Potential of Space Based Navigation for Time and Frequency Transfer

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Space Based Navigation for Time and Frequency Transfer

1. Global Navigation Satellite Systems: an overview
2. GNSS observation equation: parameters for time/frequency transfer
3. Time and Frequency Transfer Using Pseudorange Measurements
   - Single satellite synchronisation
   - Multi satellite synchronisation
   - Time/frequency transfer for a baseline
   - Time/frequency transfer between stations
4. Time and Frequency Transfer Using Carrier Phase Measurements
   - Comparison of code and phase measurements
   - Smooth code using the phase measurements
   - Combined code and phase time/frequency transfer
   - Frequency transfer only uing phase measurements
5. Summary

Global Navigation Satellite Systems

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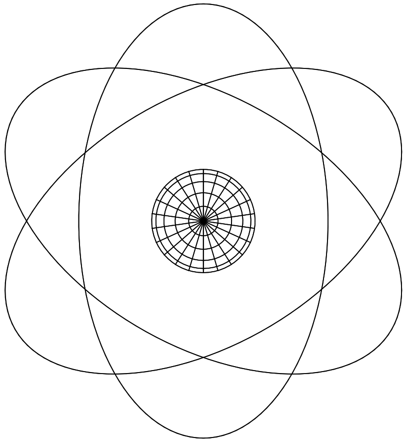
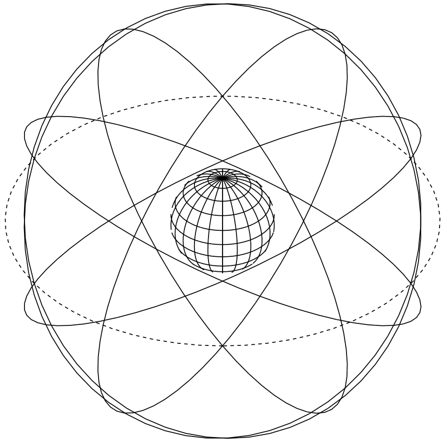
- other systems
  - there are some plans for national navigation systems
  - example: Japan, India, China

Global Positioning System

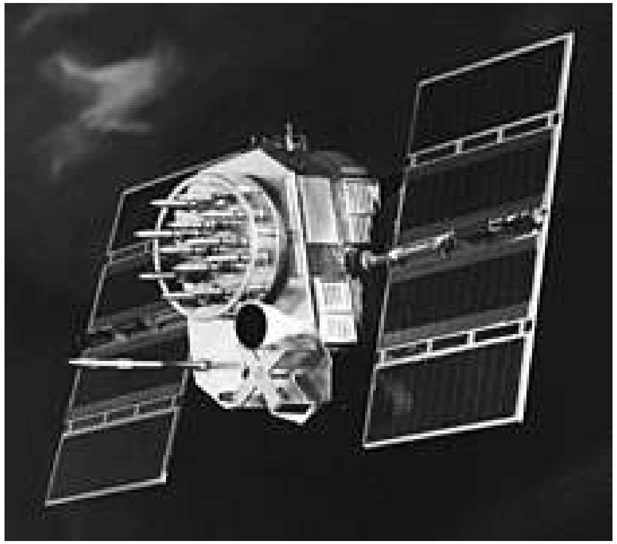
- The orbits are almost circular, the semimajor axes are $a \approx$ 26'500 km, the inclinations are $i \approx 55^\circ$. The orbital planes are separated by about 60° on the equator.
- The full constellation theoretically consists of 21 satellites and 3 active spares.
- At present 31 satellites are active including three modernized GPS satellite.

  (PRN: 12, 17, 31)
- The Orbital Planes of the GPS from the poles and from a latitude of 35°:





Global Positioning System



Block-II Satellite.

- GPS Satellites are big structures:

  The solar panels have a size of ca. 3.2 m $\times$ 1.7 m, the mass is about $m \approx 1\,000$ kg.

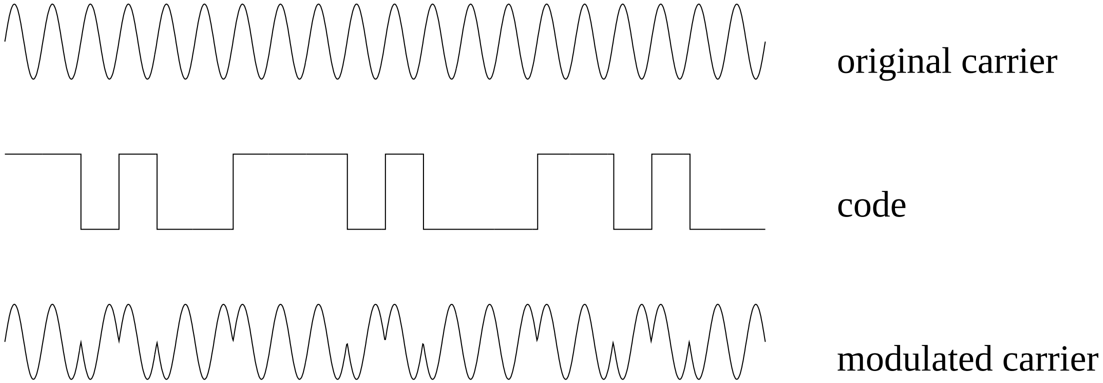
- Orbit modeling is not easy due to radiation pressure.

- Each satellite has a (series of) oscillator(s) generating two coherent carrier phases in the L-band with frequencies of

  L1: f_1 =1.57542GHz, L2: f_2 =1.2276GHz

Global Positioning System

- Information is sent by phase modulation:



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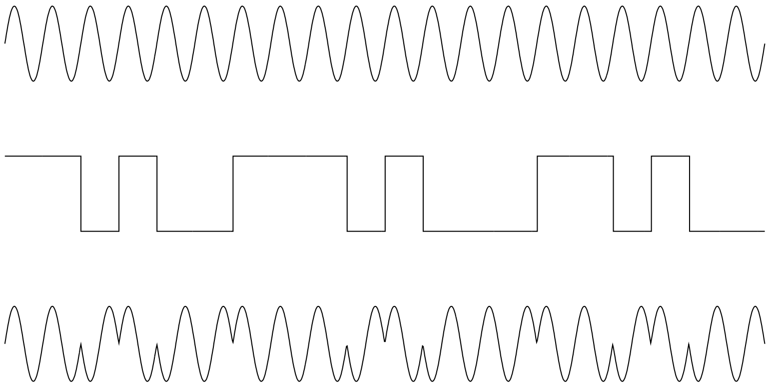

- Broadcast Ephemerides, Satellite Clock Corrections (to GPS system time), C/A—Code, and P— or Y—Code are emitted by the satellite. The first three items are only transmitted on L1.
- C/A code (Clear Access Code, generally available) allows to compute pseudorange with about 3 m accuracy, P— and Y—codes with about 0.3 m accuracy.
- P—code is the Precise or Protected code, Y—code is the encrypted version of the P—code.

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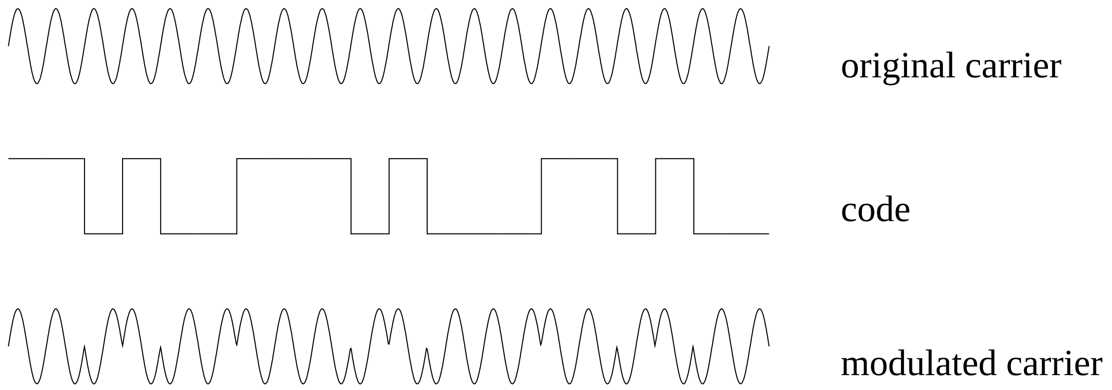

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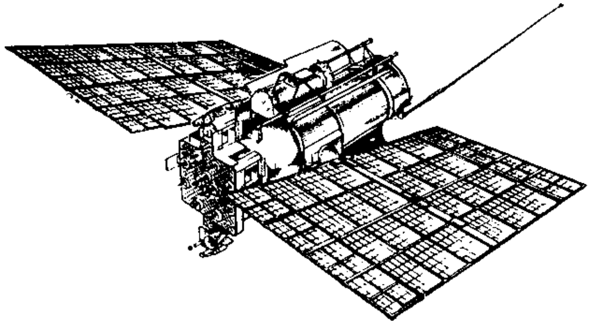
- P$-$code is the Precise or Protected code, Y$-$code is the encrypted version of the P$-$code.
- L1 and L2 are right-handed circularly polarized.
- $phase \times c$ may be reconstructed with an accuracy of $\sim$1 mm!

Global Navigation Satellite System (GLONASS)



GLONASS Satellite.

- Nominal Number of Satellites: 24

  (at present: 19 satelites, including 3 in commissioning phase, 3 unusuable, and 3 inactive)
- Number of Orbital Planes: 3
- Inclination: 64.8°, semimajor axes: 25'510 km
- Carrier frequency L1: $f_1^n = (1602 + n \cdot 0.5625)$ MHz

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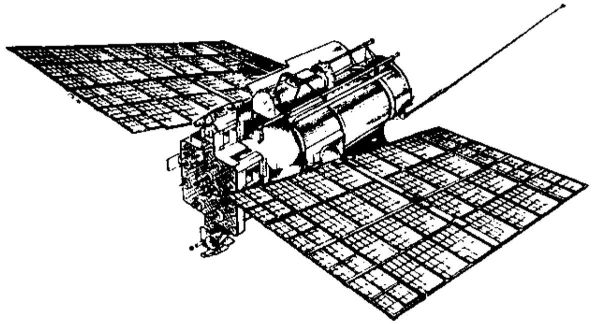

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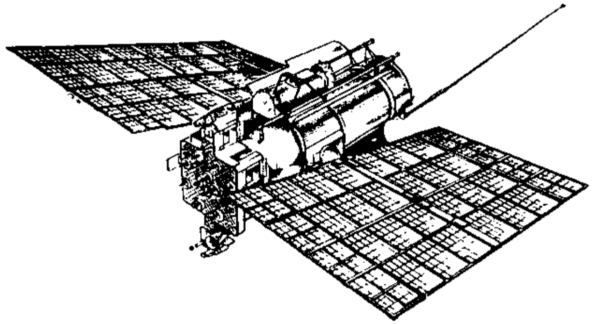

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- Last tripple launch successful on December 25, 2006

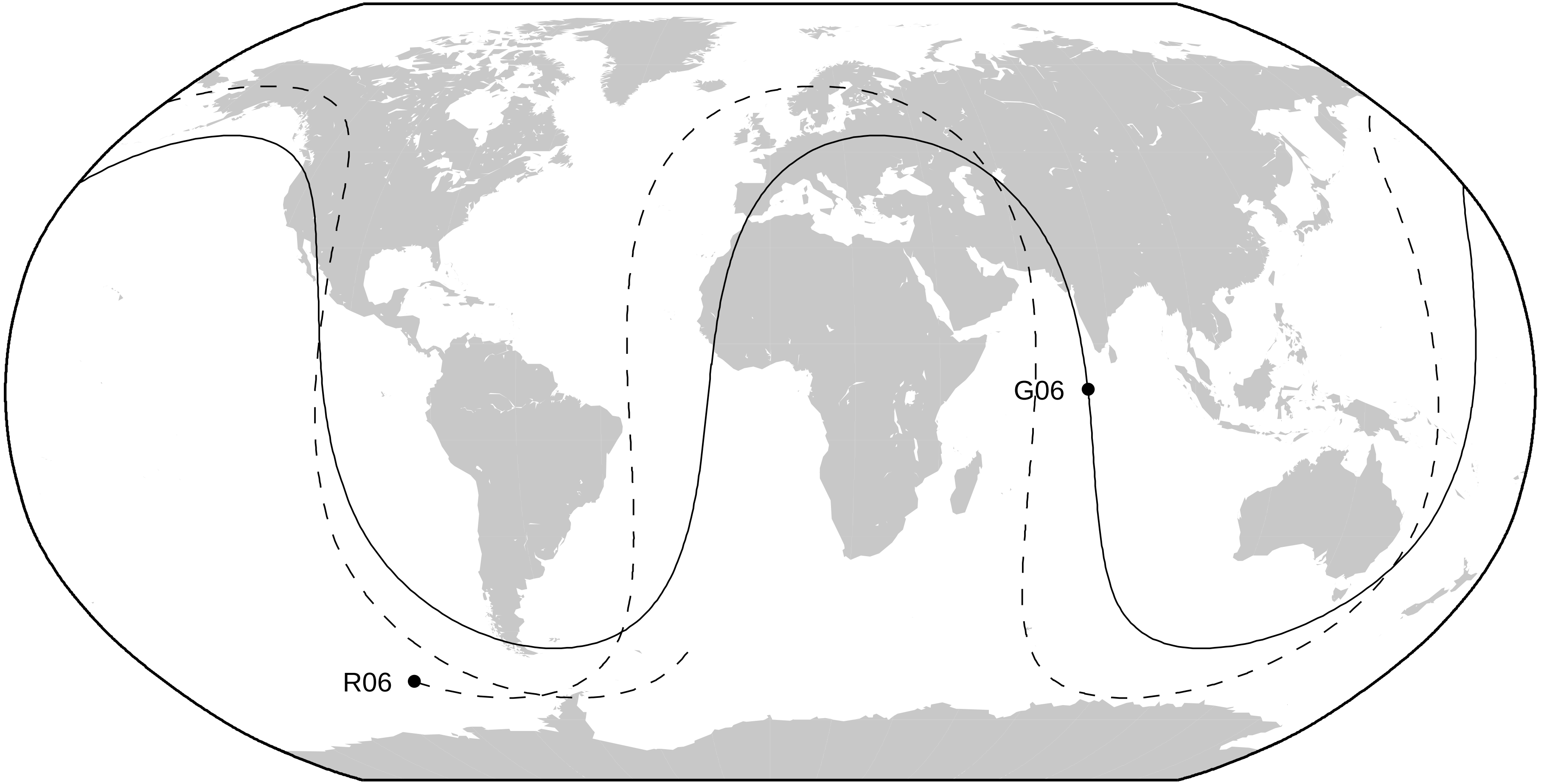
Comparison (GPS/GLONASS)

	GPS	GLONASS
Nominal number of satellites	24	24
Operational satellites (February 2007)	31	19 (16)
Orbital planes	6 (separated by 60°)	3 (separated by 120°)
Satellites per orbital plane	4 (unequally spaced)	8 (equally spaced)
Orbital radius	26’560 km	25’510 km
Inclination of orbital planes	55°	64.8°
Revolution period	$\sim$ 11 h 58 min	$\sim$ 11 h 16 min
Ground track repeatability	after one sidereal day	after eight sidereal days
Constellation repeatability	$\sim$ 23 h 56 min	$\sim$ 23 h 56 min
Signal separation technique	CDMA	FDMA
Carrier L1 (n=1. . . 12)	1575.42 MHz	1602.5625 – 1608.75 MHz
Carrier L2 (n=1. . . 12)	1227.60 MHz	1246.4375 – 1251.25 MHz
C/A-code (L1)	1.023 MHz	0.511 MHz
P-code (L1,L2)	10.23 MHz	5.110 MHz
Reference system	WGS—84	PZ—90
Time reference	UTC (USNO)	UTC (SU)

Comparison (GPS/GLONASS)

Ground track of a GPS (G06) and a GLONASS (R06) satellite

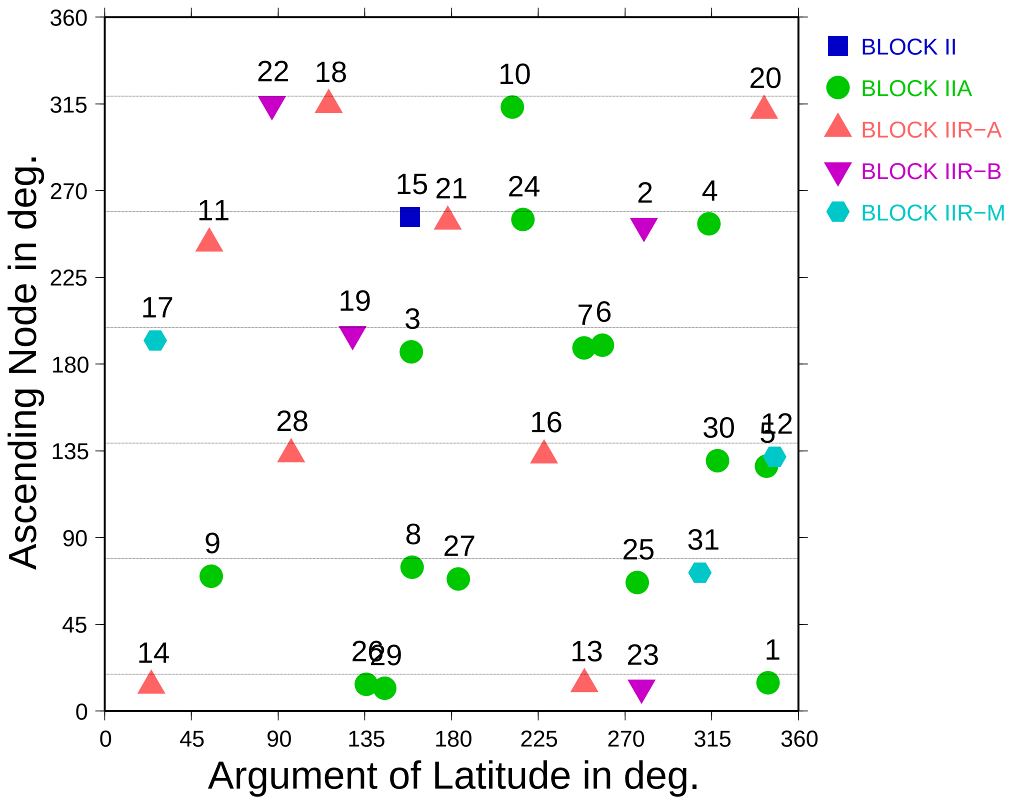
July 7, 2006

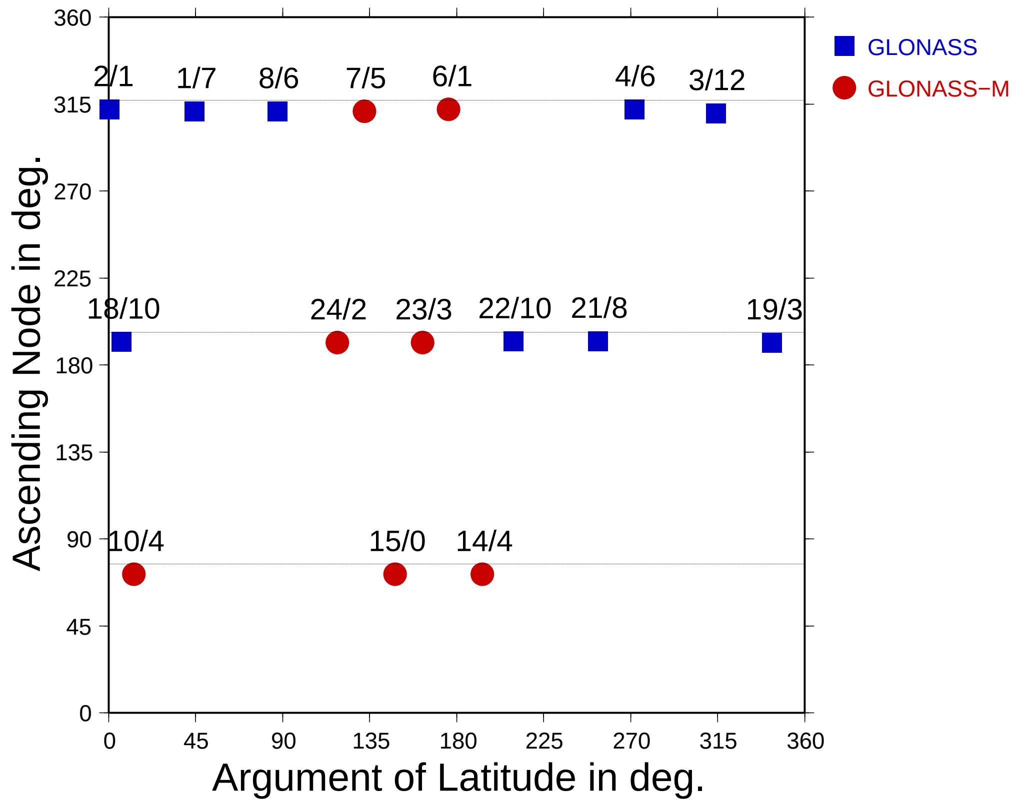


Comparison (GPS/GLONASS)

Constellation Status

February 23, 2007





GNSS Observation Equation

The basic observable is the pseudorange P_i^k, the difference of the reception time t_i of a particular signal (measured in the time frame of the receiver) and the emission time τ_i^k of the same signal at satellite k (measured in the time frame of the satellite):

$$P_i^j = c \cdot (t_i - \tau^k)$$

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Assuming an Earth without atmosphere, receivers and satellites with perfectly synchronized clocks, the pseudo-range is equal to the slant range between satellite (at time τ^k) and receiver (at time t_i).

$$P_i^j = \left| \vec{x^k}(\tau^k) - \vec{x_i}(t_i) \right|$$

GNSS Observation Equation

$$P_i^k = \left| \vec{x^k} - \vec{x}_i \right| + \Delta_{trop}{}_i^k + \Delta_{ion}{}_i^k + c\delta_i - c\delta^k$$

P_i^k	Code observation of station i to satellite k
$\vec{x}^{\,k}$	Position vector of satellite k
$\vec{x}_i$	Position vector of station i
$\Delta_{trop}{}_i^k$	Signal delay in the troposphere
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δ^k	Clock correction of the transmitter of satellite k with respect to GPS time
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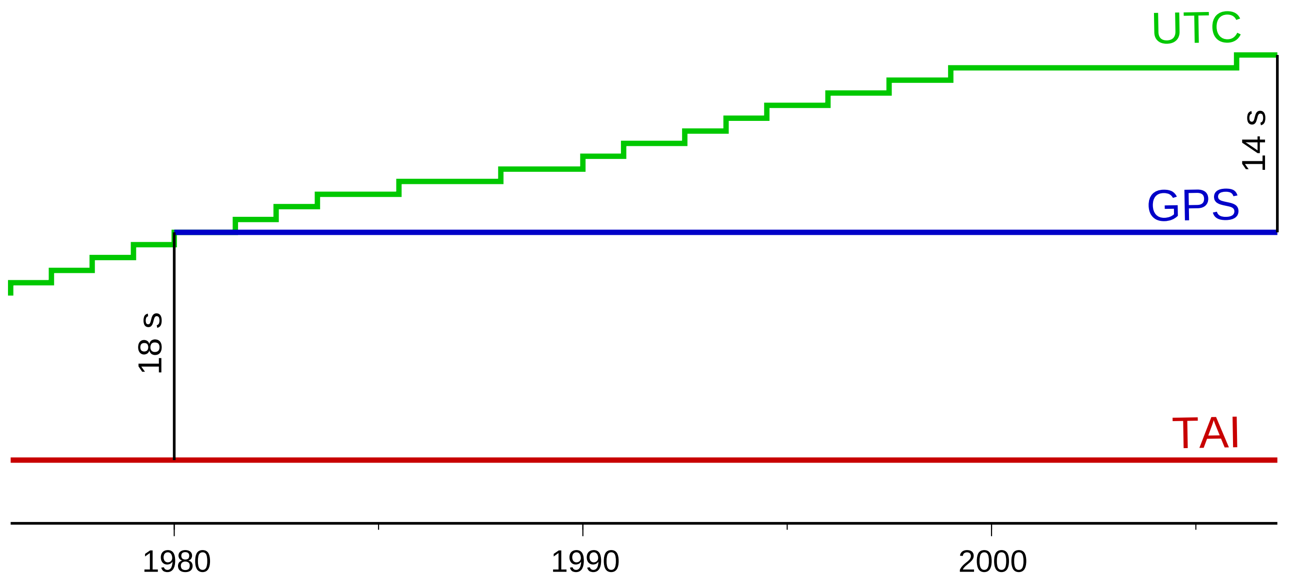
Single Satellite Synchronization

- synchronization to GPS system time and not to UTC:



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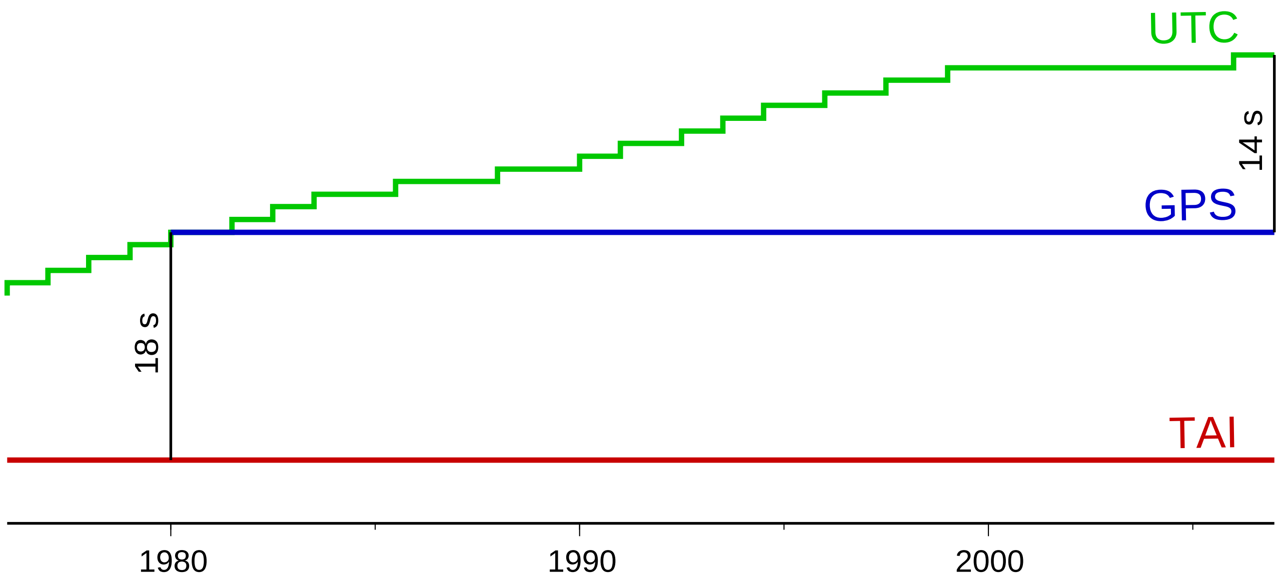

