GPS TEC calibration: details and practical aspects

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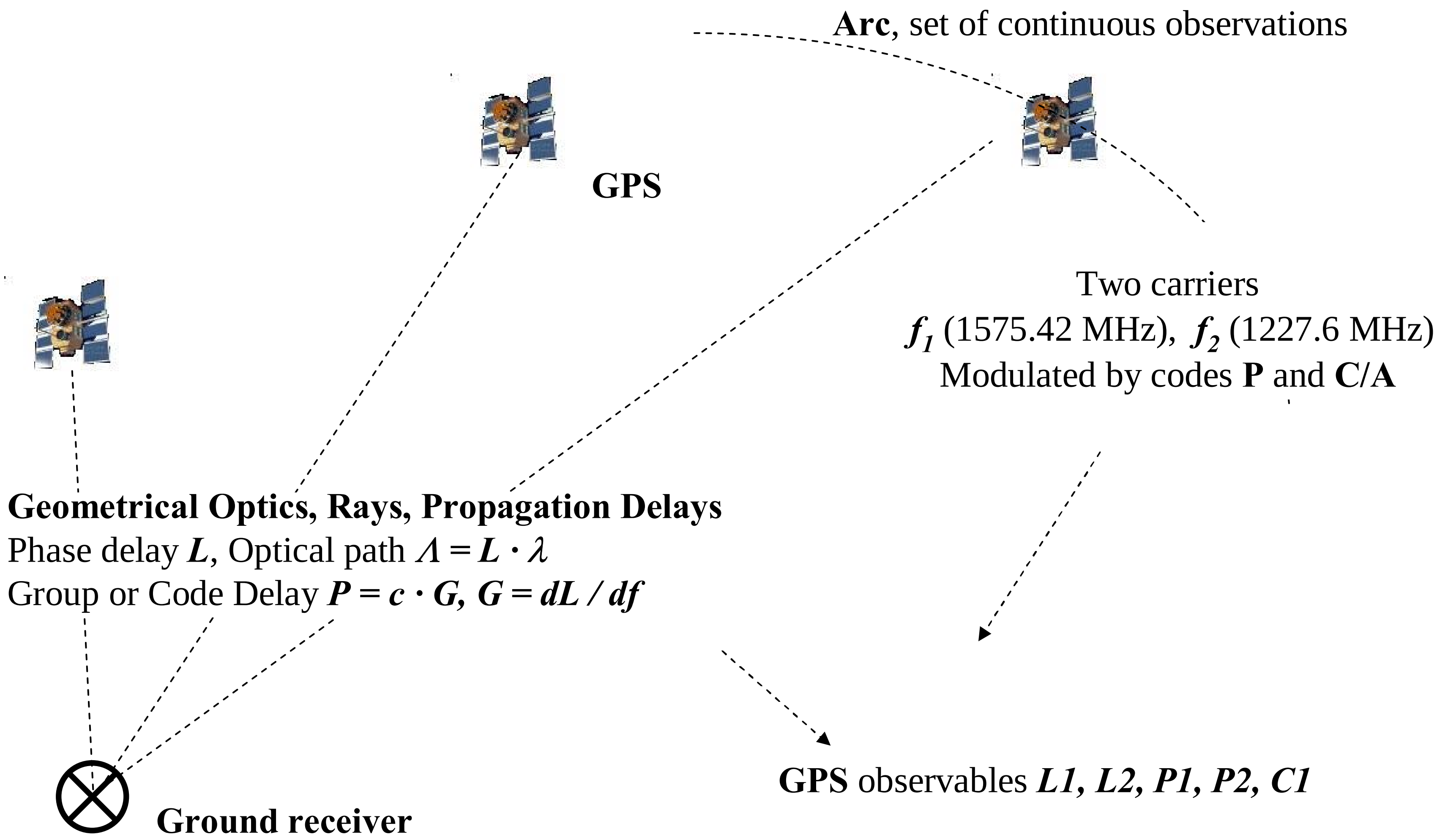
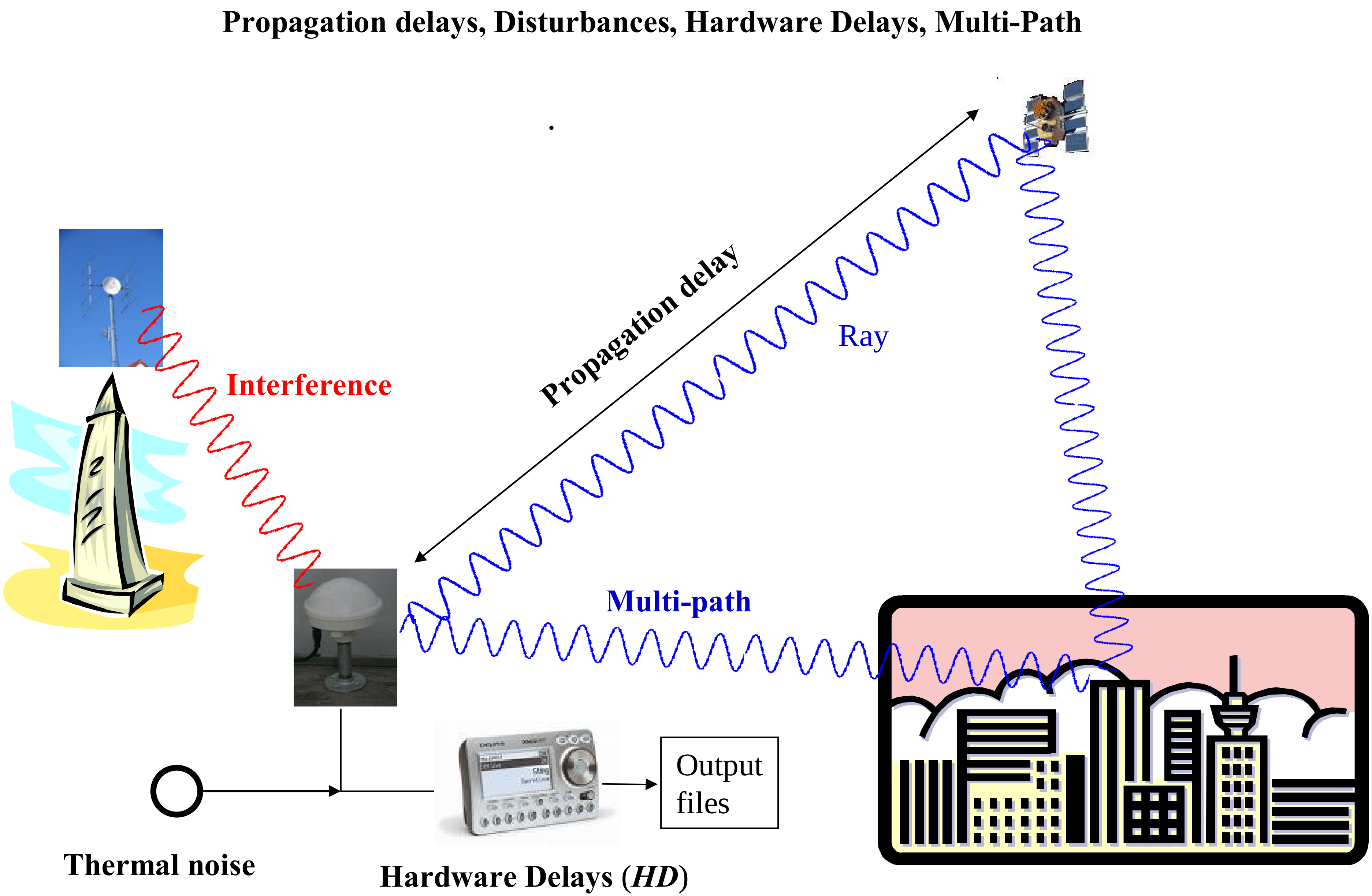
GPS scenario




Propagation delays, Disturbances, Hardware Delays, Multi-Path
Propagation delay
Ray
Interference
Multi-path
Output files
Thermal noise
Hardware Delays (HD)

Propagation Delays

Propagation and Atmospheric contributions to optical path Λ:

Geometric (**D**istance), Tropospheric, **I**onospheric

$$\Lambda \quad = \quad D + T + I$$

Equivalent Group Path P = Group delay G × speed of light

$$P = G \cdot c = D + T - I$$

Refractivity $R = n - 1$, n Index of Refraction

$$T = \int R_{atm}(s)ds \qquad I = \int R_{Iono}(s)ds \qquad R_{Iono} = -\frac{40.3 \cdot N_e}{f^2},$$

$$TEC = \int N_e(s)ds, \qquad I = -\frac{40.3 \cdot TEC}{f^2}$$

$$L = \frac{D + T + I}{\lambda} = \frac{f}{c}(D + T) - \frac{40.3TEC}{cf}$$

$$G = \frac{dL}{df} = \frac{D + T}{c} + \frac{40.3TEC}{cf^2}$$

Measurements introduce additional "delays"

Hardware electronic delays originating in satellite and receiver,	β, γ
Offset (delay, ambiguity) for phase	Ω
Noise	$\boldsymbol{n}$
Multipath	$\boldsymbol{m}$
User clock offset	τ

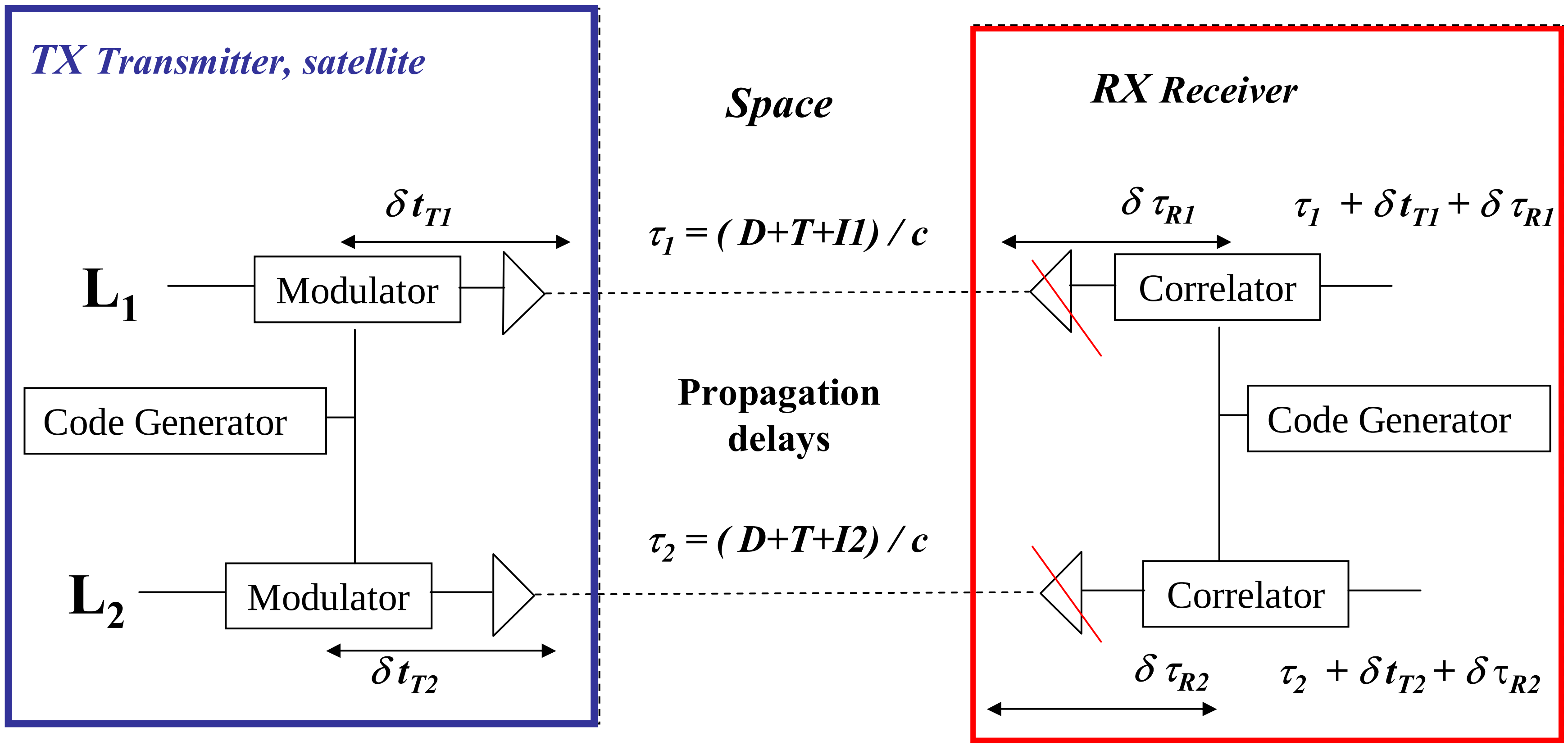
Code delay affected by user clock offset is ***pseudorange***

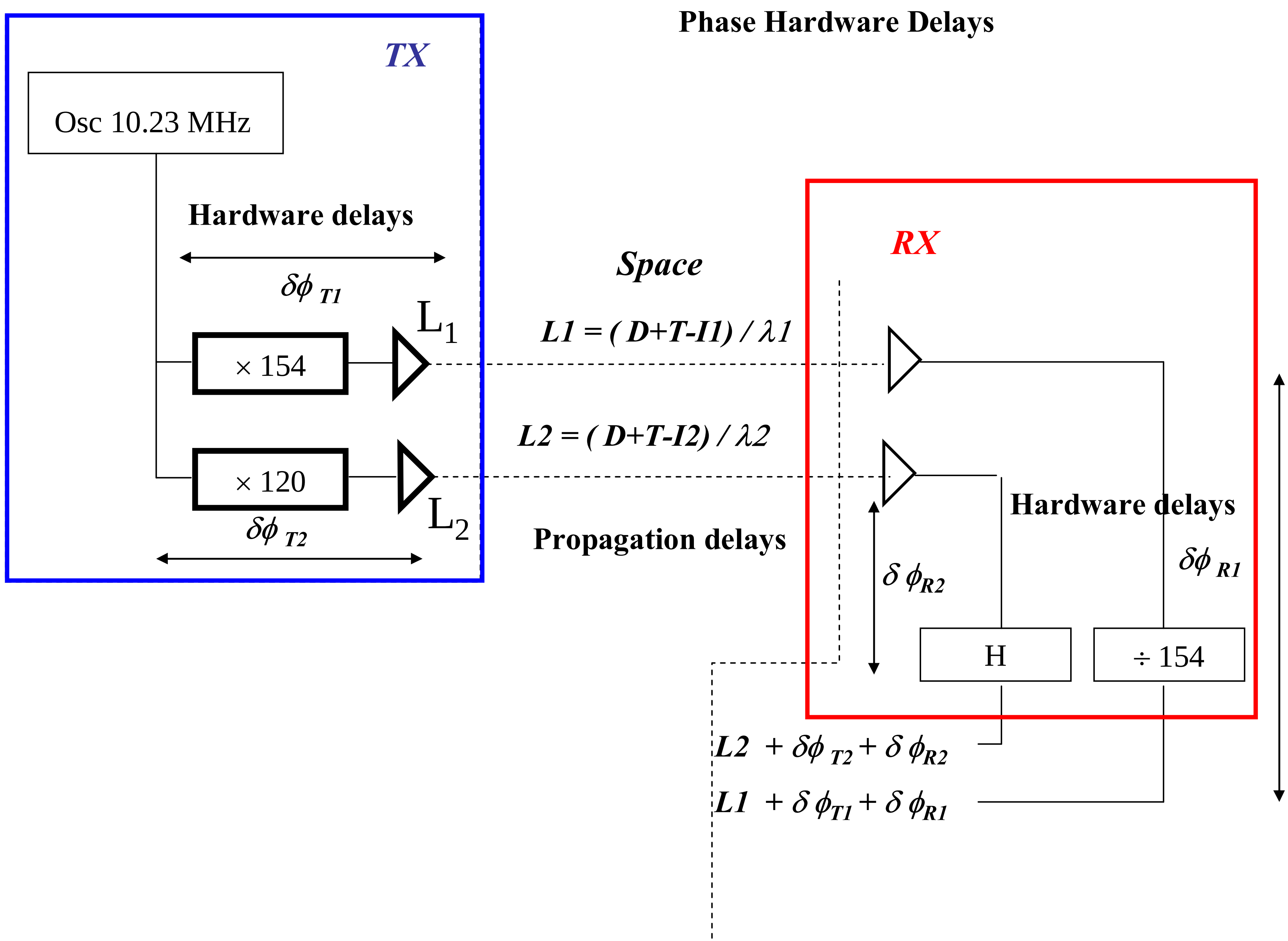
$$\boldsymbol{P} = \boldsymbol{D} + \boldsymbol{T} - \boldsymbol{I} + \beta + \gamma + \boldsymbol{n} + \boldsymbol{m} + \tau$$

For following discussion, noise and multipath can be neglected for phase delays.
Hardware delays for phase are included in Ω

$$\Lambda = \boldsymbol{D} + \boldsymbol{T} + \boldsymbol{I} + \Omega$$

Code hardware delays





Phase Hardware Delays
TX
Osc 10.23 MHz
Hardware delays
δϕ T1
L1
× 154
× 120
L2
δϕ T2
Space
L1 = (D+T-I1) / λ1
L2 = (D+T-I2) / λ2
Propagation delays
RX
Hardware delays
δ ϕR2
δϕ R1
H
÷ 154
L2 + δϕ T2 + δ ϕR2
L1 + δ ϕT1 + δ ϕR1

Availing GPS delays ***P1, P2, L1, L2, C1***

Users aiming to determine their position, will get rid of ionospheric contribution taking proper combinations of them.

Users aiming to investigate ionosphere, will simply compute differential delays

Differential pseudorange

$$P2 - P1$$

Differential phase path

$$\Lambda 1 - \Lambda 2 = L1 \cdot \lambda 1 - L2 \cdot \lambda 2$$

Both differential delays are in meters.

Following steps:

Show dependence on ***TEC***

Transform to ***TEC units* (10^{16} electrons/m^{2}), *TECu***

The differential Delays

For the carrier i (i = 1,2), contributions with no index do not depend on frequency and cancel out forming differential delays

$$P_i = G_i \cdot c = D + T - I_i + \beta_i + \gamma_i + n_i + m_i + \tau,$$

$$\underline{\Delta P = P2 - P1 = I1 - I2 + \Delta\beta + \Delta\gamma + \Delta n + \Delta m}$$

$$\Lambda_i = D + T + I_i + \Omega_i$$

$$\underline{\Delta\Lambda = \Lambda 1 - \Lambda 2 = I1 - I2 + \Delta\Omega}$$

$$I2 - I1 = k \cdot TEC \quad k = 40.3TEC\left(\frac{1}{f_2^2} - \frac{1}{f_1^2}\right)$$

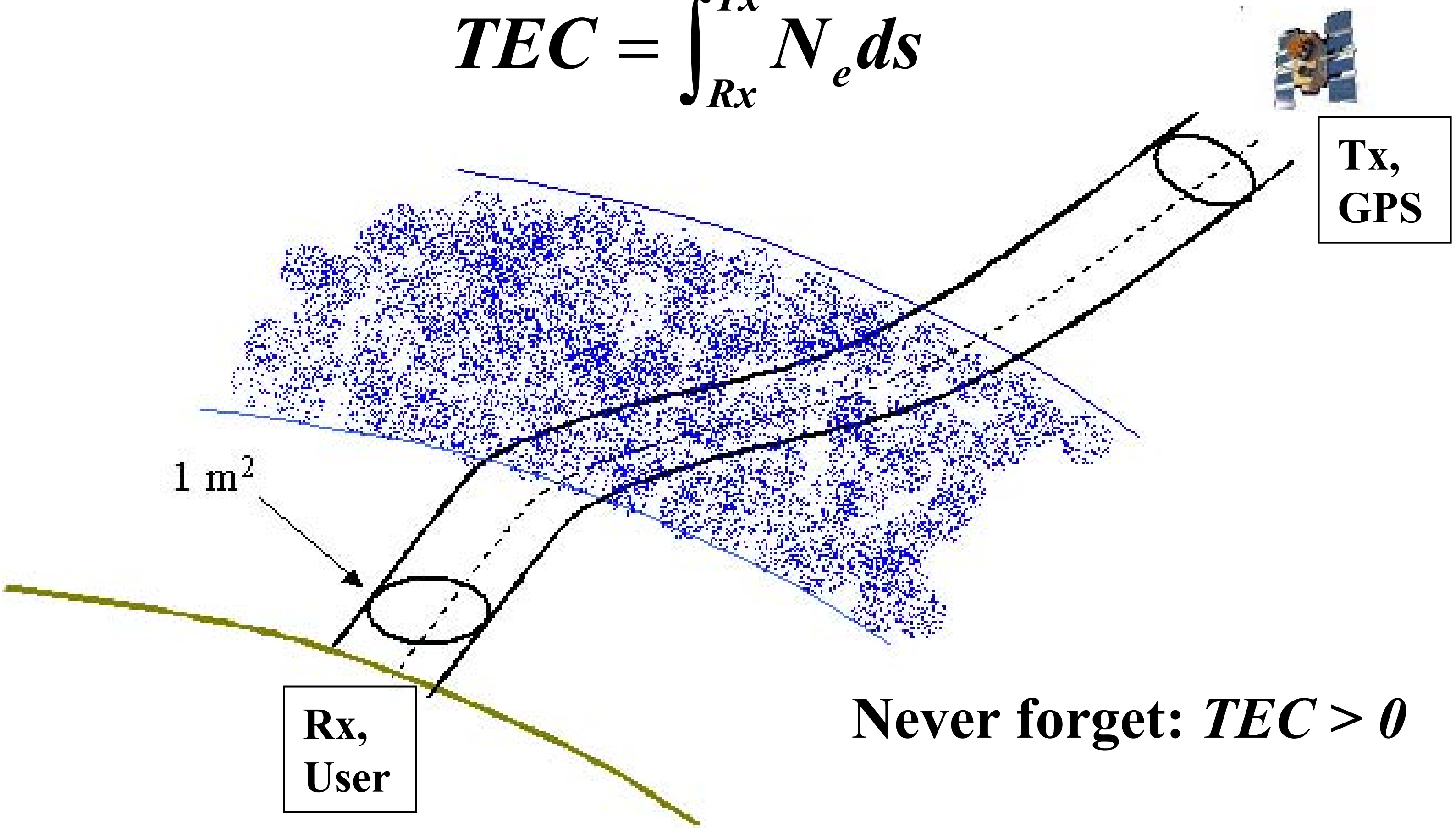
Divide by $k \cdot 10^{-16}$, <u>drop out</u> the Δ symbol to obtain the ***phase slants*** S_P and ***group or code slants*** S_C in ***TECu***, 1 ***TECu*** = 10^{16} electrons/m^2, disregard radio noise n

$$S_P = \frac{1}{k} \cdot (\Lambda 1 - \Lambda 2) = TEC + \Omega$$

$$S_C = \frac{1}{k} \cdot (P2 - P1) = TEC + m + \beta + \gamma$$

The classical interpretation of ***TEC*** as the **numbers of electrons** contained in a column of unitary base along the ray

$$TEC = \int_{Rx}^{Tx} N_e ds$$



Never forget: *TEC > 0*

Note for the following: expressions for observations like

$$\boldsymbol{S = TEC + b}$$

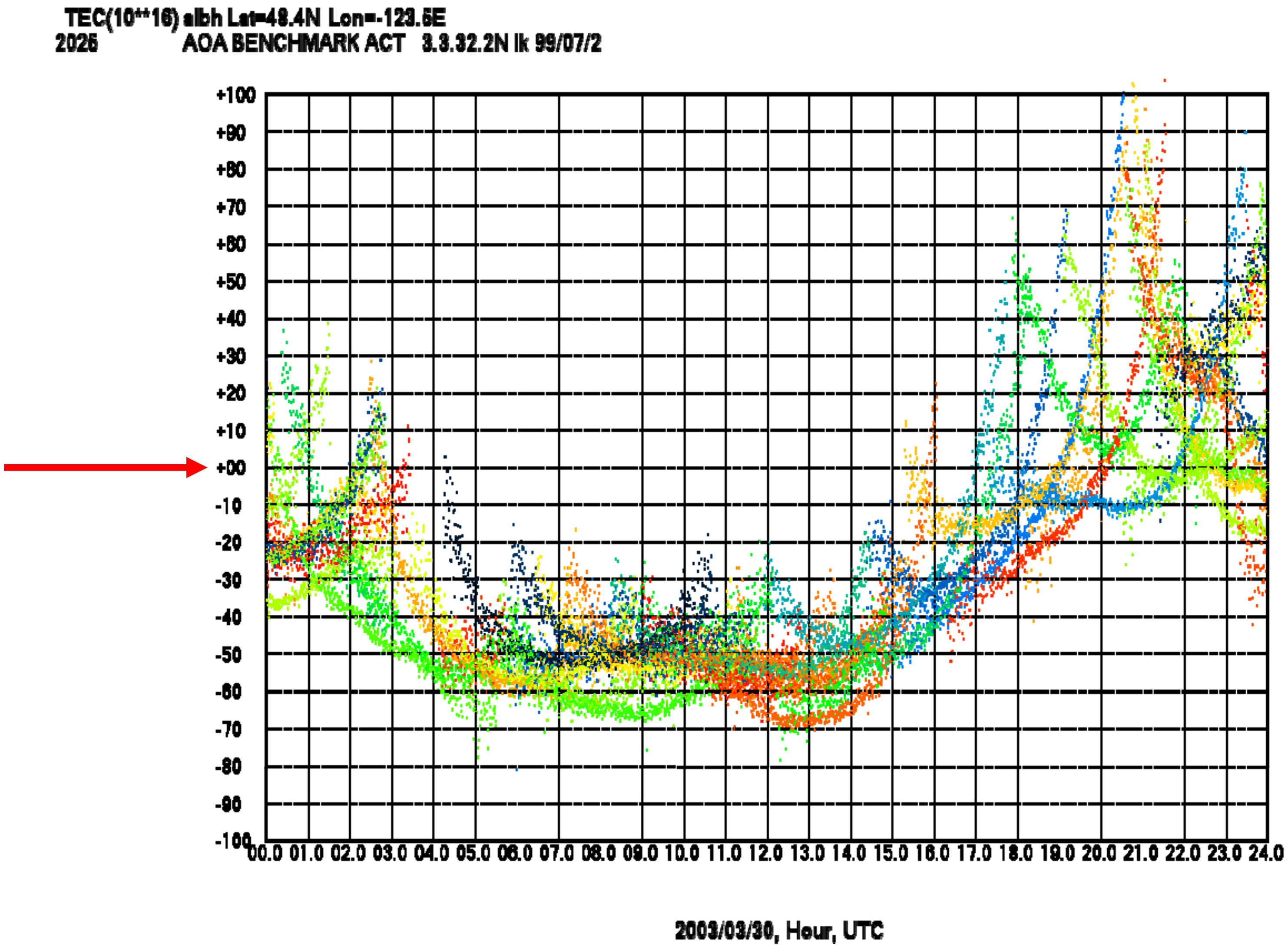
denote the set of all available observations used for performing some specific task.

Actually observations should be indexed as $\boldsymbol{S_{ijt}}$ meaning that the individual observed quantity , the ***“slant ”***, refers to $\boldsymbol{i^{th}}$ satellite, $\boldsymbol{j^{th}}$ station, $\boldsymbol{t^{th}}$ time.

Biasing terms can still be indexed according to satellite and station (not time as assumed to be constant), but also according to the specific observed arc.

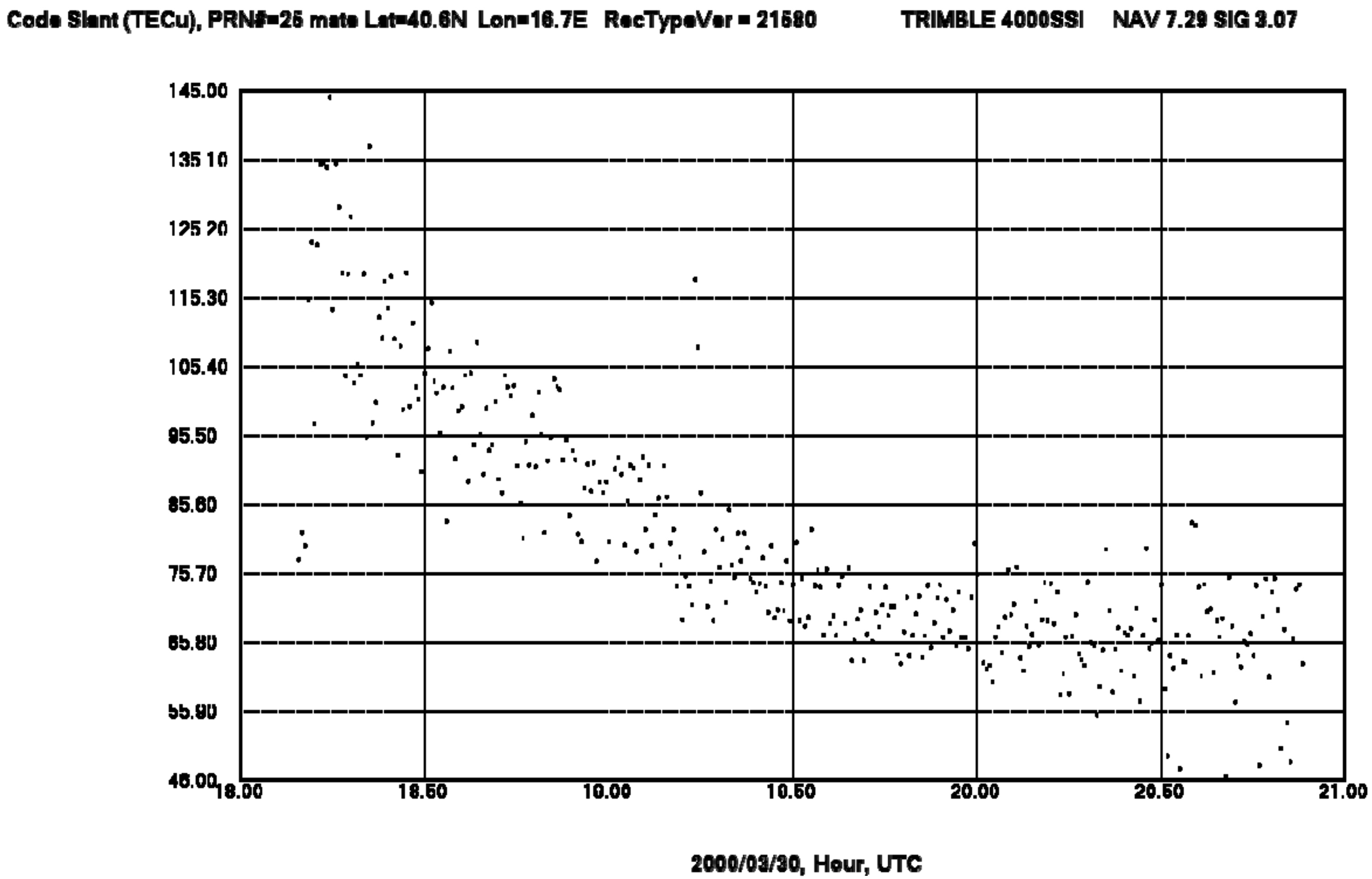
When needed for clarity, indexing will be explicitly adopted.

Plot of S_C arcs for one day

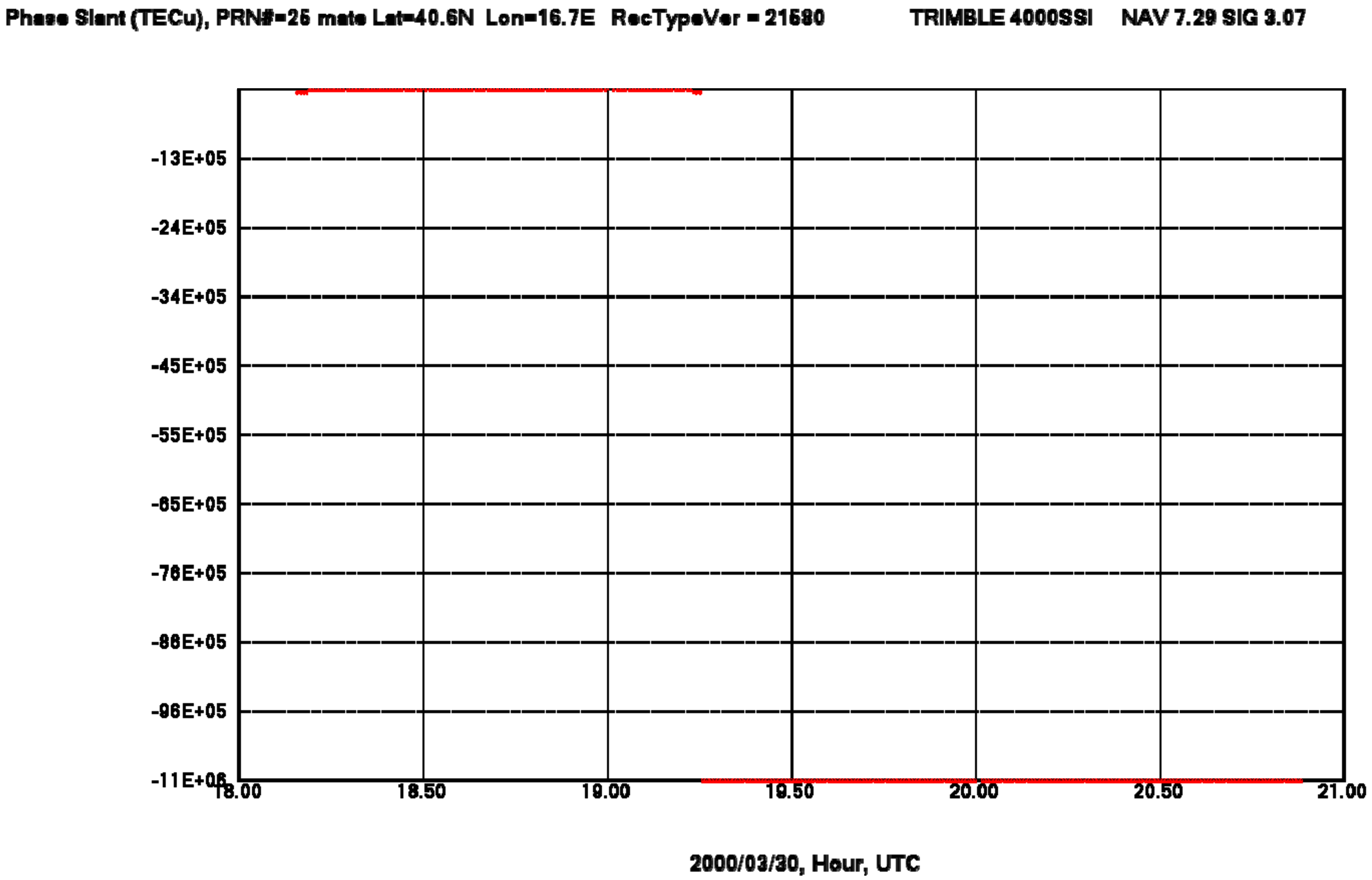


* Evidence that calibration is needed: TEC is a positive quantity

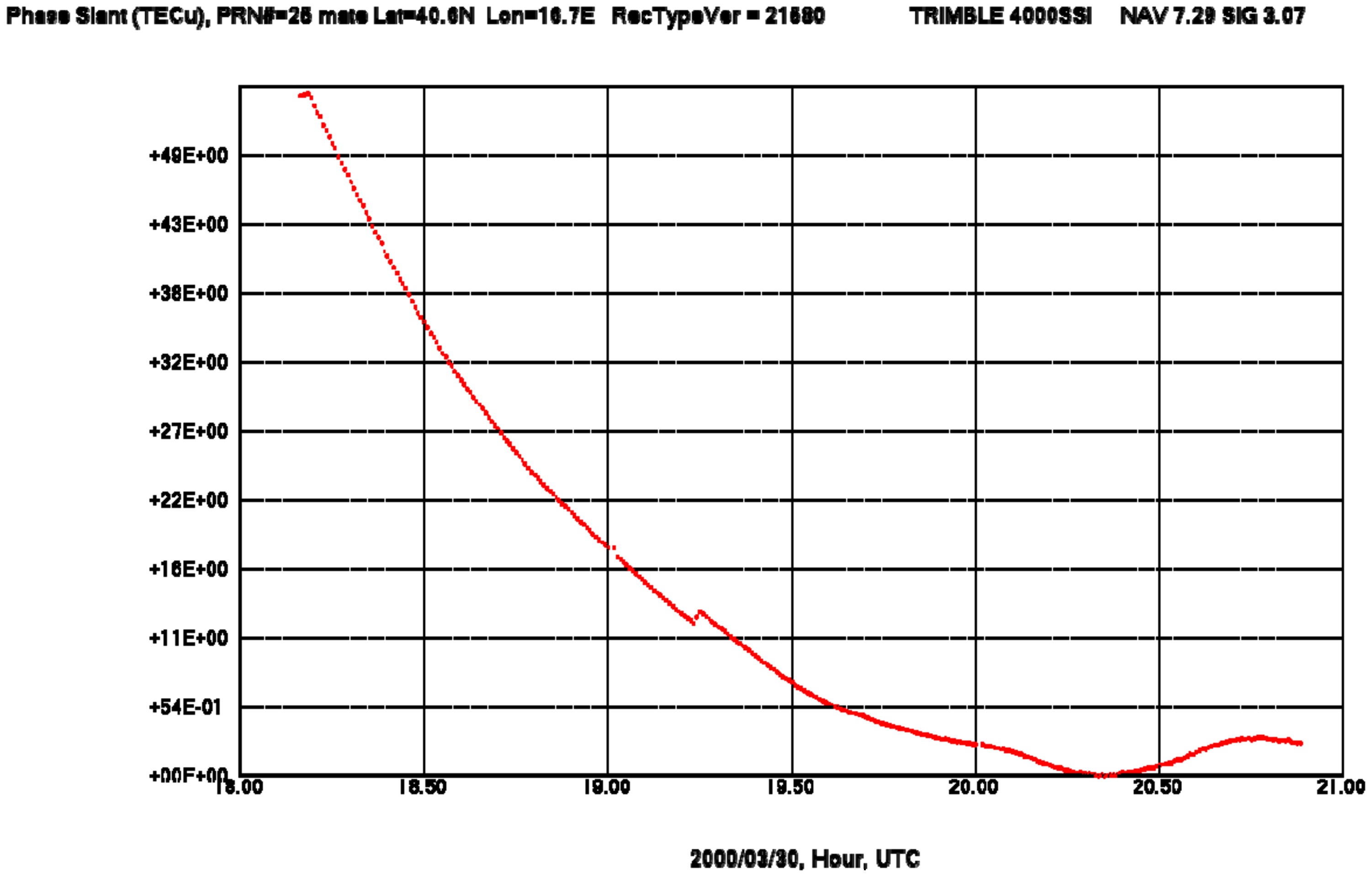
Sample S_C , one arc: the common situation



Sample $\boldsymbol{S_P}$, one arc: the common situation (phase jumps)



Sample S_P, one arc„ : after removing jumps, fixing the minimum to zero



Offset Ω is an arbitrary quantity: can we set it in some useful way?

