Global positioning system (GPS)
- Part I -

Thomas Hobiger

Space-Time Standards Group

National Institute of Information and
Communications Technology (NICT), Japan

NiCT

Content

- GPS overview
- GPS Signal and Receiver Architectures
- Software receivers – NICT's developments
- Error Sources (special focus on troposphere)

NiCT

GPS

- NAVSTAR GPS (Global Positioning System)
  - Satellite navigation system developed by US DoD
  - Operated by US Air Force GPS Wing
- History
  - 1978/2 First satellite launch
  - 1983 Freely available for civilian use
  - 1993 Fully operational (FOC)
  - 2000/5 S/A Termination
  - 2009/8 30 operational satellites

NiCT

GNSS

- Global Navigation Satellite Systems
  - GPS (US)
  - GLONASS (Russia)
  - Galileo (EU)
  - Compass (China)
- Regional Navigation Satellite Systems
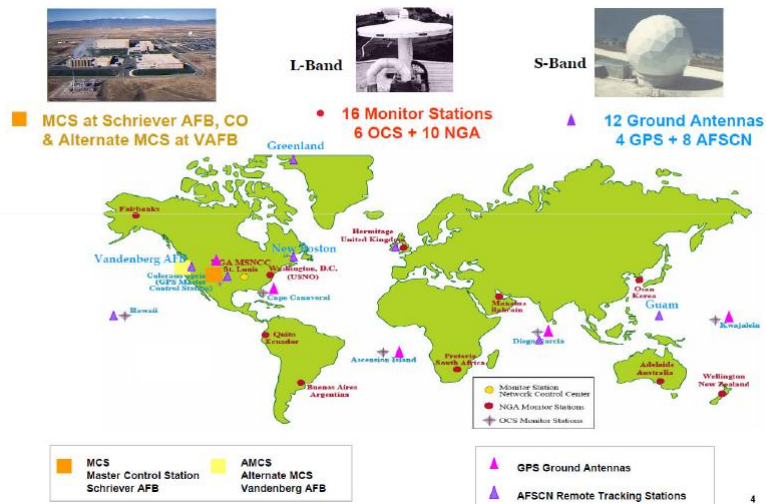 - QZSS (Japan)
  - IRNSS (India)

NiCT

GPS Space Segment

- Satellite Constellation
  - 6 Planes x 4 = 24 Satellites (Nominal)
  - Altitude: 20,100km
  - Inclination: 55°
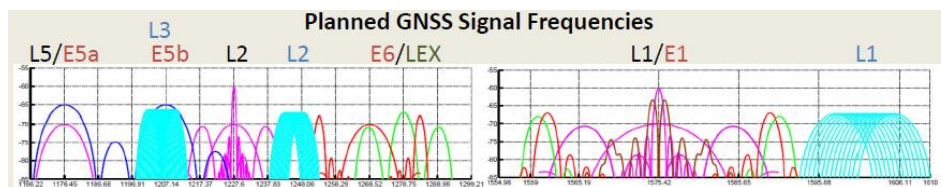 - Period: 1/2 Sidereal Day (11h 58' 2")

NiCT

GPS Ground Segment

(from Harrington, GPS Status and Modernization, 2009)

NiCT

GNSS constellation

Number of planned GNSS Satellites

System	2009	2012	2015	2018
GPS	30	32	32	32
GLONASS	17	24	24	24
Galileo	0	15	27	27
Compass	2	12	30	35
QZSS	0	1	3	3
IRNSS	0	7	7	7
Total	**49**	**91**	**123**	**128**

Planned GNSS Signal Frequencies

GPS signal and receiver architecture

GPS receiver - summary

- Provides "replica" codes, compares them with incoming signals
- Core parts
  - Acquisition: Search Doppler shift and code phase
  - Code tracking (delay lock loop)
  - Carrier tracking (Phase/Doppler tracking loop)
  - Decode navigation message
- Output:
  - Pseudo-Range
  - Carrier phase and Doppler frequency
  - Navigation data

NiCT

GPS software receivers

+ Cheap and easy to implement

+ Very flexible

+ Testing of new algorithms, prototyping

+ Floating point precision

- Slow, consume complete CPU performance

- Difficult to miniaturize

- Not all replica signals available (e.g. P-code tracking)

NiCT

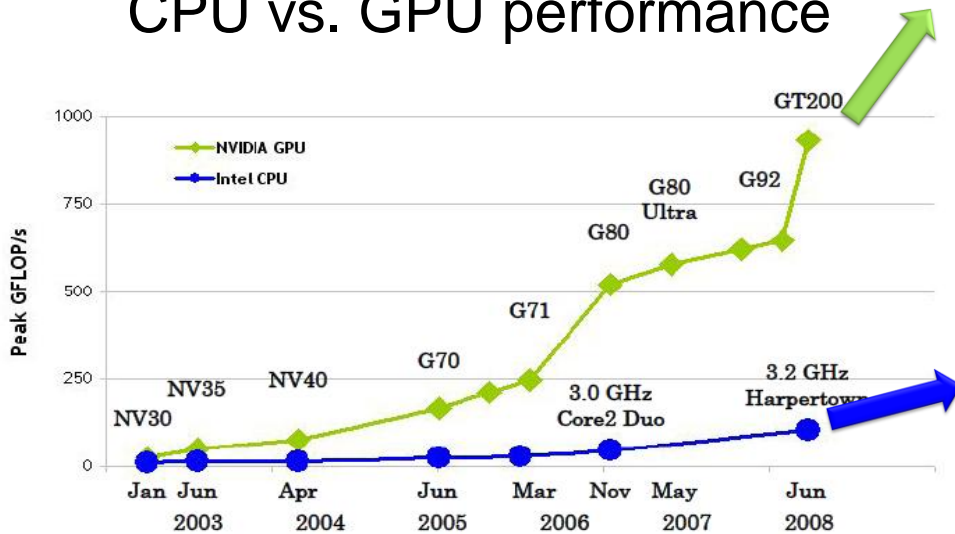# GPS software receiver running on a GPU – ongoing developments at NICT

Graphics processing unit(GPU)
a "perfect" parallel processor

Originally no scientific purposes!
Development mainly driven by game industry

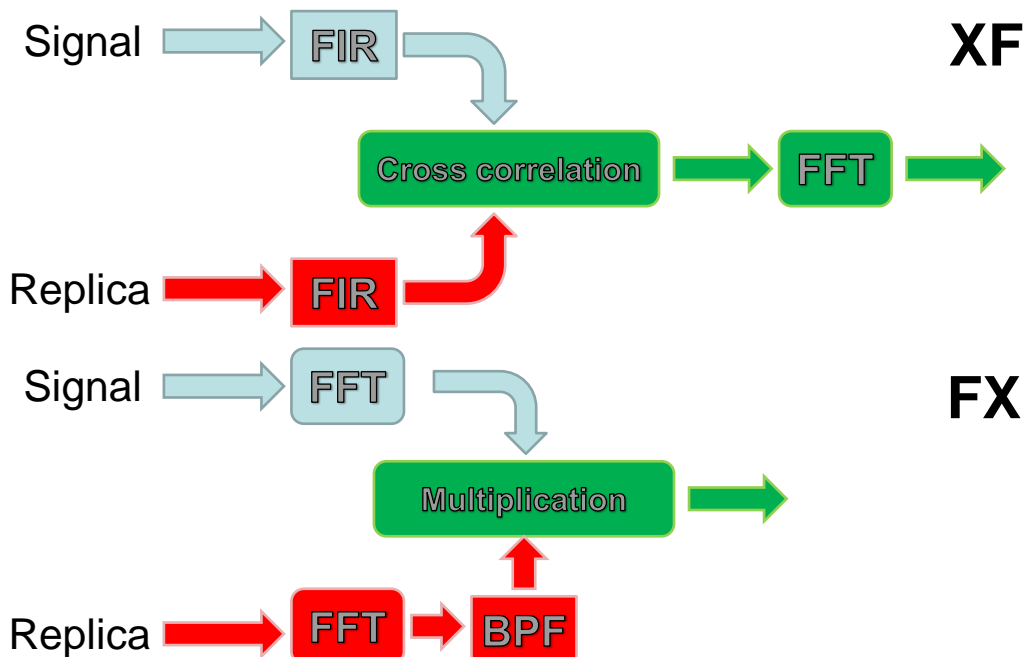# CPU vs. GPU performance

Porting a GNSS software radio on the GPU

- Card used for this study: NVIDIA GTX 280
  - Processor Cores   240
  - Processor Clock   1296 MHz
  - Memory   1GB GDDR3
- C-like coding environment, "Compute Unified Device Architecture (CUDA)"
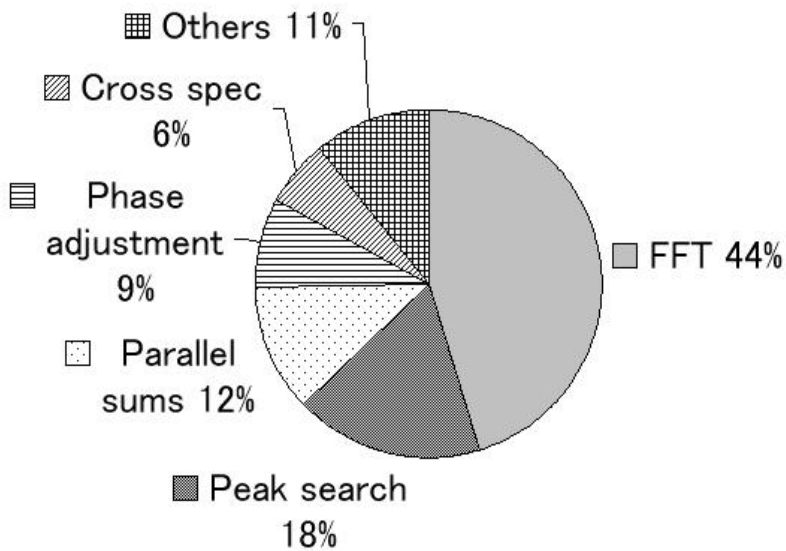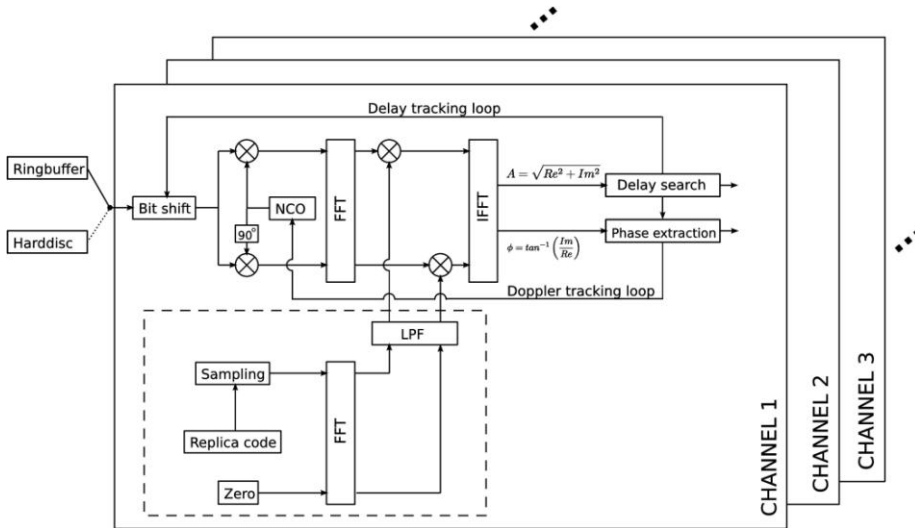- RF down-conversion and digitization done by hardware

Correlation Engine

- Purpose: Compute cross-spectrum from incoming and replica signal
- Hardware receivers usually have a few lags, early / prompt / late scheme
- Software receivers can compute a much finer / wider cross-correlation function, allows to solve multi-path issues, help tracking weaker signals, …
- Two choices:
  - XF: do cross-correlation, thereafter FFT
  - FX: FFT on signal and replica, multiply spectra
- XF can work with smaller lag space, but requires FIR filter

NiCT

Signal ⟹ FIR ⟹   **XF**

Cross correlation ➡ FFT ➡

Replica ➡ FIR ➡

Signal ⟹ FFT ⟹   **FX**

Multiplication ➡

Replica ➡ FFT ➡ BPF ➡

NiCT

The multi-channel SW receiver architecture

Results

<u>Real-time</u>

8 Msps
2009/03/25
6:06-18:06 UT

cut-off: 20 deg

RMS (delays)
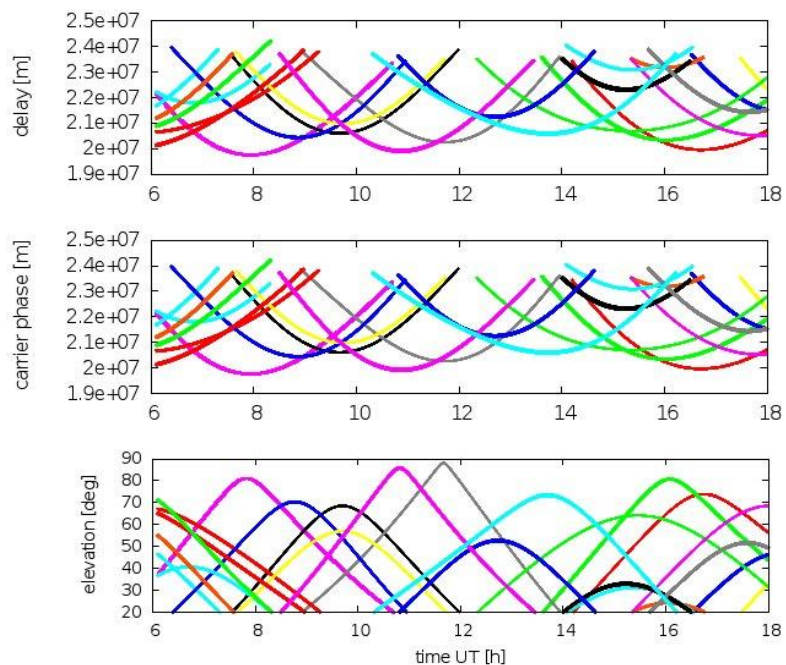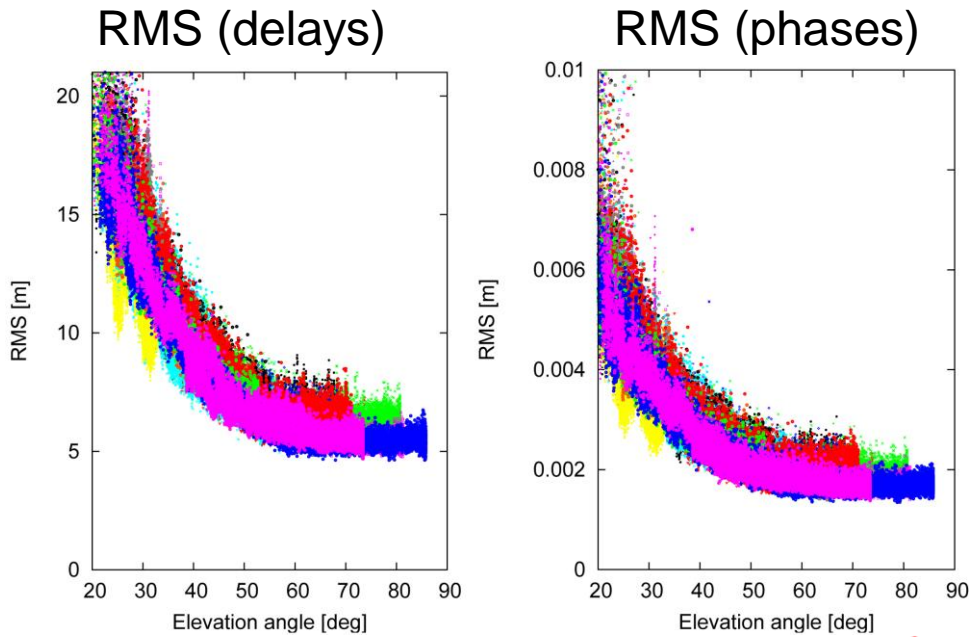
RMS (phases)
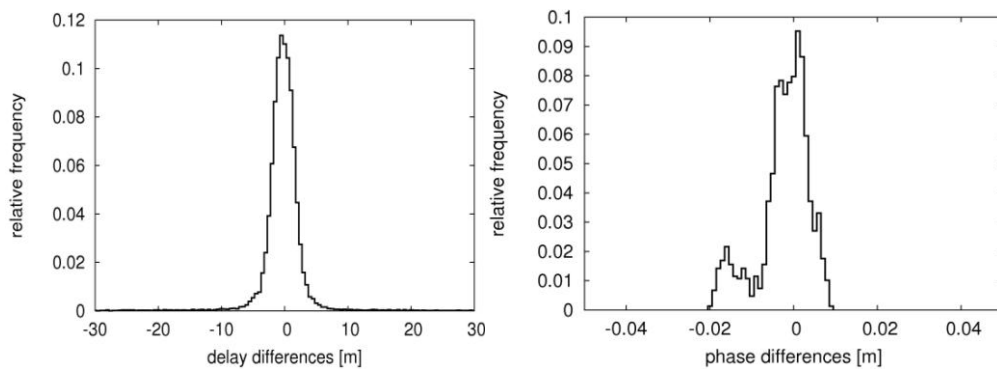