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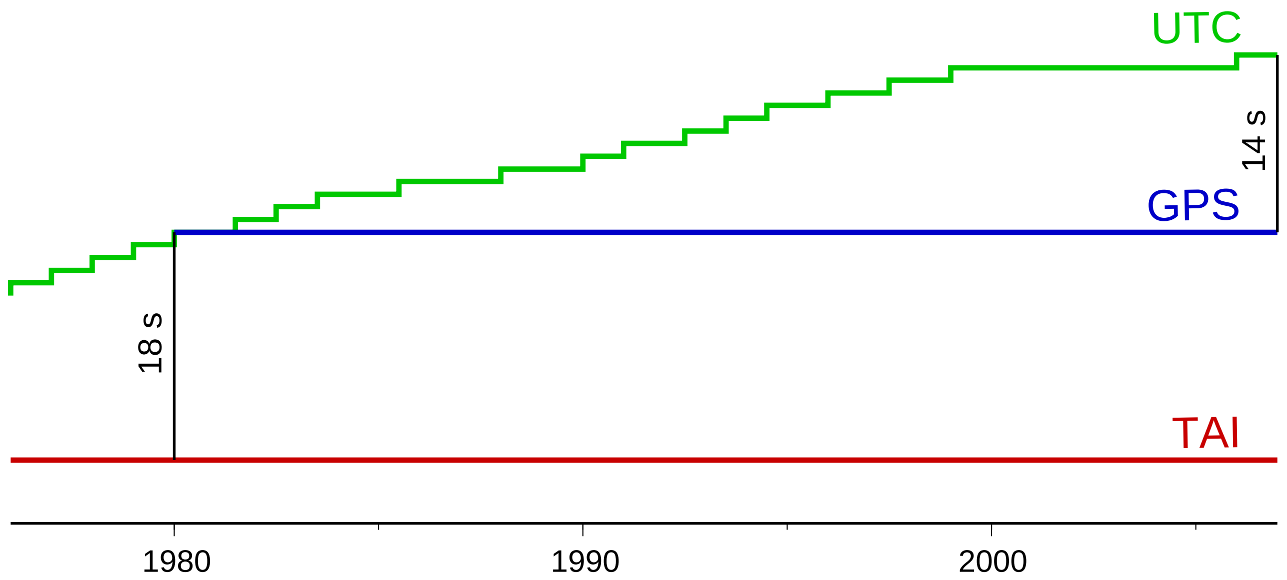

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- Disadvantage: Only one observation at the time
  - more observations promise better results ($\sqrt{n}$–law)
  - limited by the uncertainty of the broadcasted GPS system time

Multi Satellite Synchronization

- Multiple satellites are used for the synchronization.
  - use of a multi–channel receiver that is able to track all satellites in view

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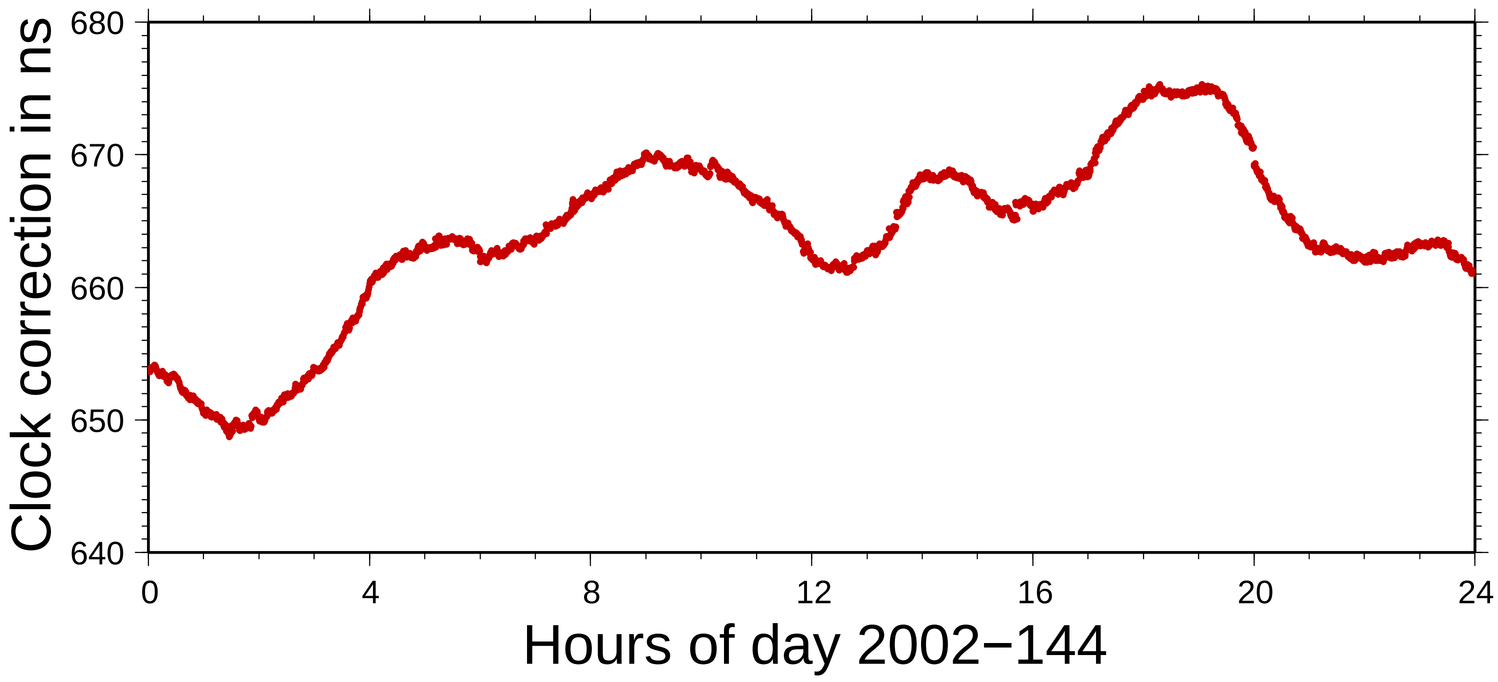
- Example for a multi satellite synchronization for Brussels:



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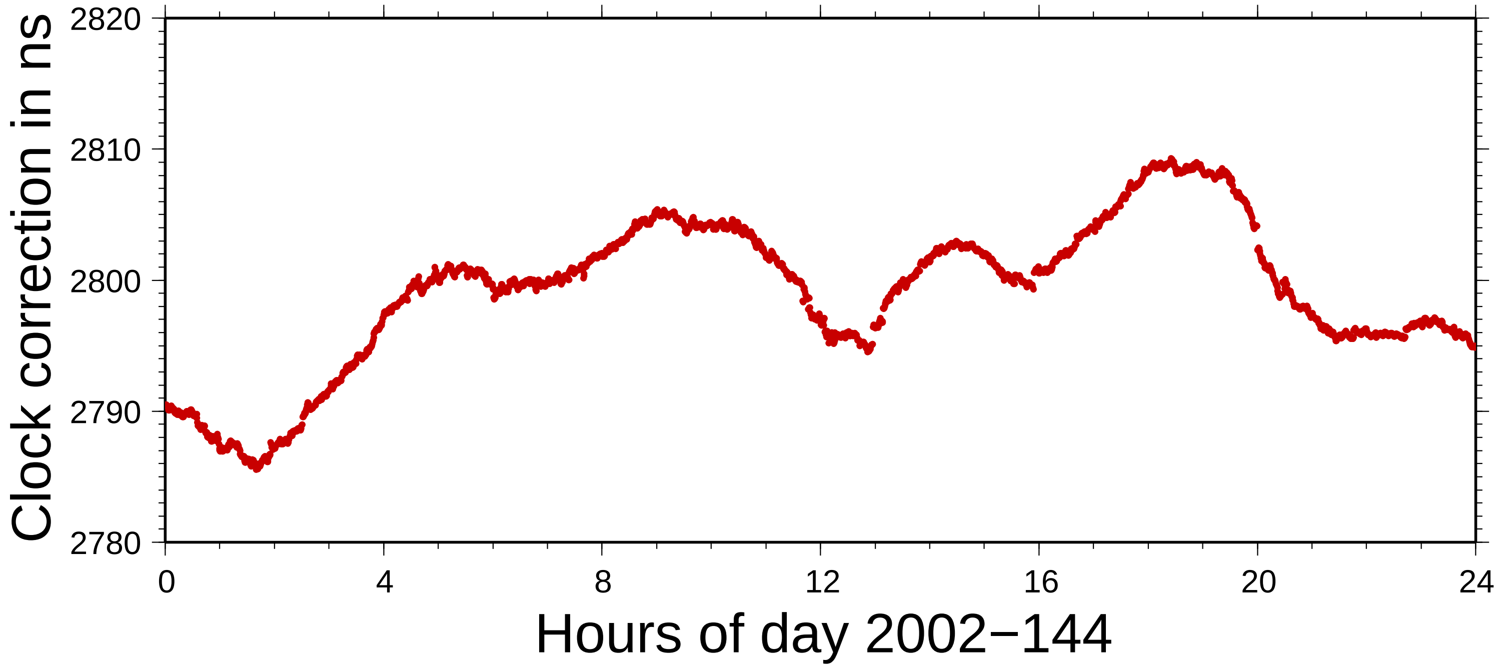
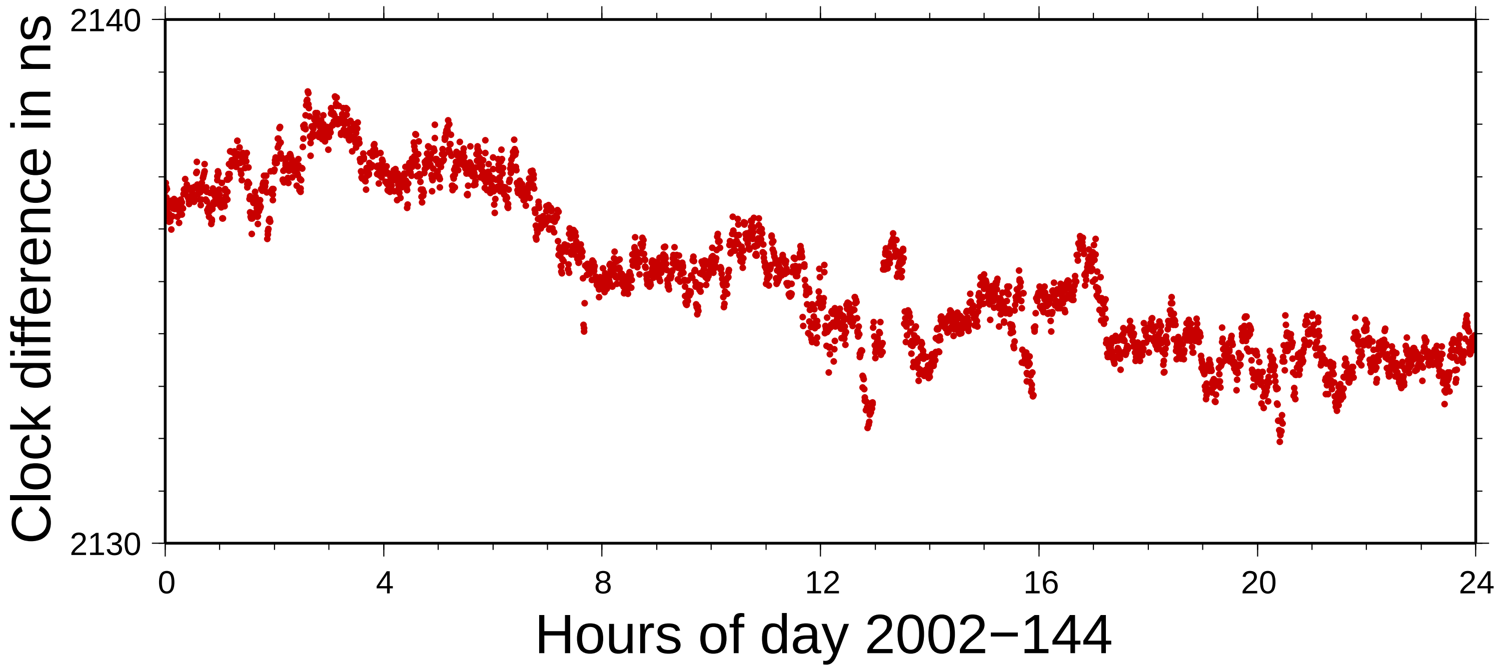


Baseline-wise clock comparison

- Clock differences between two stations (baseline):
  - common error sources cancel out

- Example for a multi satellite clock comparison for the baseline Braunschweig—Brussels:



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- Only satellites that are commonly observed by both stations have to be considered for the processing.
  - for single-satellite observations this require a special organzation effort.

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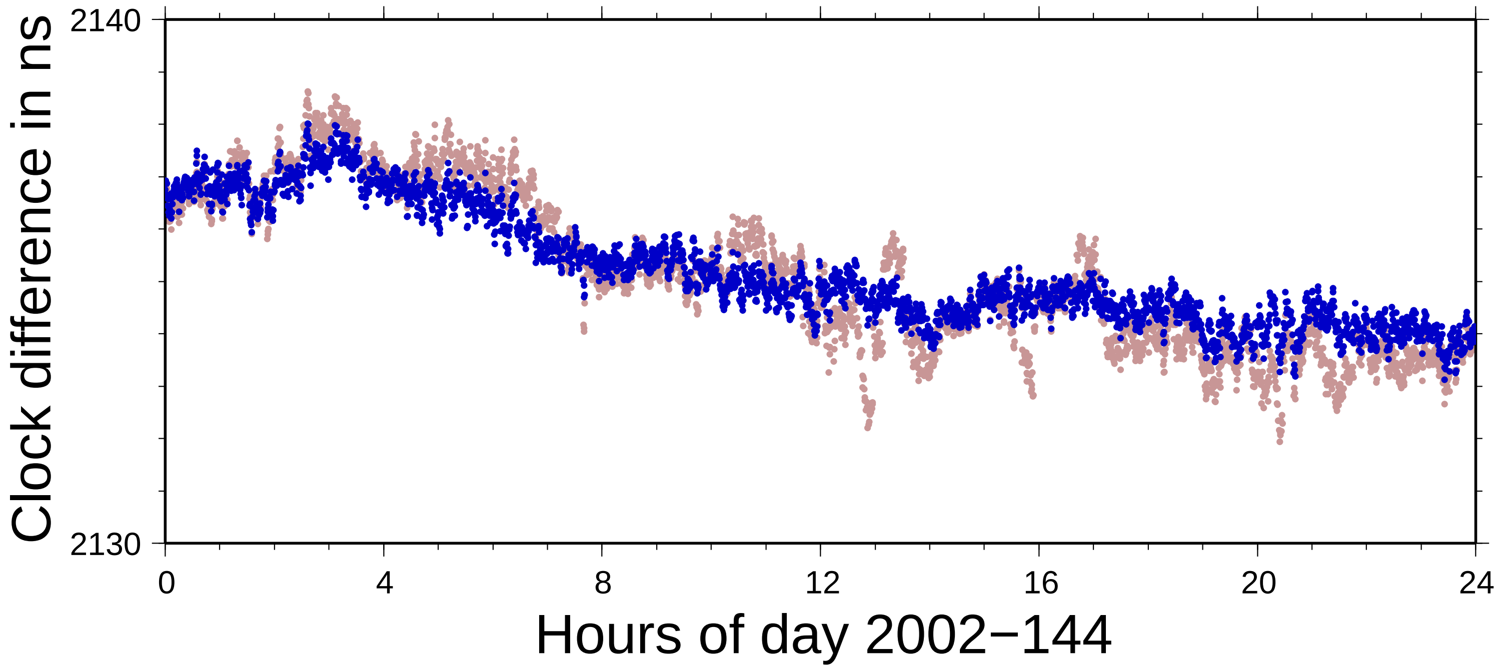
- Example for a multi satellite clock comparison for the baseline Braunschweig—Brussels:



Baseline-wise clock comparison

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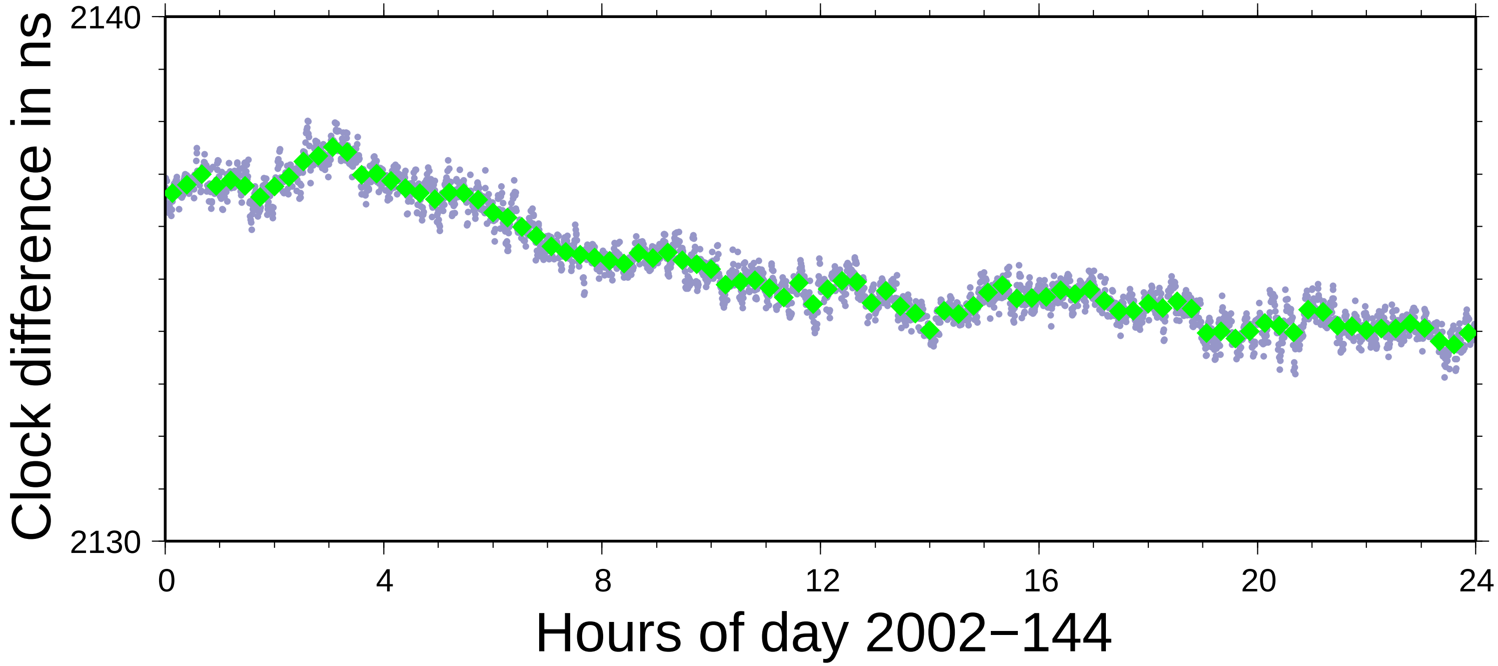

GPS code based time transfer for TAI

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- Percentage of time transfer links contributing to TAI
  - 28% C/A–code single channel receivers (Common view to only one satellite)
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GPS code based time transfer for TAI

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- Percentage of time transfer links contributing to TAI
  - 28% C/A–code single channel receivers (Common view to only one satellite)
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- Time transfer results are affected by:
  - uncertainty of the broadcast satellite orbits
  - influence of the ionosphere (use dual frequency data)

Dual-frequency clock comparison

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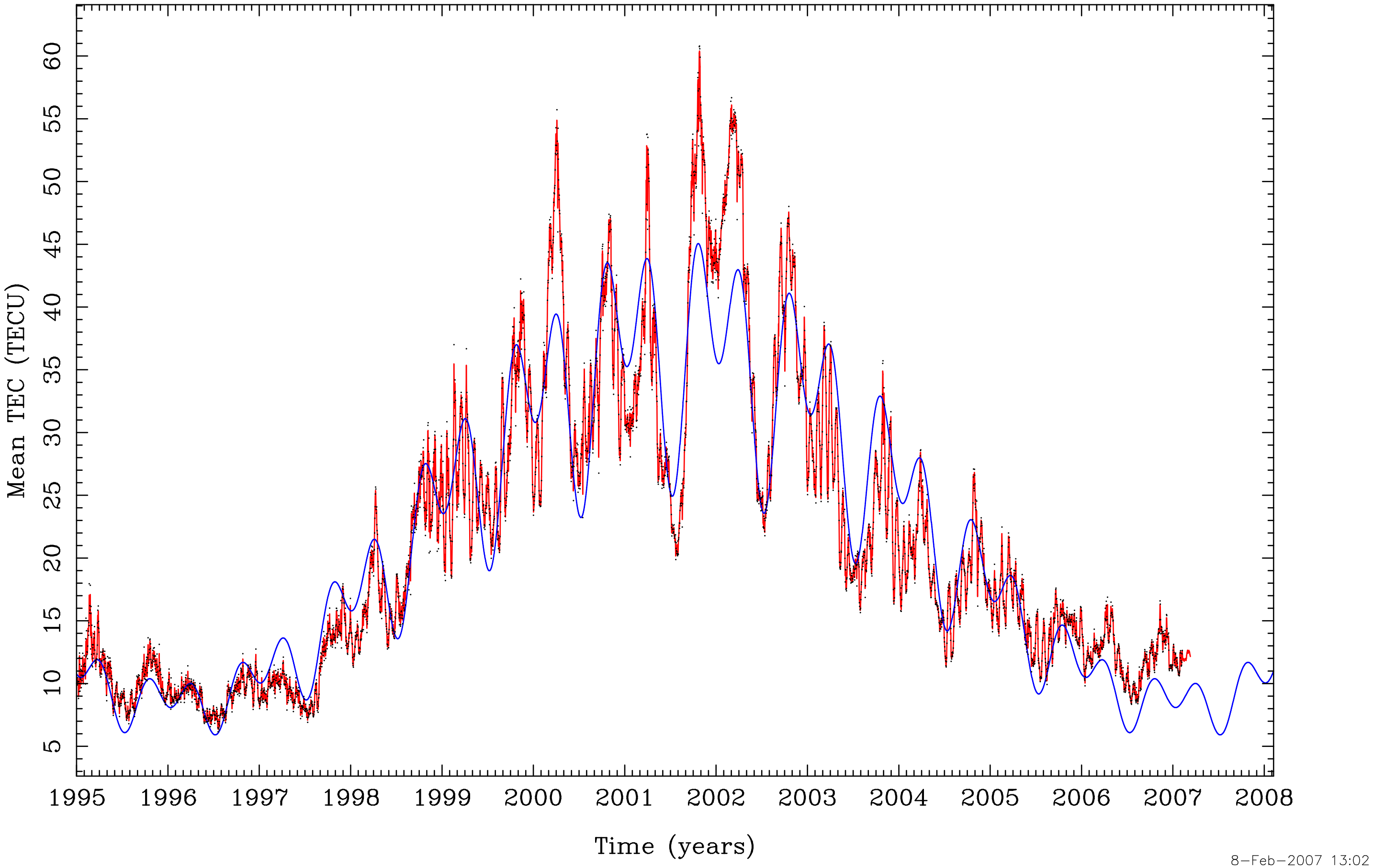
\end{aligned}$$

- Forming a ionosphere–free linear combination:

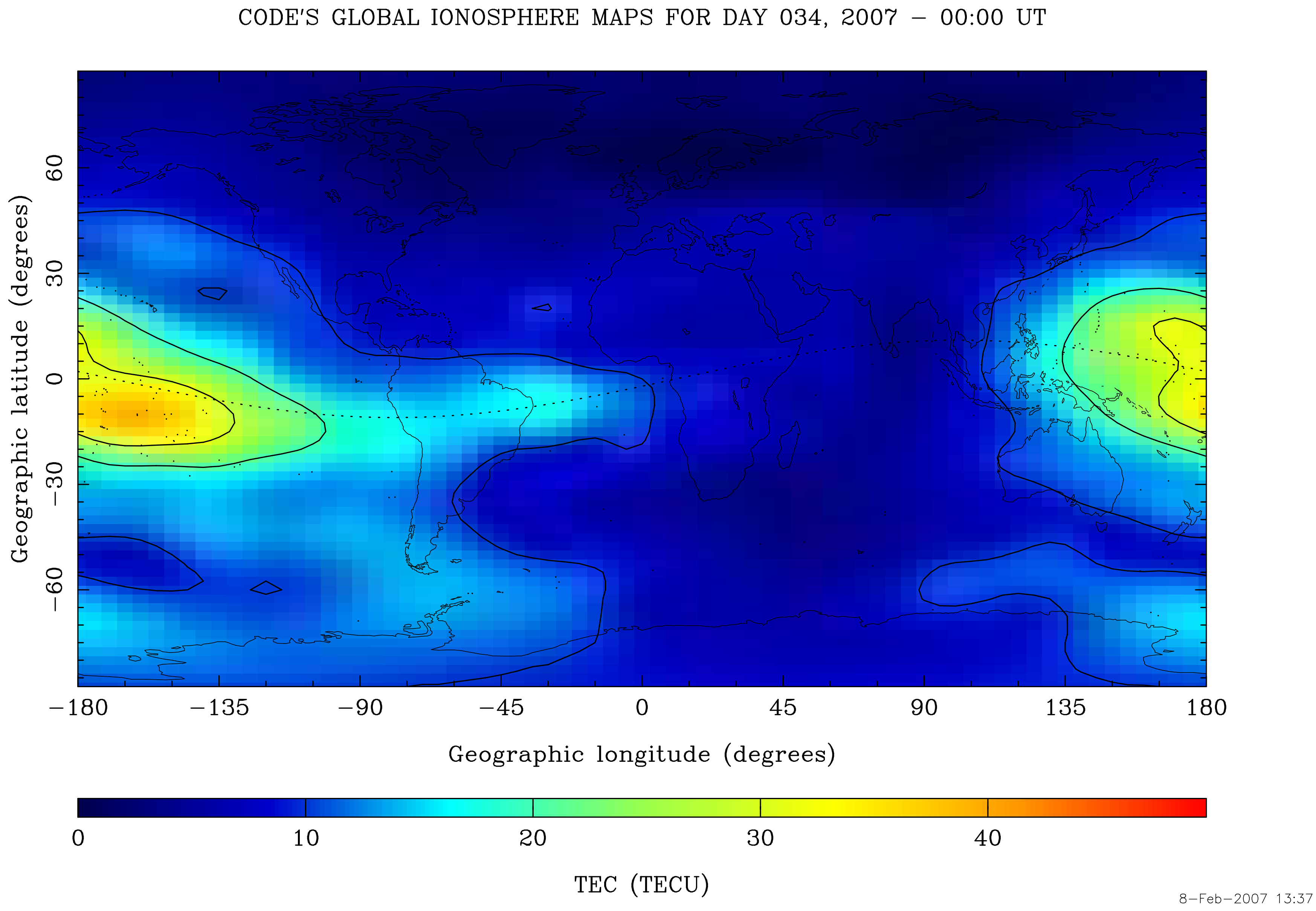
$$\begin{aligned}
P_{3\,i}^{\,k} &= \frac{f_1^2}{f_1^2 - f_2^2} \cdot P_{1\,i}^{\,k} - \frac{f_2^2}{f_1^2 - f_2^2} \cdot P_{2\,i}^{\,k} \\
P_{3\,i}^{\,k} &= 2.5457 \cdot P_{1\,i}^{\,k} - 1.5457 \cdot P_{2\,i}^{\,k}
\end{aligned}$$

GNSS and Ionosphere



Mean TEC since January 1, 1995 estimated by CODE AC, covering a full Solar activity cycle.