A new set of observables: Phase slants leveled to Code

Operator **<·>** is a properly selected weighted (possibly robust) average

Build, arc by arc, the <u>leveled</u> slants S_L

$$S_L = S_P - < S_P - S_C >$$

$$< S_P - S_C > = \Omega - < m > - \beta - \gamma$$

$$S_L = TEC + < m > + \beta + \gamma$$

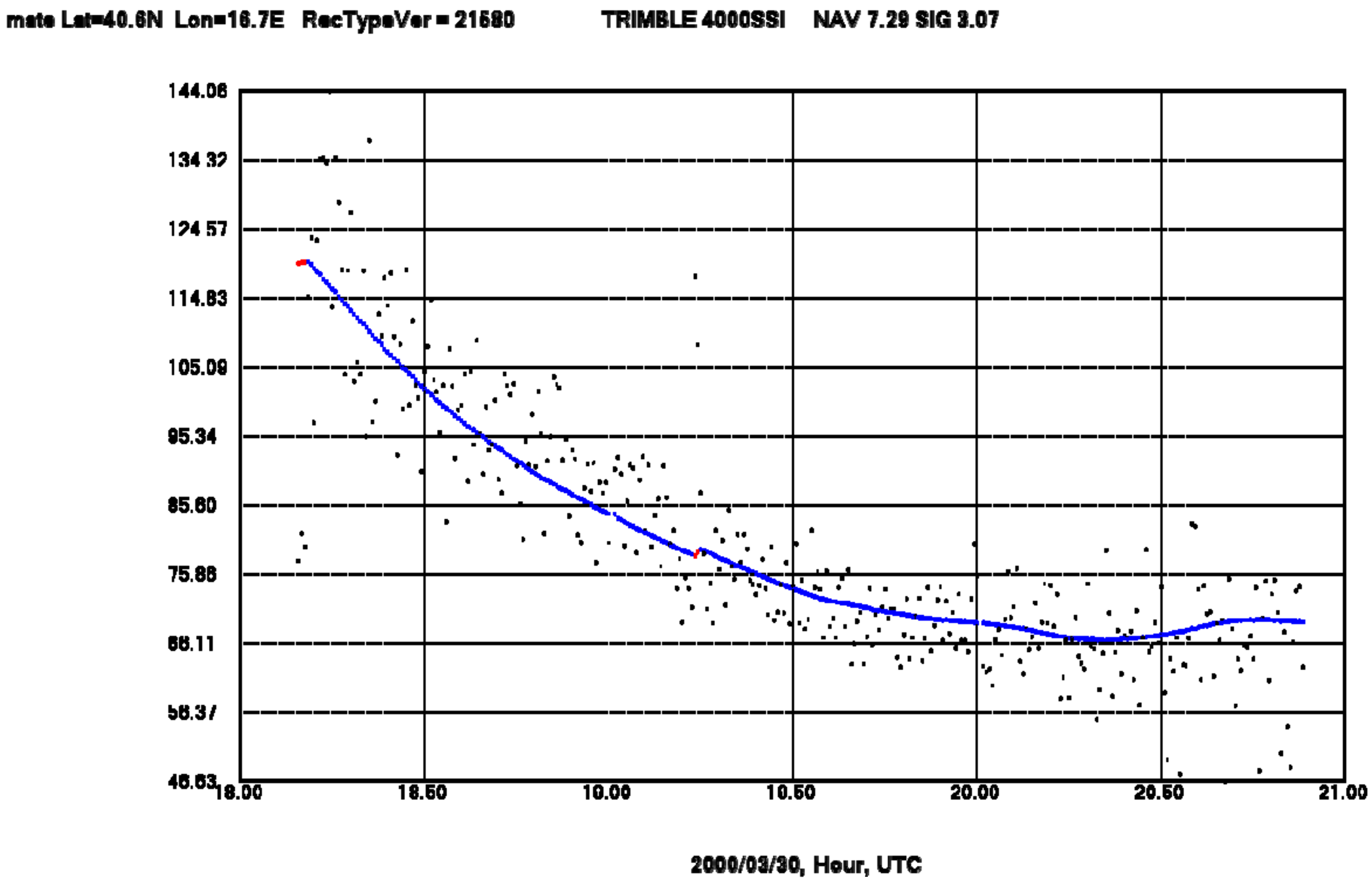
Properties of S_L

Noise is the same (neglected) of phase slants

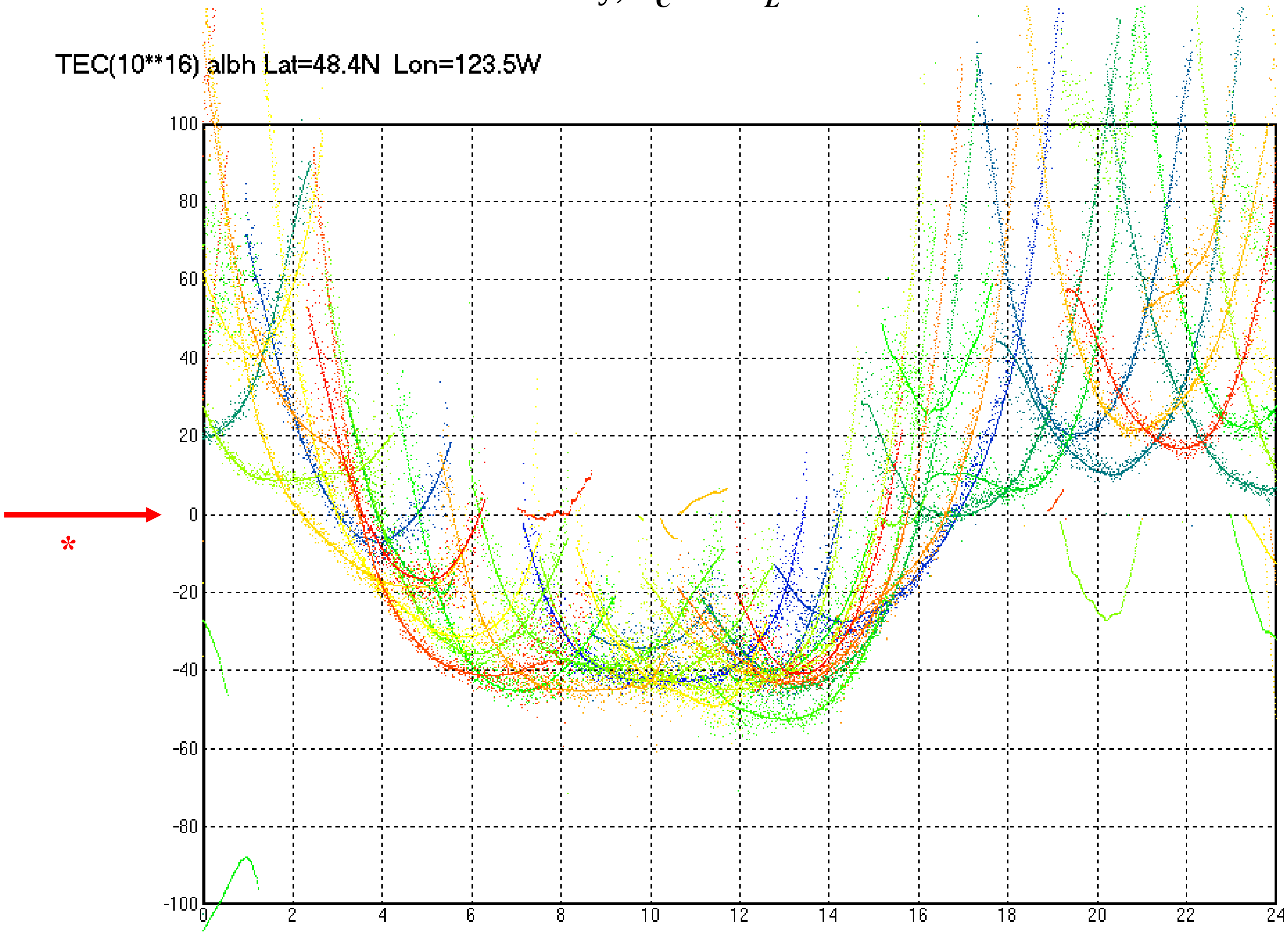
Biased exactly as code slants

But: an arc dependent constant leveling error $\lambda = < n > + < m >$ appears

Sample $\boldsymbol{S_C}$ and $\boldsymbol{S_P}$ with properly selected phase offset $\Omega = \boldsymbol{S_L}$



One day, S_C and S_L arcs



*** Evidence that calibration is needed: TEC is a positive quantity**

Summary of the observables

$$S_P = TEC + \Omega$$

$$S_C = TEC + m + \beta + \gamma$$

$$S_L = TEC + \lambda_{Arc} + \beta + \gamma$$

Ω	Offset, constant but arbitrarily changing from arc to arc
β, γ	Hardware biases: delays in electronics of transmitter and receiver. One β for satellite, one γ per station.
m	Multi-path,
λ	Leveling error, $<m>$, changing generally (but not arbitrarily) from arc to arc.
TEC	The quantity to estimate, variable from observation to observation

Following topics will be discussed in the following

GPS ionospheric observables

Reliability of leveled slants

Problems with multipath

Problems with receivers?

***TEC* expansion**

Reliability of the thin shell approximation

Calibration

The thin-shell, single-station, multi-day solution of individual arc offsets

Validation

Use of ionospheric models to validate the calibration techniques

Features of observations, **Code slants**

$$S_C = TEC + n + m + \beta + \gamma$$

Advantages: the electronic delays are physical quantities, stable or undergoing slow aging in controlled environmental conditions: they are generally considered constants over long times (up to 1 month).

One β per satellite, one γ for station: a favorable unknowns/observations budget.

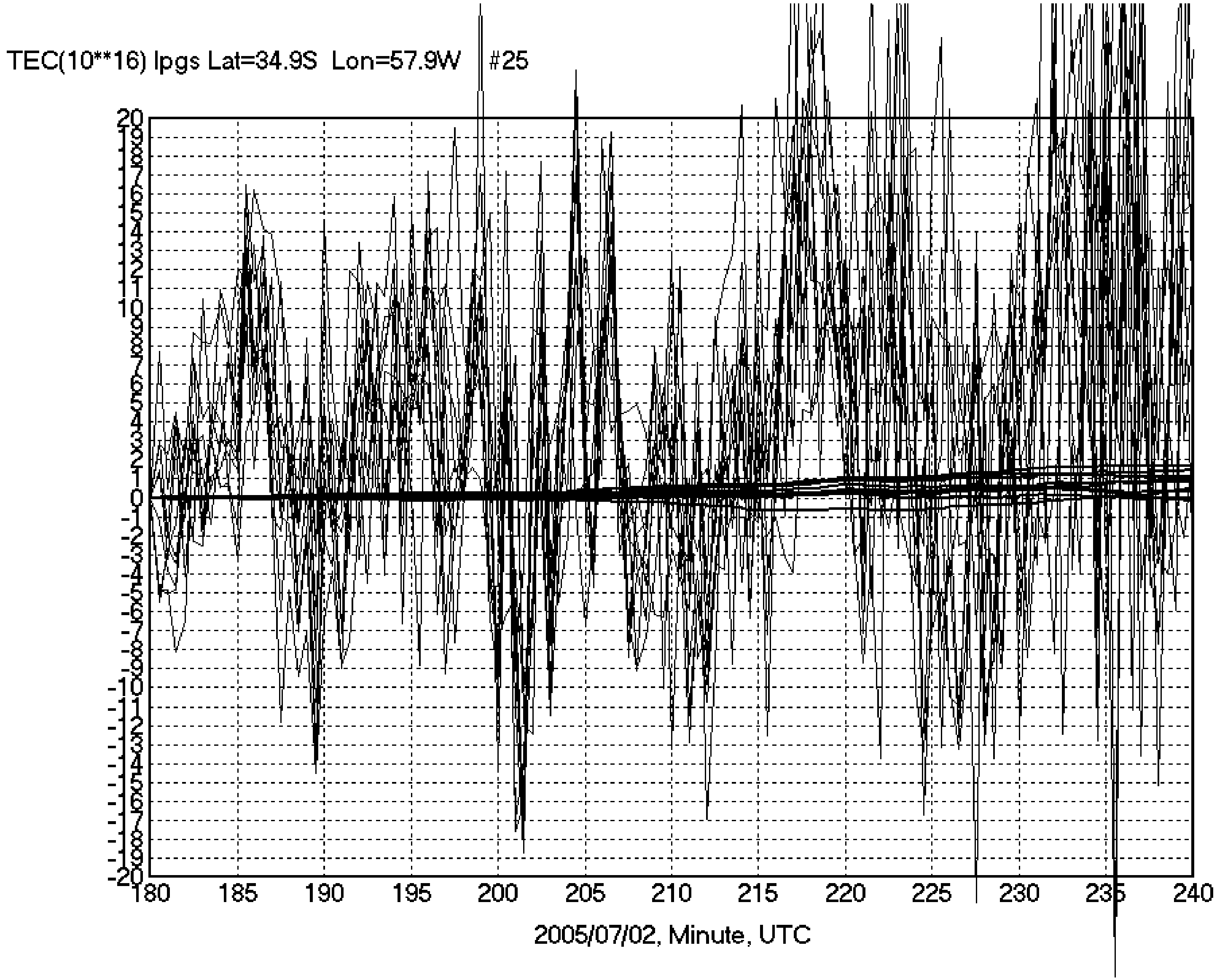
n: strong radio noise (non linear techniques used to evaluate pseudo-ranges), but still a stochastic variable with zero mean (resulting in consistent estimations)

Can multipath m be considered a disturbance?

How to distinguish it from noise? Period of GPS orbits is 12 sidereal hours: day after day the same satellite will occupy the same position with an advance of ≈ 4 minutes: if same environment day after day, m will advance by the same amount.

Plot a fraction of arc of the same satellite day by day with an advance of ≈ 4 minutes

Note: to avoid TEC variability, what is plotted for each arc is $TEC(t) - TEC(t_0)$, t_0 being the beginning of each arc. Both S_G and S_Φ relative to the same arc are plotted .



TEC(10**16) lpgs Lat=34.9S Lon=57.9W #25
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
180
185
190
195
200
205
210
215
220
225
230
235
240
2005/07/02, Minute, UTC

Features of observations: Phase slants

$$S_P = TEC + \Omega$$

No significant noise and multipath (above slide)

Modest equations/unknown budget: one unknown per arc

Global single day solution, 200 stations

Unknowns: coefficients of TEC expansion plus around 1000 unknown offsets, compared to 200+30 hardware biases.

Possibility to use first differences (in time) of the observations of one arc. Only TEC coefficients remain: calibration relies entirely on the model used for the expansion.

Other possibility: solving by geodetic techniques for the ambiguities and therefore for the offsets.

Leveled slants: $\boldsymbol{S_L} = \boldsymbol{TEC} + \lambda + \beta + \gamma$

$$\lambda = <\boldsymbol{m}>$$

As for code slants, one unknown per satellite β and for station γ

Same observations/unknown budget of phase slants $\boldsymbol{S_P}$, apart the leveling error, constant arc by arc

Commonly assumed: disregard leveling error $\lambda = <\boldsymbol{m}>$

In leveling error, the mean of a stochastic variable , **<*n*>** has been neglected as a quantity with (likely) zero mean: it can be considered a disturbance that will not significantly affect the ultimate accuracy of calibration.

Does the same holds for **<*m*>** ?

No: multi-path is **not** a stochastic variable and it has **no zero mean**

The **close stations experiment** can evidence this statement

Availability of close stations

Many co-located IGS stations are available:

darr/darw, dav1/davr, gode/godz, gol2/gold,kou1/kour, mad2/madr, mat1/mate

ohi2/ohi3, reyk/reyz, tcms/tnml, thu2/thu3, tid1/tid2, tid1/tidb, tid2/tidb, zimj/zimz

and the combinations of *wtza, wtzj, wtzr, wtzt*.

Besides IGS stations, a special set of observation has been set up by the group of La Plata University, Argentina (C.Brunini, F.Azpiliqueta).

Close to the IGS station **"*lpgs*",** the additional stations ***"blue"***, ***"red0"*** and ***"asht"*** have been set up for present investigation, whose characteristics will be described in (*).

Duration: days 182/205 and 262/269 , 2005

(*) ***Journal of Geodesy***

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Calibration Errors on Experimental Slant Total Electron Content (TEC) Determined with GPS
L. Ciraolo, F. Azpilicueta, C. Brunini, A. Meza, S. M. Radicella

Updated availability of close station (2008)

cagl/cagz; cont/conz; darr/darw; dav1/davr; gode/godz;

gol2/gold; harb/hrao; hers/hert; irkj/irkm; irkj/irkt;

irkm/irkt; joz2/joze; kir0/kiru; lhas/lhaz; mad2/madr;

mat1/mate; mdvj/mdvo; mets/metz; mobj/mobn; nya1/nyal;

ohi2/ohi3; suth/sutm; tcms/tnml; thu2/thu3; tid1/tid2;

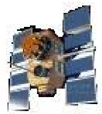
tid1/tidb; tid2/tidb; tixi/tixj; tro1/trom; tsk2/tskb;

usn3/usno; wtza/wtzj; wtza/wtzr; wtza/wtzs; wtza/wtzz;

wtzj/wtzr; wtzj/wtzs; wtzj/wtzz; wtzr/wtzs; wtzr/wtzz;

wtzs/wtzz; yakt/yakz; yar2/yarr; zimj/zimm;

The close stations experiment



β

Station 1

$$S1_{PRN} = TEC + \lambda 1 + \beta_{PRN} + \gamma 1$$

TEC

Station 2

$$S2_{PRN} = TEC + \lambda 2 + \beta_{PRN} + \gamma 2$$

< 100 m

$$S1 - S2 = \gamma 1 - \gamma 2 + \lambda 1 - \lambda 2$$

Not dependent on PRN

The close stations experiment

In equations of observation

$$\boldsymbol{S = TEC} + \beta + \gamma + \lambda$$

Consider observations to satellite ***i*** from stations ***j*** e ***k***

$$\boldsymbol{S_{ij} = TEC_{ij}} + \beta_i + \gamma_j + \lambda_{Arc\_\_i}$$

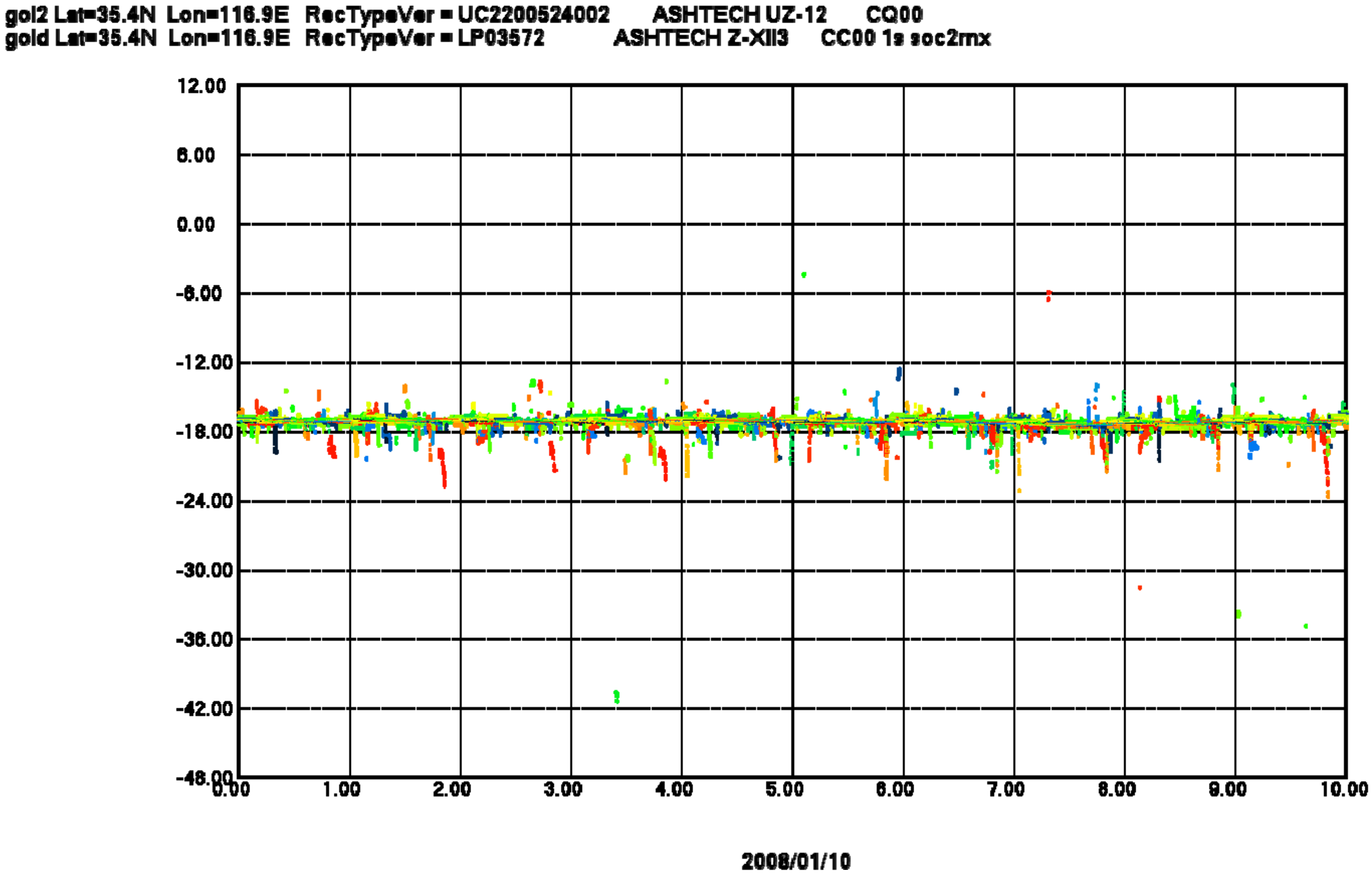
$$\boldsymbol{S_{ik} = TEC_{ik}} + \beta_i + \gamma_k + \lambda_{Arc\_k}$$

For close stations (up to few km) $\boldsymbol{TEC_{ij} = TEC_{ik}}$ satellite bias contribution is canceled

$$\boldsymbol{S_{ij} - S_{ik}} = \gamma_j - \gamma_k + \lambda_{Arc\_i} - \lambda_{Arc\_k}$$

If contribution of leveling error is not significant, plotting $\boldsymbol{S_{ij} - S_{ik}}$ one gets points close to the difference $\gamma_j - \gamma_k$ **, a constant quantity for the investigated pair of stations.**

$S_{i1} - S_{i2}$, $i=1..$all satellites, ***TECu***



The situation for *gol2/gold* is rather uncommon

Most of times the situation is quite different as

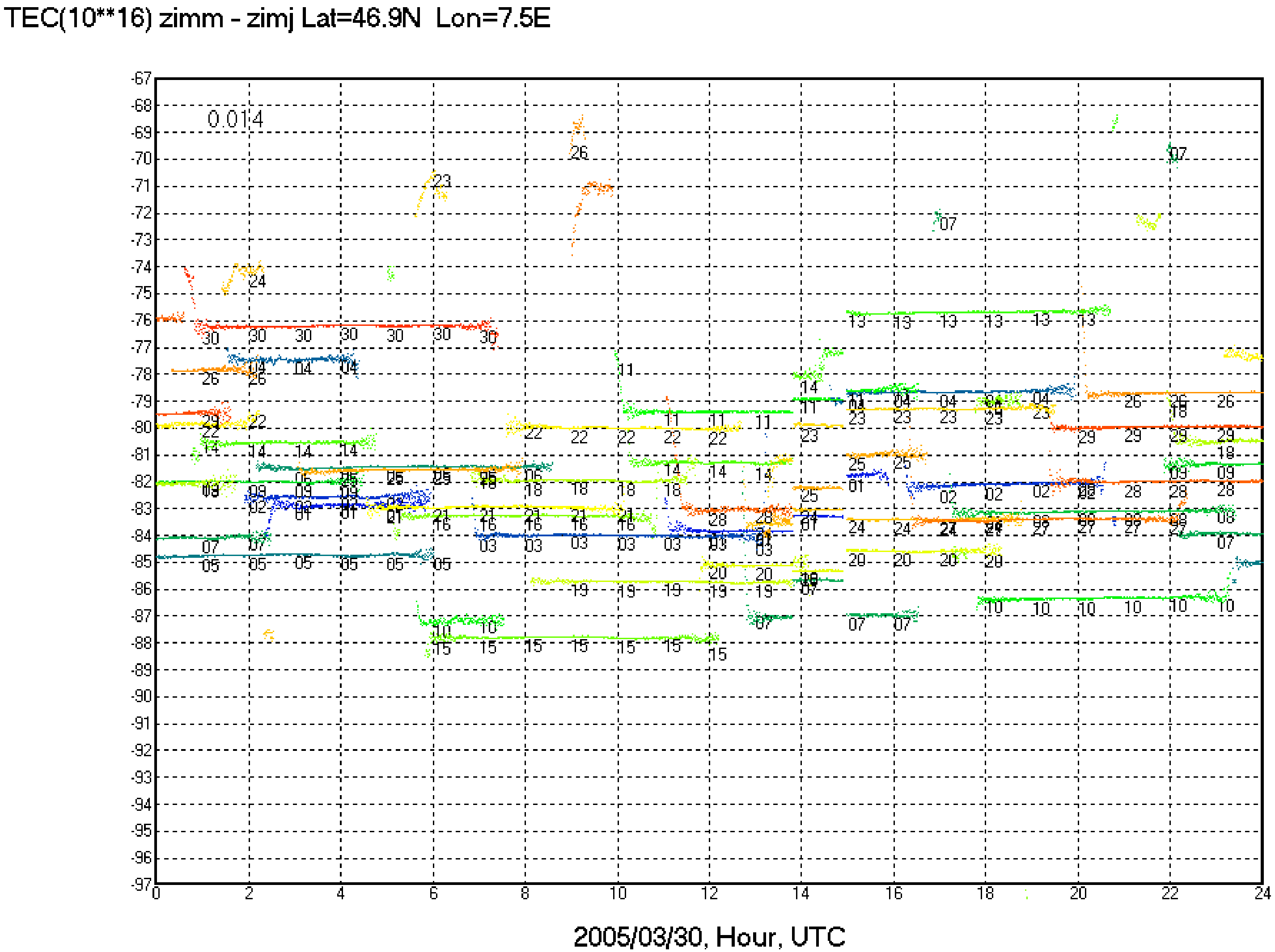
a significant spread among satellites appears

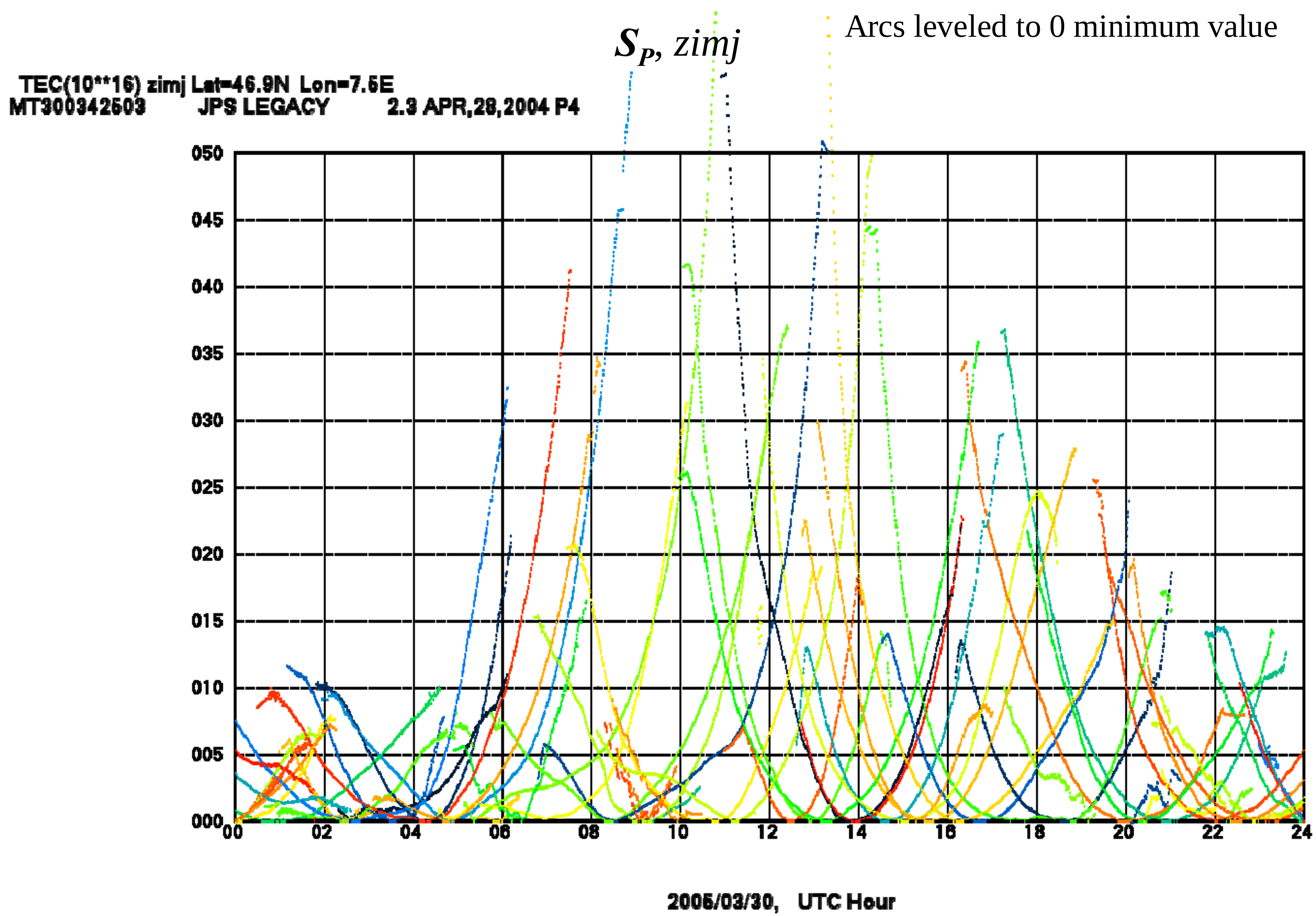
As shown in following slides

Possible cause

the leveling error $\lambda = < m >$?

