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Satellite Navigation Science and Technology for Africa

23 March - 9 April, 2009

TEC Calibration Techniques: Single-station estimation of arc offsets

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TEC Calibration Techniques

The Single-station estimation of arc offsets

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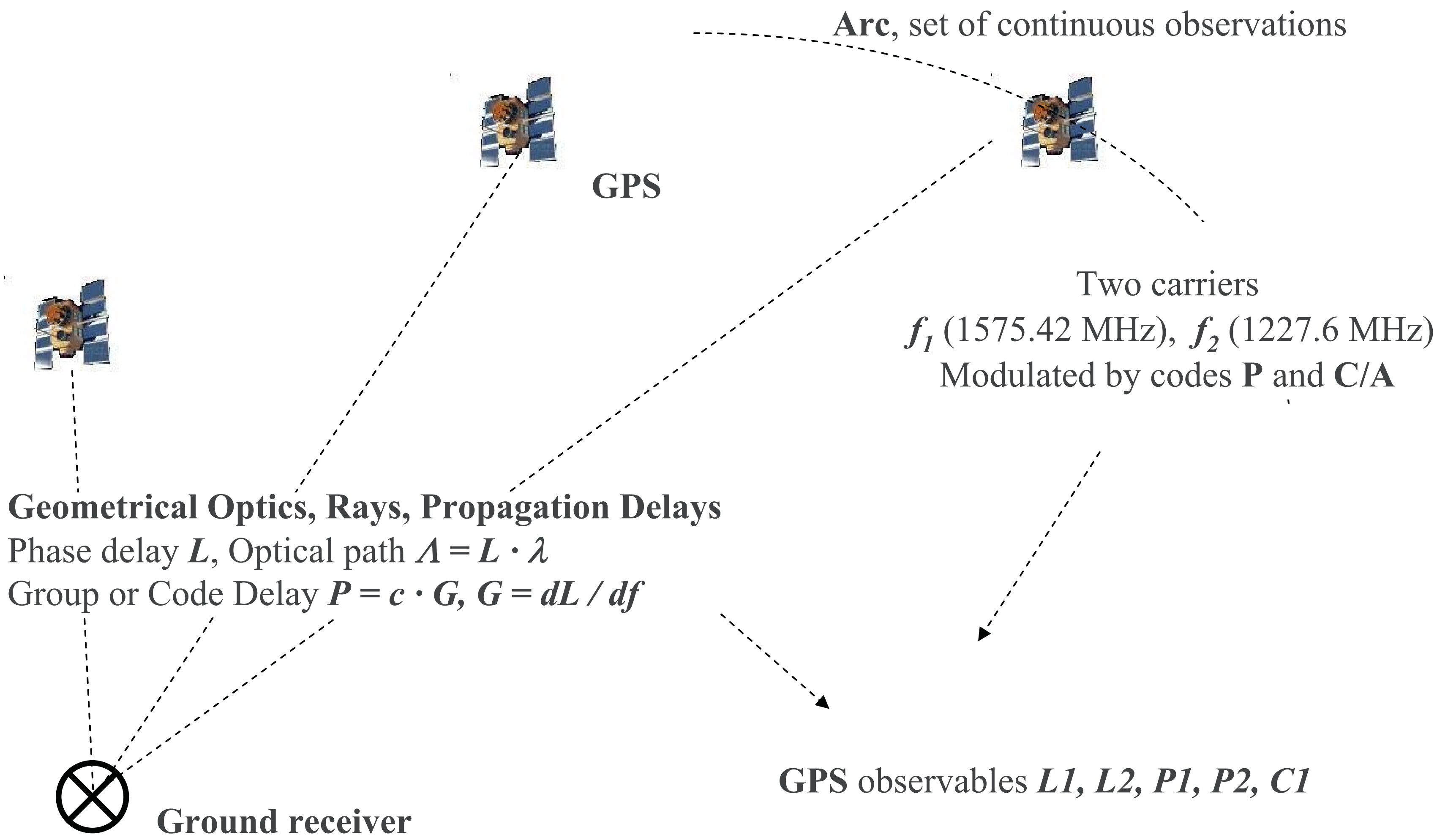
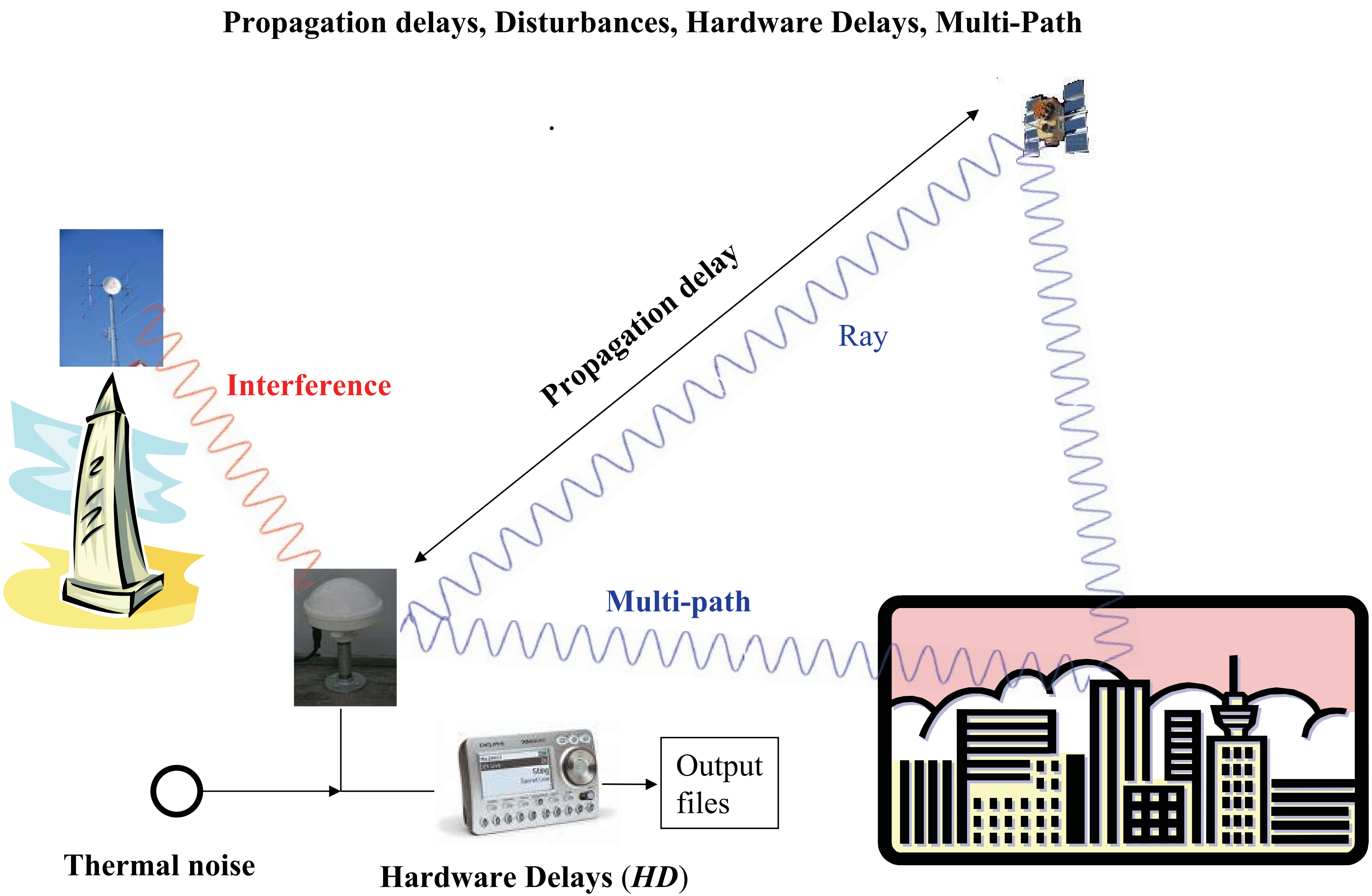
GPS scenario




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	$\boldsymbol{\Omega}$
Noise	$\boldsymbol{n}$
Multipath	$\boldsymbol{m}$
User clock offset	τ

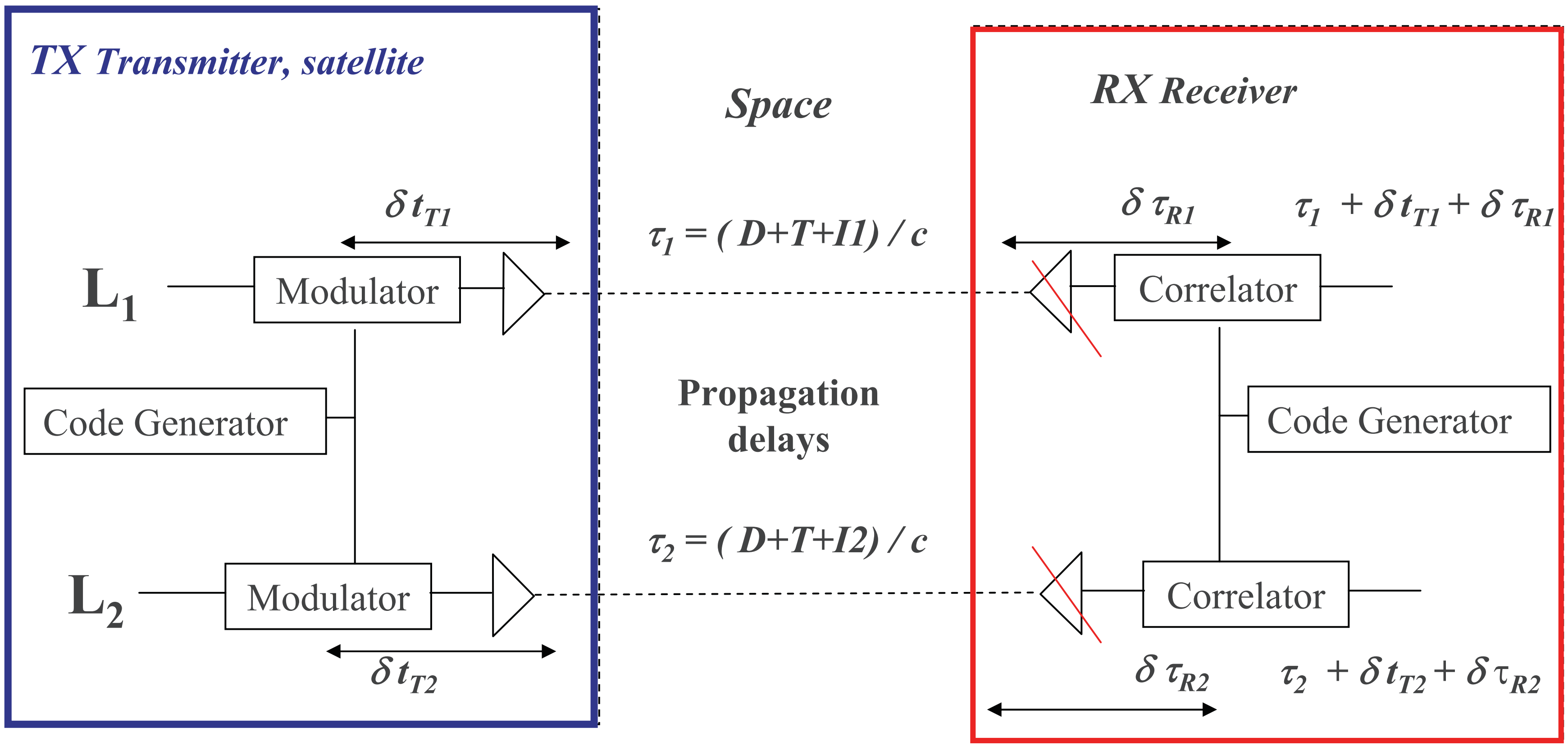
Code delay affected by user clock offset is ***pseudorange***

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

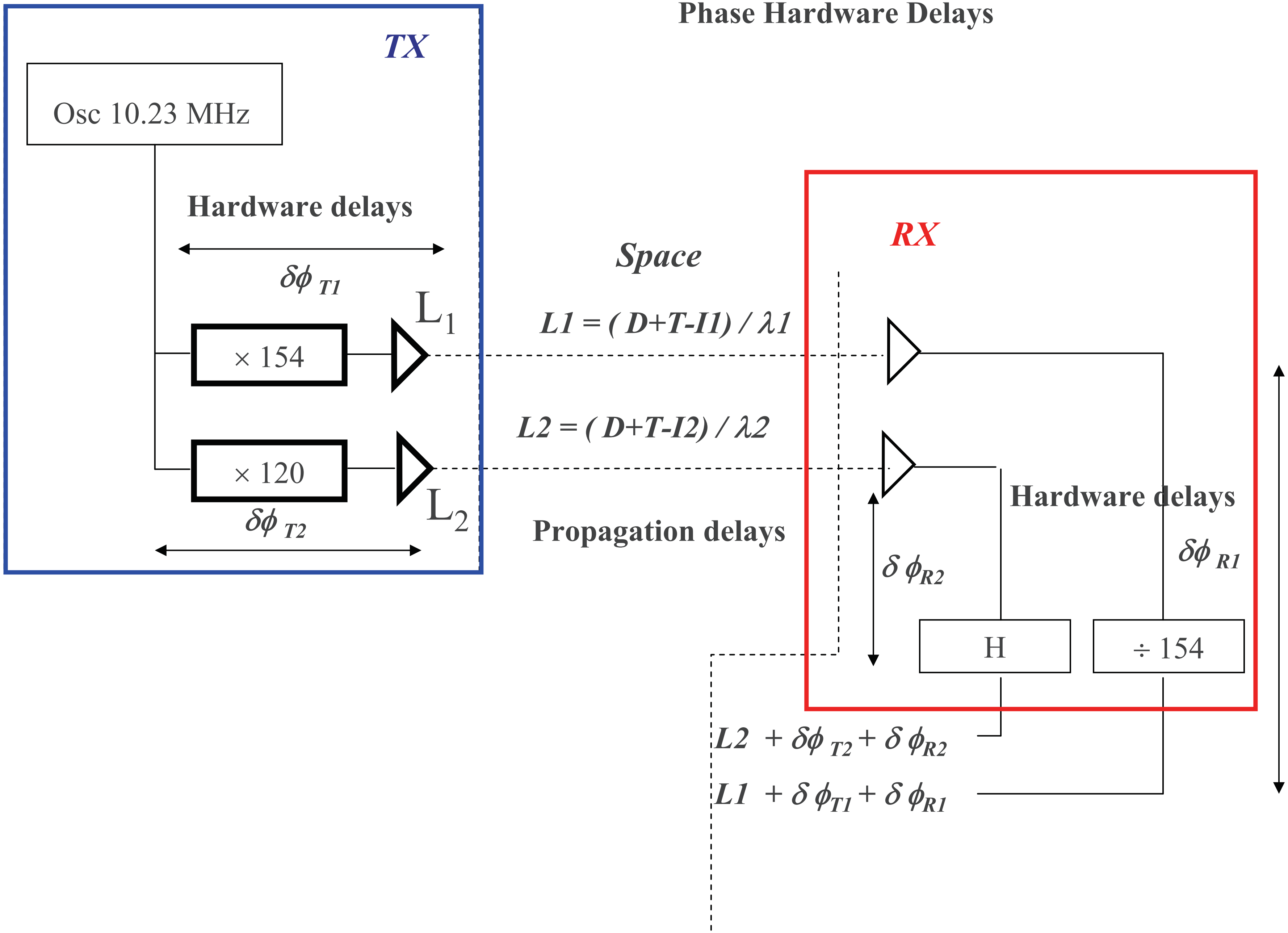
For following discussion, noise and multipath can be neglected for phase delays.
Hardware delays for phase are included in $\boldsymbol{\Omega}$

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

Code hardware delays



Phase Hardware Delays



For participants who have been “ Navigating to RINEX files”

```
 2.10           OBSERVATION DATA    G (GPS)             RINEX VERSION / TYPE
teqc  2002Mar14     ODC group           20040530 03:31:22UTCPGM / RUN BY / DATE
Solaris 2.7|Ultra 2|cc SC5.0|=+-|*Sparc                     COMMENT
teqc  2002Mar14     ODC group           20040530 03:31:20UTCCOMMENT
teqc  2002Mar14     gpsodc(auto)        20040530 03:31:13UTCCOMMENT
BIT 2 OF LLI FLAGS DATA COLLECTED UNDER A/S CONDITION       COMMENT
 SNR is mapped to RINEX snr flag value [1,4-9]              COMMENT
    SNR:  >=316 >=100 >=31.6 >=10 >=3.2    >0 bad=0         COMMENT
L1 & L2:      9     8     7     6     5     4     1         COMMENT
teqc_cut_splice windowed: start @ 2004 May 29 00:00:00.000  COMMENT
teqc_cut_splice windowed:  end  @ 2004 May 29 23:59:30.000  COMMENT
URUM                                                        MARKER NAME
21612M001                                                   MARKER NUMBER
unknown             GeoForschungsZentrum Potsdam            OBSERVER / AGENCY
289                 AOA SNR-8000 ACT    3.3.32.3            REC # / TYPE / VERS
366                 AOAD/M_T    NONE                        ANT # / TYPE
   193031.2854  4606855.9474  4393315.7337                  APPROX POSITION XYZ
        0.0460        0.0000        0.0000                  ANTENNA: DELTA H/E/N
     1     1                                                WAVELENGTH FACT L1/2
     5    L1    L2    C1    P1    P2                        # / TYPES OF OBSERV
    30.0000                                                 INTERVAL
teqc_cut_splice windowed: start @ 2004 May 29 00:00:00.000  COMMENT
teqc_cut_splice windowed:  end  @ 2004 May 29 23:59:60.000  COMMENT
  2004     5    29     0     0    0.0000                    TIME OF FIRST OBS
  2004     5    29    23    59   30.0000                    TIME OF LAST OBS
                                                            END OF HEADER
 04  5 29  0  0  0.0000000  0  8G 5G 7G 4G24G17G 9G20G28
 -16270915.280 7 -12678636.310 7                   21972522.323    21972526.236
 -18926790.994 8 -14748140.587 8                   21393323.463    21393327.322
 -25123559.692 8 -19576793.621 8                   20282560.885    20282563.441
 -21393958.279 8 -16670613.899 8                   20948800.132    20948804.025
  -9455527.933 6  -7367946.556 7                   23707971.468    23707976.765
  -6126629.626 6  -4774000.590 6                   23630600.906    23630604.841
  -5152666.049 6  -4015066.512 6                   24281104.532    24281108.888
  -4928214.953 5  -3840170.881 6                   24428341.818    24428346.048
 04  5 29  0  0 30.0000000  0  8G 5G 7G 4G24G17G 9G20G28
```