Comparison with HW receiver, which shares the same antenna

➢Differences within formal errors
➢phases show small systematic differences (drift of the hardware receiver)

Applications

- Open-loop tracking
- Tracking of weak signals
- Atmosphere/ionosphere studies
- Training and educational purposes

- **NICT's two-way satellite time-transfer, based on similar software radio is going to be ported to the GPU**

NiCT

GPS error sources

NiCT

Error sources

- Ephemeris/orbit quality $\rightarrow$ can be cancelled out by forming differences (see next talk)
- SV clock Parameter $\rightarrow$ can be cancelled out by forming differences (see next talk)
- Ionospheric Delay $\rightarrow$ measurements at two different frequencies allow to calculate first order ionosphere errors
- Tropospheric Delay $\rightarrow$ difficult to handle, estimate in post-processing
- Multipath $\rightarrow$ avoid !!!
- Code Tracking Noise

NiCT
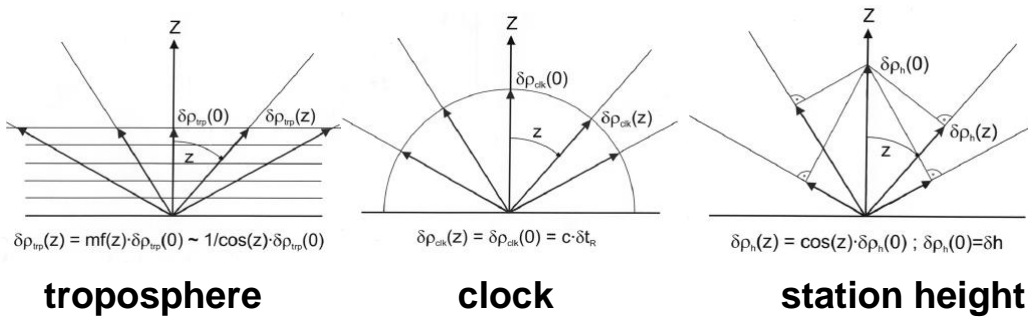
Usual approach

- Use "mapping function" M(z) which relates slant troposphere delays to zenith
- Model only zenith troposphere in dependence of time
- Thus quality of the mapping function defines capability to model low elevation troposphere errors
- M(z) models based on climatologic data or numerical weather prediction models

NiCT

Troposphere error
– coupling with height and clock

troposphere   **clock**   **station height**

$\delta\rho_{trp}(z) = mf(z)\cdot\delta\rho_{trp}(0) \sim 1/\cos(z)\cdot\delta\rho_{trp}(0)$ $\delta\rho_{clk}(z) = \delta\rho_{clk}(0) = c\cdot\delta t_R$ $\delta\rho_h(z) = \cos(z)\cdot\delta\rho_h(0)$; $\delta\rho_h(0)=\delta h$

→ **When clock parameters are estimated, significant correlations between station height and troposphere exist. Biases in the other two parameters can lead to wrong clock estimates**

NiCT

NICT's approach

- Direct 4D ray-tracing through numerical weather models
- Apply troposphere corrections on slant GPS observables
- Since weather models are not 100% perfect, estimate residual troposphere error with $1/\cos(z)$ mapping function

NiCT

NICT's approach (ctd.)

- Kashima ray-tracing service (KARATS) allows users to upload GPS observation files
- Ray-tracing carried out for each observable, corrections are applied and modified files sent back to the user
- KARATS is expected to be available to the public soon
- Currently post-processing mode, real-time mode under development

/NiCT

Spatial coverage
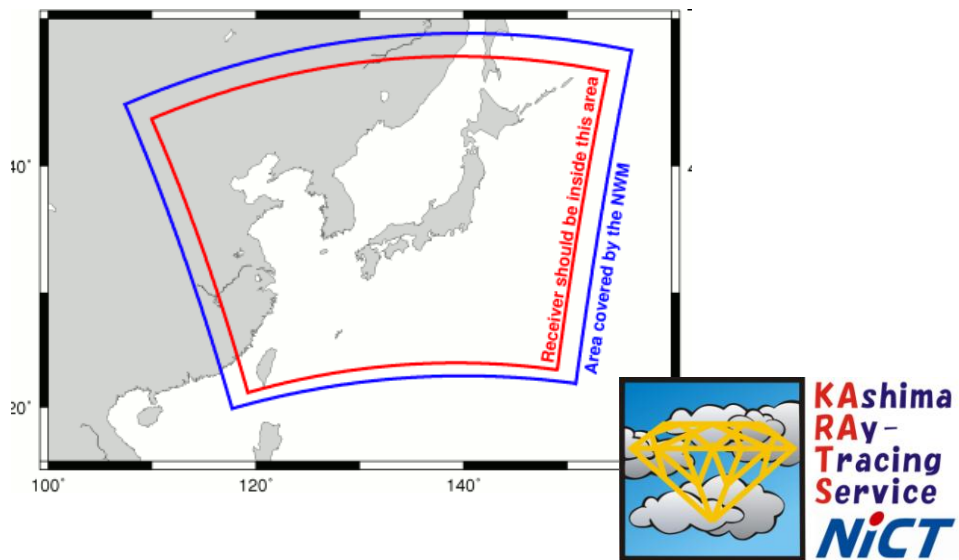
Thank you for your attention !

Global Positioning System (GPS)
- Part II, Time Transfer -

Space-Time Standard Group
New Generation Network Research Center
National Institute of Information and
Communications Technology (NICT), Japan

Why do we need a time transfer technique?

Do you want to know...
  - What is the time of my clock?
  - How accurate is my clock?
  - How does my UTC compare to the rest of the world?
....

Time transfer technique gives these solutions for you.
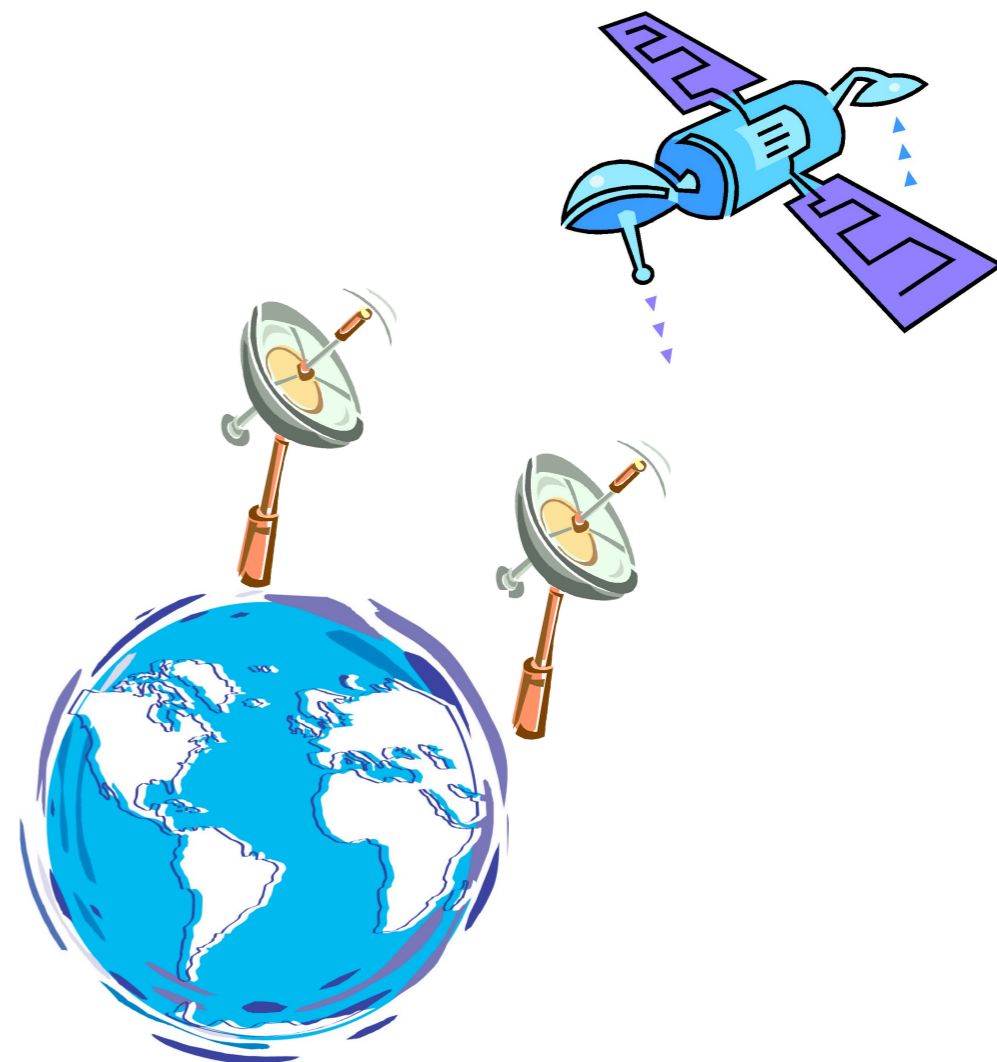
Time Transfer via a GPS Signal

Two stations receive the same GPS signal at the same time.

$$\tau_i^k = dt_i - dt^k$$

$$\tau_j^k = dt_j - dt^k$$

Subtraction of these two observations, cancels the satellite clock offset which is a common component in both observations.

$$\Delta\tau_{ij} = \left[dt_i - dt^k \right] - \left[dt_j - dt^k \right]$$
$$= dt_i - dt_j$$

This method is called *Common-View*

Output of Time Transfer Receiver, *CGGTTS* Format

```
PRN CL  MJD  STTIME TRKL ELV AZTH   REFSV      SRSV    REFGPS   SRGPS  DSG IOE ...
 25 FF 53367 005000  780 281   60  -821671      -9     +3944     -1   21 032 ...



PRN CL  MJD  STTIME TRKL ELV AZTH   REFSV      SRSV    REFGPS   SRGPS  DSG IOE ...
 25 FF 53367 005000  780 480 1213  -825805     -18      -189    -10    6 032 ...
```

Pick up data of two stations, and
find out the same entries of
      PRN, MJD, STTIME, TRKL
and, subtract two
      REFSV or REFGPS
values.

You can do common-view even if you don't know
multiplication and division!!!

Why is Common-View Easy?

Data file of time transfer receiver has this answer.

True measurements obtained by GPS receiver

$$\tau_i^k(t) = \underline{\rho_i^k(t, t - \tau_i^k) + I_i^k} + \underline{T_i^k} + \underline{[dt_i(t) - dt^k(t - \tau_i^k)] + e_i^k}$$

Compute with broadcast message

Compute with model

REFSV computed by the receiver

$$\tau_i'^k(t) = dt_i(t) - dt^k(t - \tau_i^k) + e_i^k + \underline{\varepsilon_i^k}$$

Model error

Where,

$$\rho_i^k = \frac{\left\| \mathbf{r}^k(t - \tau_i^k) - \mathbf{r}_i(t) \right\|}{C}$$

How to make time transfer data?

Specified by CCTF Group on GNSS Time Transfer Standards (CGGTTS).

i: GPS short-term observations:
  - The pseudo-range data are measurements of a laboratory reference 1 pps signal against the 1 pps signal received from the satellite.
  - Each pseudo-range measurement includes a value of the received signal integrated over a time. This integration time should be 1 second or less.
  - One given pseudo range data is characterized by its date corresponding to the date of the laboratory 1 pps.
  - The start time of a track is thus the date of the first pseudo-range data, which corresponds, in reality, to a received signal integrated over a time interval ending on this date.

ii: Least-squares quadratic fits are applied on successive and non-overlapping sets of 15 pseudo-range measurements. The quadratic fit results are estimated at the date corresponding to the midpoint of each set.

iii: Corrections listed below are evaluated at the dates corresponding the results of ii) and applied to these results:
- geometric delay from ground-antenna coordinates and broadcast ephemerides.
- ionospheric delay from broadcast parameters.
- tropospheric delay.
- Sagnac correction.
- periodic relativistic correction due to the eccentricity of the GPS satellite's orbit.
- L_1 - L_2 broadcast correction.
- receiver delay.
- antenna and local-clock cable delays.

iv: Clock corrections for access to GPS time, as derived from a 2nd-order polynomial whose coefficients are contained in the GPS message, are evaluated at the dates corresponding to the results of ii) and applied to the results of iii).

v: The nominal track length corresponds to the recording of 780 short-term measurements.

vi: At the end of the track, a number of least-squares linear fits are performed. The results of these linear fits are estimated at the date corresponding to the middle of the actual track.