$S_{L1} - S_{L2}$, all satellites

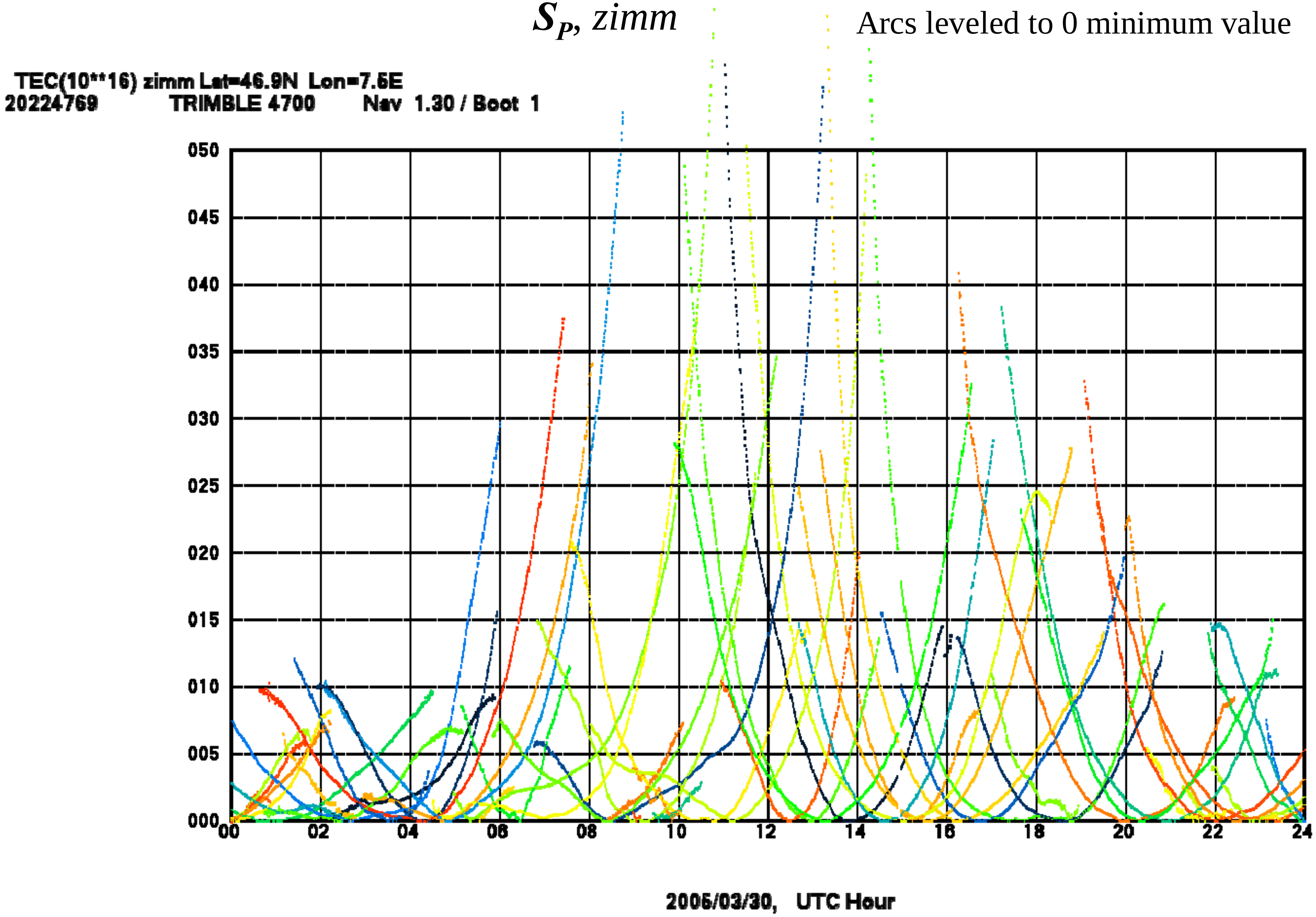




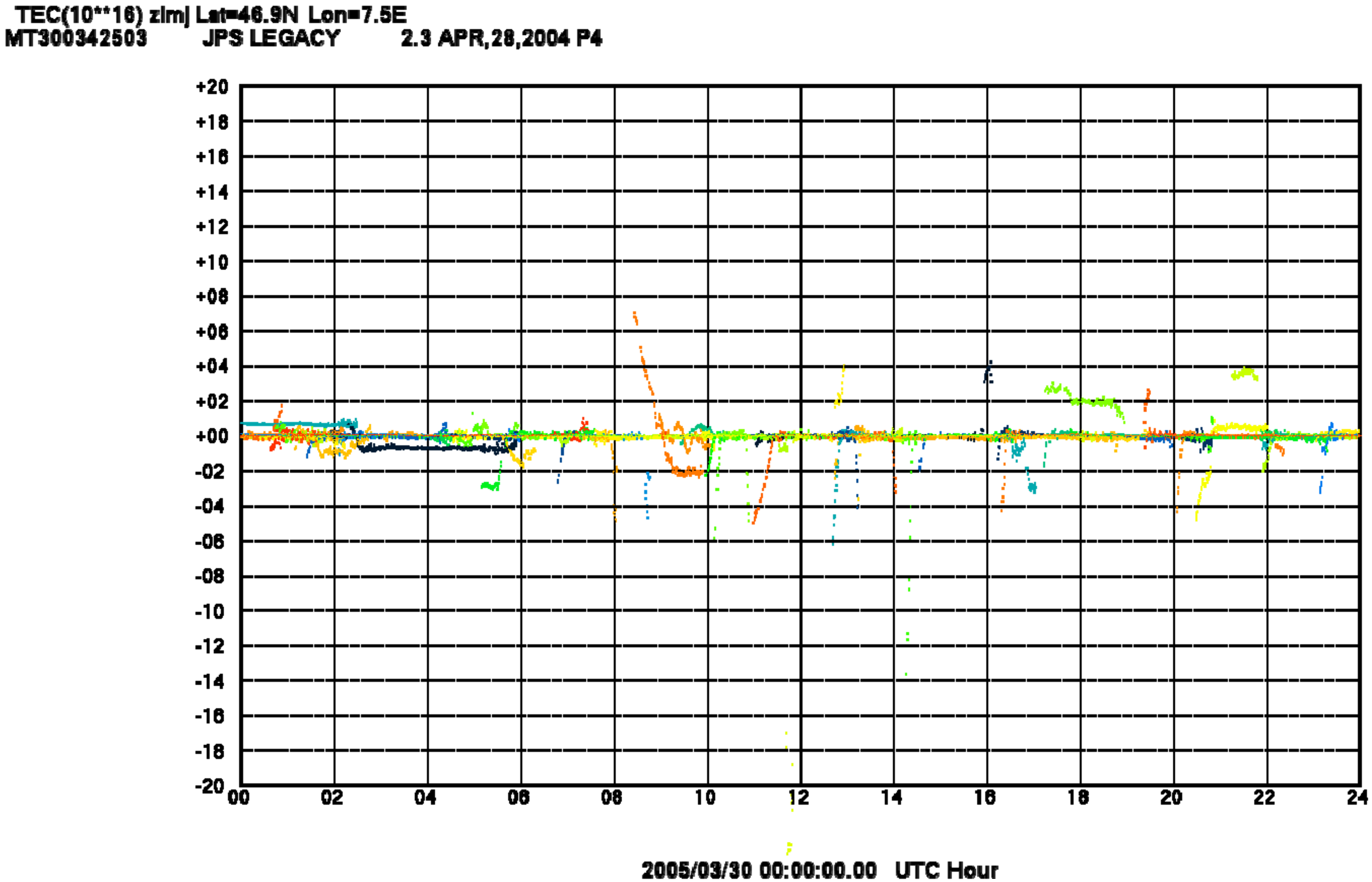
S_P, zimj
Arcs leveled to 0 minimum value
TEC(10**16) zimj Lat=46.9N Lon=7.5E
MT300342503 JPS LEGACY 2.3 APR,28,2004 P4
050
045
040
035
030
025
020
015
010
005
000
00
02
04
06
08
10
12
14
16
18
20
22
24
2005/03/30, UTC Hour

S_P, *zimm*

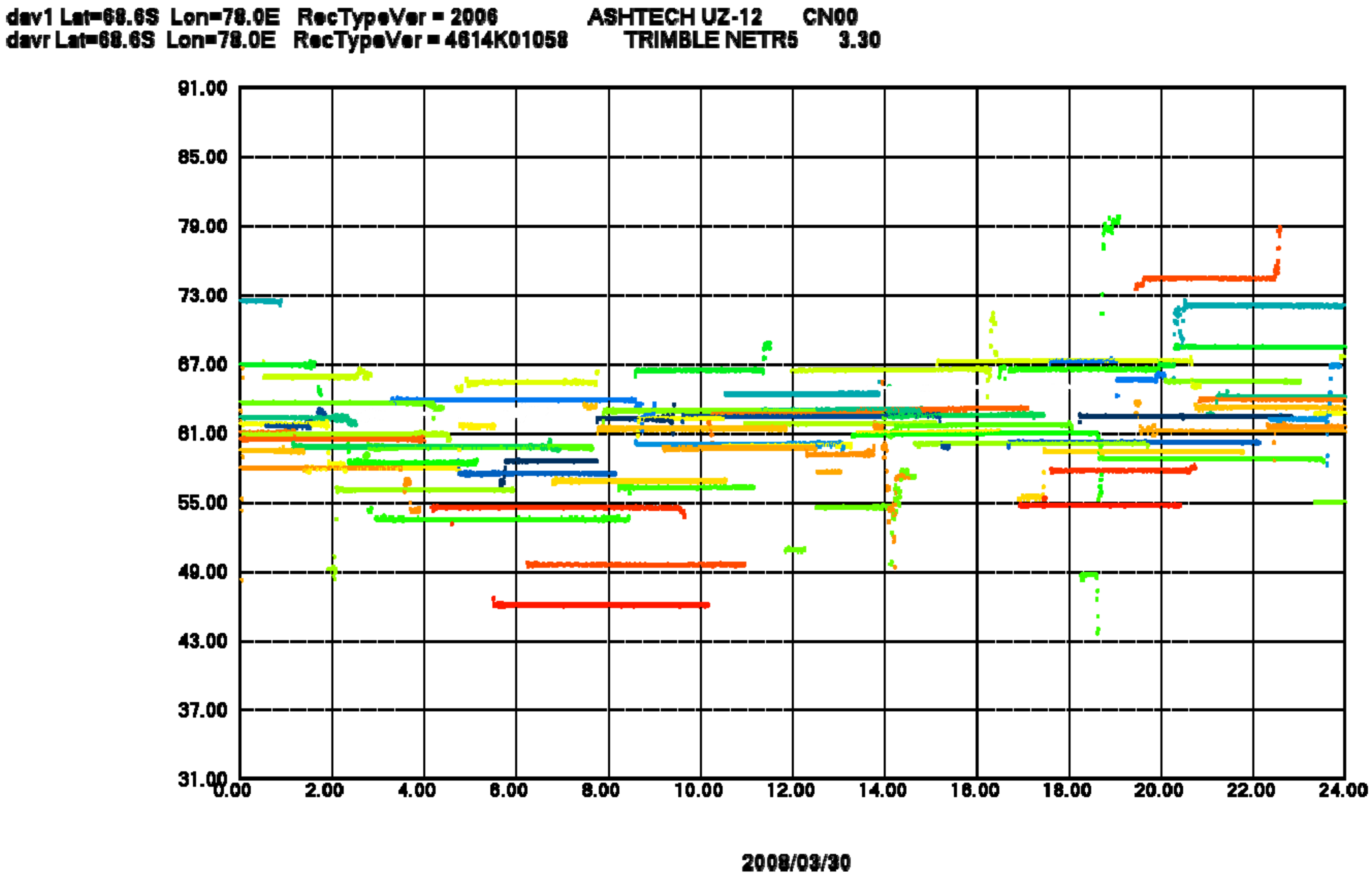
Arcs leveled to 0 minimum value



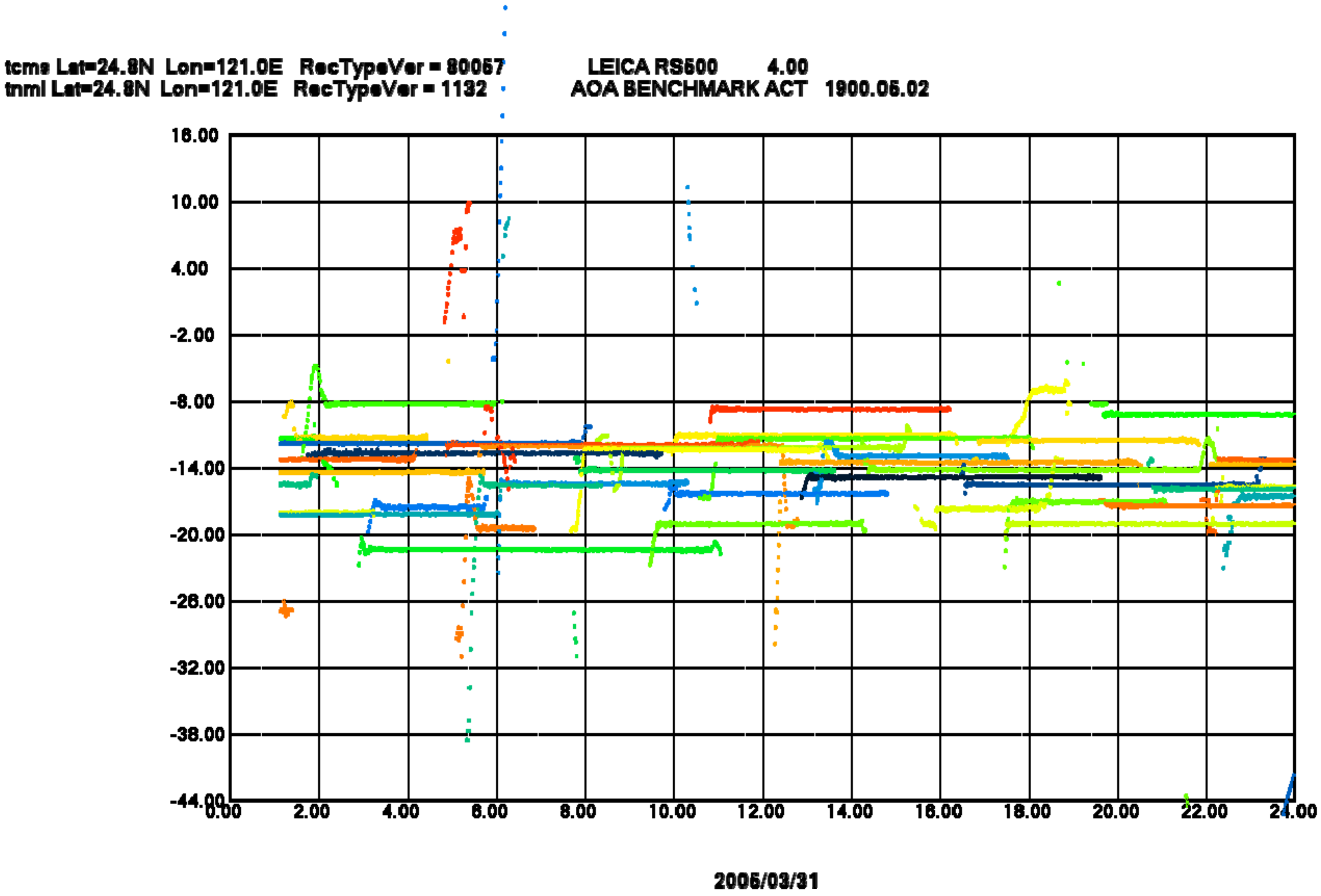
$S_P\,(zimj)$ - $S_P\,(zimm)$



$S_{L1} - S_{L2}$, all satellites



$S_{L1} - S_{L2}$, all satellites



Is this spread due to multipath?

The spread among satellites, according to

$$\boldsymbol{S_{ij}} - \boldsymbol{S_{ik}} = \gamma_j - \gamma_k + \lambda_{Arc\_i} - \lambda_{Arc\_k}$$

provides with an estimation of the spread of $\lambda_{Arc\_i} - \lambda_{Arc\_k}$ around $\gamma_j - \gamma_k$

The split antenna experiment seems to confirm it.

The receivers of *"blue"* and *"red0"*, of the same firm, have been fed from the same antenna.

Implications: *"blue"* and *"red0"* see exactly the same multipath.

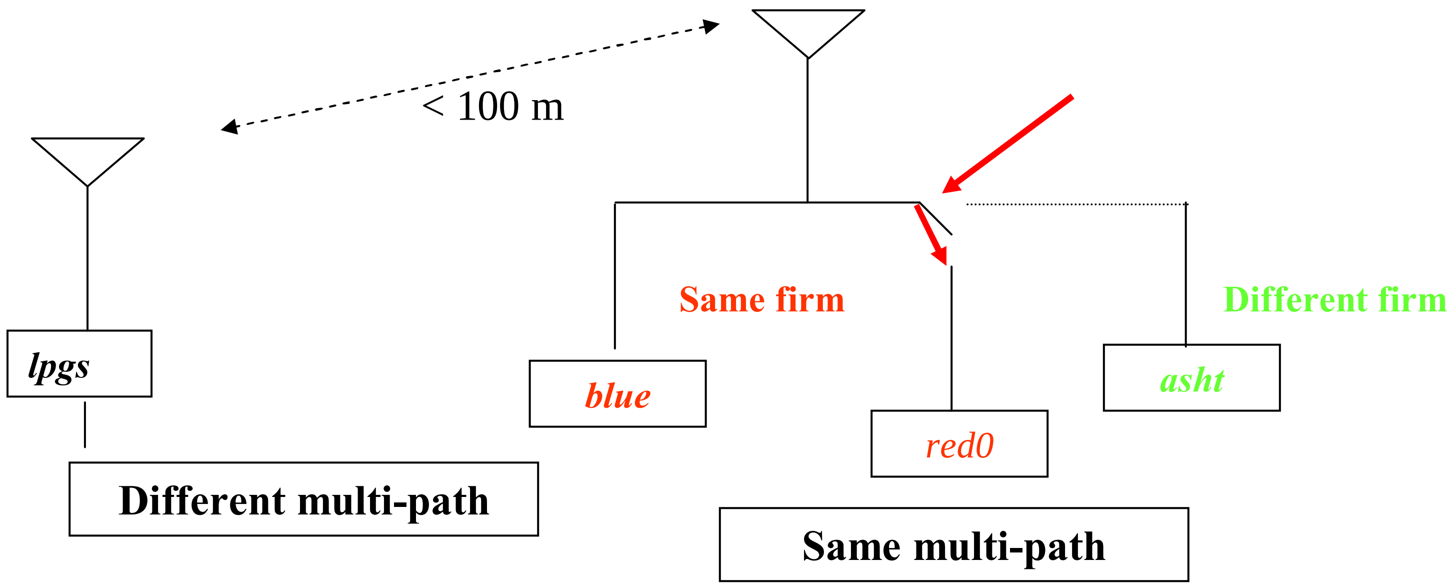
Besides IGS stations, a special set of observation has been set up by the group of La Plata University, Argentina (C.Brunini, F.Azpiliqueta).

Close to the IGS station ***"lpgs"***, the additional stations ***"blue"***, ***"red0"*** and ***"asht"*** have been set up to perform the following experiments

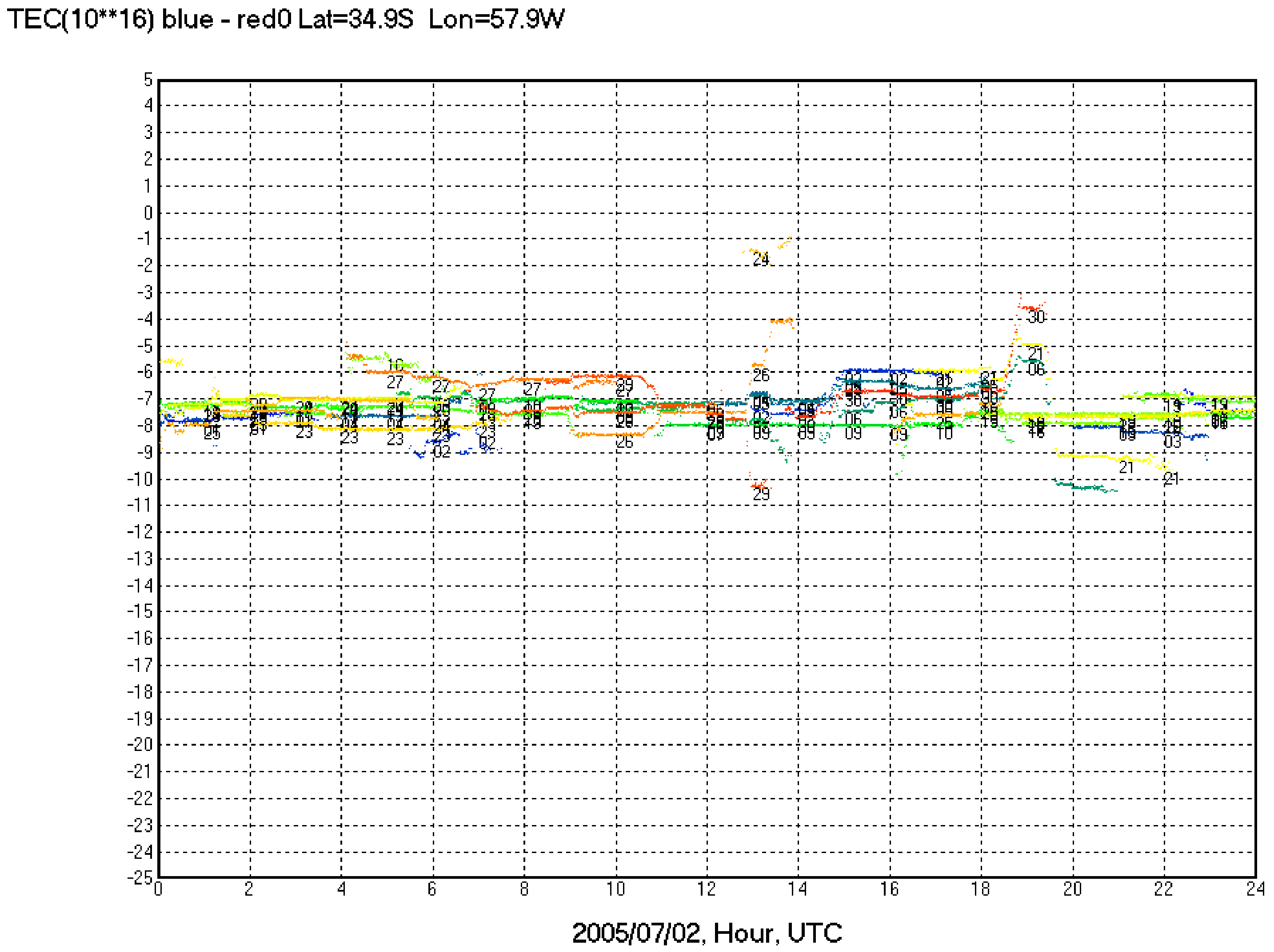
Close stations: different multipath; same or different way of processing multipath

Split antenna, receivers of same firm: same multipath, same way of processing it

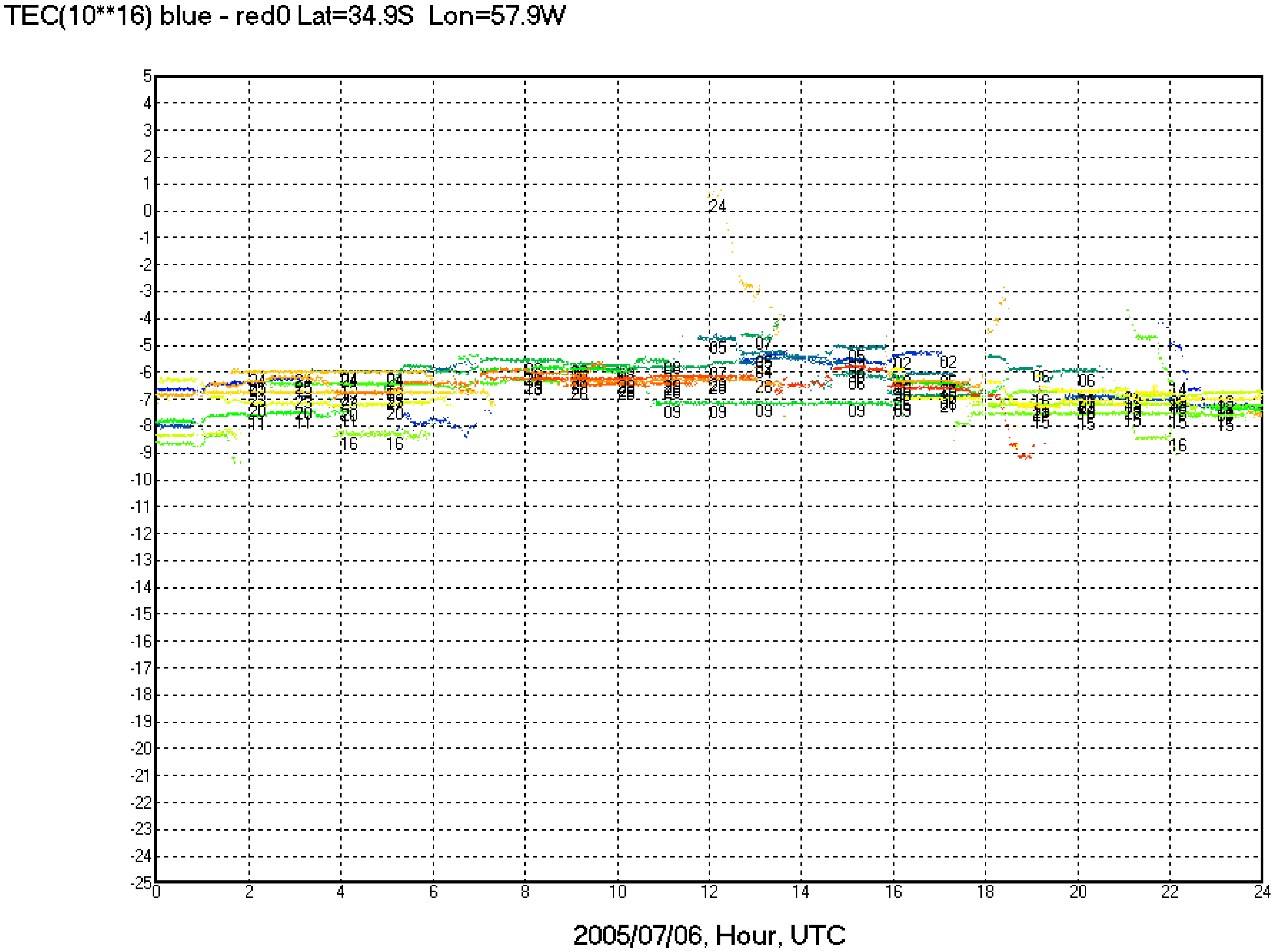
Split antenna, receivers of different firms: same multipath, different way of processing



Split antenna, same multipath, same type of receiver



Split antenna, same multipath, same type of receiver



To reduce errors in observations, what is needed is

Recipes to reduce multipath effects

-care antenna environment and radio-technical coupling

In the normal situation, the observed discrepancies amount to several ***TECu***.

If this is due to multi-path only, great care must be taken in selecting a weighted average <·> using small weights when multi-path is expected to be large:

-avoid short arcs

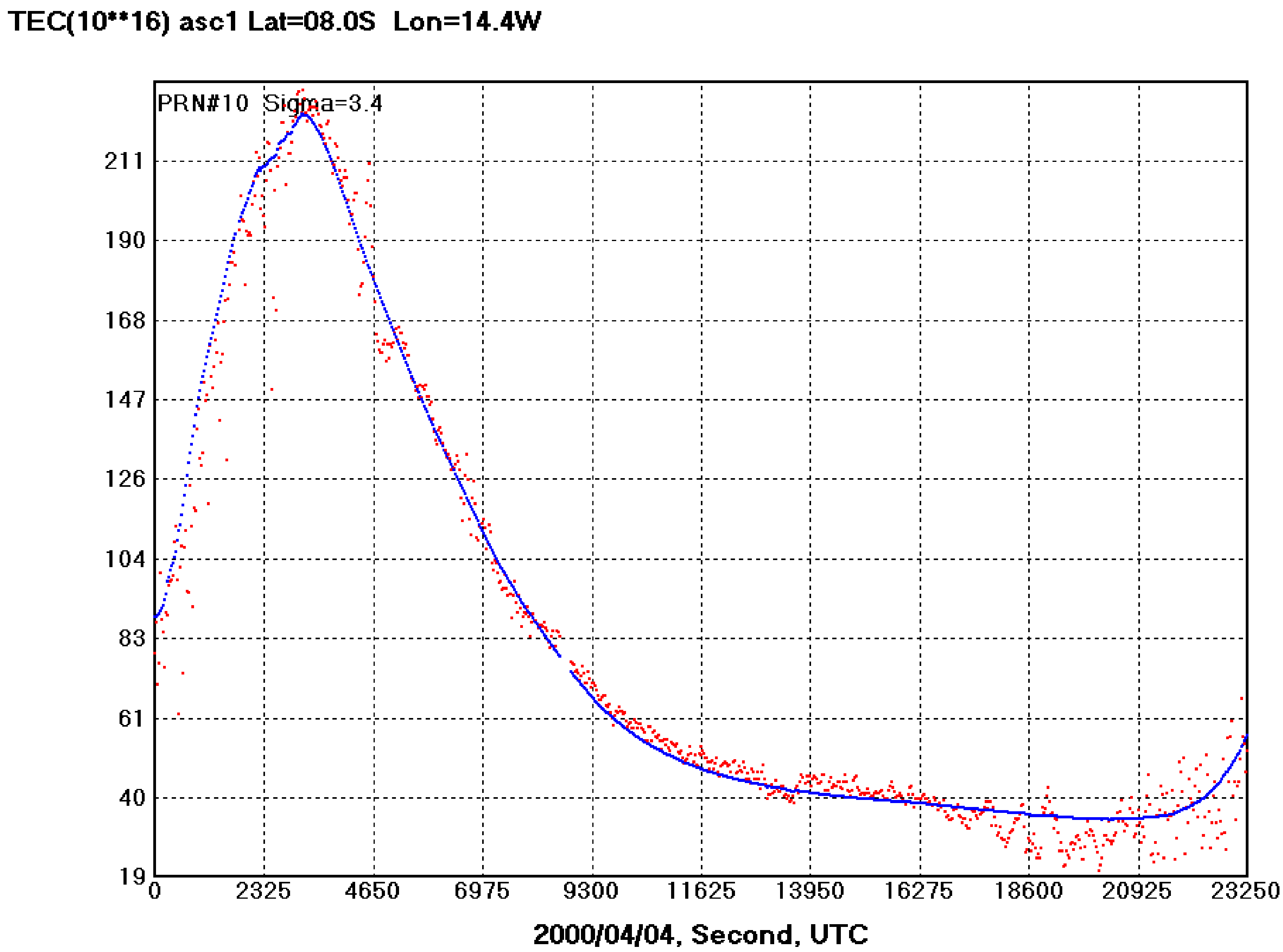
-care the selection of weights

-use an elevation mask as higher as possible (where ***m*** is reasonably less strong)

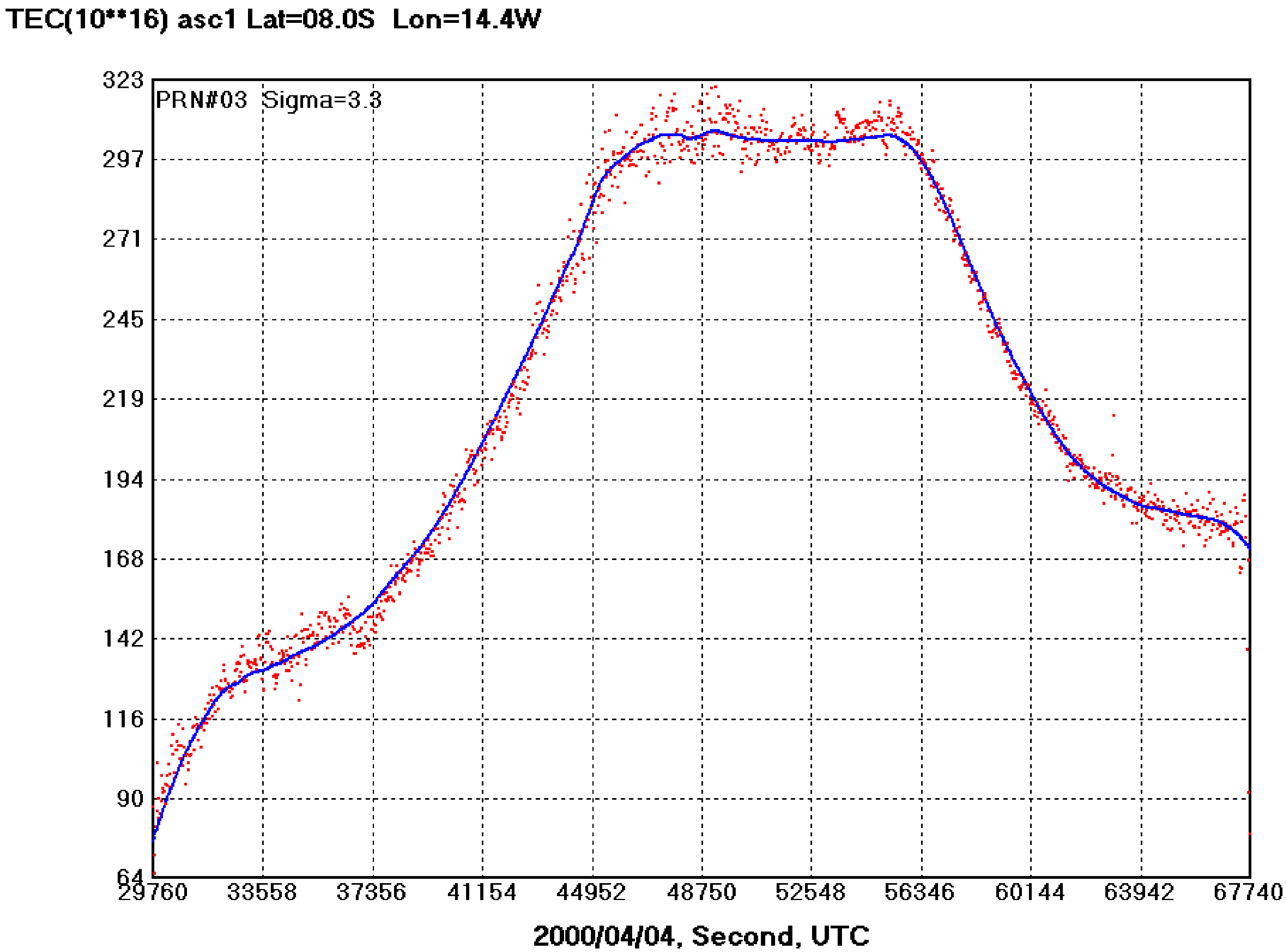
empirically, using past experience

trying to estimate them from the plots of $S_G - S$, which according to the equations of the reported observables is $m + n - \langle m + n \rangle$

$$W = 1 \text{ if } Abs(S_G - S) < Sigma_{SG-S}$$
$$W = \{Sigma_{SG-S} / Abs(S_G - S)\}^{2n}$$



TEC(10**16) asc1 Lat=08.0S Lon=14.4W
PRN#10 Sigma=3.4
211
190
168
147
126
104
83
61
40
19
0
2325
4650
6975
9300
11625
13950
16275
18600
20925
23250
2000/04/04, Second, UTC


TEC(10**16) asc1 Lat=08.0S Lon=14.4W
PRN#03 Sigma=3.3
323
297
271
245
219
194
168
142
116
90
64
29760
33558
37356
41154
44952
48750
52548
56346
60144
63942
67740
2000/04/04, Second, UTC

But are we dealing with actual multipath only?

For some station pairs, strange patterns appear.

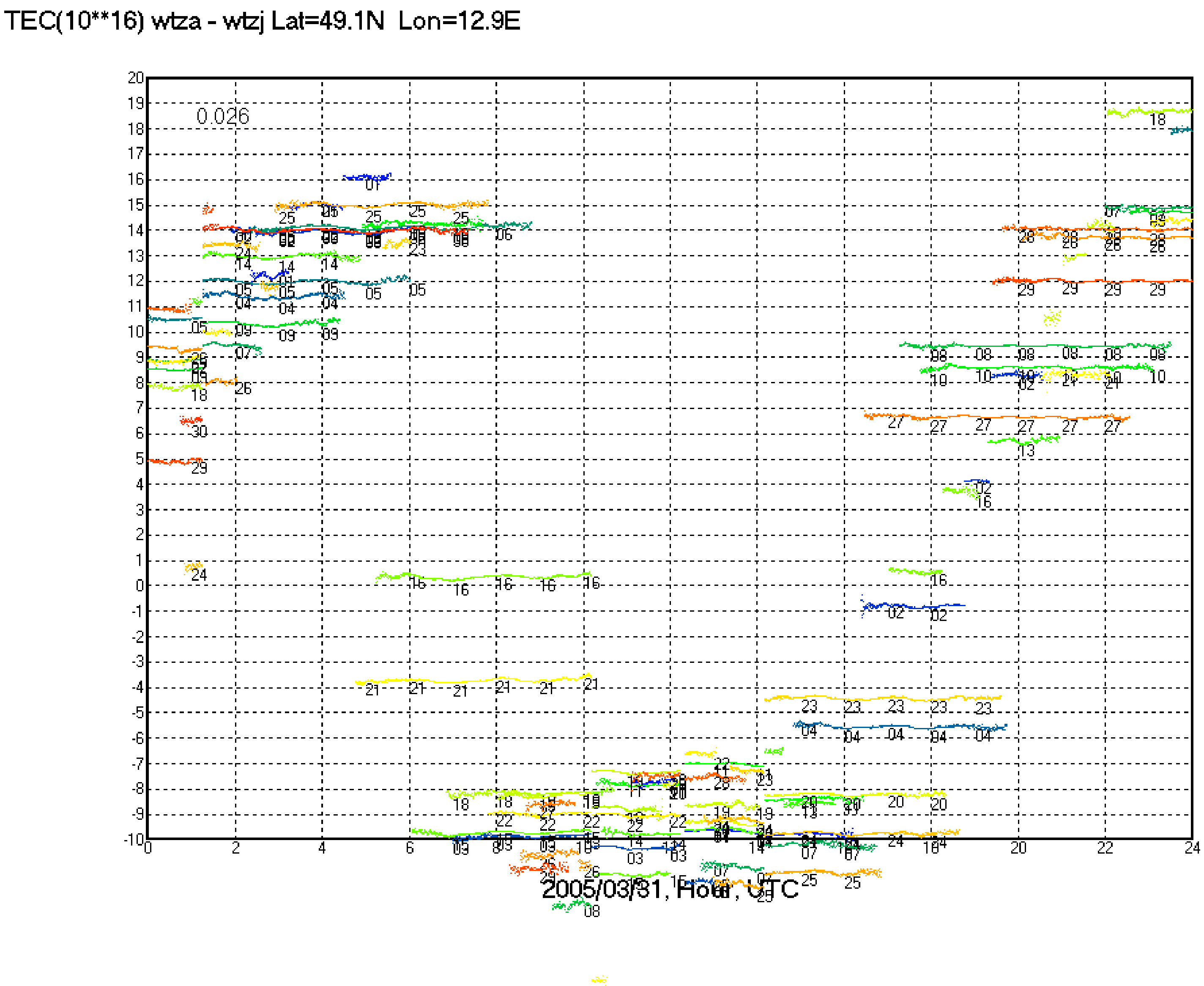
In the following, station *"wtzj"* compared to the colocated *"wtza"*, *"wtzr"*, *"wtzt"*, *"wtzz"*, exhibits a strange pattern.

The problem is limited to *"wtzj"* , as the plots for other pairs are "normal".

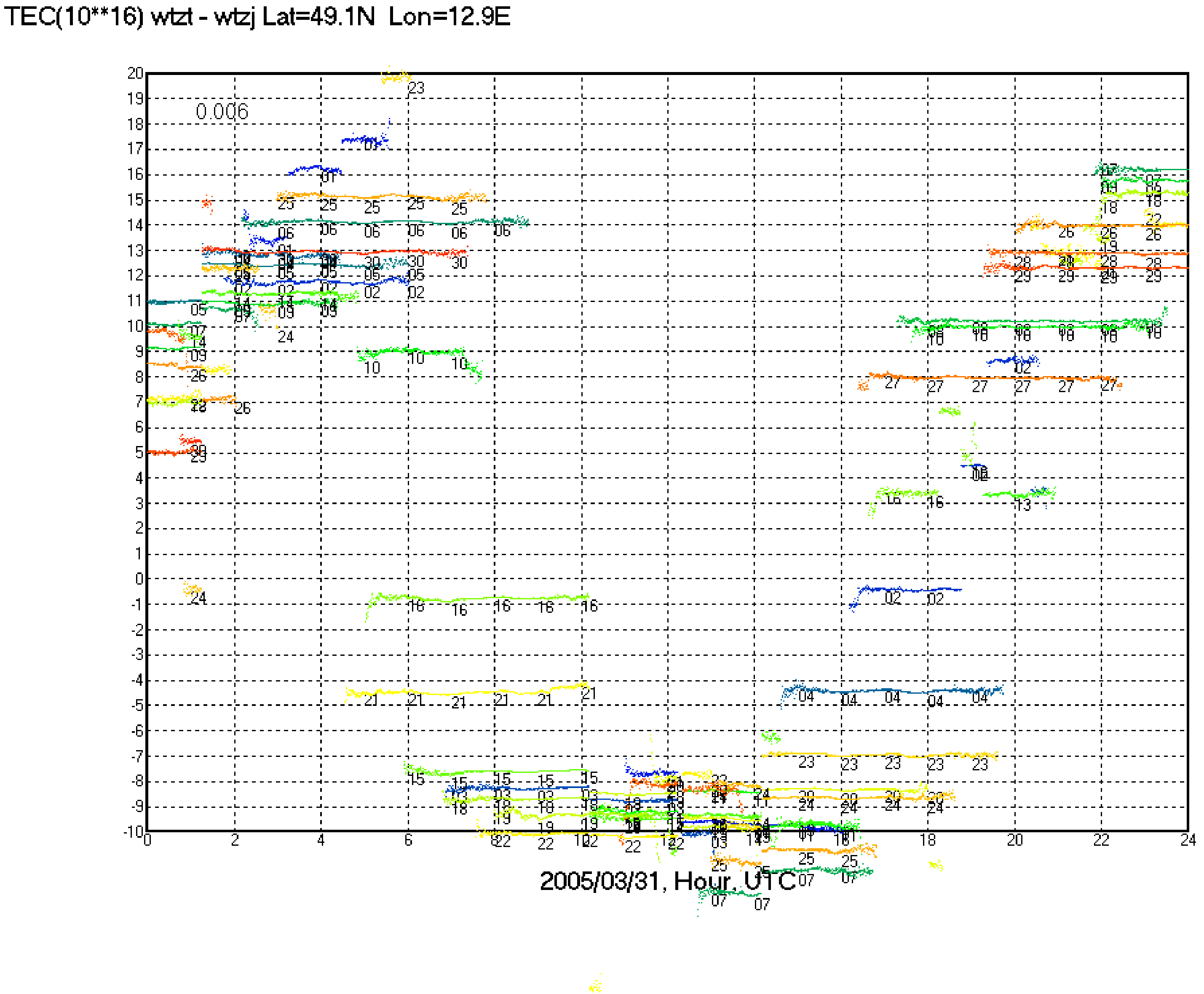
Is it a thermal drift of station bias?