PRN #05

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

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

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

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

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

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

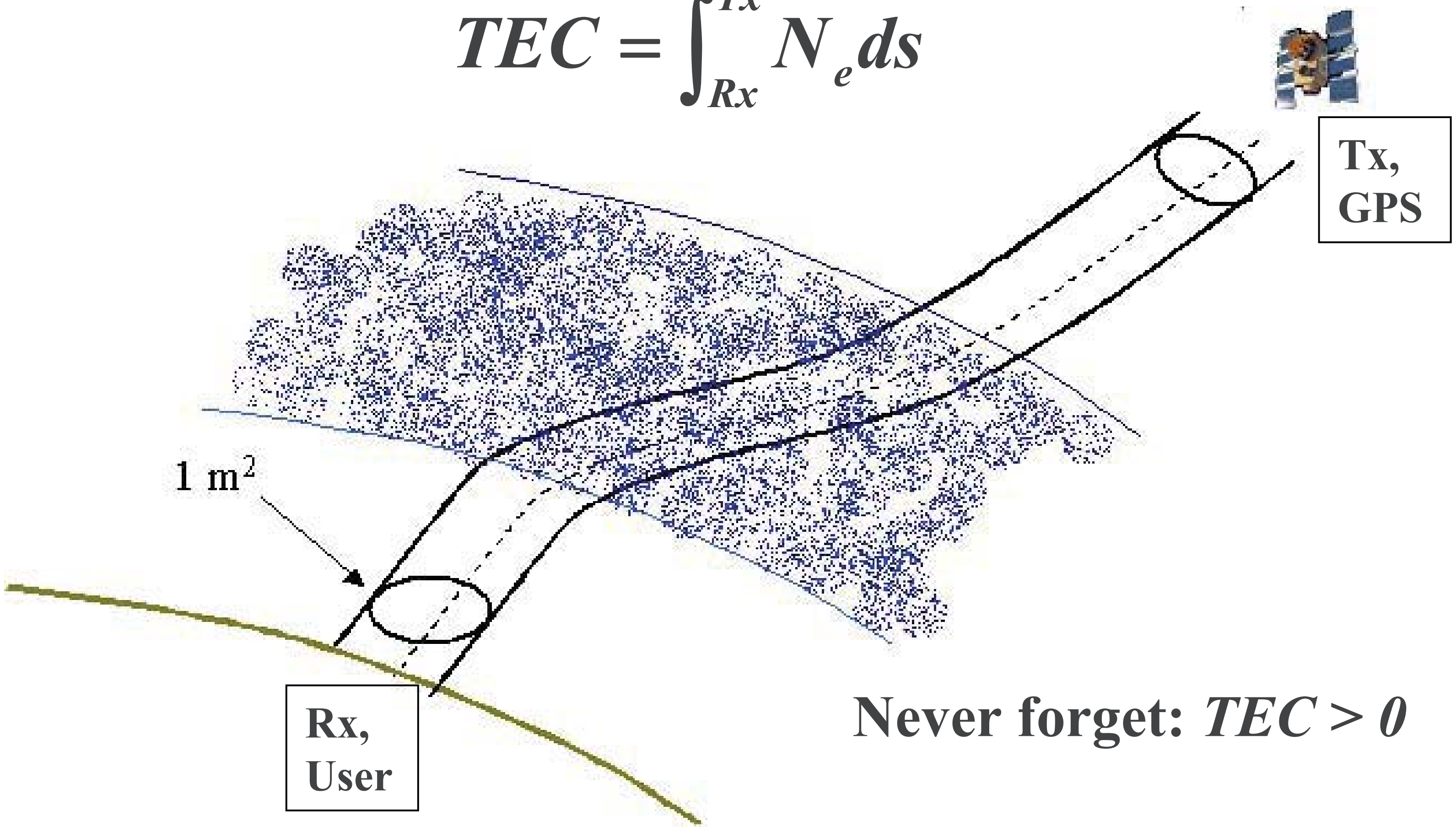
Divide by $\boldsymbol{k \cdot 10^{-16}}$, drop out the Δ symbol to obtain the ***phase slants*** $\boldsymbol{S_P}$ and ***group or code slants*** $\boldsymbol{S_C}$ in ***TECu***, 1 ***TECu*** = 10^{16} electrons/m^2, disregard radio noise $\boldsymbol{n}$

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

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

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

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

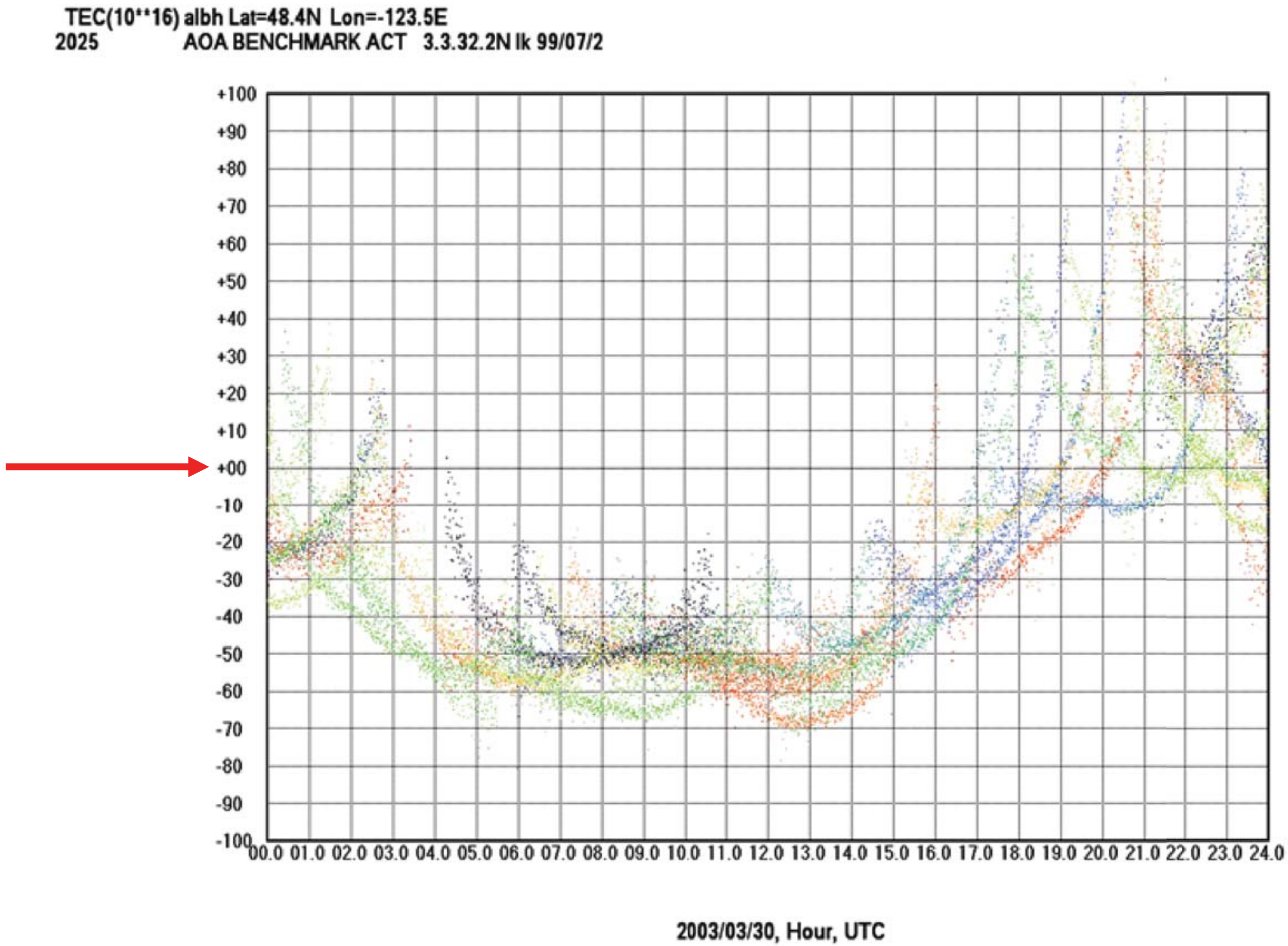
denote the set of all available observations used for performing some specific task.

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.

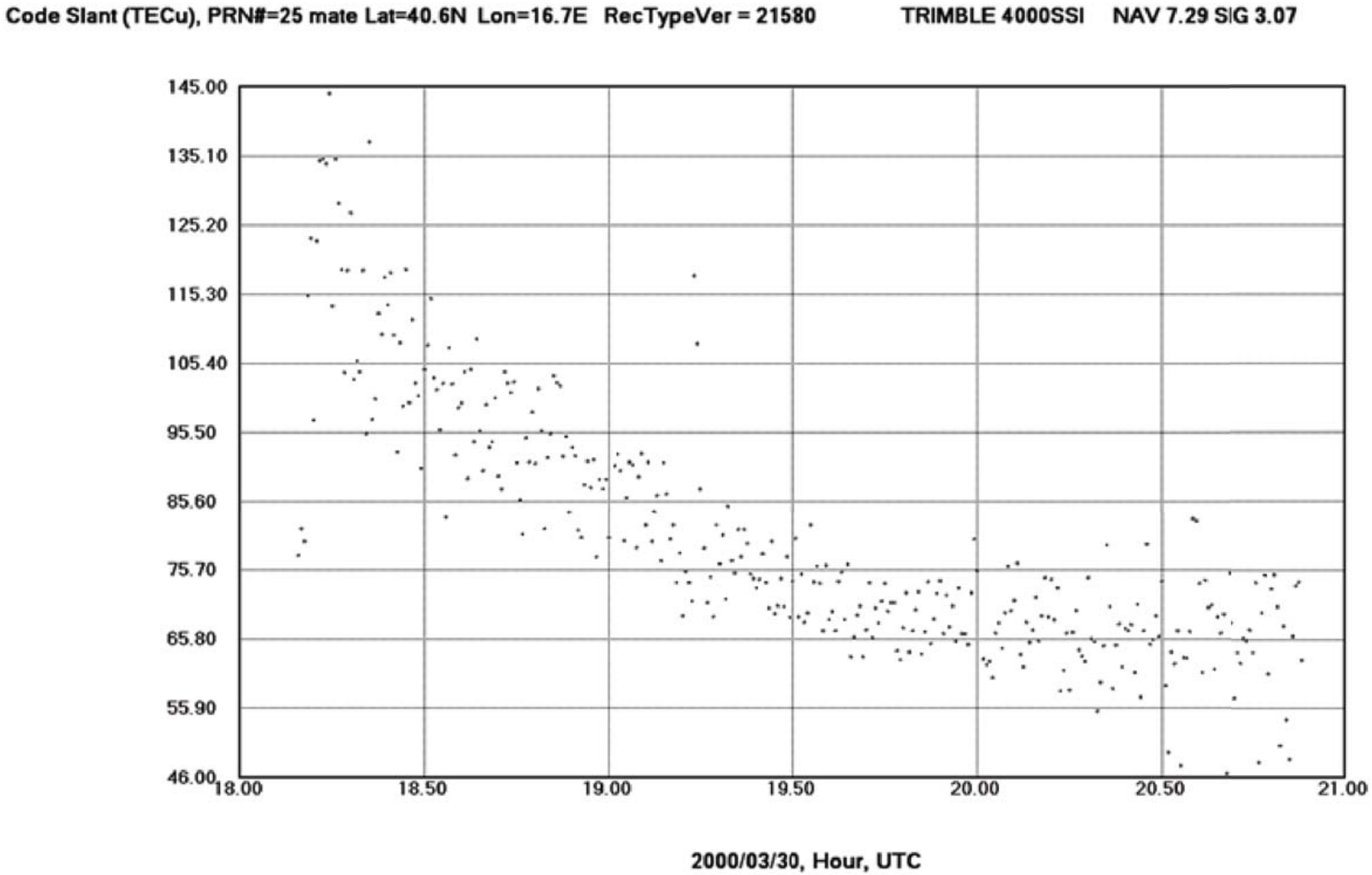
When needed for clarity, indexing will be explicitly adopted.

Plot of S_C arcs for one day

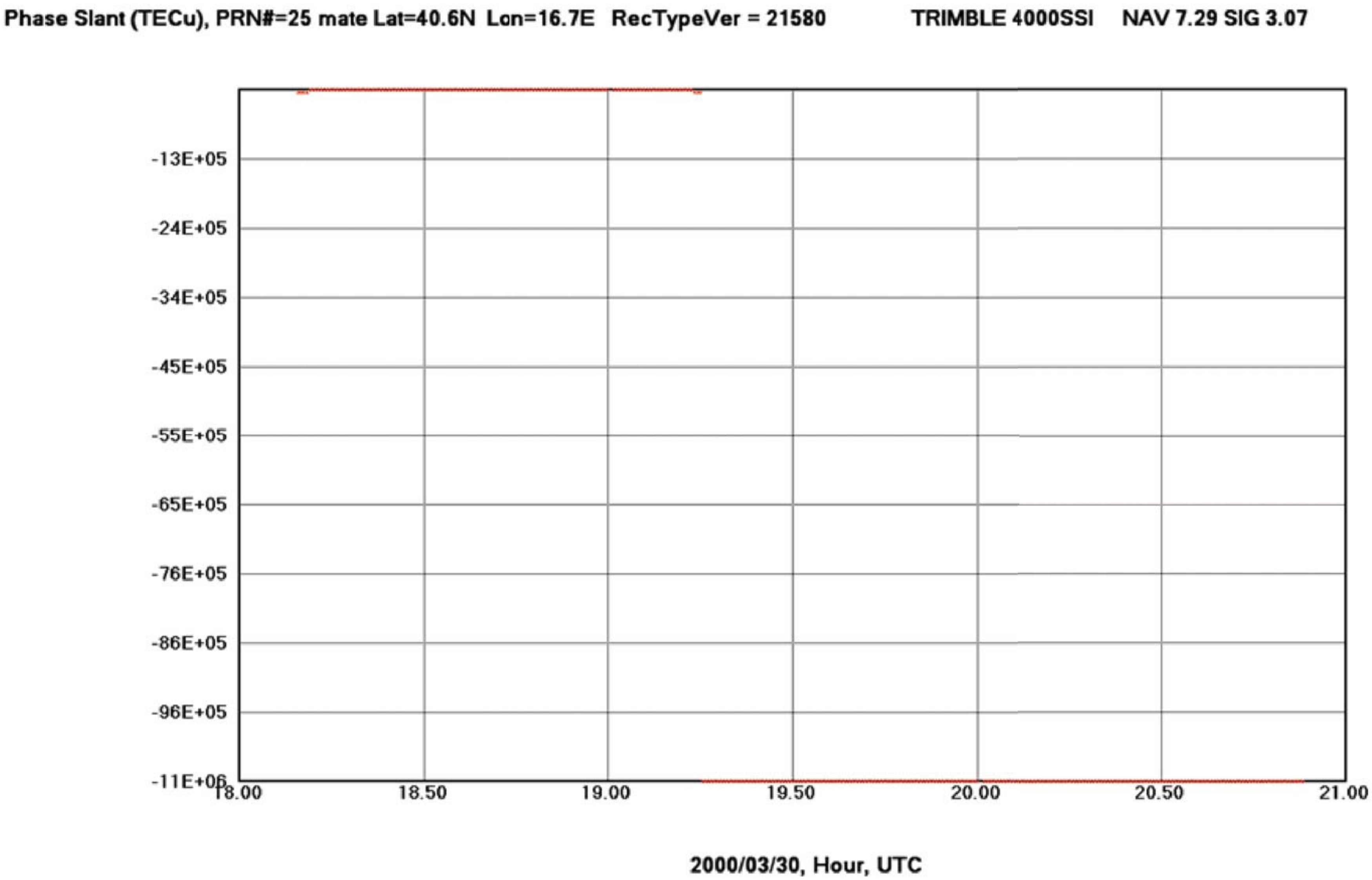


* Evidence that calibration is needed: TEC is a positive quantity

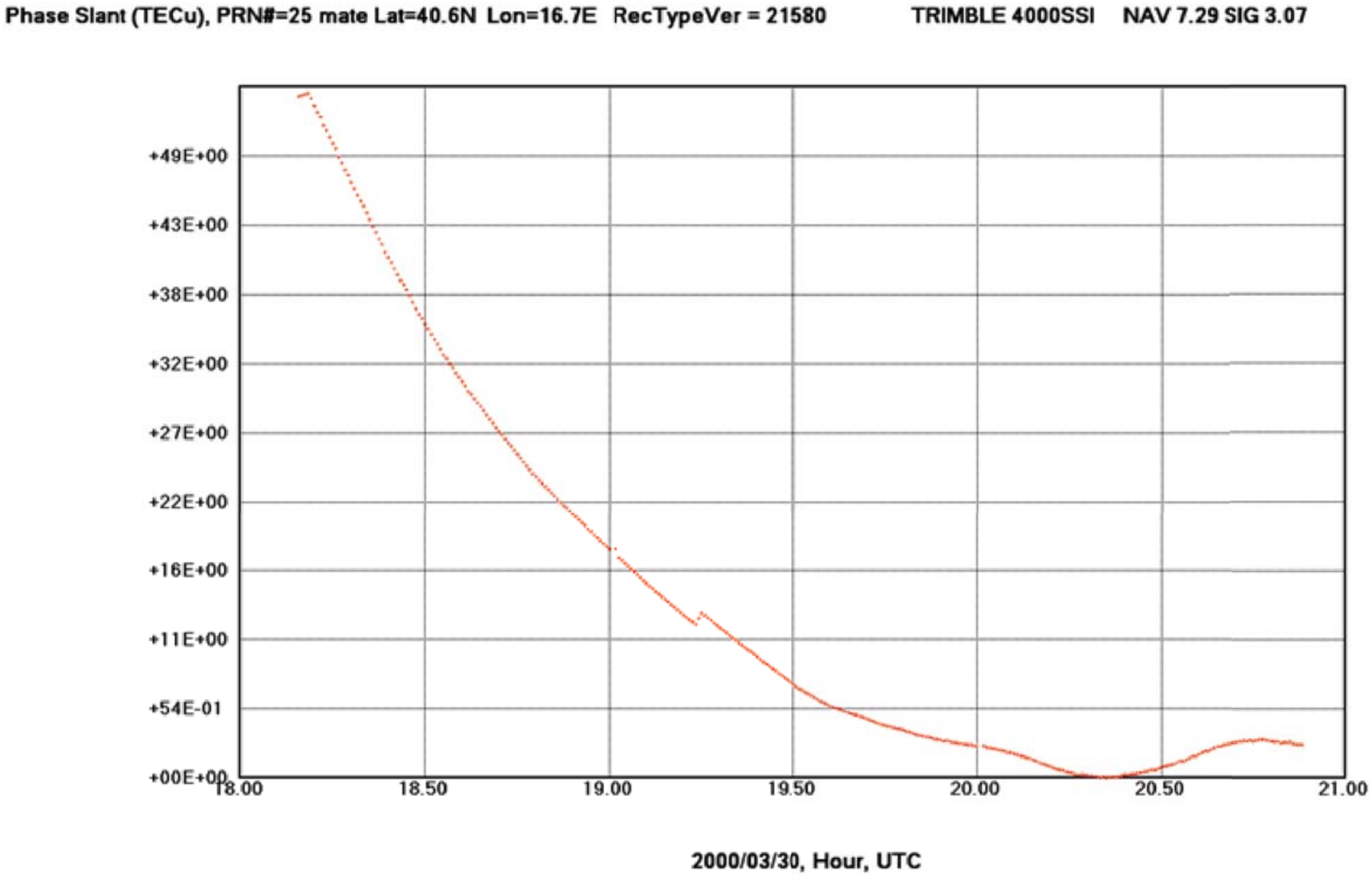
Sample S_C, one arc: the common situation