CGGTTS (or CCTF) data format:

```
PRN CL  MJD   STTIME TRKL ELV AZTH   REFSV       SRSV      REFGPS     SRGPS  DSG IOE MDTR SMDT MDIO SMDI MSIO SMSI ISG CK
              hhmmss  s   .1dg .1dg   .1ns       .1ps/s     .1ns      .1ps/s .1ns     .1ns.1ps/s.1ns.1ps/s.1ns.1ps/s.1ns
  4 FF 53371 000200  780 499 2183  -4750412    +205        +142        +7   16 900  103  +10   33   +4  -25  +15  25 03
```

PRN,   the satellite vehicle PRN number

CL,   the hexadecimal number that corresponds to the Common View class of the track

MJD,   the five digit Modified Julian Date of the start of the track

STTIME,   hour, minute, and second (in UTC) of the start of the track

TRKL,   the track length in seconds (a full track is 780 seconds)

ELV,   the elevation of the satellite at the midpoint of the track

AZTH,   the azimuth of the satellite at the midpoint of the track

REFSV,   the time difference (measured in .1 nanosecond) between the laboratory reference clock and satellite time, referred to the midpoint of the pass via a linear fit

SRSV,   the slope determined via the linear fit to produce REFSV (measured in .1 picosecond per second)

REFGPS,   the time difference (measured in .1 nanosecond) between the laboratory reference clock and GPS system time, referred to the midpoint of the pass via a linear fit

SRGPS,   the slope determined via the linear fit to produce REFGPS (measured in .1 picosecond per second)

DSG,   the root mean square of the residuals of the linear fit used to produce REFGPS

IOE,   the index of ephemeris, a three digit decimal code indicating the ephemeris used for computations

MDTR,   the modeled tropospheric delay (measured in .1 nanosecond) referred to the midpoint of the pass via a linear fit

SMDT,   the slope determined via the linear fit to produce MDTR (measured in .1 picosecond per second)

MDIO,   the modeled ionospheric delay (measured in .1 nanosecond) referred to the midpoint of the pass via a linear fit

SMDI,   the slope determined via the linear fit to produce MDIO (measured in .1 picosecond per second)

MSIO,   the measured ionospheric delay (measured in .1 nanosecond) referred to the midpoint of the pass via a linear fit, 9999 indicates no data available

SMSI,   the slope determined via the linear fit to produce MSIO (measured in .1 picosecond per second)

ISG,   the root mean square of the residuals of the linear fit used to produce MSIO

CK,   the data line check sum in hexadecimal format, computed as the sum of the ASCII values of the preceding 115 columns, modulo 256

* Optional data may be presented beyond the check sum column, and is not included in the CK value

Which is better, REFSV or REFGPS?

Some receivers have a software problem;

PRN	CL	MJD	STTIME	TRKL	ELV	AZTH	REFSV	SRSV	REFGPS	SRGPS	DSG	IOE	...
4	FF	53395	120200	780	189	1469	-4318737	220	-306	428	17	16	...

PRN	CL	MJD	STTIME	TRKL	ELV	AZTH	REFSV	SRSV	REFGPS	SRGPS	DSG	IOE	...
4	FF	53395	120200	780	187	1470	-4318567	+181	-200	-27	17	016	...

Satellite clock offset = REFSV - REFGPS:
  receiver #1 = -431873.7 ns - -30.6 ns = -431843.1 ns
  receiver #2 = -431856.7 ns - -20.0 ns = -431836.7 ns

➡ **6.4 ns different???**

Note: you should take care of the IOE parameter.
If IOE is different, satellite clock offset or orbit error would remain.

Measurement noise.
 - Multi-path.
 - Variation of signal-to-noise ratio.
 - Temperature variation (especially outside equipment).
    Cannot be eliminated on the analysis stage.

Correction model error (single CV with 5,000 km BL)
 - Ionospheric delay (EL > 30), 15 ns.
 - Satellite coordinates, 8 ns.
 - Tropospheric delay (EL > 30), 2 ns.
 - Antenna coordinates, ? ns.
    Can improve with the accurate correction model.

Several Approaches of GPS Time Transfer

Precision (vertical axis, from coarse to fine)

Analysis (horizontal axis, simple ←→ complicate)

Usage of carrier phase

MC or P3/AV

Corrected
MC or P3/CV

P3/CV

MC/CV

AV: all-in-view
CV: common-view
MC: multi-channel
P3: dual frequency
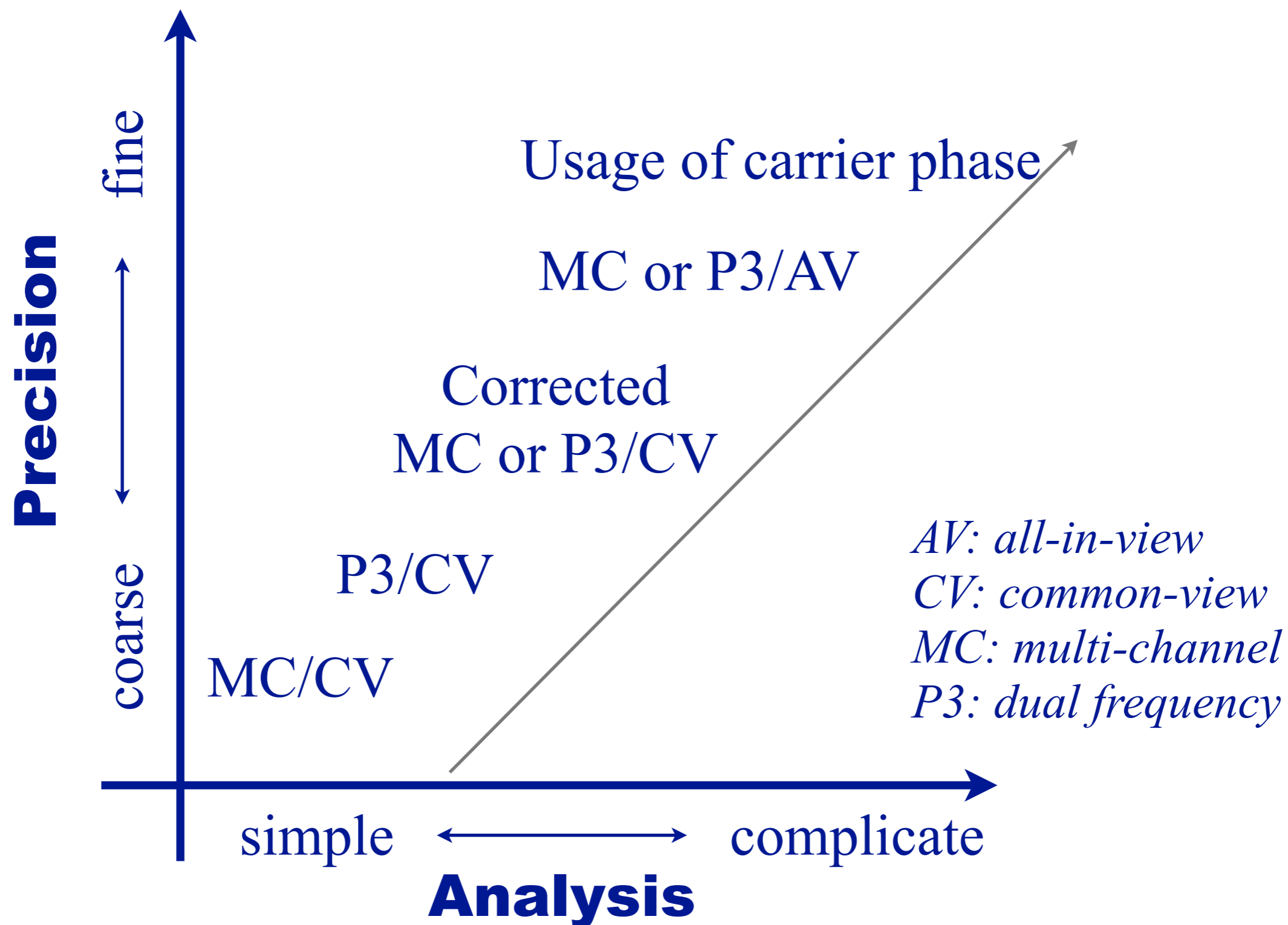
GPS Time Transfer Receivers

- Single-channel, single-frequency receiver (*CV, AV*)
  - Classical (and obsolete) time transfer receiver.
  - Requires BIPM GPS tracking schedule for the common-view.

- Multi-channel, single-frequency receiver (*CV, AV*)
  - Can receive signals from more than one satellite at the same time.
  - Improvement time transfer precision due to the averaging effect.
  - Widespread receiver in the timing community.

- Multi-channel, dual-frequency receiver (*P3CV/AV, CP*)
  - Can measure ionospheric delay with dual-frequency measurements.
  - Most popular receiver now.
  - Geodetic type is applicable to carrier phase time transfer.

Usage of Geodetic Receiver for Time Transfer

Ionosphere delay is the largest error source of GPS time transfer. However, because the ionosphere is a dispersive medium for radio waves, dual frequency receiver eliminates this delay with linear combination of L1 and L2 observations.

Dr. Defraigne of ORB, Belgium proposed to use the geodetic receiver for time transfer purpose (TAIP3).

$$P_3 = \frac{1}{f_1^2 - f_2^2}(f_1^2 P_1 - f_2^2 P_2)$$

Where,

$f_1 = 154 \times 10.23$ MHz

$f_2 = 120 \times 10.23$ MHz

Correction models of Broadcast Message

Because time transfer receivers output CGGTTS data in realtime, there is a limitation of utilizable correction models.

Broadcast orbits.
- Six Keplerian orbit parameters, rate of I, RA, and harmonic correction terms.
- Reference frame: antenna phase center of WGS-84.
- Clock offset: quadratic fitting polynomial parameters.
- Update period: ~ 2 hours.
- Accuracy: ~ 1 m.

Ionosphere correction model (Klobuchar model).
- Global model with only 2 x 3 parameters.
- Three amplitude coefficients of the vertical delays, and three period coefficients, which can be obtained from navigation message.

International GNSS Service

The IGS global system of satellite tracking stations, data centers, and analysis centers puts high-quality GNSS data and data products on line in near real time to meet the objectives of a wide range of scientific and engineering applications and studies.

Available products;
- GPS satellite ephemerides.
- Glonass satellite ephemerides.
- Geocentric coordinates
    of IGS tracking stations.
- Earth rotation parameters.
- Atmospheric parameters.
  - tropospheric zenith path delay.
  - ionospheric TEC grid (GIM).

GMT 2009 Oct 18 16:46:49
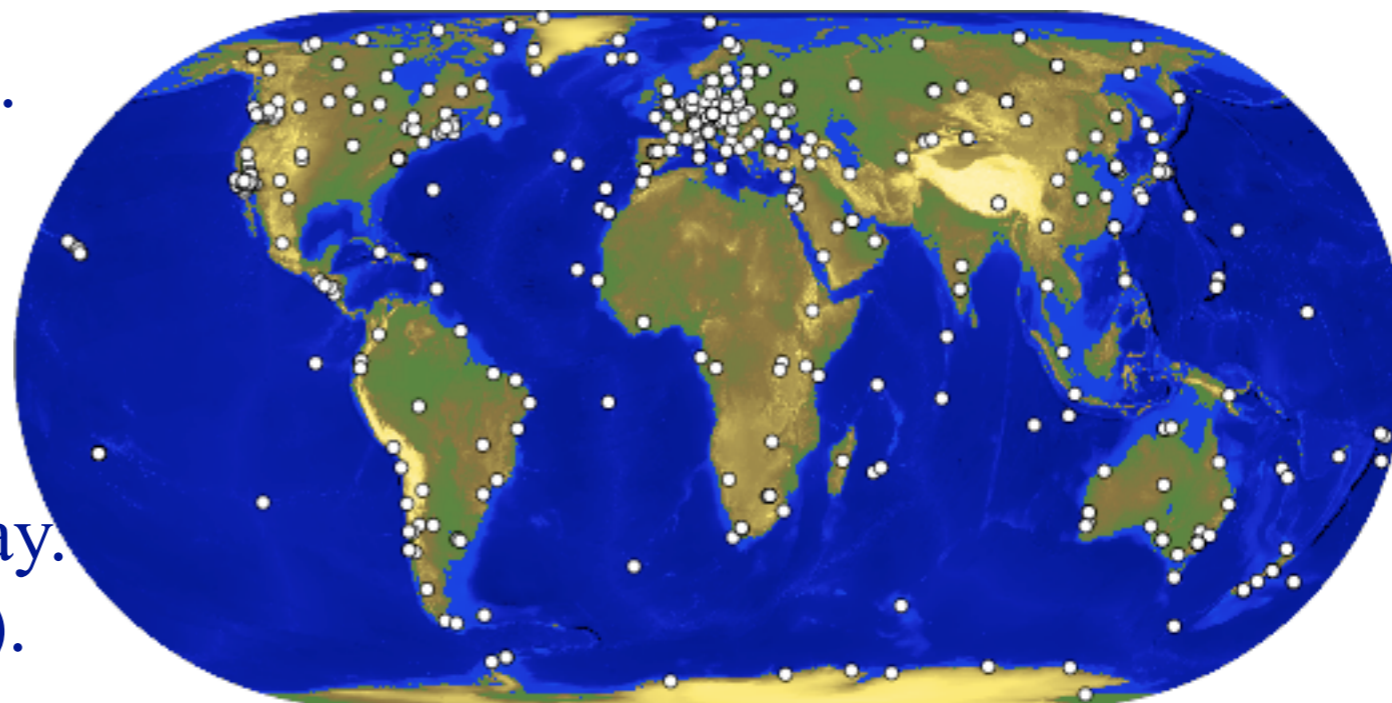
IGS Satellite Ephemerides

GPS satellite orbits.
- A set of position vectors with respect to IGS05 (equivalent to ITRF2005).
- Time interval is 15 min, interpolation is required.
- Satellite position is center of mass,
   correction of antenna phase center is also required.
- Three types: ultra-rapid (real-time ~ 3h), rapid(17h), final(~13d).
      * rapid orbit is sufficient for the time transfer purpose.
- Accuracy: 3 cm ~ 5 cm (ultra-rapid), ~ 2.5 cm (rapid, final)

GPS satellite clock offset.
- Reference frame is IGS time scale (not GPS Time).
- Time interval is 5 min, interpolation is required.
      * time interval of ultra-rapid is 15 min.
- Accuracy: 150 ps ~ 3 ns (ultra-rapid), 75 ps (rapid, final)

Earth Fixed and Inertial Frame

Because a station on the Earth moves with time varying rotation, the signal traveling time between satellite and receiver has to be computed within the inertial reference frame.