GNSS and Ionosphere



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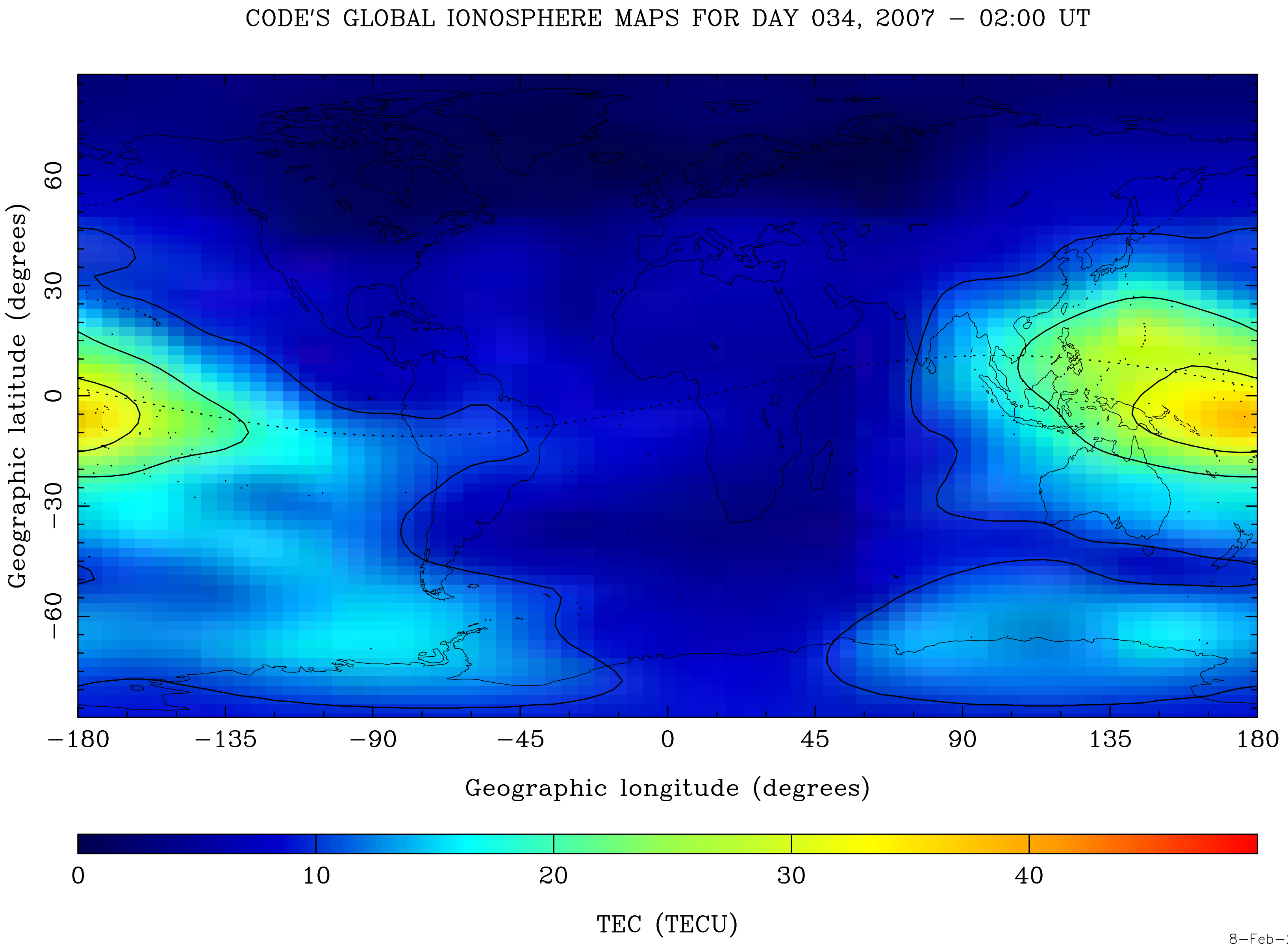

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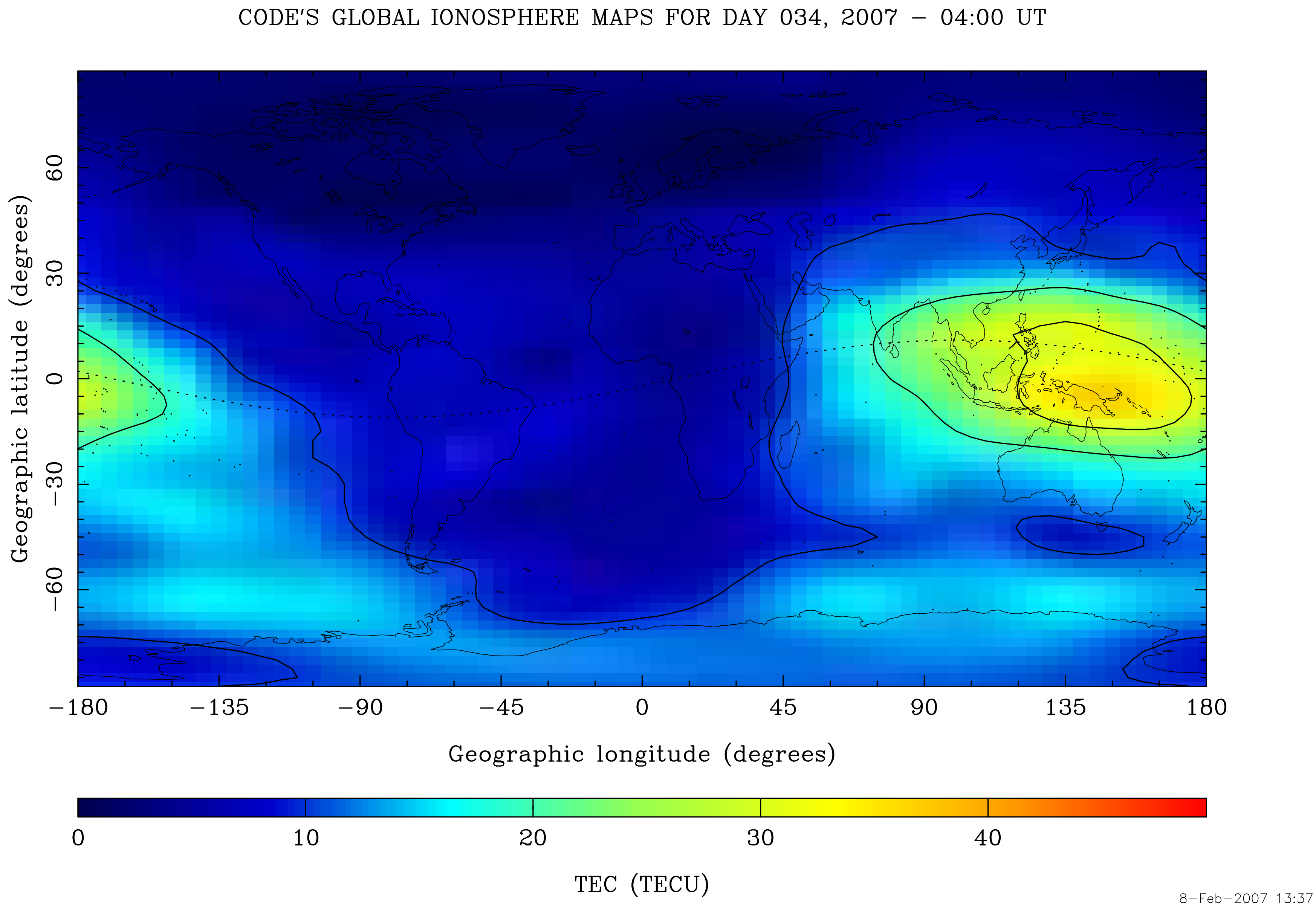
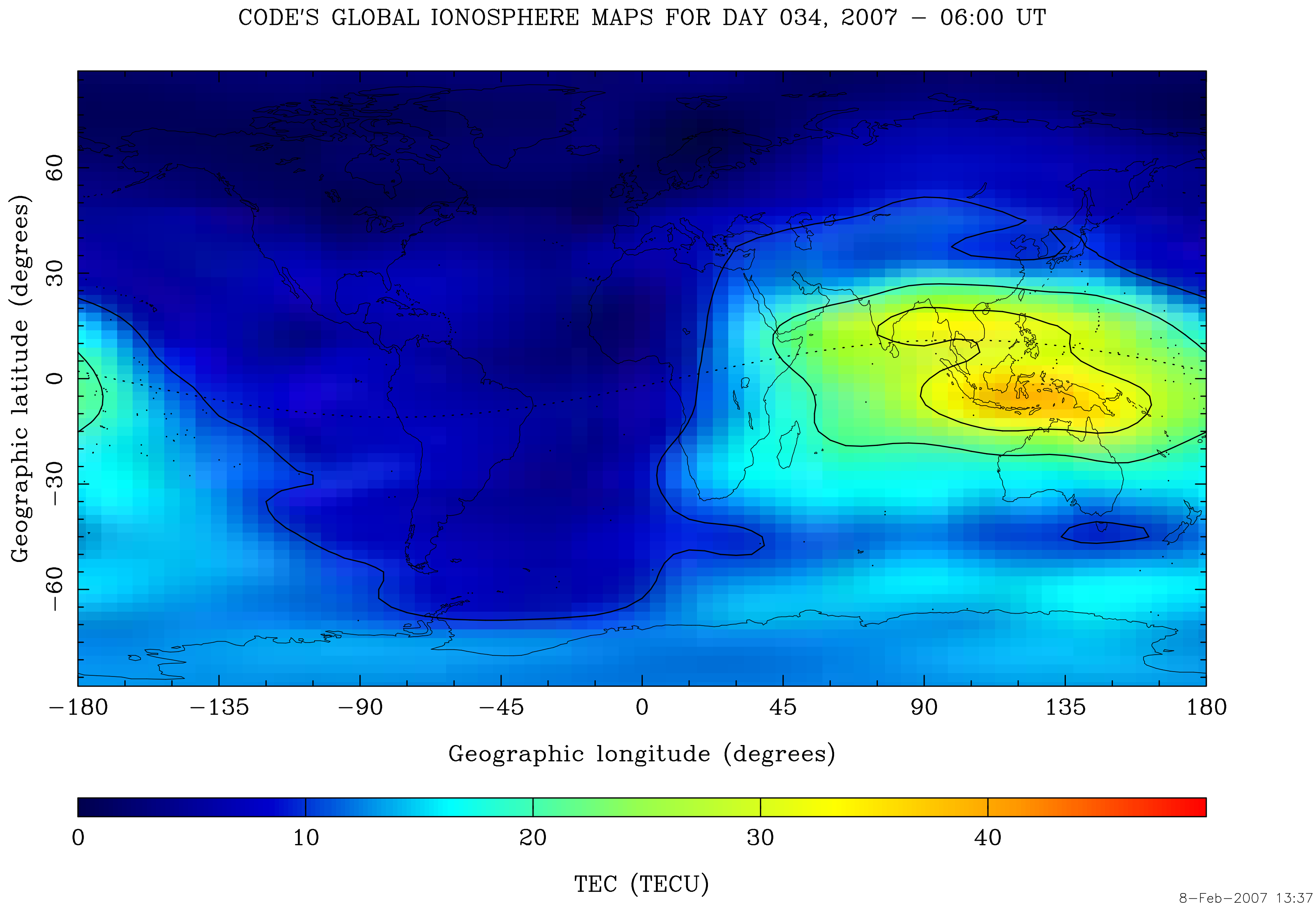


GNSS and Ionosphere



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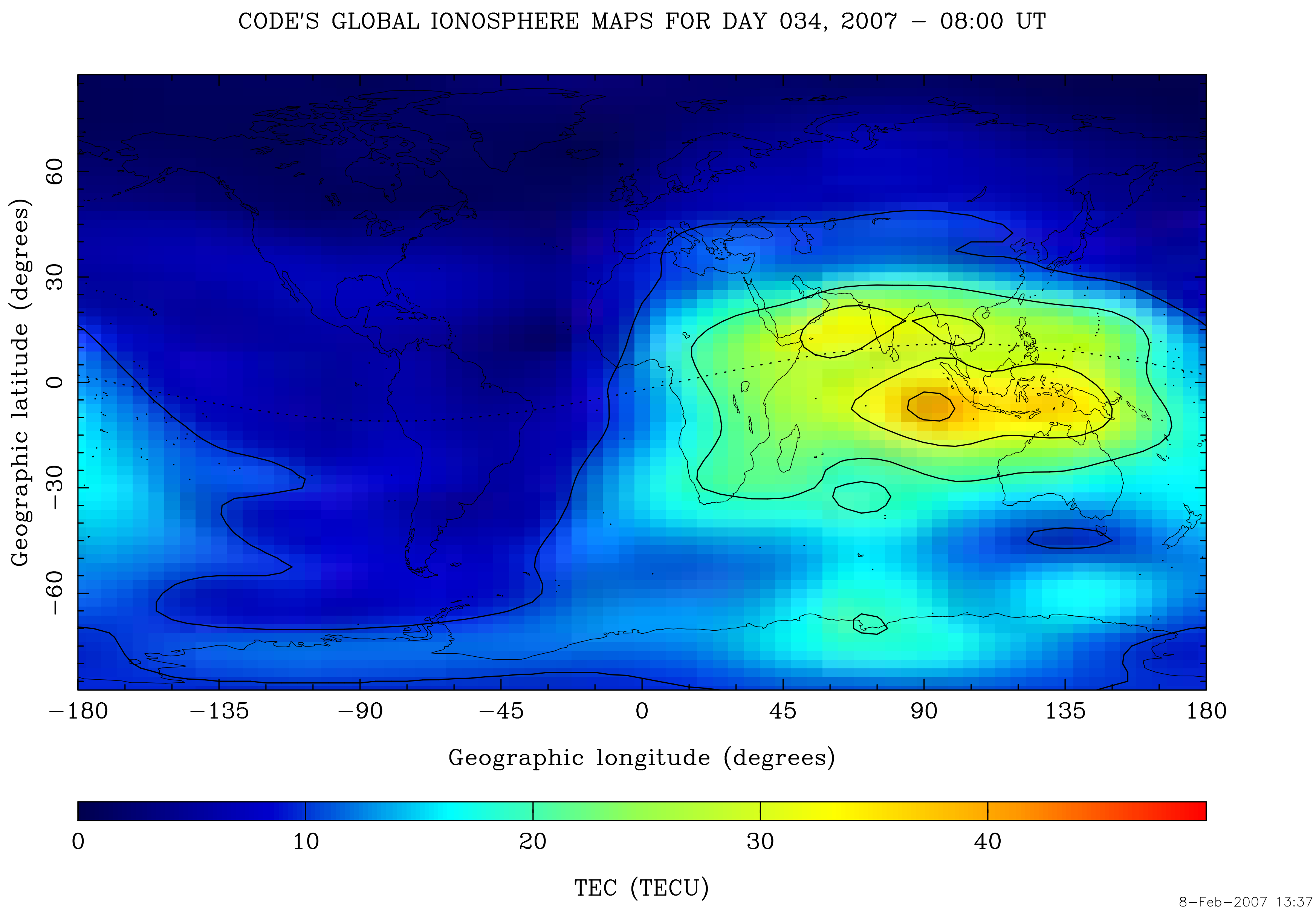

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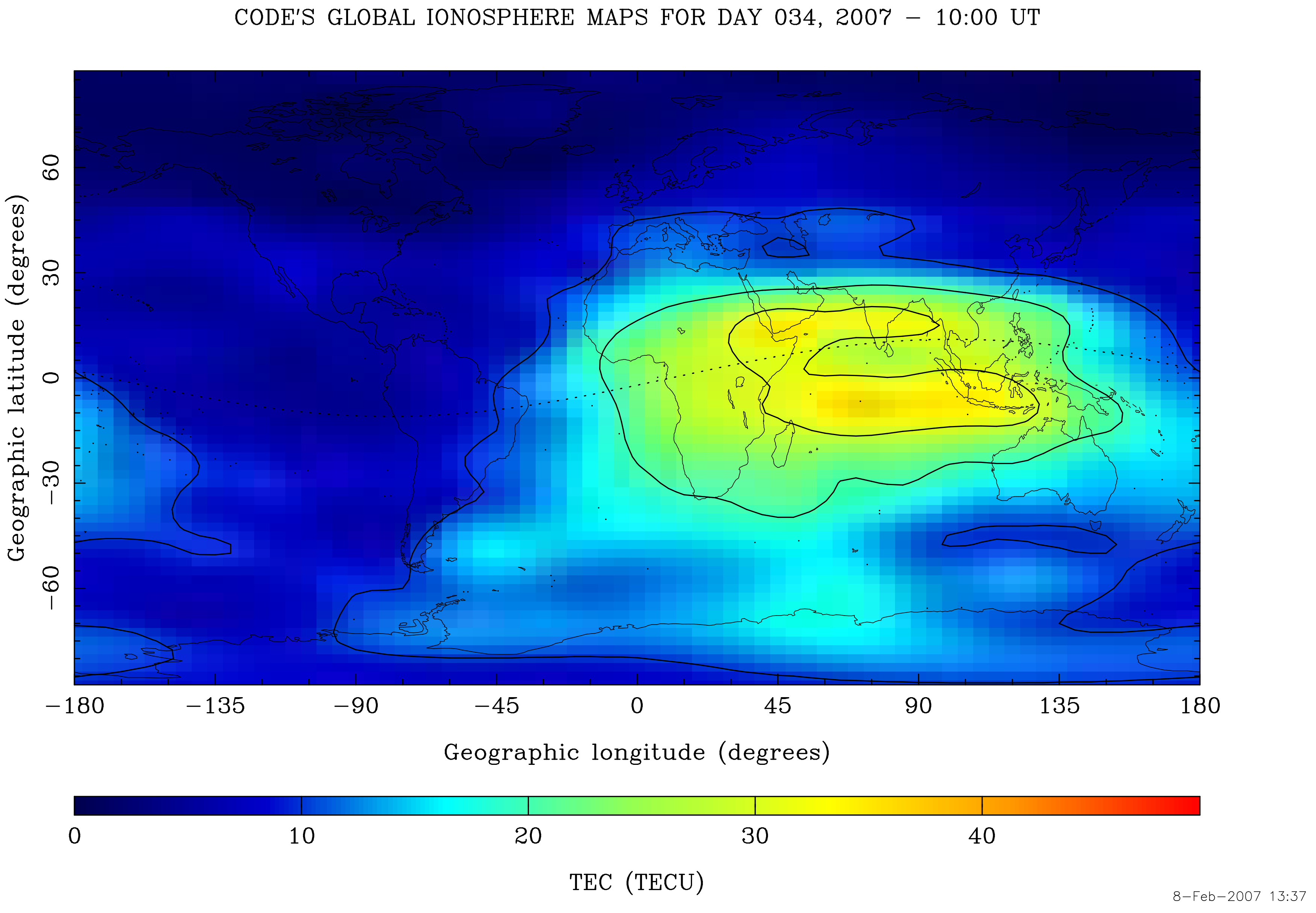

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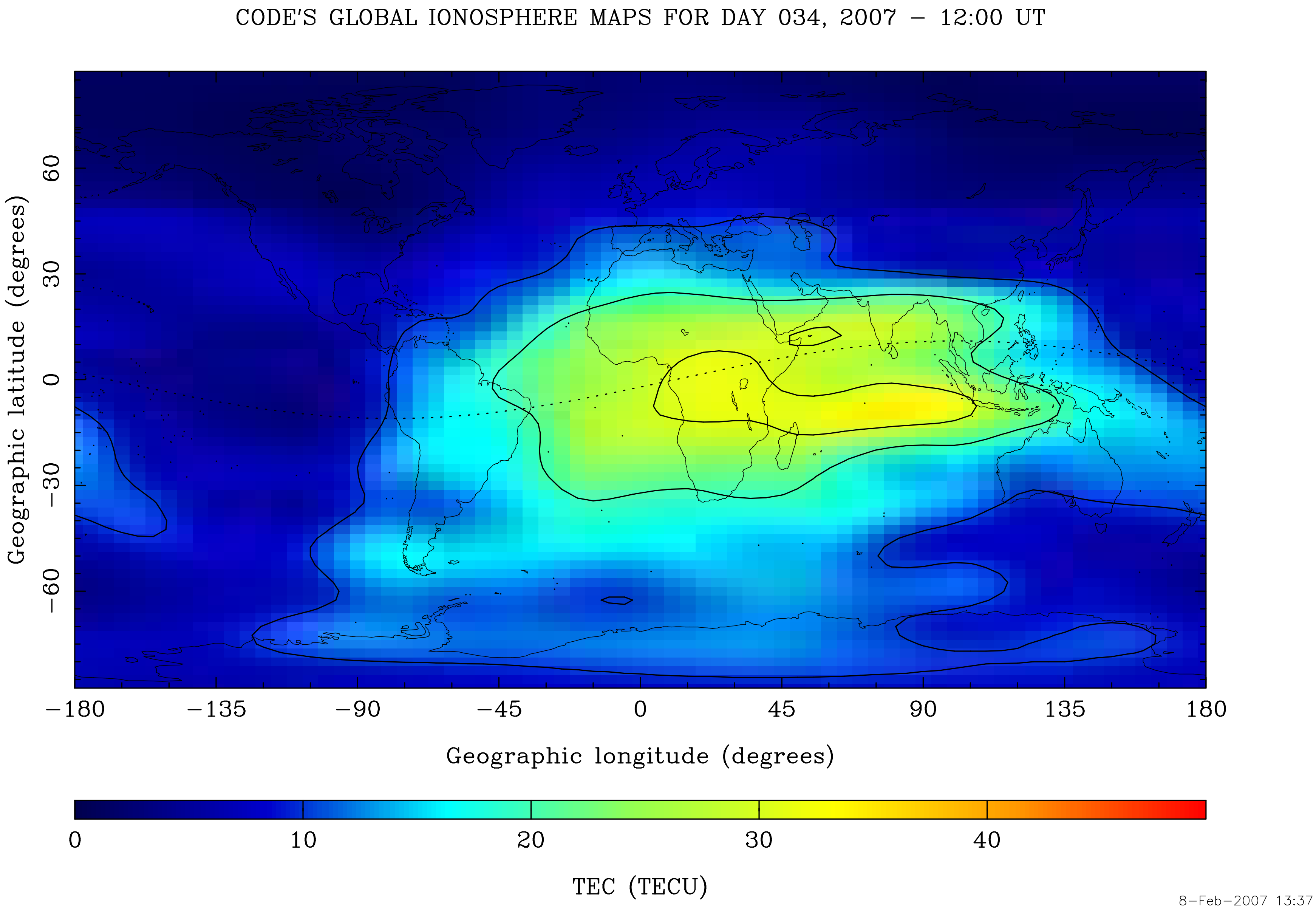

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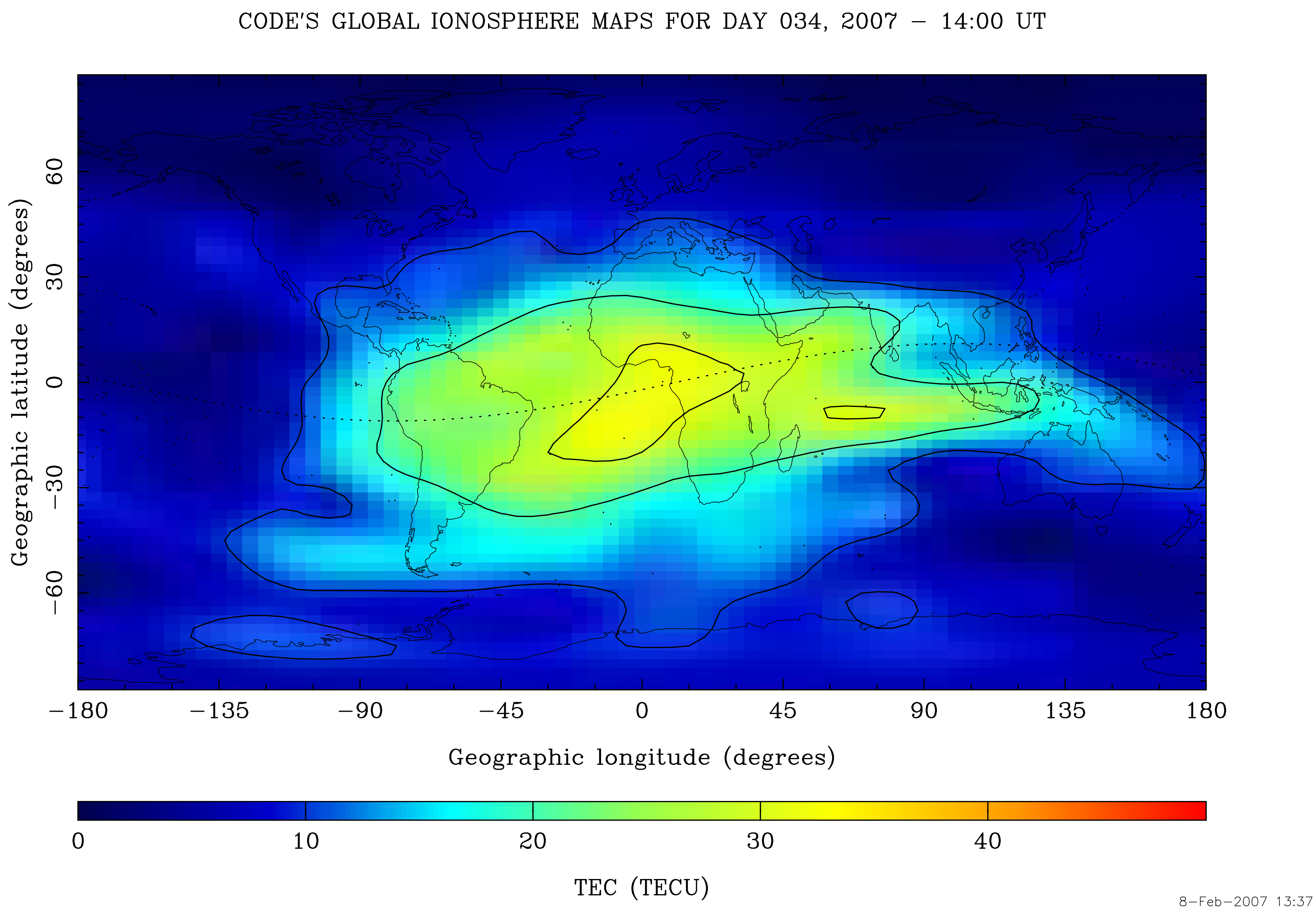

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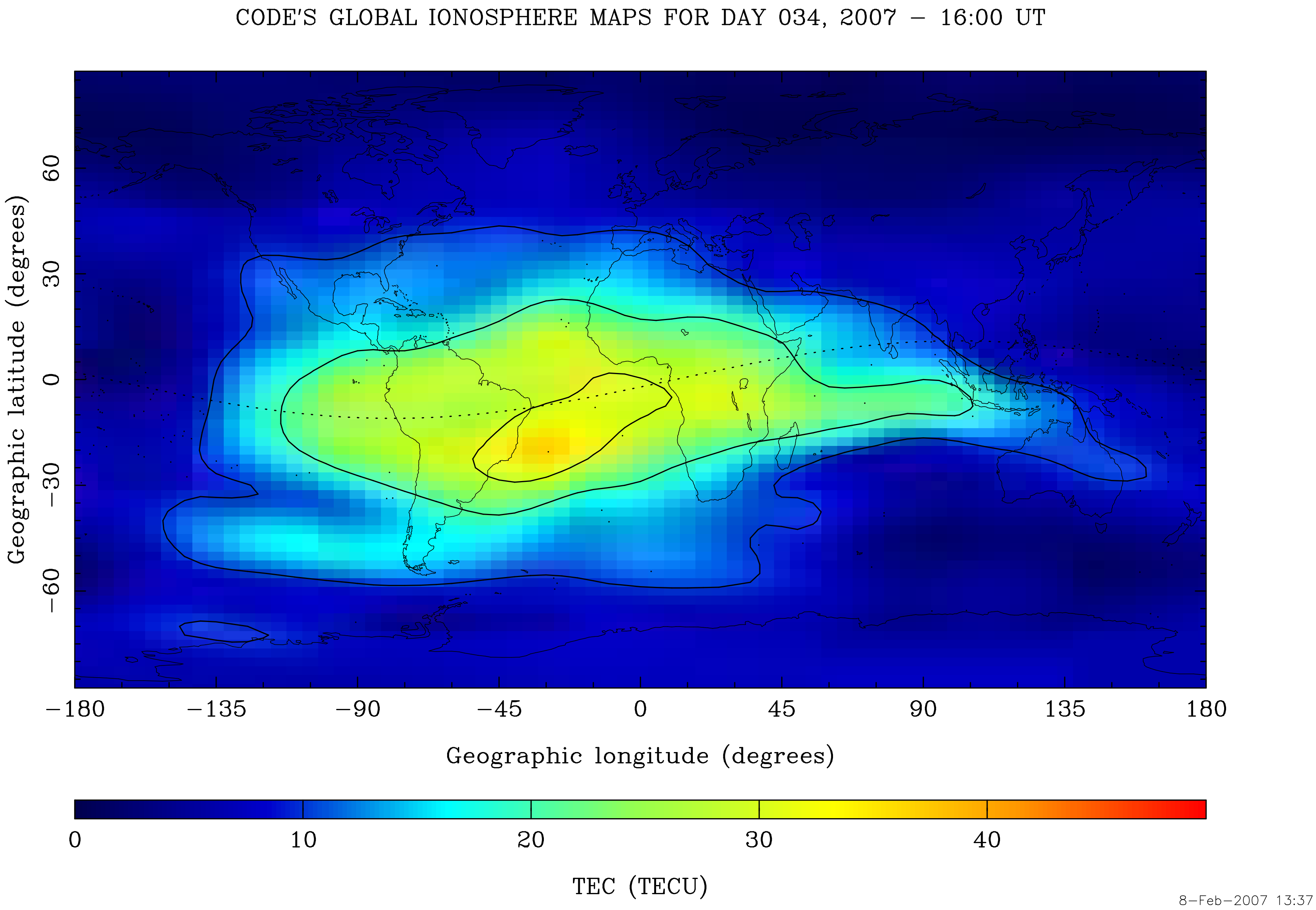

