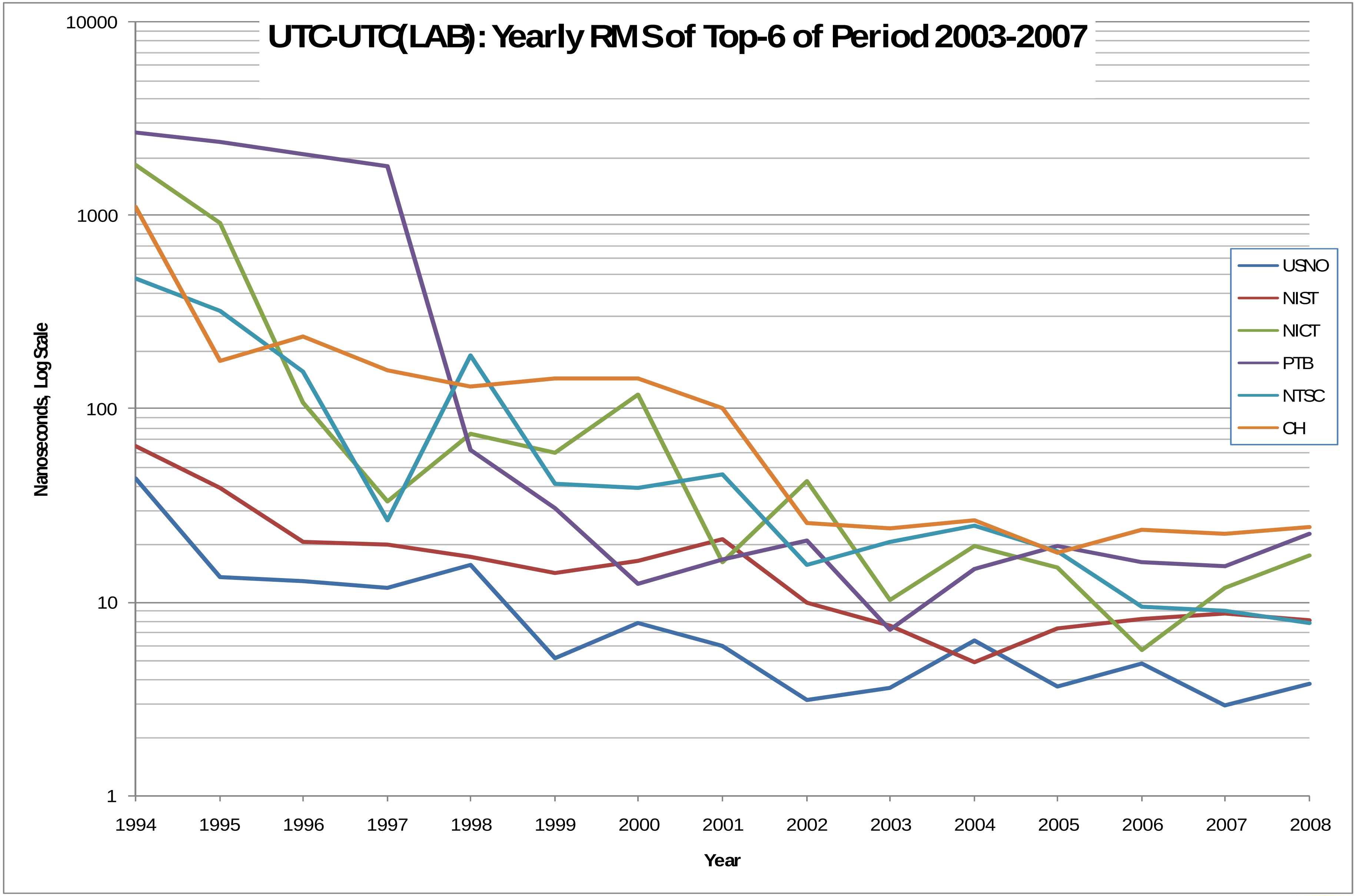
GPS Time and UTC Timing Service

- GPS Time counts in weeks and seconds of a week from midnight of January 5/6, 1980 UTC
- Weeks begin at the Saturday/Sunday transition
- Weeks are counted using 10 bits and roll-over every 19.7 years (1024 weeks - Aug 22, 1999 was last GPS Time rollover)
- The time during the week is determined by counting the number of 1.5 second epochs since the beginning of the week
- The GPS UTC correction defines leap second offset and also contains the precise corrections to UTC(USNO), typically accurate to a few nanoseconds

