Die « Precise Timing Facility » für Galileo

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Outline

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- PTF Tasks & Performance
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Motivation & Background
Galileo System Architecture
Galileo Constellation

MEO constellation
- 23200 km altitude (29600 km radius)
- 14h 05m (17 revs in 10 d)
- 56° inclination
- 3 orbital planes

30 satellites
- 27 operational
- 3 spares
- 9 + 1 per plane

2 launchers
- Soyuz (2 S/C)
- Ariane-5 (6 S/C)
Galileo Satellites

- Mass 680 kg (launch mass)
- 1.5 kW electrical power (begin of life)
- Size 1.2m x 1.1m x 2.7m
- Lifetime >12 Jahre
- 3-axis stabilized
- 4 reference clocks
  - 2 x Rb ($2 \cdot 10^{-13}$ @ 1000s)
  - 2 x H-Maser ($2 \cdot 10^{-14}$ @ 1000s)
- Laser retro reflector
- Navigation payload ~80 kg
- SAR transponder ~20 kg
Galileo Ground Segment

Source: ESNIS
Galileo Closed-Loop System Architecture

- **Ground Control Segment (GCS)** manages **spacecraft** (orbits, relative spacing, health status, …)
- **Ground Mission Segment (GMS)** manages **payload** (navigation signal power levels, coding, encryption, …)
- World-wide network of **signal monitoring stations (GSS, > 40)** monitors navigation **signals**
- Data are fed back by terrestrial links in real-time from monitoring stations to GCC
- Mission control and data uplink centres: Oberpfaffenhofen/D, Fucino/I
Ground Control Centre (GCC) Oberpfaffenhofen

- Located on campus of DLR (German aerospace research centre) in Oberpfaffenhofen (25km southwest of Munich)
- Inauguration September 2008
- Staff ca. 100 people
- Installation of all technical equipment (servers, consoles, antennas) on-going
- Operational from autumn 2009 to support launch and operations of IOV satellites
- Dimensioned to fully support FOC phase as one of two redundant GCC’s
Industrial Consortium (IOV Phase)

- Customer: EC, Brussels
- Technical Authority: ESA, Noordwijk
- Satellite Contractor (4 S/C): EADS Astrium GmbH, Ottobrunn
- Satellite Integration and AIV Contractor: Thales Alenia Spacy Italia (TAS-I), Rome
- GMS Contractor: Thales Alenia Space France (TAS-F), Toulouse
- GCS Contractor: EADS Astrium Ltd, Portsmouth
- User Receivers Development: Septentrio (Belgium) and NovAtel (Canada)
Basics of Time & Frequency
## Time & Frequency

<table>
<thead>
<tr>
<th>TIME</th>
<th>FREQUENCY</th>
<th>( f = \frac{(t_b - t_a)}{\Delta T} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Second</td>
<td>1.0 s</td>
<td>1 s/day</td>
</tr>
<tr>
<td>Millisecond</td>
<td>0.001 s</td>
<td>1 ms/day</td>
</tr>
<tr>
<td>Microsecond</td>
<td>0.000001 s</td>
<td>1 us/day</td>
</tr>
<tr>
<td>Nanosecond</td>
<td>0.000000001 s</td>
<td>1 ns/day</td>
</tr>
<tr>
<td>Picosecond</td>
<td>0.000000000001 s</td>
<td>1 ps/day</td>
</tr>
<tr>
<td>Femtosecond</td>
<td>0.000000000000001 s</td>
<td>1 fs/day</td>
</tr>
</tbody>
</table>
Signal delay measurements (pseudoranges) to at least four satellites provide user time and position.

- Satellite clocks need to be precisely known.
- Remember: 1 ns = 30 cm.
The Basic Principle of Satellite Navigation (2/2)

- The pseudorange measurements $\rho_i$ are determined w.r.t. the individual satellite clock time $T_i$

- A common time reference, the GNSS system time $T_s$, is used to combine the individual measurements

- A real-time prediction of each satellite's clock time $T_i$ over $t$ is needed:

  $$(T_i - T_s) = T_{0i} + T_{1i} \cdot (t - t_0) + T_{2i} \cdot (t - t_0)^2$$

  $[t_0 = \text{epoch of last update of satellite clock } i]$  

- Requirement: $T_i$ and $T_s$ sufficiently stable during $(t - t_0)$
Satellite Time

- Ti, satellite time, is driven by satellite master clock (Rb or H-maser)
System Time

- In Galileo, $T_s$, system reference time, is called Galileo System Time (GST)

- GST is generated by the Precise Timing Facility (PTF)