What will it happen to the calibration with discrepancies amounting to almost 25 *TECu* , and having no knowledge of the behavior of the station (evidenced only by the availability of close stations) ?

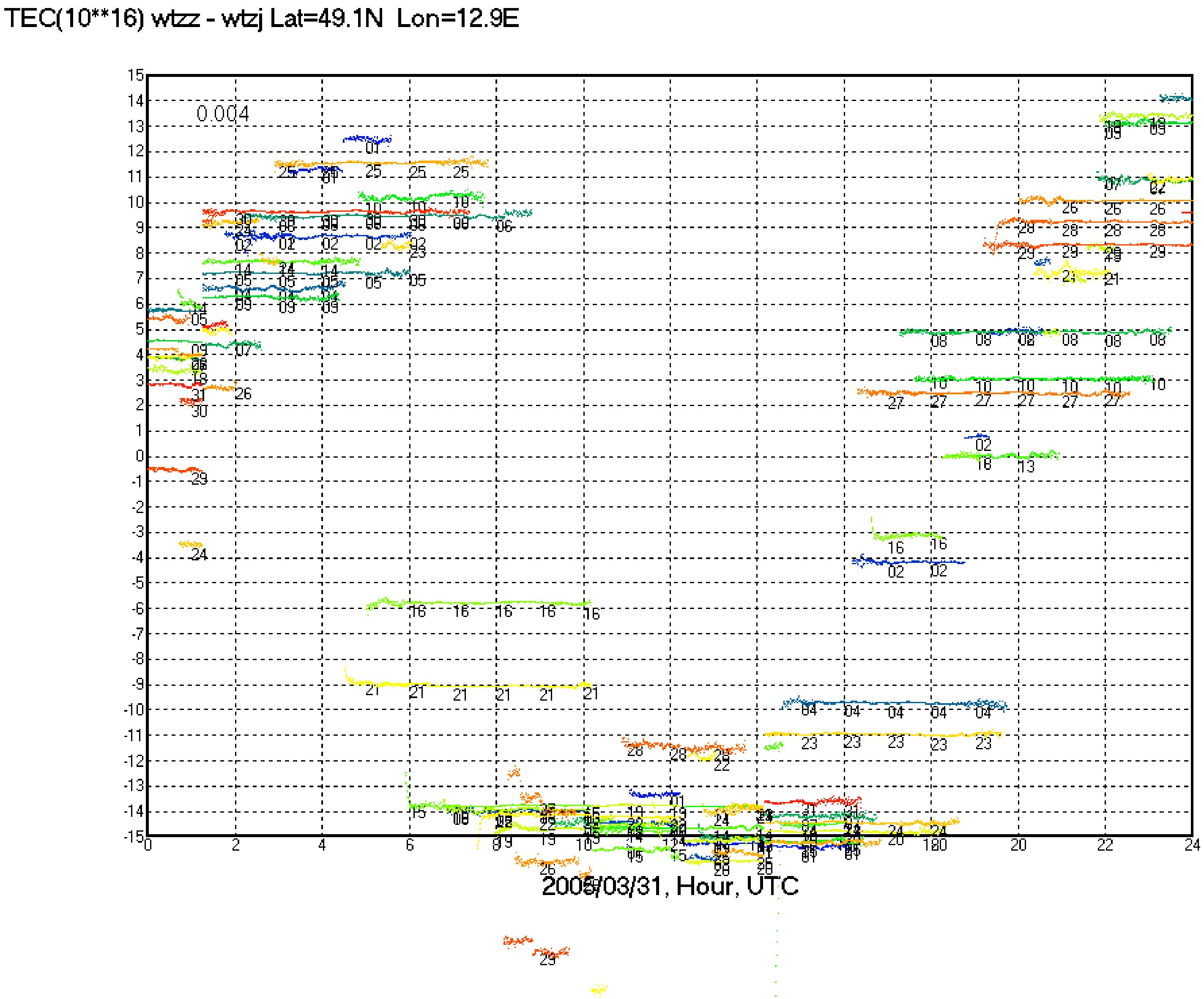
$S_{L1} - S_{L2}$, all satellites



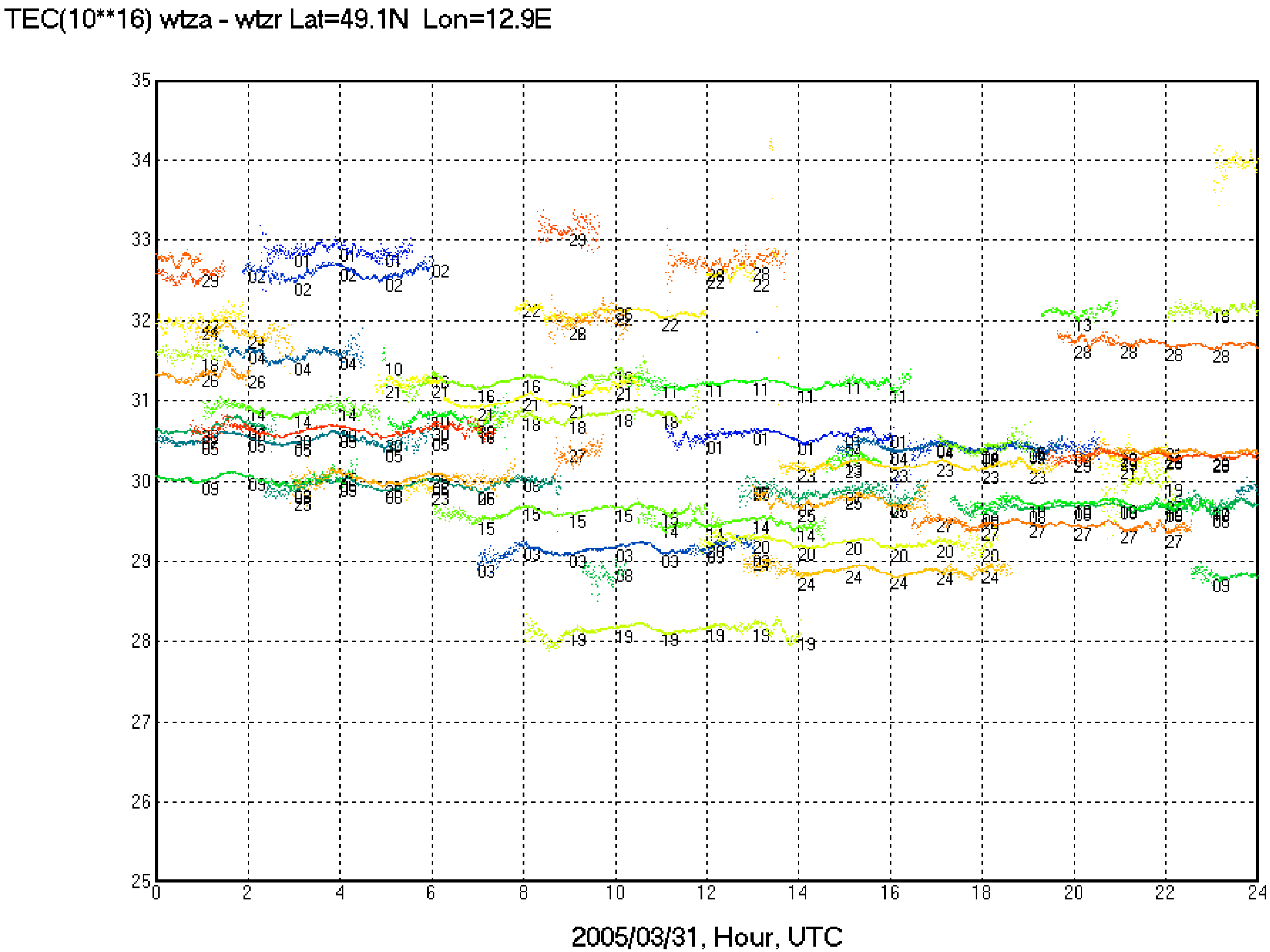
$S_{L1} - S_{L2}$, all satellites



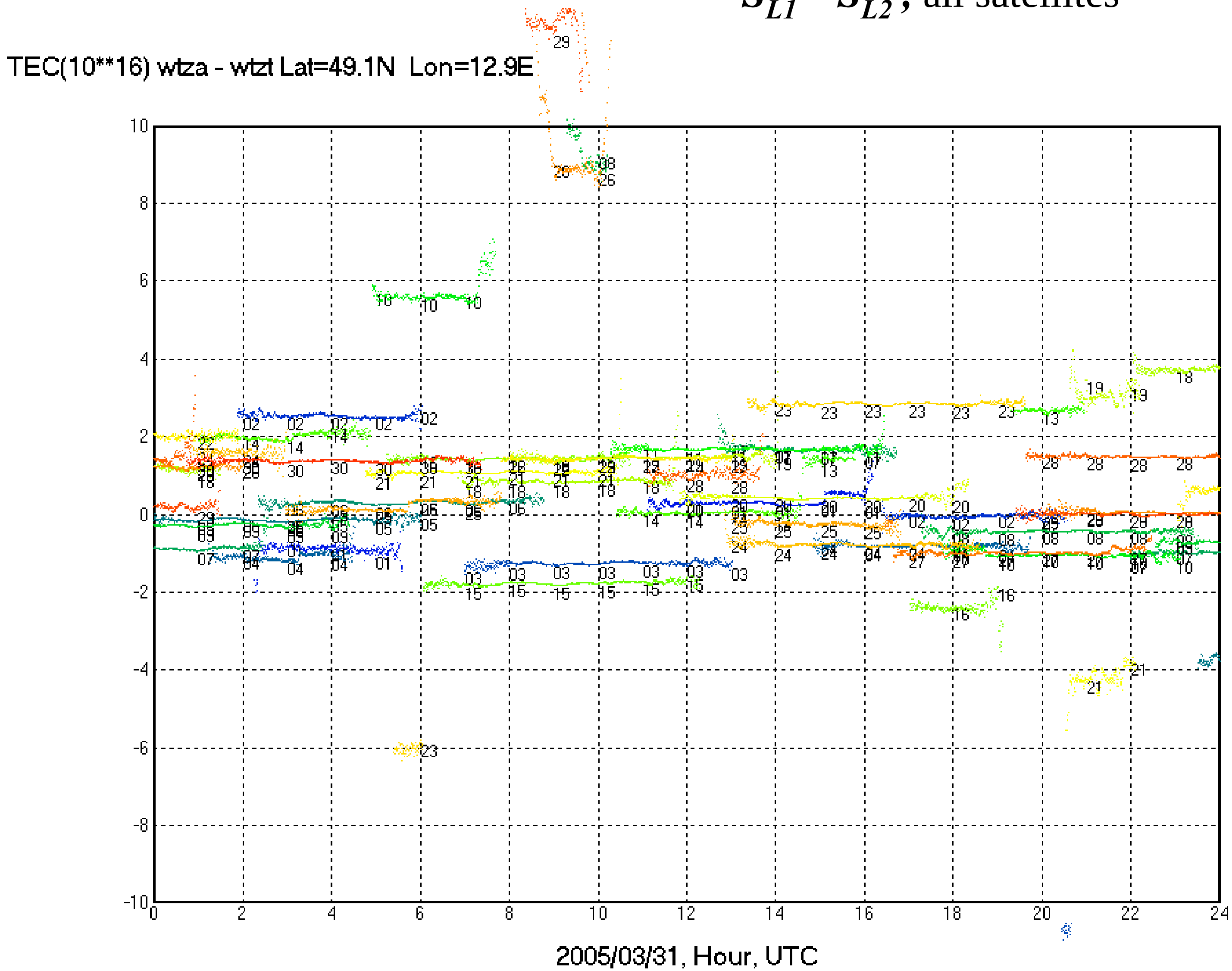
$S_{L1} - S_{L2}$, all satellites



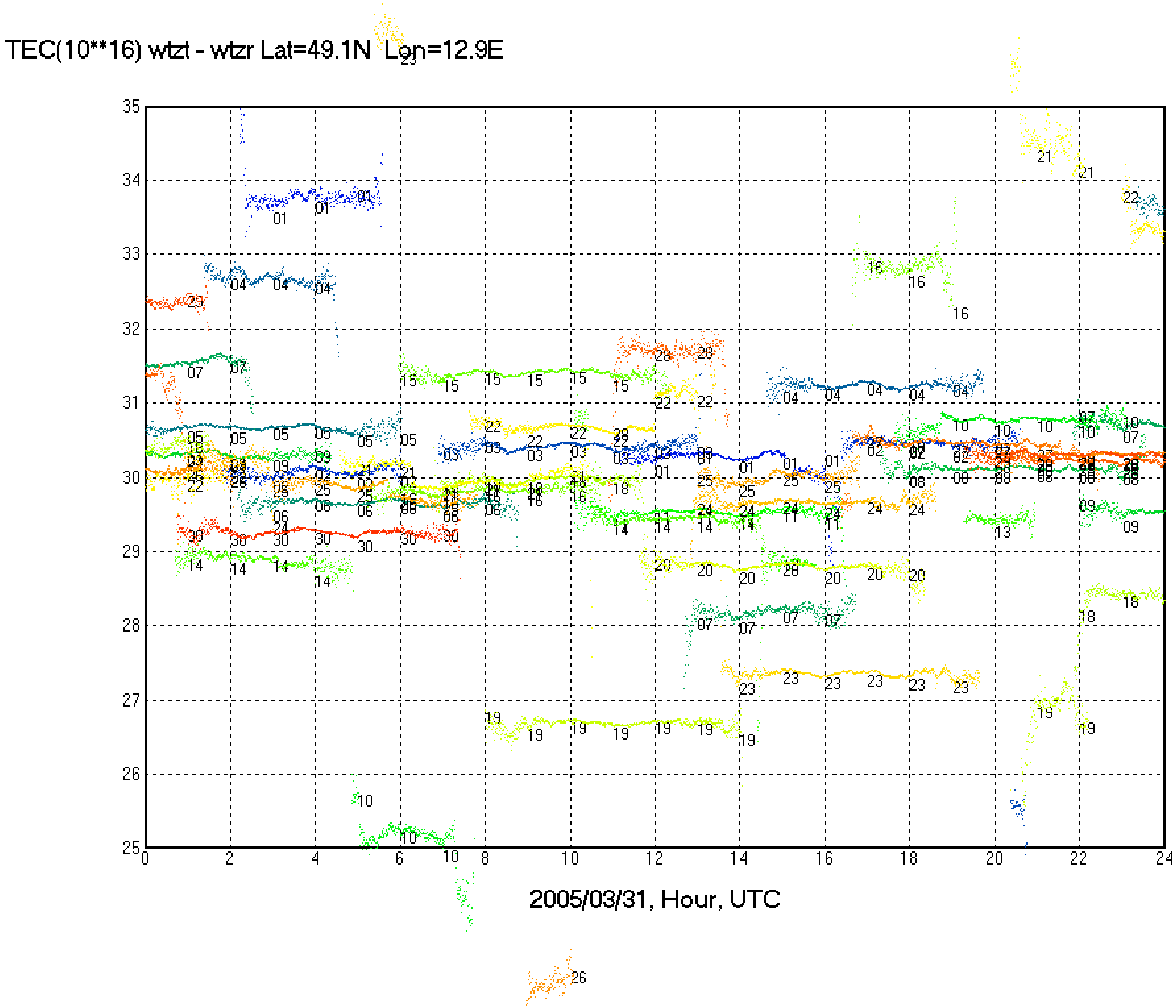
$S_{L1} - S_{L2}$, all satellites



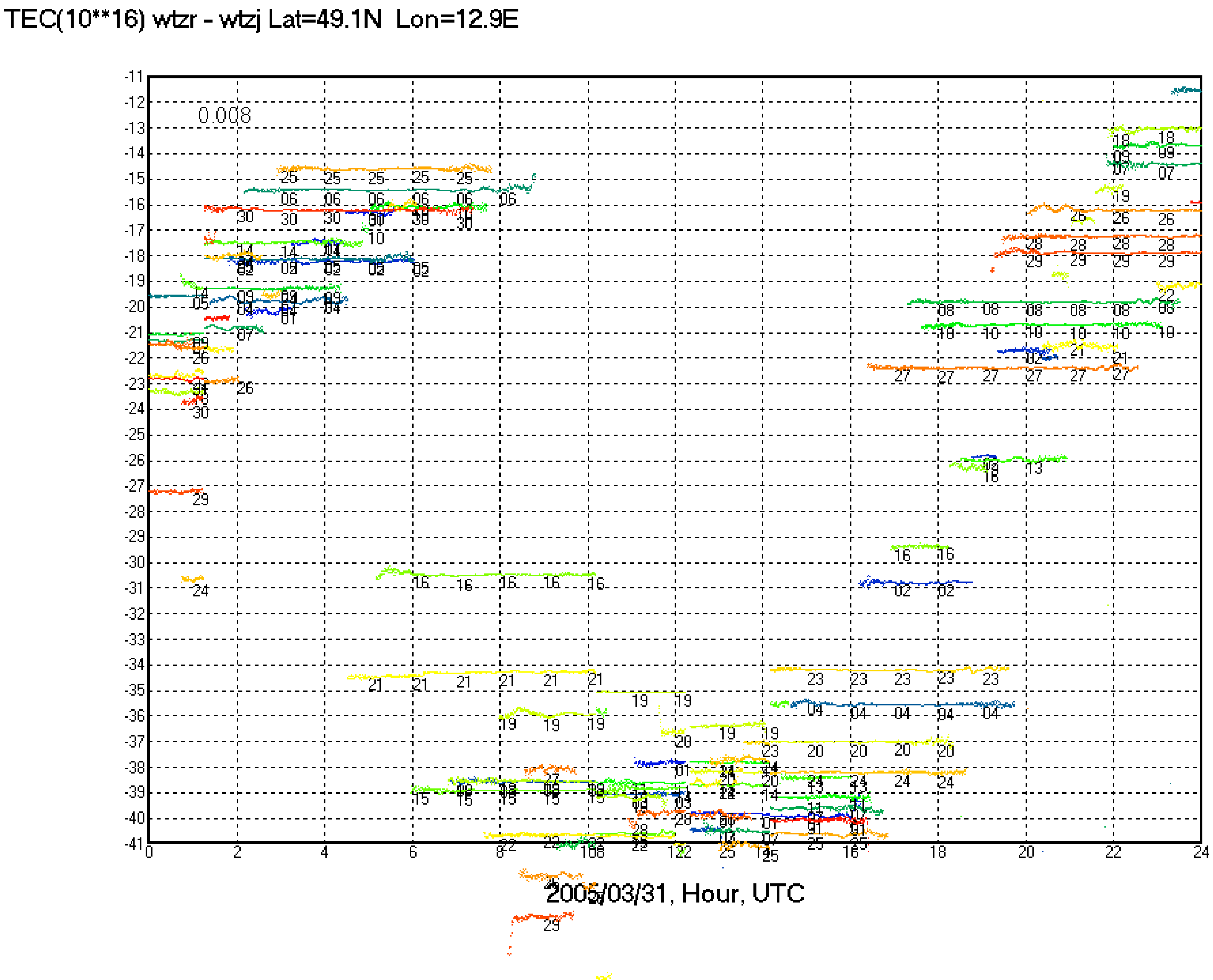
$S_{L1} - S_{L2}$, all satellites



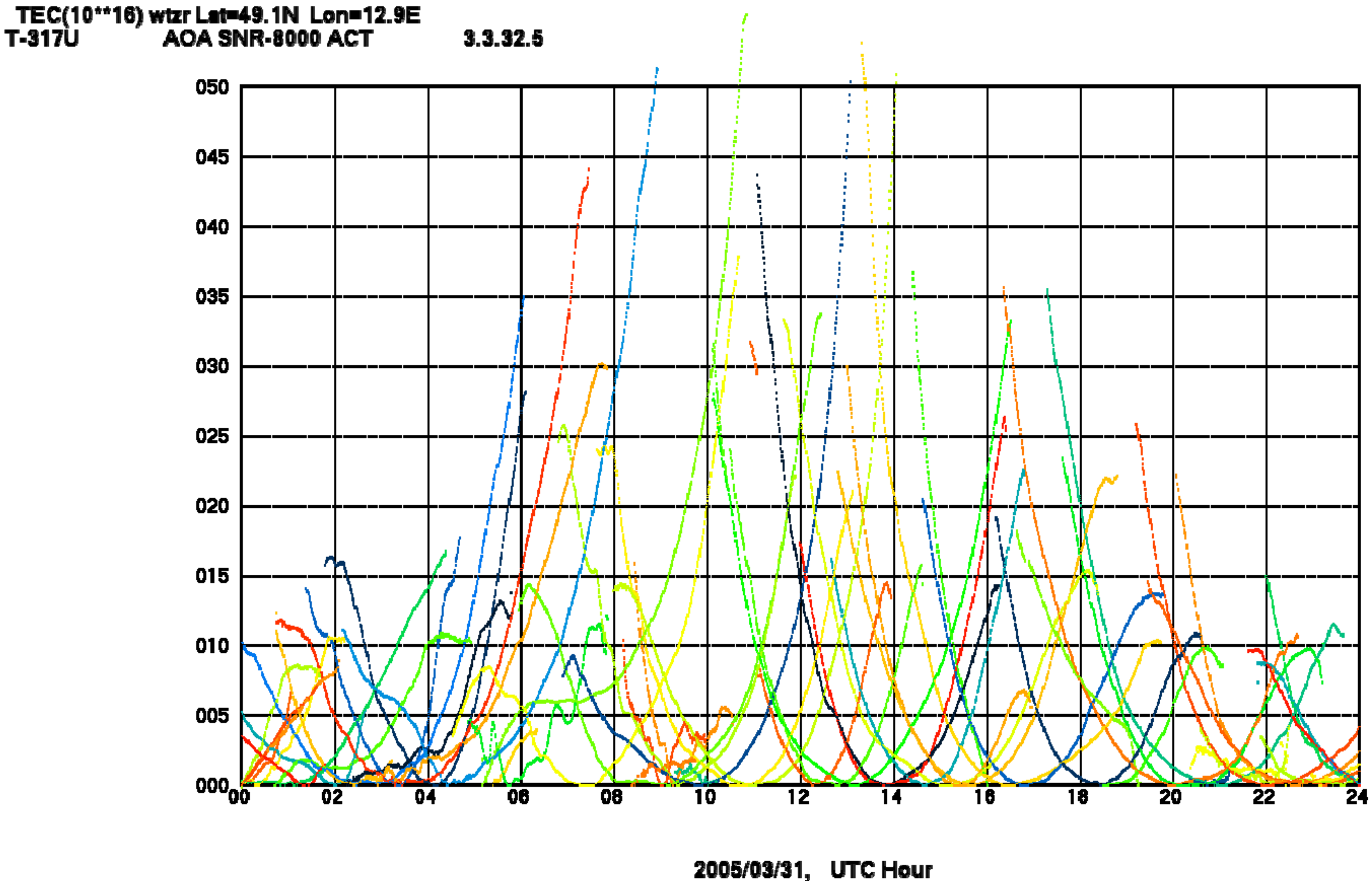
$S_{L1} - S_{L2}$, all satellites



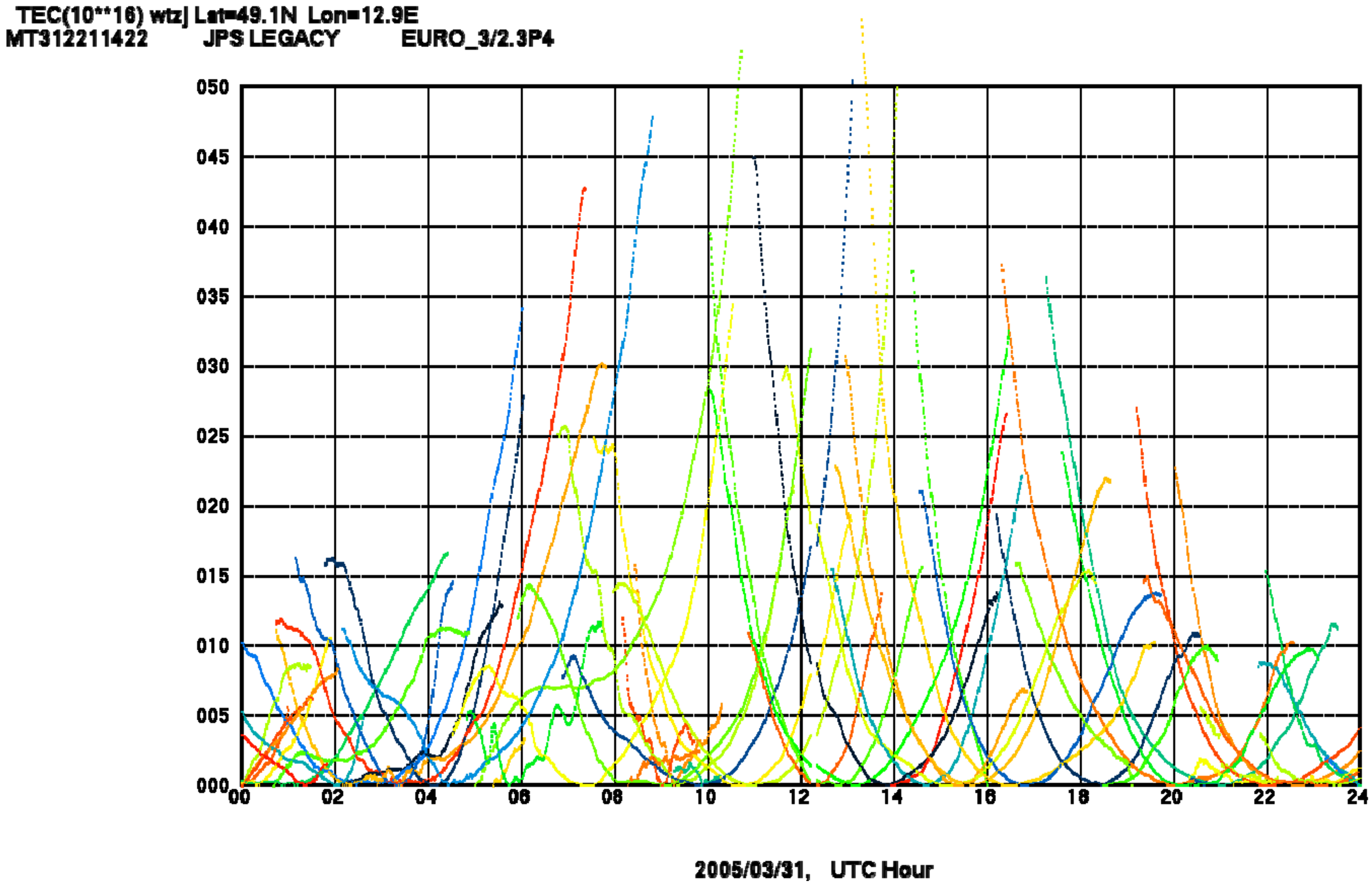
$S_{L1} - S_{L2}$, all satellites



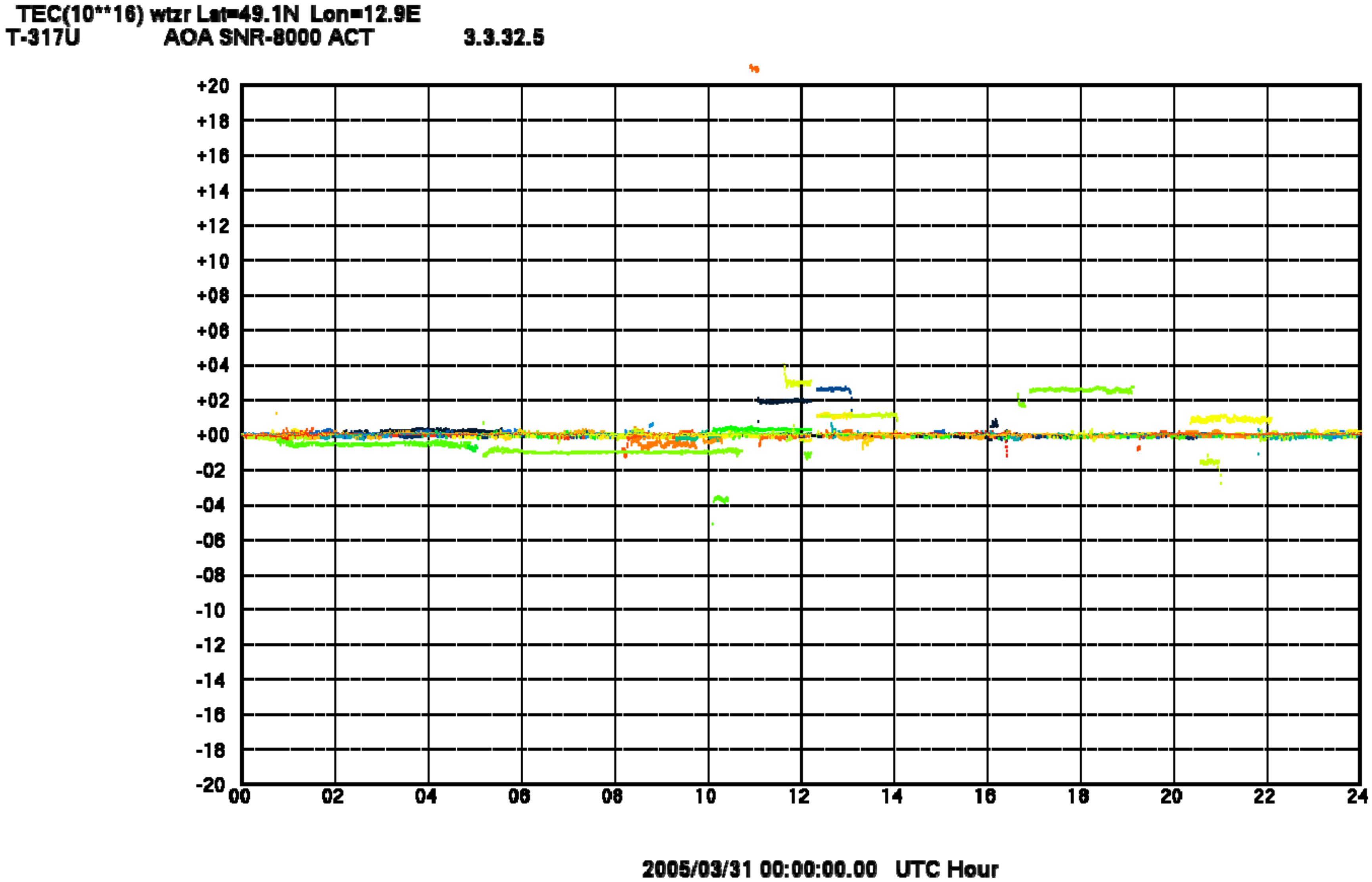
Arcs leveled to 0 minimum value



Arcs leveled to 0 minimum value



$S_P\,(wtzj)$ - $S_P\,(wtzr)$

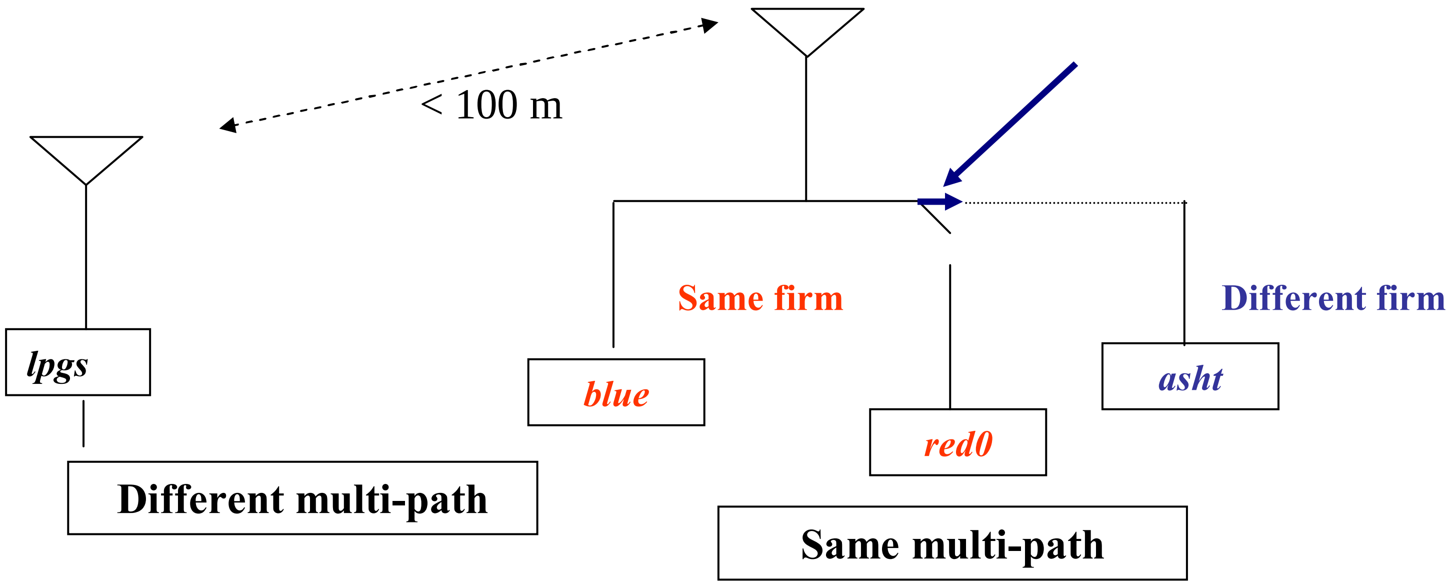


Still: **only multipath or some other problem**?

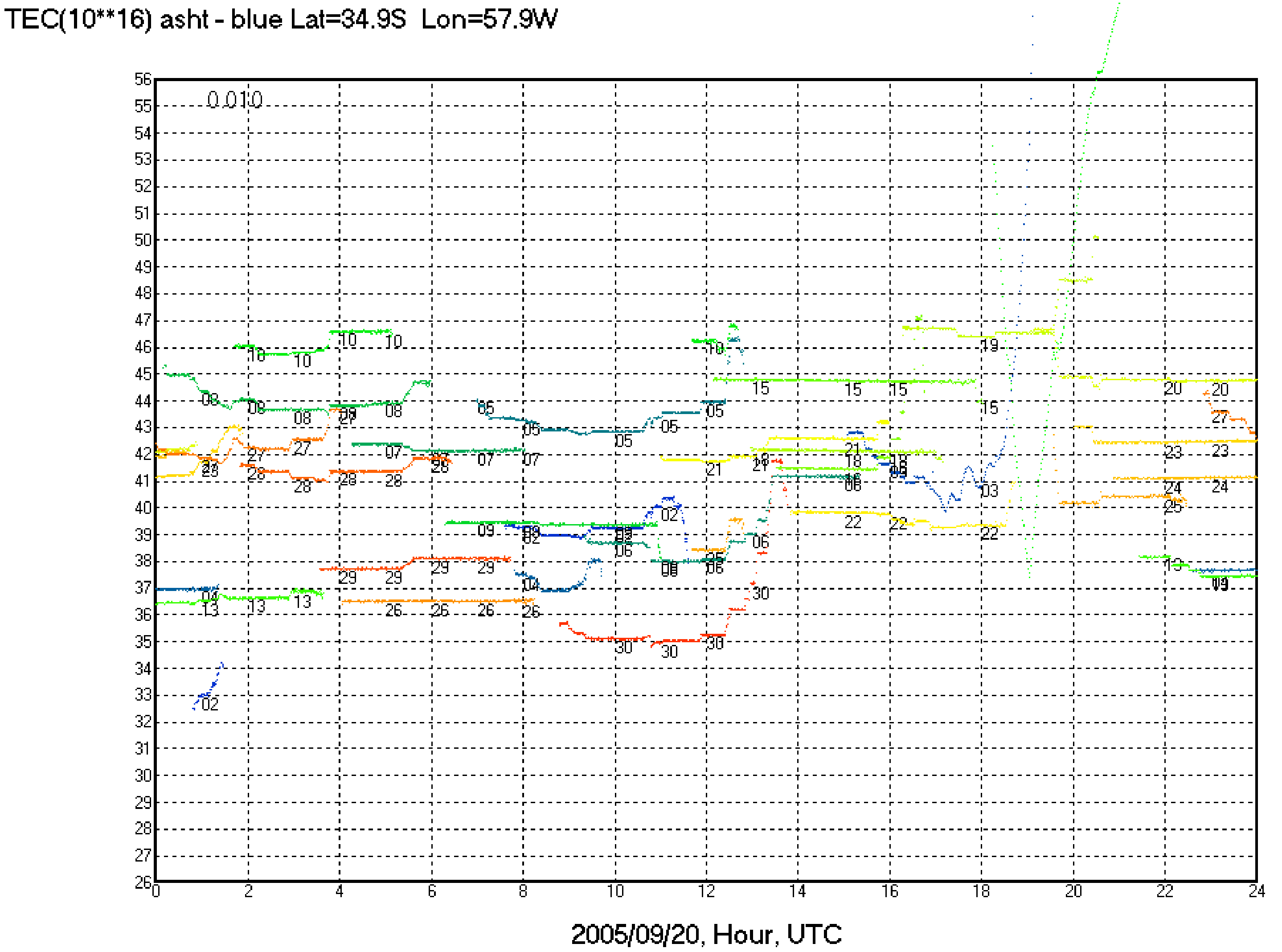
Back to the split antenna experiment,

but using receivers of different firms.

