USNO GPS OPS

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GPS Timekeeping Function

Twofold:

- **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 UTC timing services (time dissemination) to support communication systems, banking, power grid management, etc…
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

USNO

Timing Links

USNO

Timing data

Satellite Signal

NGA

EOP data

Master Control Station

Control

Satellite Signal

GAO

Data

AMC

Frequency

Monitor Station
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 23rd hour on Dec 31, 2008 (a 60th second); example: 59, 60, 0, 1, …
Historical GPS Performance

UTC(USNO) - UTC via GPS

- Daily Average Points
- Running 30 day 2-Sigma

Modified Julian Day (MJD)

Nanoseconds

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June 25, 2008

USNO Research Project # N0001408WX21292
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)
• 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

- USAF Site (6)
- NGA Site, AII (8)
- NGA Site, Phase III-AII (3)
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
GPS SATELLITE SIGNALS
BPSK Example

Carrier
\[ \sqrt{2P} \sin(\omega_c t) \]

Data Signal
\[ d(t) = 1,0,1 \]

Spreading Function
\[ z(t) = 1,0,0,1,0,1 \]

Data – Spreading
\[ f(t) = d(t) \oplus z(t) \]
\[ = 0,1,0,1,1,0 \]

Modulated Signal
\[ T(t) = f(t) \sqrt{2P} \sin(\omega_c t) \]
\[ = (d(t) \oplus z(t)) \sqrt{2P} \sin(\omega_c t) \]
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

- L5 (1176.45 MHz)
- L2 (1227.6 MHz)
- L1 (1575.42 MHz)
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)
GNSS Timing Interoperability
• 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

- GST-TAI, UTC-TAI
- CV, TWSTFT

Time Service Provider

UTC

UTC(USNO)

UTC(k)

Existing Interface

Planned Interface

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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

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

* 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.