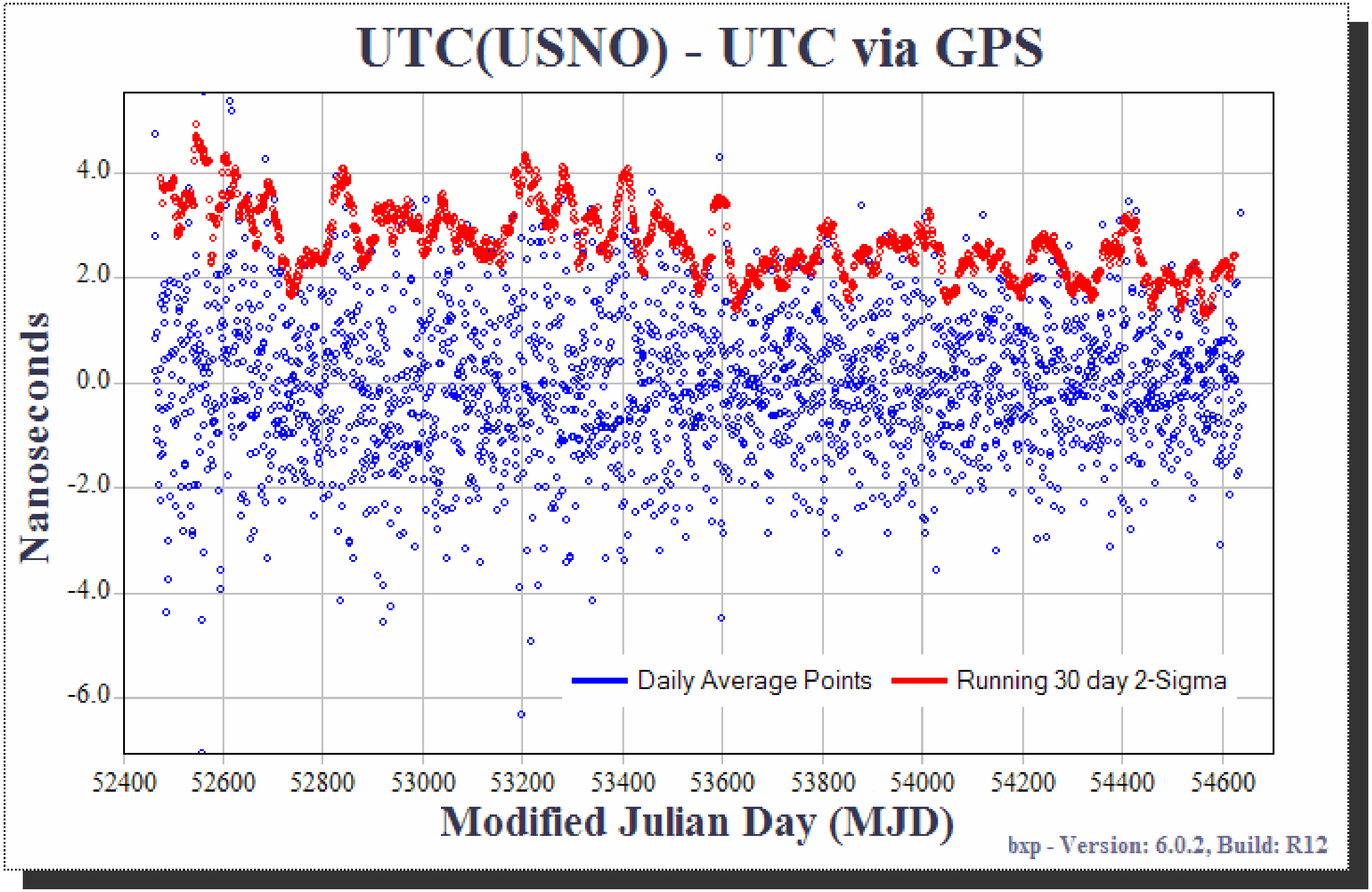
Leap Second Announcement

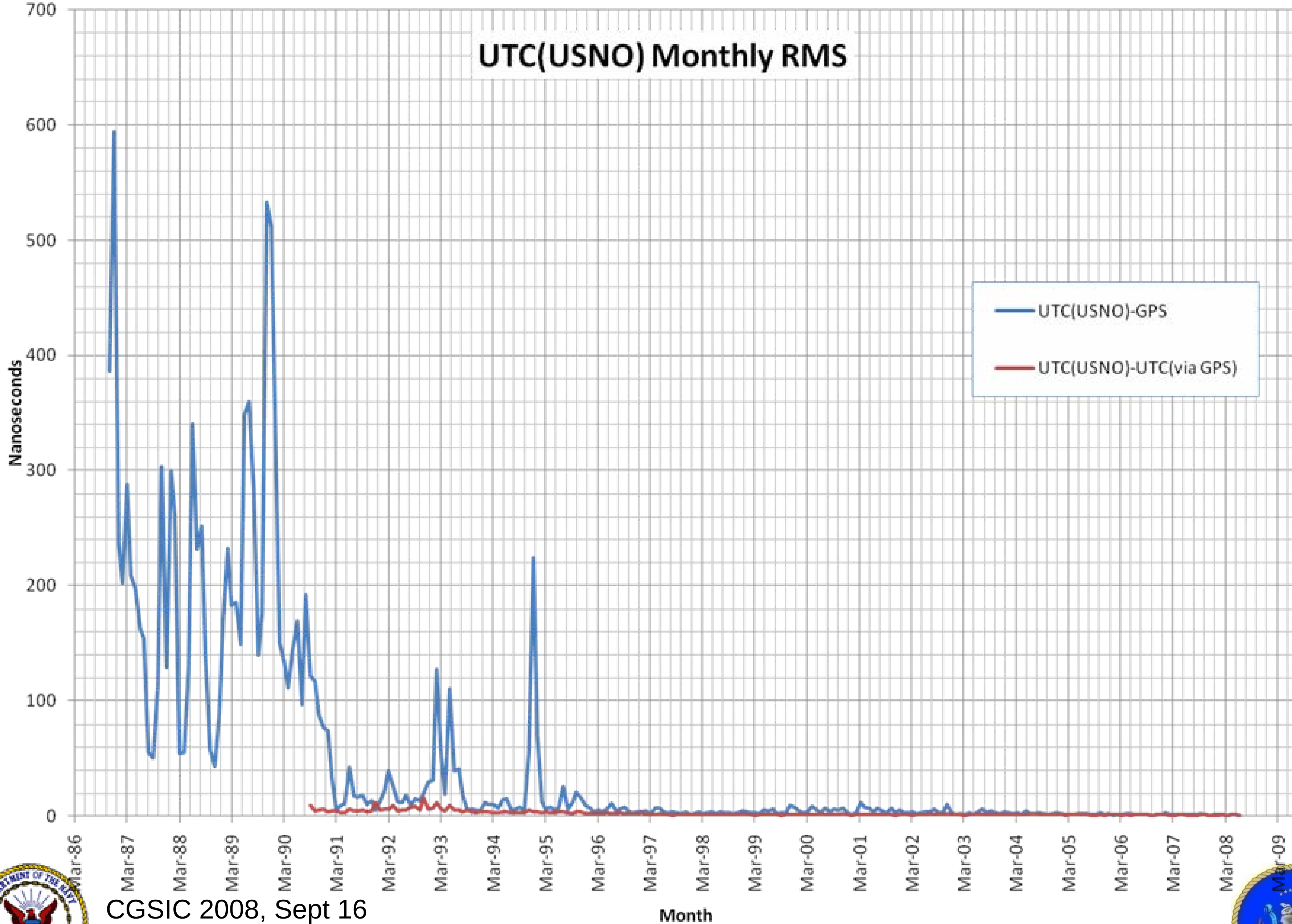
- Leap seconds are intended to keep UTC close to the imperfect rotation of the Earth.

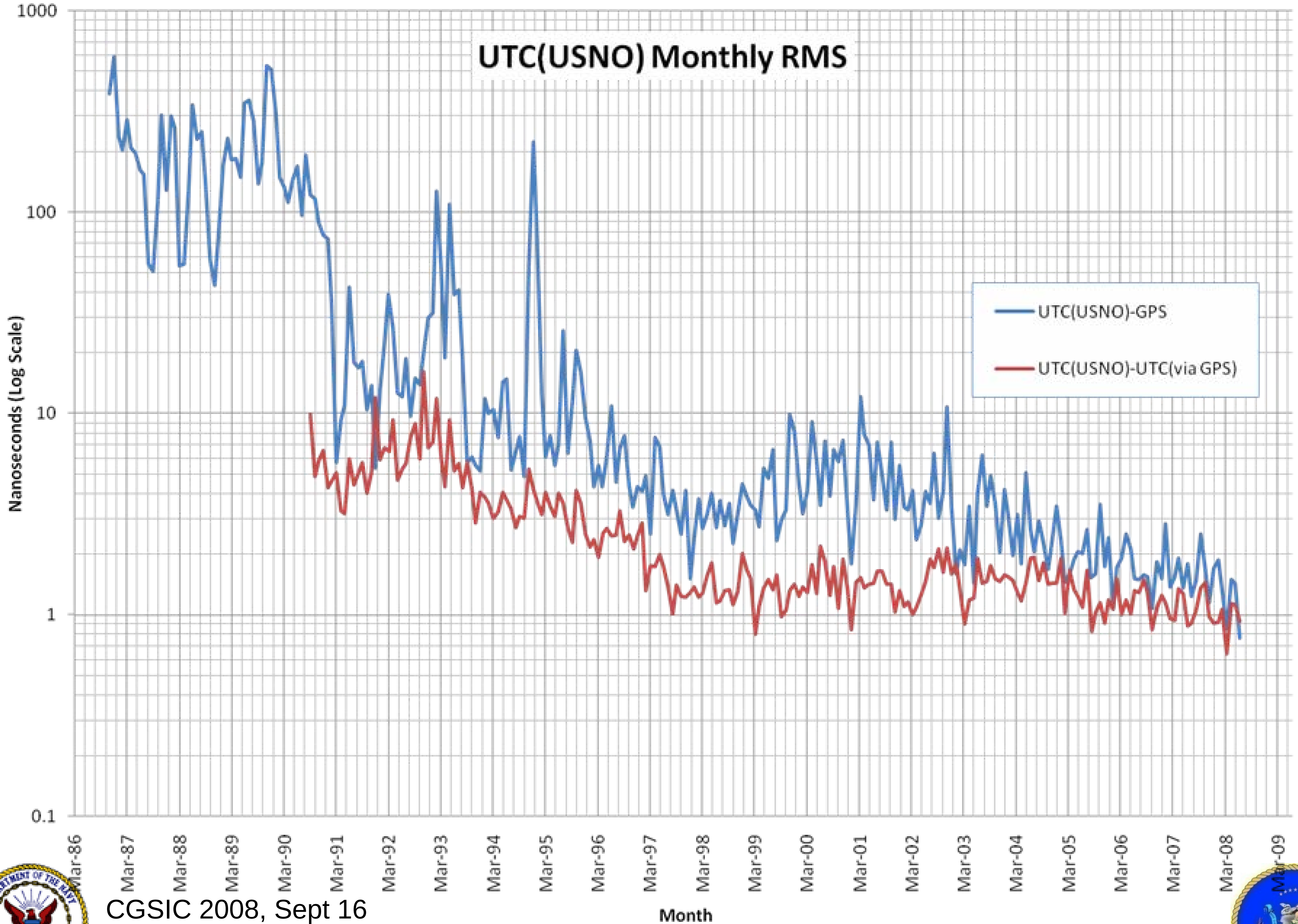
- IERS Leap Second Announcement: July 4, 2008
  - GPS Time is currently ahead of UTC by 14 seconds
  - As of January 1, 2009, GPS Time will be ahead of UTC by 15 seconds.
  - Implementation: count an extra second during the 23^{rd} hour on Dec 31, 2008 (a 60^{th} second); example: 59, 60, 0, 1, …