- GST is represented in real-time as 10 MHz and 1-pps signal

- GST performance specification:
  - Relative frequency instability over $t = 1$ day: $4 \times 10^{-15}$ (equiv. to offset of 0.3 ns/day)
  - Frequency accuracy relative to UTC over $t = 1$ day: $5.4 \times 10^{-14}$ (95%)
  - Autonomy of operation: uncertainty of UTC – GST shall not exceed 28 ns after ten days of operation without external feedback
Galileo Precise Timing Facility (PTF)
Location of PTF within Galileo Architecture

Source: ESNIS
The PTF’s Three Main Functions

- Three main functions:

  1) Generate Galileo System Time (GST)

  2) Steer GST towards International Coordinated Time (UTC)

  3) Compute the GST-GPS System Time Offset (GGTO)
PTF – the Heartbeat of Galileo

Source: TAS
PTF Architecture

- To fulfill its three major tasks, PTF consists of:
  - An ensemble of atomic clocks, and clock measurement equipment
  - Time transfer equipment
  - Timescale computation and generation S/W
PTF Look-Alike

AHM clocks with control equipment

Equipment for clock stability determination

Switch matrix for time generation and distribution
How Does the PTF Solve its Tasks?
PTF Task 1: Generate Galileo System Time (GST)

- The highly accurate time reference (‘heartbeat’) of the whole Galileo system.
  - Needs both short and long term stability

- GST instability specification: 300 ps @ day
  - Or think of it in this way: GST will lose 1 sec in about 10 million years

Clock measurement
PTF Atomic Clocks – Provide Short-term Stability

4 x Caesium (Cs) atomic clock

2 x Active H-Maser (AHM) atomic clock
Relative Frequency Instability of Atomic Clocks

![Graph showing the relative frequency instability of different types of atomic clocks: compact Rb, commercial caesium, passive maser, active maser, PTB CS2, and two examples of fountain clocks. The graph plots $\sigma_y(\tau)$ against $\tau / s$ for different time scales.]

Source: PTB

Atomic clocks implemented in Galileo PTF

1 day
Why Atomic Clocks?

- The idea of a quantum based frequency standard
- James Clerk Maxwell, 1870:

> If, then, we wish to obtain standards of length, time, and mass which shall be absolutely permanent, we must seek them not in the dimensions, or the motion, or the mass of our planet, but in the wave-length, the period of vibration, and the absolute mass of these imperishable and unalterable and perfectly similar molecules.


\[ \nu_0 = \frac{(E_2 - E_1)}{h} \]

\( h \): Planck - constant

\[ 1 \text{ s} = n \cdot \frac{1}{\nu_0} \]
Detection of the Transition Frequency $v_0$

Application of external radiation $v$:

$$v(t) = v_0 + \epsilon(t)$$

$t$ = observation time  
$v_0$ = unperturbed transition frequency  
$\epsilon(t)$ = statistical fluctuations (noise) plus systematic offsets

The SI second is defined as

$n = 9\,192\,632\,770$ transitions between $E_{g3}$ and $E_{g4}$ of the Cs$^{133}$ atom
Properties of the Recorded Transition Line $v_0$

$\Delta p = \text{statistical fluctuations (noise)}$

$\Delta v = \text{recorded line width}$

(ideally: “Fourier-limited” $\sim 1/\Delta t$)

requires:

- no spontaneous emissions
- low noise interrogation

Transition detection can be performed by interrogating RF field (RF atomic clocks) or by interrogating laser (optical clocks)
Why Optical Will Replace RF Atomic Clocks in Future (1/2)

- Today, RF atomic clocks ($v_0 = \text{GHz}$) are approaching their theoretical performance limit:
  - Quantum noise limited frequency instability: $10^{-14} t^{-1/2}$
  - Frequency accuracy: $\sim 4 \times 10^{-16}$
- Most systematic noise effects are independent of transition frequency
- Optical transition frequencies ($v_0 = \text{THz}$) can be recorded with much smaller line widths $\Delta v$
- Promise improvement of two to three orders of magnitude in frequency instability
- **Goal**: $10^{-18}$
- A few minor technical problems: spectral purity of interrogation laser, clock comparison technique, …
Why Optical Will Replace RF Atomic Clocks in Future (2/2)

- Progress over the last ~fifty years:

Source: PTB
PTF Task 2: Steer GST to World-Time UTC

- GST shall be aligned to UTC (within certain limits)
- To provide long-term stability
- Compare Galileo System Time to:
  - European Timing Labs: UTC(k) laboratories
  - GPS System Time (USNO, Washington)
Specification of Galileo System Time vs. UTC

95% of time GST shall be in this region

Predicted time offset (2sigma) shall be in this band

Source: ESA
Why GST is Aligned to UTC (1/2)