Spread will appear again, suggesting that its cause is more the way by which multipath is processed rather than multipath itself.

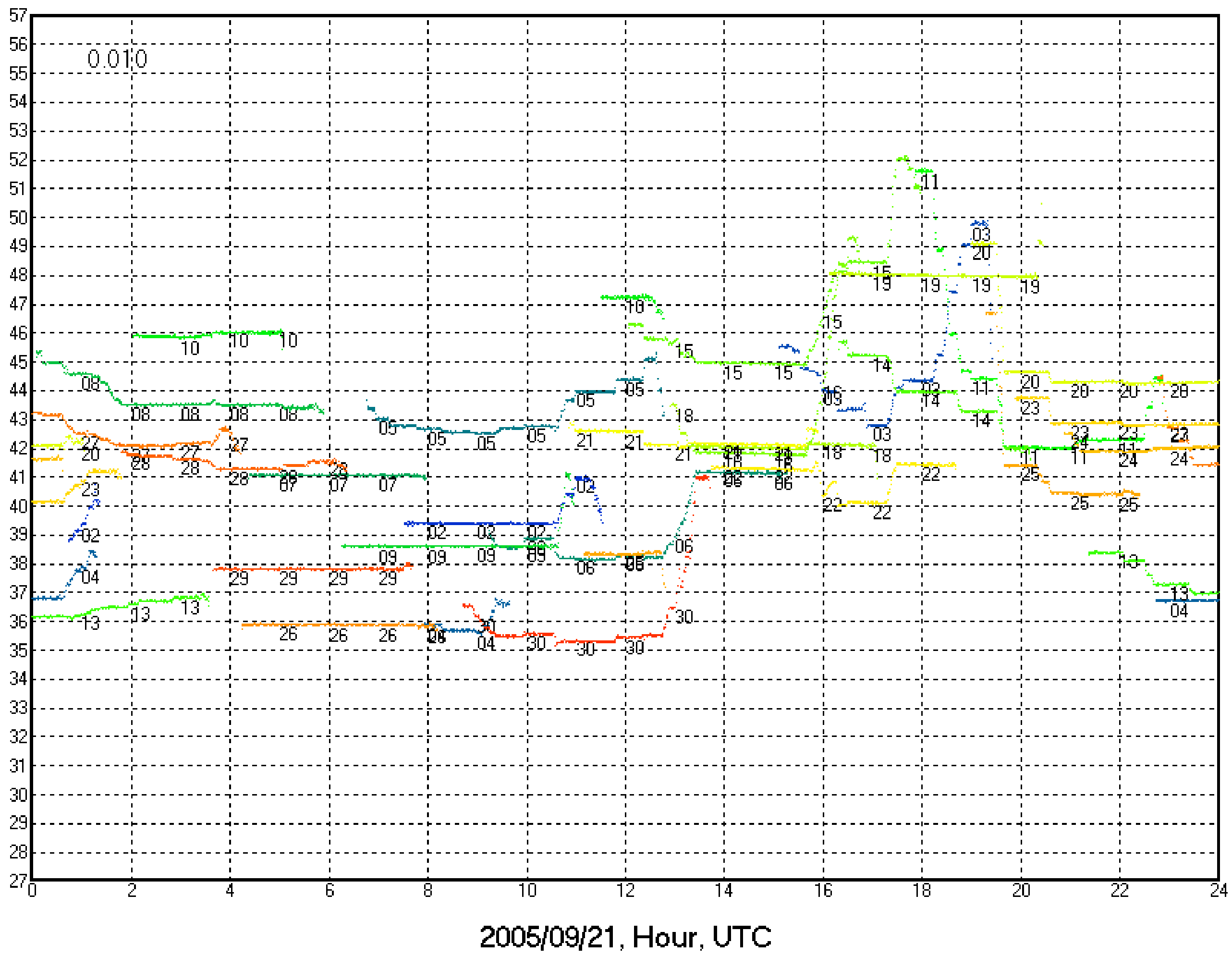


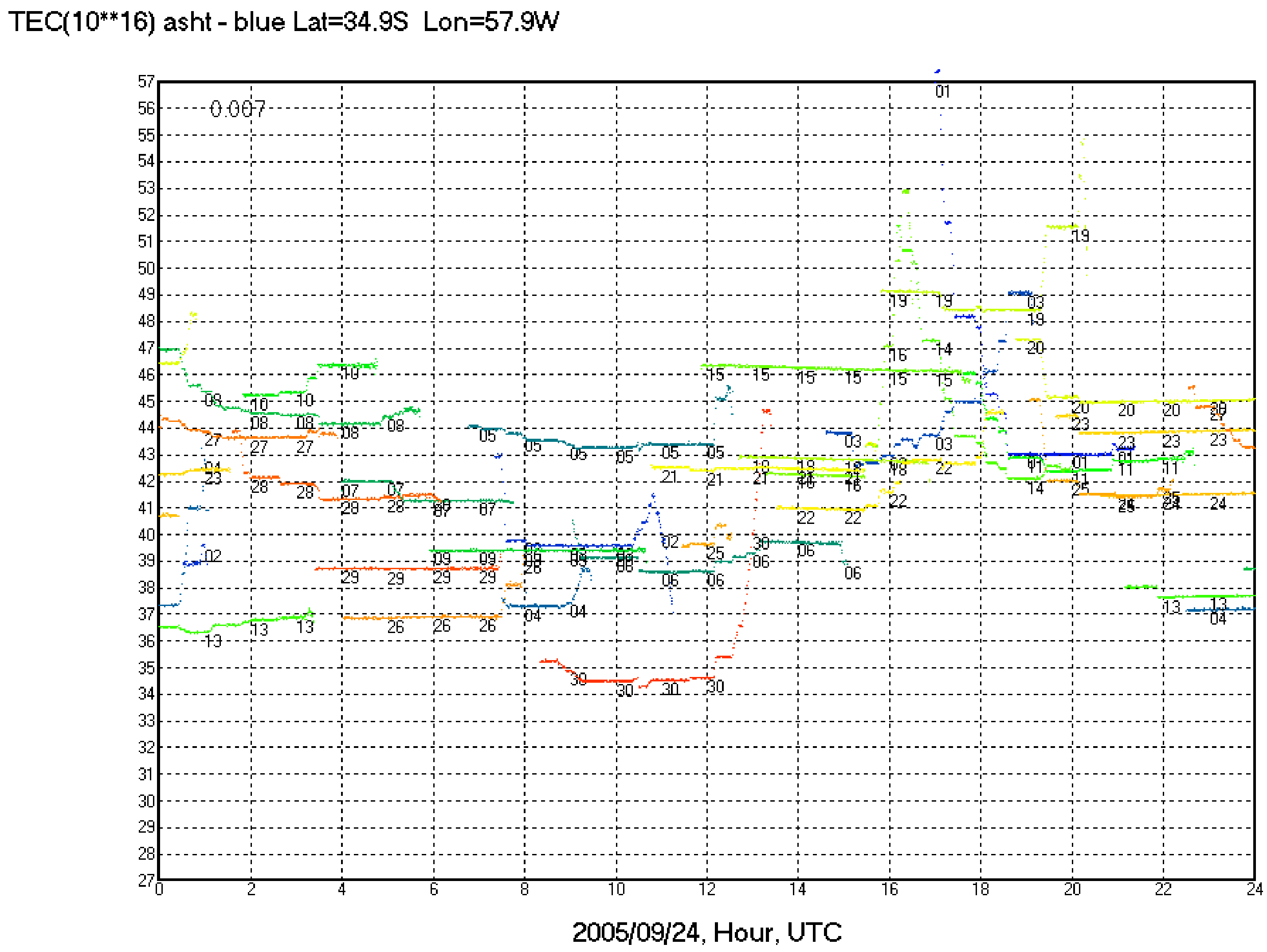
Split antenna, same multipath, different type of receiver



Split antenna, same multipath, different type of receiver

TEC(10**16) asht - blue Lat=34.9S Lon=57.9W




TEC(10**16) asht - blue Lat=34.9S Lon=57.9W
0.007
2005/09/24, Hour, UTC

Conclusion of above experiments

Leveled to code slants are affected by the leveling error λ

The leveling error λ is most likely due to multipath (*)

Receivers of the same type produce similar λ's, but there is no way to estimate their magnitude

Different types of receivers produce different λ's observing the same ray

(*) other possible cause are possible, but not up to now investigated: studying scintillation it has been evidenced effect due to interference of other GPS satellites (still sidereal-time synchronous effects)

Is it correct modeling leveled slants $\boldsymbol{S_L}$ disregarding λ?

For many station pairs, answer is <u>negative</u>

Still: **no a priori method exists to notice that something is wrong unless availing two or more stations** (see above plot of slants from close stations).

The results of the close stations experiment seem to evidence the need to introduce an additional satellite "bias", the leveling error λ , dependent on the receiving station

(**<u>and</u>** the receiver type == way of extracting pseudorange).

Leveling error λ is an arc dependent unknown: this implies that

No advantage is taken using leveled slants $\boldsymbol{S_L}$ with respect to phase slants (but this will need introducing one unknown per arc).

The choice of the calibration method

Aiming to

a simple solution (thin shell)

avoiding the problems of slants leveled to code S_L
(when leveling error is disregarded)

mitigating the errors of mapping function

It is natural to select a **single station** solution using **phase slants** S_P or leveled slants SL

Notes about V_{Eq} approach

It takes automatically into account of plasmaspheric contribution

It is easier to model at low latitudes than actual vertical ***TEC***

It presents some more difficulty to model at low elevations

The single station solution: Calibration

Observations

Phase slants S_P

Assumptions

One thin shell at 400 km

Elevation mask: 10^o

TEC expressed through V_{Eq} at the ionospheric point, by the mapping function $sec\ \chi$

V_{Eq} expressed as a proper expansion of horizontal coordinates ***l, f*** with one set of coefficients at each time $V_{Eq}(l, f) = \Sigma_n c_n p_n(l,f)$

$$S_{ijt} = \Sigma_n c^{(t)}_n p_n (l_{ijt}, f_{ijt}) \sec \chi_{ijt} + \Omega_{Arc}$$

The unknowns are now the coefficients $c_n^{(t)}$ and the offsets Ω_{Arc}

To solve the system

$$S_{ijt} = \Sigma_n c^{(t)}{}_n p_n (l_{ijt}, f_{ijt}) \sec \chi_{ijt} + \Omega_{Arc}$$

extra assumptions are taken to reduce the number of coefficients $\Sigma_n c^{(t)}{}_n$

Using as horizontal coordinates ***Modified Dip Angle*** and ***Local Time***, we can assume that for a set of adjacent epochs (up to ±15 minutes), the coefficients $c_n^{(t)}$ keep constant.

This allows also reducing computing resources during solution using commonly used standard methods for sparse systems.

After the solution of the system, we avail with

Calibrated slants along the observed rays $TEC_{ijt} = S_{ijt} - \Omega_{Arc}$

“Mapped slants” at given coordinates l_{ijt}, f_{ijt}

Vertical ***TEC*** above the station (ionospheric point at the its zenith)

$$VTec(t) = \sum_n c_n^{(t)} p_n \left(l_{ijt}^{Zenith}, f_{ijt}^{Zenith} \right) \sec \chi_{ijt}$$

Performance of the proposed calibration method must be now investigated

1) A first look: will it provide same ***TEC***'s from colocated stations?

2) **Internal consistency:** compute the residuals

$$R_{ijt} = S_{ijt} - \Sigma_n c^{(t)}_n p_n (l_{ijt}, f_{ijt}) \sec \chi_{ijt} - \Omega_{Arc}$$

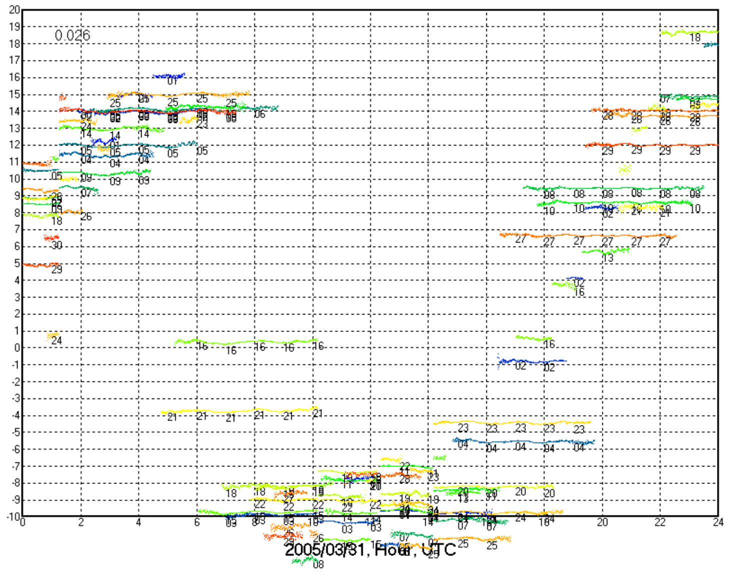
Small residuals mean good internal consistency, but do not help in asserting the accuracy of the method.

3) External consistency, namely the comparison with completely independent observations, should be the only way to assert the accuracy.
Possible observations: Incoherent Scatter Radar (**ISR**), Two-Frequency Radar Altimeter (**RA-2**). Problems: very few ***ISR***'s, **RA-2** needs its own calibration.

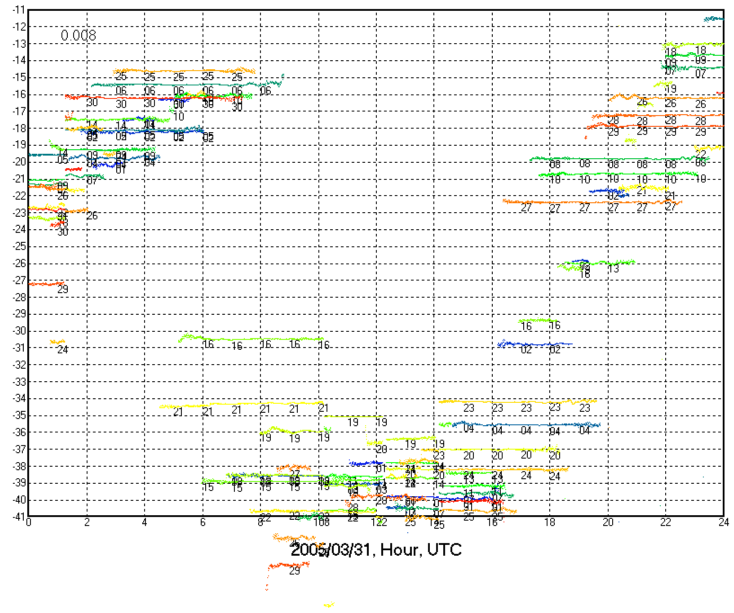
Only possibility: using artificial truth data obtained using ionospheric models

A first look: worth adopting the above procedure for calibration?

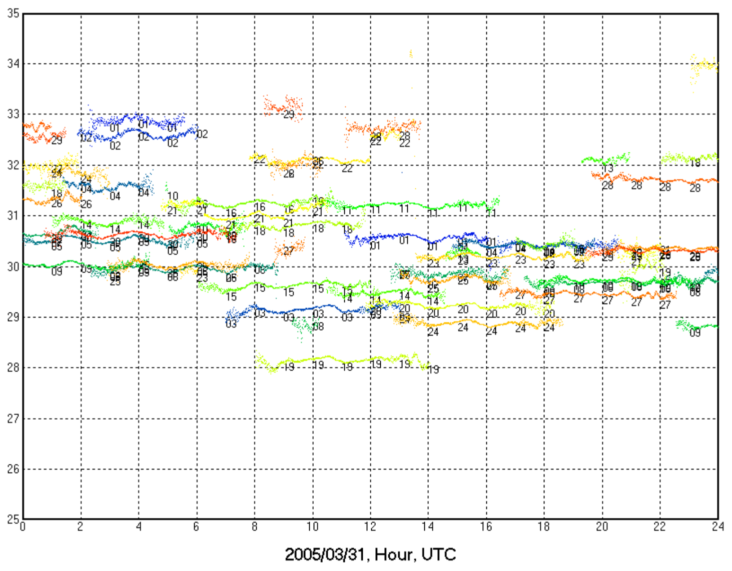
TEC(10**16) wtza - wtzj Lat=49.1N Lon=12.9E



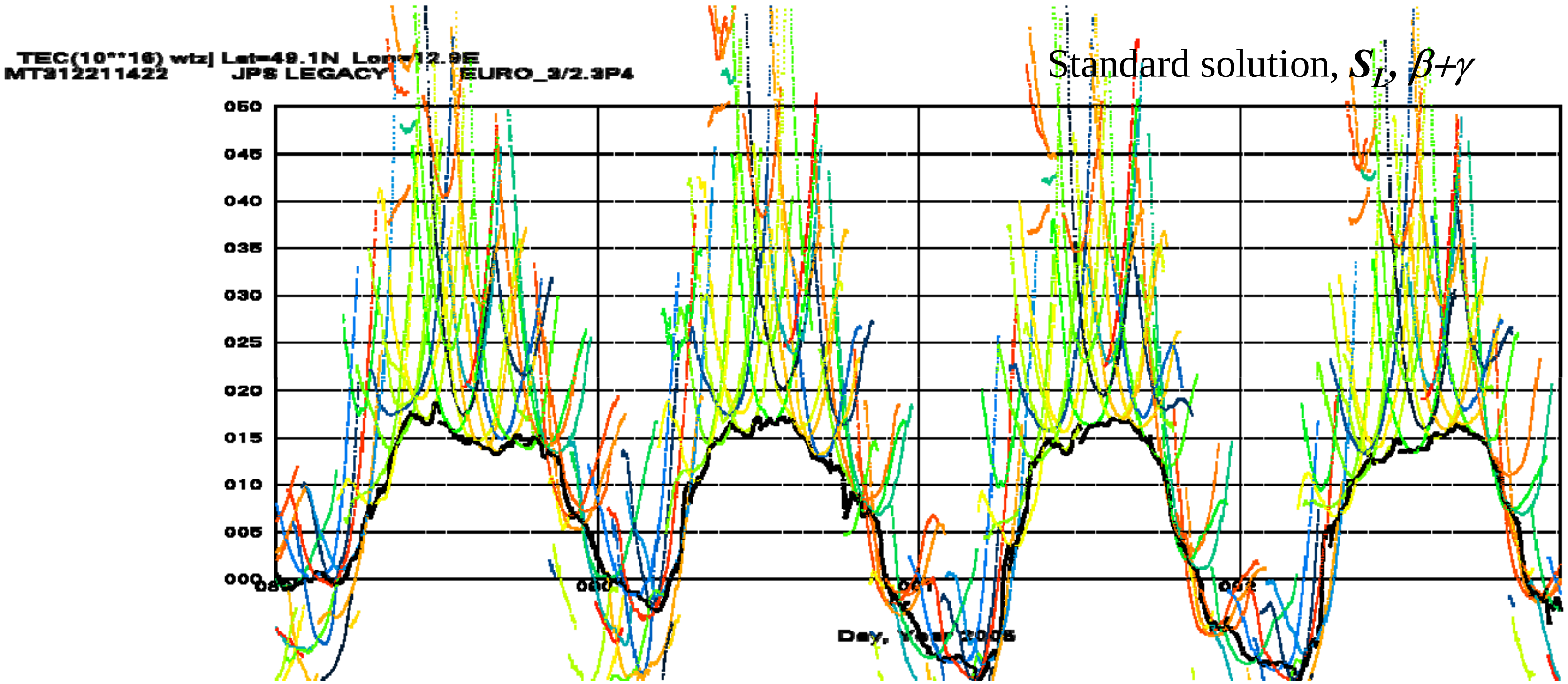
TEC(10**16) wtzr - wtzj Lat=49.1N Lon=12.9E

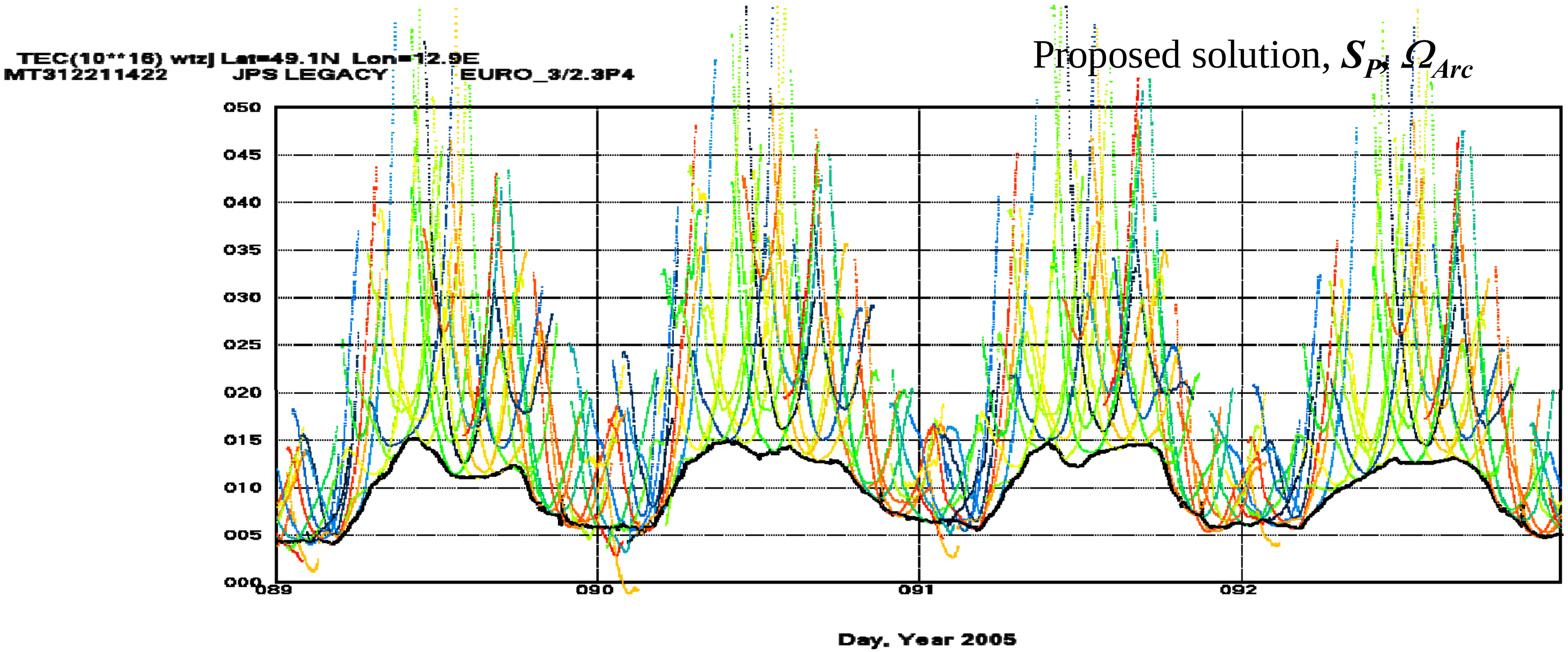


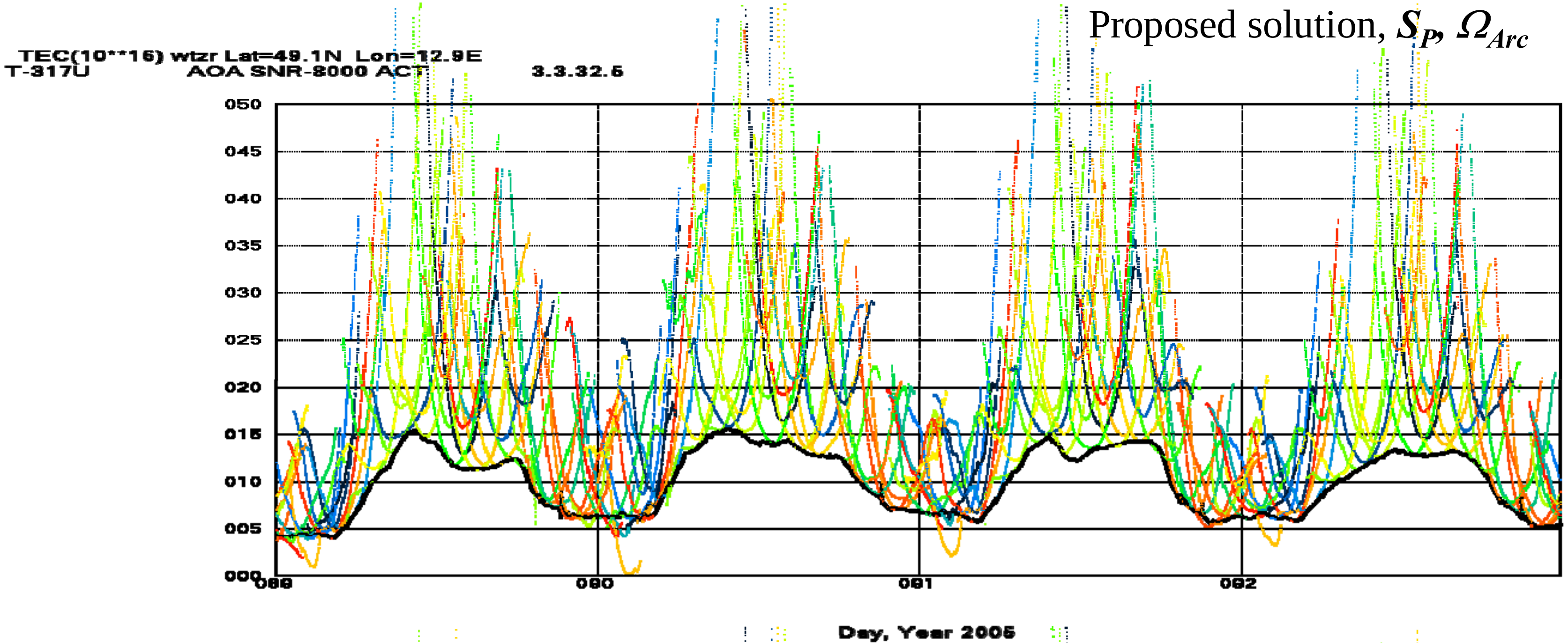
TEC(10**16) wtza - wtzr Lat=49.1N Lon=12.9E

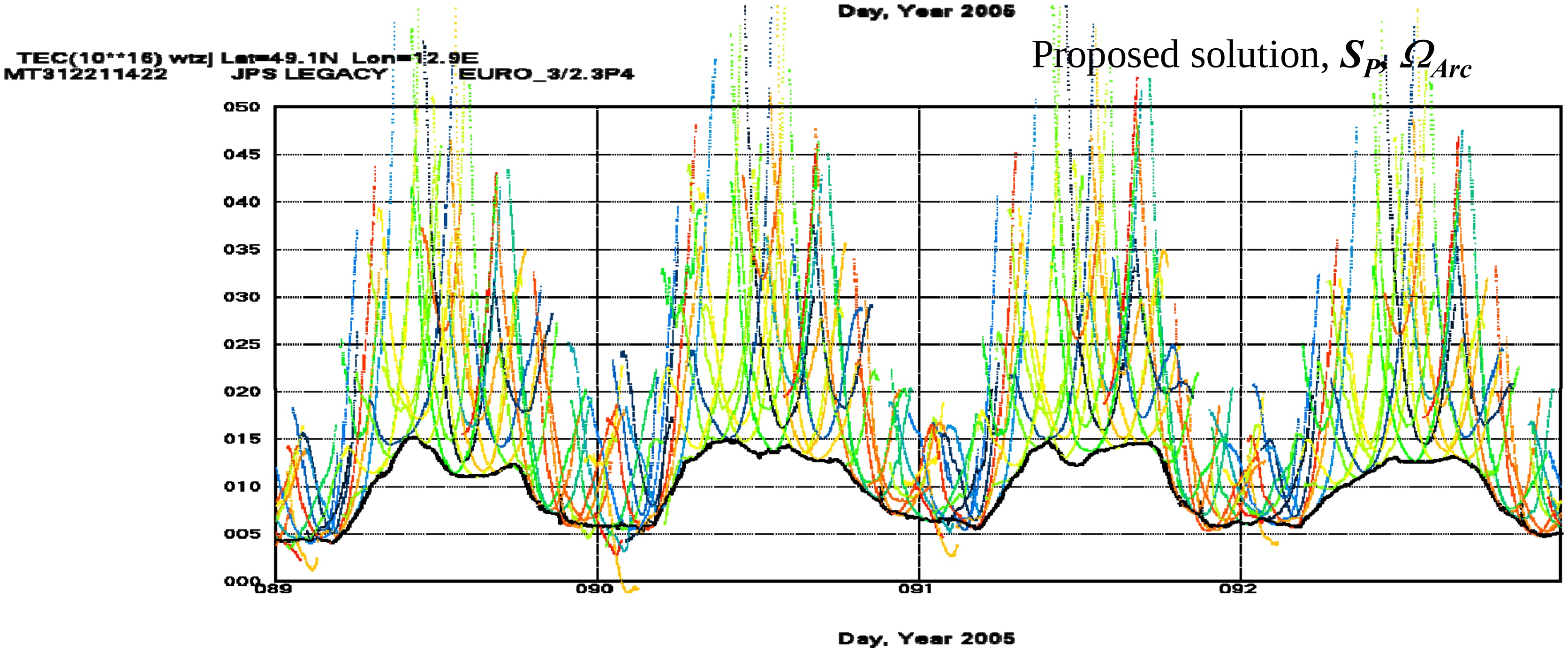


Close station plots for ***wtza, wtzj, wtzr*** suggest that something is wrong with ***wtzj***. Try arc offsets and standard biases calibration for the above stations


TEC(10**16) wtzj Lat=49.1N Lon=12.9E
MT312211422
JPS LEGACY
EURO_3/2.3P4
Standard solution, S_L, $\beta+\gamma$
050
045
040
035
030
025
020
015
010
005
000
089
090
091
092
Day, Year 2005


TEC(10**16) wtzj Lat=49.1N Lon=12.9E
MT312211422
JPS LEGACY
EURO_3/2.3P4
Proposed solution, S_P, Ω_{Arc}
050
045
040
035
030
025
020
015
010
005
000
089
090
091
092
Day, Year 2005


Proposed solution, S_P, Ω_{Arc}
TEC(10**16) wtzr Lat=49.1N Lon=12.9E
T-317U AOA SNR-8000 ACT 3.3.32.5
050
045
040
035
030
025
020
015
010
005
000
089
090
091
092
Day, Year 2005

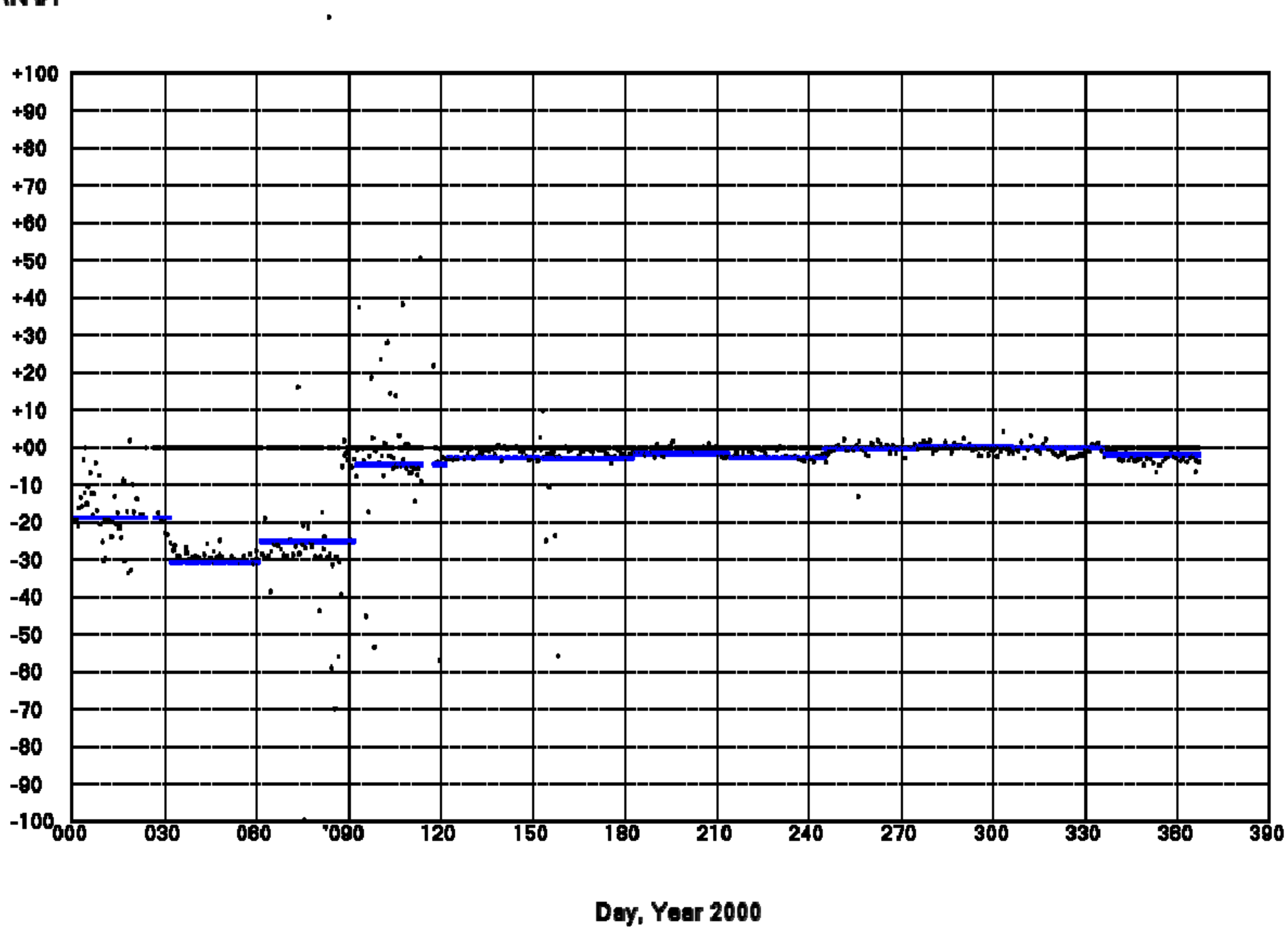

Proposed solution, S_P, Ω_{Arc}
TEC(10**16) wtzj Lat=49.1N Lon=12.9E
MT312211422 JPS LEGACY EURO_3/2.3P4
050
045
040
035
030
025
020
015
010
005
000
089
090
091
092
Day, Year 2005

How do traditional and proposed solution compare?