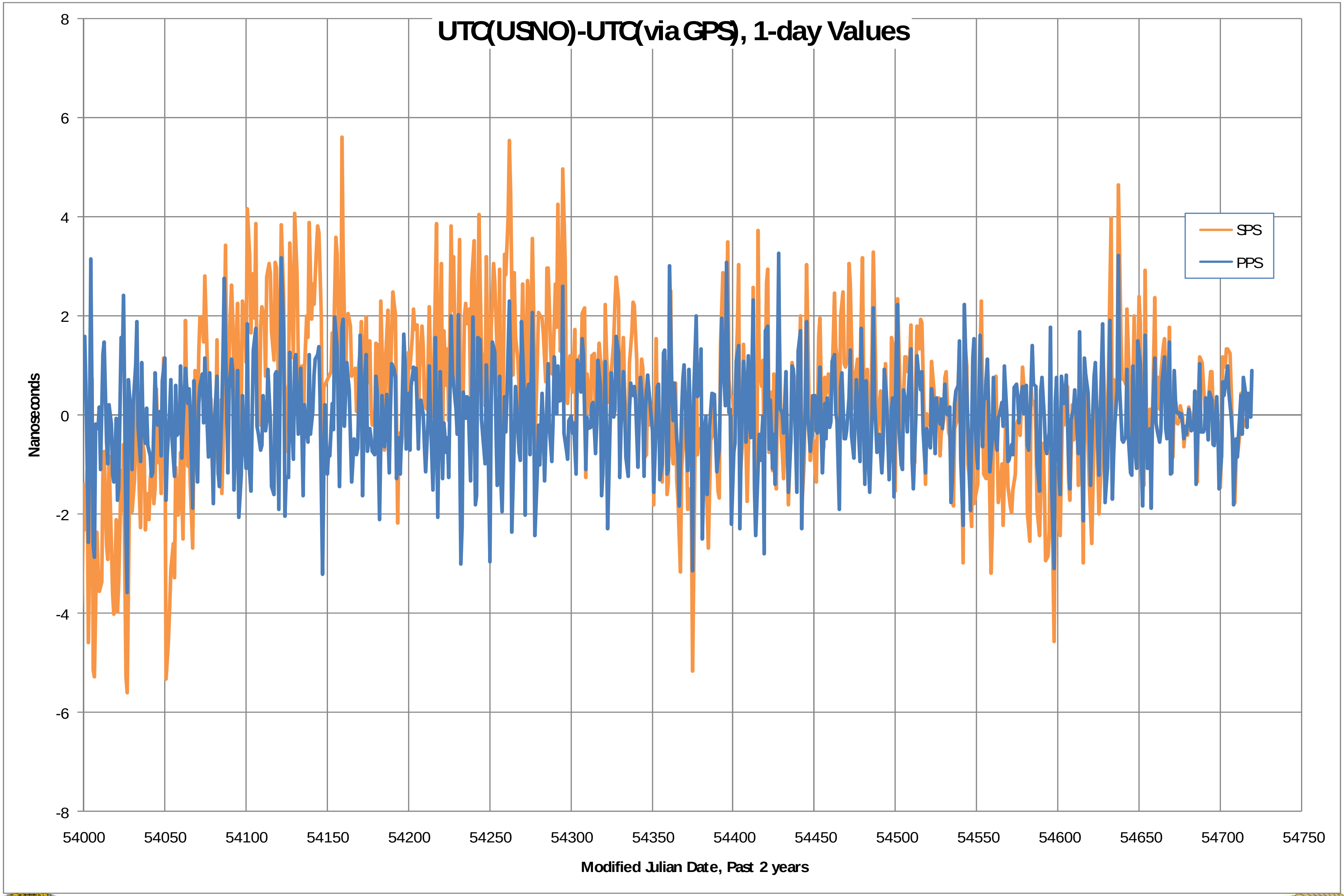

UTC-UTC(LAB): Yearly RMS of Top-6 of Period 2003-2007
Nanoseconds, Log Scale
10000
1000
100
10
1
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
Year
USNO
NIST
NICT
PTB
NTSC
CH

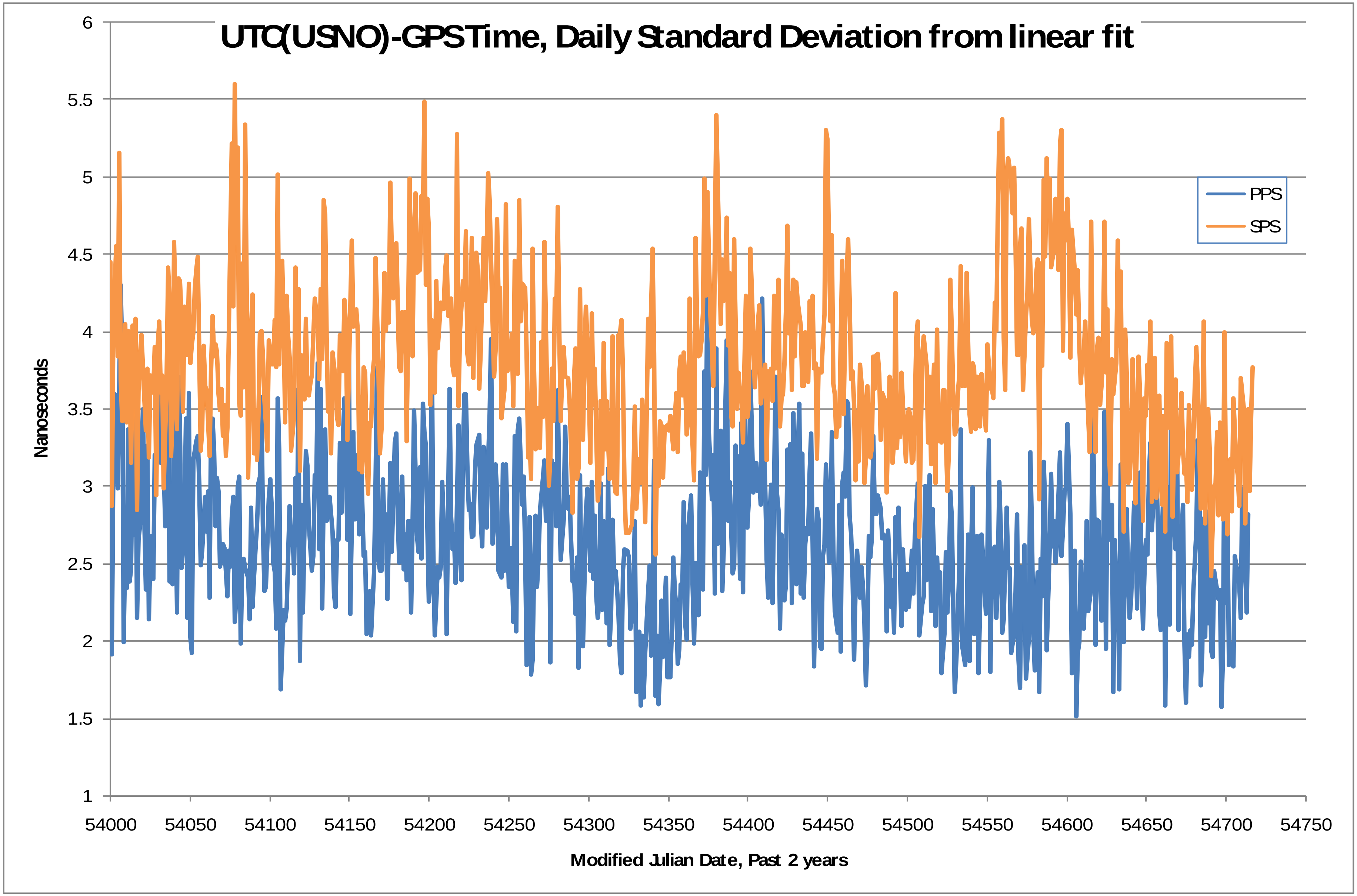
Historical GPS Performance




UTC(USNO) Monthly RMS
700
600
500
400
300
200
100
0
Nanoseconds
UTC(USNO)-GPS
UTC(USNO)-UTC(via GPS)
Mar-87
Mar-88
Mar-89
Mar-90
Mar-91
Mar-92
Mar-93
Mar-94
Mar-95
Mar-96
Mar-97
Mar-98
Mar-99
Mar-00
Mar-01
Mar-02
Mar-03
Mar-04
Mar-05
Mar-06
Mar-07
Mar-08
Month


UTC(USNO) Monthly RMS
1000
100
10
1
0.1
Nanoseconds (Log Scale)
UTC(USNO)-GPS
UTC(USNO)-UTC(via GPS)
Mar-86
Mar-87
Mar-88
Mar-89
Mar-90
Mar-91
Mar-92
Mar-93
Mar-94
Mar-95
Mar-96
Mar-97
Mar-98
Mar-99
Mar-00
Mar-01
Mar-02
Mar-03
Mar-04
Mar-05
Mar-06
Mar-07
Mar-08
Mar-09
Month


UTC(USNO)-UTC(via GPS), 1-day Values
8
6
4
2
0
-2
-4
-6
-8
Nanoseconds
54000
54050
54100
54150
54200
54250
54300
54350
54400
54450
54500
54550
54600
54650
54700
54750
Modified Julian Date, Past 2 years
SPS
PPS


UTC(USNO)-GPSTime, Daily Standard Deviation from linear fit
Nanoseconds
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
54000
54050
54100
54150
54200
54250
54300
54350
54400
54450
54500
54550
54600
54650
54700
54750
Modified Julian Date, Past 2 years
PPS
SPS

Three Components the GPS System

Space Segment

- Satellite
- Satellite Ranging Signal and Navigation/Timing Data
- Constellation Design to Provide Coverage, Availability