- What does a user need:
  - Absolute time mark
  - Time of day, year (if possible corrected for time zone, daylight saving)
  - Some need also relative frequency synchronization

- But: which timescale to synchronize to?
Why GST is Aligned to UTC (2/2)

- There are many timescales around the world:
  - Some 50 countries generate their own national time UTC(k), with k = USNO (US), PTB (Germany), NPL (UK), NIM (China), …
  - UTC (“without brackets”) is the legal basis for all these national timescales:
    - Computed by BIPM (Paris, France) on paper
    - Weighted mean of ~250 atomic clocks around the world (operated in national UTC(k) labs)
  - UTC(USNO) is very close to UTC due to the heavy weight of the USNO clocks in the BIPM process
    - USNO generates also GPS system time, is nearly identical to UTC(USNO) and UTC
  - Galileo System Time (GST) shall follow (predicted) UTC to facilitate interoperability
Number of Clocks in EU (Galileo) and USNO (GPS)

Source: ESA
Routine Clock Comparison Links between UTC(k) Labs

North America

Europe

Asia

South America

Africa

Oceania

Organization of the International Time Links

April 2005

- Laboratory equipped with TWSTFT
- Laboratory equipped with dual frequency GPS reception
- TWSTFT
- TWSTFT by Ku band with X band back-up
- GPS CV single-channel link
- GPS CV single-channel back-up link
- GPS CV multi-channel link
- GPS CV multi-channel back-up link
Galileo Time Service Provider (GTSP)

- In Galileo, it’s the GTSP which computes and provides the steers for GST to follow UTC:

Source: Helios
GTSP Implementation

- Collects clock data from leading European timing labs
- Provides daily steers to PTF
- Realized by European industry consortium
- Scientific support by European National Metrological Institutes
- Prototype operations at CNES
- Under Contract with Galileo Supervising Authority (GSA)
Complete Process of User Synchronisation in Galileo

1. Pseudorange measurement
2. Satellite clock offset
3. TAI offset
4. Leap second

User clock → Satellite clock → Galileo System Time → TAIp → UTCp
Time Parameters Broadcast in Galileo SIS

- Satellite i clock prediction factors $T_{0i}$, $T_{1i}$, $T_{2i}$ (explained before)

- Week number (12 bits), Second-of-Week (i.e. Time of Week in seconds, 20 bits)

- Reference epoch: GST week zero started on a Saturday/Sunday in August 1999:
  

  This way, week number and second-of-week number are equal in GPS and Galileo

- Offset $a_0$ and predicted rate $a_1$ of GST vs. UTC

- Offset of UTC vs. TAI (before and after scheduled leap second)

- Week number and day number of leap second (1\textsuperscript{st} July and/or 1\textsuperscript{st} January)
PTF Task 3: Compute the GST-GPS System Time Offset (GGTO)

- Galileo Mission Requirements formulate: “The Galileo services shall be able to operate on a non-harmful interference basis with the GPS services and the GLONASS services”
- GGTO allows the user to utilize a combination of both GPS and Galileo signals for navigation and synchronization, i.e. a GPS-Galileo combination, not GPS or Galileo
- Particularly helpful in situations with limited visibility to the sky: no need to compute the offset in receiver
- On system level, GGTO is determined using time transfer techniques (Common-View and TWSTFT) between PTF and USNO (= provider of GPS time)
- Broadcast by both the GPS and Galileo constellations
The GGTO Problem

Source: DLR
GGTO Implementation

- Requirement: predict and disseminate GGTO with uncertainty of **5ns (2sigma)**

- Solution:
  - **Method 1:** USNO provides UTC(USNO) – GPS time; TWSTFT between USNO and PTF provides UTC(USNO) – GST (baseline for IOV phase)
  - **Method 2:** Common-View reception of GNSS (i.e. GPS and Galileo) signals at USNO and PTF with a combined GPS/Galileo receiver (will be implemented for FOC)

- New problem: USNO and PTF will compute slightly different values for GGTO

- Solution: GPS value and Galileo value will be harmonized before emission within above uncertainty limit
PTF Status & Summary (1/2)

- Galileo will generate its own reference time scale, Galileo System Time (GST)
- GST will be computed by the PTF, based on an ensemble of atomic clocks
- PTF will be installed in new GCC Oberpfaffenhofen
- Functional/performance verification will start in autumn 2009
PTF Status & Summary (2/2)

- GST will be steered to UTC by the GTSP
- Makes the huge European time & frequency expertise and infrastructure available to all Galileo users
- Enhances competitiveness of Galileo wrt. GPS
- Both USNO (responsible for GPS time) and PTF will compute GGTO
- GGTO will be harmonised and transmitted by both constellations to reduce user computation efforts, e.g. in limited visibility conditions