move
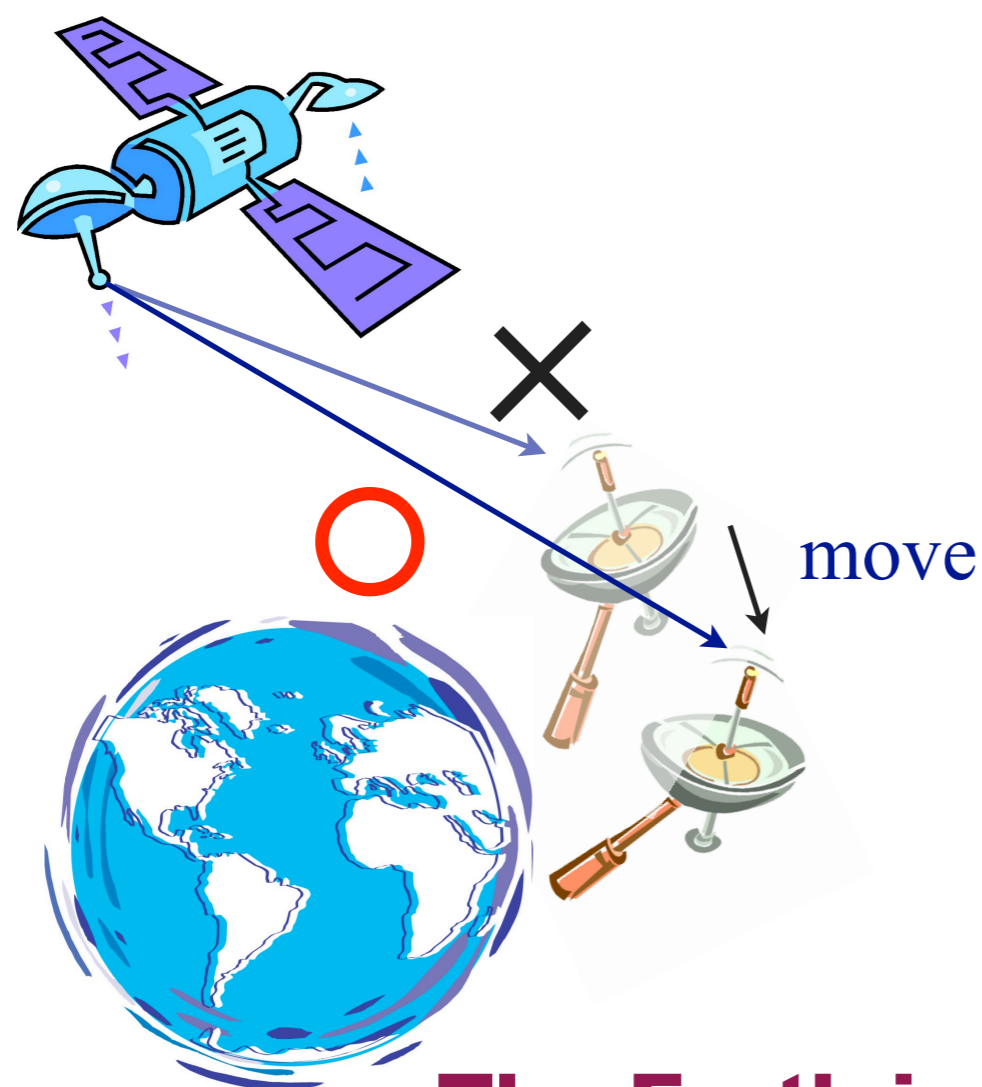
$$\begin{bmatrix} X_{TRF} \\ Y_{TRF} \\ Z_{TRF} \end{bmatrix} = \mathbf{PNSW}_{3x3} \begin{bmatrix} X_{CRF} \\ Y_{CRF} \\ Z_{CRF} \end{bmatrix}$$

Where,

   P, Precession

   N, Nutation

   S, Earth orientation

   W, Polar motion

The Earth is rotating!

Satellite Antenna Offsets

IGS orbits and clock offsets refer to the satellite center of mass, however, the measurements are made to antenna phase center.
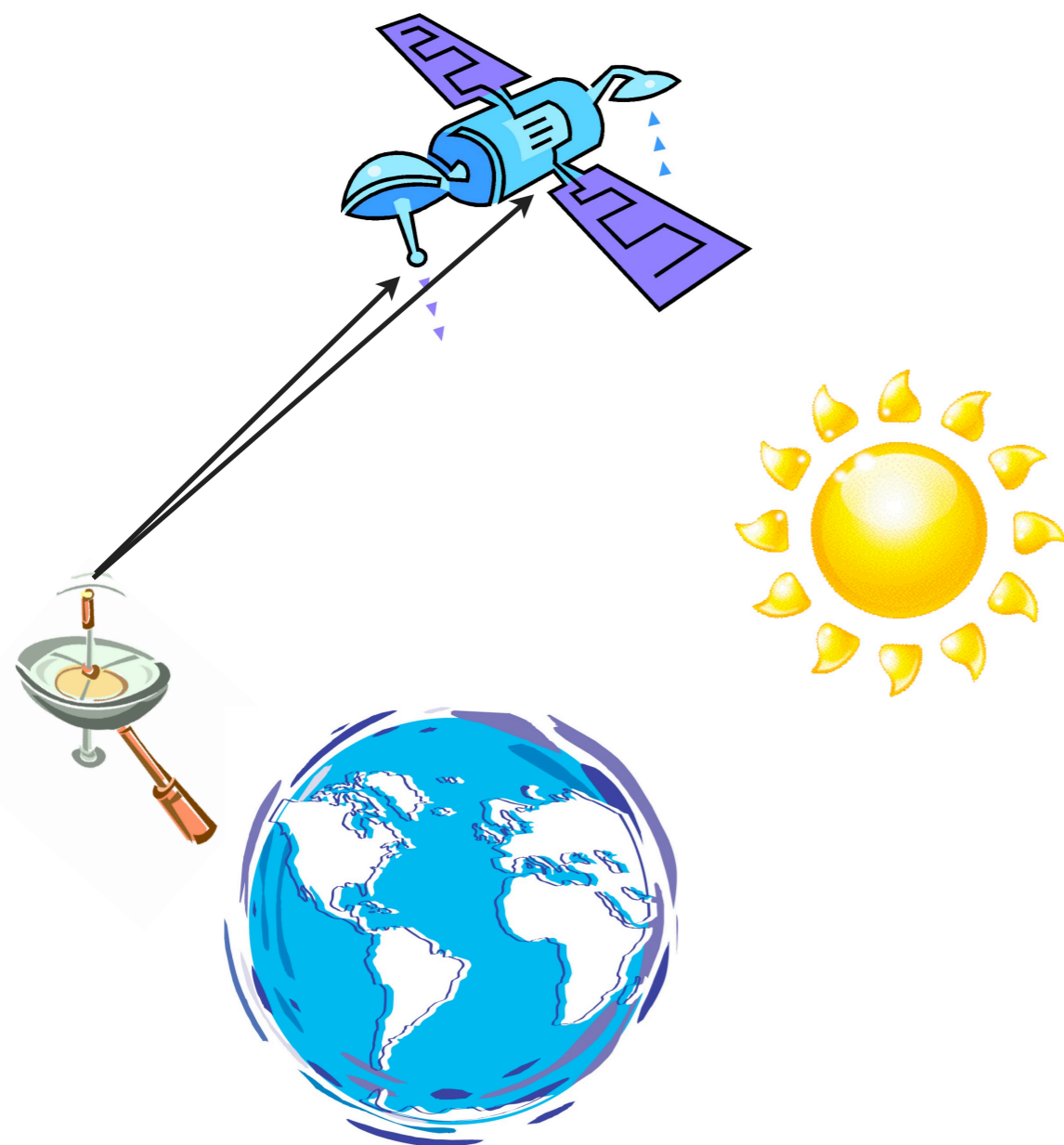
Correction of antenna phase center is provided with satellite body fixed (SBF) coordinates. However, range between satellite and receiver is computed with inertial reference frame. We need to convert from SBF to inertial frame.

Direction of satellite is determined by positions of Earth and Sun. Therefore,
1. compute sun position in the space.
2. compute direction of satellite.
    SBF to inertial frame.
3. compute position of antenna phase center in the space.

If you only have a single-frequency receiver, do not be pessimistic. You can use IGS TEC map, and can get the similar precision as if you use the P3 observations.

- TECs of 2 hour, 5 deg x 2.5 deg grid.
- Single layer model at height 450 km.
- Provided with IONEX file format.
- Rapid and final products.
- Accuracy of rapid products is
    2 - 9 TECU.

Sat.

Ionospheric pierce point

Rx

Sub-ionospheric point

Single layer model
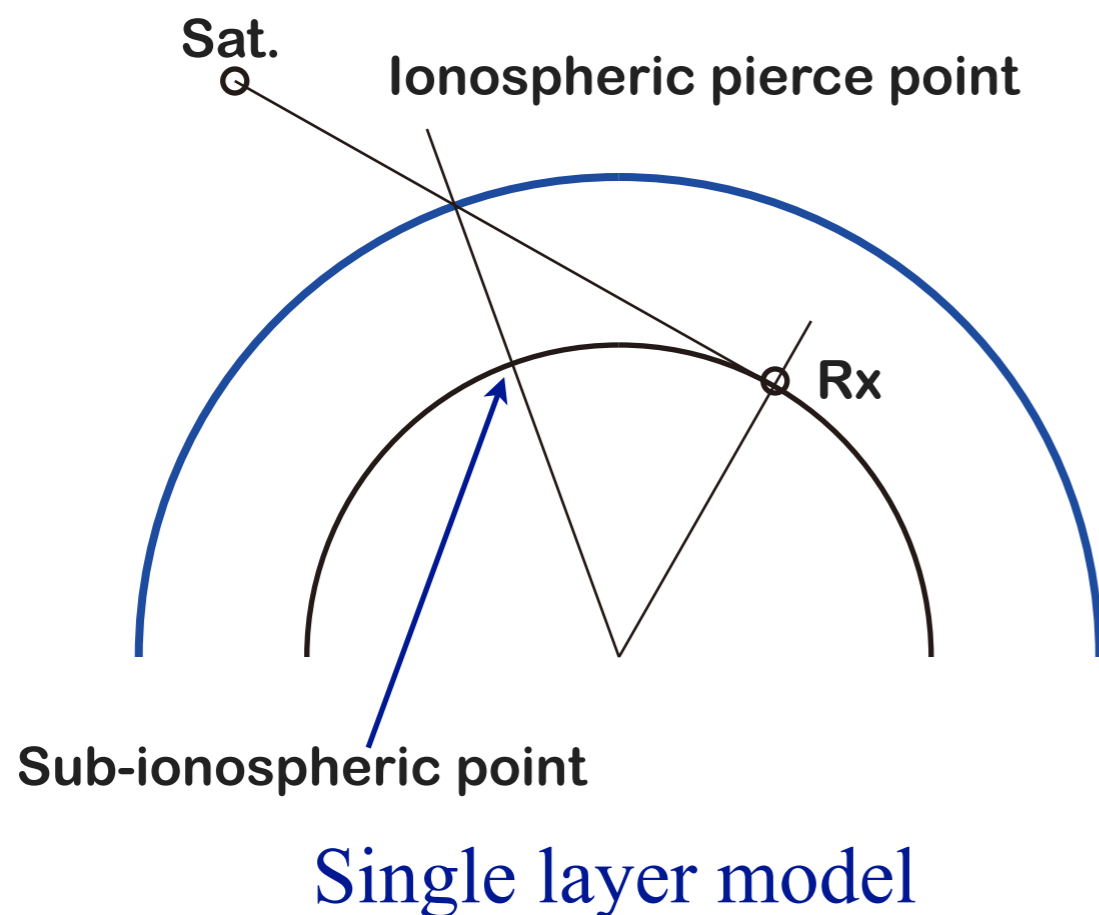
Is P3 always better than GIM?

Observation noise of P3 is 3 times bigger than it of P1. If your measurement environment is suffering from:
   - You have a lot of multi-path.
   - You are using code-less receiver.
   - Location of geomagnetic latitude is mid-latitude.
perhaps GIM is better than P3 under the above environment.

Code-less receiver.
   Since P-code is not a civil code, some receivers do not use the replica code in cross-correlation process. In most cases, P-code's noise of such receivers poorer than noise of C/A code.
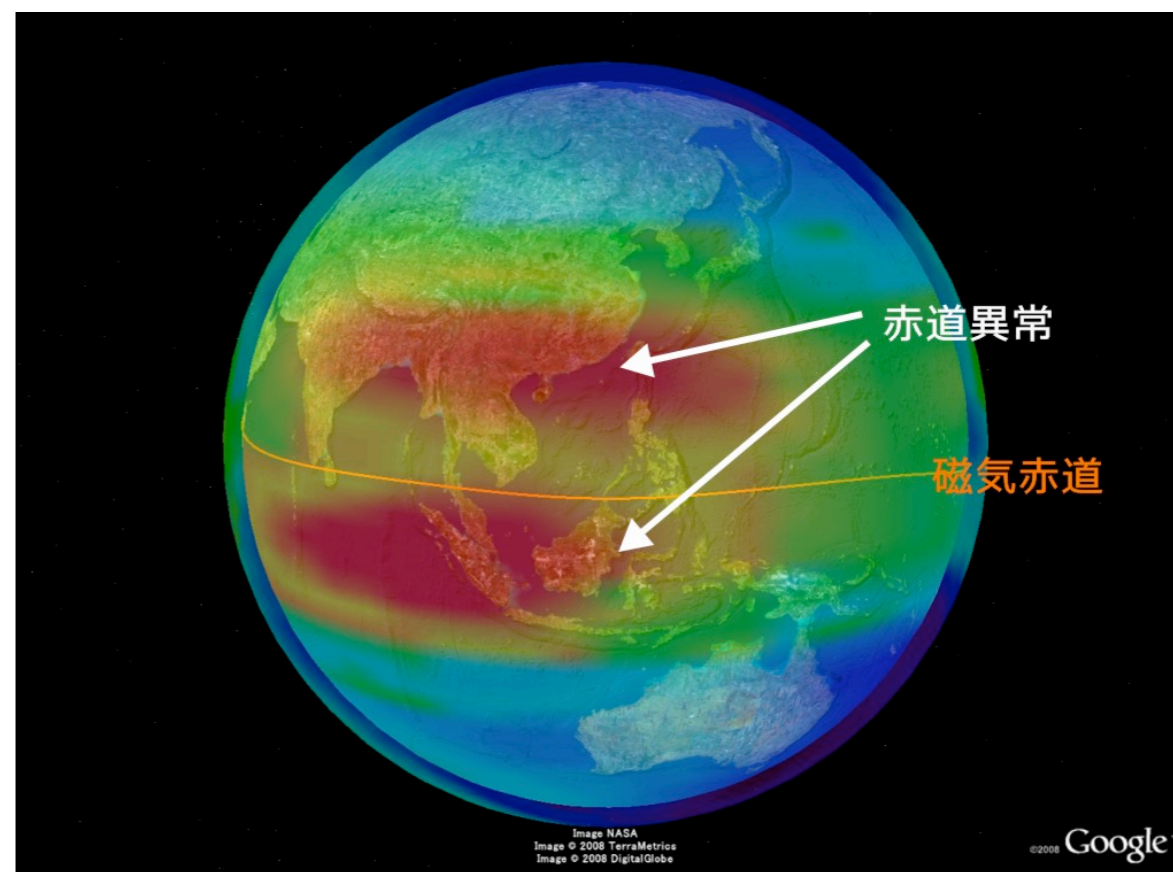
Try and choose the better.