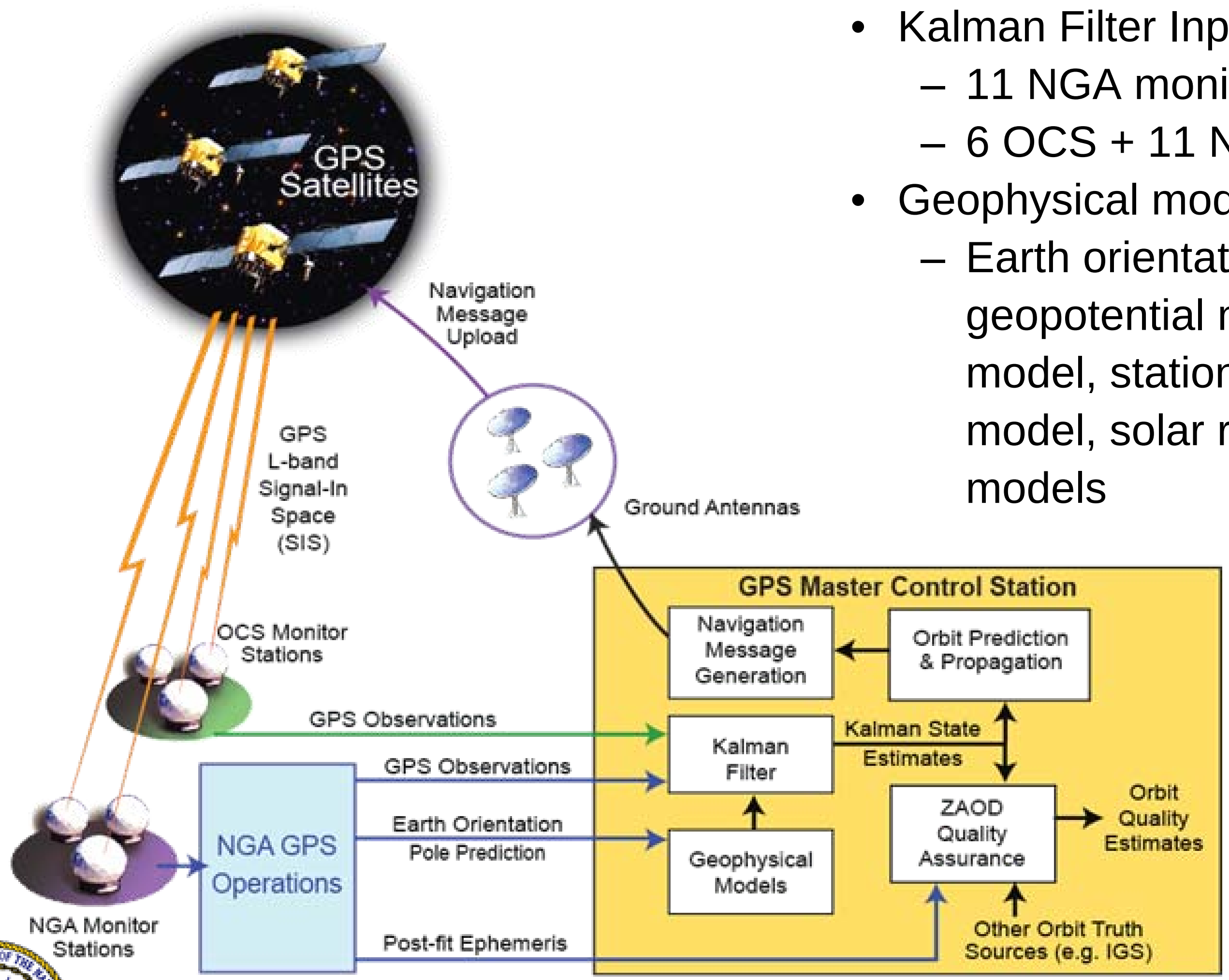
Control Segment

- Network of Ground Monitoring Station fixed to the Earth at known geodetic reference points
- Orbit and Satellite Clocks estimation
- Command and Control uplink capability

User Segment

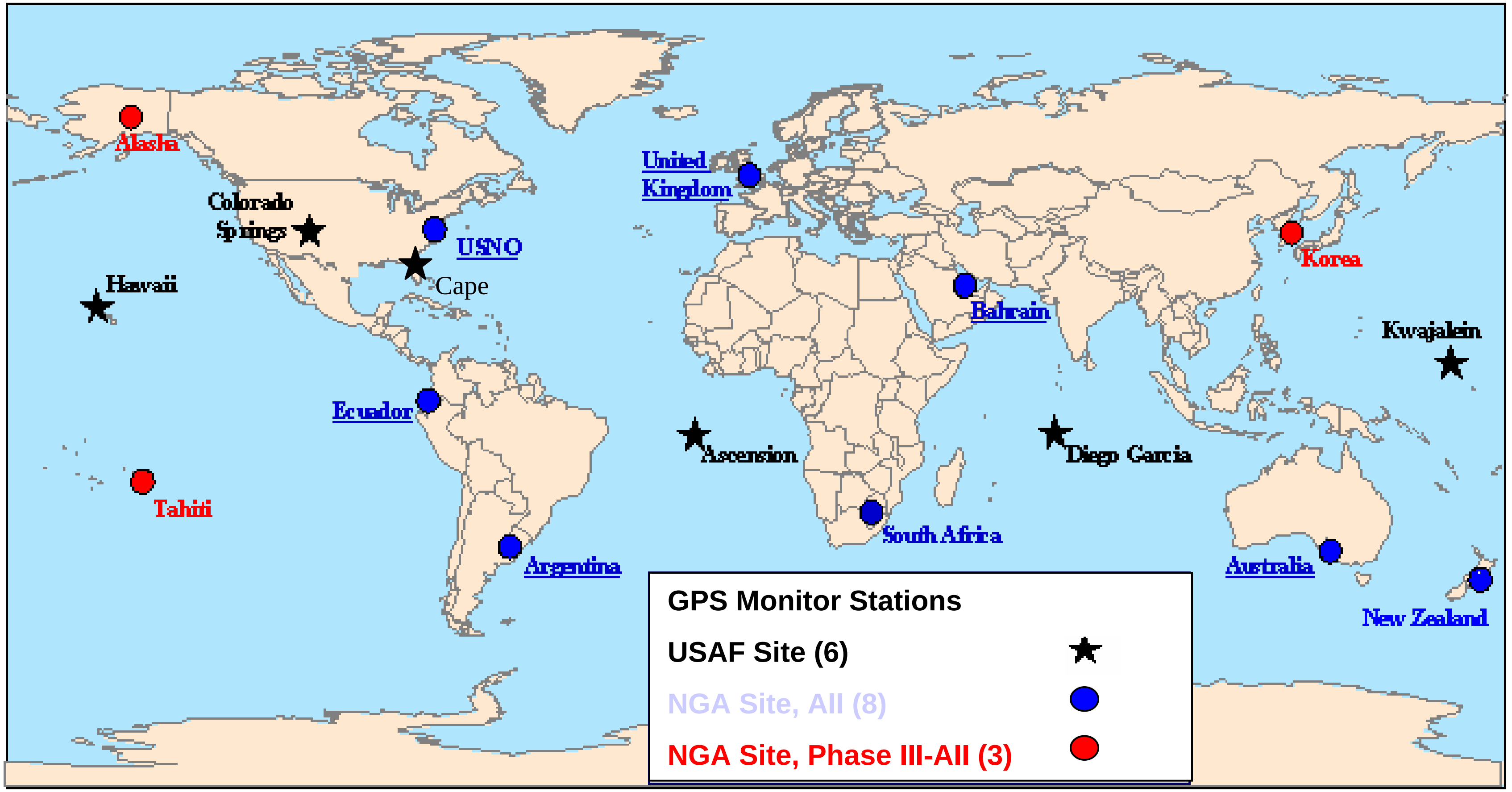
- Secure Military User Equipment (MUE)
- Civil application User Equipment (CUE)

GPS Control Segment



- Kalman Filter Inputs
  - 11 NGA monitor stations (MS)
  - 6 OCS + 11 NGA = 17 MS
- Geophysical models
  - Earth orientation parameters, geopotential model, tropospheric model, station tide displacement model, solar radiation pressure models

GPS Monitor Stations



Precise Positioning Service (PPS)
USNO Receivers

- AOA TTR-12 SM / SAASM
  - 12-channel based on GPS MSRE
  - Dual-frequency
  - All-in-view Tracking
  - Temperature stabilized antenna electronics & cables
- Primary purposes
  - GPS Time Monitoring for GPS MCS
  - CV Time Transfer between DC & CO

Standard Positioning Service (SPS)
USNO Receivers

- Current Operations
  - 3 Motorola Oncore-based receiver system (TTS-2)
    - 8-channel, single frequency

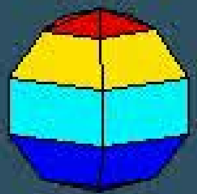
- Carrier-Phase GNSS Receivers
  - 3 Ashtech Z-12T
    - JPL Real Time Global Differential System
  - NovAtel GPS/WAAS/EGNOS/GLONASS
    - Monitor UTC(USNO)-WNT
  - Septentrio and upgraded NovAtel are being prepared for operations

GPS/GNSS Signal Design

- How GPS works
- GPS CDMA spread spectrum signal
- How signals are generated and received
- GPS error budget

GPS Navigation and Timing

- Each GPS satellite carries an Atomic clock that is precisely synchronized to a common internal navigation time scale
- Each satellite broadcasts its precise position in space
- A GPS receiver records the time difference between the receiver clock and the transmitted satellite clock, which provides a measure of distance between the user and the satellite
- These time difference measurements, used with knowledge of the satellite's position, allow the user to solve for the user-unknown position and time
- Four satellites are required to compute the four dimensions of X, Y, Z (position) and Time.

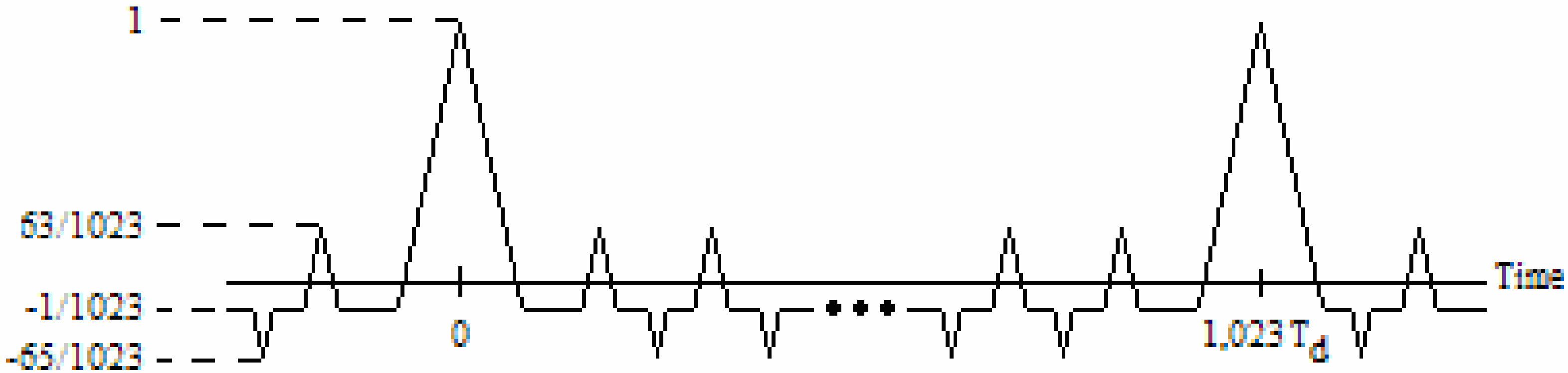


↑
Suppose this is a GPS satellite...