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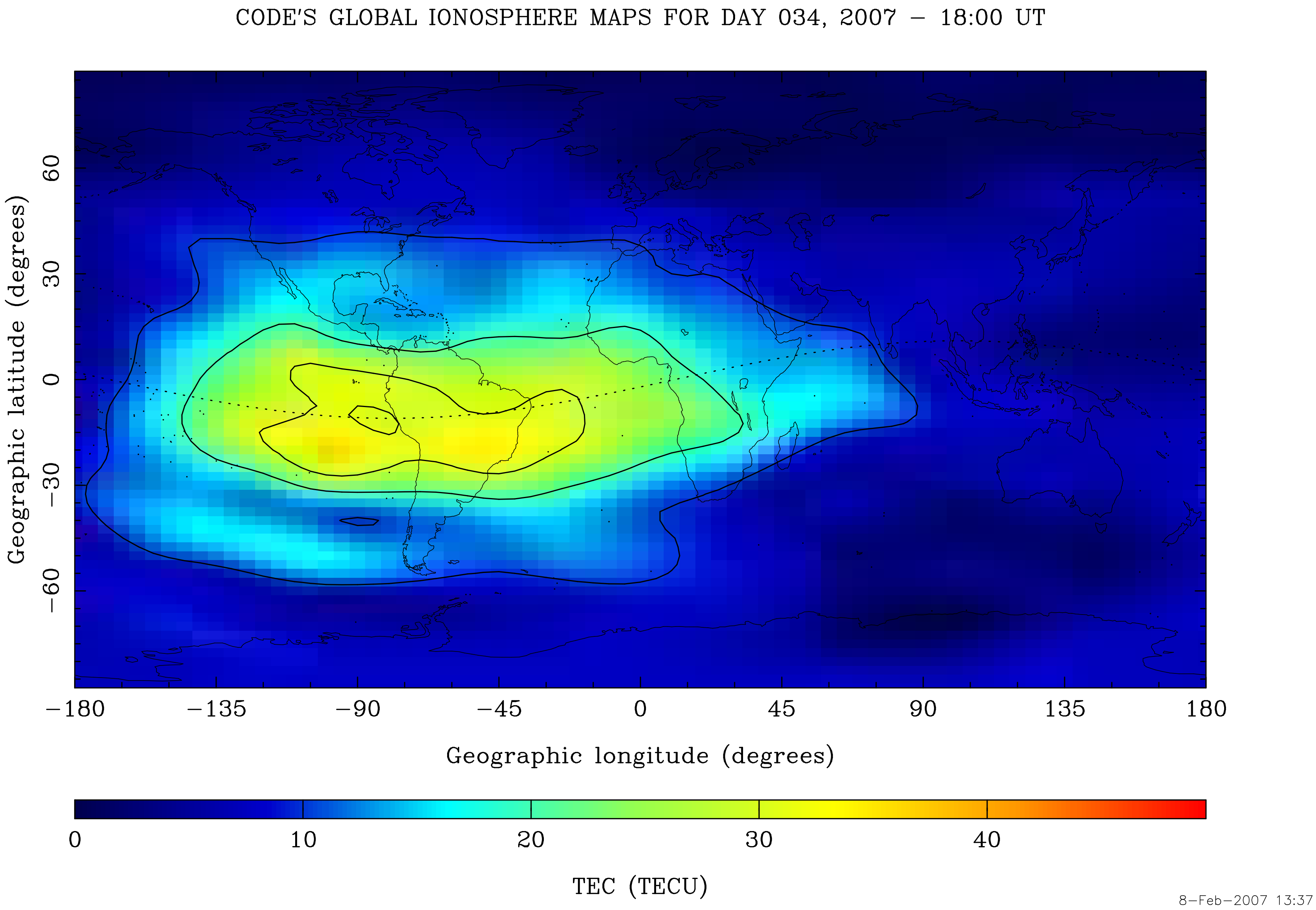

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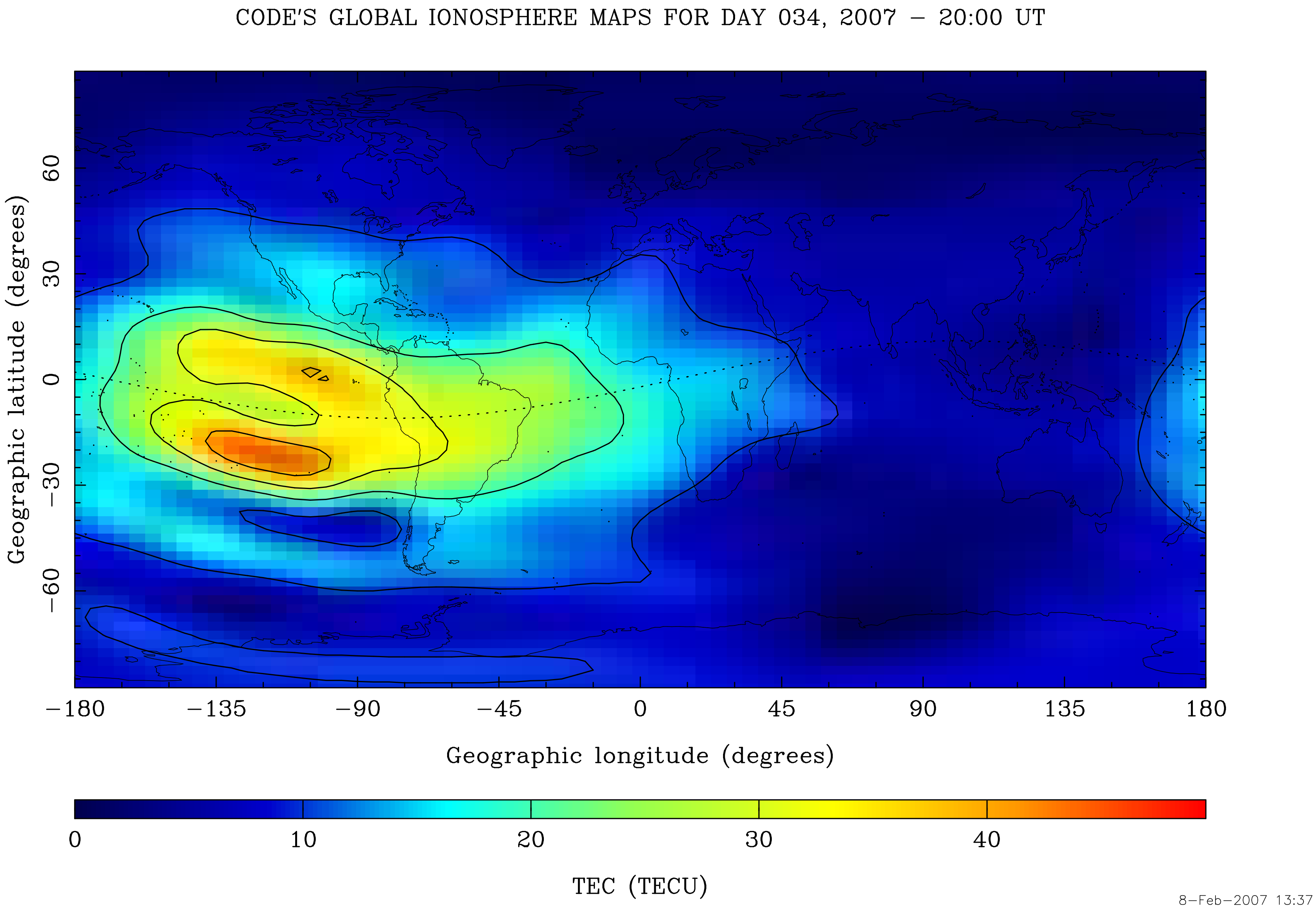

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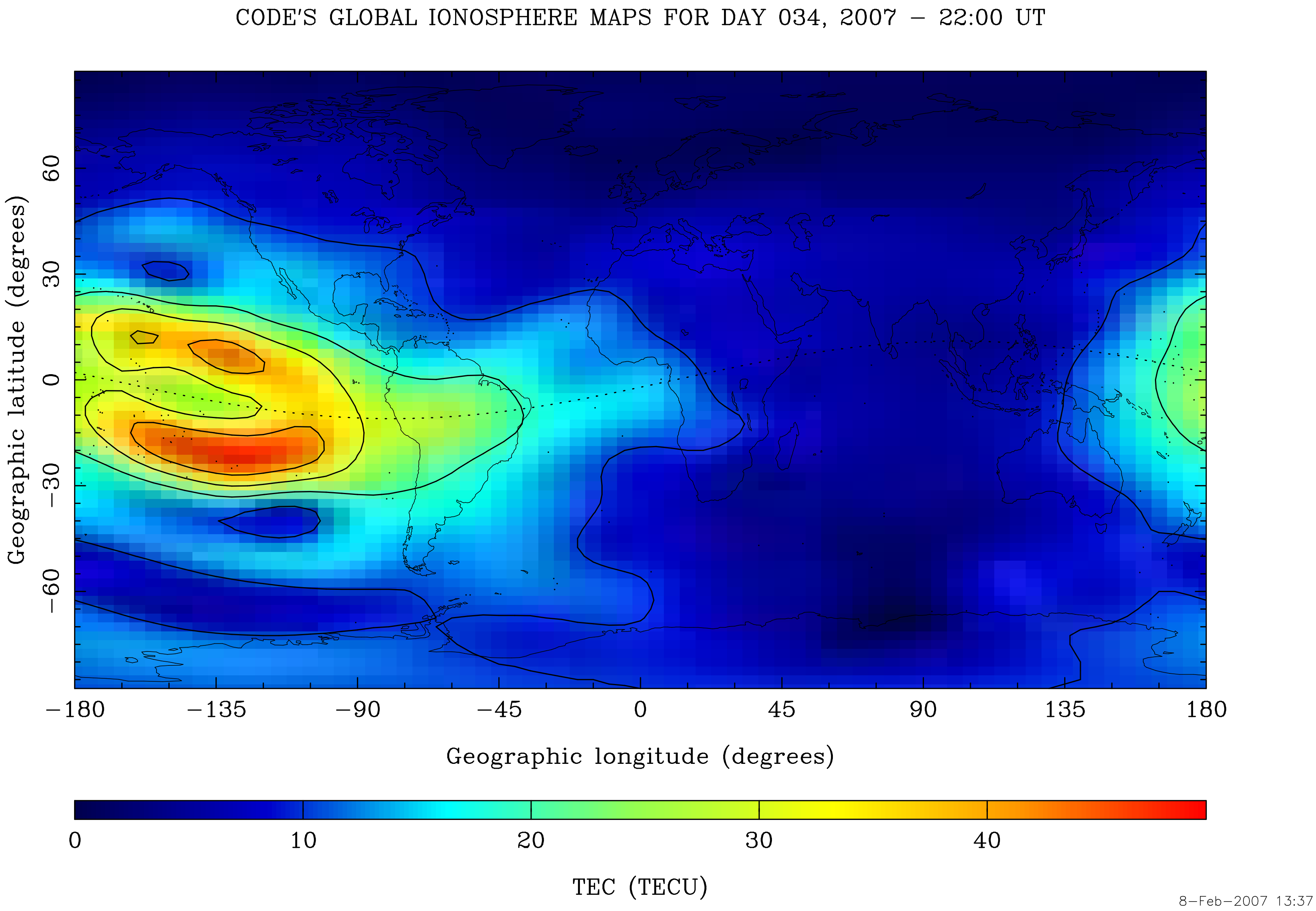

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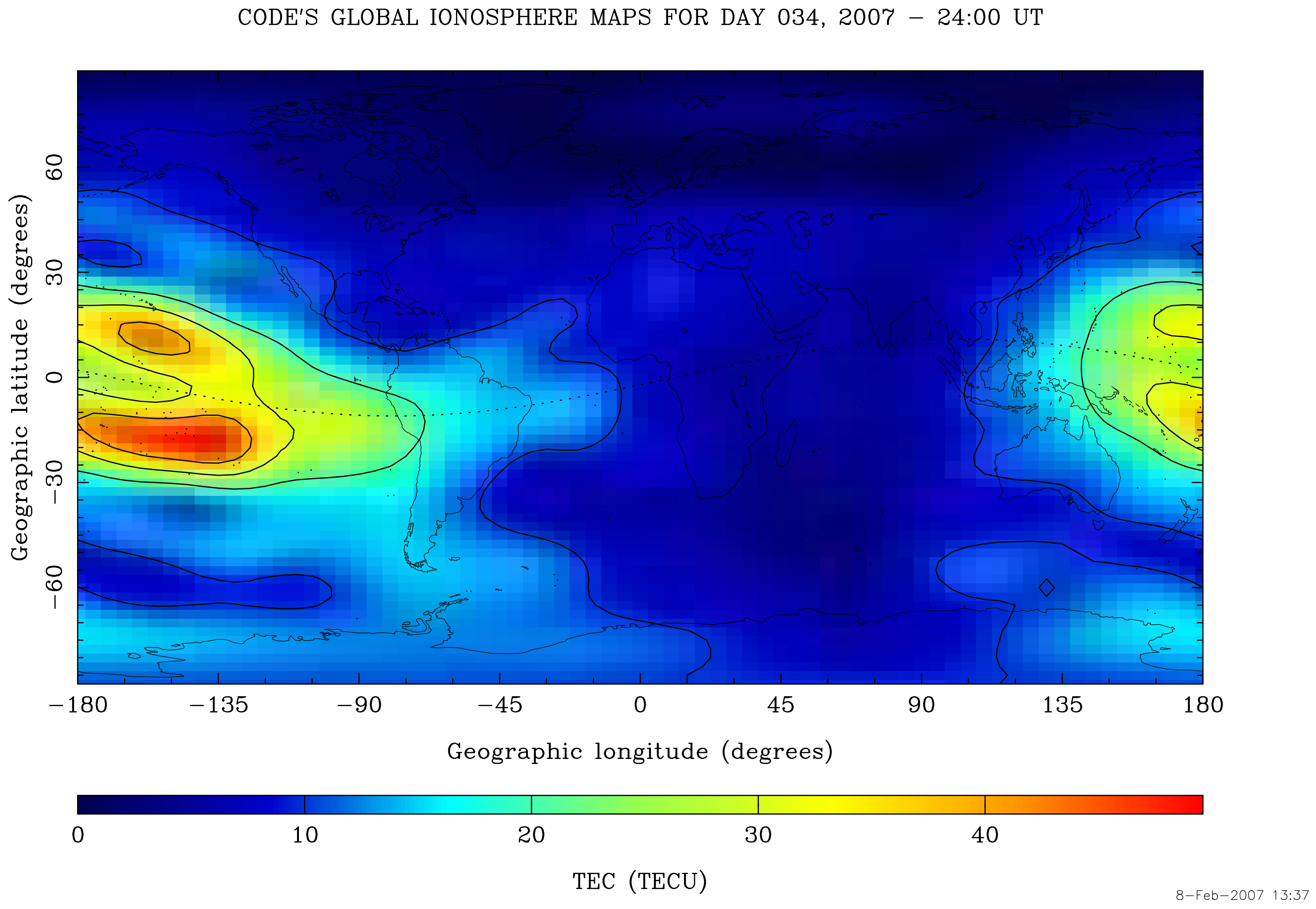

GPS Types of Measurements

Measurement types:

• **C/A Code**	on L1	(noise	10 – 100 m	or	33 – 333 ns)
• **P-Code**	on L1 and L2	(noise	0.2 – 10 m	or	0.6 – 33 ns)
• **phase**	on L1 and L2	(noise	0.001 – 0.01 m	or	0.003 – 0.03 ns).

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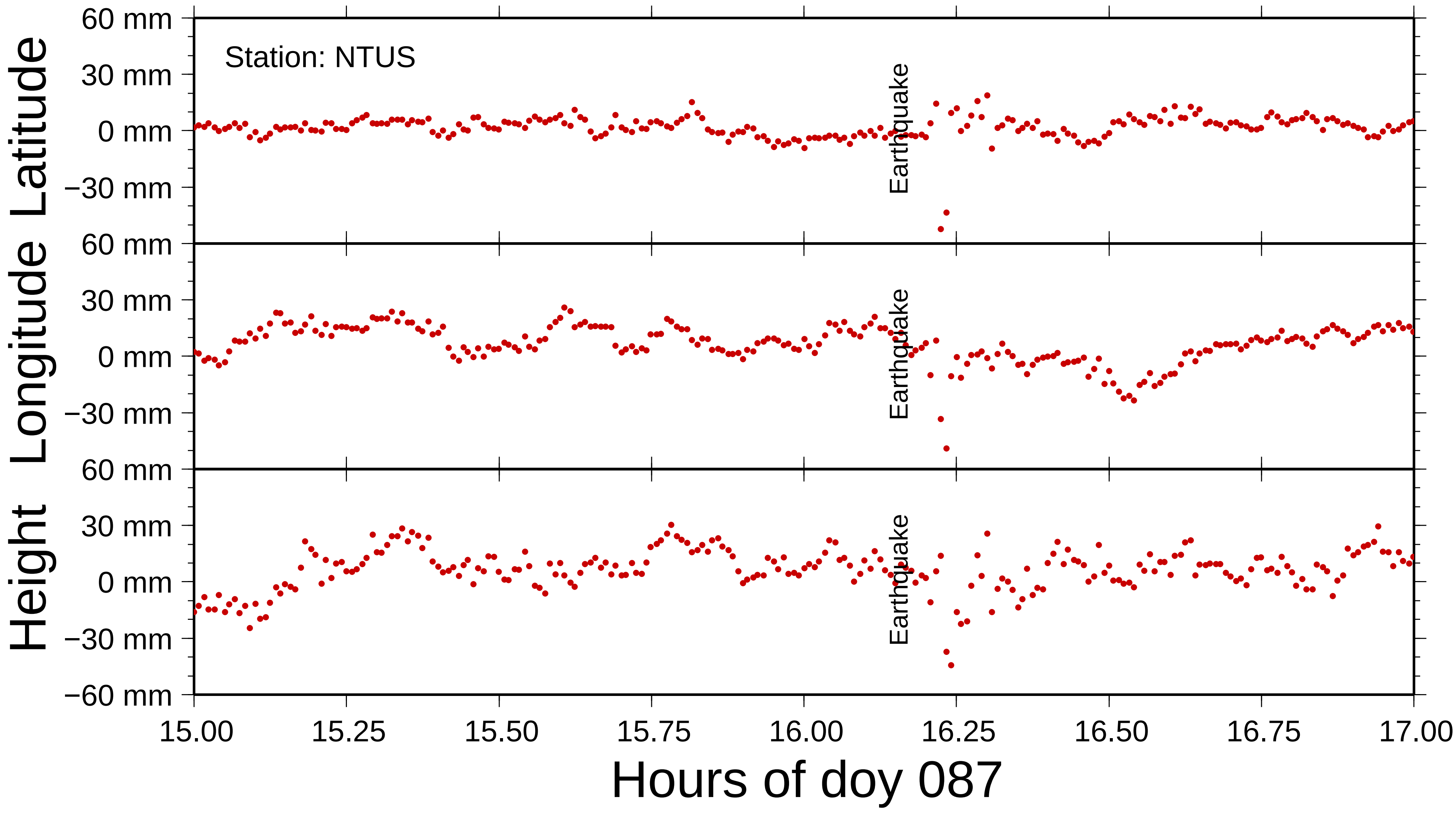
Phase measurements:

- measurement of cycles (entire cycles and fractionals) of the carrier phase
- resolution of better than 1% of the wavelength
- problem: unknown (integer) number of cycles between the satellite and the receiver at the beginning of the measurement (inital phase ambiguity)
- possible cycle slips: error in counting the entire cycles during a mesaurement (need for detection and correction)
- provided by high–end geodetic type receivers.

Motivation to Use Carrier Phase Data

Kinematic Solution during an Earthquake



GNSS Observation Equations

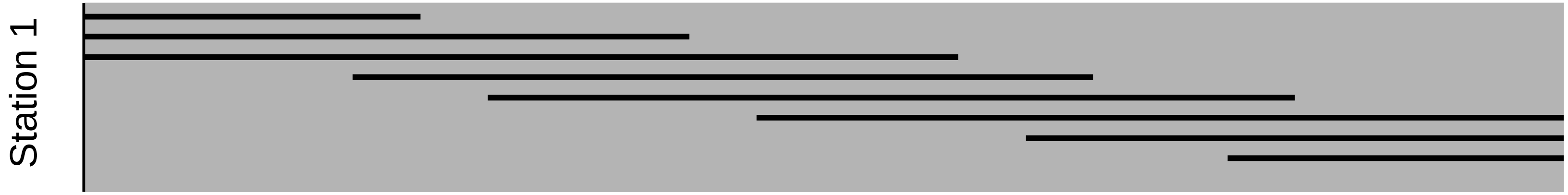
$$P_i^k = \left|\vec{x^k} - \vec{x_i}\right| + \Delta_{trop}{}_i^k + \Delta_{ion}{}_i^k + c\delta_i - c\delta^k$$

$$L_i^k = \left|\vec{x^k} - \vec{x_i}\right| + \Delta_{trop}{}_i^k - \Delta_{ion}{}_i^k + c\delta_i - c\delta^k + \lambda N_i^k$$

P_i^k, L_i^k	Code/phase observation of station i to satellite k
$\vec{x}_i, \vec{x}^{\,k}$	Position vector of station i and satellite k, respectively
$\Delta_{trop}{}_i^k$	Signal delay in the troposphere
$\Delta_{ion}{}_i^k$	Signal delay in the ionosphere
δ_i, δ^k	Clock correction of the receiver at the station i, and transmitter of satellite k with respect to GPS time
c	Speed of light
N_i^k	Phase ambiguity (one and the same for one pass)
λ	Wavelength of the carrier phase

Geodetic Time and Frequency Transfer

Principle of the Geodetic Time and Frequency Transfer



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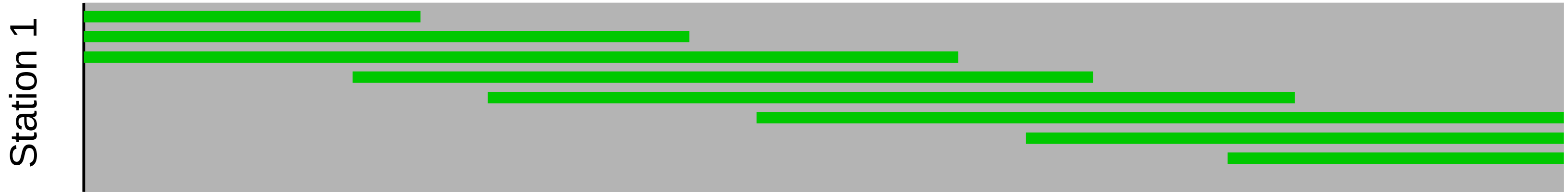

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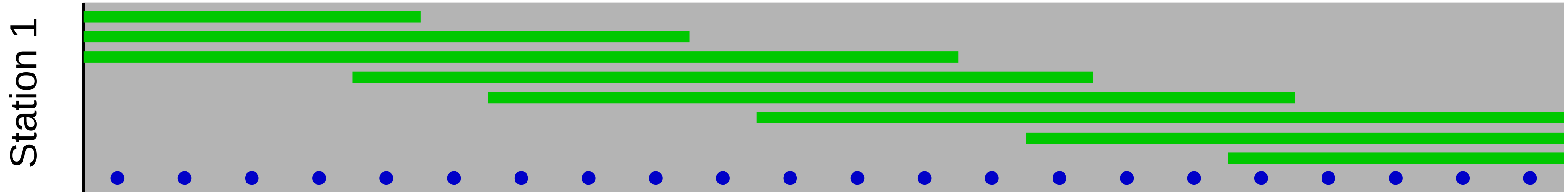

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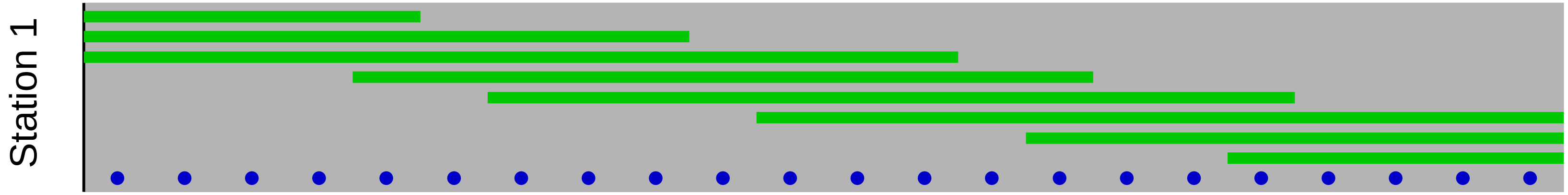

⇒ From carrier phase we can get only the change of the receiver clock in time.

Geodetic Time and Frequency Transfer

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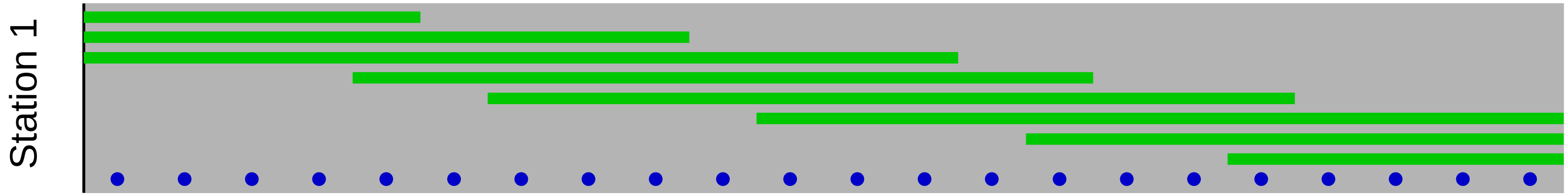

- Add pseudorange observations to have a direct access to the receiver clock parameters.