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



Sample $\boldsymbol{S_P}$, 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

$$S_L = S_P - \langle S_P - S_C \rangle$$

$$\langle S_P - S_C \rangle = \Omega - \langle m \rangle - \beta - \gamma$$

$$S_L = TEC + \langle m \rangle + \beta + \gamma$$

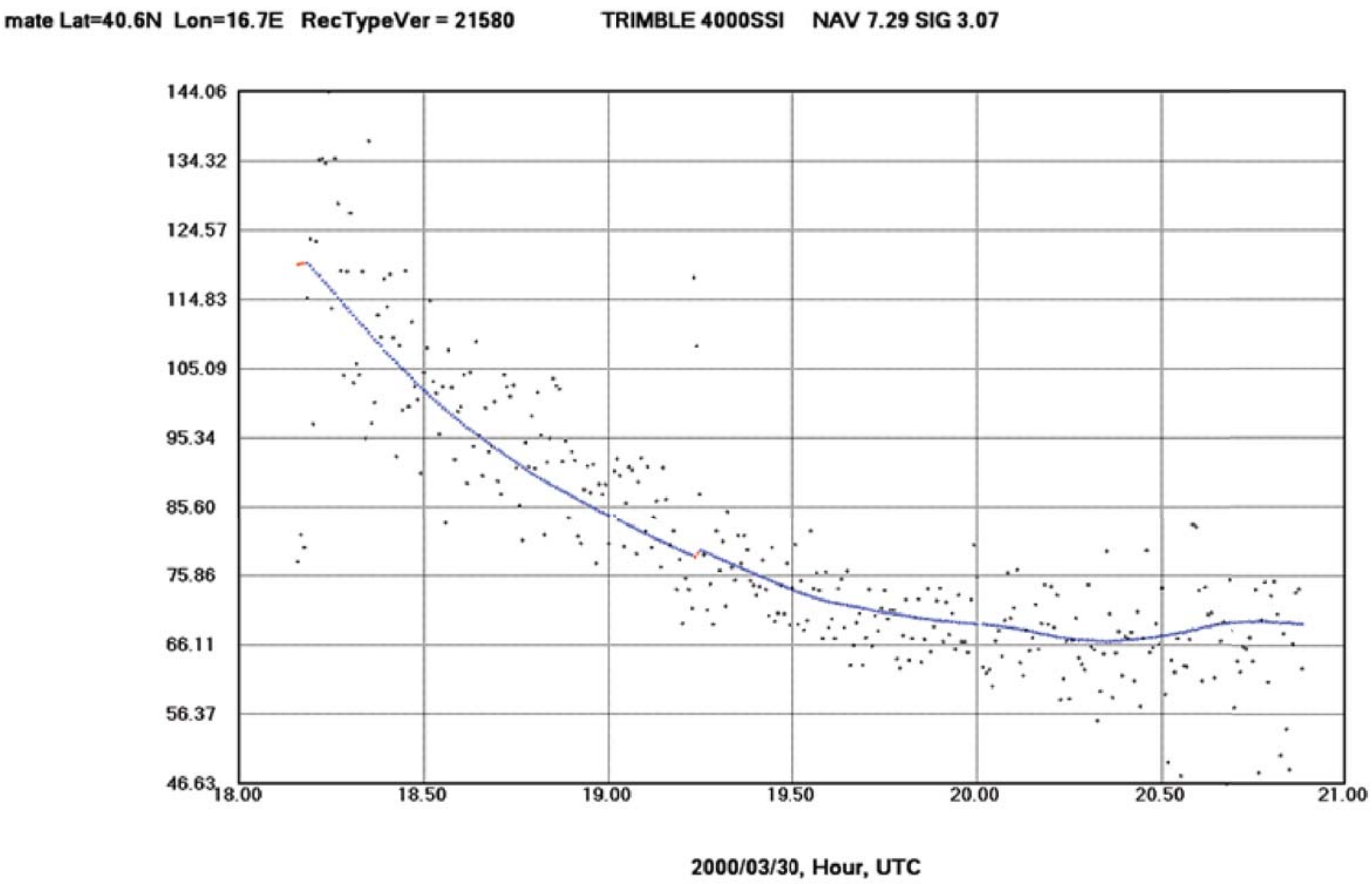
Properties of S_L

Noise is the same (neglected) of phase slants

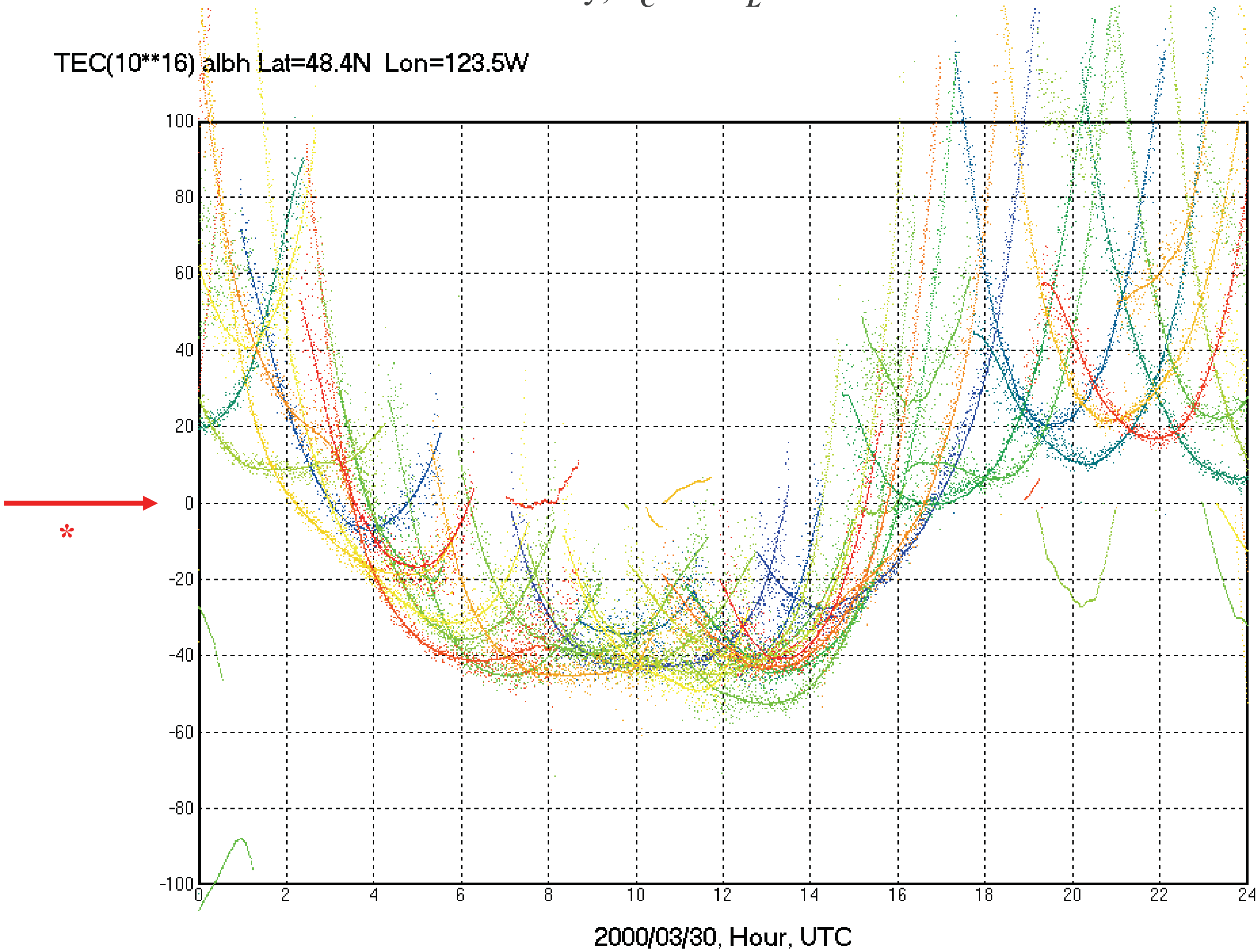
Biased exactly as code slants

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

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



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, $\langle m \rangle$, changing generally (but not arbitrarily) from arc to arc.
TEC	The quantity to estimate, variable from observation to observation

All terms appearing in observed slants are unknown

The calibration or de-biasing of GPS differential delays

Differential delays ***S*** provide with slant Total Electron Content (***TEC***) biased by unknown terms (hardware biases β, γ or phase offsets Ω)

$$S = TEC + [\ \beta, \gamma\ ; \Omega\ ]$$

Number of unknowns = number of TEC*s *plus number of $[\ \beta, \gamma\ ; \Omega\ ]$

Calibration is some algorithm able to provide with estimates the set of unknown terms $[\ \underline{\beta}, \underline{\gamma}\ ; \underline{\Omega}\ ]$ in order to get the actual ***TEC***

$$TEC = S - [\ \underline{\beta}, \underline{\gamma}\ ; \underline{\Omega}\ ]$$

Given the unavailability of independent measurements of ***TEC,*** the only way to perform calibration is to expand ***TEC*** using proper base functions of time and position

$$TEC\ (\ P\ ,\ t\ ) = \Sigma\, c\ \ \Psi(\ P\ ,\ t\ )$$

The coefficients ***c*** become a new set of unknowns to be estimated together with the "biasing" terms using standard minimization algorithms

$$S = \Sigma\, c\ \ \Psi(\ P\ ,\ t\ ) + [\ \beta, \gamma\ ; \Omega\ ]$$

Number of unknowns = number of c plus number of $[\ \beta, \gamma\ ; \Omega\ ]$

By-products of calibration

In addition to calibrated slants (***TEC***'s), the knowledge of the coefficients ***c*** of ***TEC*** expansion **,** functions of time, will enable to estimate slants along directions different from the ones of the actual observations.

$$S\ (P^*, t) = \Sigma\, c(t)\ \Psi(P^*, t)$$

The most familiar is ***VEC***, the Total Electron Content relative to the zenith of the station, vertical ***TEC***

$$\mathrm{VEC(t)} = S\ (P^{Sta}, t) = \Sigma\, c(t)\ \Psi(P^{Sta}, t)$$

Therefore ***VEC*** is not a measured, but a computed quantity

Factors affecting the reliability of calibration

Calibration: solve the system

$$\boldsymbol{S = \Sigma c\ \Psi (P , t) + [\beta, \gamma ; \Omega]}$$

in the unknowns $\boldsymbol{c}$, $\boldsymbol{\beta, \gamma , \Omega}$

Reliability of calibration relies on

reliability of observations *S* themselves

$$\boldsymbol{S = TEC + [\beta, \gamma ; \Omega]}$$

adequacy of the model used for the expansion of *TEC*

$$\boldsymbol{TEC (P , t) = \Sigma c\ \Psi (P , t)}$$

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**

$$\boldsymbol{S_C = TEC + n + m + \beta + \gamma}$$

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 $\boldsymbol{\beta}$ per satellite, one γ for station: a favorable unknowns/observations budget.

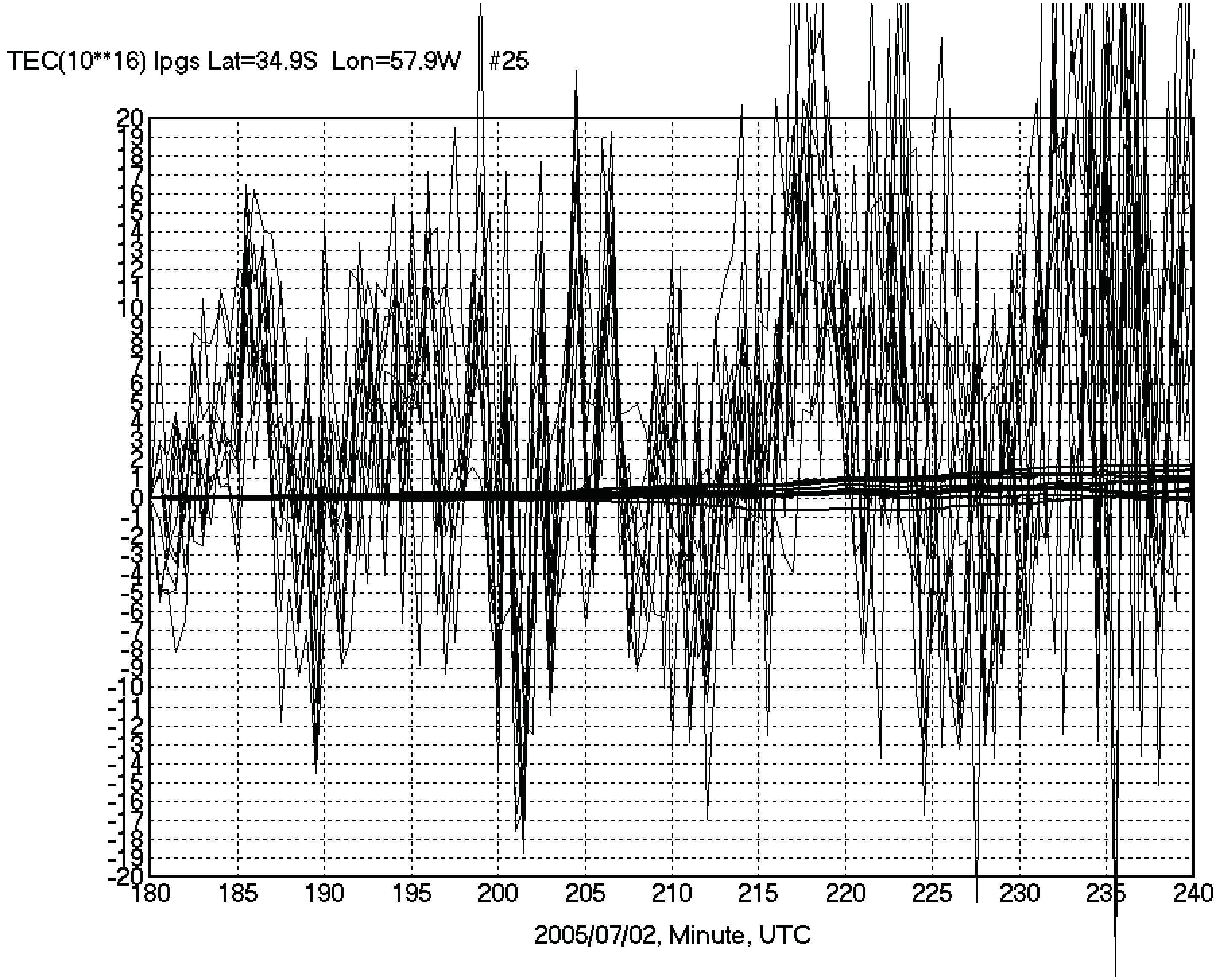
n: strong radio noise (non linear techniques used to evaluate pseudo-ranges), but still a stochastic variable with zero mean (resulting in consistent estimations)

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 $\boldsymbol{TEC(t) - TEC(t_0)}$, $\boldsymbol{t_0}$ being the beginning of each arc. Both $\boldsymbol{S_G}$ and $\boldsymbol{S_\Phi}$ relative to the same arc are plotted .