赤道異常

磁気赤道

Image NASA
Image © 2008 TerraMetrics
Image © 2008 DigitalGlobe

©2008 Google

Provided by Dr. M. Nakamura, NICT.

Limitation of Common-View

For long baselines:
- Decrease of the number of common satellites observed by the stations.
- The elevation angle of observed common satellites becomes lower.
- The error of propagation delay model cannot be canceled out.
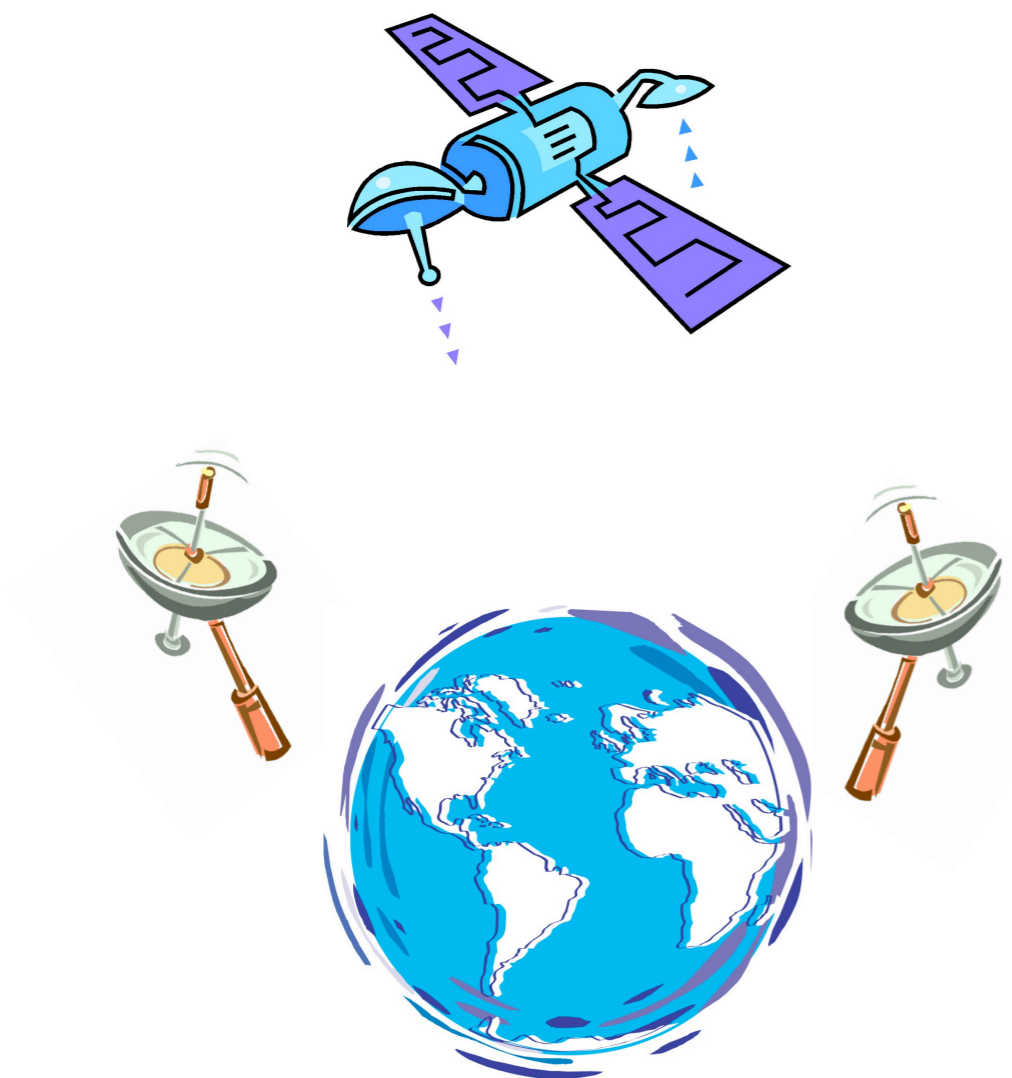
You should use *All-in-View* when you want to compare with very distinct station.

GPS All-in-View

BIPM has been using All-in-View for TAI GPS link since Sep. 2006 (Circular T No. 225).

Characteristics of all-in-view.
- Can use all satellites in the view.
- Baseline independent.
- Reduce the systematic error due to the antenna position error.
- Requires rigorous delay correction models.
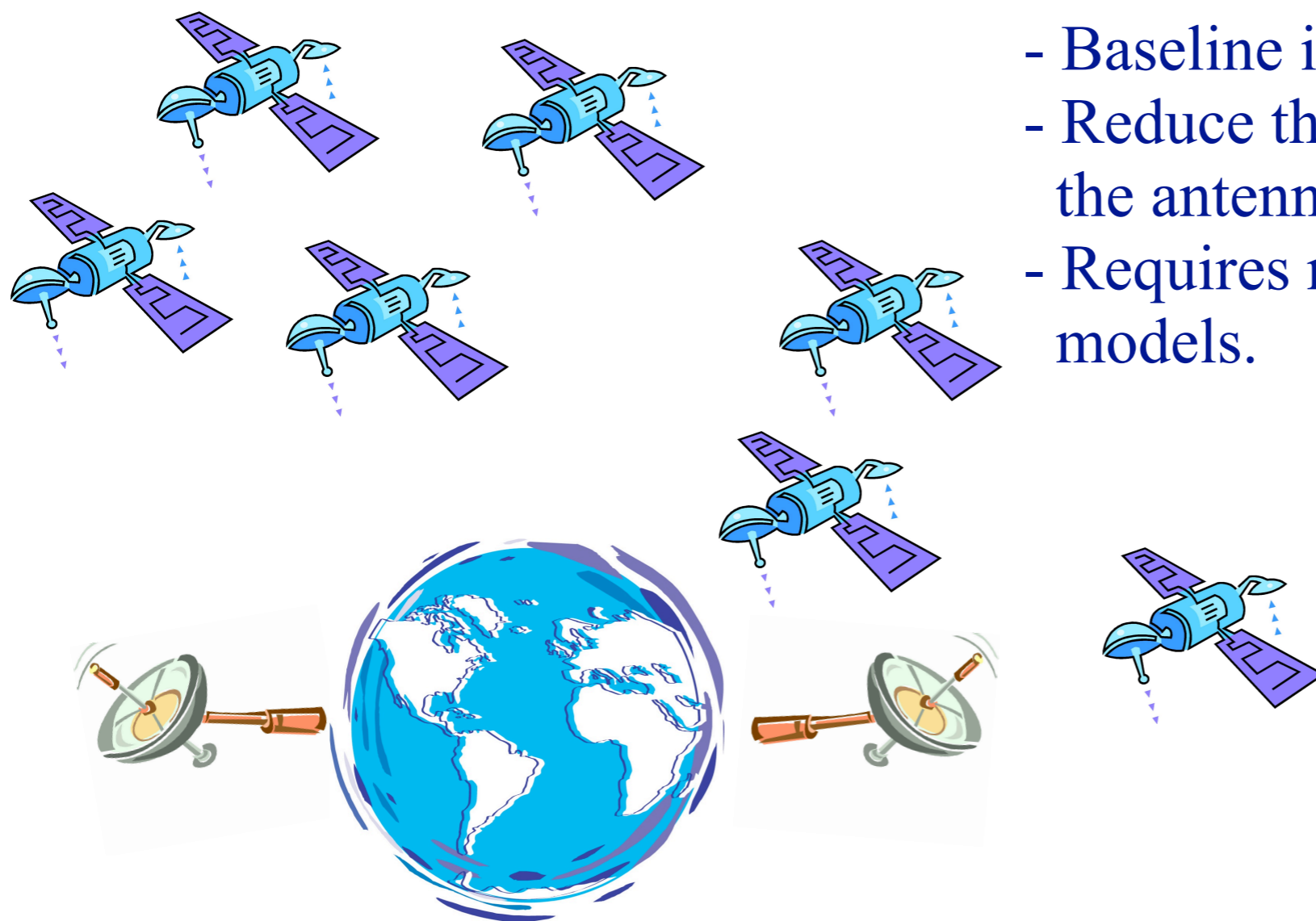
Case Studies

- Stations: NICT, TL, NIST, USNO
- Receiver: all station use ASHTECH Z-XII Metronome
- Period: April 1st to June 30 in 2009
- Comparison: six cases.
  - Multi-channel and P3 common-view
    with raw CGGTTS data.
  - Multi-channel common-view with IGS GIM/EPH.
  - P3 common-view with IGS EPH.
  - Multi-channel all-in-view with IGS GIM/EPH.
  - P3 all-in-view with IGS EPH.

Case #1, Multi-Channel Common-View
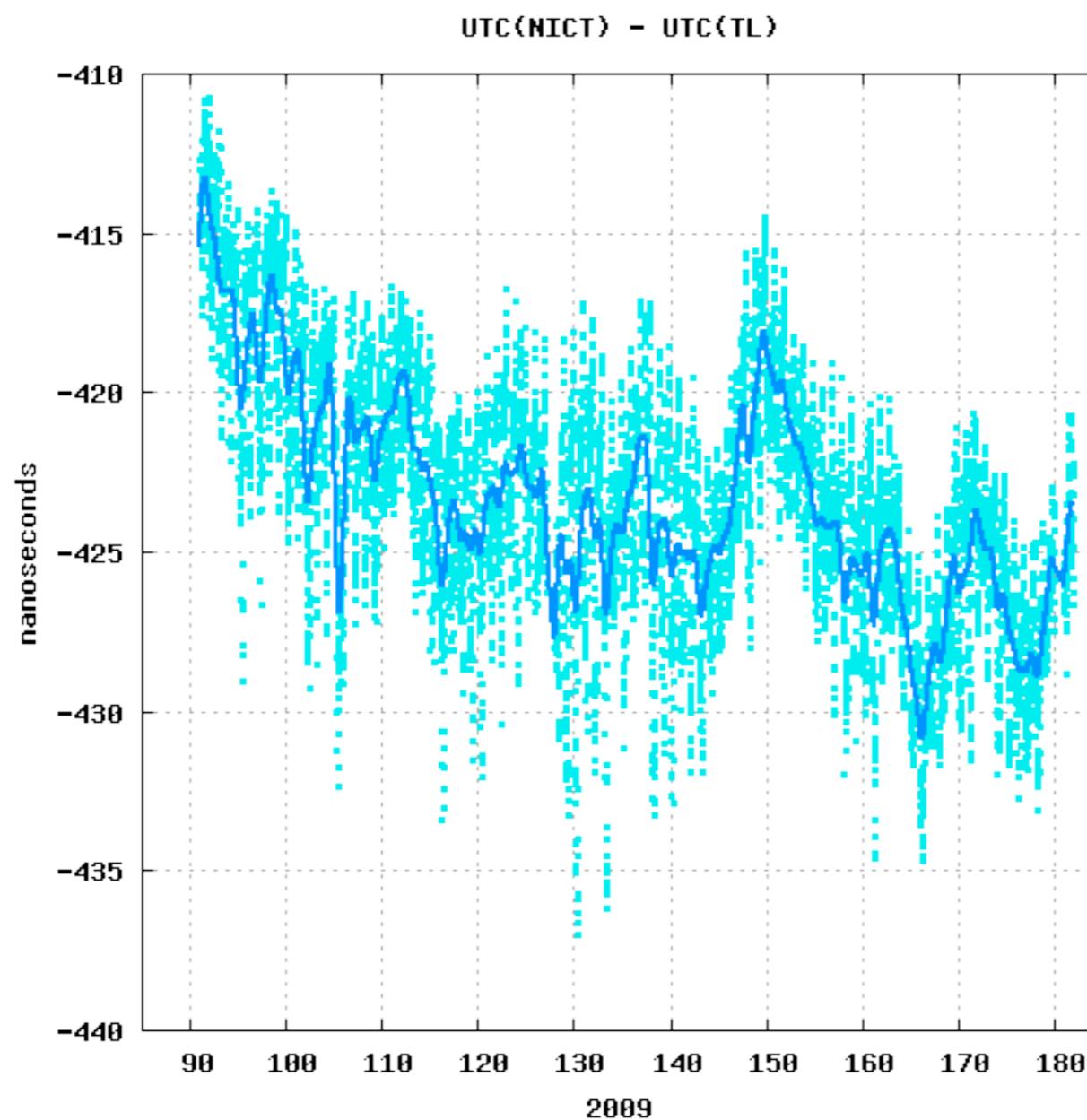
Post-Fit RMS: 2.366 ns