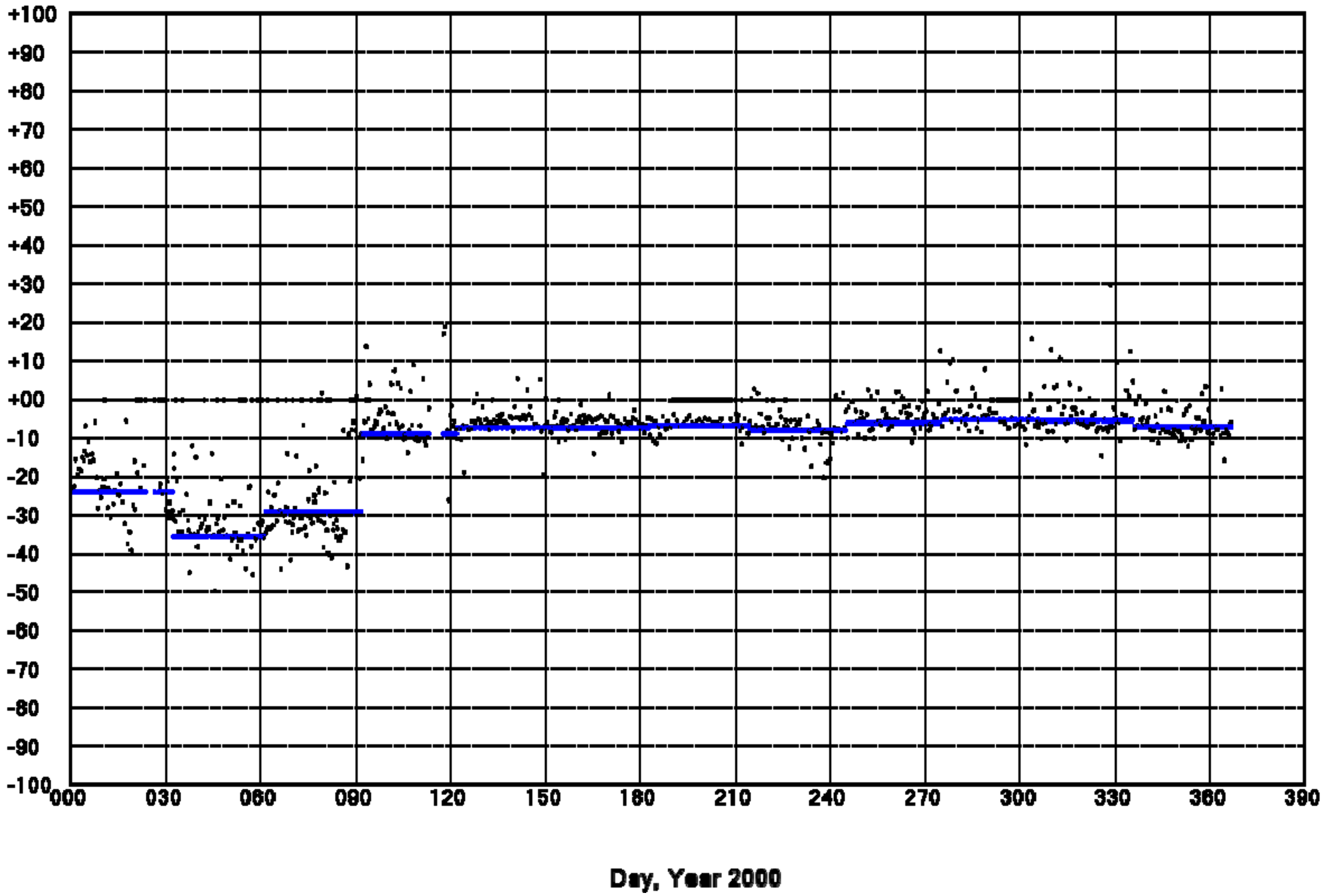
In the following slides it can be seen that the two solutions agree in the average, but the difference in bias can amount to 10 ***TECu***

The pattern of the jumps, similar for different satellites, simply indicates that something has changed in the receiver

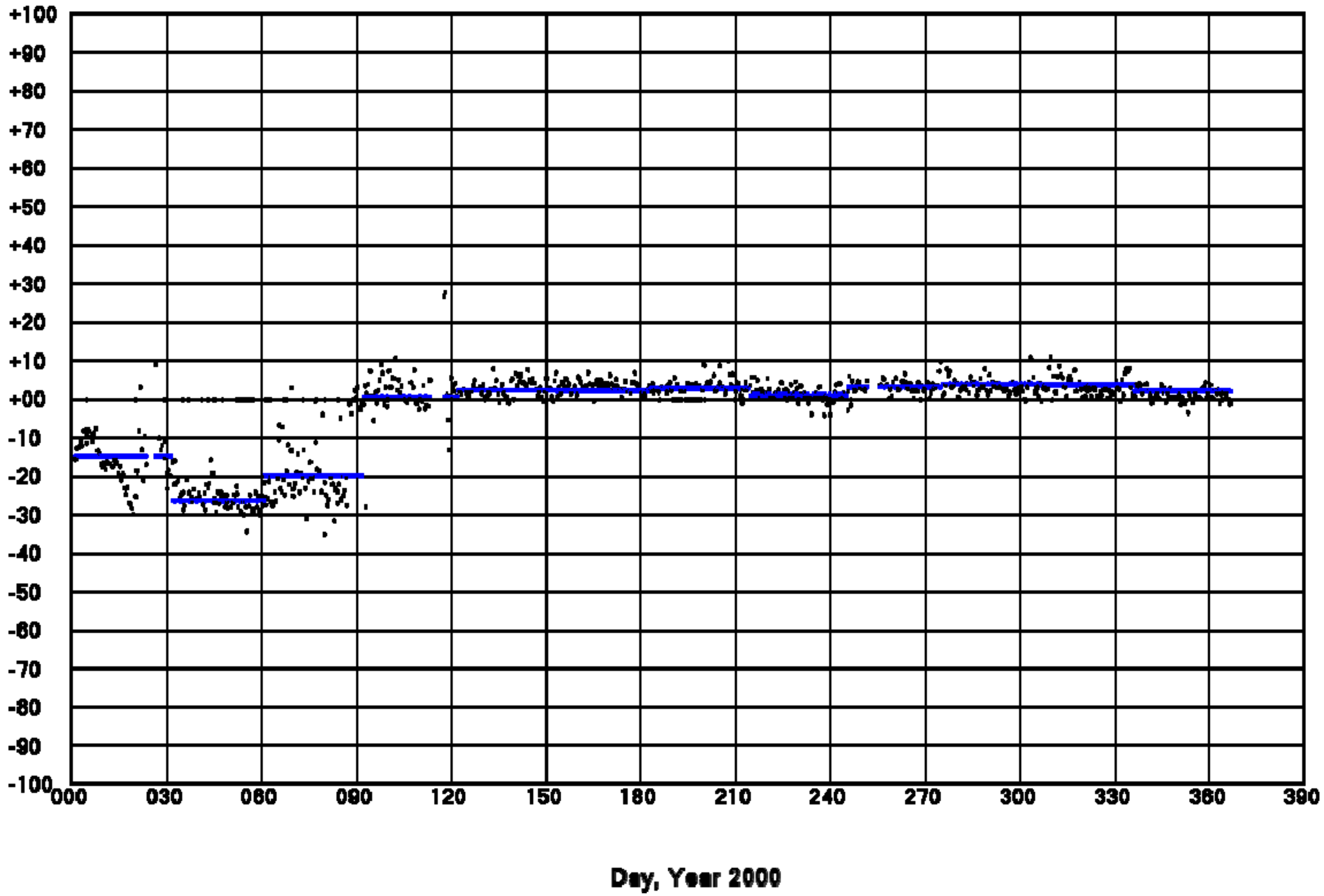
Station brus PRN #1



Station brus   PRN #4



Station brue   PRN #24



Next topic: how can artifical data help in estimating

the reliability of calibration techniques?

How accuracy of calibration techniques can be estimated

Examination of residuals

$$\boldsymbol{Res_{ijt} = S_{ijt} - \Sigma_n c^t{}_n p_n (l_{ijt}, f_{ijt}) \sec \chi_{ijt} - \Omega_{Arc}}$$

After a calibration run will provide with useful information about the

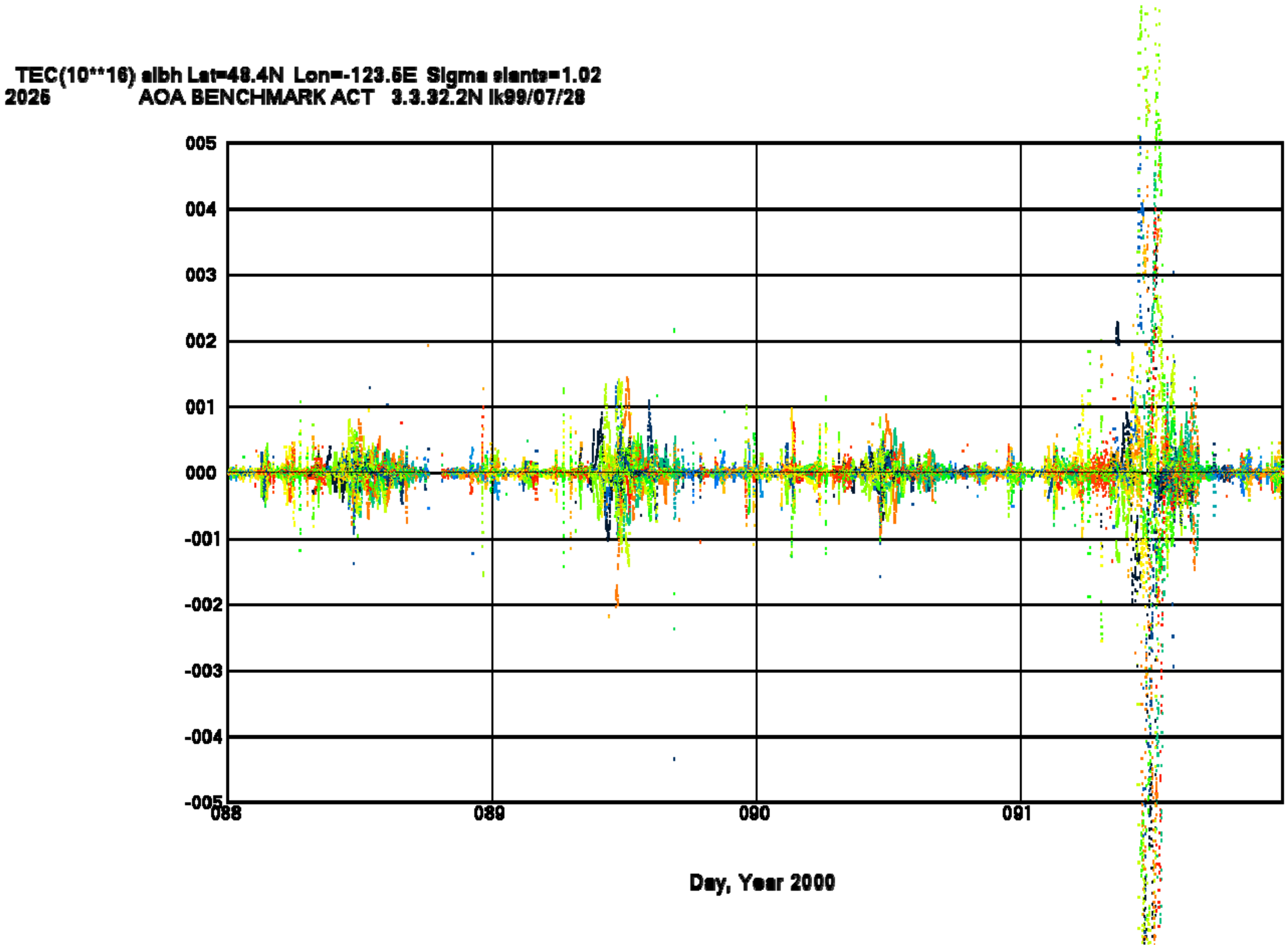
Internal consistency of the solution

Residuals are plotted in the following examples for few sample stations.

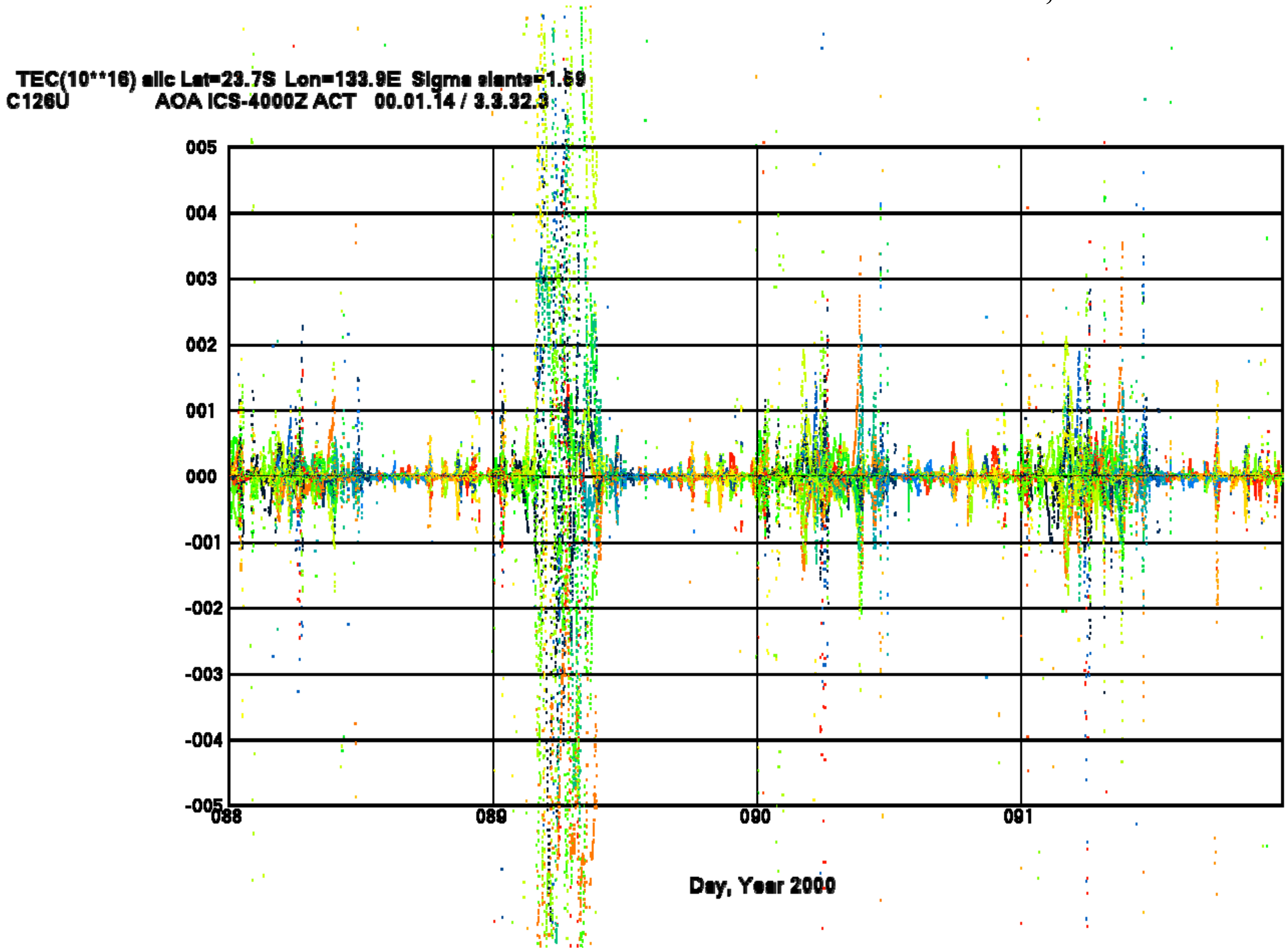
Standard deviation of the individual samples is reported.

Internal consistency of the method is estimated from the residuals (actual data)

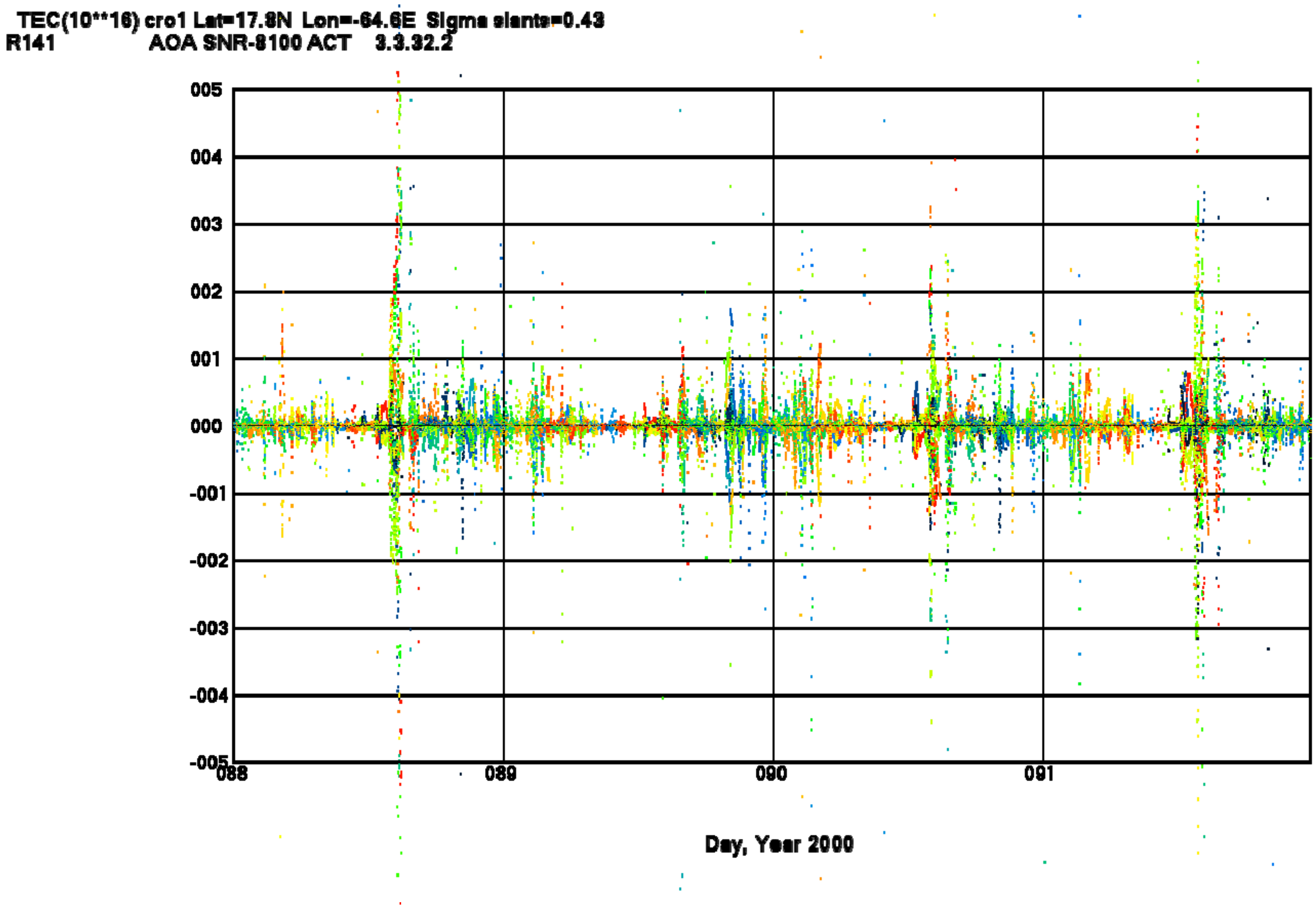
$$Res_{ijt} = S_{ijt} - \Sigma_n c^t{}_n p_n (l_{ijt}, f_{ijt}) \sec \chi_{ijt} - \Omega_{Arc}$$



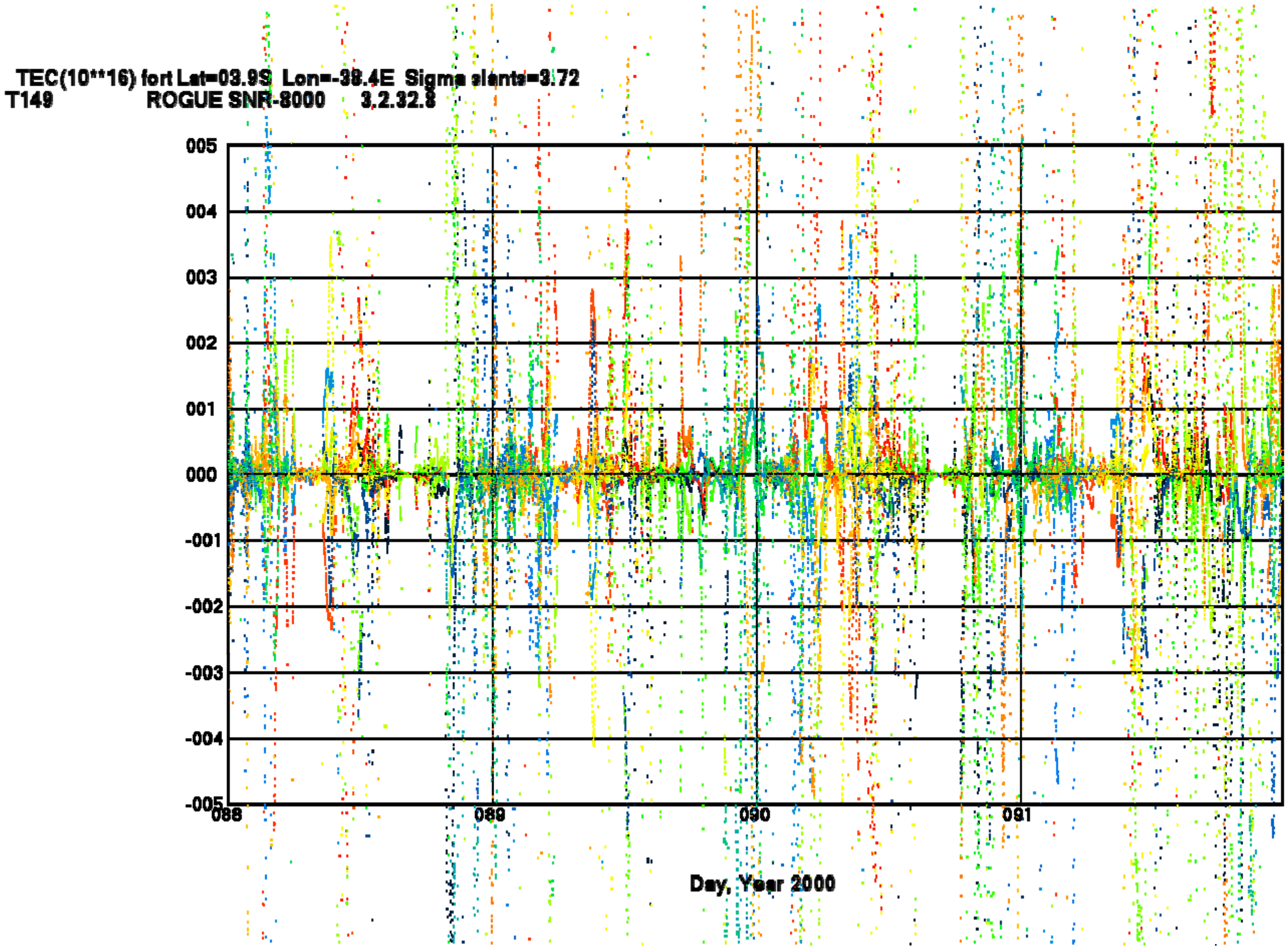
Residuals, actual data



Residuals, actual data



Residuals, actual data



Sigma of the shown sample residuals ranges from ≈ .5 to 4 ***TECu*** according to latitude.

Is this an estimation of the accuracy of the calibration?

No, as this requires a comparison with truth data, which are unavailable

(Incoherent Scatter Radar, Radar Altimeter may help, but are not sufficient).

What can look more like truth data?

Artificial data produced by Ionospheric Models.

But keeping in mind that agreement with artificial data is a condition

necessary but not sufficient to validate the method

The artificial data

Ionospheric models enable to estimate median electron density at some time at some geographic location, i.e. given date and time, latitude, longitude, height.

$$N_e = N_e(t, \phi, \lambda, h)$$

TEC is the integral of electron density along the ray-path from satellite to receiver,

$$TEC = \int N_e(P)ds$$

which will be numerically evaluated as the sum

$$TEC \approx \sum N_e(P_i)\delta s_i$$

or with any more effective numerical algorithm (Gauss, …)

Model TEC computation

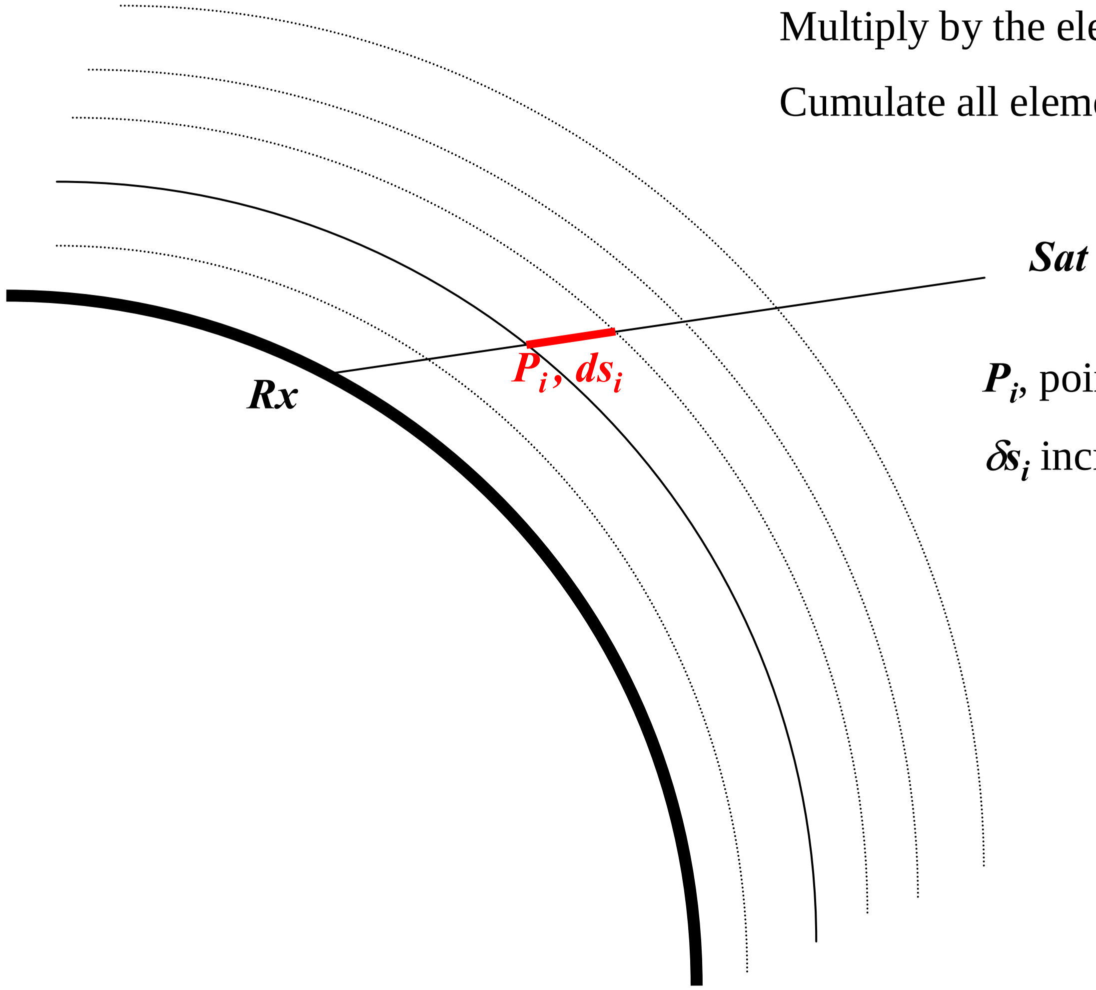
$$TEC = \int N_e(P)ds \approx \sum N_e(P_i)\delta s_i$$

Divide the path in elements δs_i

At each point P_i compute the electron density $N_e(P_i)$ provided by the model

Multiply by the element length δs_i

Cumulate all elements



P_i, point on the generic i^{th} shell

δs_i increment in arc length

Simple uses of artificial data: the mapping function

Which errors do affect the **standard approach** (actual vertical ***TEC***) of mapping function?

<u>Using an artificial ionosphere</u>:

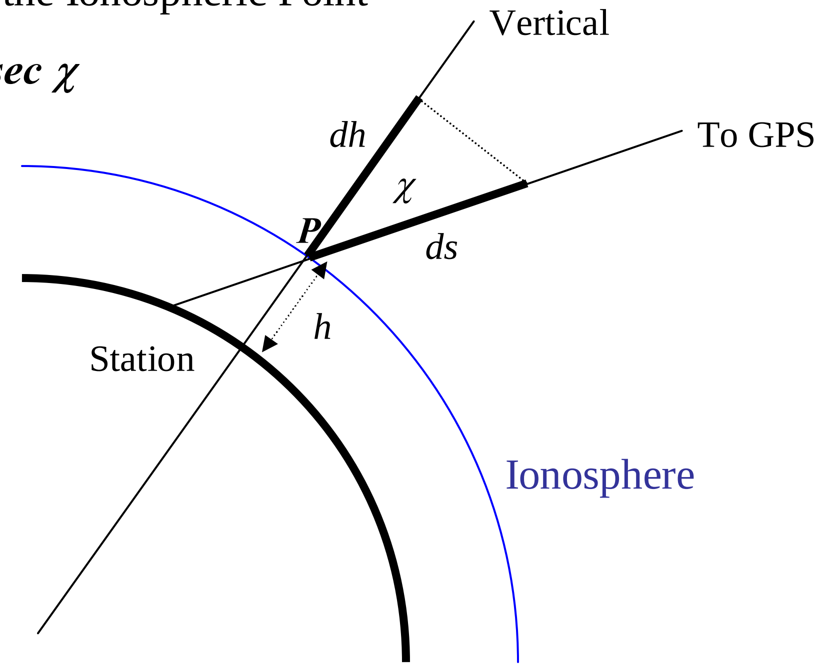
Compute χ

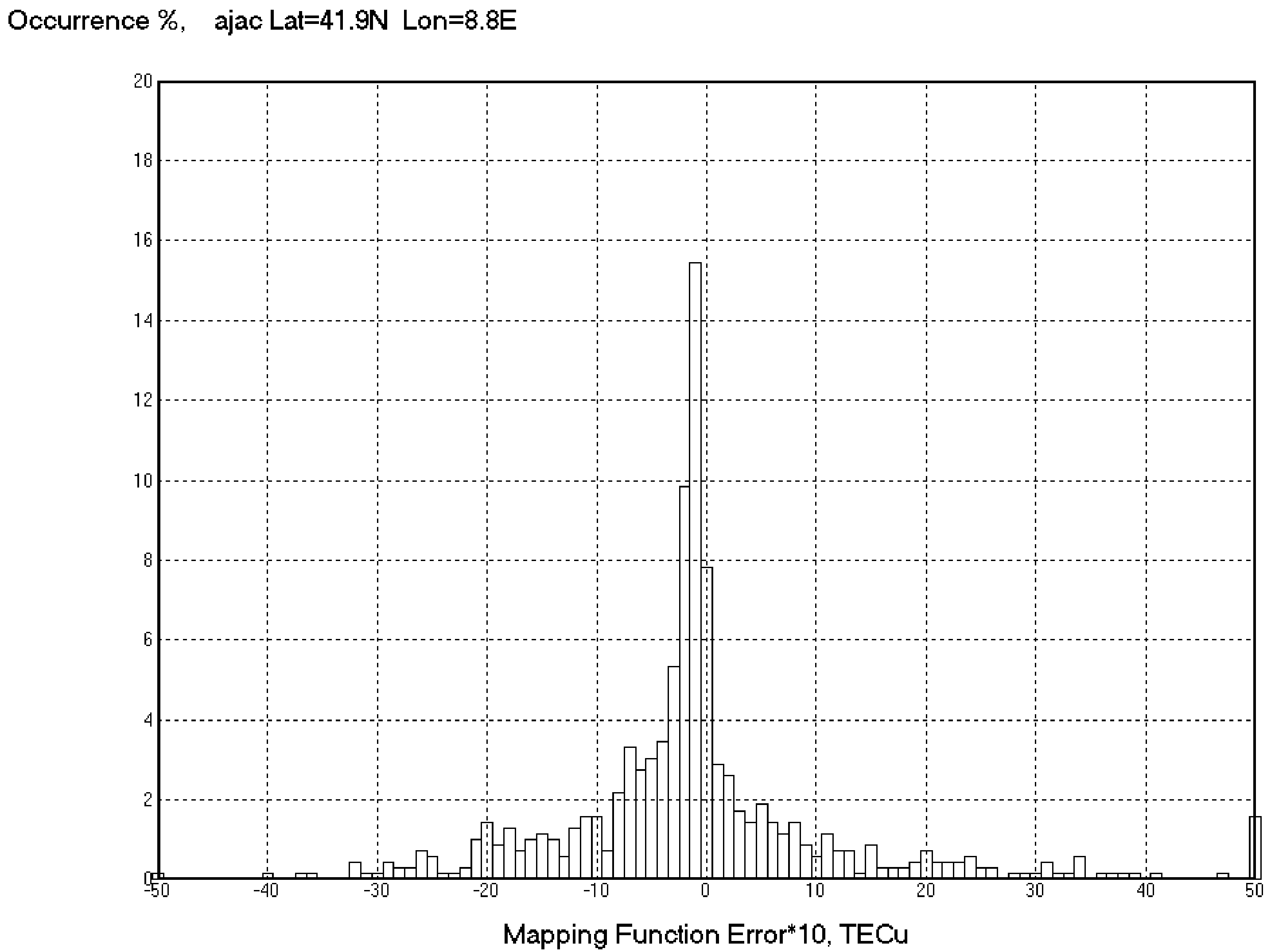
Compute Slant $\boldsymbol{S}$

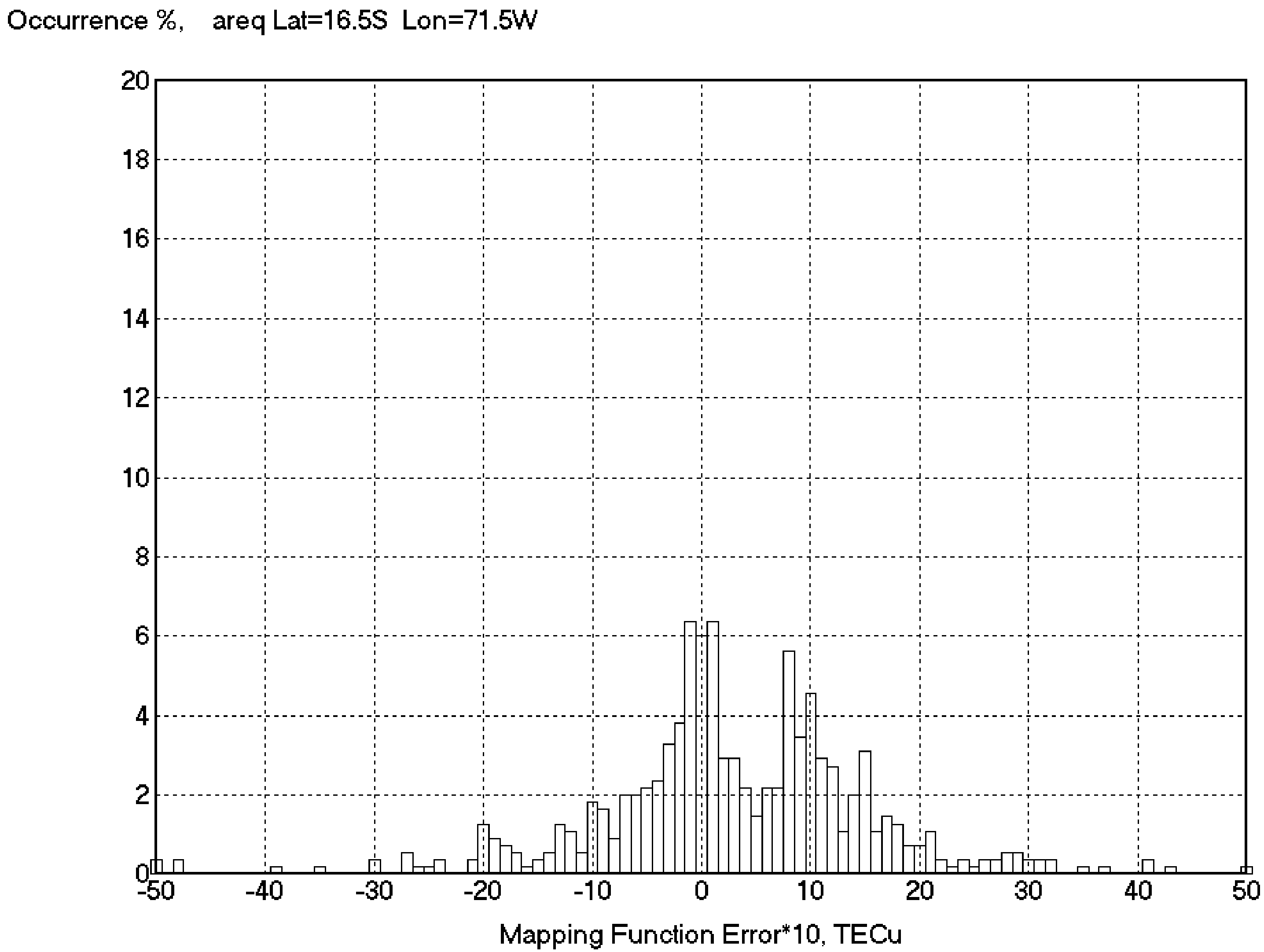
Compute Vertical TEC $\boldsymbol{V}$ at the Ionospheric Point

Error: $\boldsymbol{S - V \sec \chi}$

Plot Error distribution




Occurrence %, ajac Lat=41.9N Lon=8.8E
20
18
16
14
12
10
8
6
4
2
0
-50
-40
-30
-20
-10
0
10
20
30
40
50
Mapping Function Error*10, TECu


Occurrence %, areq Lat=16.5S Lon=71.5W
20
18
16
14
12
10
8
6
4
2
0
-50
-40
-30
-20
-10
0
10
20
30
40
50
Mapping Function Error*10, TECu

Simple uses of artificial data: ***VEC and VEq***

In the Single-Station / Arc Offset calibration the ***V***ertical ***Eq***uivalent TEC ***VEq*** for which it is exactly ***S = VEq sec*** χ is used.