TEC(10**16) lpgs Lat=34.9S Lon=57.9W #25
2005/07/02, Minute, UTC

Features of observations: Phase slants

$$\boldsymbol{S_P = TEC + \Omega}$$

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

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

As for code slants, one unknown per satellite $\boldsymbol{\beta}$ and for station $\boldsymbol{\gamma}$

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 **<u>not</u>** a stochastic variable and it has **<u>no zero mean</u>**

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***

DOI 10.1007/s00190-006-0093-1

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;

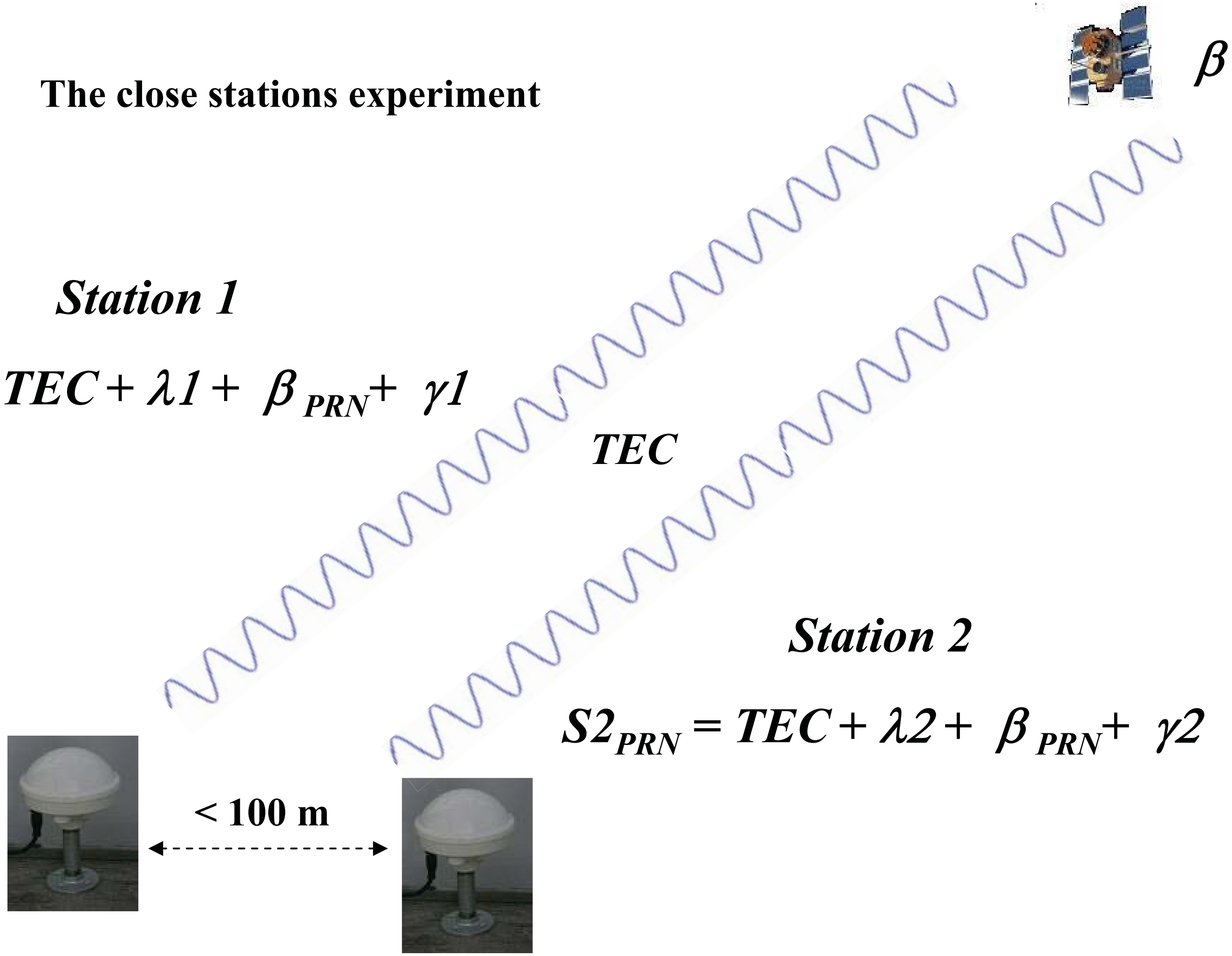
tid1/tidb; tid2/tidb; tixi/tixj; tro1/trom; tsk2/tskb;

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



Station 1

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

Station 2

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

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

Not dependent on PRN

The close stations experiment

In equations of observation

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

Consider observations to satellite $\boldsymbol{i}$ from stations $\boldsymbol{j}$ e $\boldsymbol{k}$

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

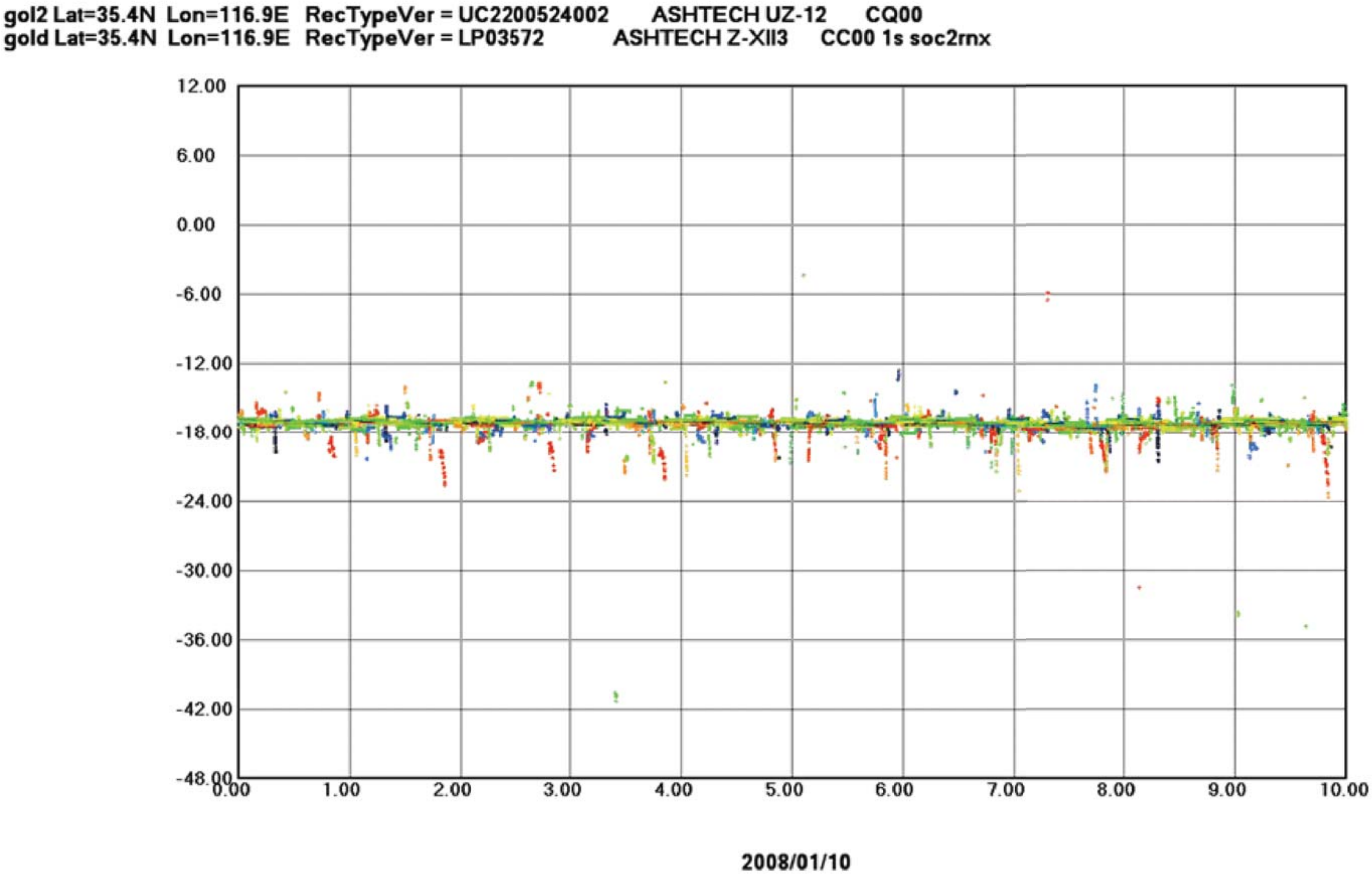
$$\boldsymbol{S_{ik} = TEC_{ik} + \beta_i + \gamma_k + \lambda_{Arc\_k}}$$

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

<u>Most of times</u> the situation is quite different as

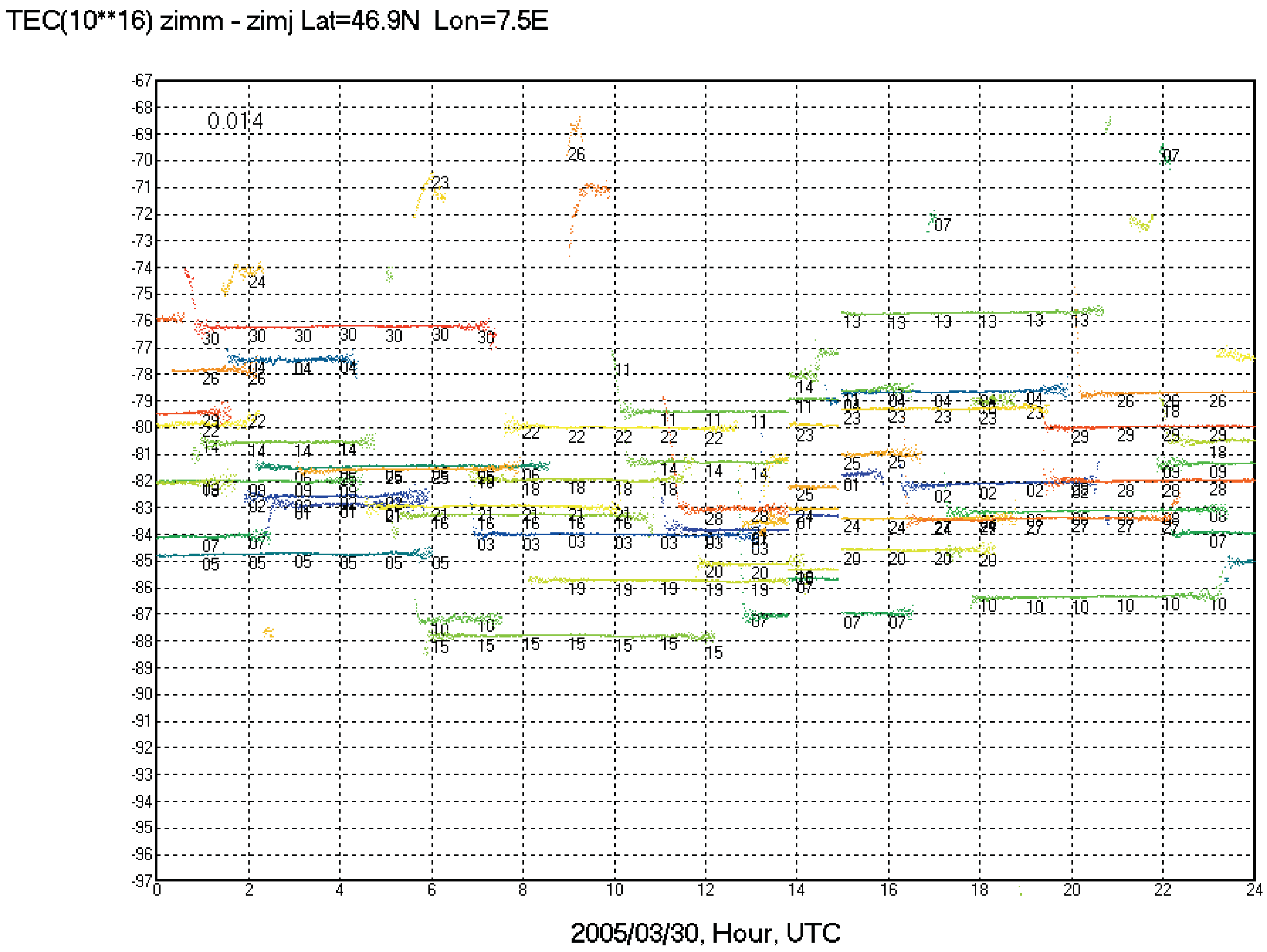
a significant spread among satellites appears