Case #2, P3 Common-View

Uncorrected MC/CV
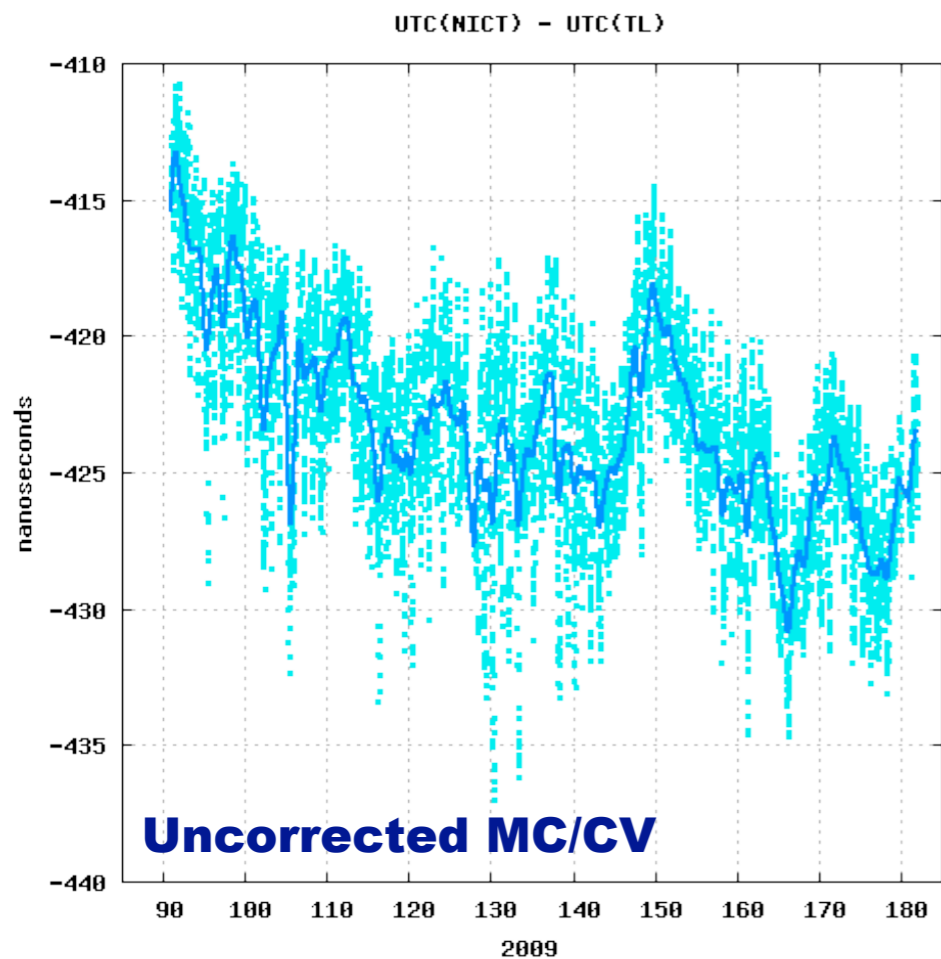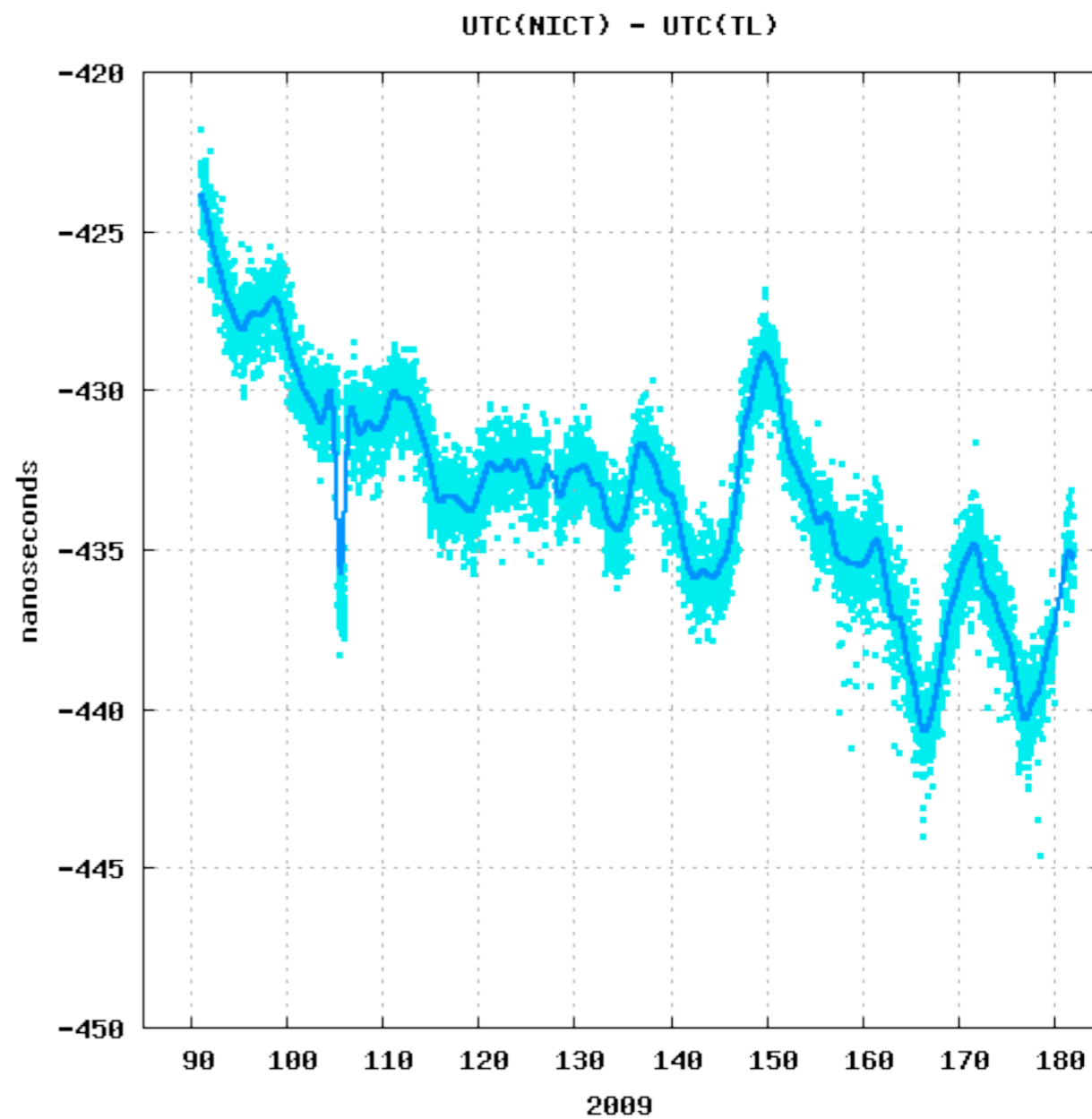
Post-Fit RMS: 2.366 ns

Post-Fit RMS: 0.829 ns

Case #3, MC CV with Corrected CGGTTS
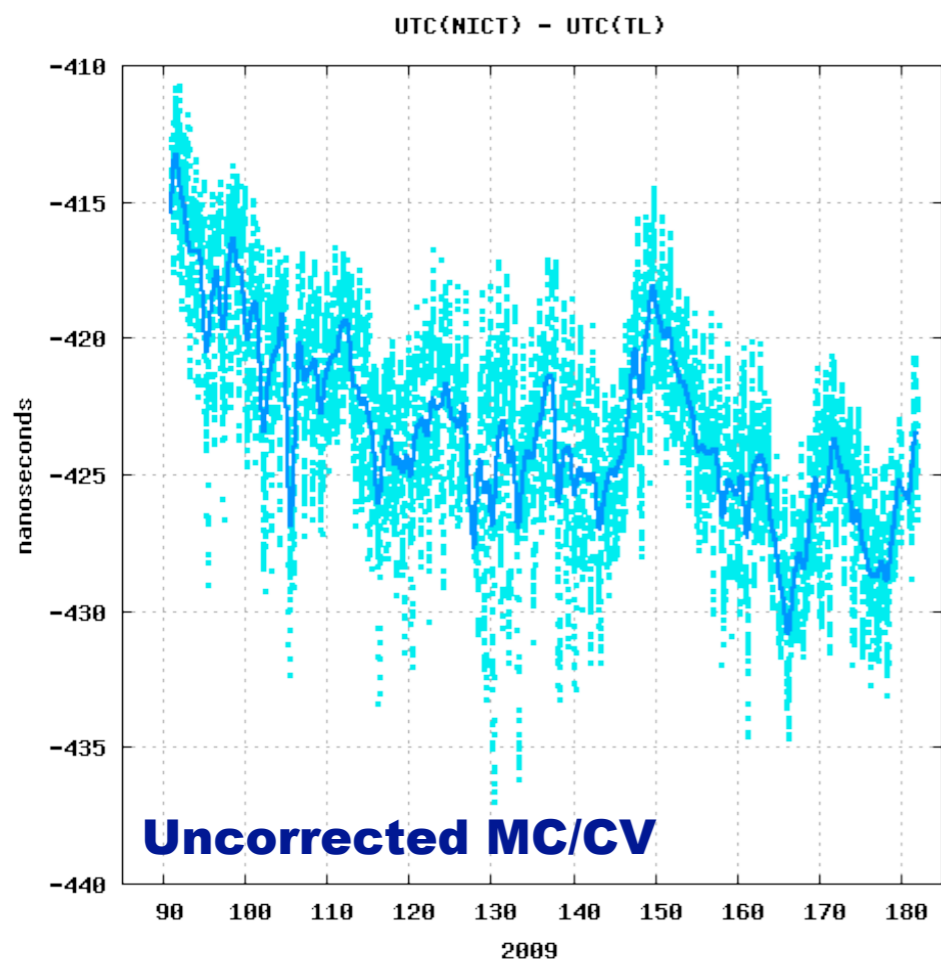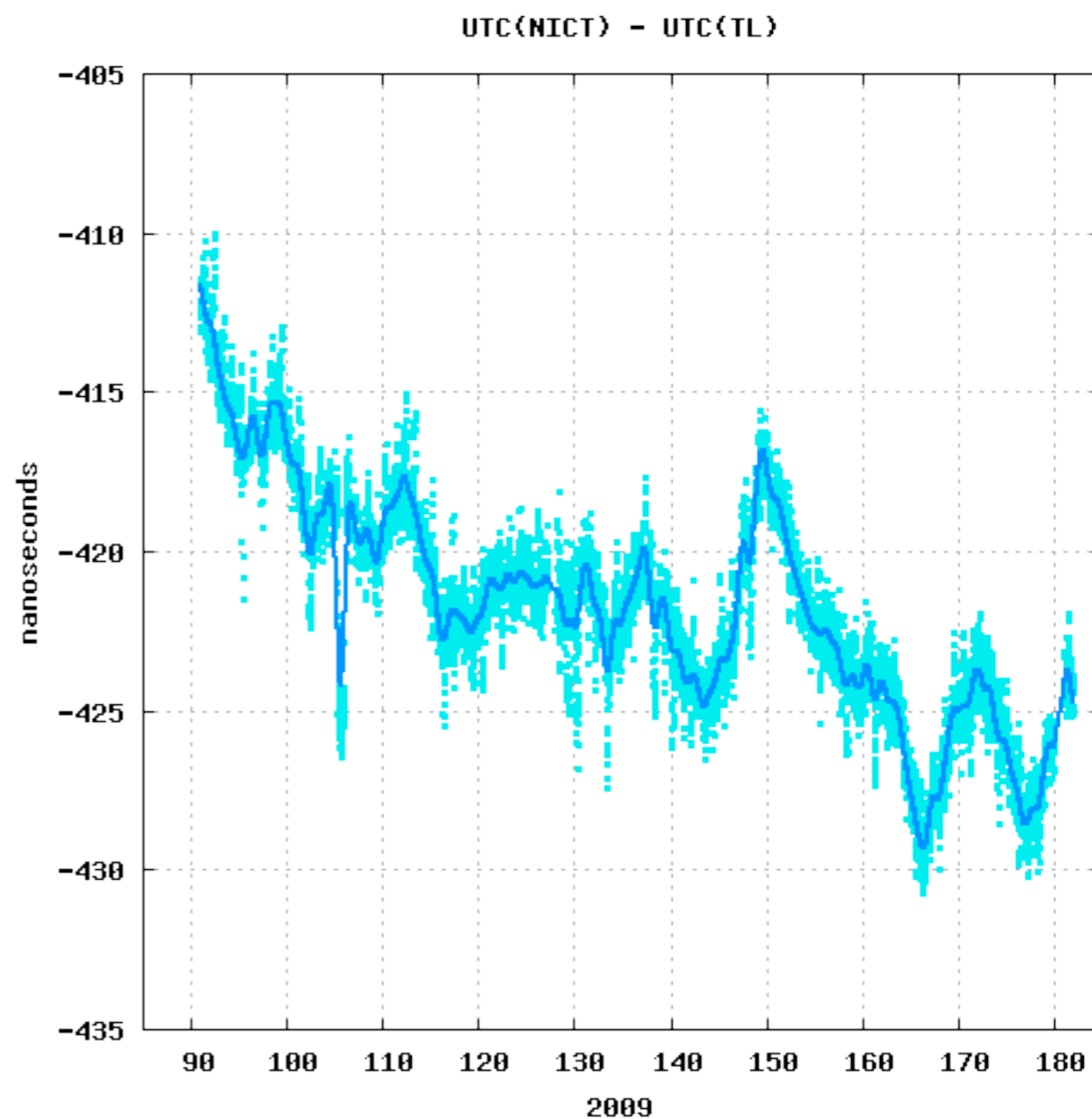
Case #4, P3 CV with Corrected CGGTTS

Uncorrected P3/CV
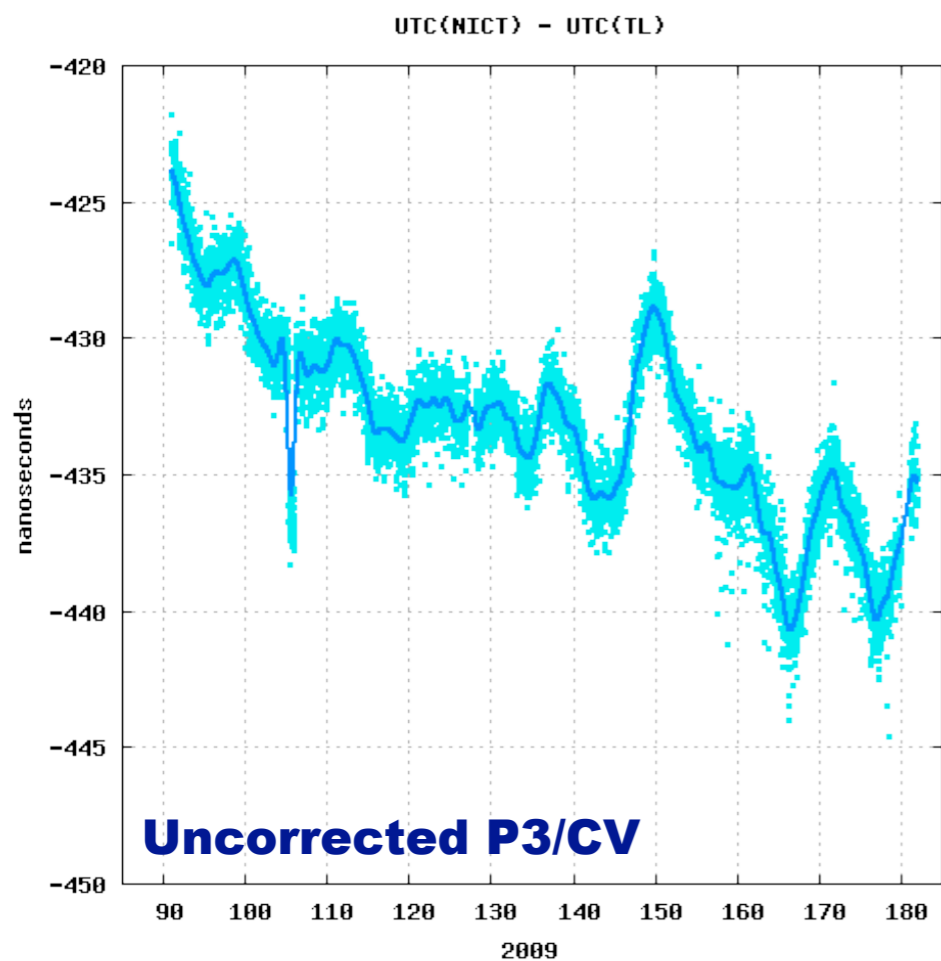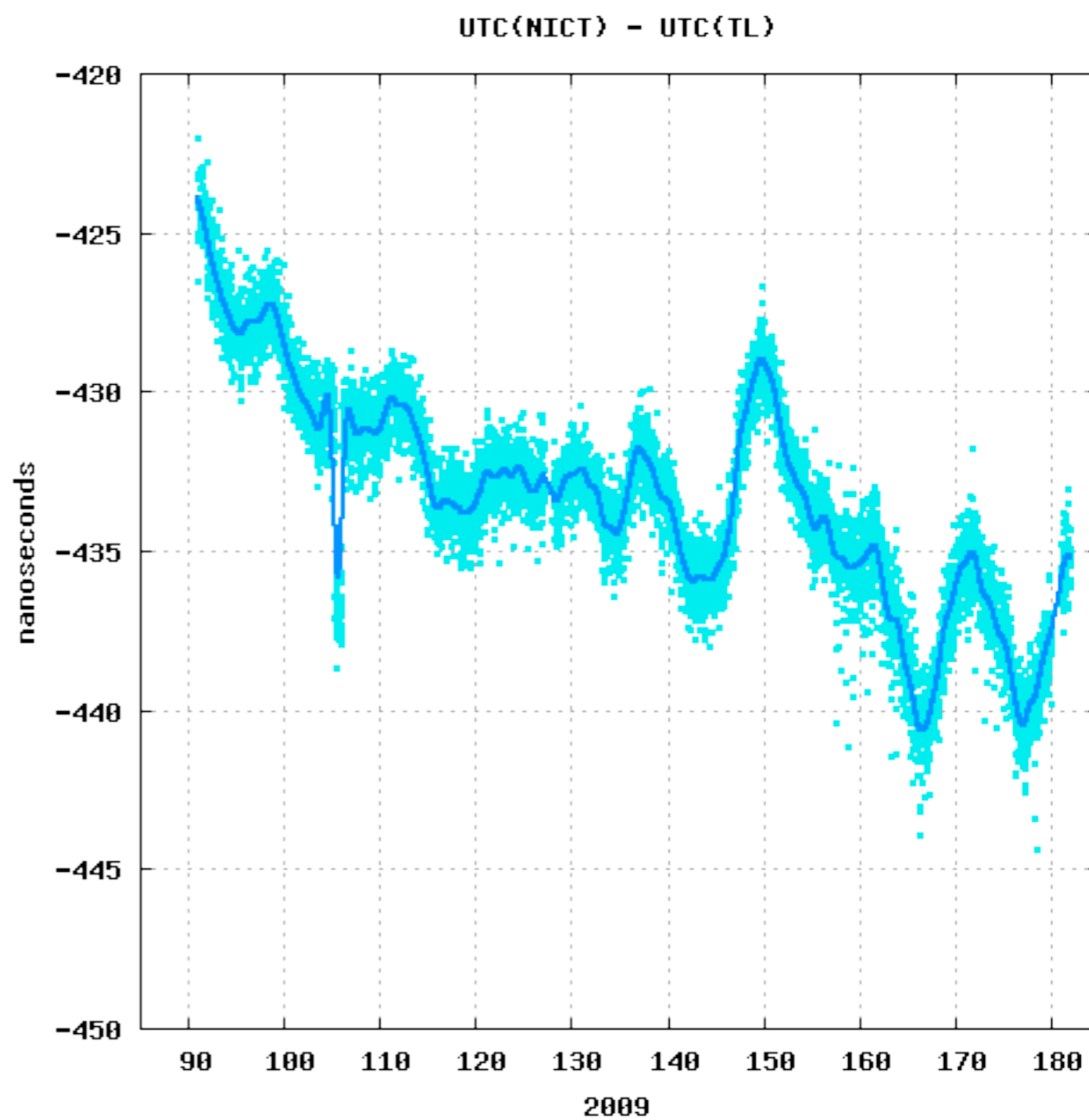
Post-Fit RMS: 0.829 ns