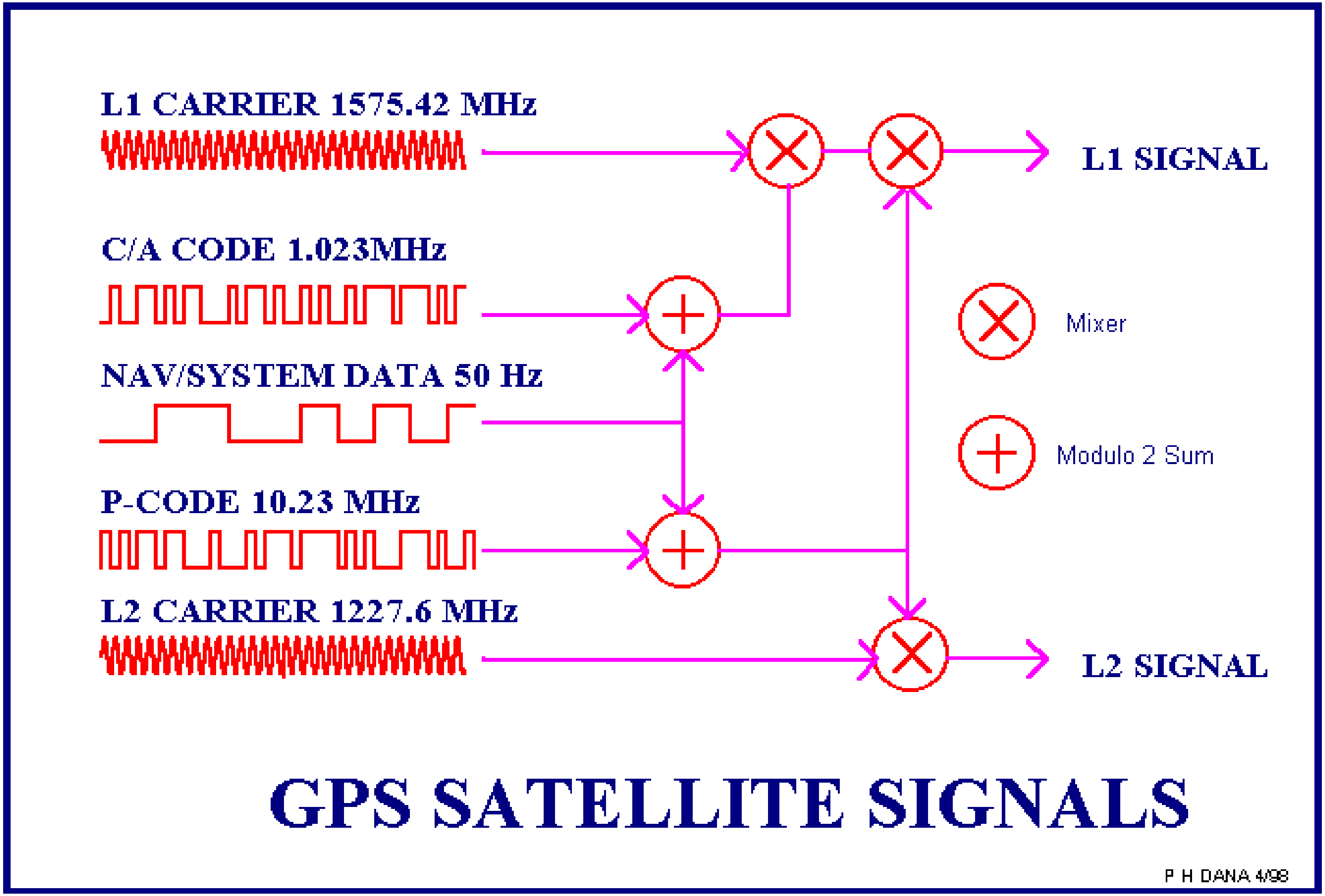
GPS Signal Design

- GPS CDMA spread spectrum signal

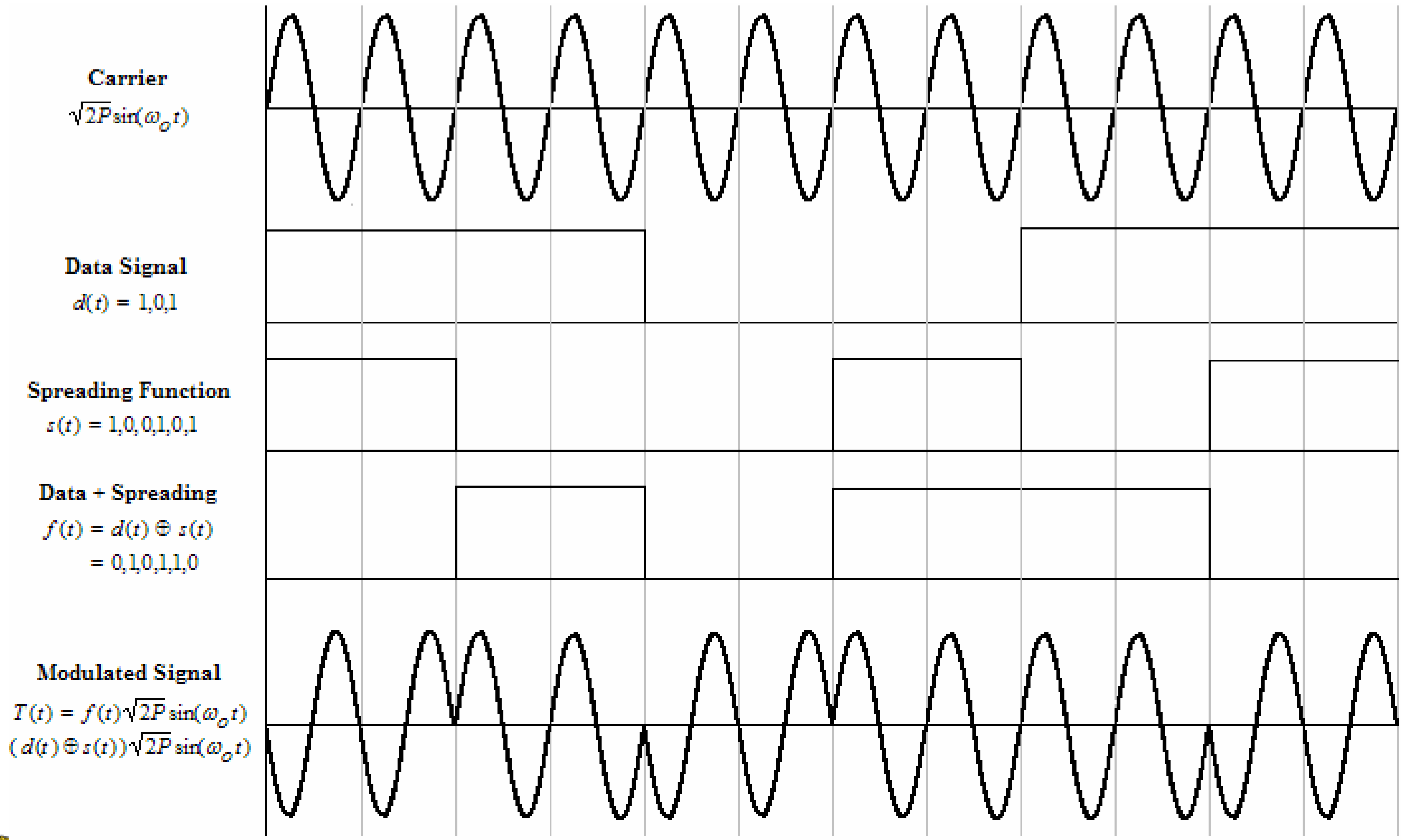
  "The usefulness of the maximal linear sequences in spread spectrum communications depends in large part on their ideal autocorrelation properties." – Robert Gold, Magnavox Research Laboratories, 1967