As shown in following slides

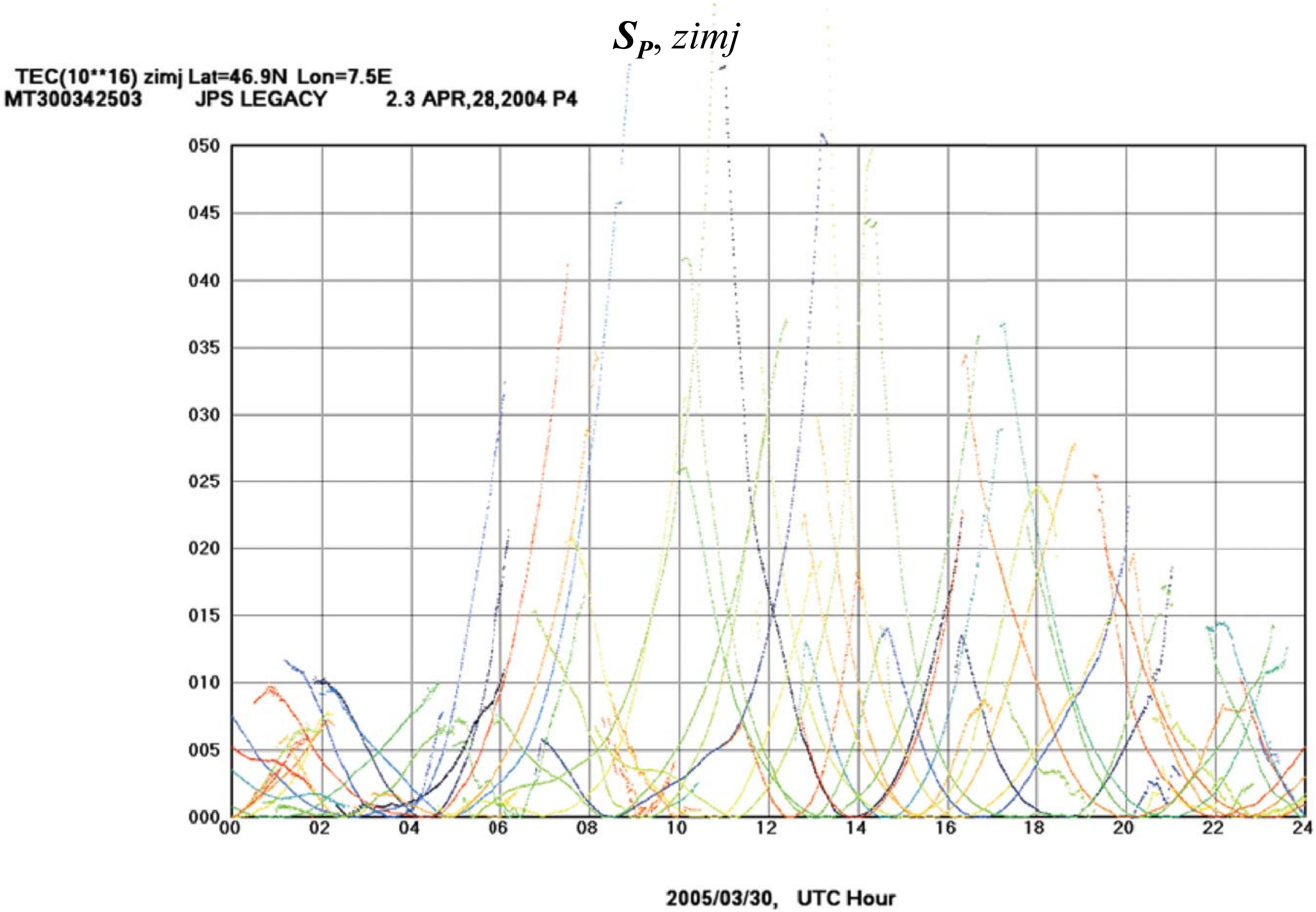
Possible cause

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

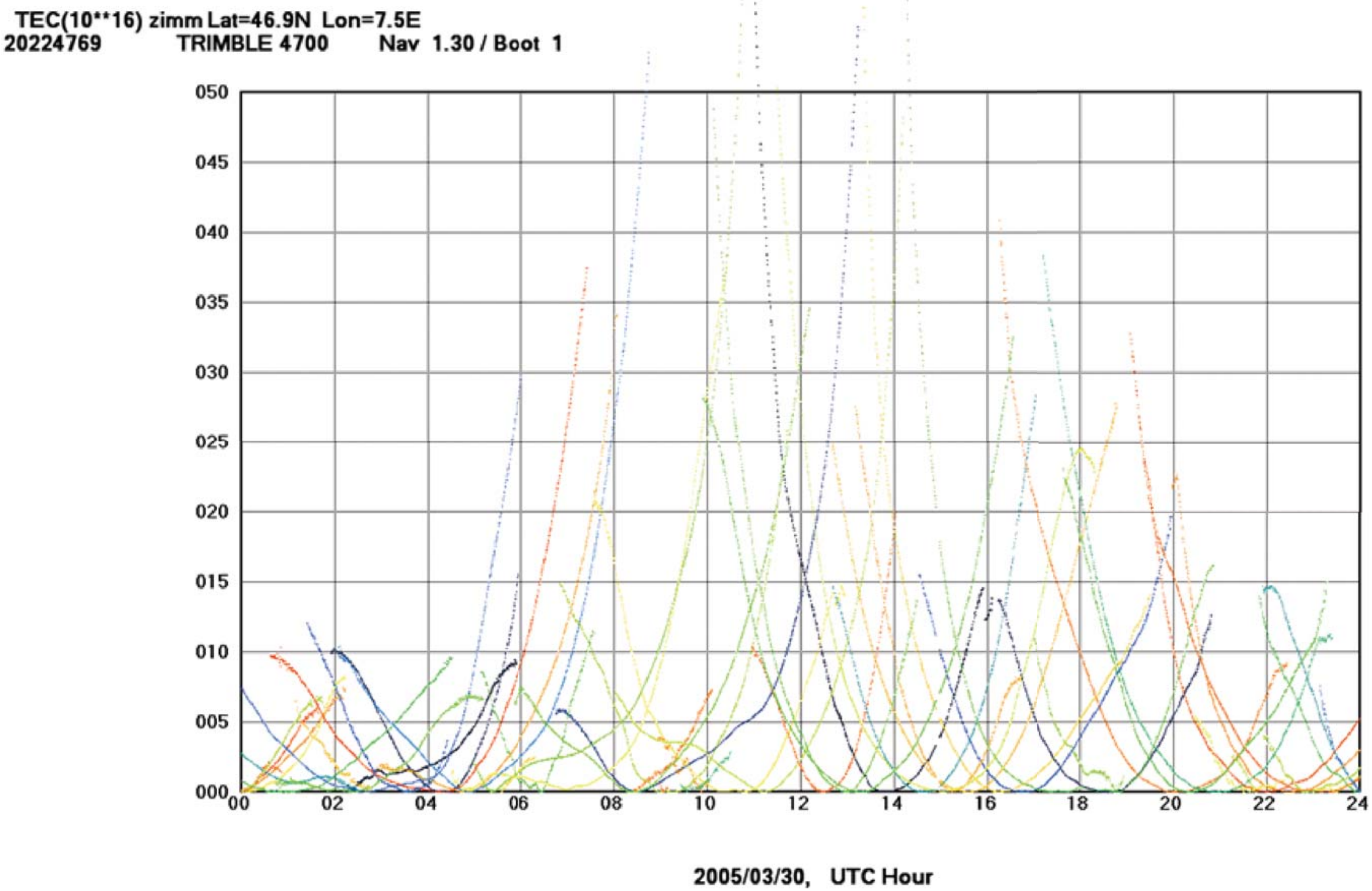
$S_{L1} - S_{L2}$, all satellites



S_P, *zimj*


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*



TEC(10**16) zimm Lat=46.9N Lon=7.5E
20224769 TRIMBLE 4700 Nav 1.30 / Boot 1
050
045
040
035
030
025
020
015
010
005
000
00
02
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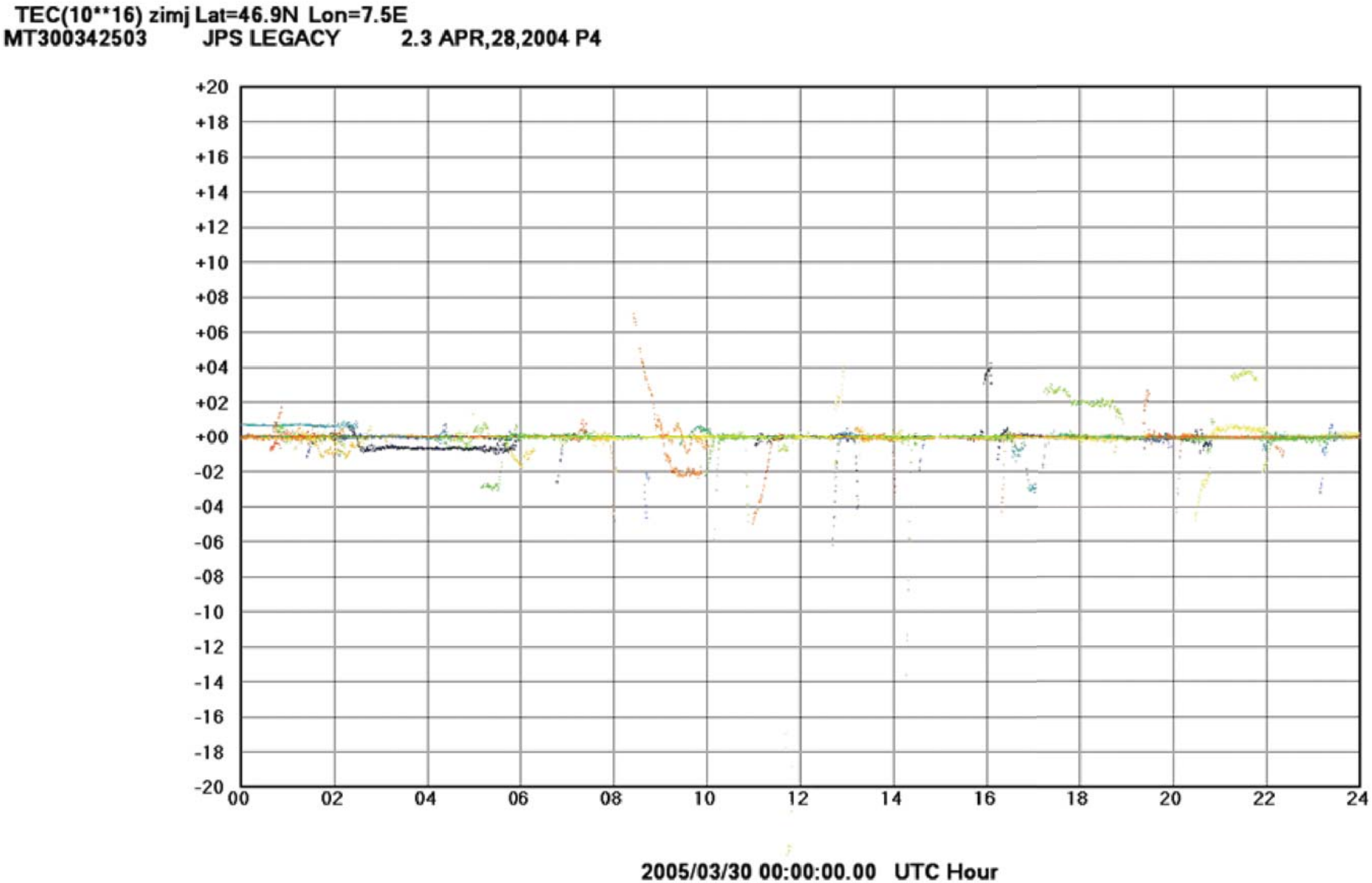
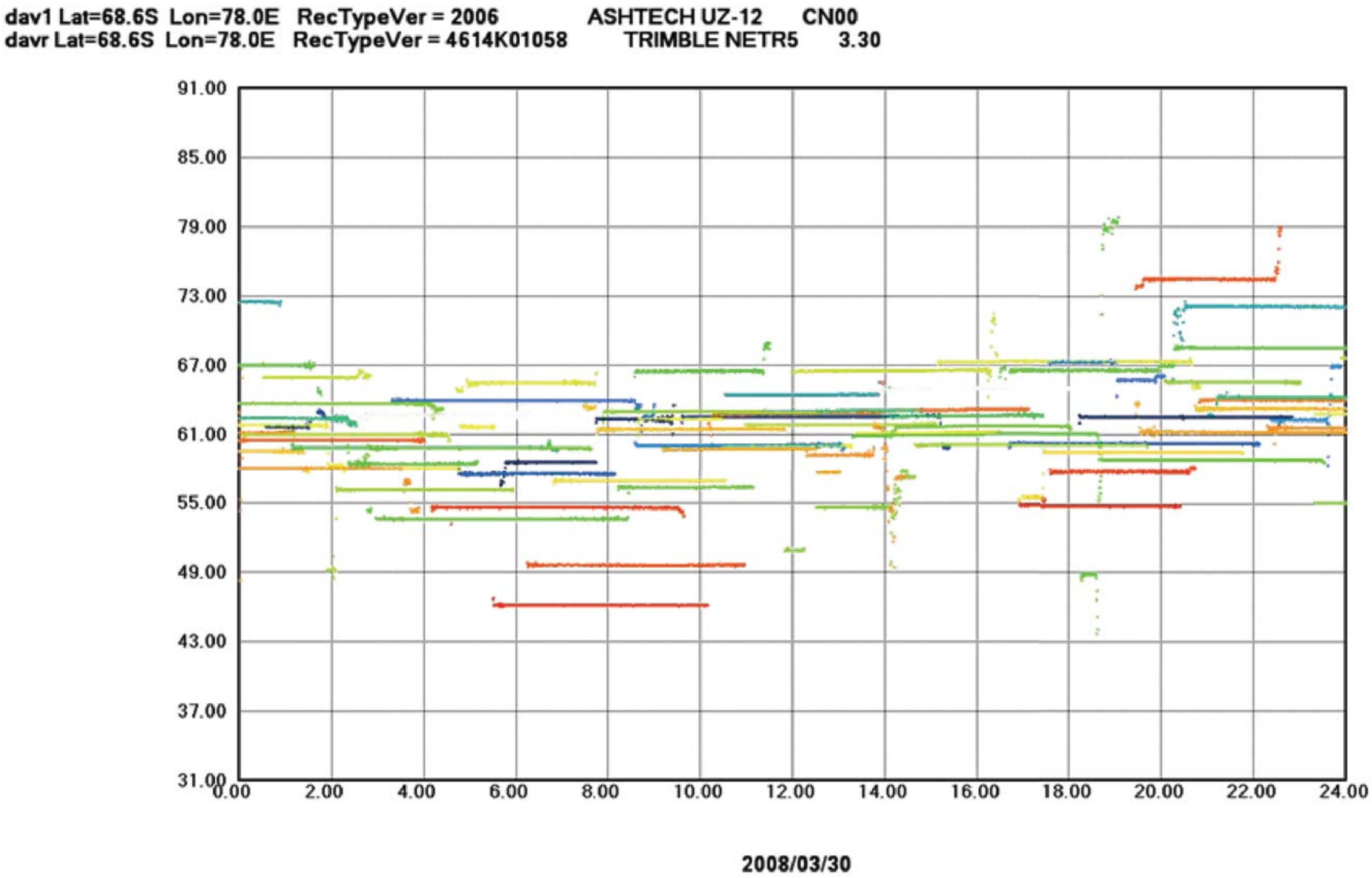
06
08
10
12
14
16
18
20
22
24
2005/03/30, UTC Hour

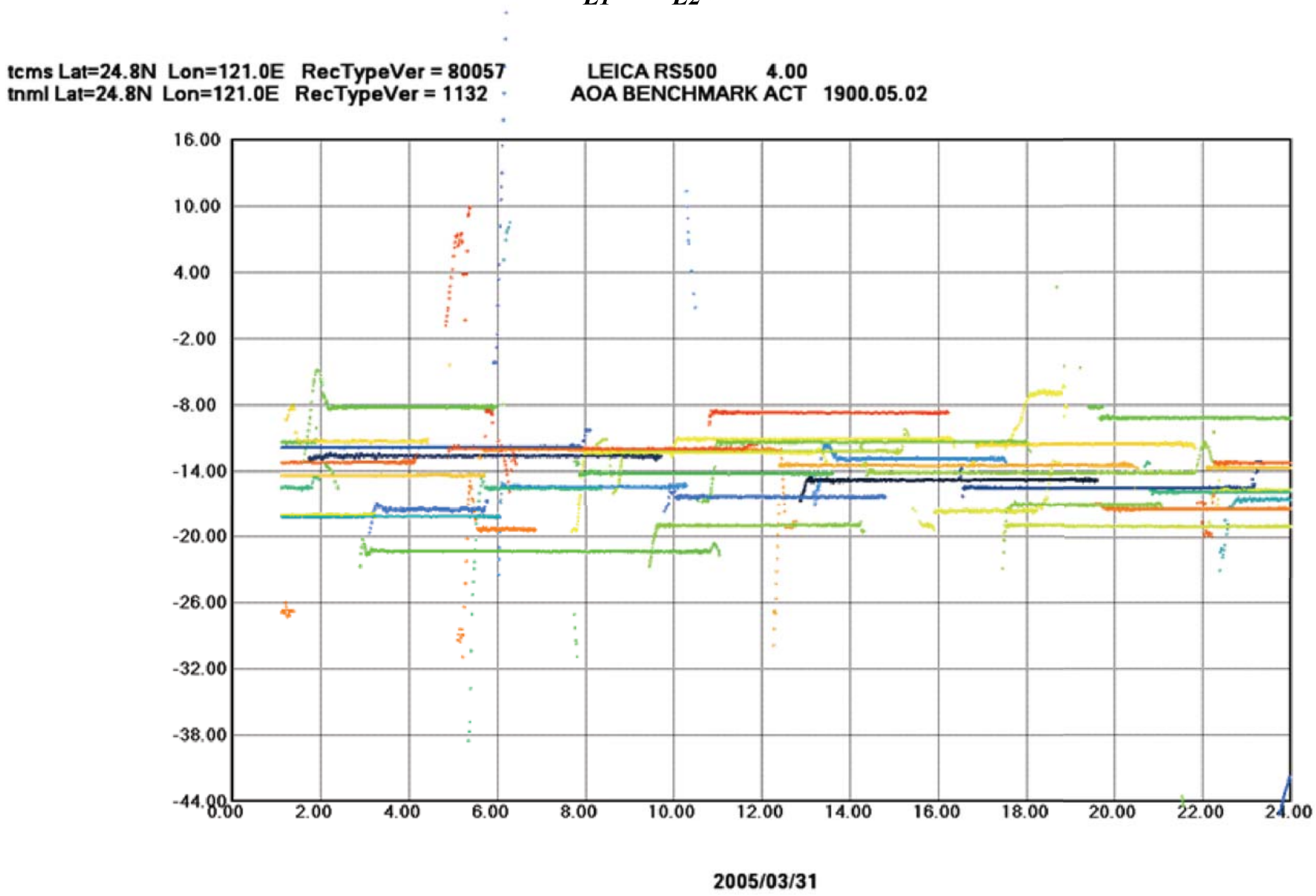
S_P (zimj) - S_P (zimm)



$S_{L1} - S_{L2}$, 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.

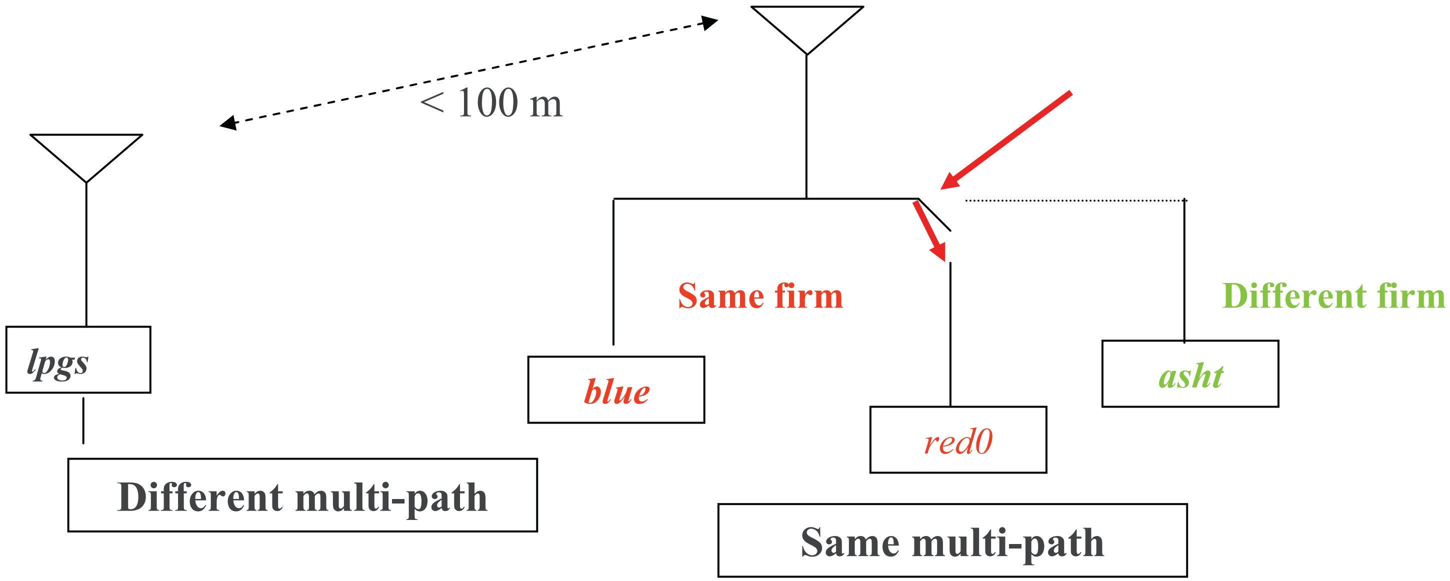
Besides IGS stations, a special set of observation has been set up by the group of La Plata University, Argentina (C.Brunini, F.Azpiliqueta).

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

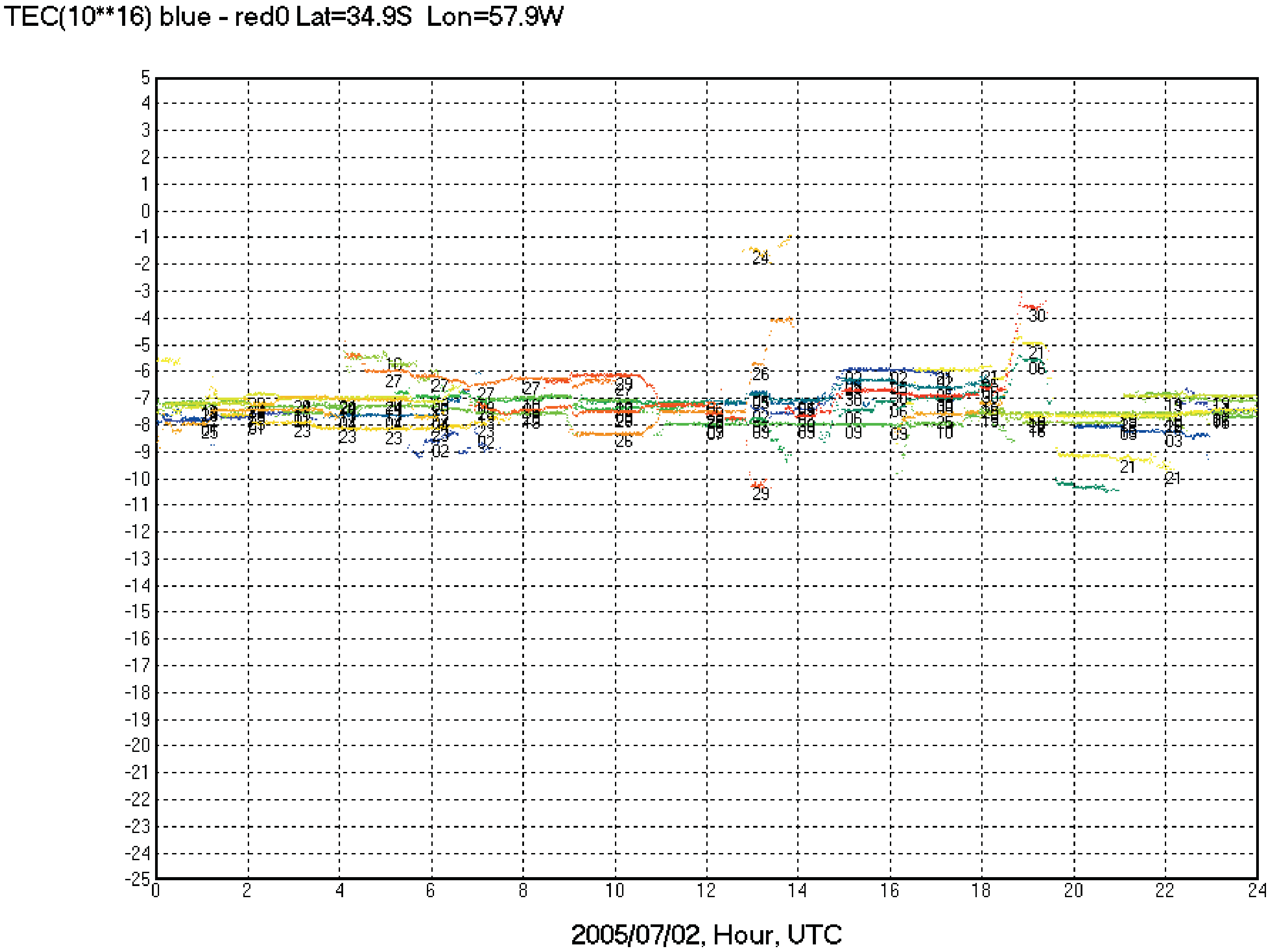
Close stations: different multipath; same or different way of processing multipath