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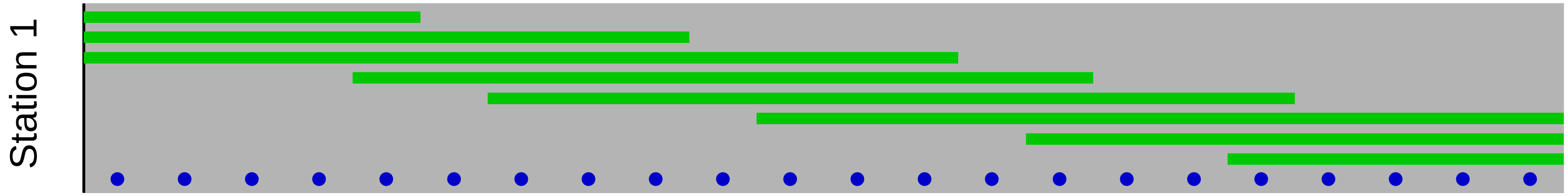

- Add pseudorange observations to have a direct access to the receiver clock parameters.
- Do not estimate one of the receiver clock parameters.

Geodetic Time and Frequency Transfer

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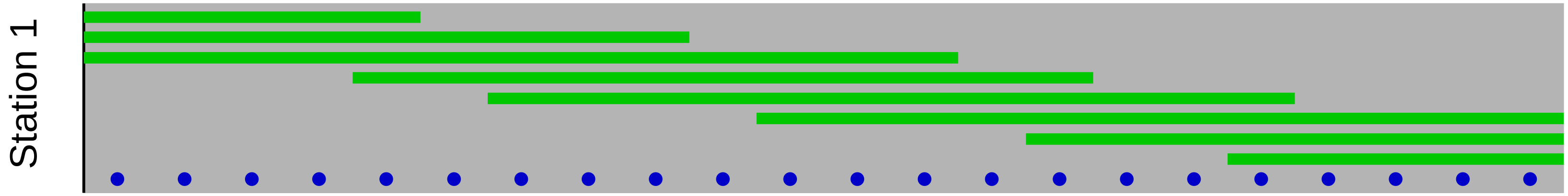

- Add pseudorange observations to have a direct access to the receiver clock parameters.
- Do not estimate one of the receiver clock parameters.
- Do not estimate one of the phase ambiguity parameters.

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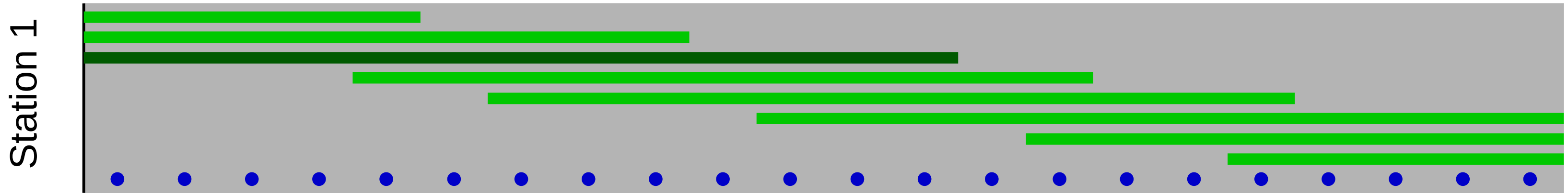

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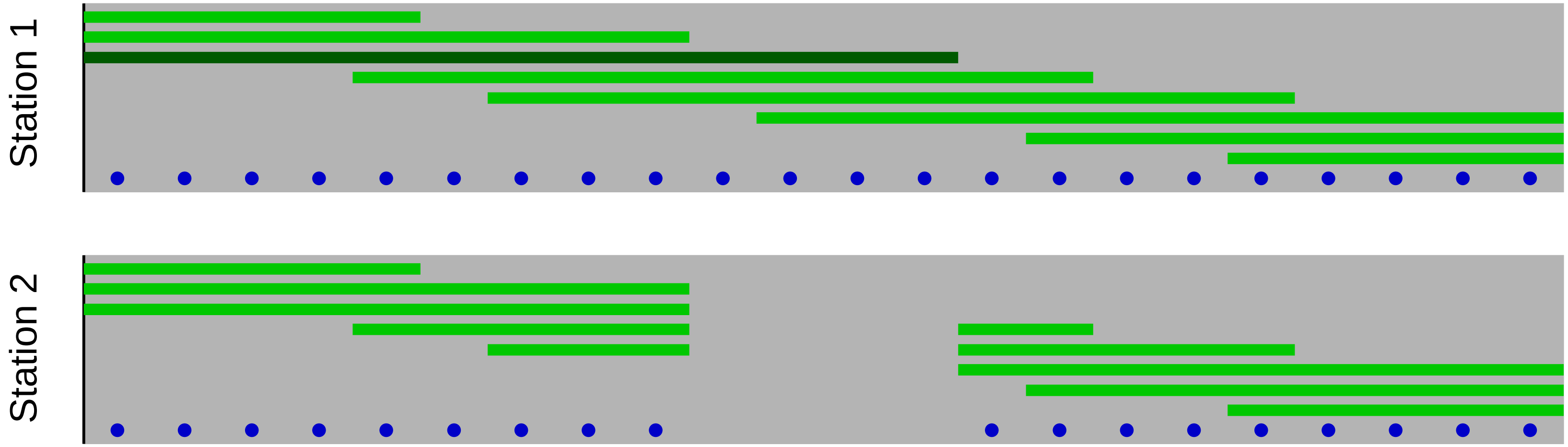

Geodetic Time and Frequency Transfer

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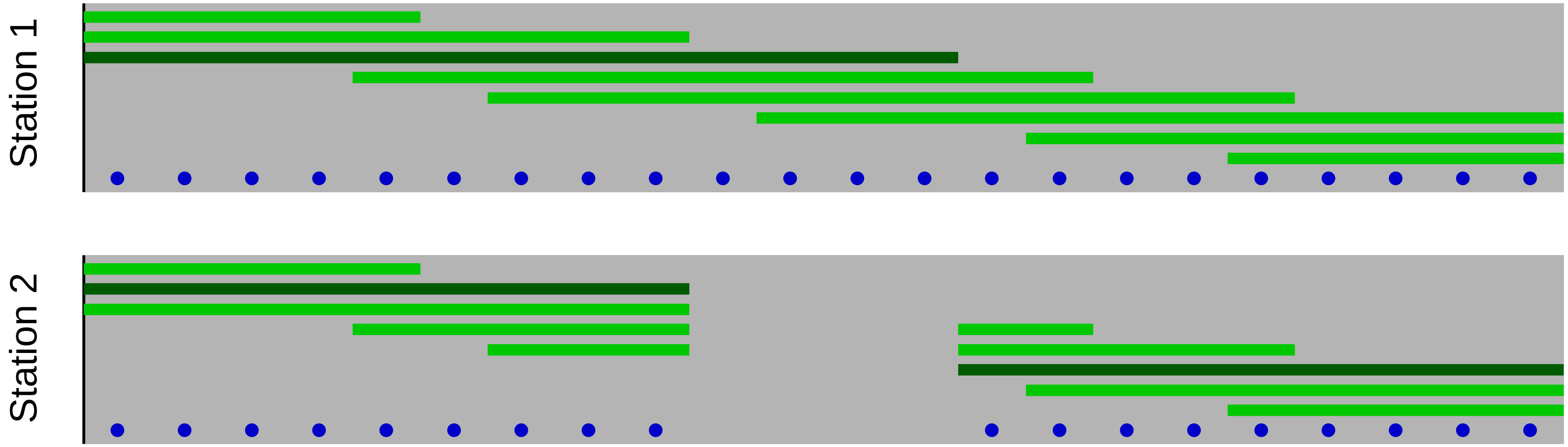
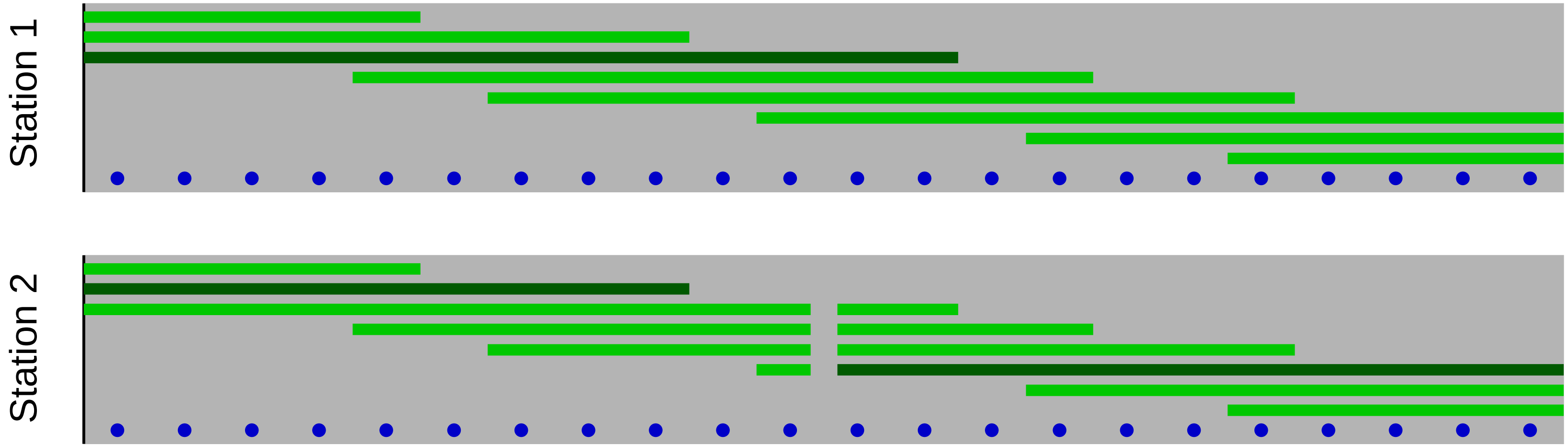


$\Rightarrow$ An interrupt in the ambiguities for all satellites leads to a discontinuity in the carrier phase solution.

Geodetic Time and Frequency Transfer

Principle of the Geodetic Time and Frequency Transfer



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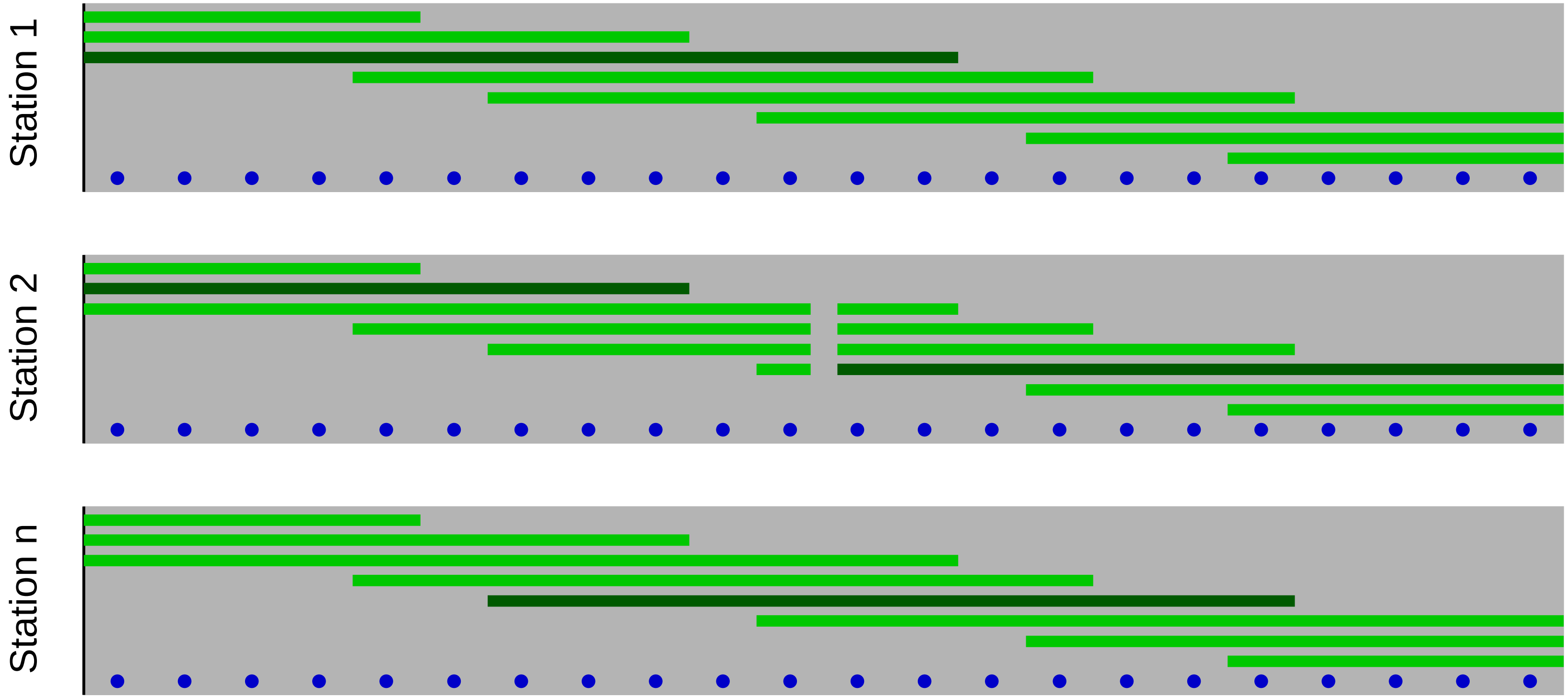

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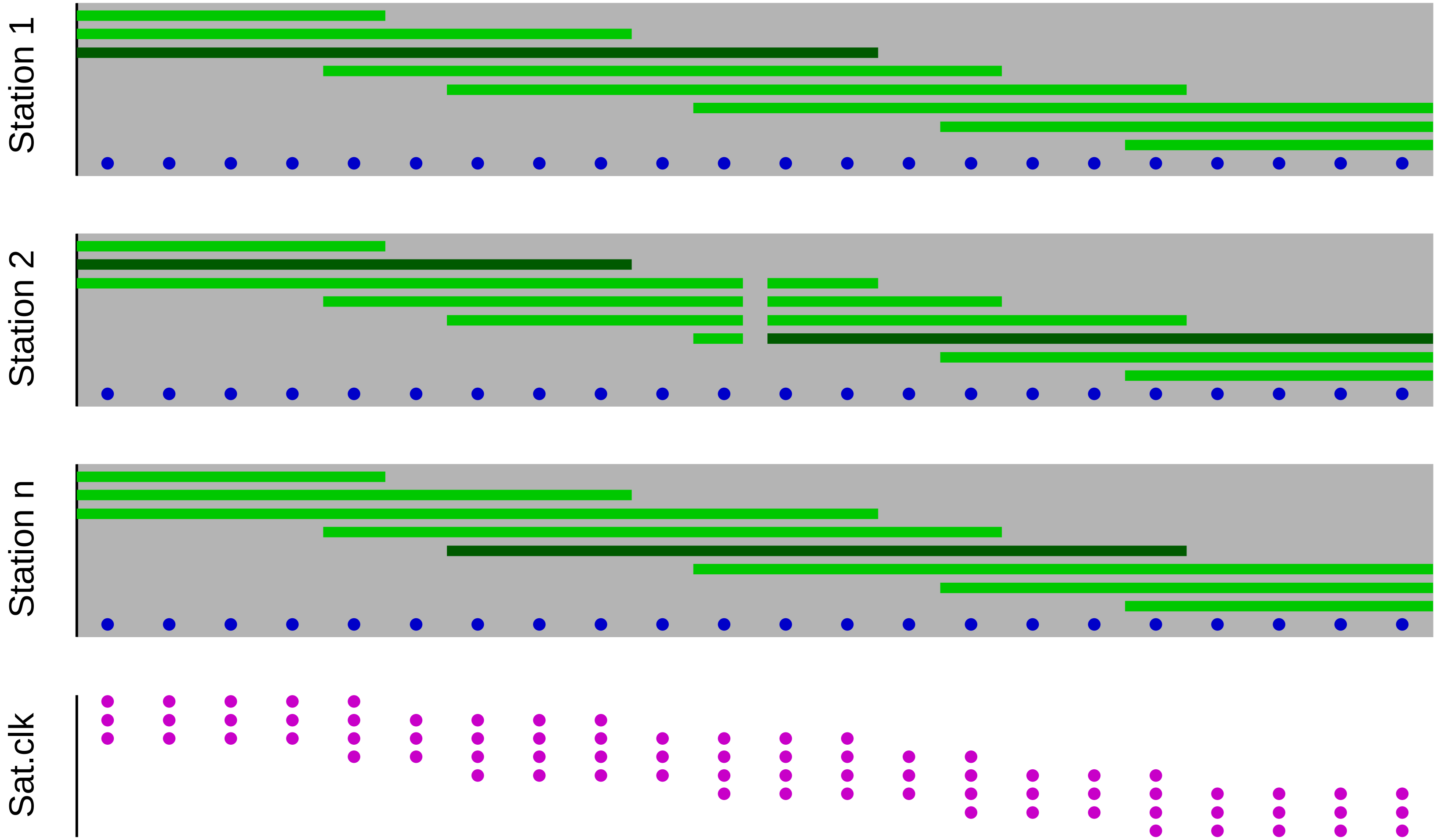
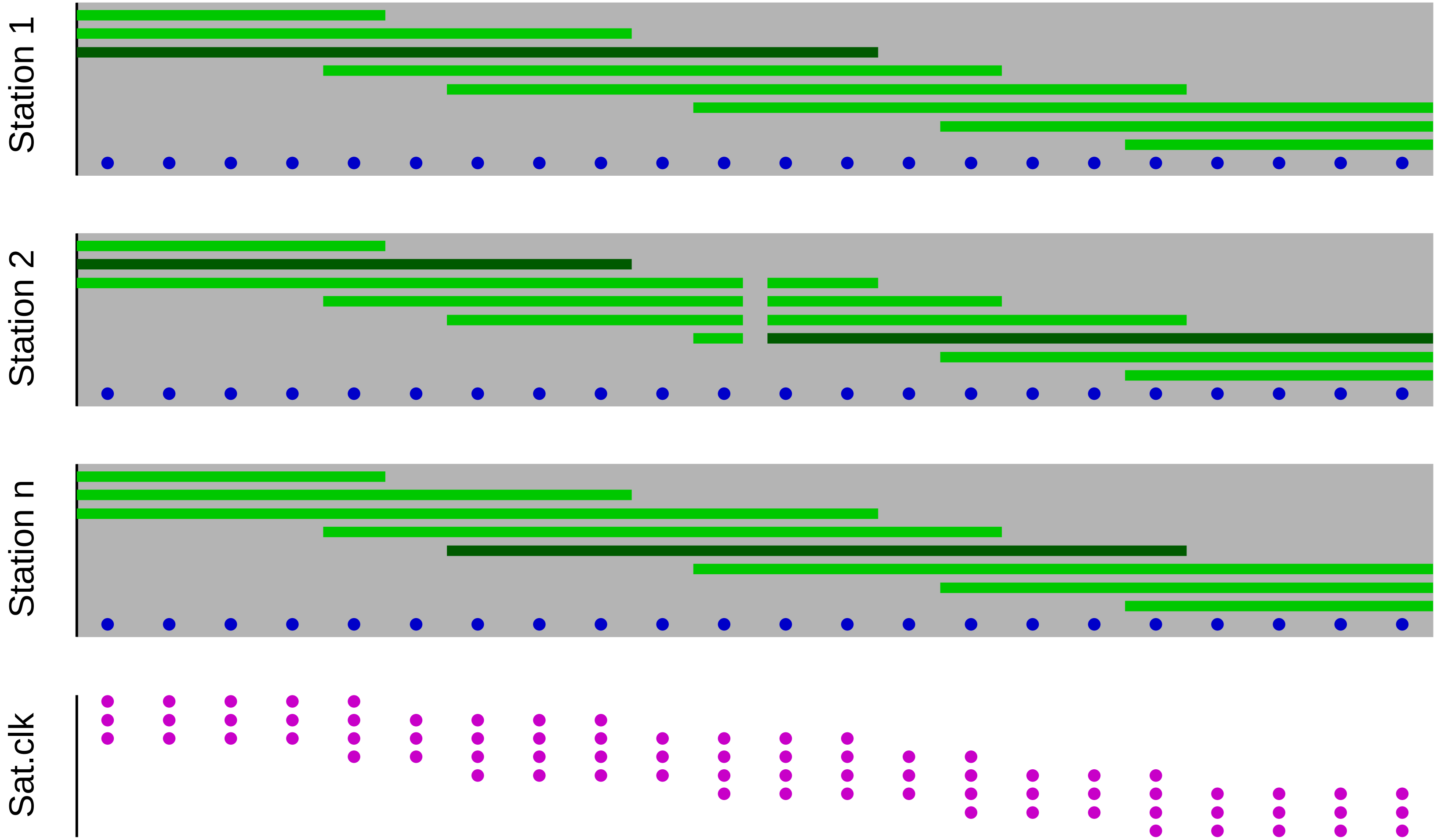


$\Rightarrow$ The satellite clock paramters are added to obtain a network solution.

Geodetic Time and Frequency Transfer

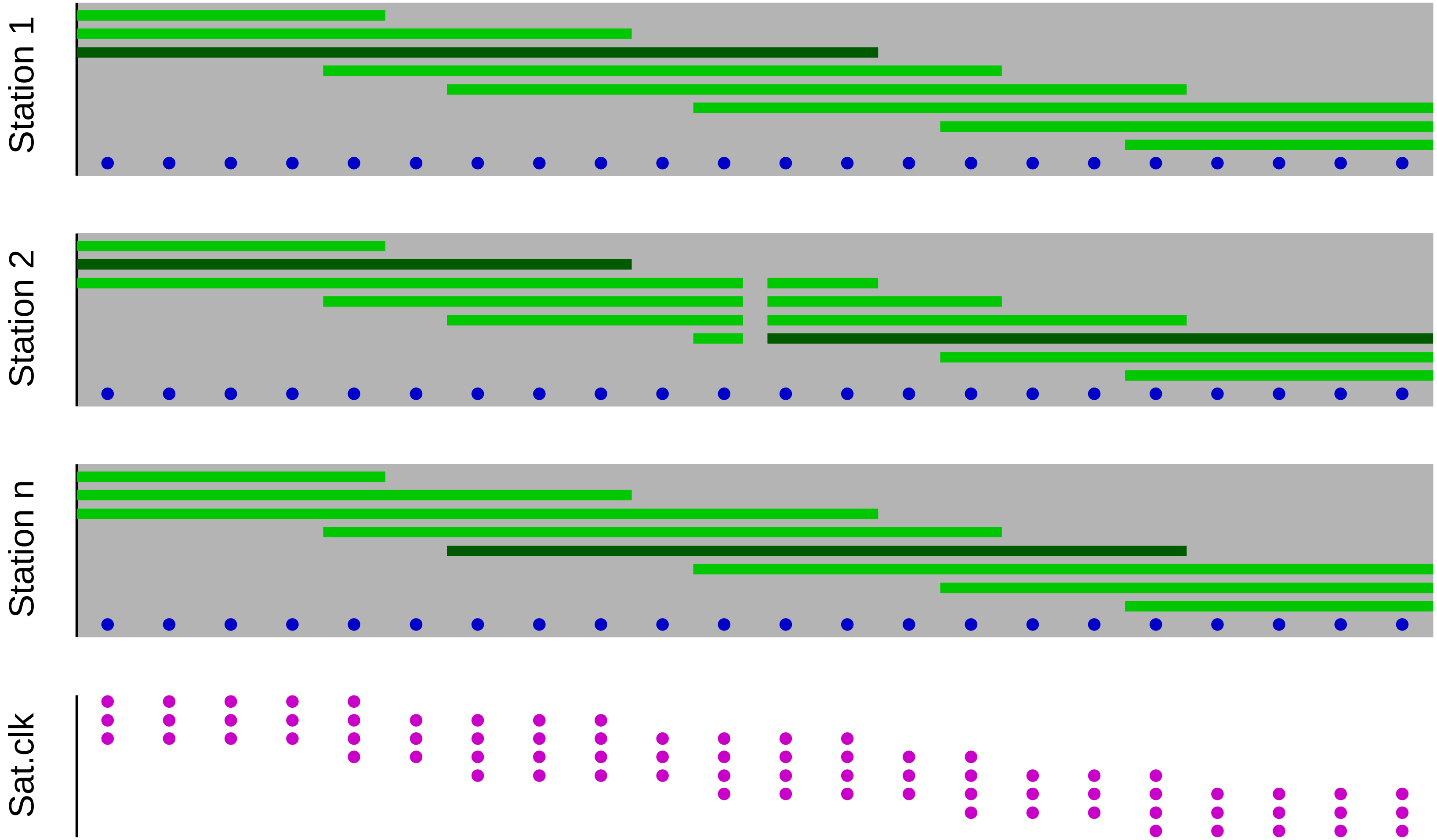
Principle of the Geodetic Time and Frequency Transfer



$\Rightarrow$ Only differences between (receiver) clocks can be interpreted.

Geodetic Time and Frequency Transfer

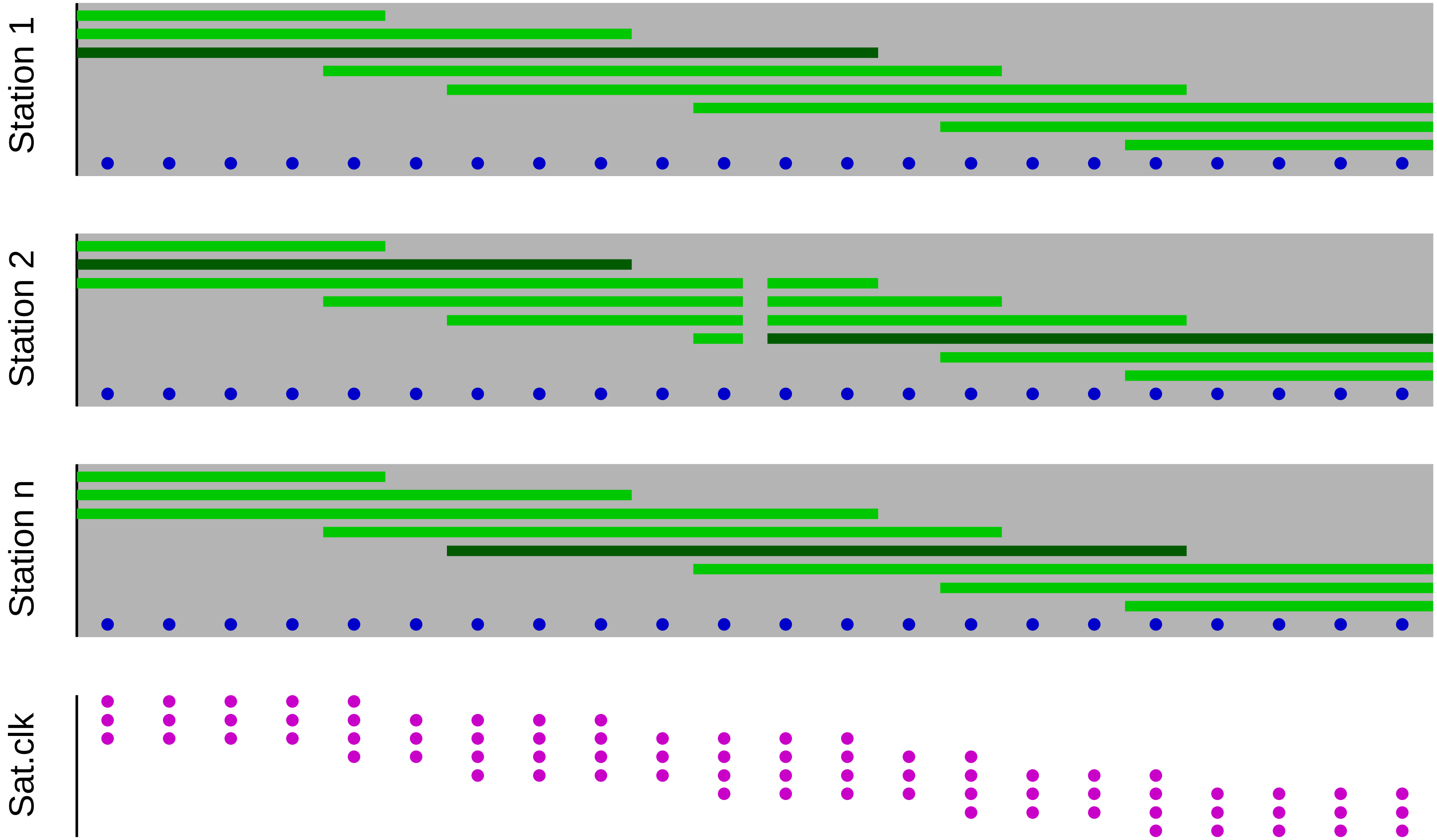
Principle of the Geodetic Time and Frequency Transfer



$\Rightarrow$ Any receiver clock difference can be extracted from the network solution.