Post-Fit RMS: 0.814 ns

Case #5, Multi-Channel All-in-View

Uncorrected MC/CV
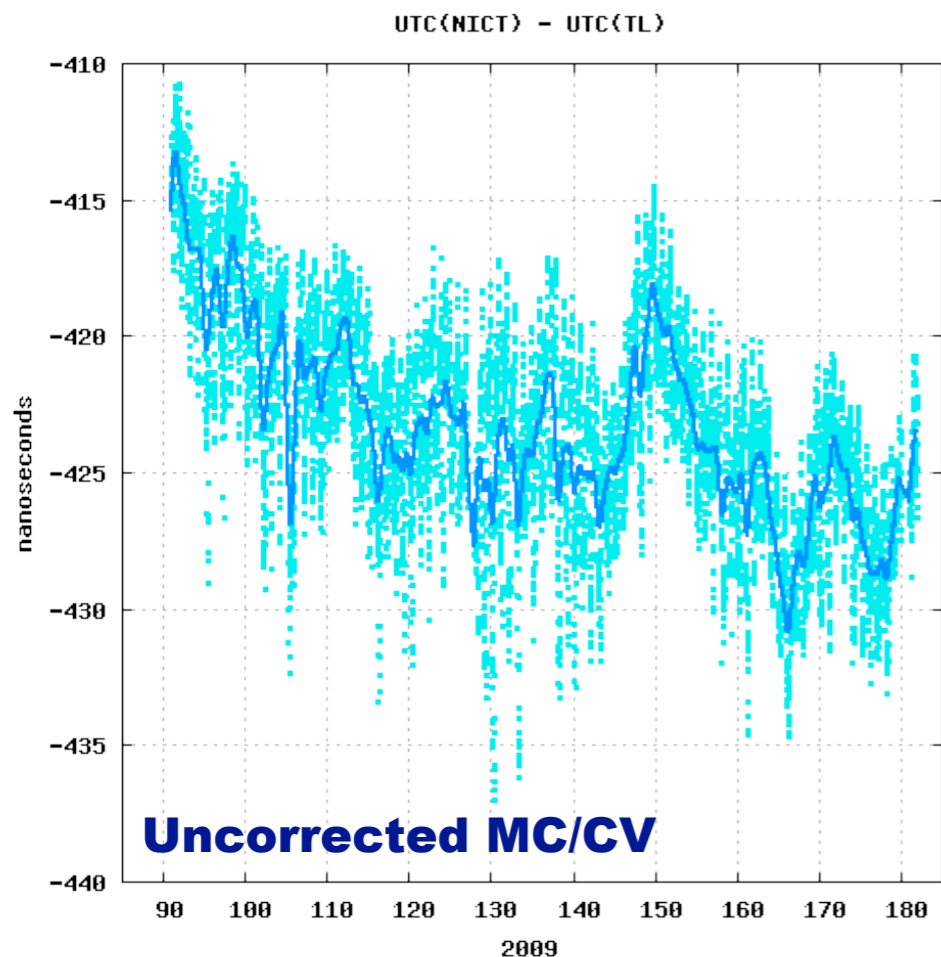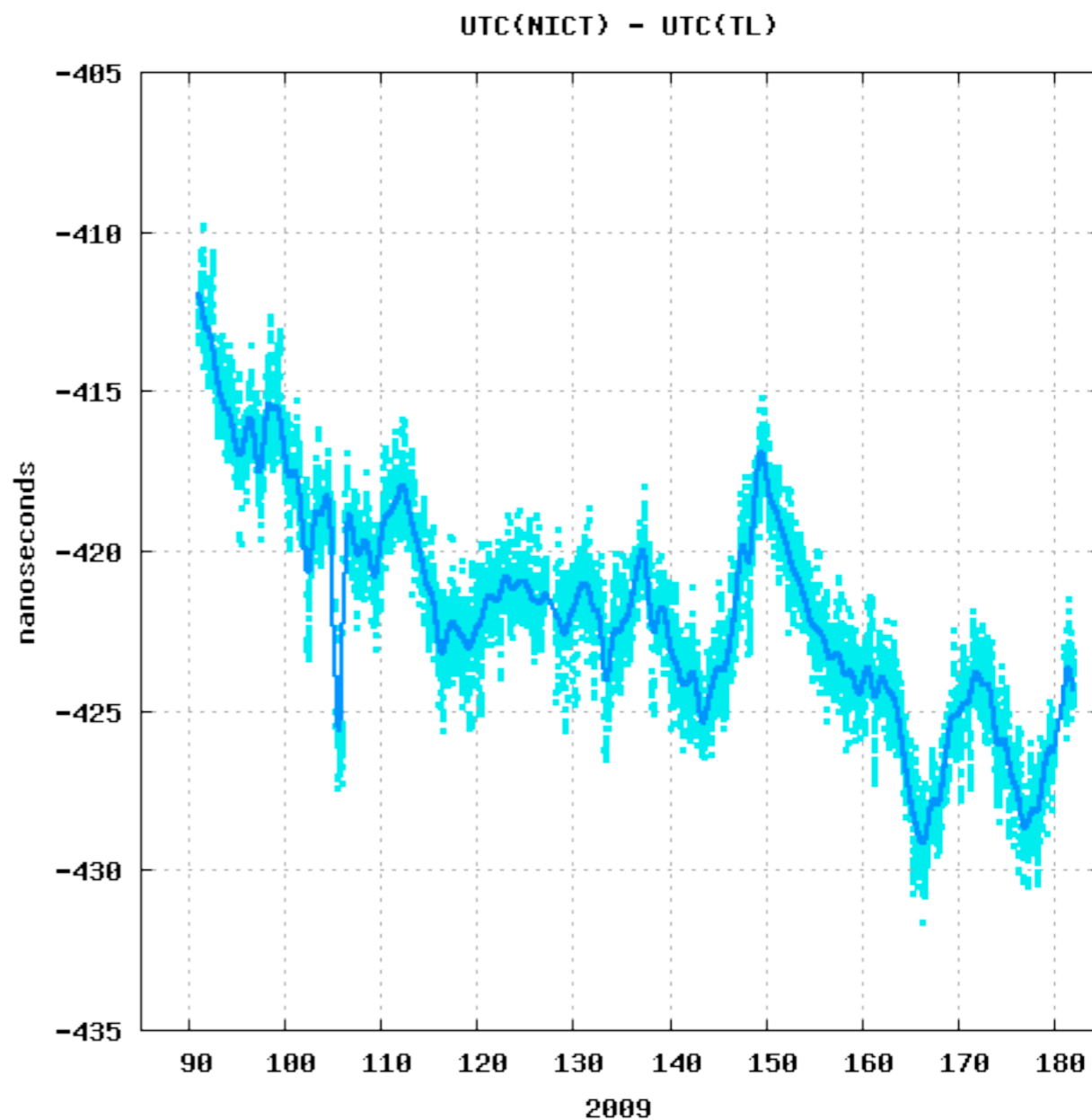
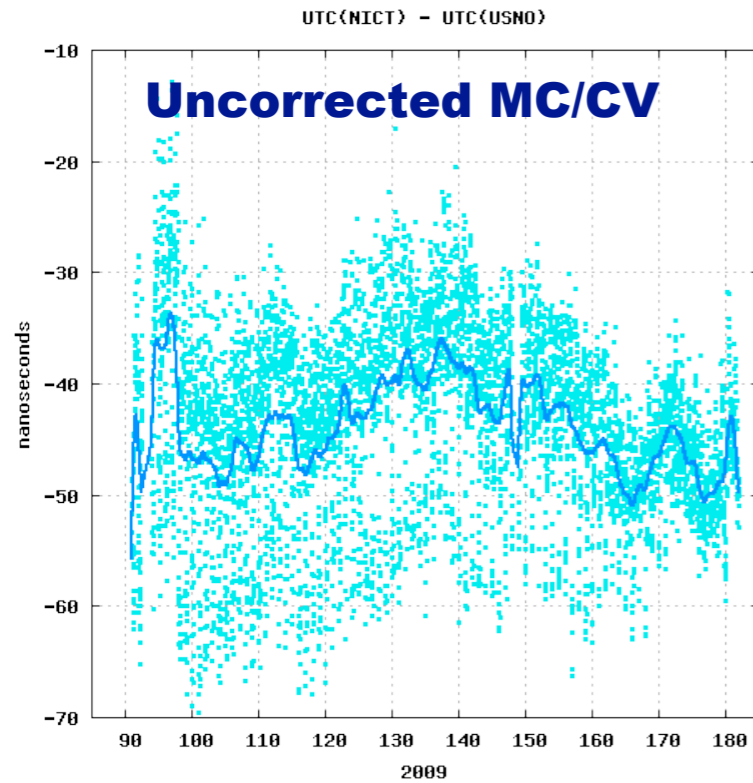**Post-Fit RMS: 2.366 ns**