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

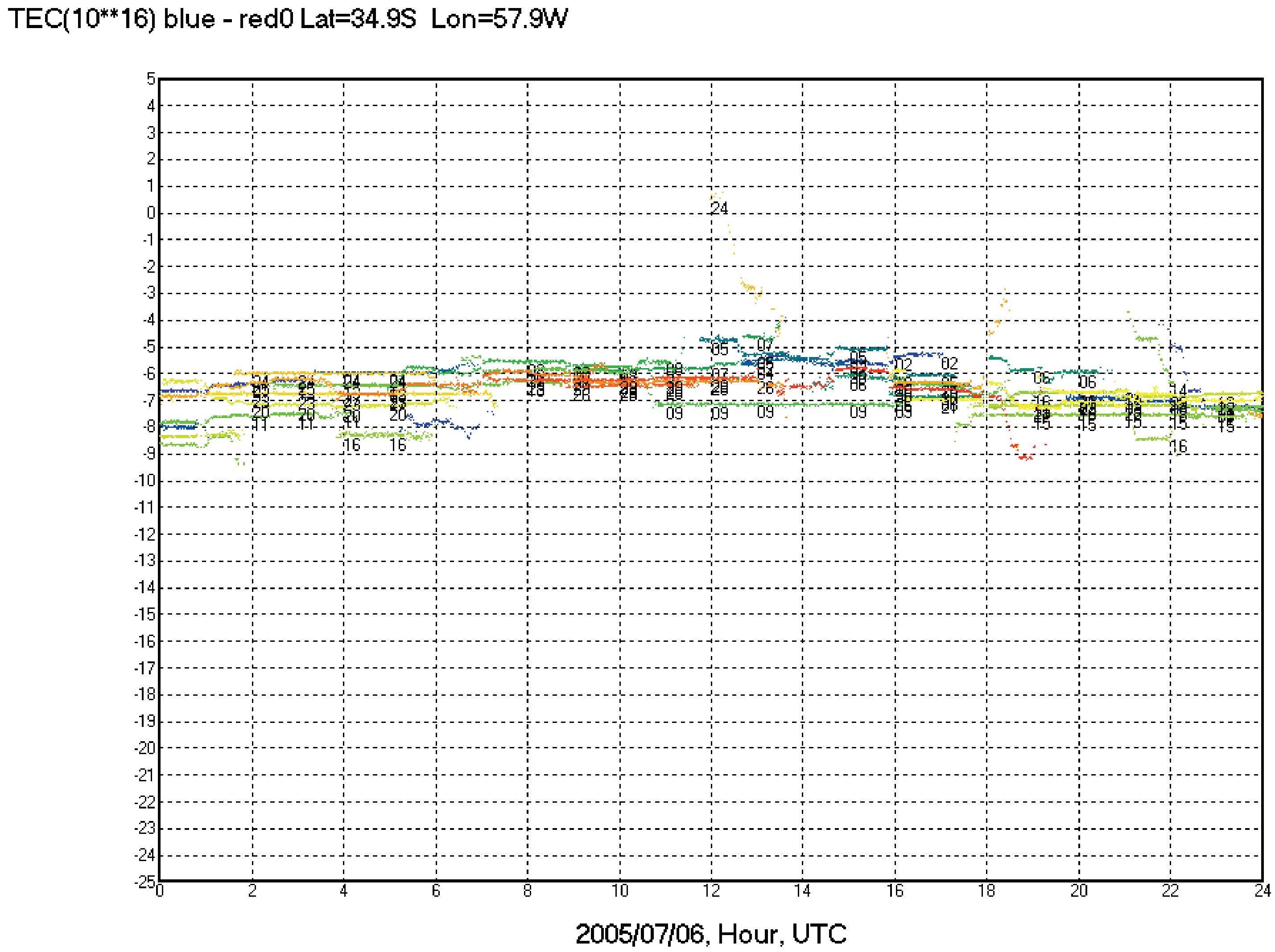
Split antenna, receivers of different firms: same multipath, different way of processing



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 $\langle\cdot\rangle$ using small weights when multi-path is expected to be large:

-avoid short arcs

-care the selection of weights

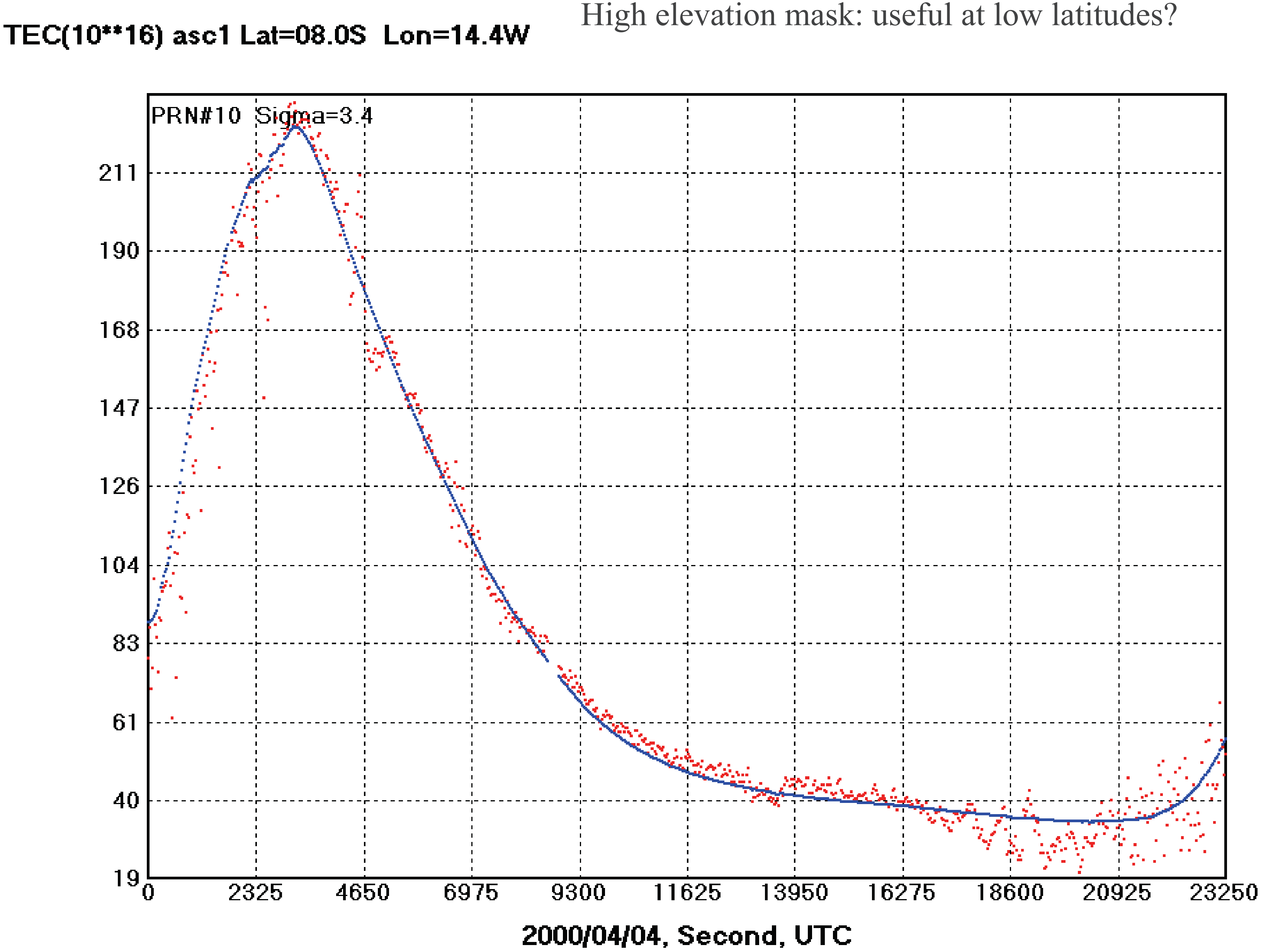
-use an elevation mask as higher as possible (where ***m*** is reasonably less strong)

empirically, using past experience

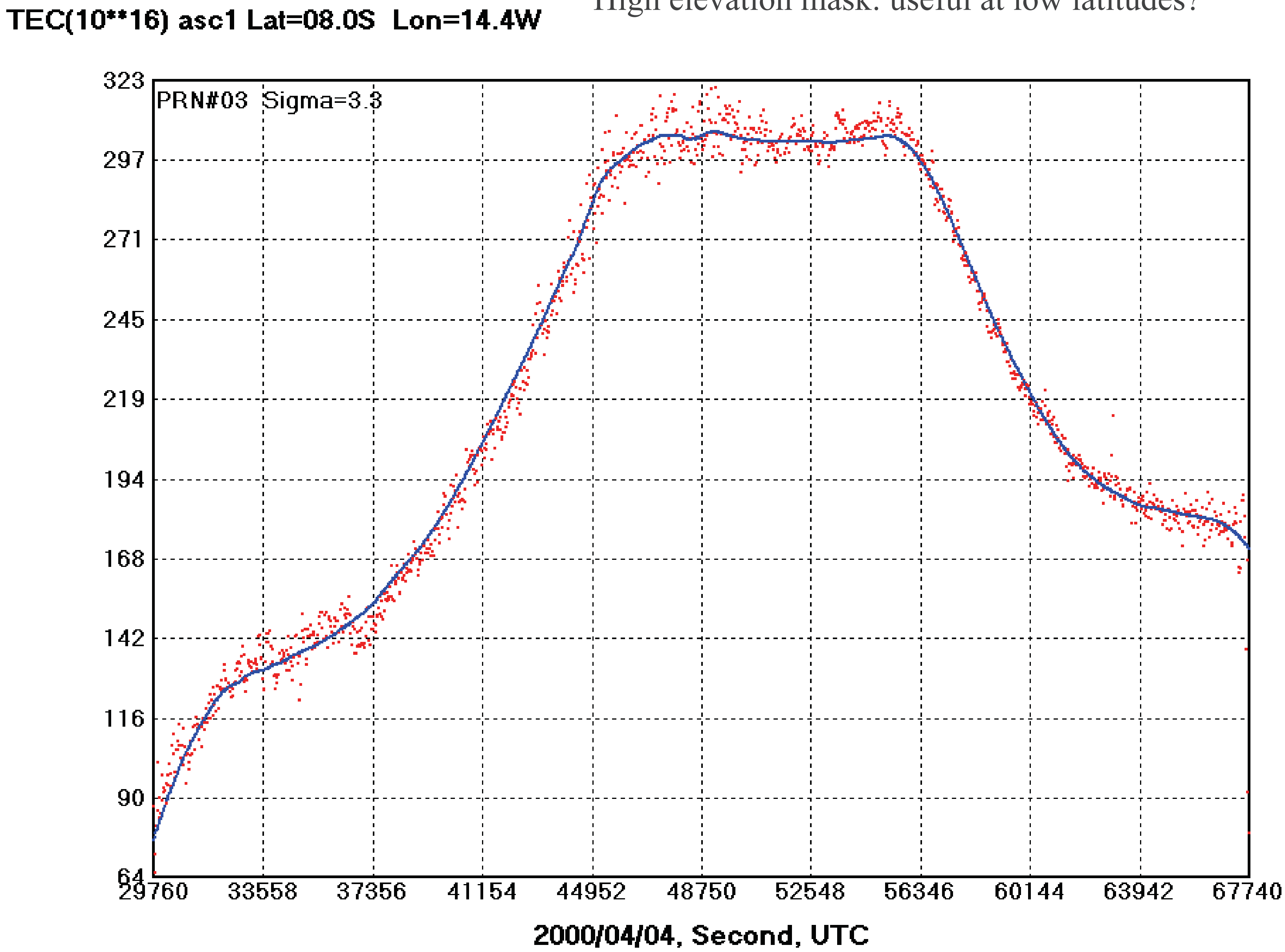
trying to estimate them from the plots of $S_G - S$, which according to the equations of the reported observables is $m + n - \langle m + n \rangle$

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

High elevation mask: useful at low latitudes?



High elevation mask: useful at low latitudes?



But are we dealing with actual multipath only?

For some station pairs, strange patterns appear.

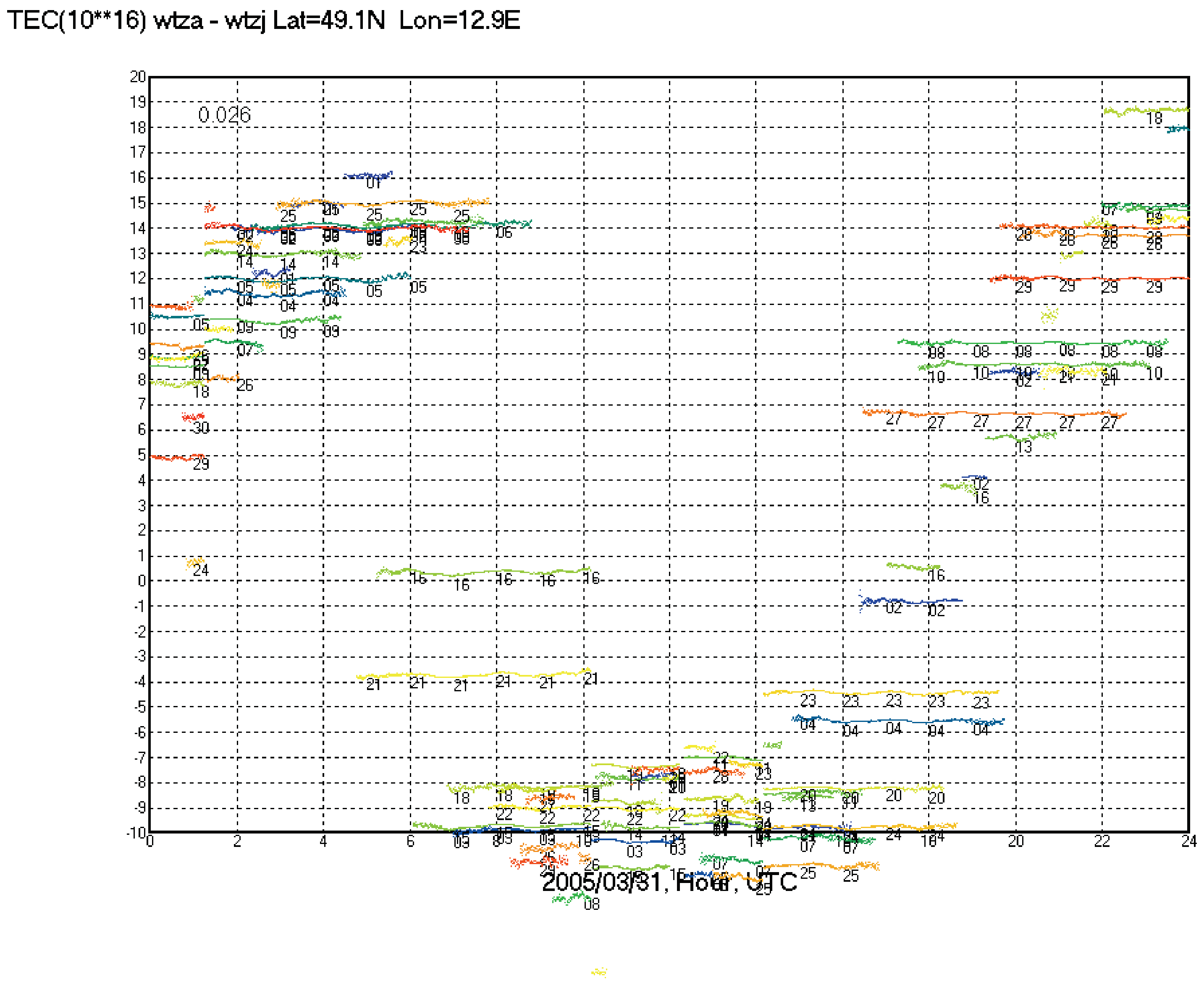
In the following, station *"wtzj"* compared to the colocated *"wtza", "wtzr", "wtzt", "wtzz",* exhibits a strange pattern.

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

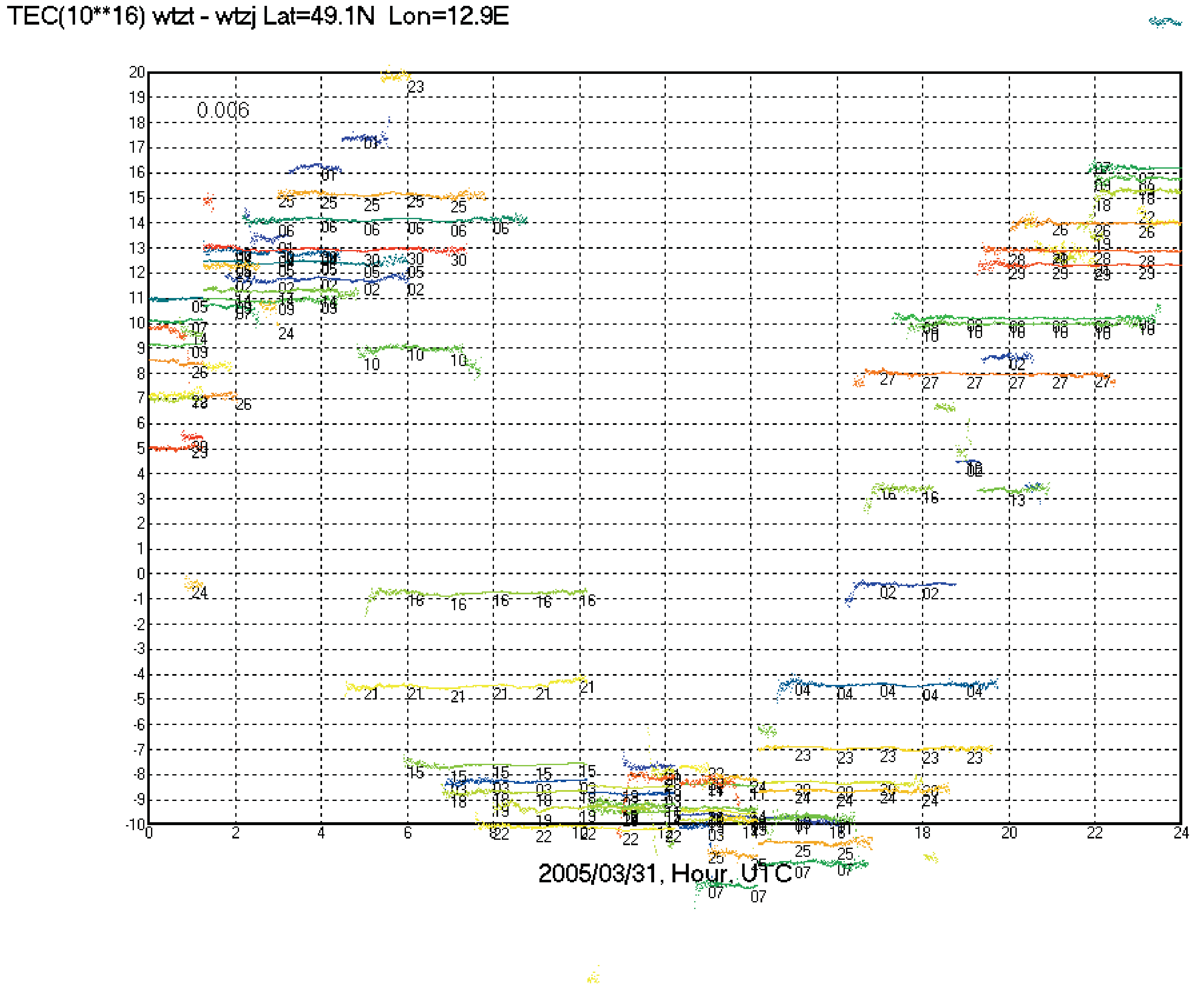
Is it a thermal drift of station bias?

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) ?