Geodetic Time and Frequency Transfer

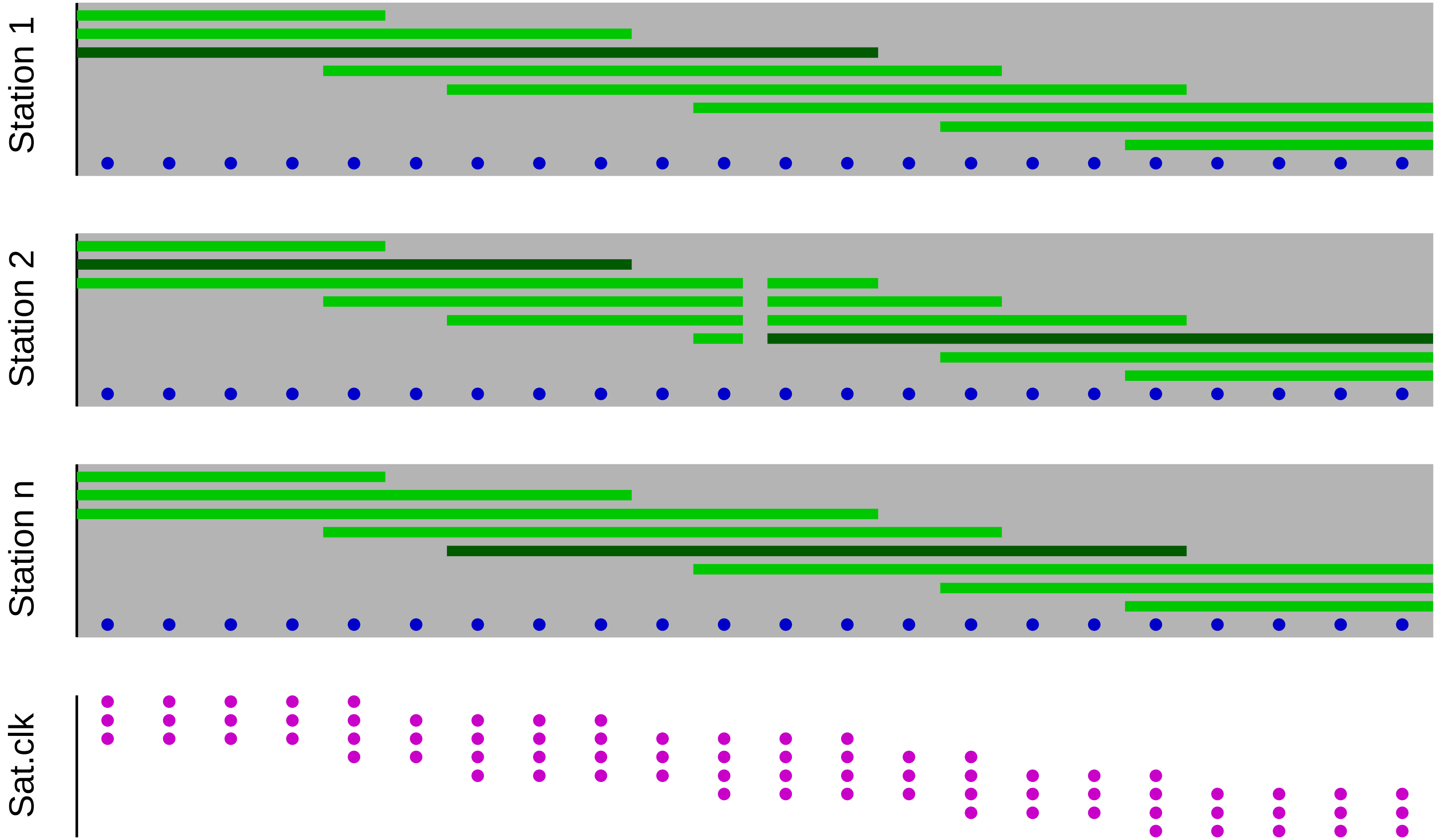
Principle of the Geodetic Time and Frequency Transfer



$\Rightarrow$ All receiver clock values are available at one and the same epoch.

Geodetic Time and Frequency Transfer

Principle of the Geodetic Time and Frequency Transfer



$\Rightarrow$ The method implies no presumptions for the receiver clocks.

Geodetic Time and Frequency Transfer

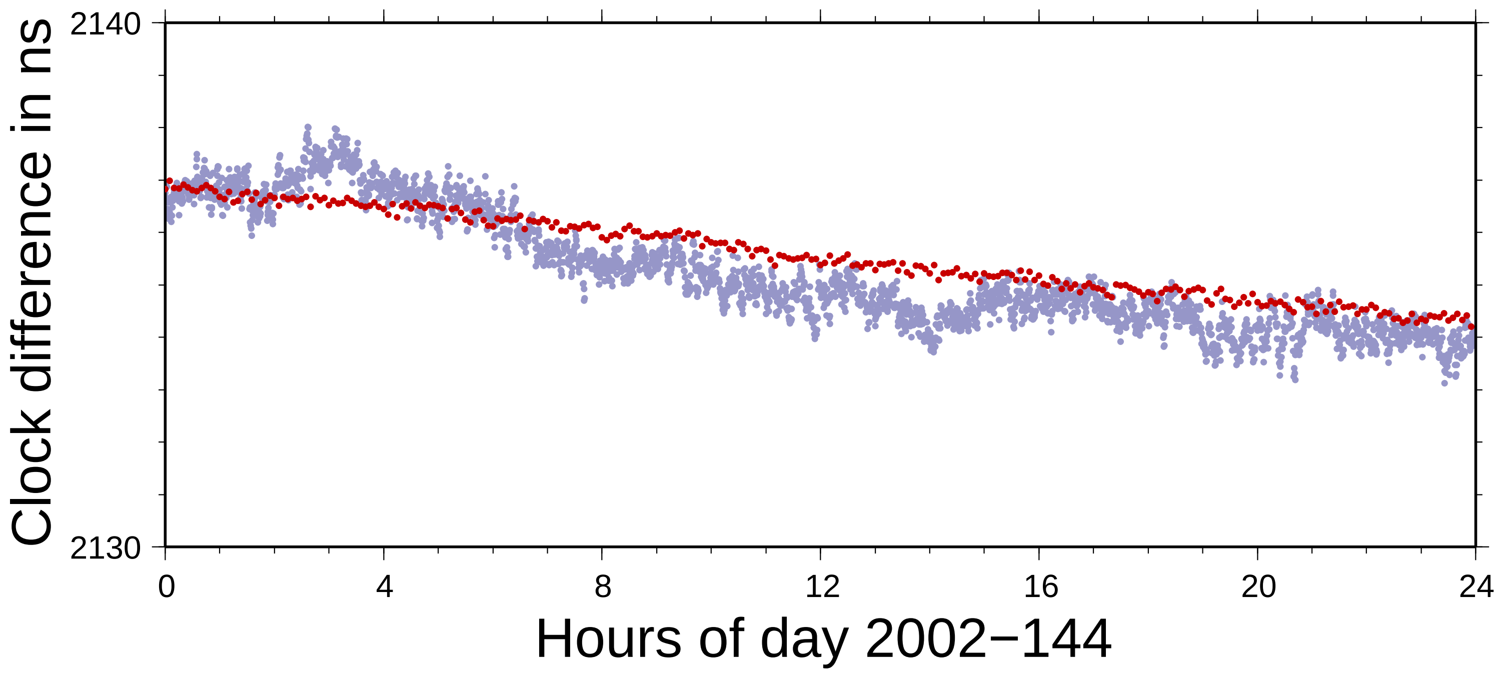
Characteristics of the Geodetic Time and Frequency Transfer

- The complete set of receiver clock values refers to one and the same epoch.
- Only differences between estimated receiver clocks can be interpreted.
- Any simultanious receiver clock difference (baseline) can be extracted from the network solution.
- The method implies no presumptions for the receiver clocks.
- From carrier phase we can get only the change of the receiver clock in time.
- An interrupt in the ambiguities for all satellites leads to a discontinuity in the carrier phase solution.

Geodetic Time and Frequency Transfer

- The pseudorange observations may be added because they have a direct access to the receiver clock parameters.
  - Even in that case the loose of the ambiguity information at one epoch reflects in a discontinuity in the resulting time series or at least in the uncertainty for an obtained frequency.

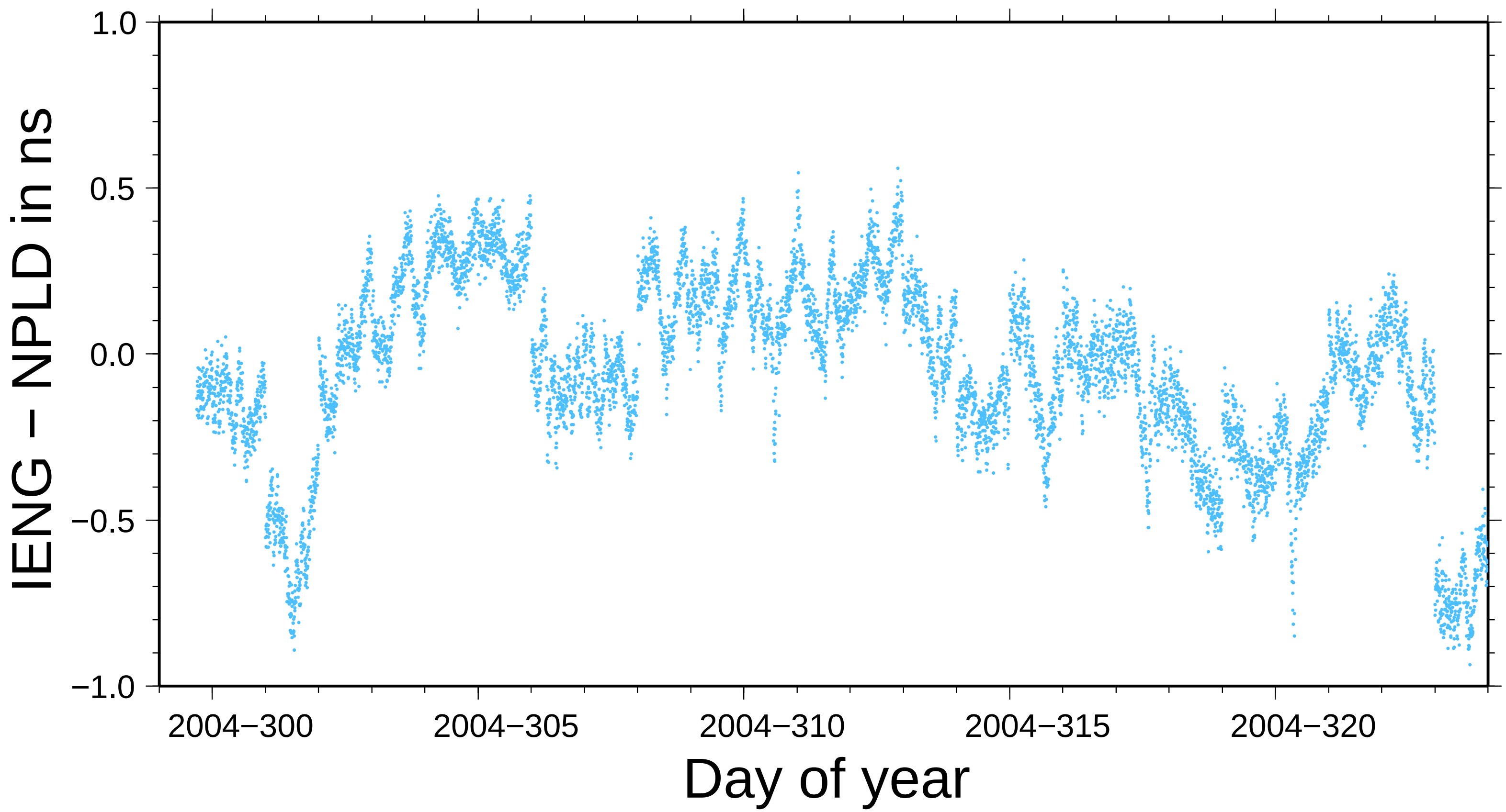
- Example for a geodetic-style clock comparison for the baseline Braunschweig—Brussels:



Geodetic Time and Frequency Transfer

Example for a geodetic time transfer for the baseline Teddington—Torino:

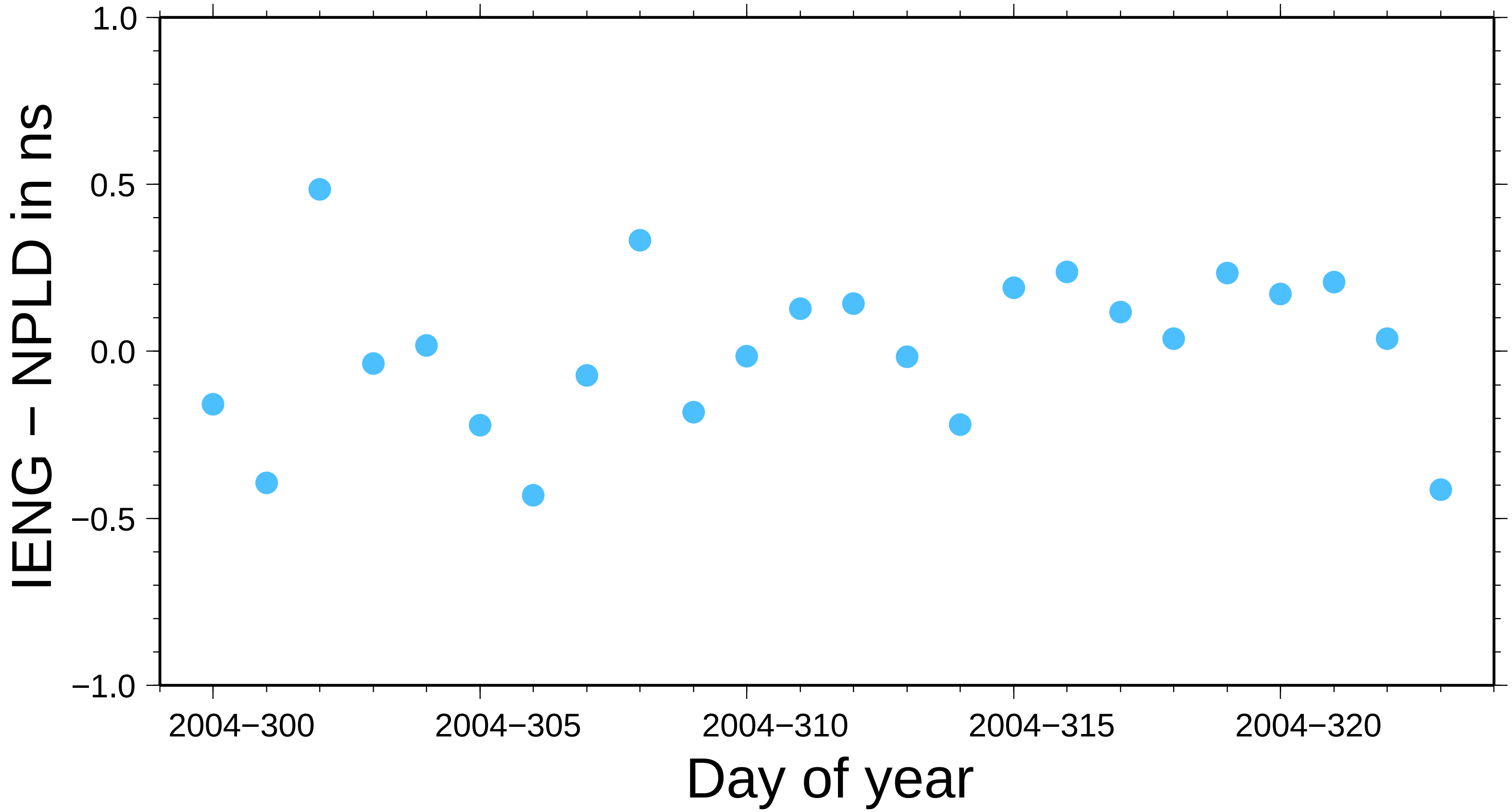
Daily independent solution using code and phase data



Geodetic Time and Frequency Transfer

Day boundary discontinuities in the geodetic time transfer between Teddington — Torino:

Daily independent solution using code and phase data



Geodetic Time and Frequency Transfer

Example for a geodetic time transfer for the baseline Teddington—Torino:

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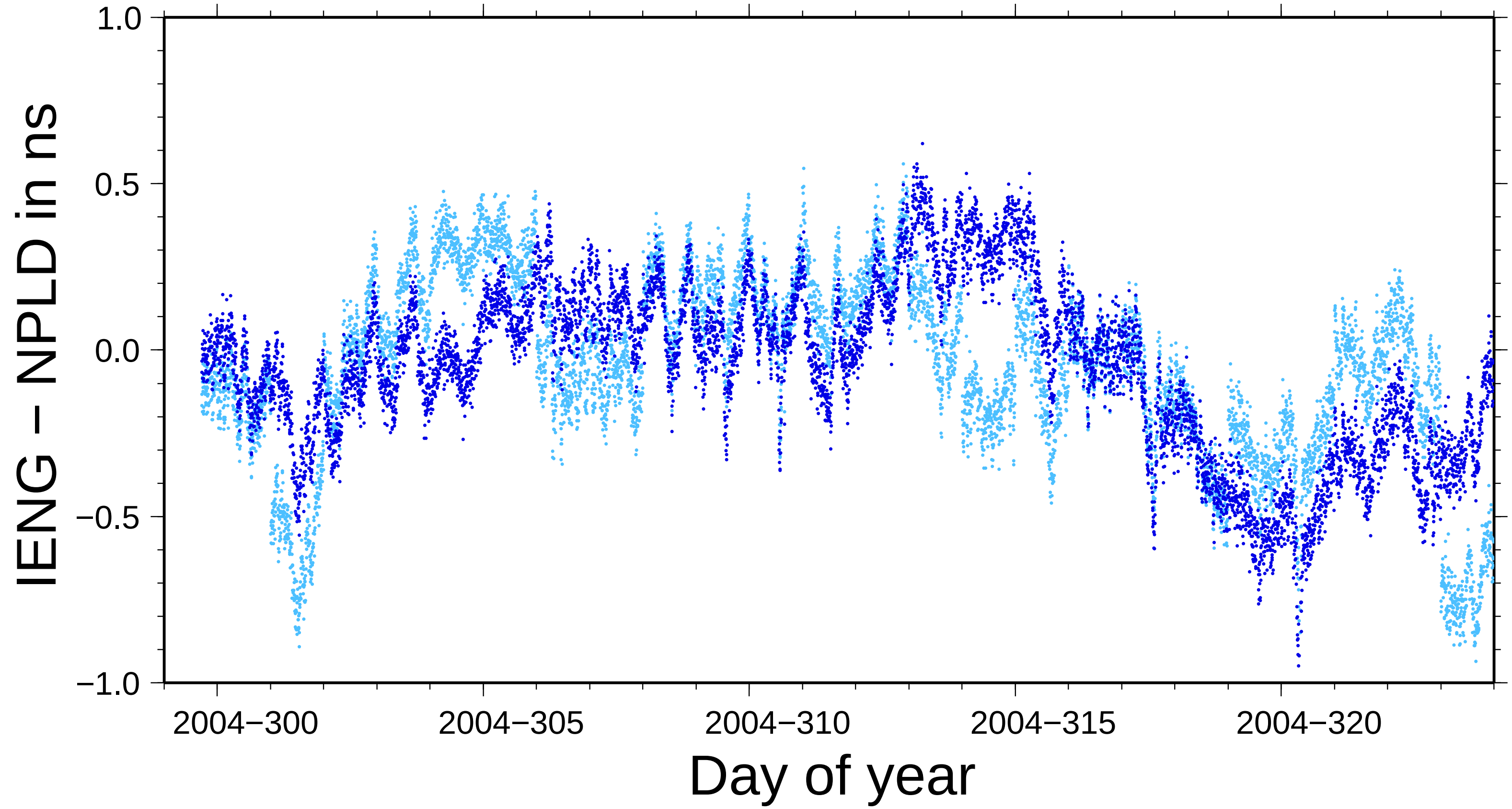
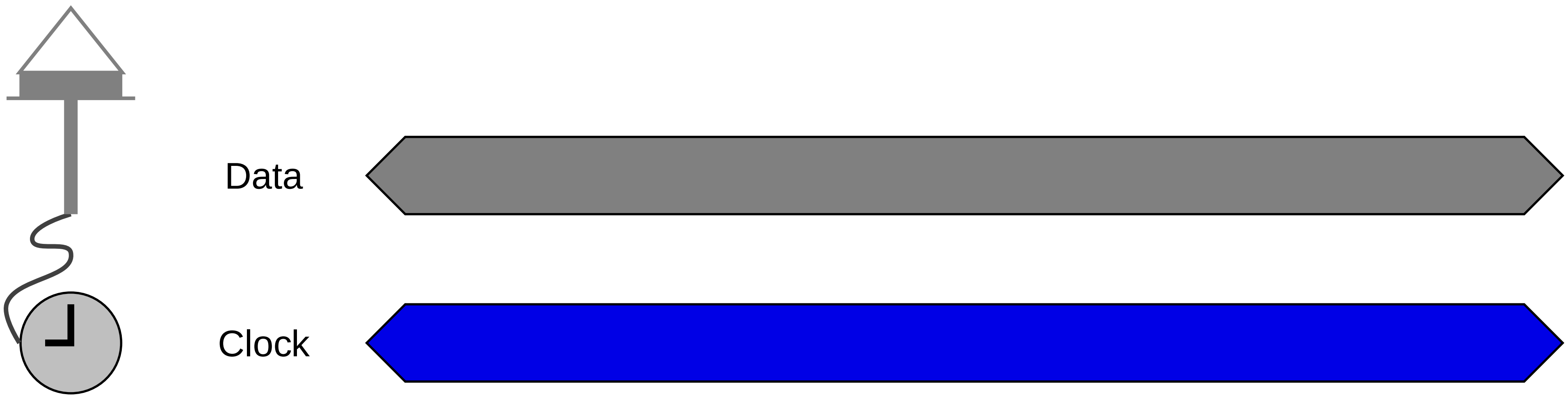
Continuous solution using code and phase data



Ambiguity Stacking



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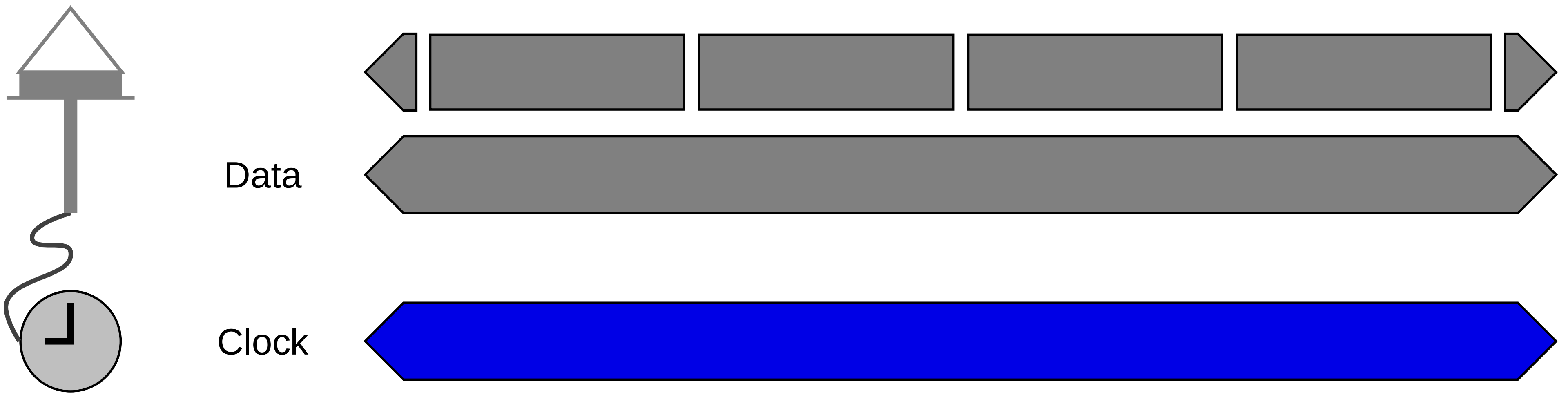

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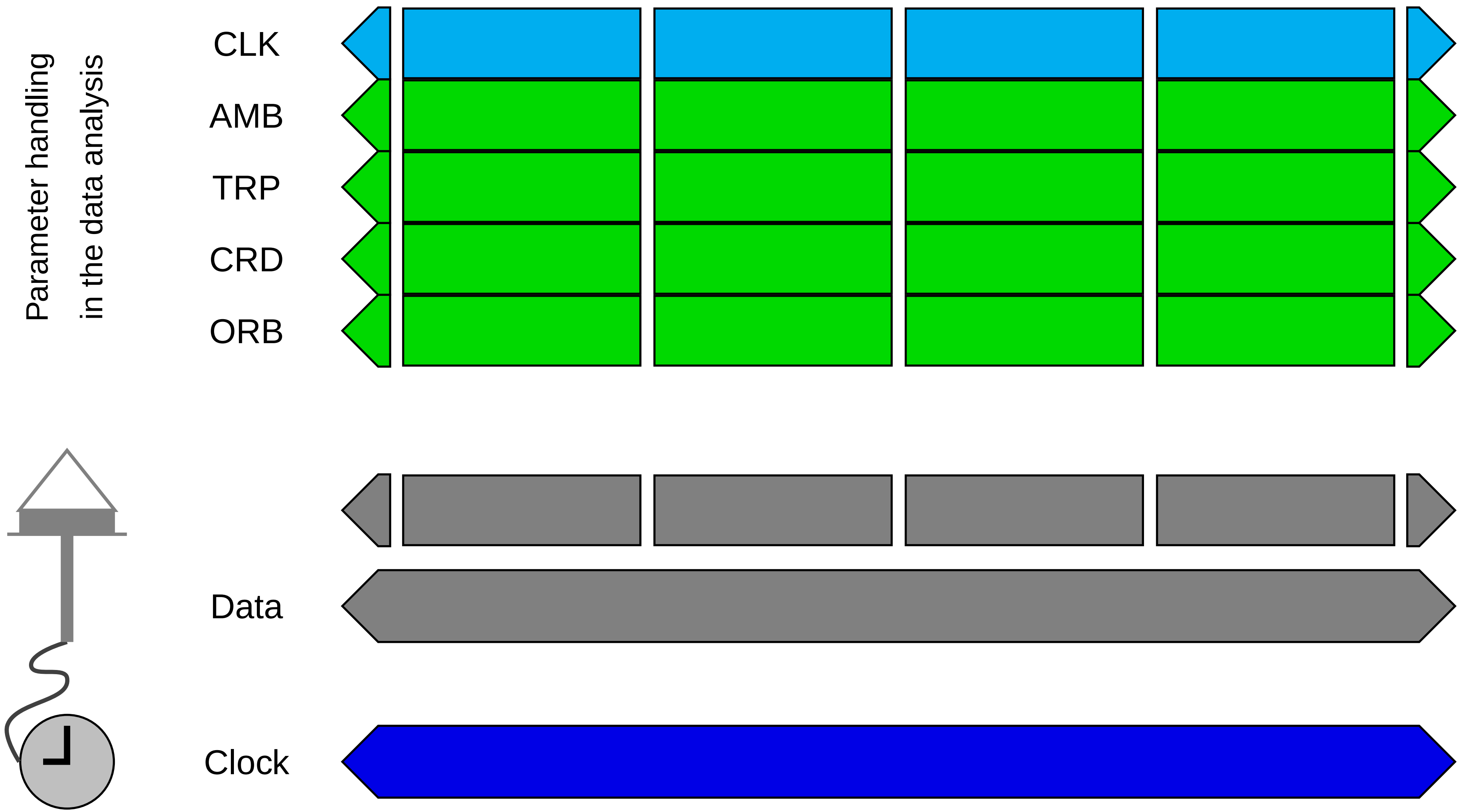