How different is ***VEq*** from actual Vertical ***TEC*** (***VEC***) ?

<u>Using an artificial ionosphere</u>:

Compute χ

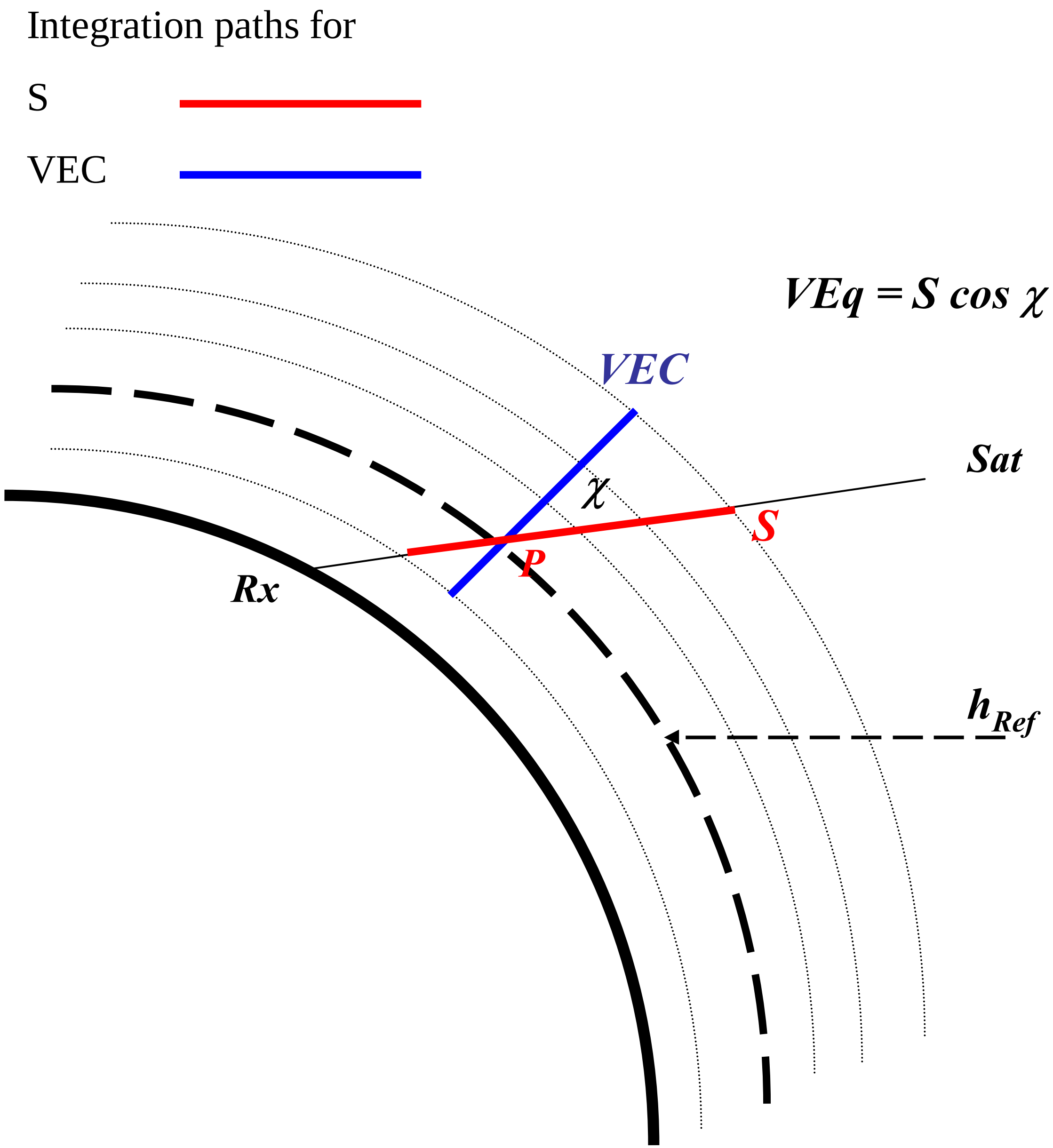
Compute Slant ***S***

By definition ***VEq = S cos*** χ

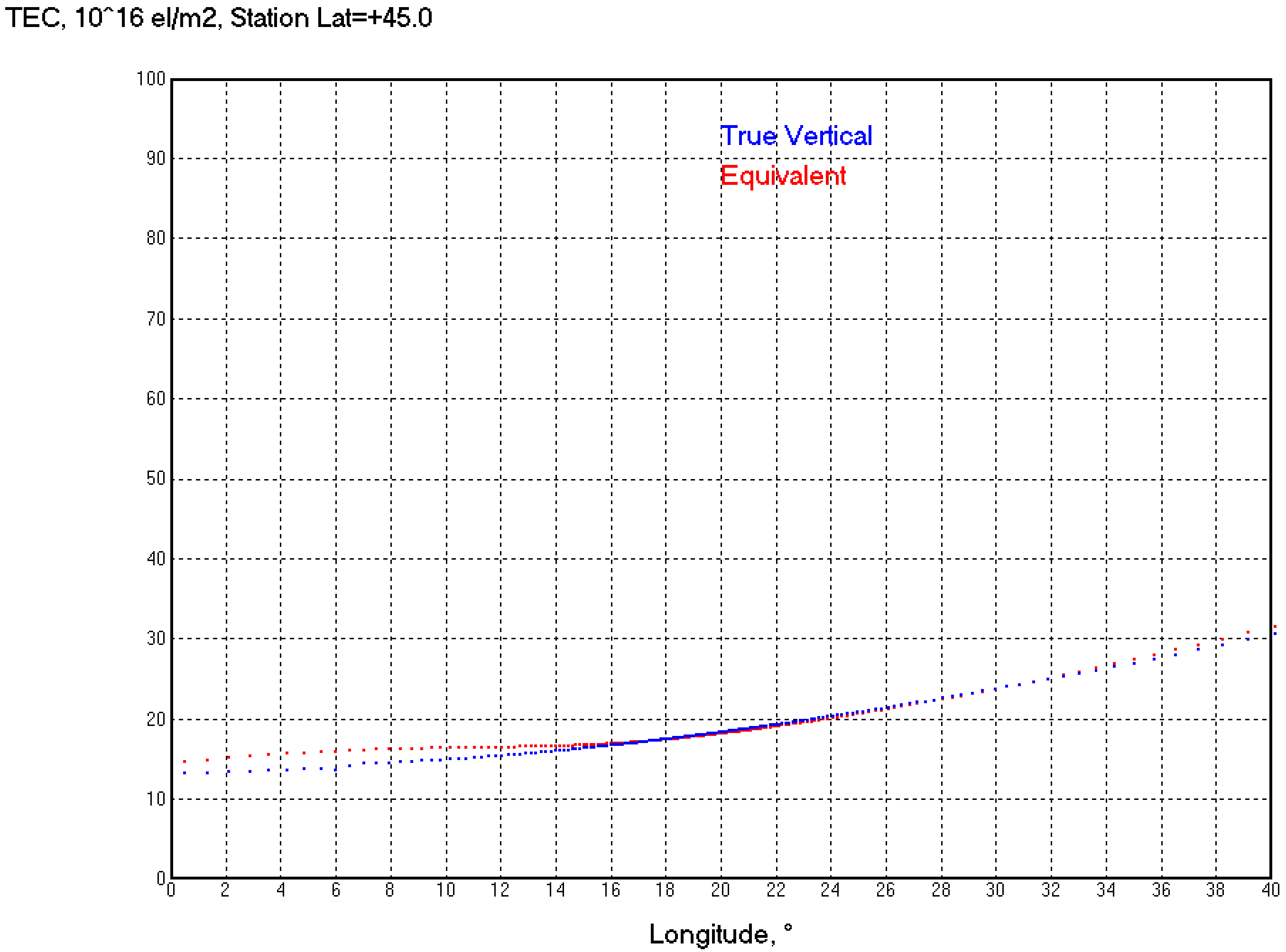
Compute Vertical TEC ***V*** at the Ionospheric Point ***VEC***

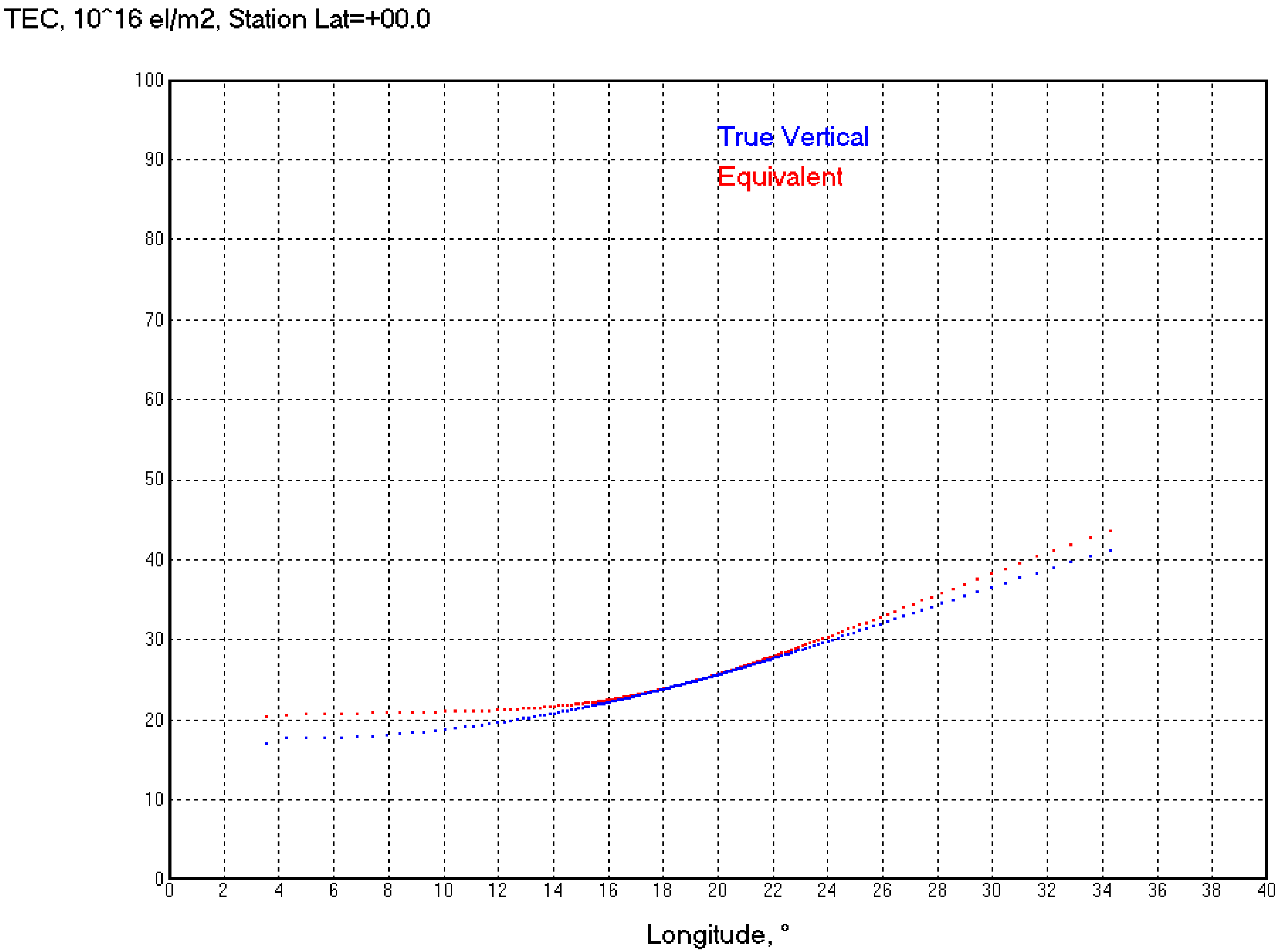
Plot ***VEC, VEq***

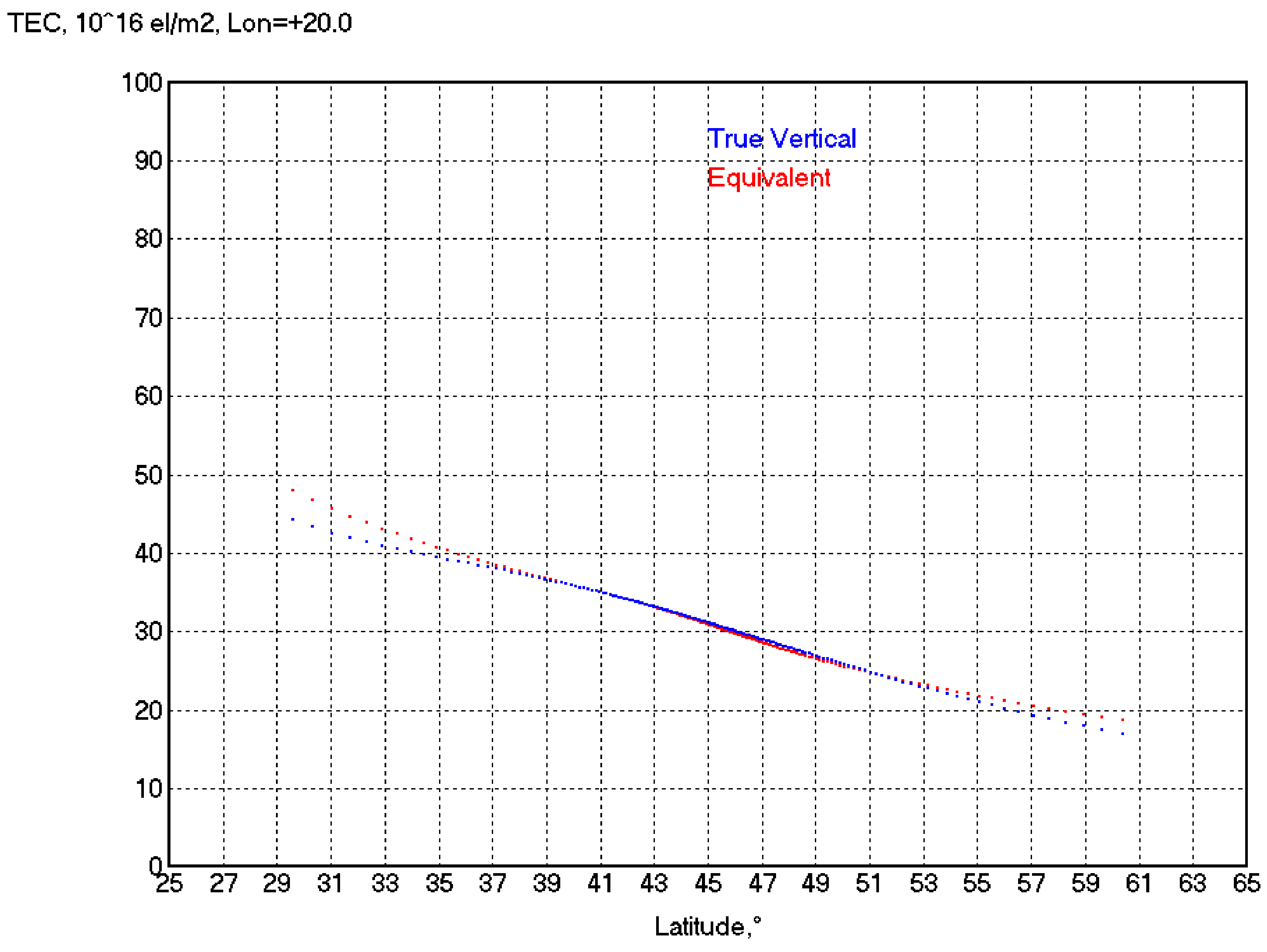
Plasmasphere can be included too using a suitable model


Integration paths for
S
VEC
VEq = S cos χ
VEC
Sat
χ
S
P
Rx
h Ref

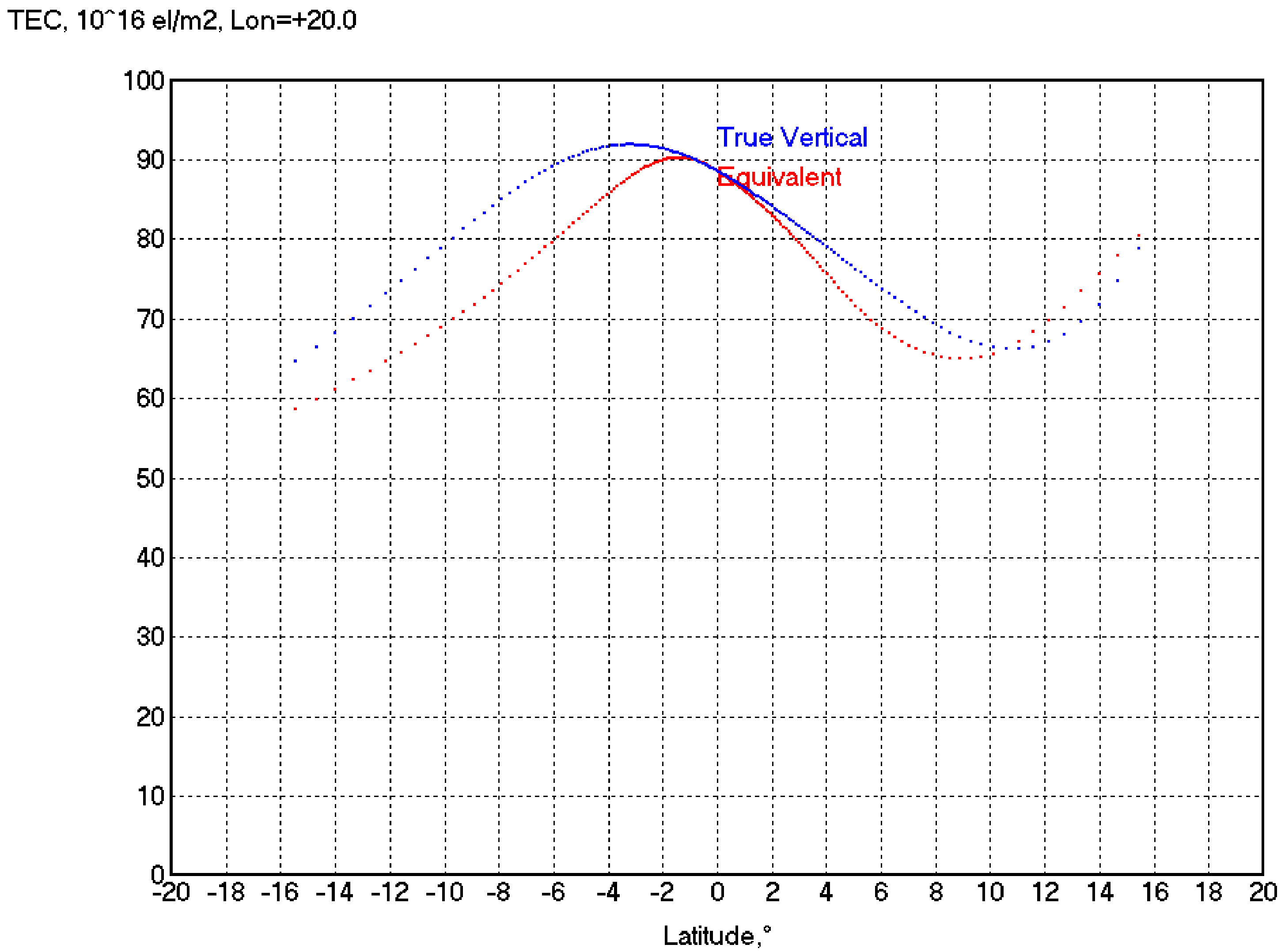
Simple uses of artificial data: How much ***VEC*** and ***VEq*** differ?




TEC, 10^16 el/m2, Station Lat=+00.0
True Vertical
Equivalent
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
Longitude, °



TEC, 10^16 el/m2, Lon=+20.0
100
90
80
70
60
50
40
30
20
10
0
True Vertical
Equivalent
25
27
29
31
33
35
37
39
41
43
45
47
49
51
53
55
57
59
61
63
65
Latitude,°


TEC, 10^16 el/m2, Lon=+20.0
True Vertical
Equivalent
100
90
80
70
60
50
40
30
20
10
0
-20 -18 -16 -14 -12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12 14 16 18 20
Latitude,°

Test of Single-Station, Arc-Offset solution

Generation of artificial truth data

Given all slants actually observed and archived

in a (quasi) complete set of IGS stations (≈ 200 per day)
for year 2000
for days 88-91 (March 28-31)

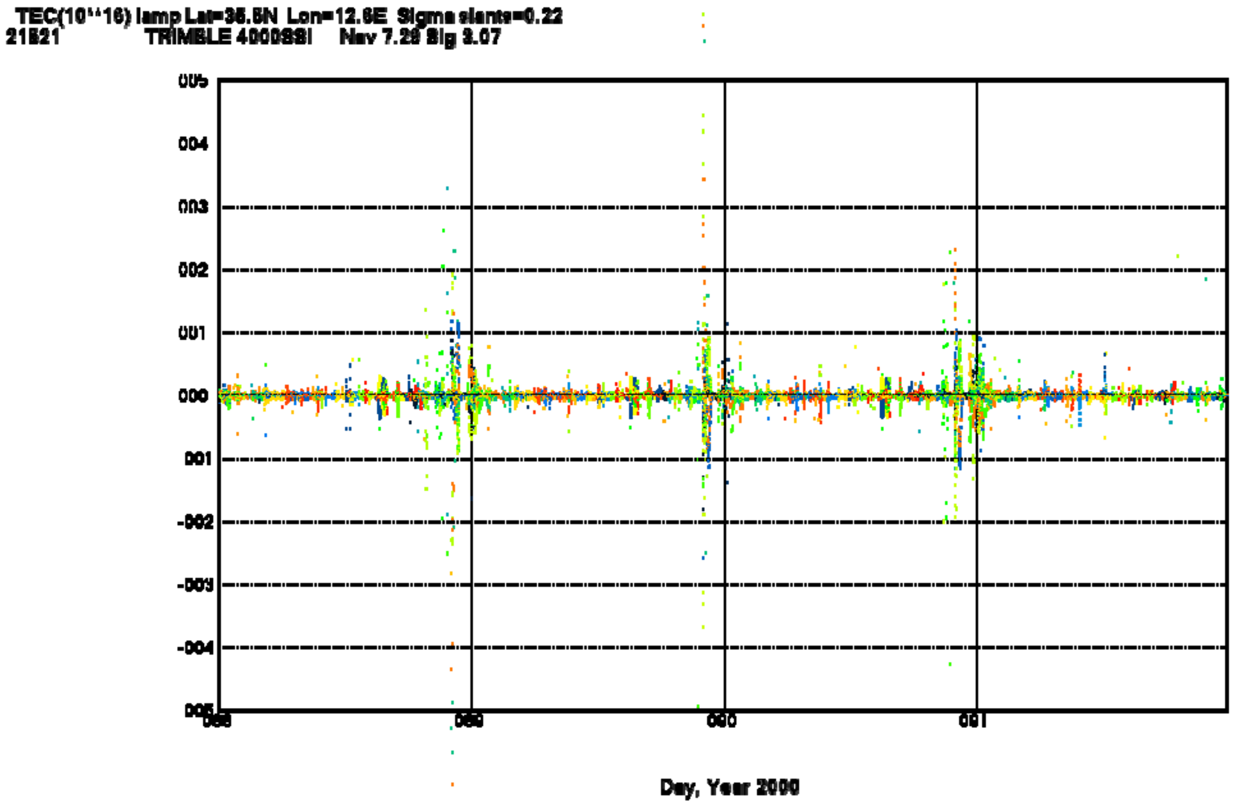
Re-compute them using
NeQuick (Az =150), integrating up to 2000 km

Therefore:

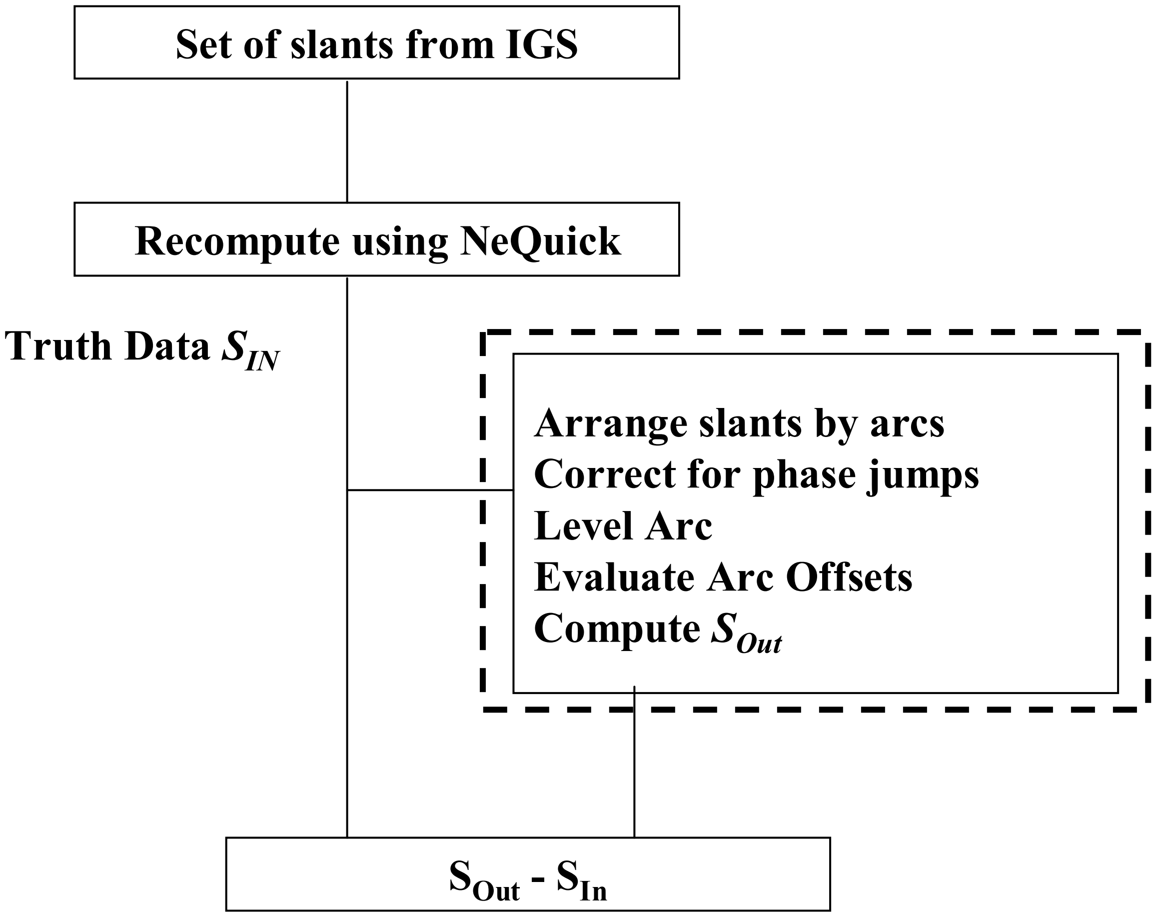
Not only the actual GPS constellation has been preserved for the reference period, but also the possible lack of observations (this will affect the solution)

Internal consistency: Residuals, simulated data

$$Res_{ijt} = S_{ijt} - \Sigma_n c^t{}_n p_n (l_{ijt}, f_{ijt}) \sec \chi_{ijt} - \Omega_{Arc}$$



Testing the calibration procedure



$\boldsymbol{S_{Out} - S_{In}}$ are plotted vs time

Worth (but expected) noting that errors at low latitudes are larger

Remark about highlighted arc:

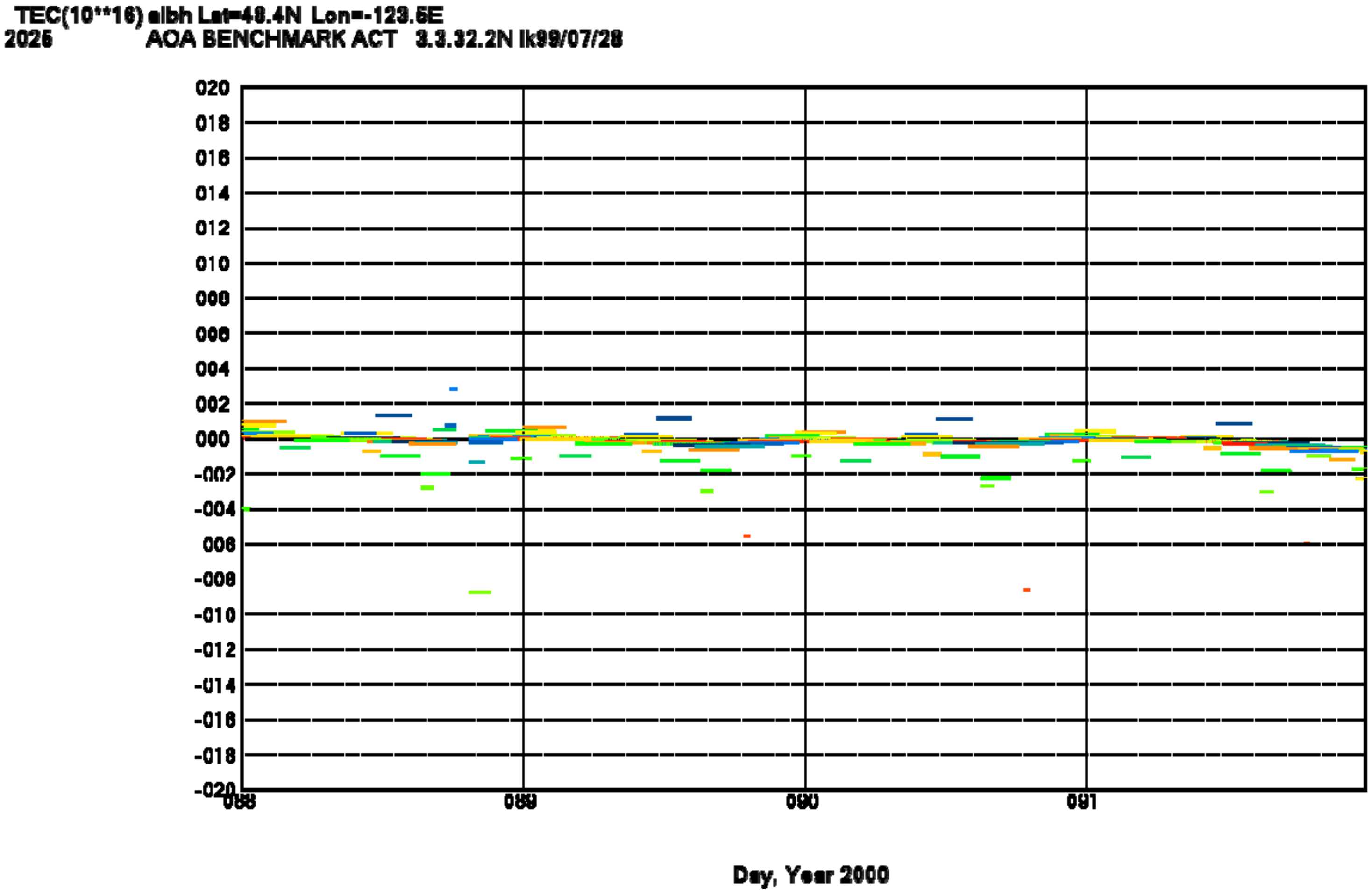
errors show a weakness of the solution**.**

These errors occur for arcs of low elevation also if, in some case, of long duration.

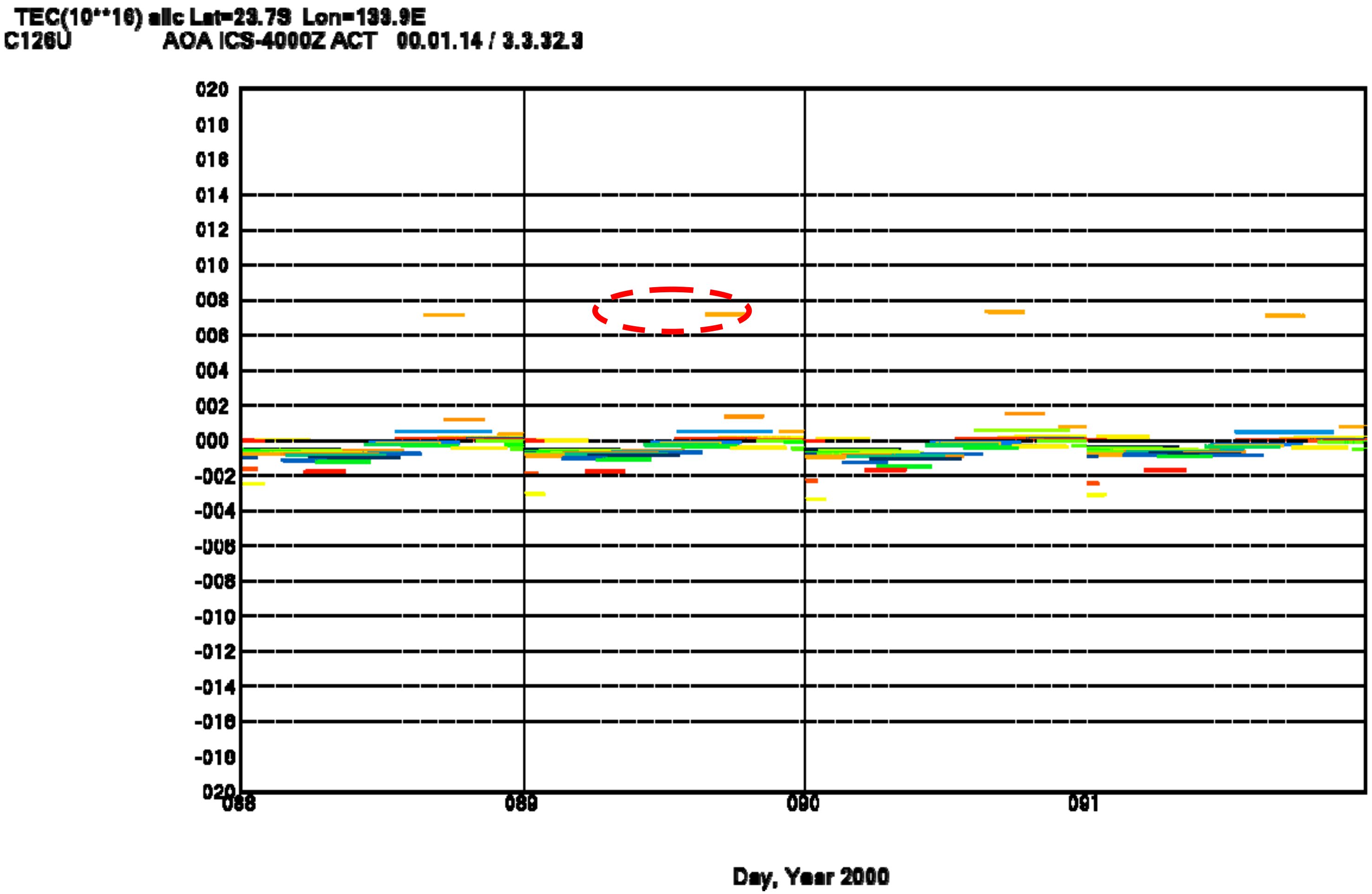
Processing real data, there is no chance to know if the subject arc is ill-calibrated (unless in presence of very strong errors)

Testing the solution with simulated data will (likely) enable to find a more effective way of avoiding such errors, or in a last instance, rejecting them