Post-Fit RMS: 0.889 ns

Case #5, P3 All-in-View

Uncorrected P3/CV
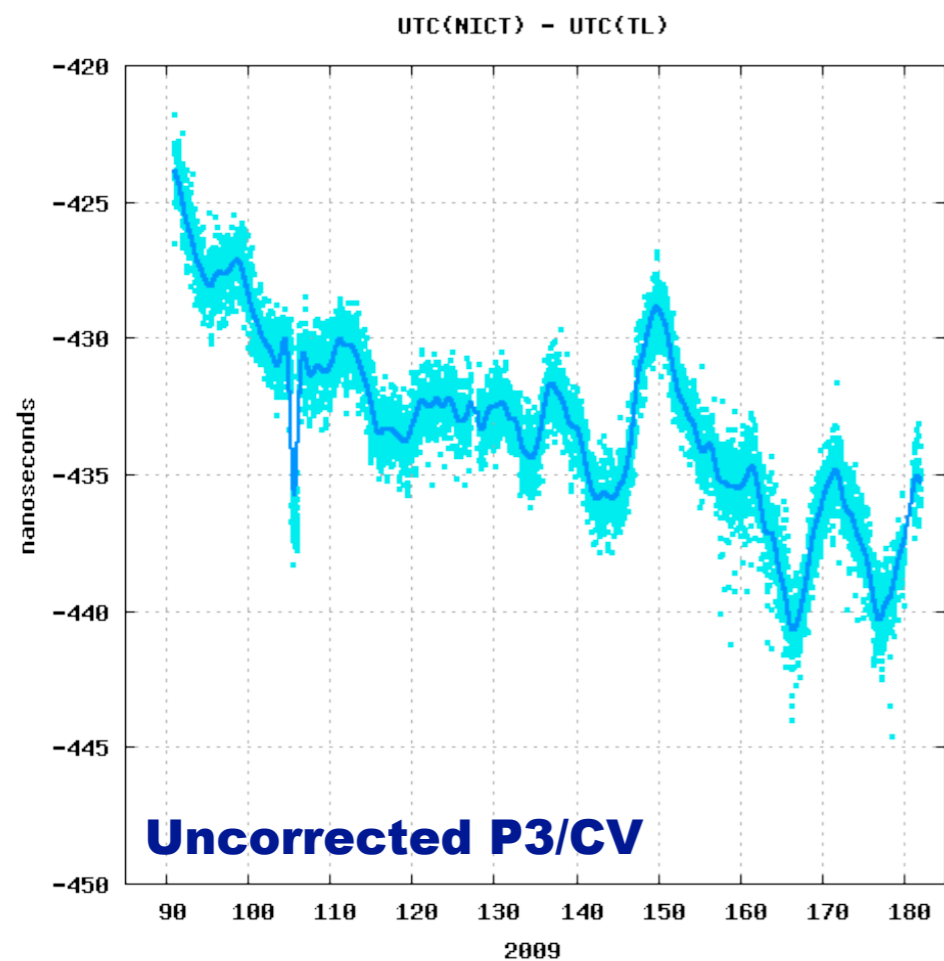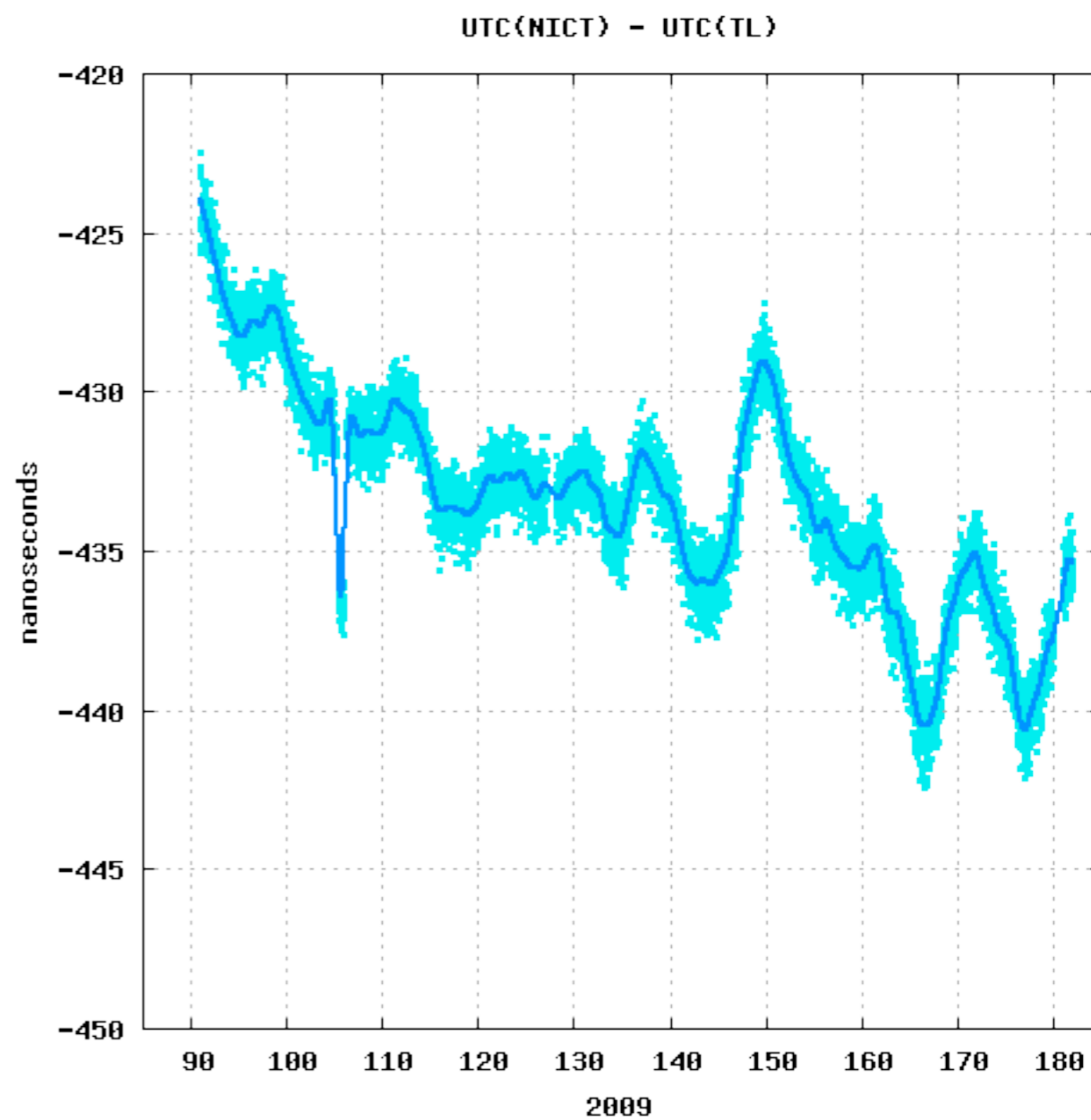
Post-Fit RMS: 0.829 ns

Post-Fit RMS: 0.667 ns

Cases of UTC(NICT) - UTC(USNO)

Uncorrected MC/CV — Post-Fit RMS: 7.478 ns

Corrected MC/CV — Post-Fit RMS: 1.374 ns
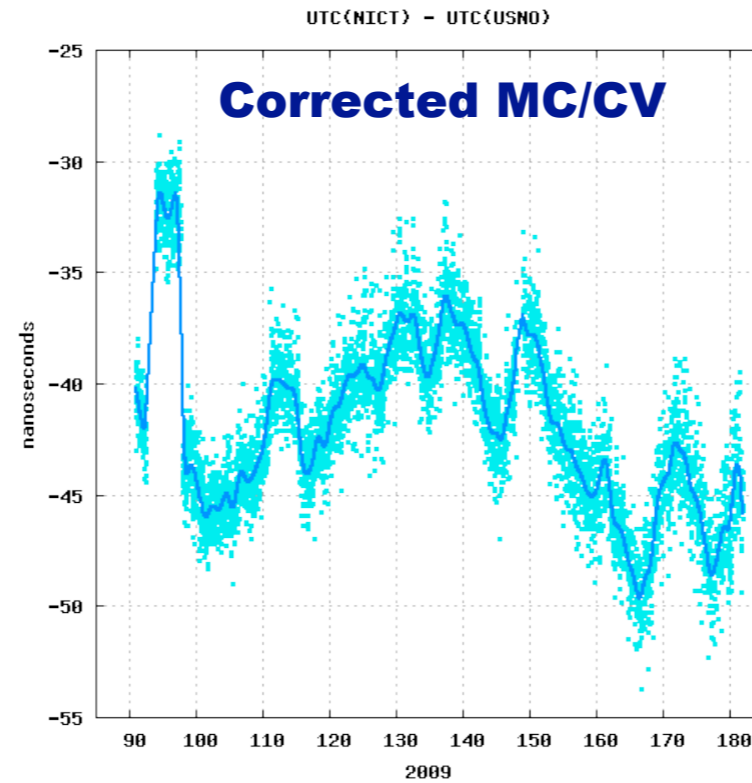
MC/AV — Post-Fit RMS: 0.854 ns
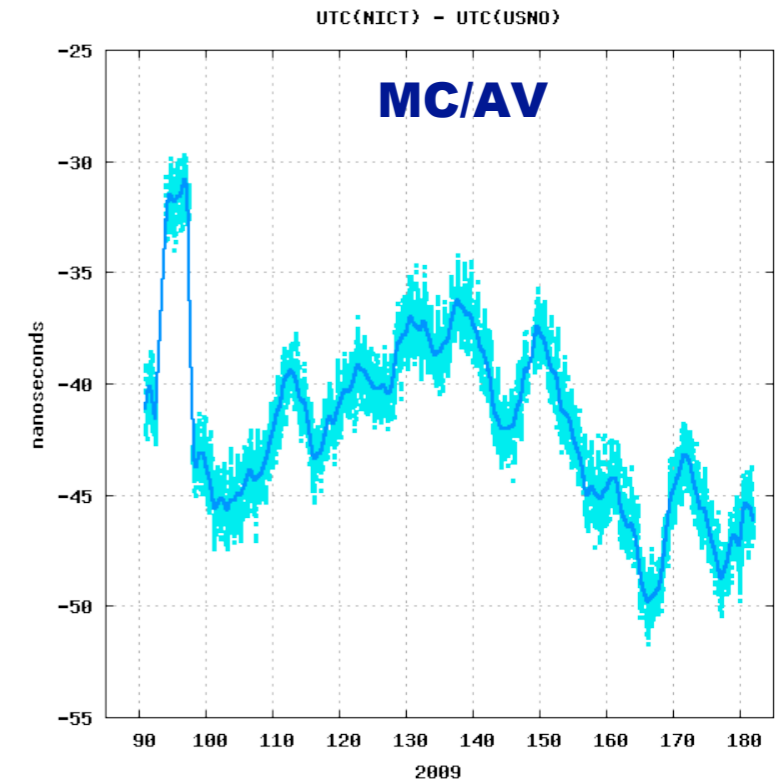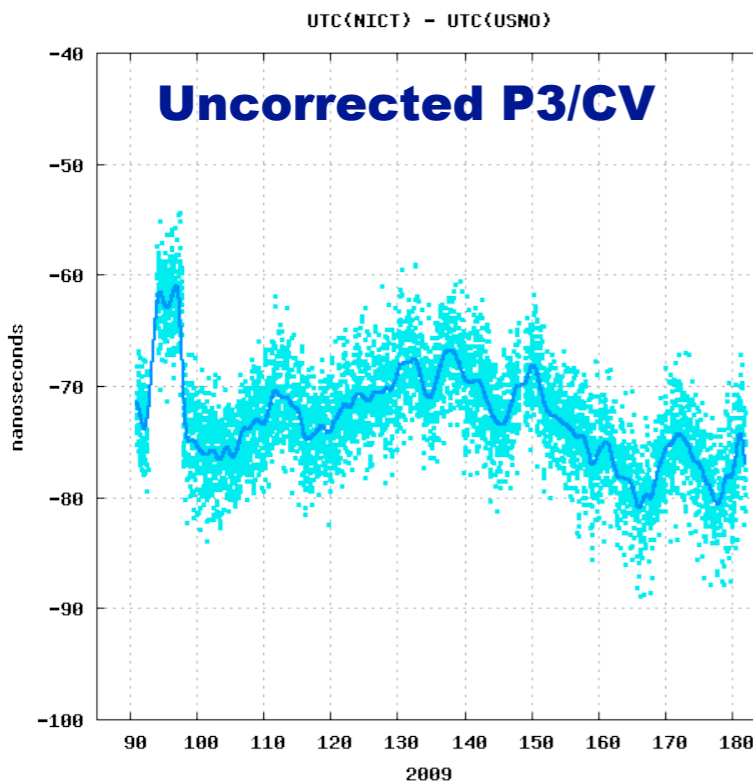
Uncorrected P3/CV — Post-Fit RMS: 2.854 ns
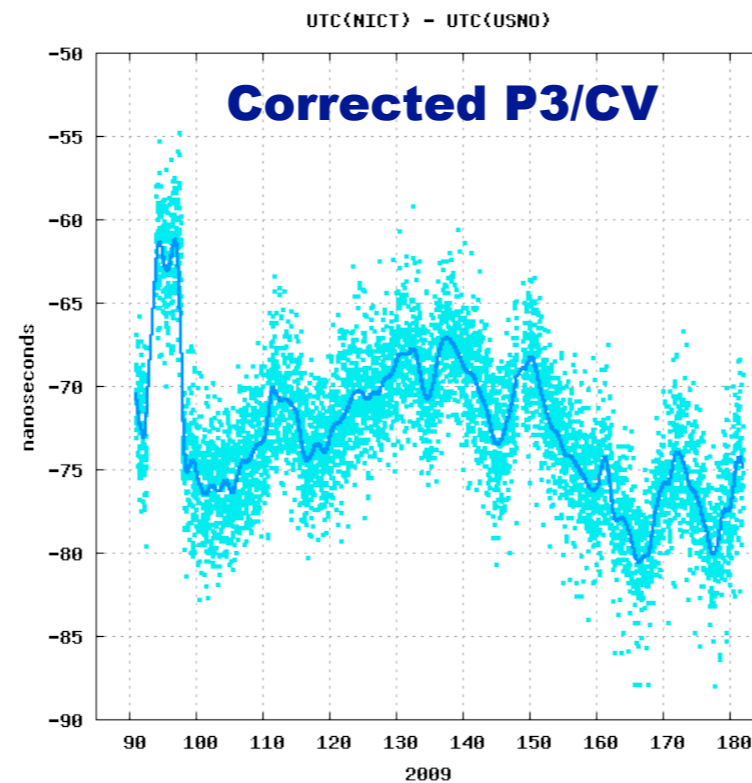
Corrected P3/CV — Post-Fit RMS: 2.513 ns
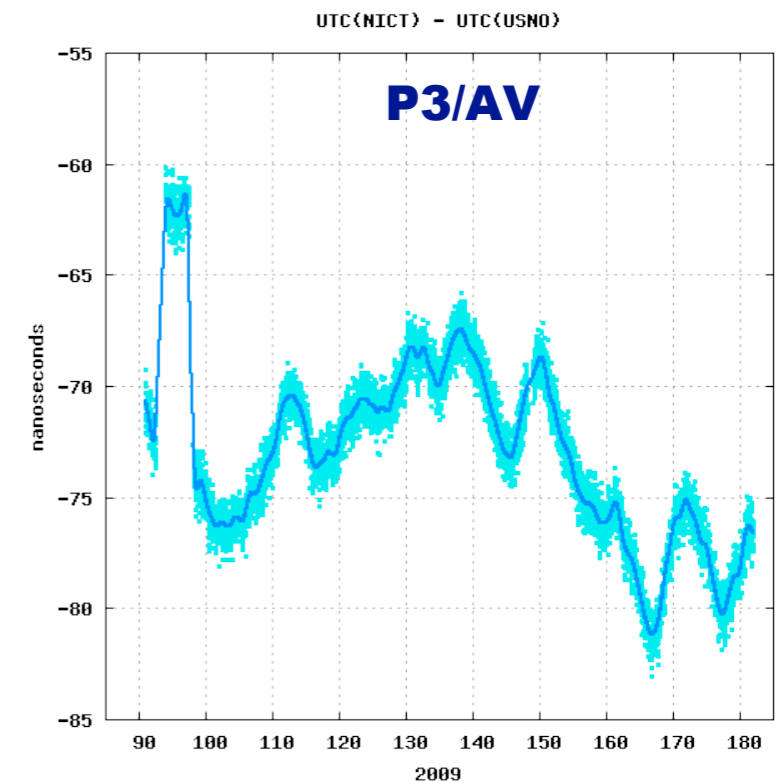
P3/AV — Post-Fit RMS: 0.634 ns

Note: scale of each plot is different.

Summary of the Case Studies

Post-fit RMS of **UTC(NICT) - UTC(k)**, unit is nanoseconds.

		TL	NIST	USNO
Raw CV	**MC**	*2.366*	*6.012*	*7.478*
	P3	*0.829*	*1.916*	*2.854*
Corrected CV	**MC**	*0.831*	*0.992*	*1.374*
	P3	*0.814*	*1.648*	*2.513*
All-in-View	**MC**	*0.889*	*0.795*	*0.854*
	P3	*0.667*	*0.665*	*0.634*

Summary

- Common-View with CGGTTS data is easy.
  - Choice the neighboring station to cancel the model errors.
  - Use P3 observations in turbulent ionosphere region.
- IGS products provide precise time transfer.
  - Usage of GIM gives the similar precision of P3 observations.
  - Correct satellite orbit and clock offsets if distance of two stations is far.
- Use all-in-view for long baseline length.
- Take care the observation environment.
  - Multi-path reduction.
  - Correct antenna position.
  - Temperature stabilization.
  - Feed clean reference signal, signal level, harmonic reduction, ...

You can obtain sufficient time transfer precision by clever data analysis when you only have a GPS receiver but no two-way system.

Thank you for your kind attention.