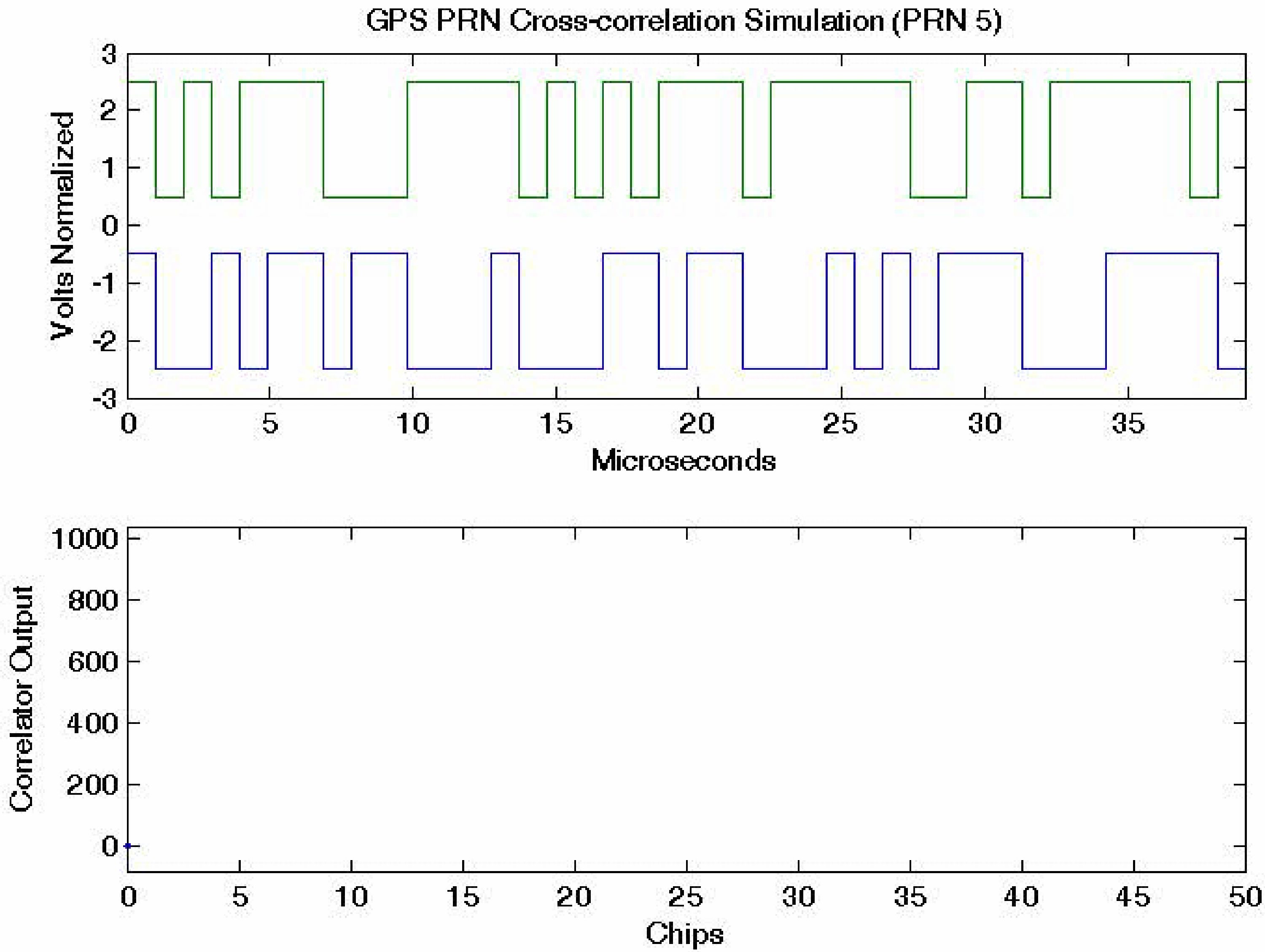


NORMALIZED AUTOCORRELATION FUNCTION


L1 CARRIER 1575.42 MHz
C/A CODE 1.023MHz
NAV/SYSTEM DATA 50 Hz
P-CODE 10.23 MHz
L2 CARRIER 1227.6 MHz
L1 SIGNAL
Mixer
Modulo 2 Sum
L2 SIGNAL
GPS SATELLITE SIGNALS
P H DANA 4/98

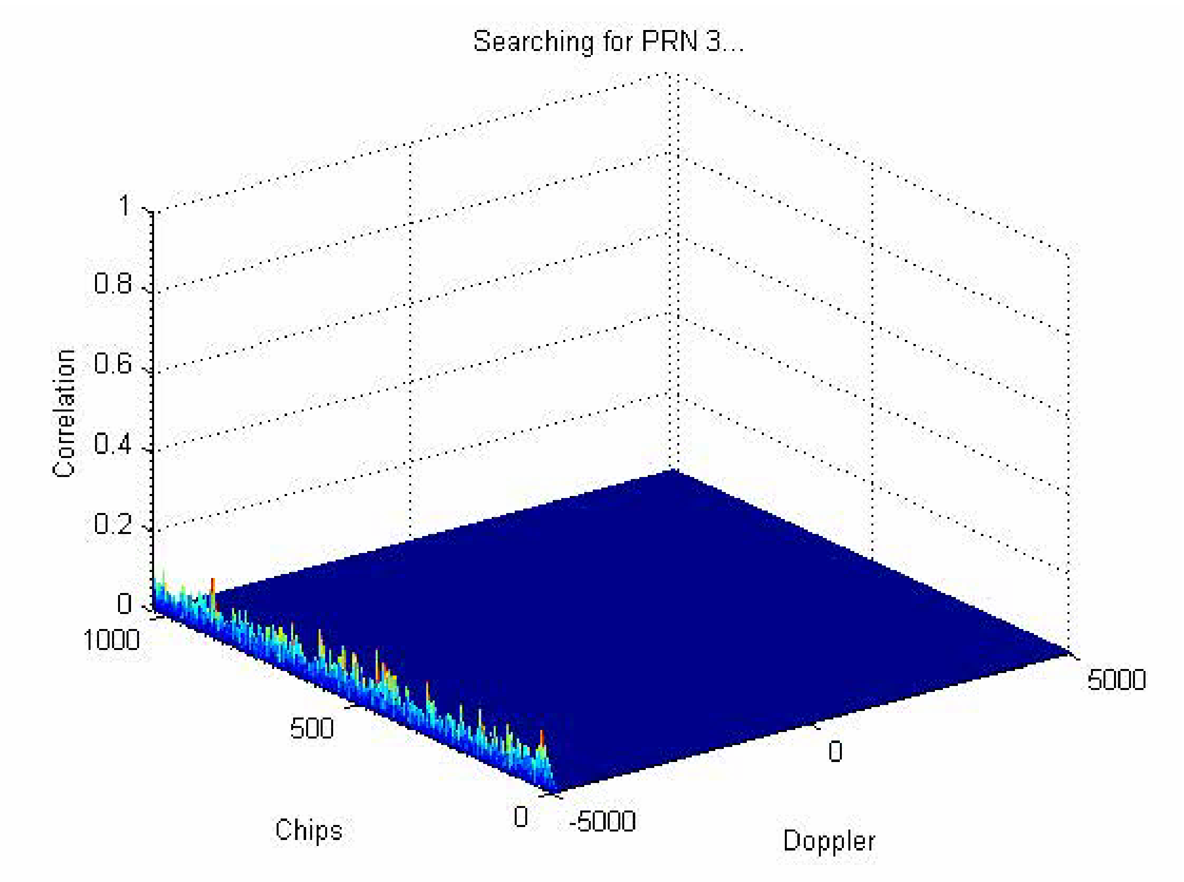
BPSK Example




GPS PRN Cross-correlation Simulation (PRN 5)
Volts Normalized
Microseconds
Correlator Output
Chips

GPS Signal Design

Example search across phase and frequency using real data (from a SiGe ADC)



GPS IIRM, IIF codes and GPS III

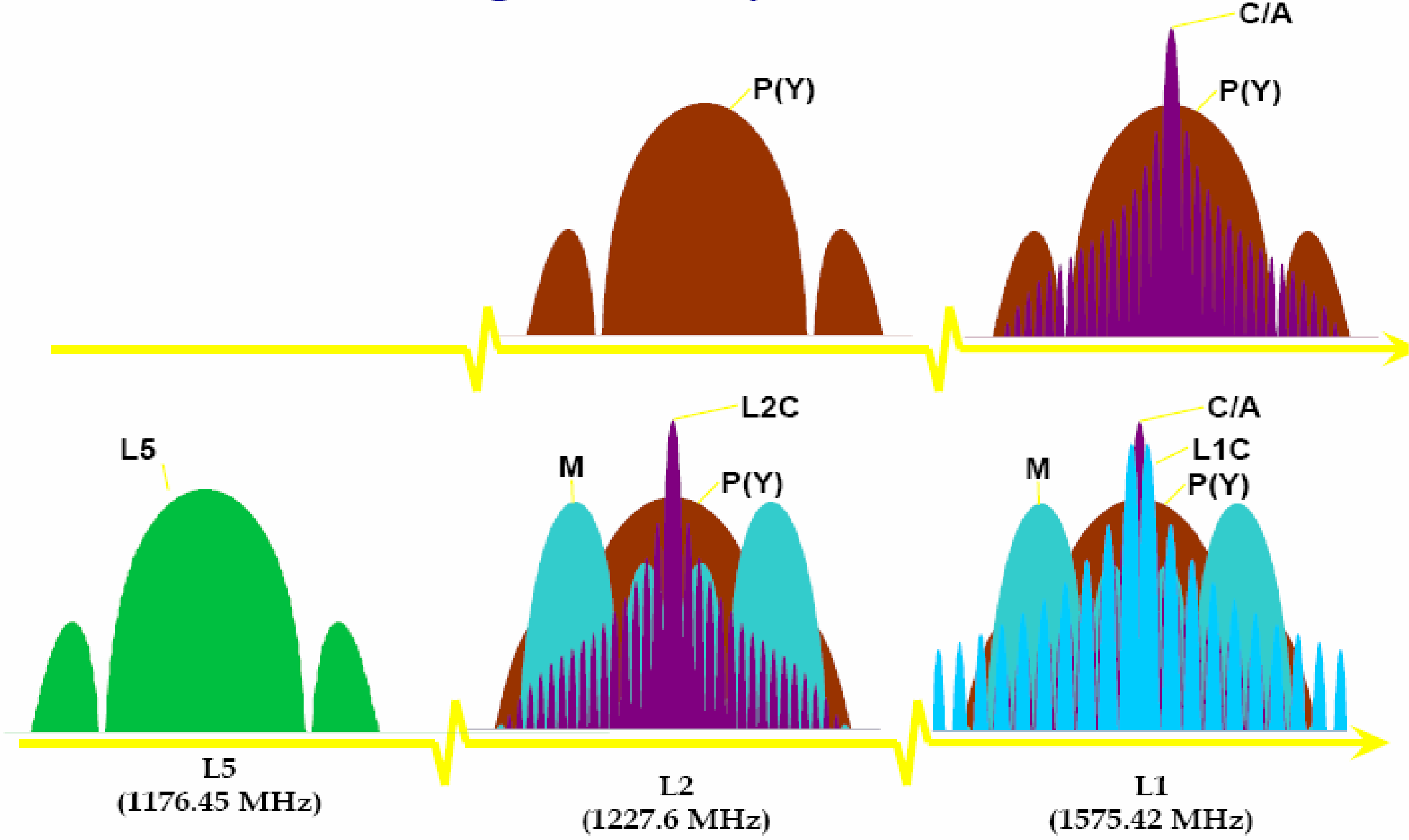
- GPS IIRM generation satellites include a new military code for both GPS L1 and L2 frequencies (M-code). Over the next decade M-code may be required for the DOD communication user community