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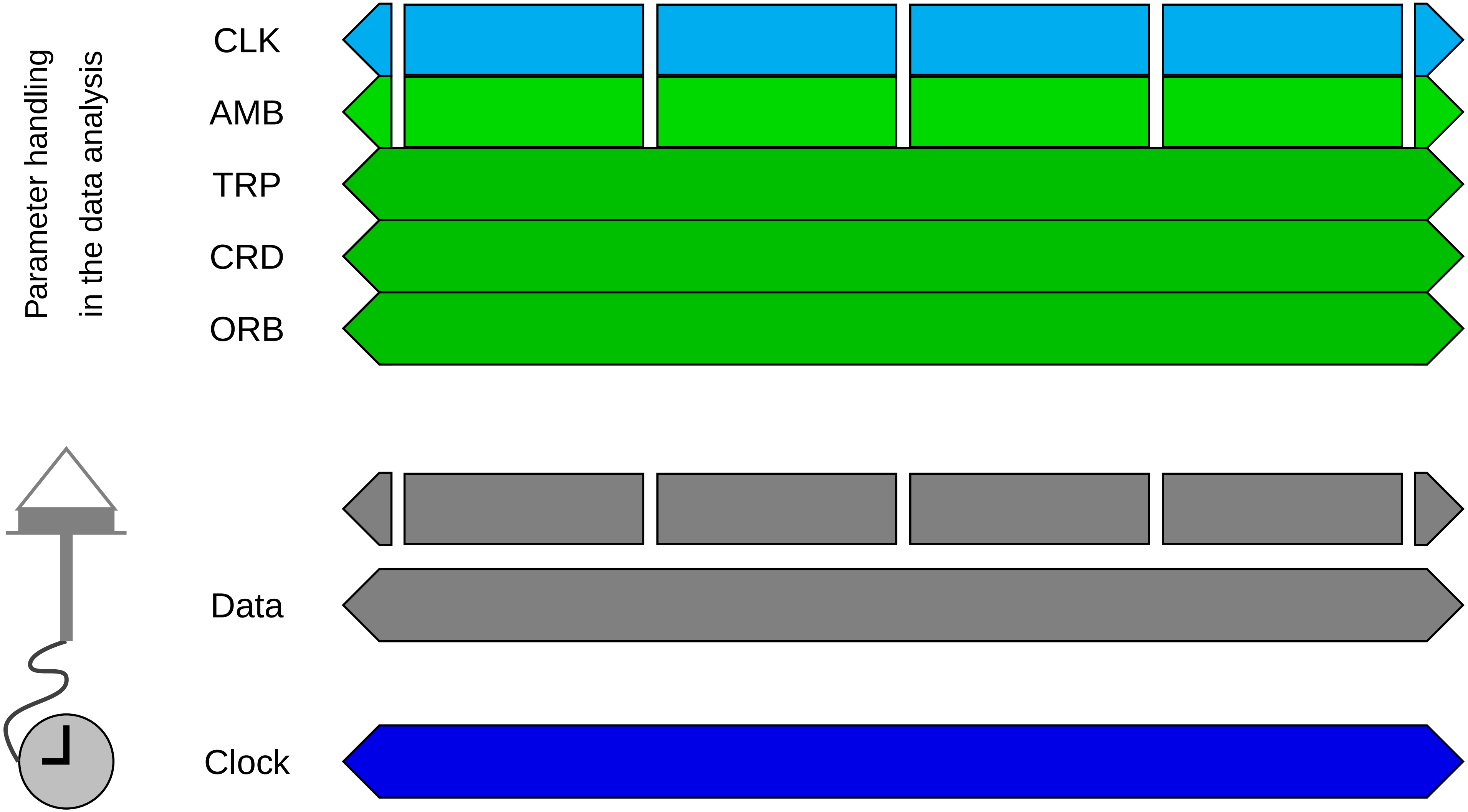

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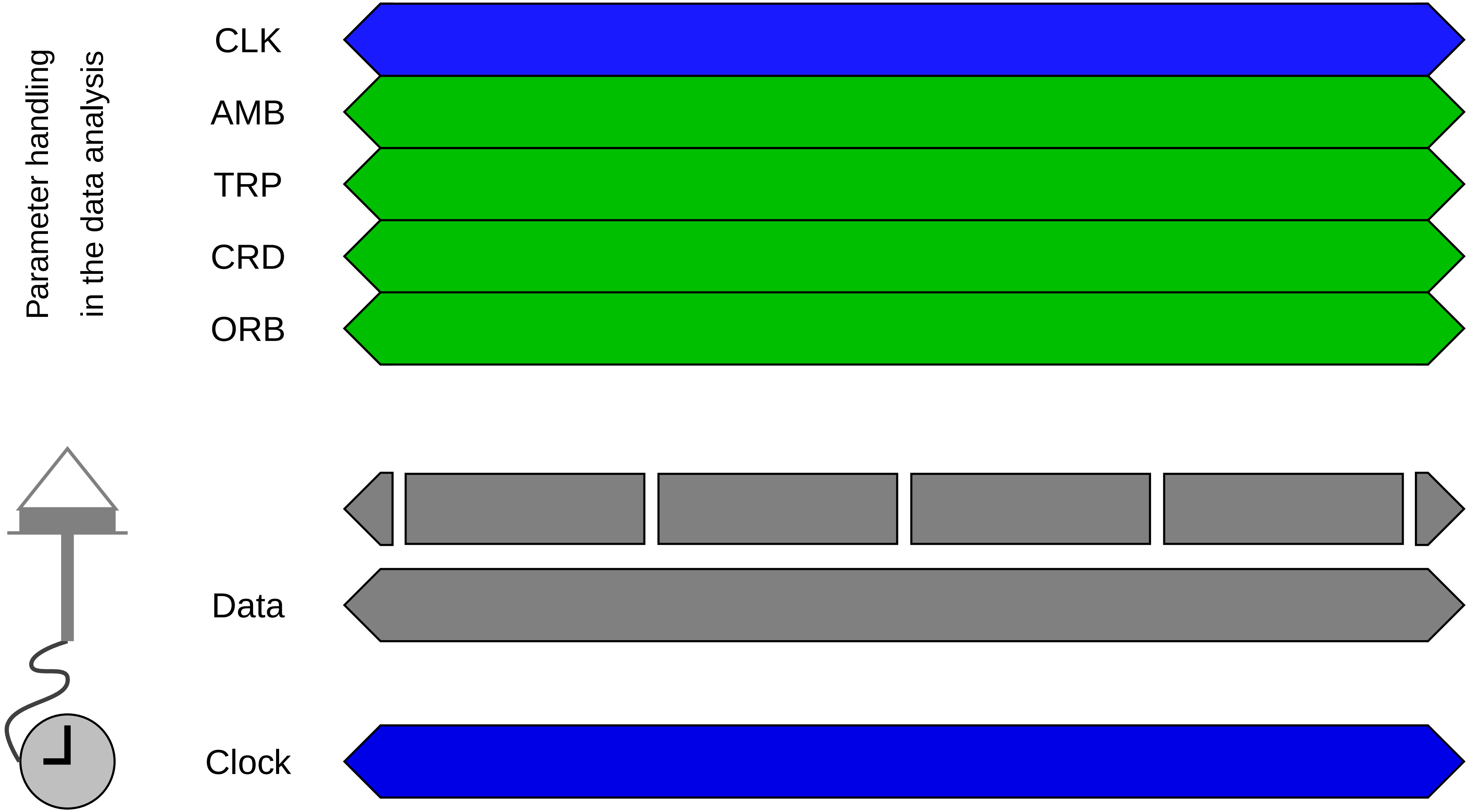

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Ambiguity stacking – what are the problems?

- Huge number of parameters
  - nobody is really interested in the ambiguity estimates
  - usually preeliminated as soon as possible

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  - keywords: station, satellite, freq./lin. comb., wavelength factor, . . .
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  - keywords: station, satellite, freq./lin. comb., wavelength factor, . . .
  - cycle slips between NEQs
  - initialization of the ambiguities considering phase-windup

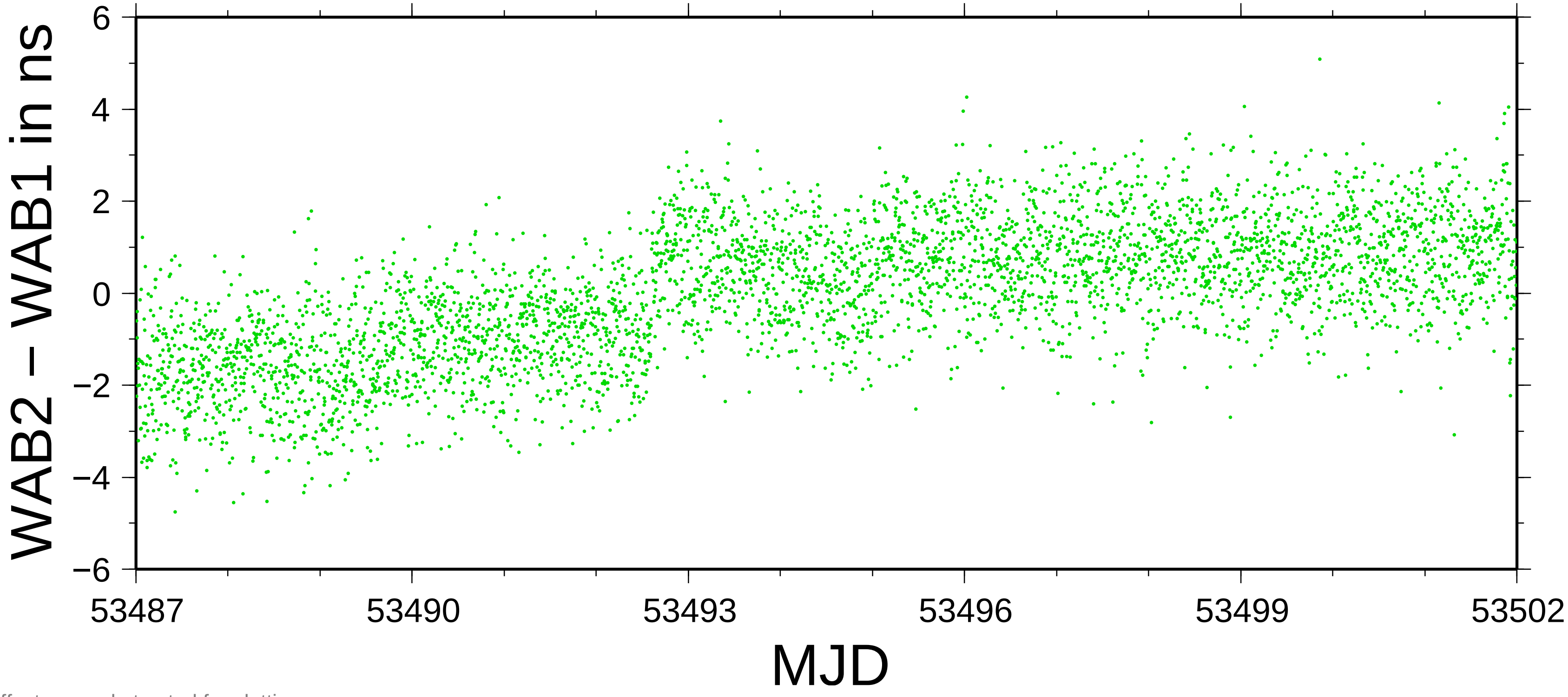
- Advantages
  - may be stacked even if some observations at the boundaries are absent
  - no relative constraints between parameters are necessary

Example: Local Baseline in Wabern

Differences for a local baseline in Wabern between

epoch–wise solution only using code data

and continuous solution only using phase data



An offset was substracted for plotting.

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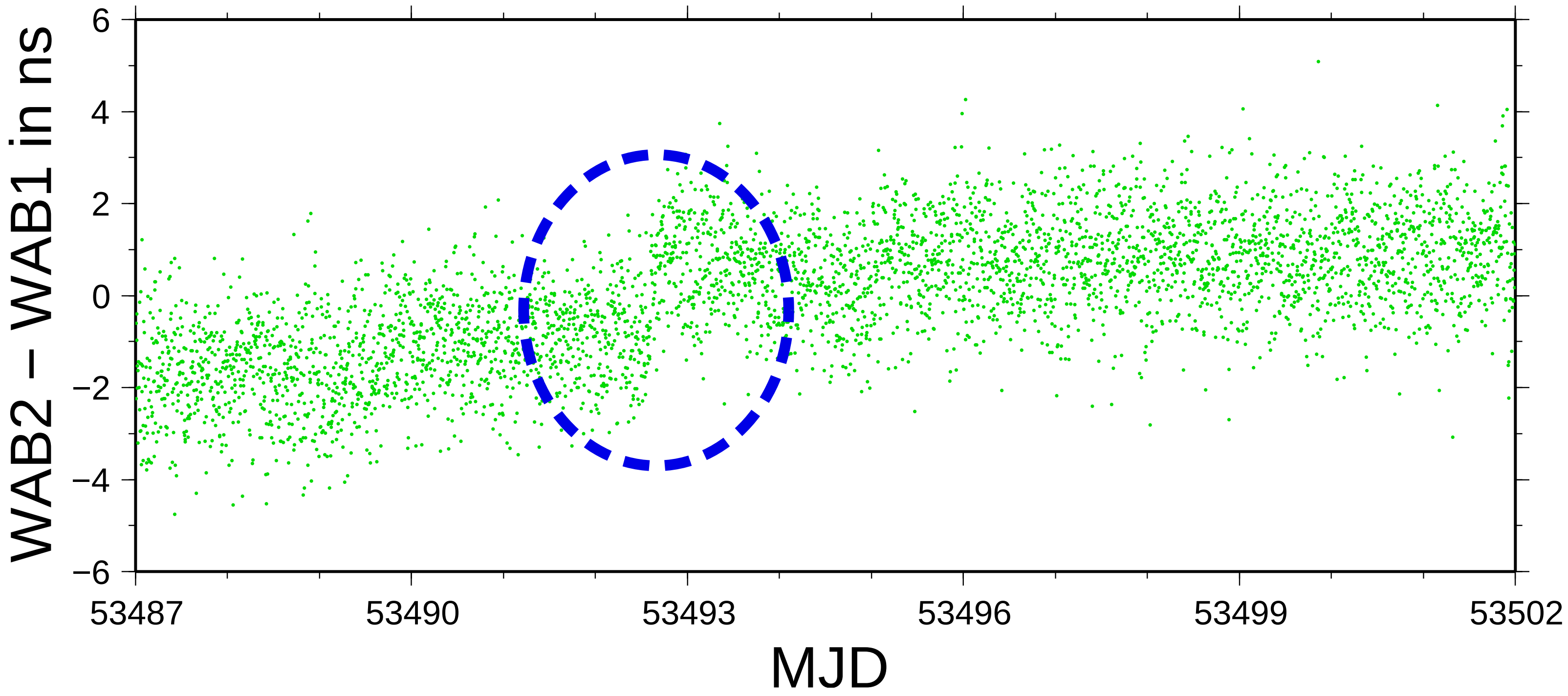

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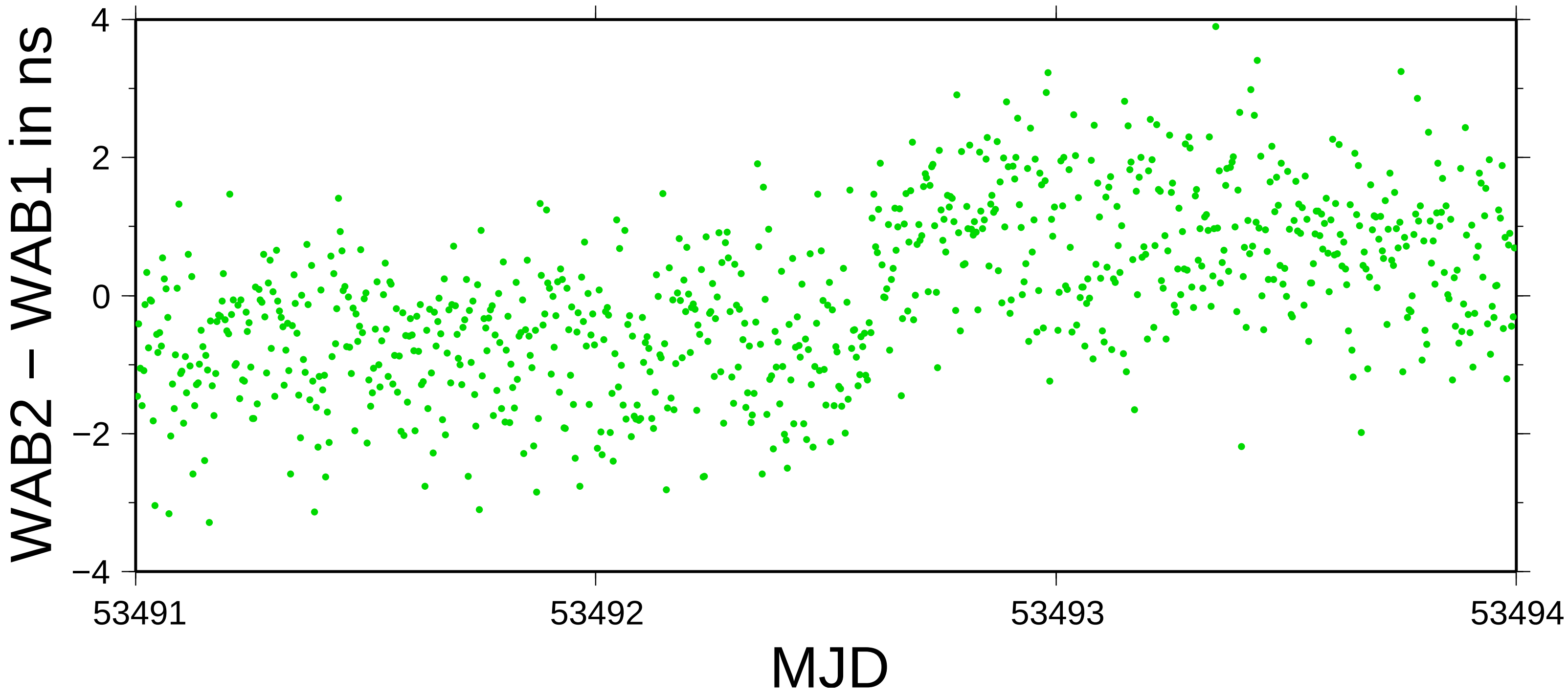

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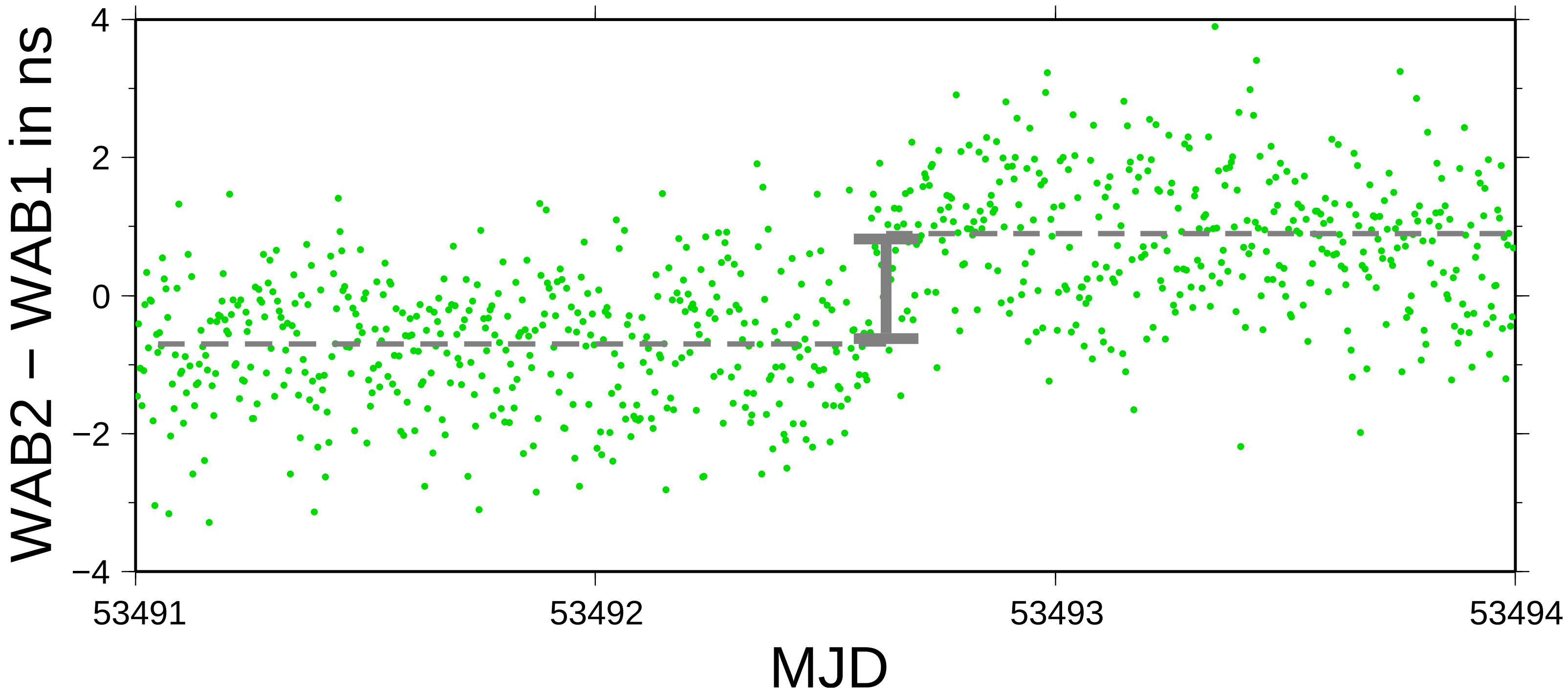

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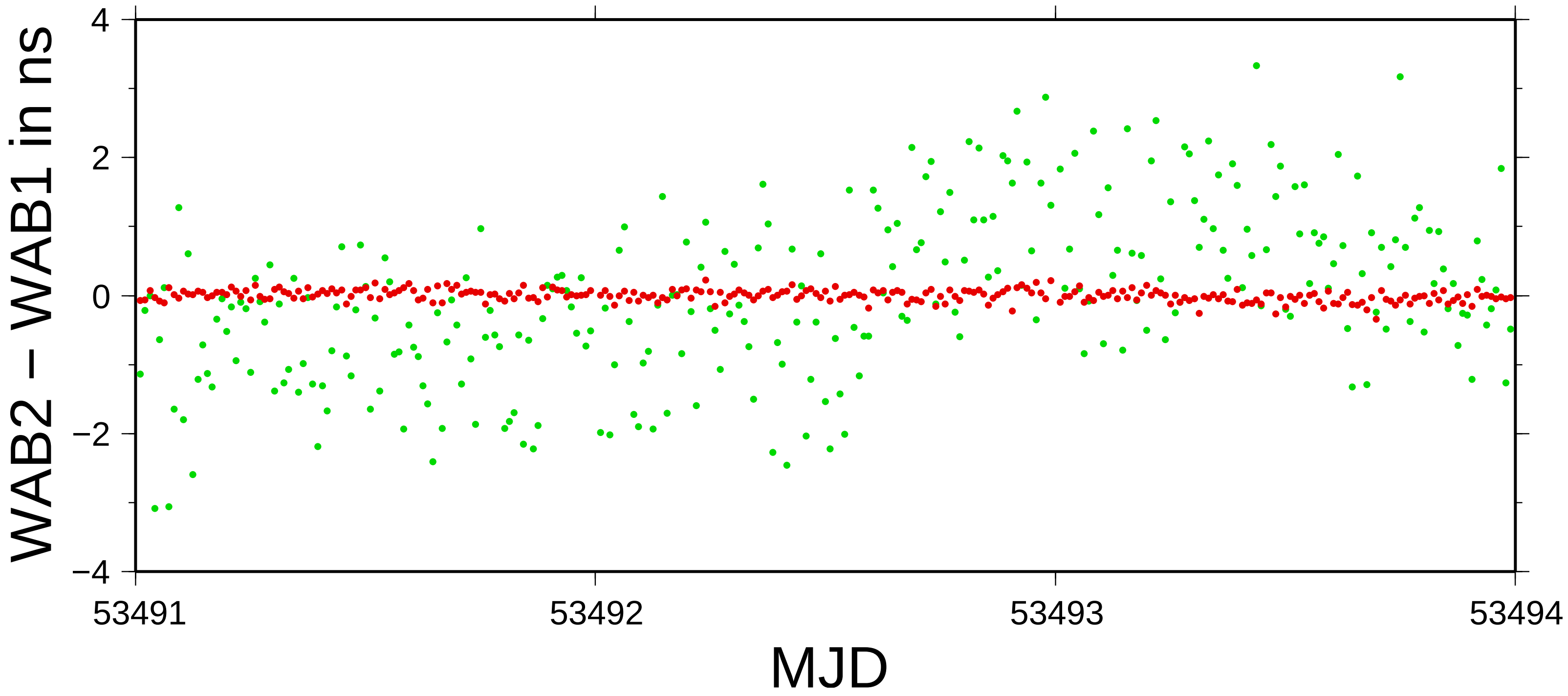
Example: Local Baseline in Wabern

Differences for a local baseline in Wabern between

epoch–wise solution only using code data

resp. continuous solution only using phase data

and the local measurements (every 15 minutes)



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Geodetic Frequency–Transfer Solution

Continuity in the phase data can be recovered with the ambiguity stacking as far as it is not disturbed, e.g., by the loss of lock to all satellites.