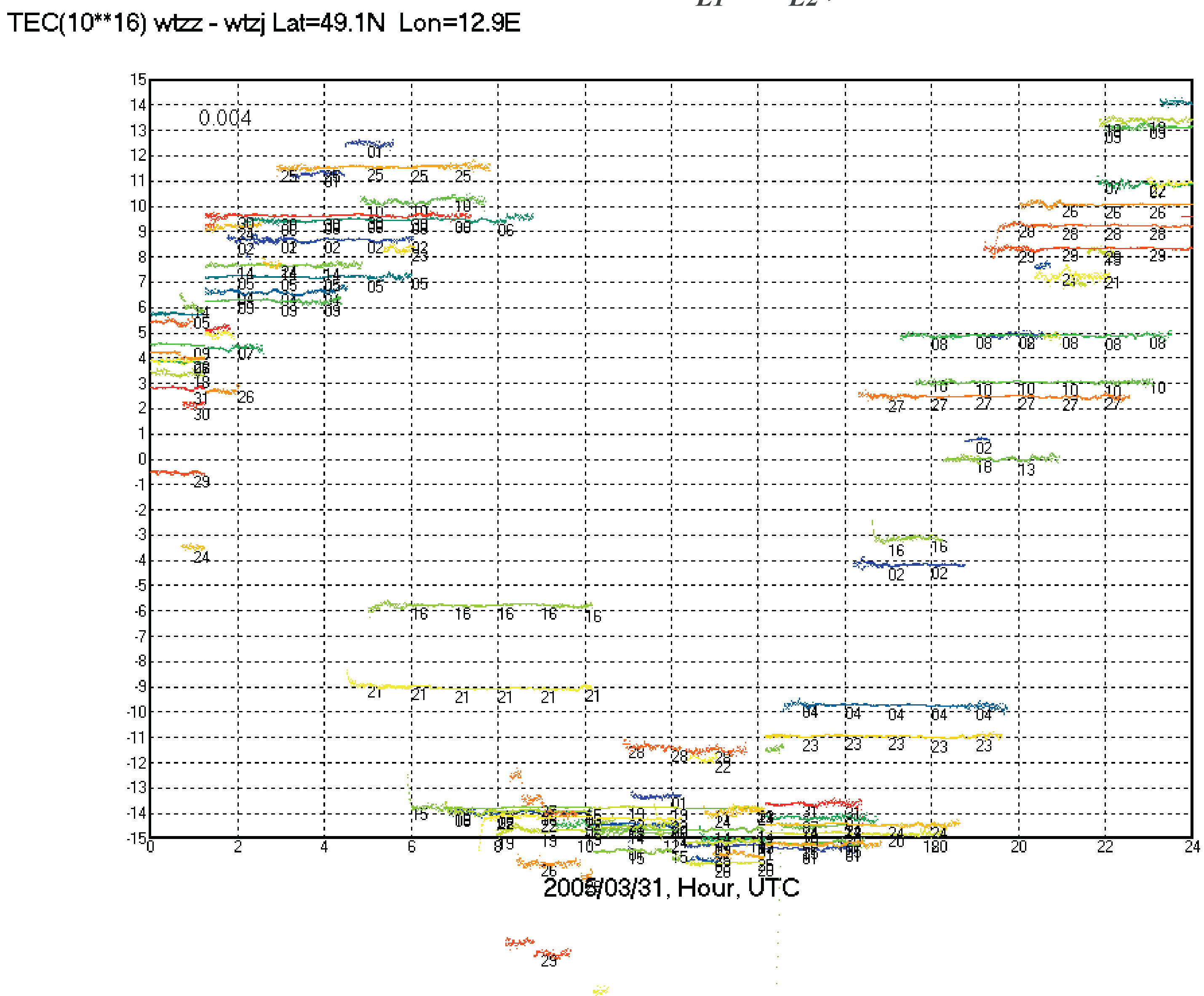
$S_{L1} - S_{L2}$, all satellites



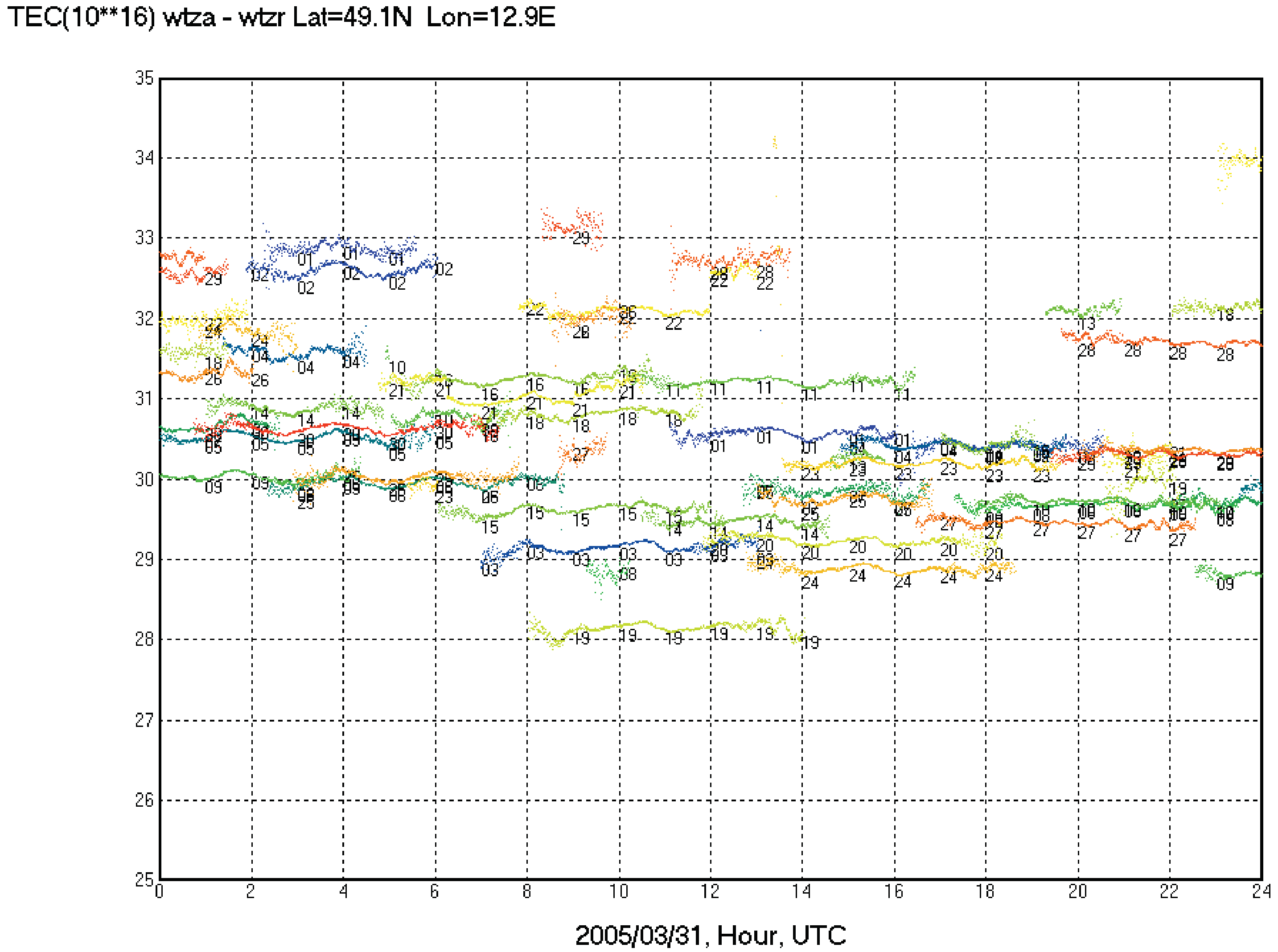
$S_{L1} - S_{L2}$, all satellites



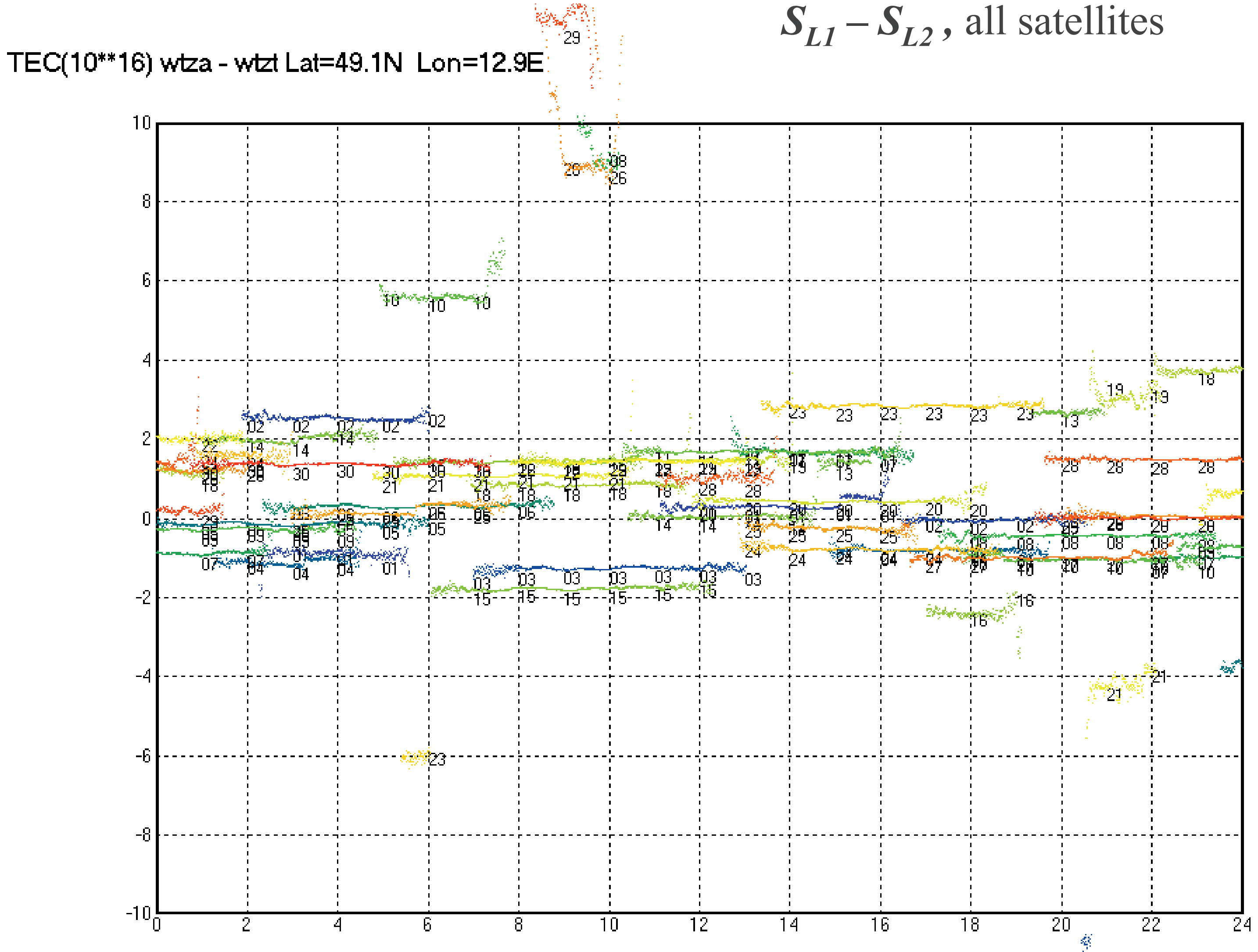
$S_{L1} - S_{L2}$, all satellites



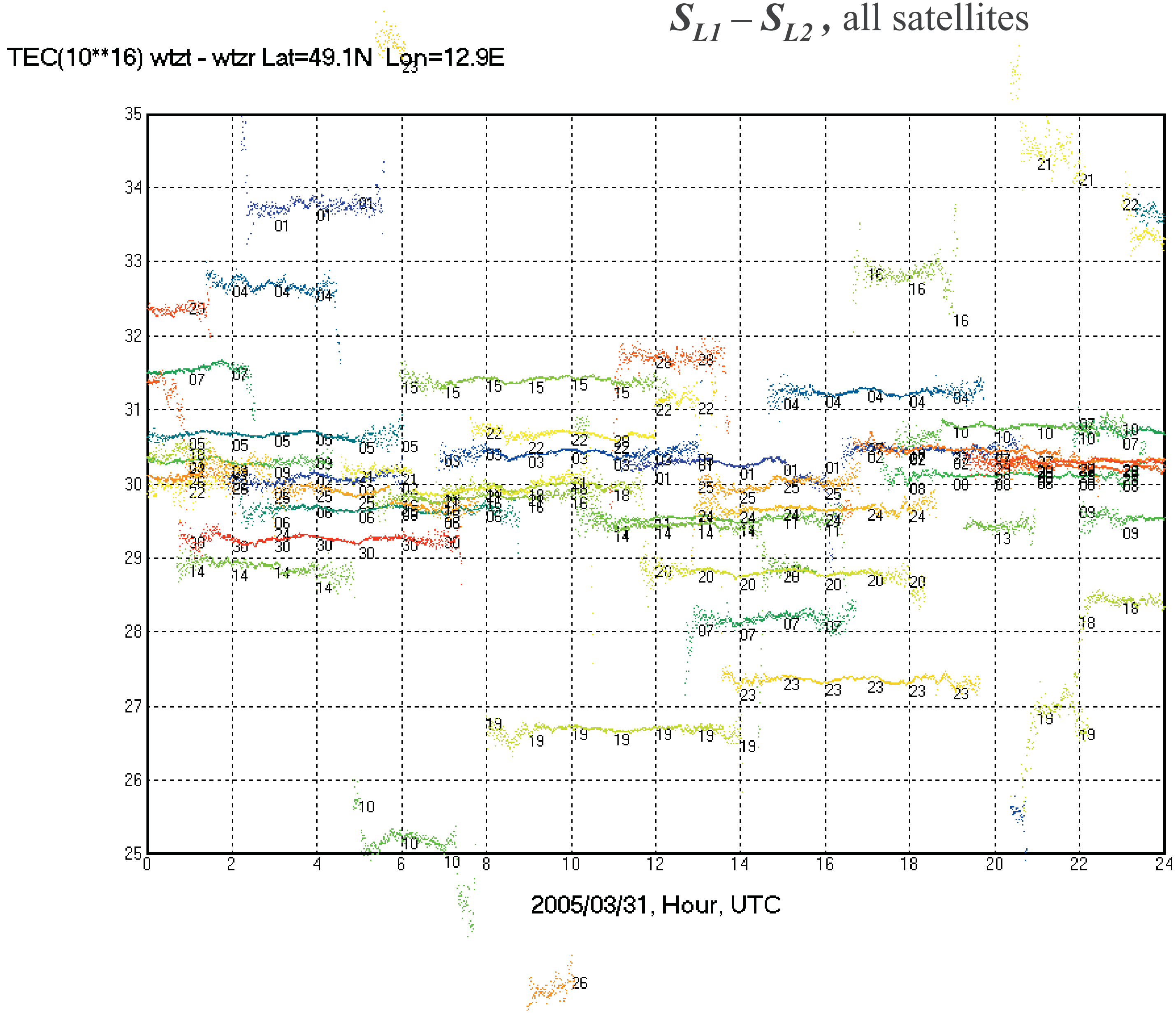
$S_{L1} - S_{L2}$, all satellites



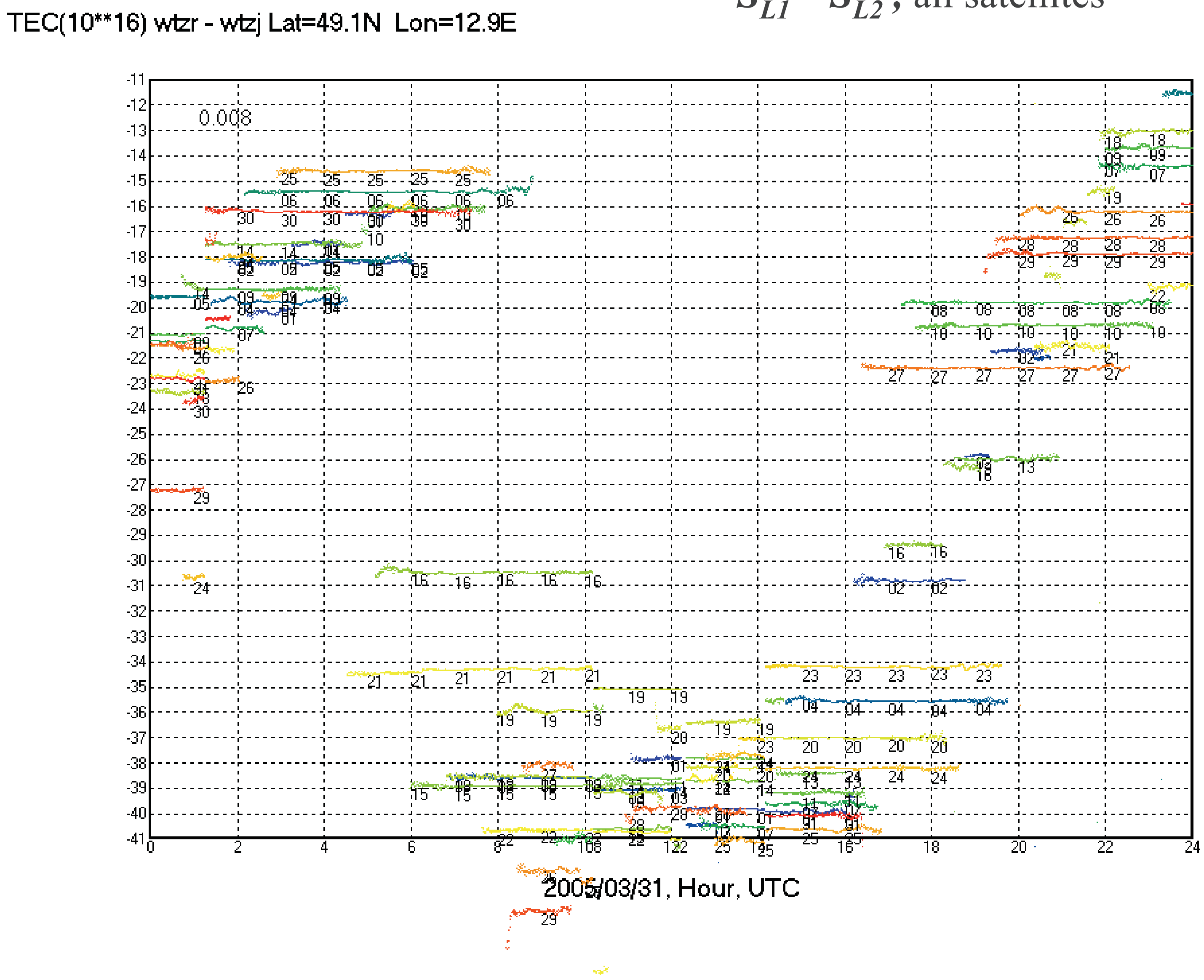
$S_{L1} - S_{L2}$, all satellites

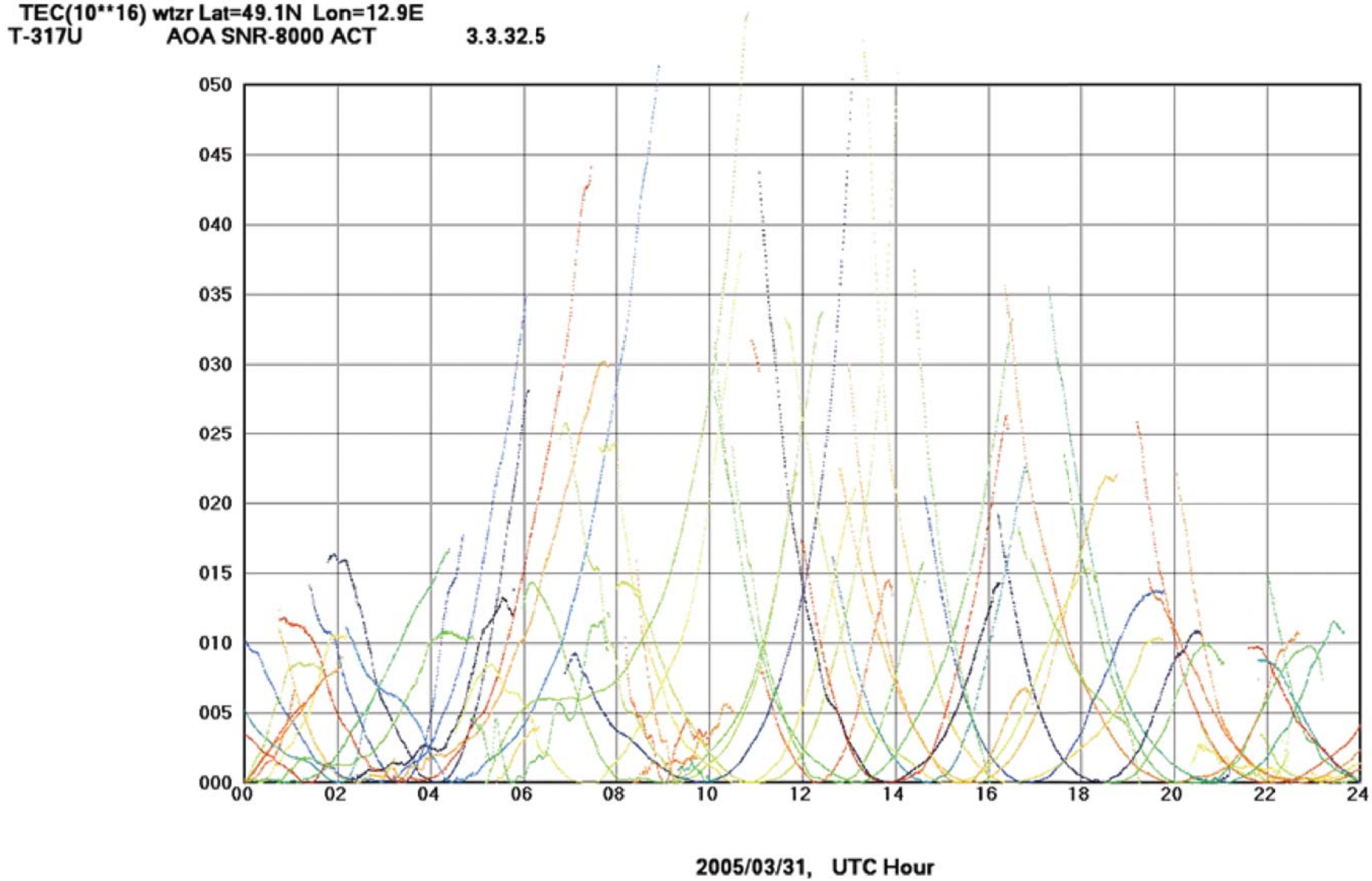


$S_{L1} - S_{L2}$, all satellites



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





TEC(10**16) wtzr Lat=49.1N Lon=12.9E
T-317U AOA SNR-8000 ACT 3.3.32.5
050
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035