- The GPS IIRM satellites also includes a new non-encrypted civil signal called L2C. This will now allow the civil community access to a true dual frequency GPS intended for civil applications. There are presently 6 GPS IIRM satellites in orbit.

- GPS IIF adds a completely new frequency band (L5 – 1176 MHz). This will add a second spectrally protected safely of life signal. GPS IIF is scheduled for first launch in the middle of 2009.

- GPS III will add a new and improve civil signal on L1 called L1C plus accuracies < one meter. (2014 first launch)

GPS Signals – Today and Future



GPS Error Budget

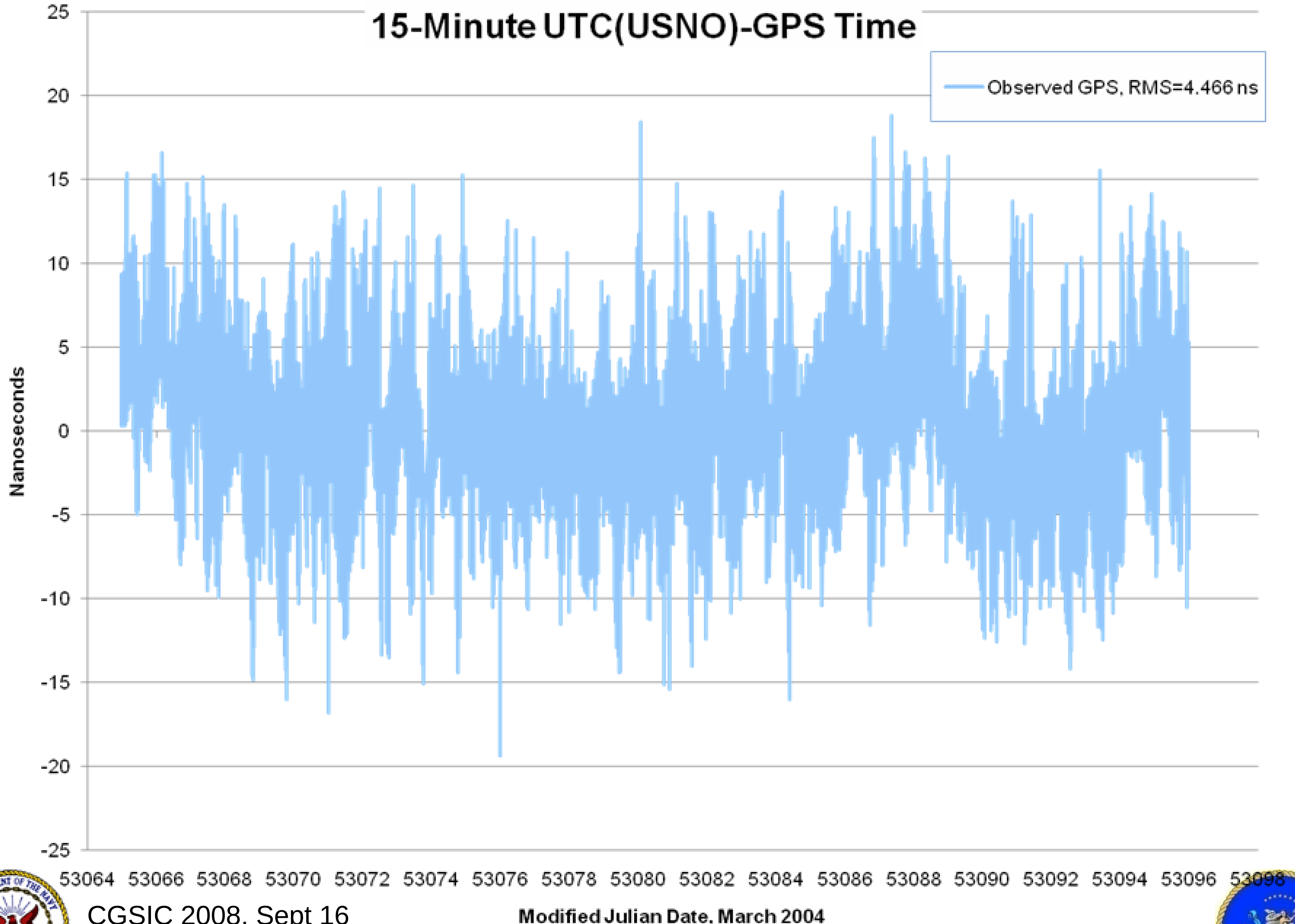
- ✓ Atmospheric Delays
  - Ionosphere Errors
    - Single Frequency L1 only error (< 10 Meter)
    - (L1 and L2) Dual Frequency GPS (<< 1 Meter)
  - Troposphere Errors (< 1 Meter Un-modeled error)
- ✓ Ephemeris/Orbit Error (< One Meter)
- ✓ Clock Error (< One Meter)
- ✓ Multipath (Meter level)
- ✓ Receiver Error (<< One Meter)