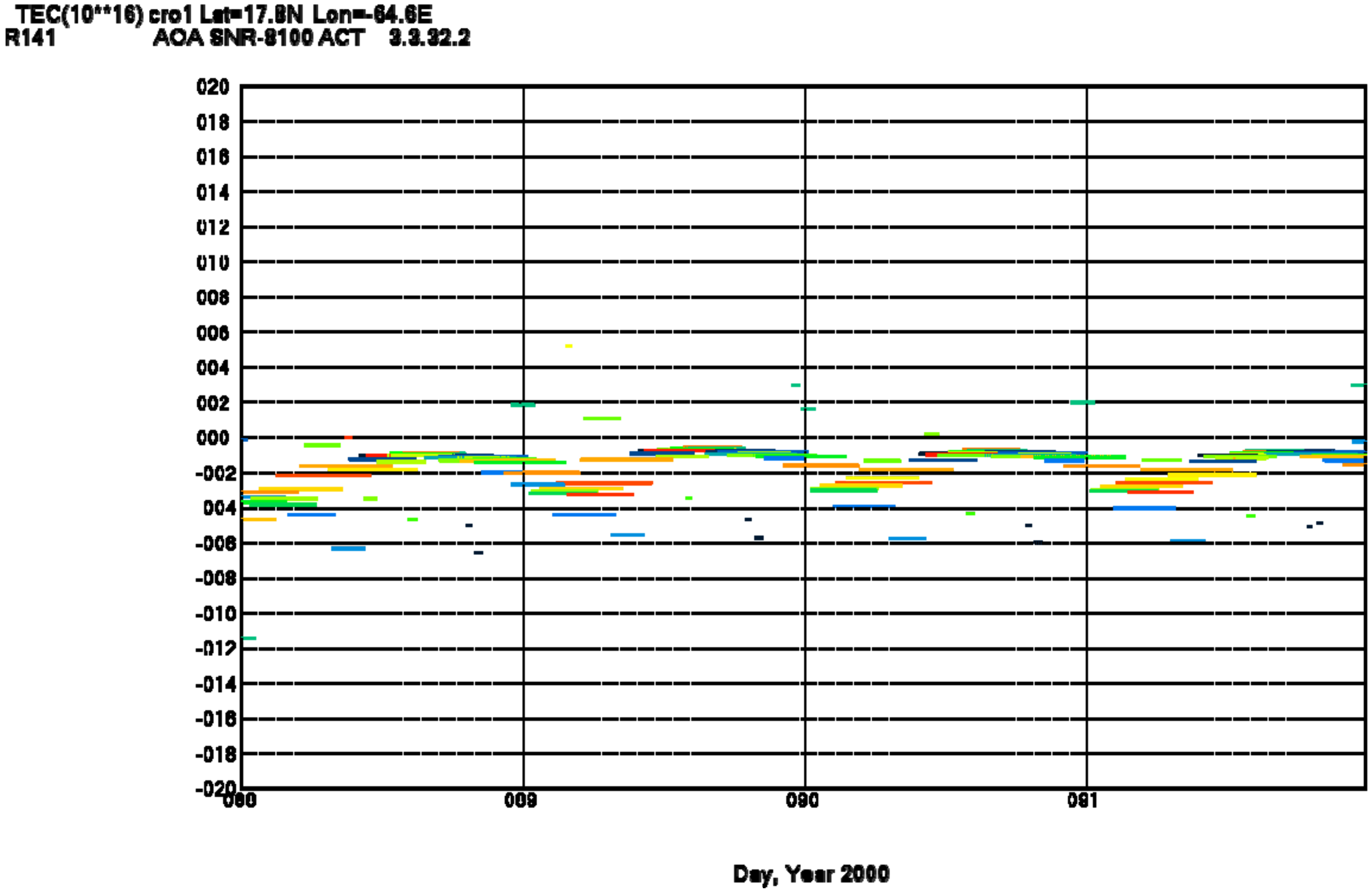
Slant$_{Out}$-Slant$_{In}$, TECu



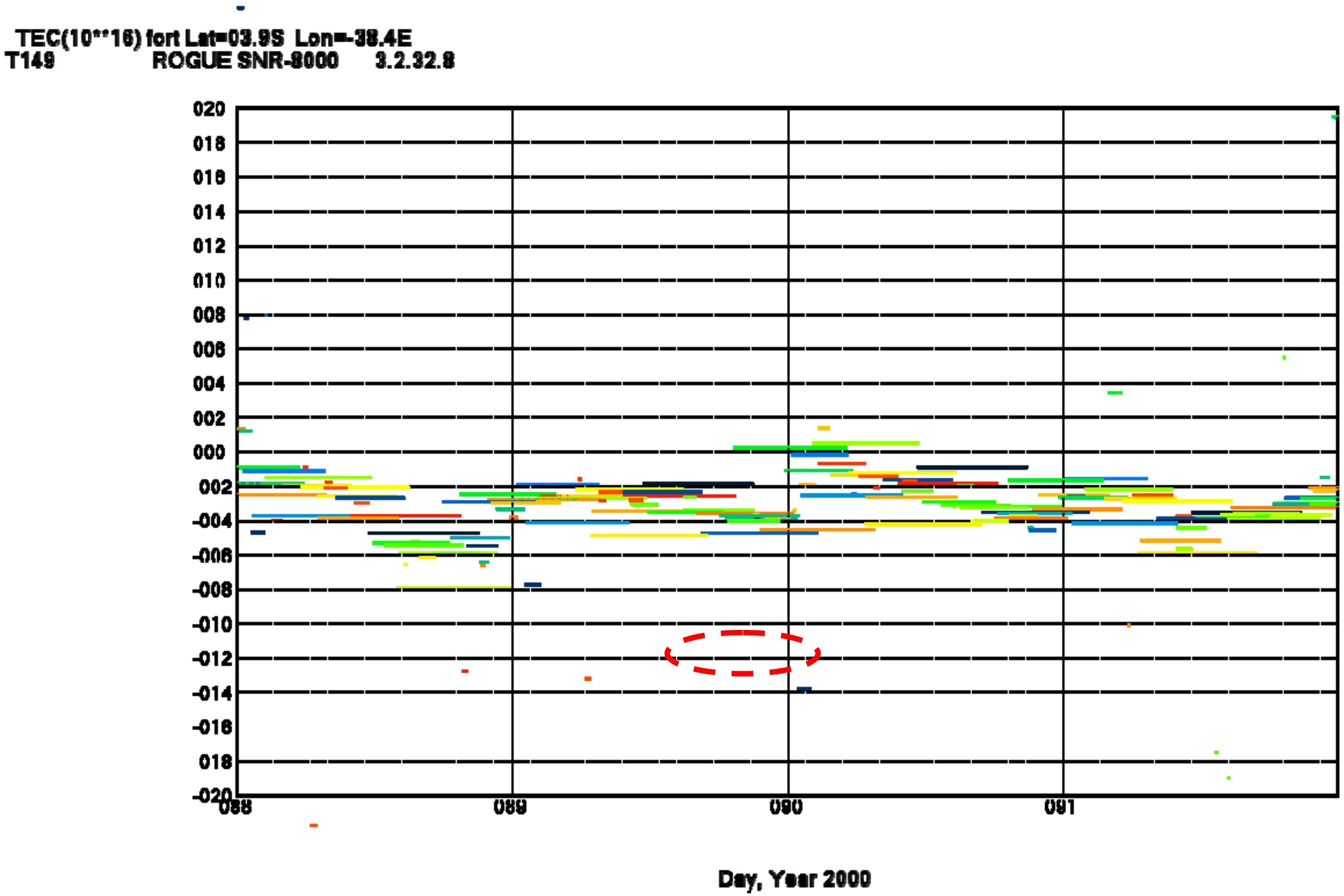
Slant$_{Out}$-Slant$_{In}$, TECu



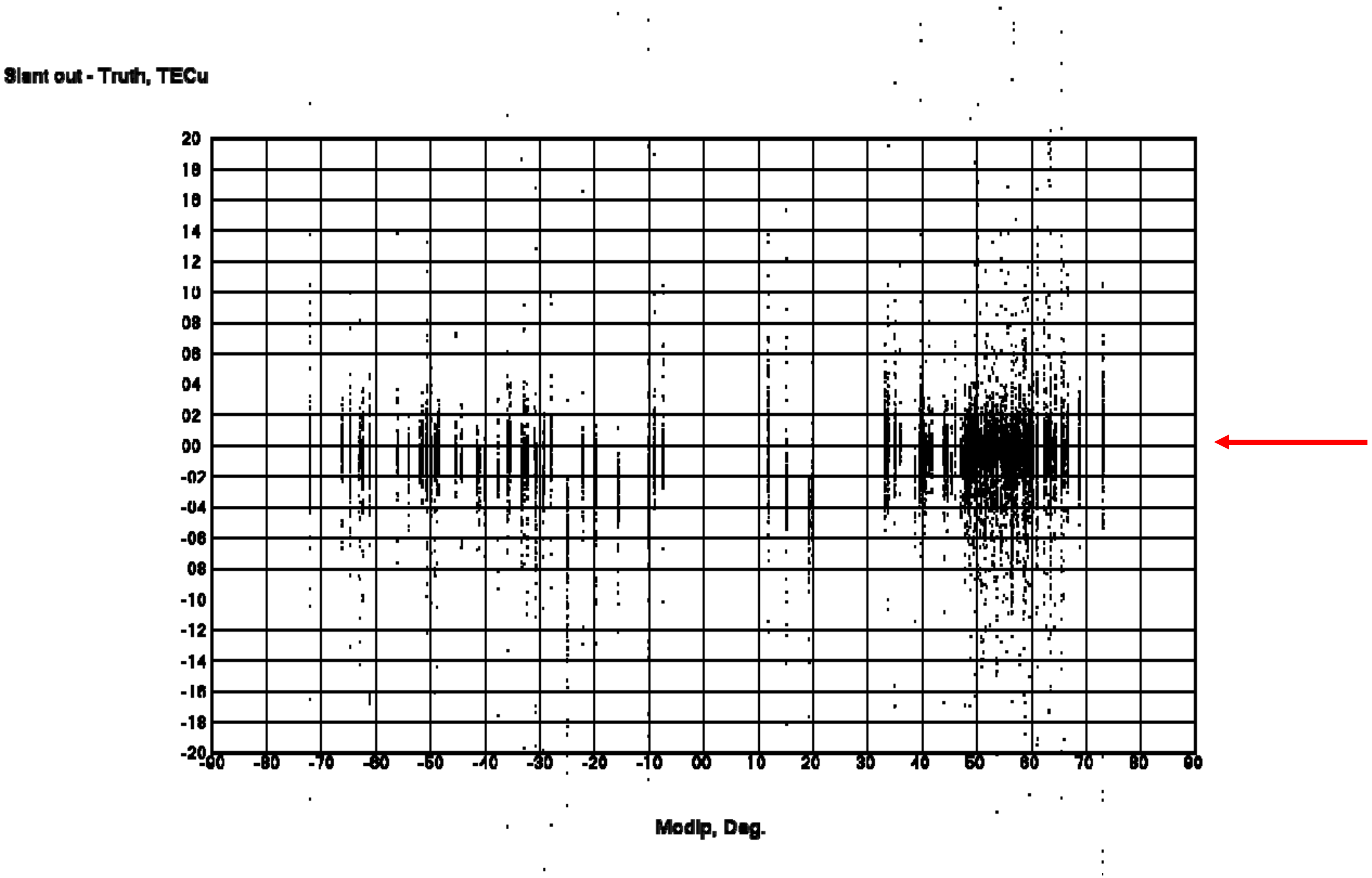
$Slant_{Out}$-$Slant_{In}$, TECu



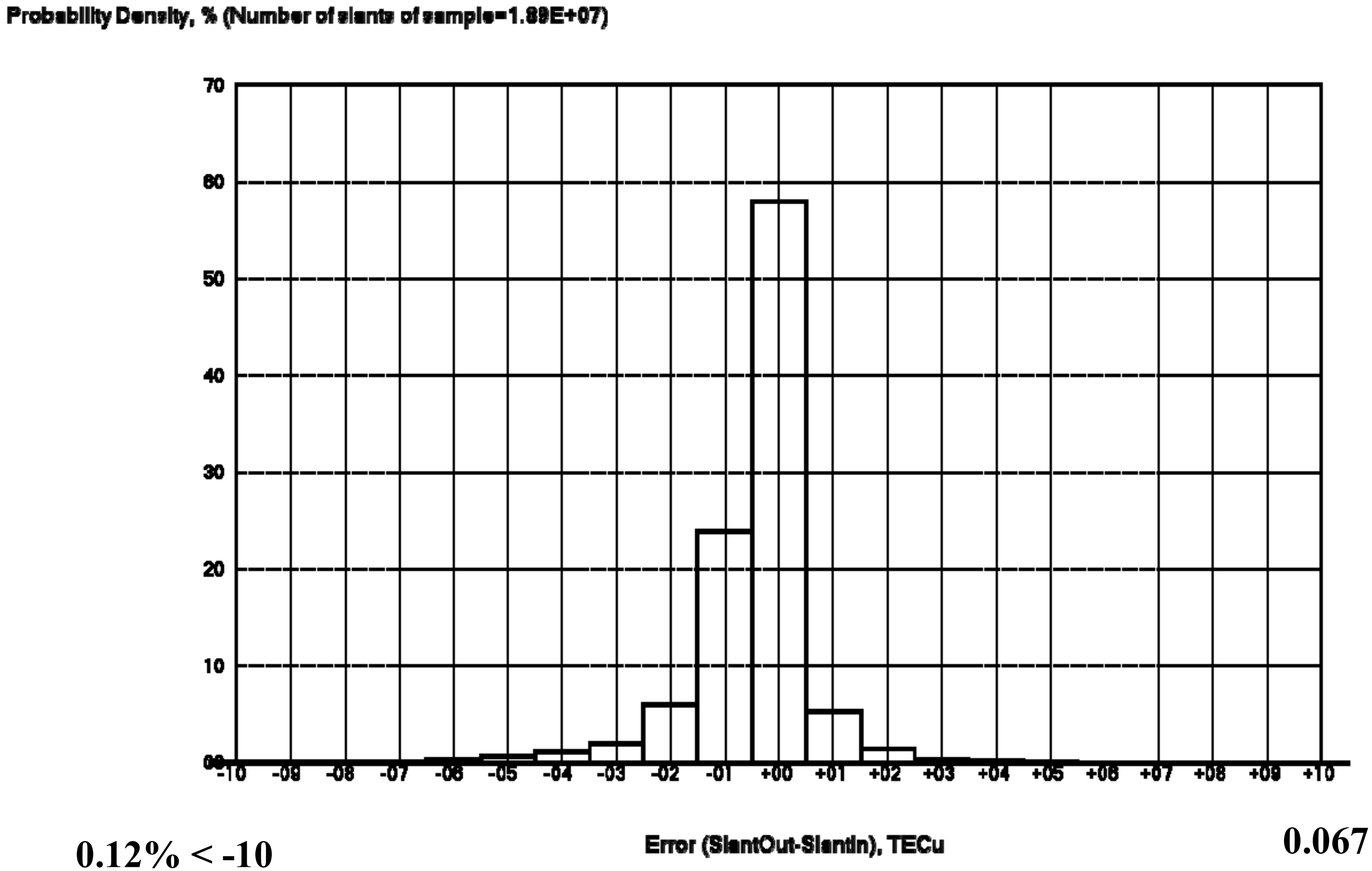
$Slant_{Out}$-$Slant_{In}$, TECu



An overall look to the errors: $S_{Out} - S_{In}$, whole set



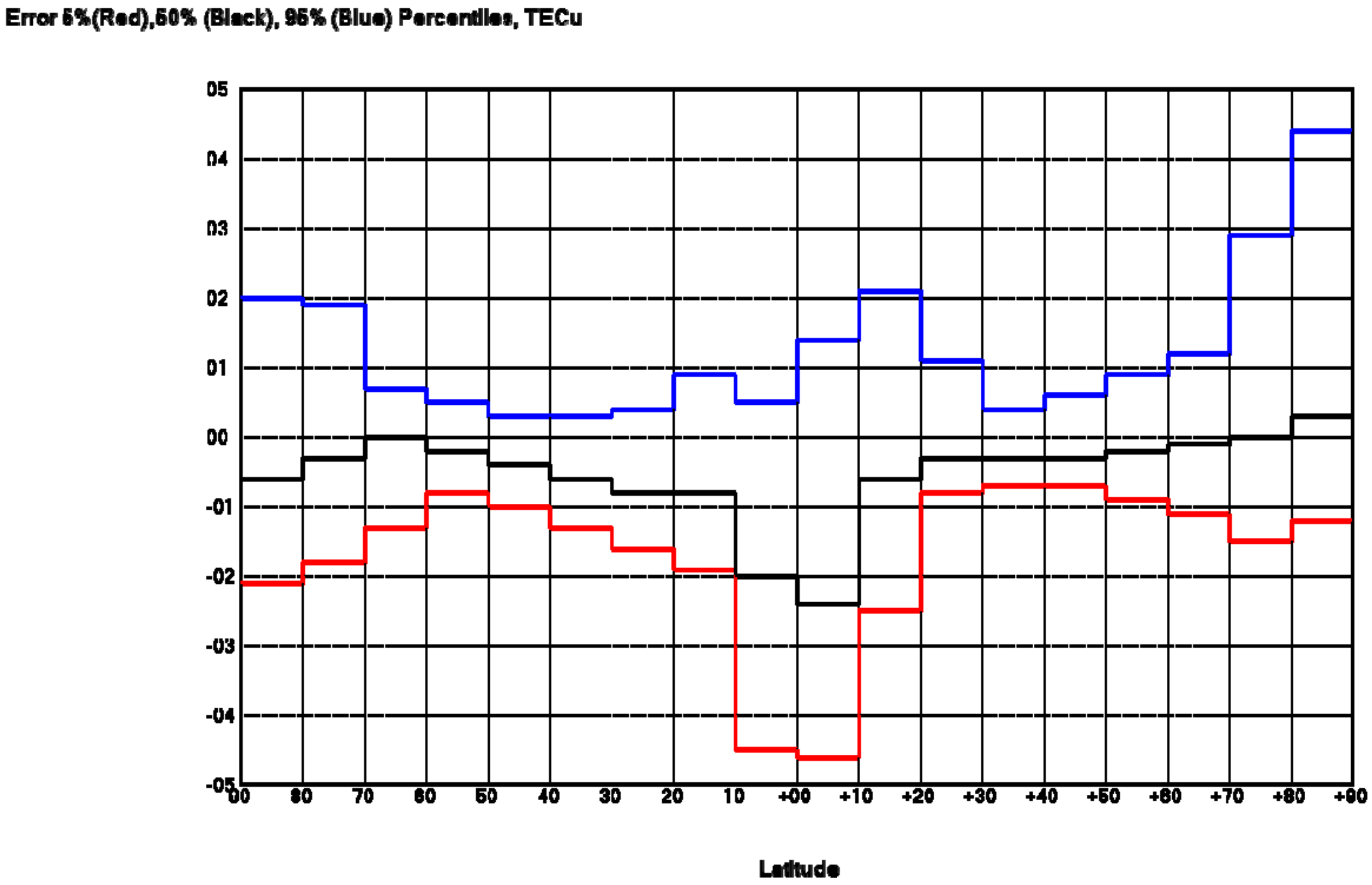
An overall look to the errors: $S_{Out} - S_{In}$, probability density



0.12% < -10

0.067 % > 10

Error's behavior vs latitude: percentiles, whole set



Simulation: role of multi-path contribution λ

An arbitrary set of ***satellite*** + ***receiver biases*** + ***multipath*** errors is added to model slants

Station bias γ = 25

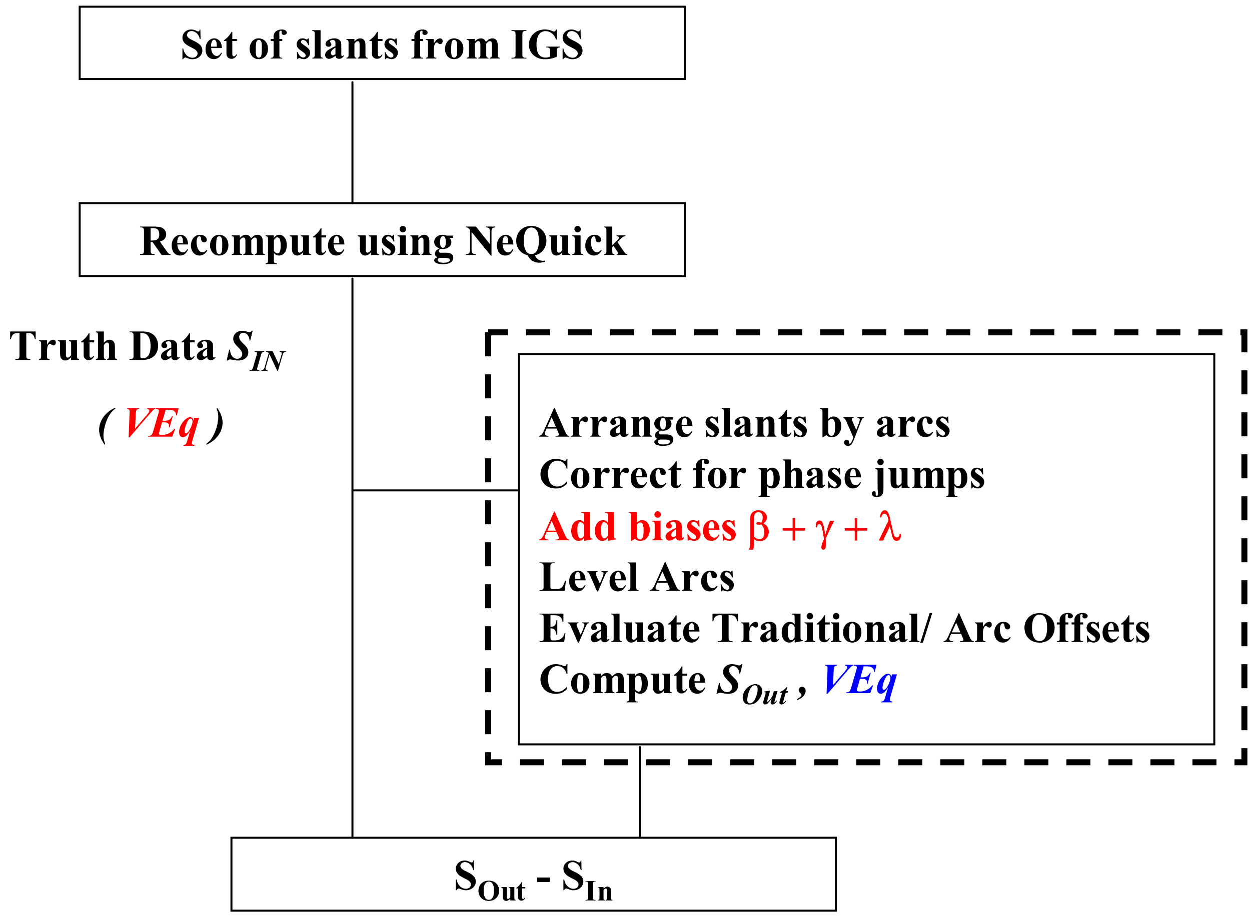
Satellite biases β_i ***= 10 * (Rnd() - Rnd()) , i=1,..,32***

LevelingError λ_{Arc} ***= 10 * Rnd()***

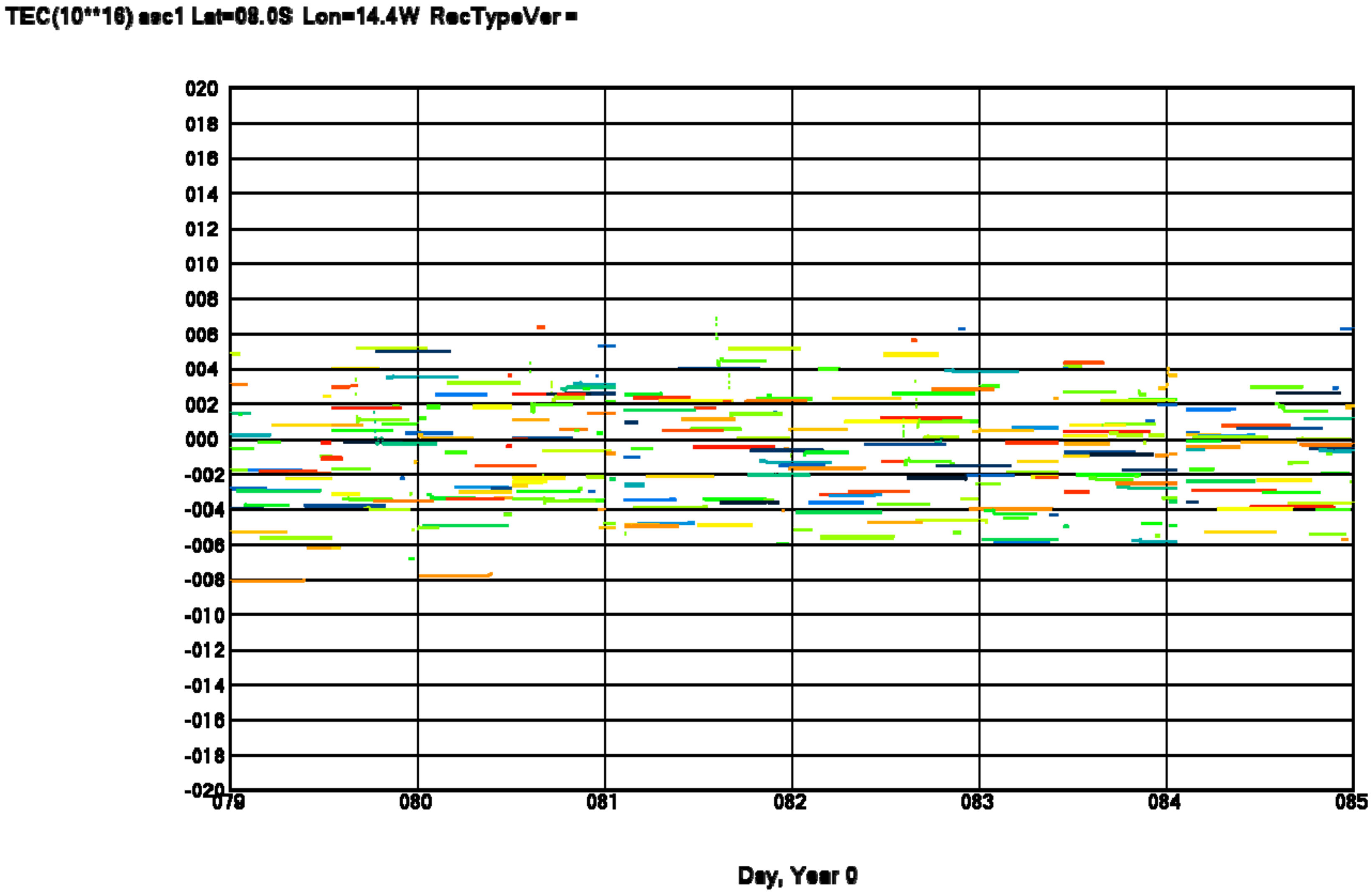
Arc Offset Ω_{Arc} ***= 1000 * Rnd()***

Arc =1.. Number of Arcs

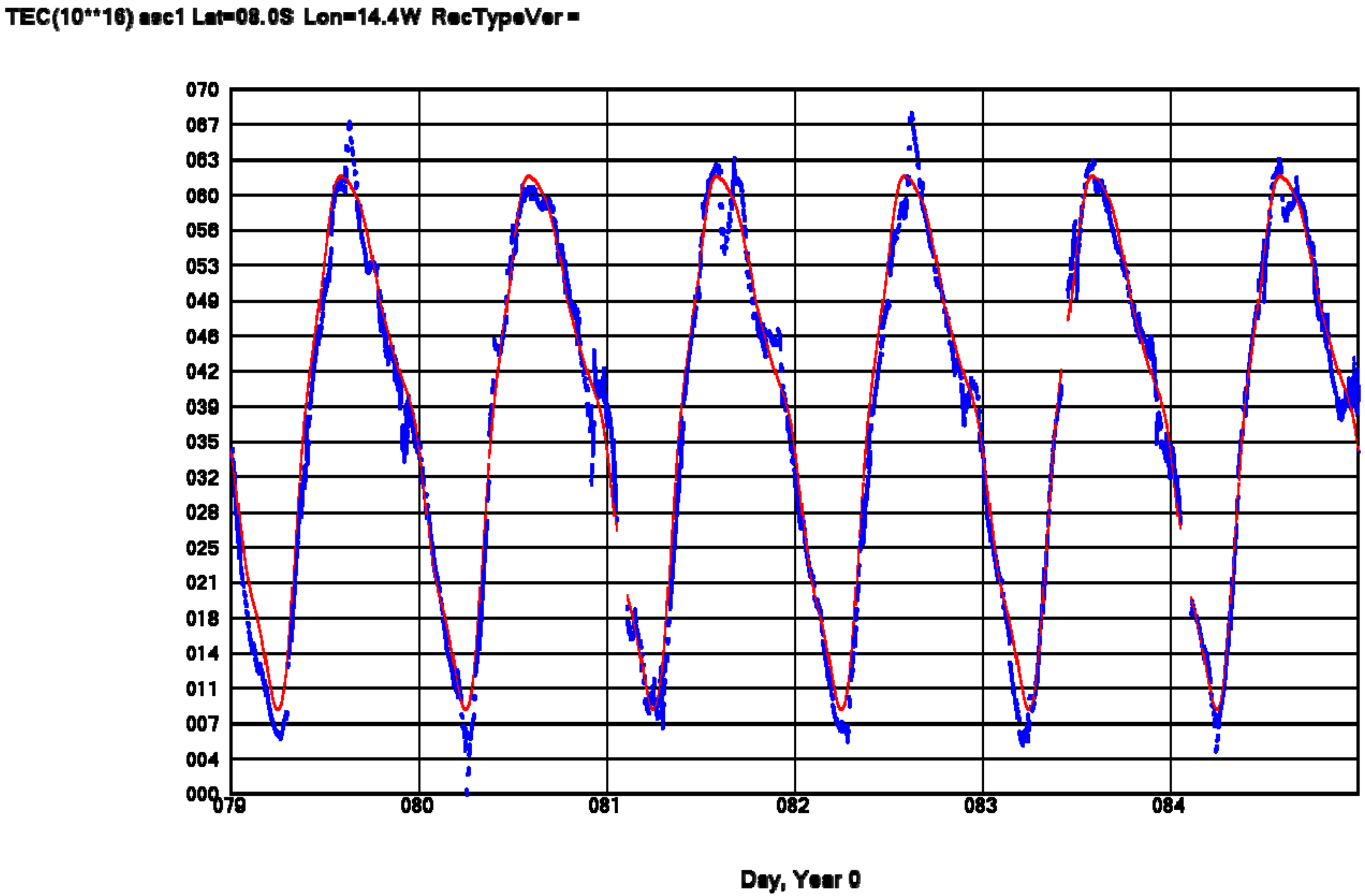
NextData are processed both by traditional and arc offset single-station calibration.


Set of slants from IGS
Recompute using NeQuick
Truth Data S_{IN}
(VEq)
Arrange slants by arcs
Correct for phase jumps
Add biases $\beta + \gamma + \lambda$
Level Arcs
Evaluate Traditional/ Arc Offsets
Compute S_{Out} , VEq
S_{Out} - S_{In}

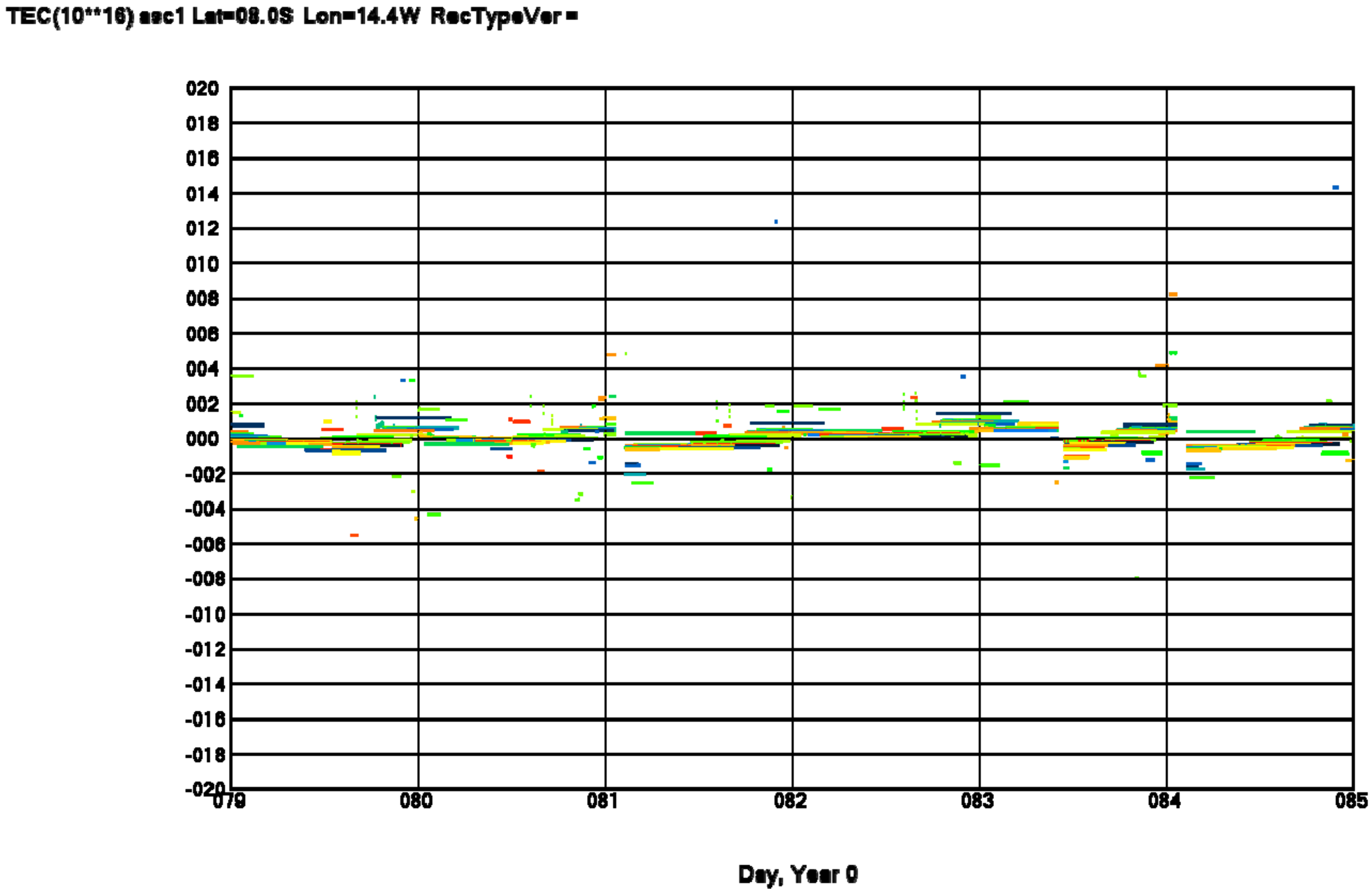
Traditional, SOut - SIn



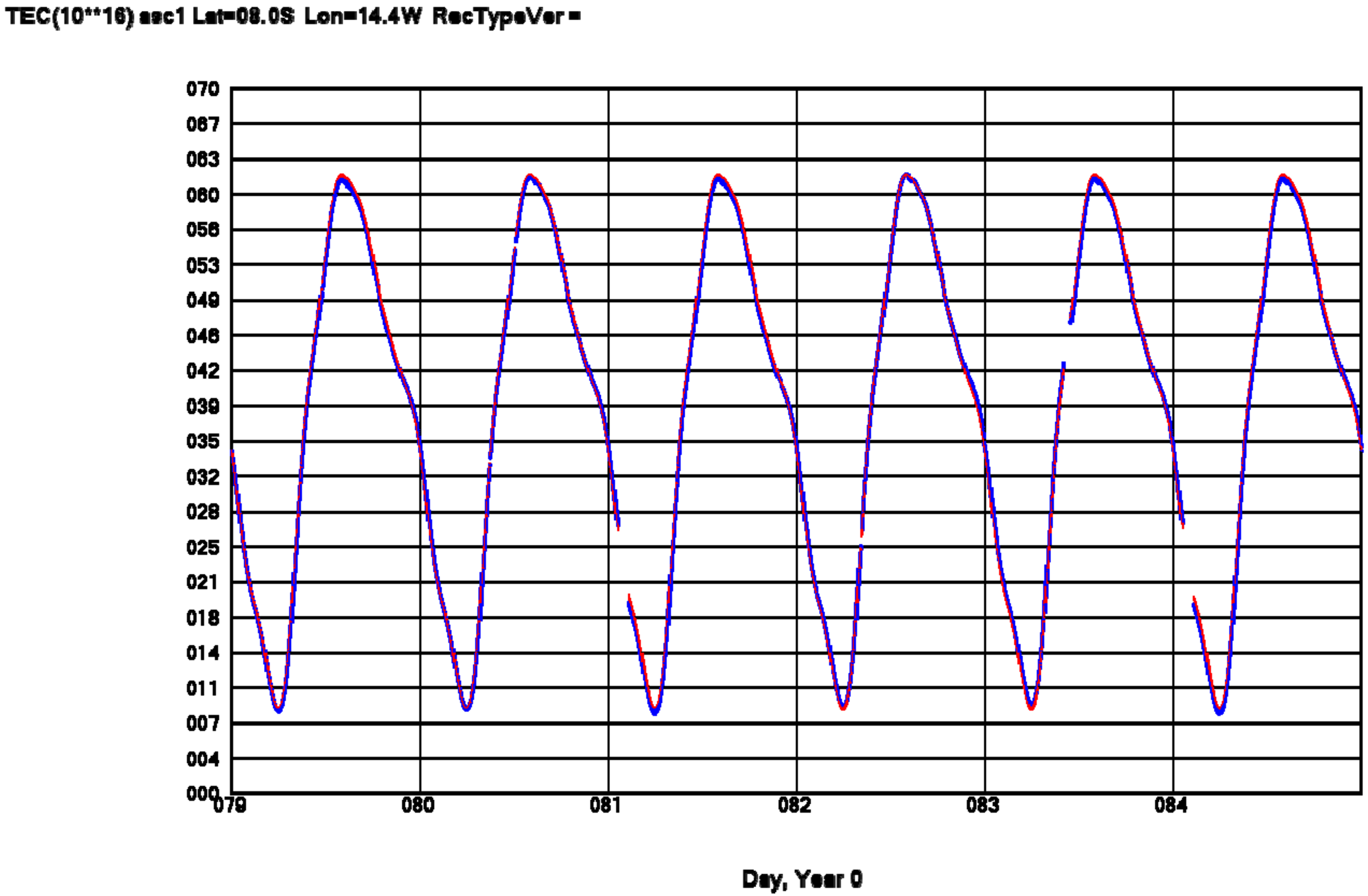
Traditional, *VEq* computed / *VEq* True



Arc Offset, SOUT - SIn



Arc Offset, *VEq* computed / *VEq* True



Thank you