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If no access to the absolute clock value is required (frequency transfer) **the use of the code data is *not* necessary anymore!**

Geodetic Frequency–Transfer Solution

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If no access to the absolute clock value is required (frequency transfer) **the use of the code data is *not* necessary anymore!**

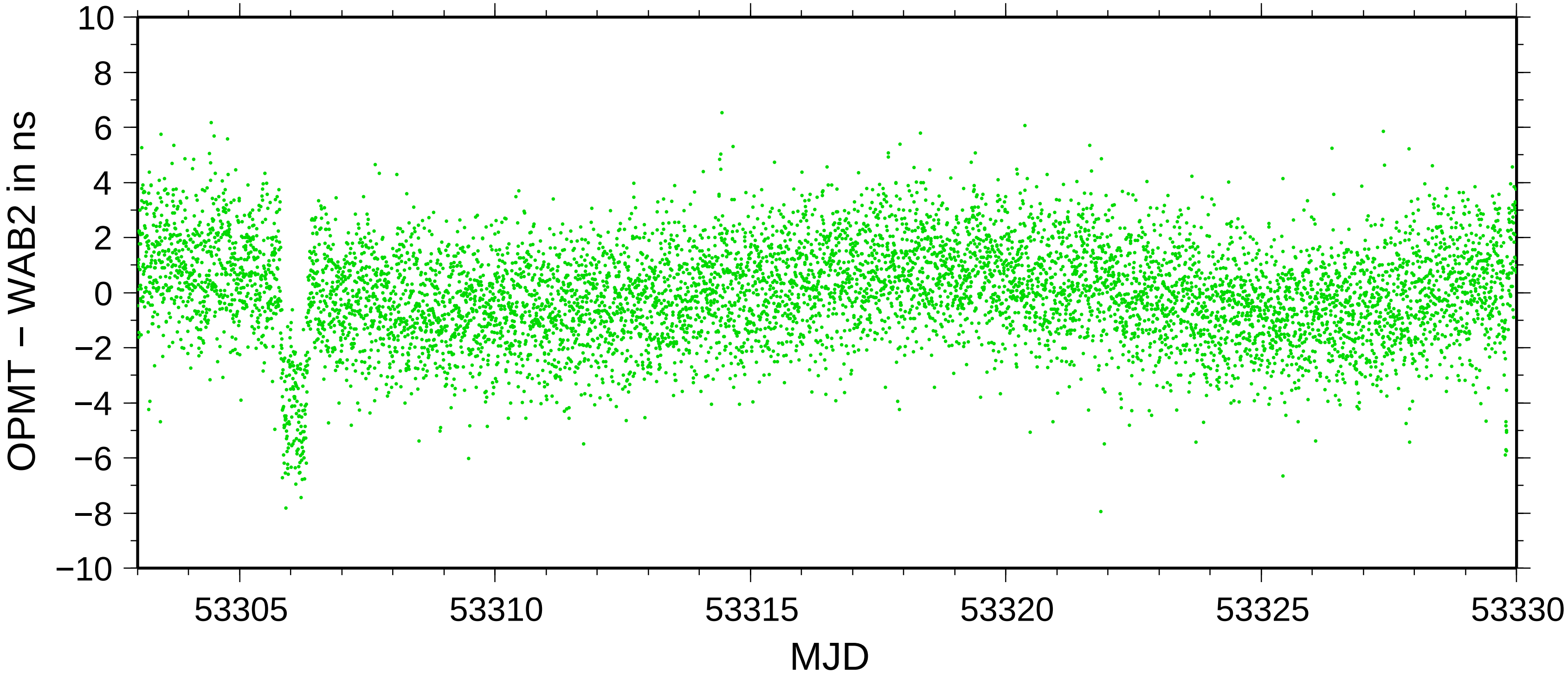
Benefit from a phase–only solution is obvious:

- Geodetic receivers are primarily designed for using the phase observations.
- Inconsistencies between the internal receiver clock for code and phase measurements have no effect on the solution.
- Multipath and related effects in the phase data is much smaller than in the code data.

Comparison of Different Solutions

Receiver clock difference between Paris and Wabern

Epoch–wise solution only using code data



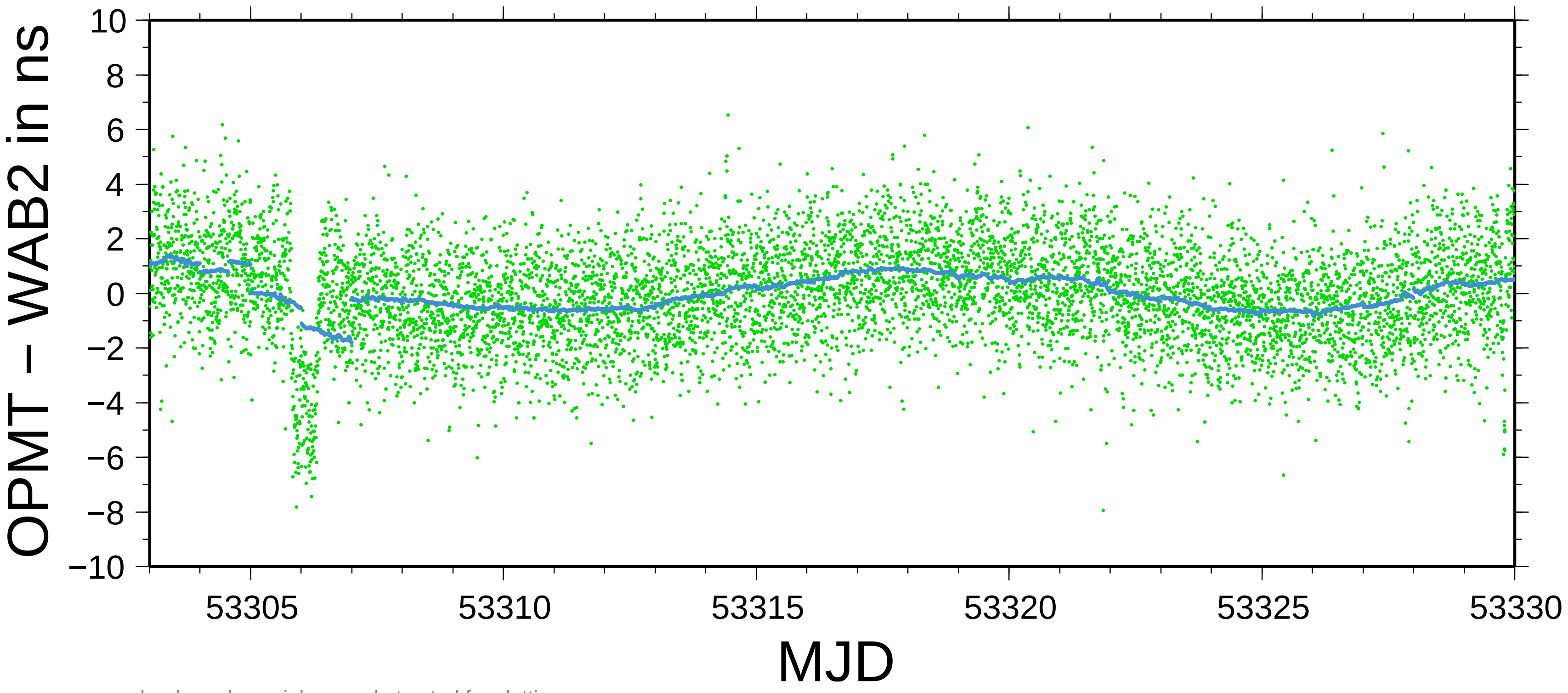
A common second order polynomial was substracted for plotting.

Comparison of Different Solutions

Receiver clock difference between Paris and Wabern

Epoch–wise solution only using code data

Daily independent solution using code and phase data



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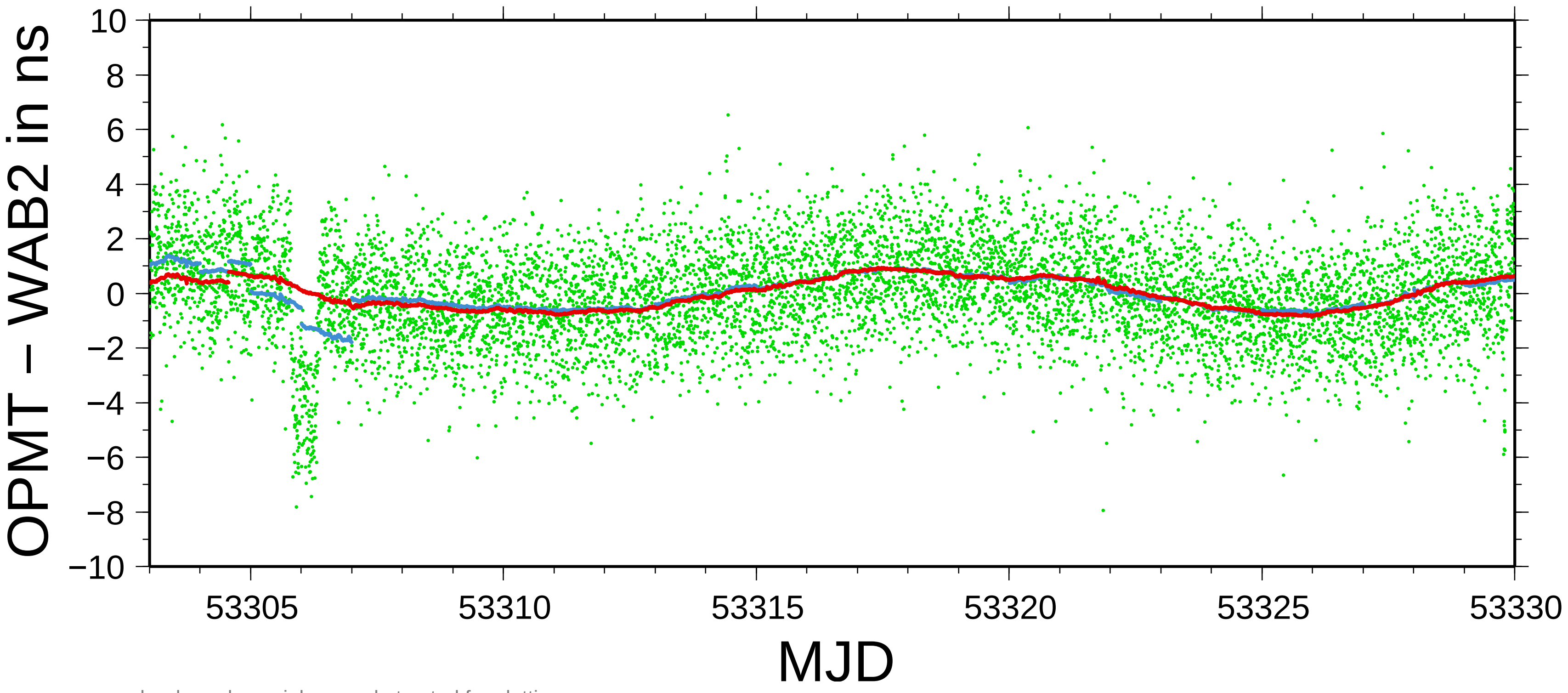
Daily independent solution using code and phase data

Continuous solution only using phase data



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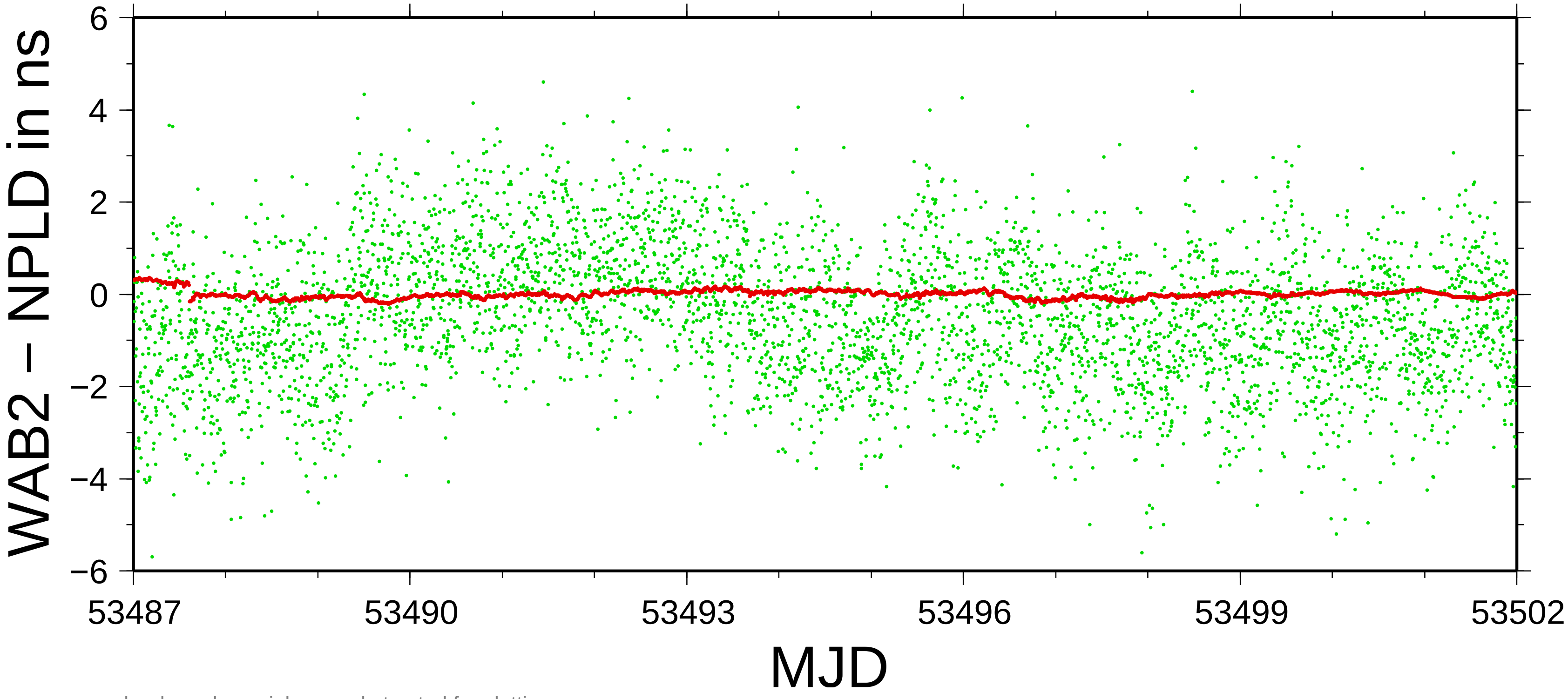
Comparison of Different Solutions

Receiver clock difference between Teddington and Wabern

Continuous solution only using phase data

Epoch–wise solution only using code data



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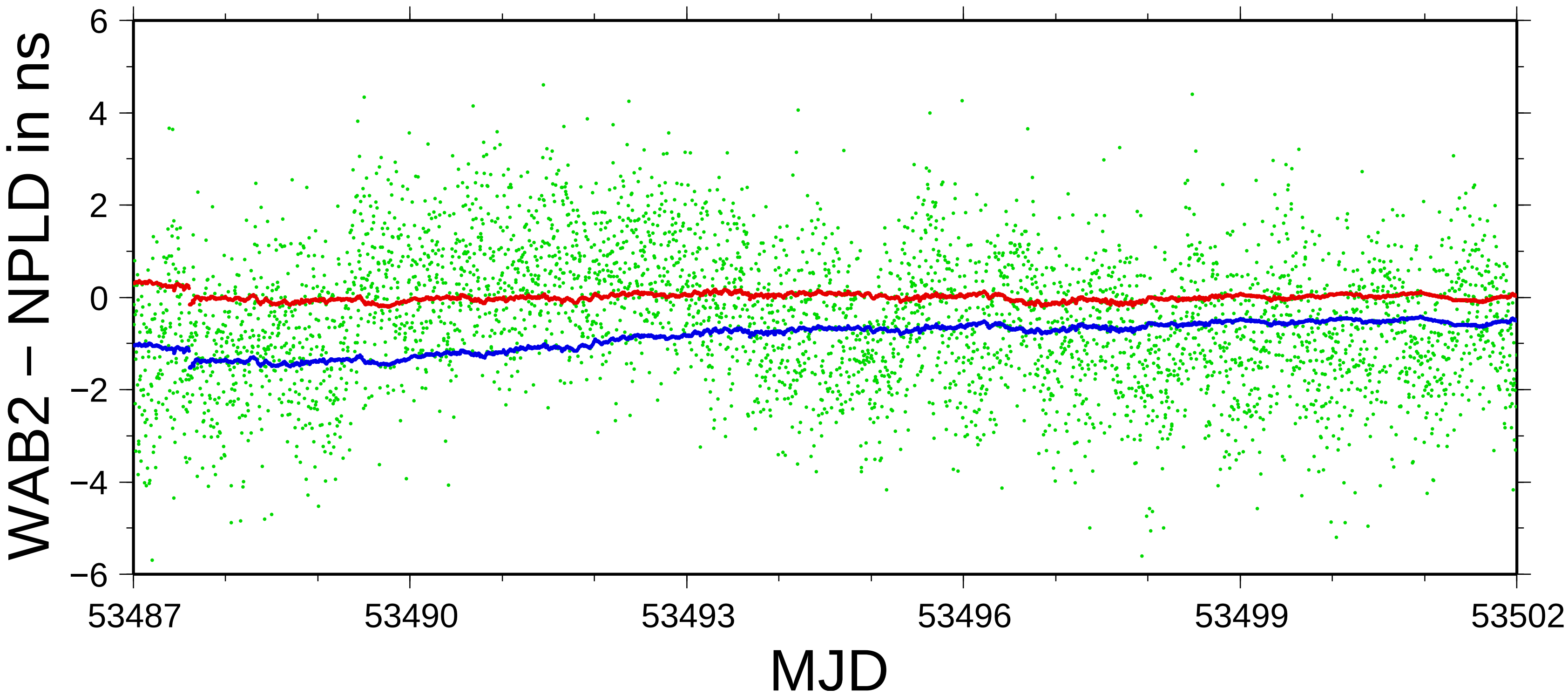
Comparison of Different Solutions

Receiver clock difference between Teddington and Wabern

Continuous solution only using phase data

Epoch–wise solution only using code data

Continuous solution using code and phase data



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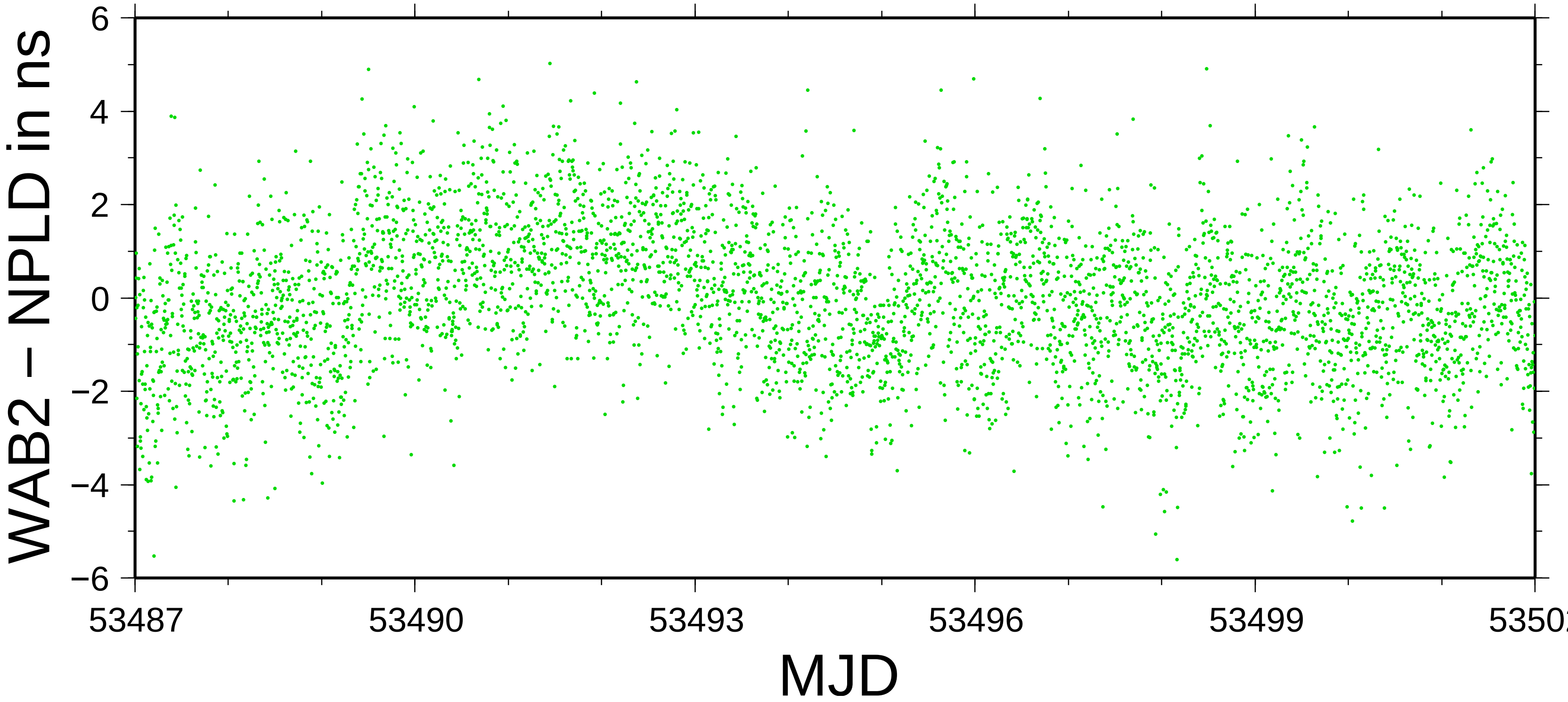
Impact of Multipath

Differences for the baseline Teddington and Wabern

epoch–wise solution only using code data

and continuous solution only using phase data



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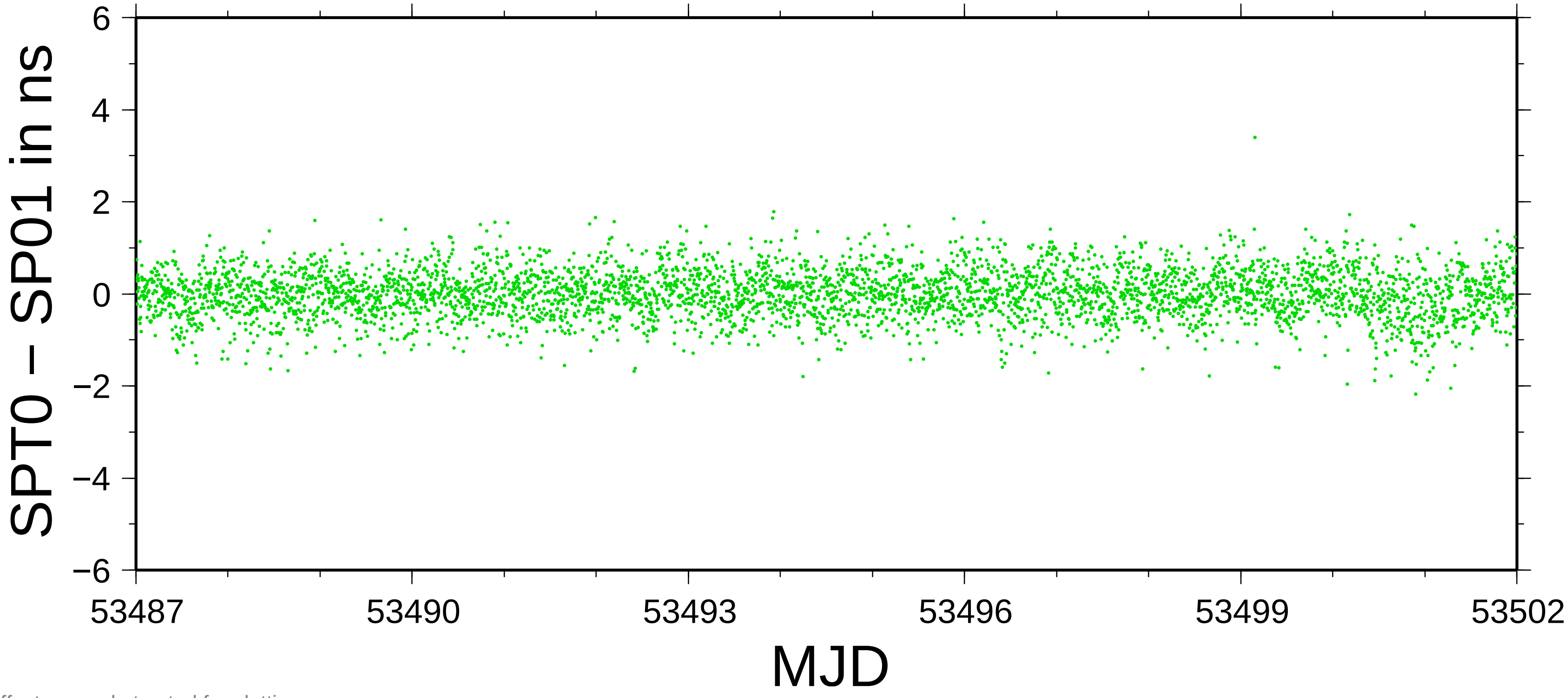
Impact of Multipath

Differences for a zero–baseline in Boras between

epoch–wise solution only using code data

and continuous solution only using phase data



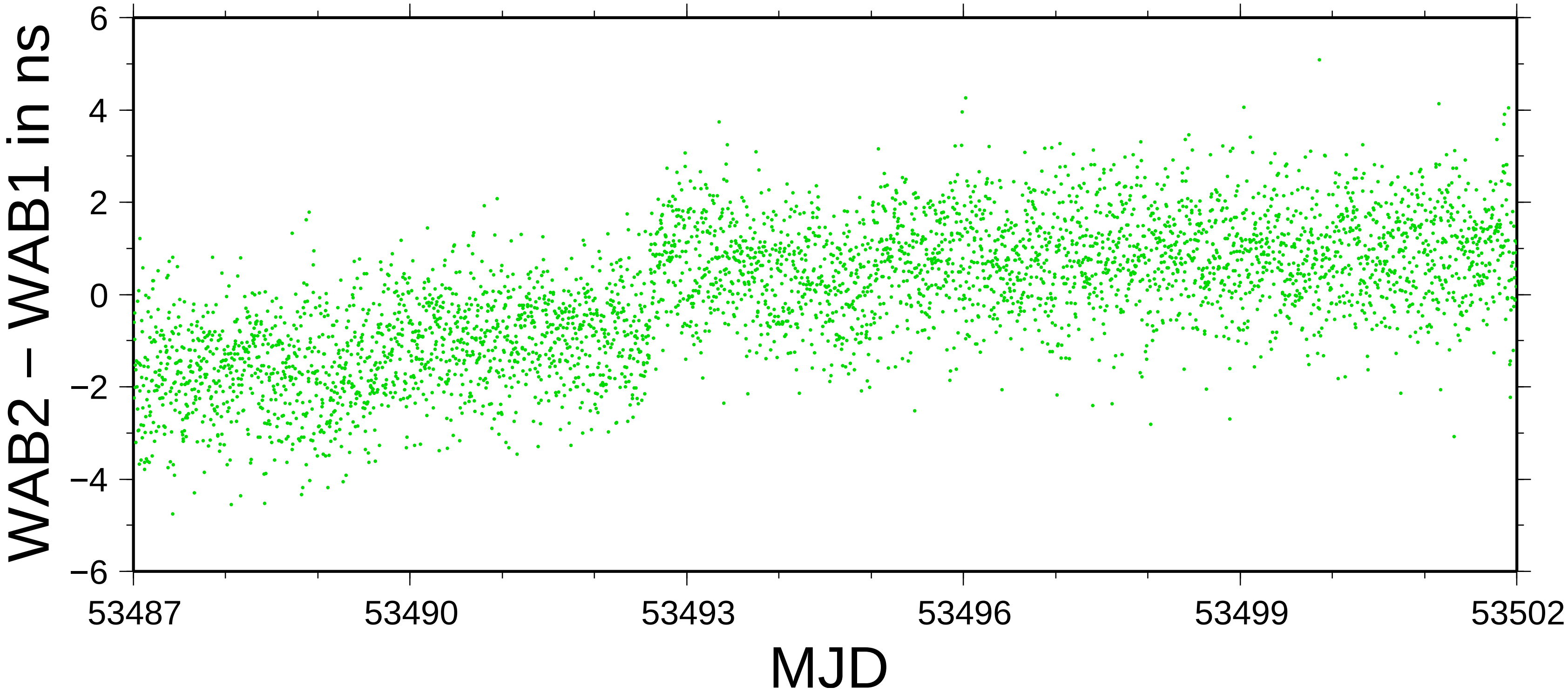
An offset was substracted for plotting.

Impact of Multipath

Differences for a local baseline in Wabern between

epoch–wise solution only using code data

and continuous solution only using phase data



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Geodetic Time and Frequency Transfer

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  Three product lines with different latencies are provided: final (2 weeke), rapid (18 hours), ultra–rapid (3 hours). The ultra–rapid orbits contain a predicted part for real–time applications.

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