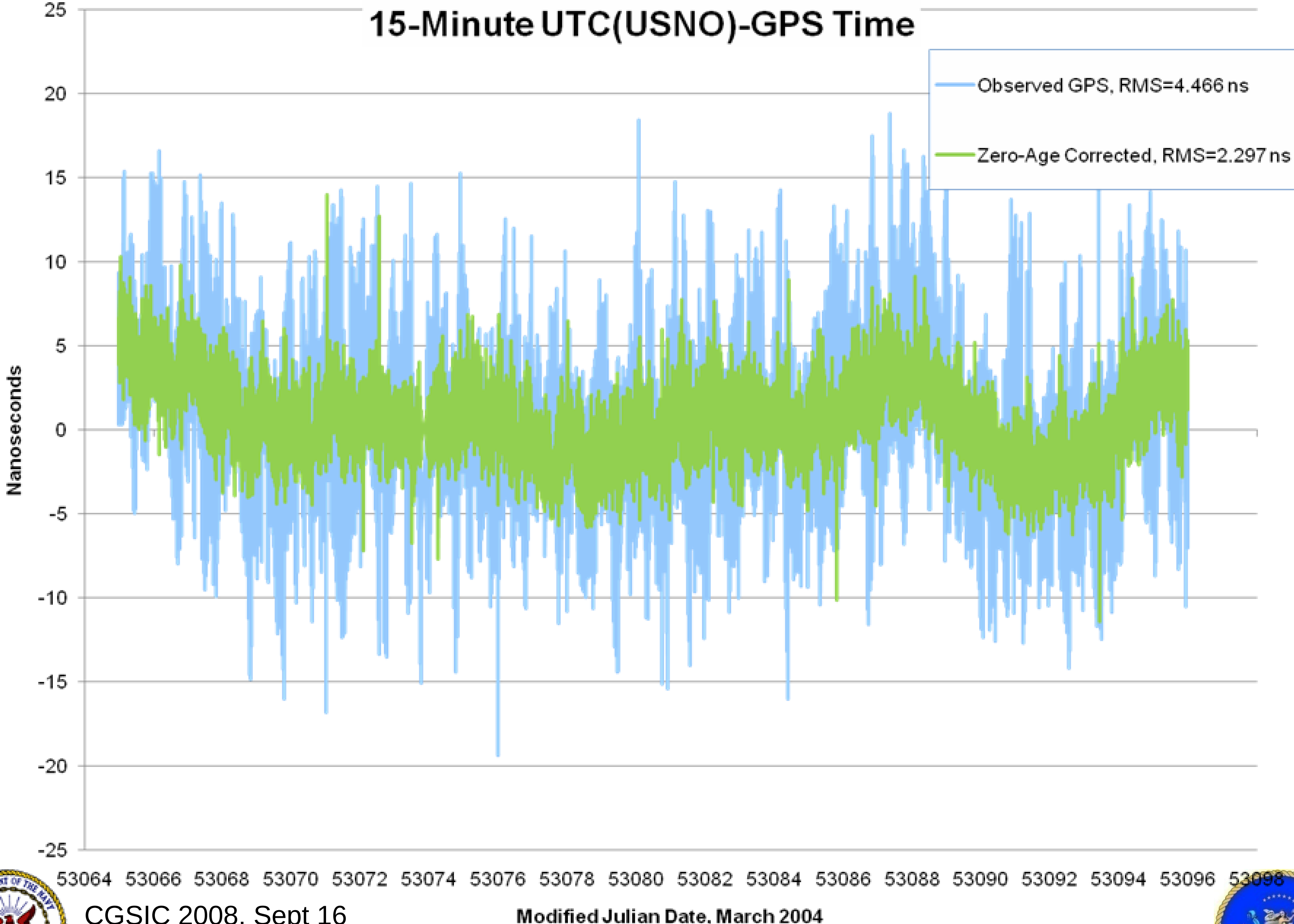
New and Improved Navigation Message

- **Legacy NAV message orbit and clock correction quantization errors will soon dominate GPS accuracy**
  - Errors are ~ 30 cm (1 ns) RMS with peak errors of 1m
- **ICD-200, 700, 705, 800 navigation message contains quantization improvements for M-code and new civil signals**
  - New and Improved Clock and Orbit message improves quantization error to < 1 cm (30 ps)

GPS III CDD Time Transfer Accuracy Requirement Rationale (I)

- CDD Threshold for dynamic timing user case:
  - 15.1 nanosecond (2 sigma) = 15 ns (2 Sigma) GPS error, assuming global average with two satellites failed
- CDD Objective for dynamic timing user case:
  - 4.55 nanosecond (2 sigma) = 4.5 ns (2 Sigma) GPS error, assuming global average with two satellites failed
- CDD Threshold for static timing user case:
  - 2.5/3.0 nanoseconds (2 sigma) = 1.5 ns (2 Sigma) (averaged over 24 hours)
- CDD Objective for static timing user case:
  - 1.0 nanosecond (2 Sigma) = 0.5 ns (2 sigma) GPS error (averaged over 24 hours)


15-Minute UTC(USNO)-GPS Time
Observed GPS, RMS=4.466 ns
Nanoseconds
25
20
15
10
5
0
-5
-10
-15
-20
-25
53064
53066
53068
53070
53072
53074
53076
53078
53080
53082
53084
53086
53088
53090
53092
53094
53096
53098
Modified Julian Date, March 2004


15-Minute UTC(USNO)-GPS Time
Observed GPS, RMS=4.466 ns
Zero-Age Corrected, RMS=2.297 ns
Nanoseconds
25
20
15
10
5
0
-5
-10
-15
-20
-25
53064 53066 53068 53070 53072 53074 53076 53078 53080 53082 53084 53086 53088 53090 53092 53094 53096 53098
Modified Julian Date, March 2004

GNSS Timing Interoperability

Time Scales

- GPS, GLONASS, and Galileo each maintain an independent navigation time scale loosely traceable to UTC (typically +/- 50 ns).
- To combine all systems, the differences between these navigation time scales need to be accounted for.
- Can be solved as part of the navigation solution by using additional unknowns.

Galileo, GLONASS and GPS Time Offset message

- **GPS and Galileo System Time Offset is intended to support**
  - Urban canyon or some other visibility limited navigation user requirement
  - User only tracking a total of four in view satellites
  - Mix of GPS, GLONASS, and Galileo satellites
  - From Cold start
- Goal is 1.5 meter accuracy (5 ns)

How to account for the GPS / GALILEO system time difference

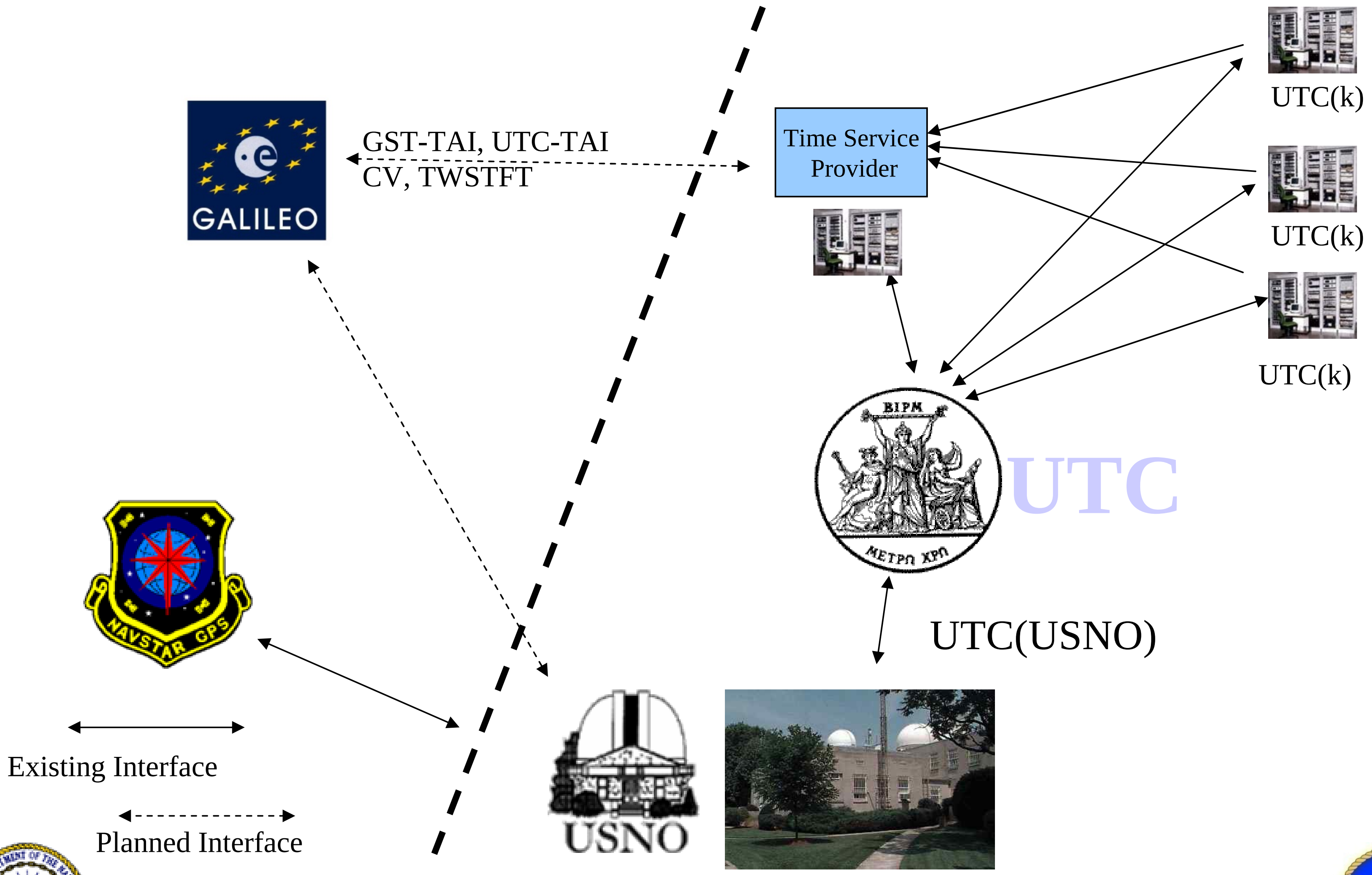
Options to produce GNSS to GPS time offset:

1. Determination of Time Difference by:

- **The underlying GPS and GNSS system time could be physically measured by traditional time transfer techniques (Two-way, common view, etc…) and included in the systems navigation data.**
- **The difference could be precisely estimated in near real time using combined GPS/GNSS monitor station receivers and included in the systems navigation data.**

2. Offset estimated in GPS-GNSS user equipment at the cost of one SV tracked per GNSS systems (additional unknowns)

GPS/Galileo Interface to UTC Time Services



GGTO Message

- GPS/GNSS Time Offset (GGTO) message is defined in IS-GPS-200 as CNAV message type 35
- The message utilizes 68 bits
- GNSS Type ID:

  000 = no data available

  001 = Galileo

  010 = GLONASS

  011 through 111 = reserved for other systems

GGTO Parameters

Table 30-XI. GPS/GNSS Time Offset Parameters

Parameter		No. of Bits**	Scale Factor (LSB)	Effective Range***	Units
A_{0GGTO}	Bias coefficient of GPS time scale relative to GNSS time scale	16*	2^{-35}		seconds
A_{1GGTO}	Drift coefficient of GPS time scale relative to GNSS time scale	13*	2^{-51}		sec/sec
A_{2GGTO}	Drift rate correction coefficient of GPS time scale relative to GNSS time scale	7*	2^{-68}		sec/sec^2
t_{GGTO}	Time data reference Time of Week	16	2^{4}	604,784	seconds
WN_{GGTO}	Time data reference Week Number	13	2^{0}		weeks
GNSS ID	GNSS Type ID	3			see text

* Parameters so indicated shall be two's complement with the sign bit (+ or -) occupying the MSB;

** See Figure 30-8 of IS-GPS-200 for complete bit allocation;

*** Unless otherwise indicated in this column, effective range is the maximum range attainable with indicated bit allocation and scale factor.