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025
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02
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06
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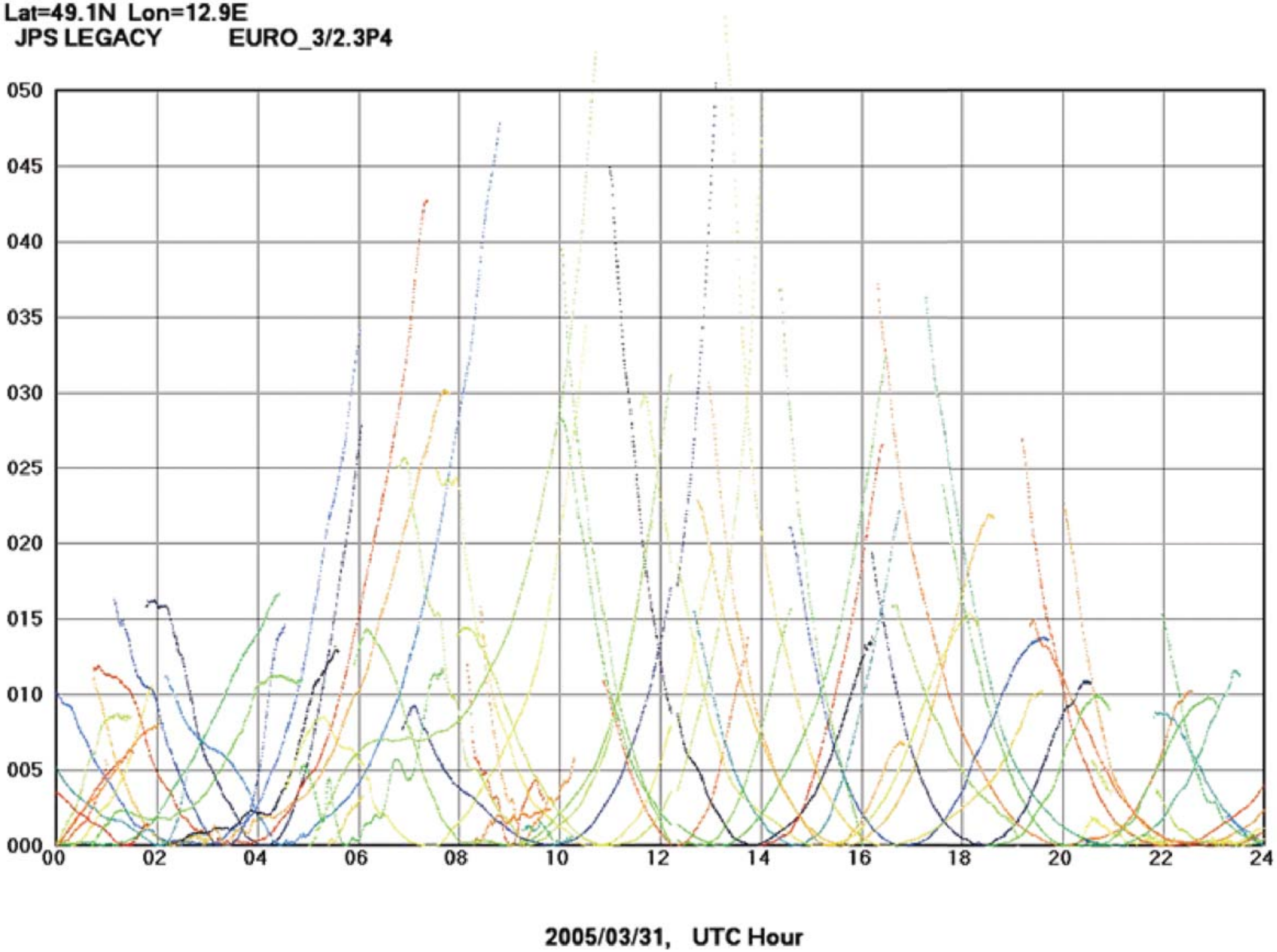
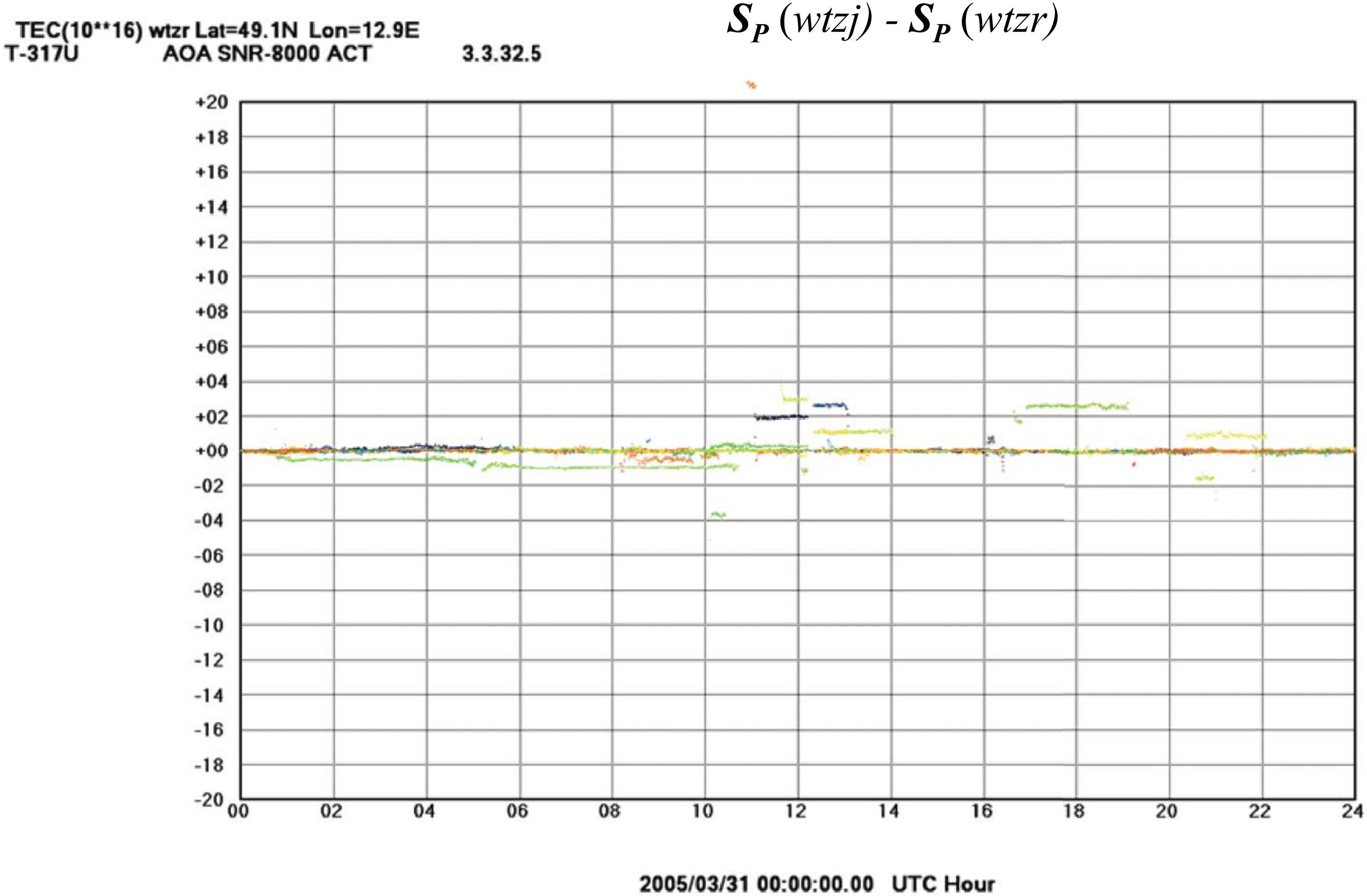
12
14
16
18
20
22
24
2005/03/31, UTC Hour

TEC(10**16) wtzj Lat=49.1N Lon=12.9E
MT312211422 JPS LEGACY EURO_3/2.3P4



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

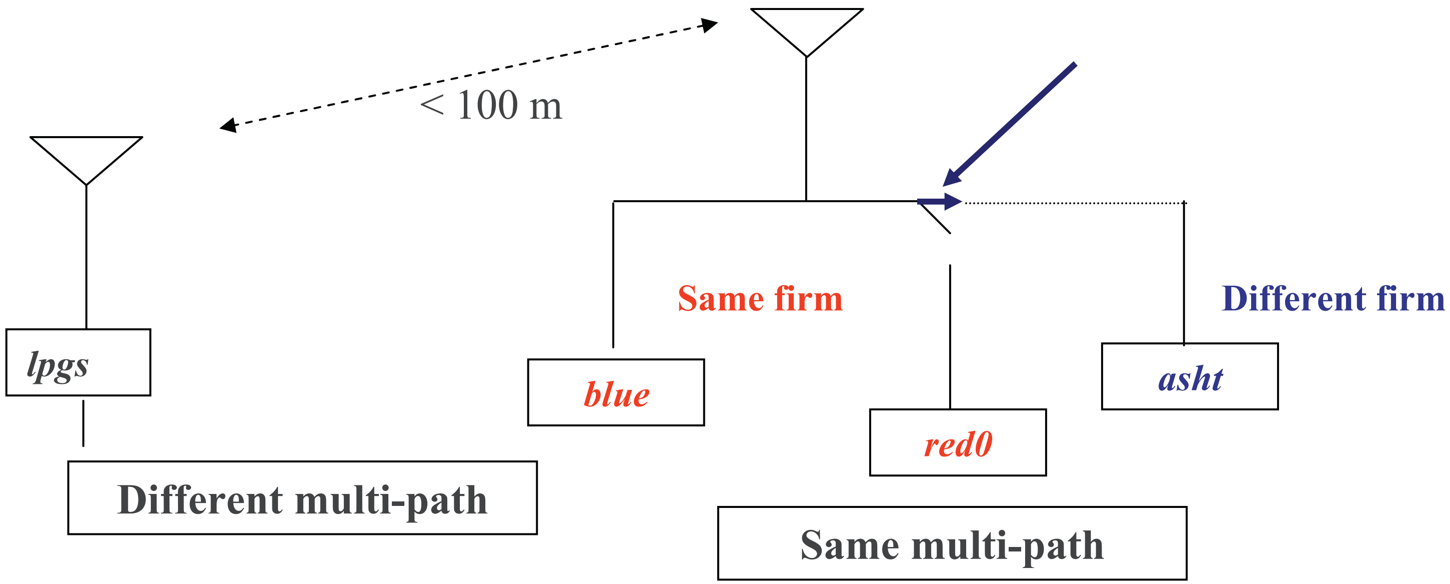


Still: **only multipath or some other problem**?

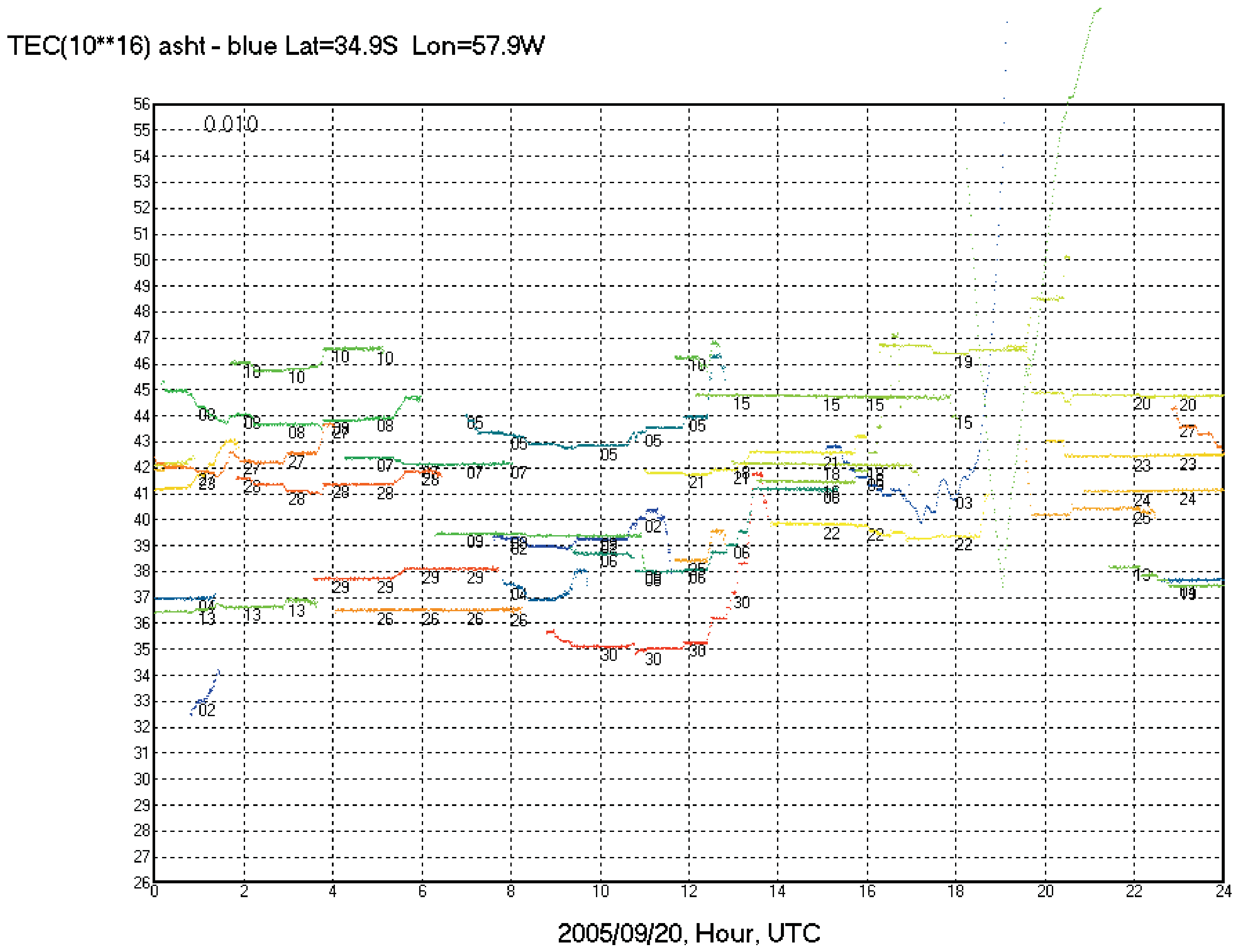
Back to the split antenna experiment,

but using receivers of different firms.

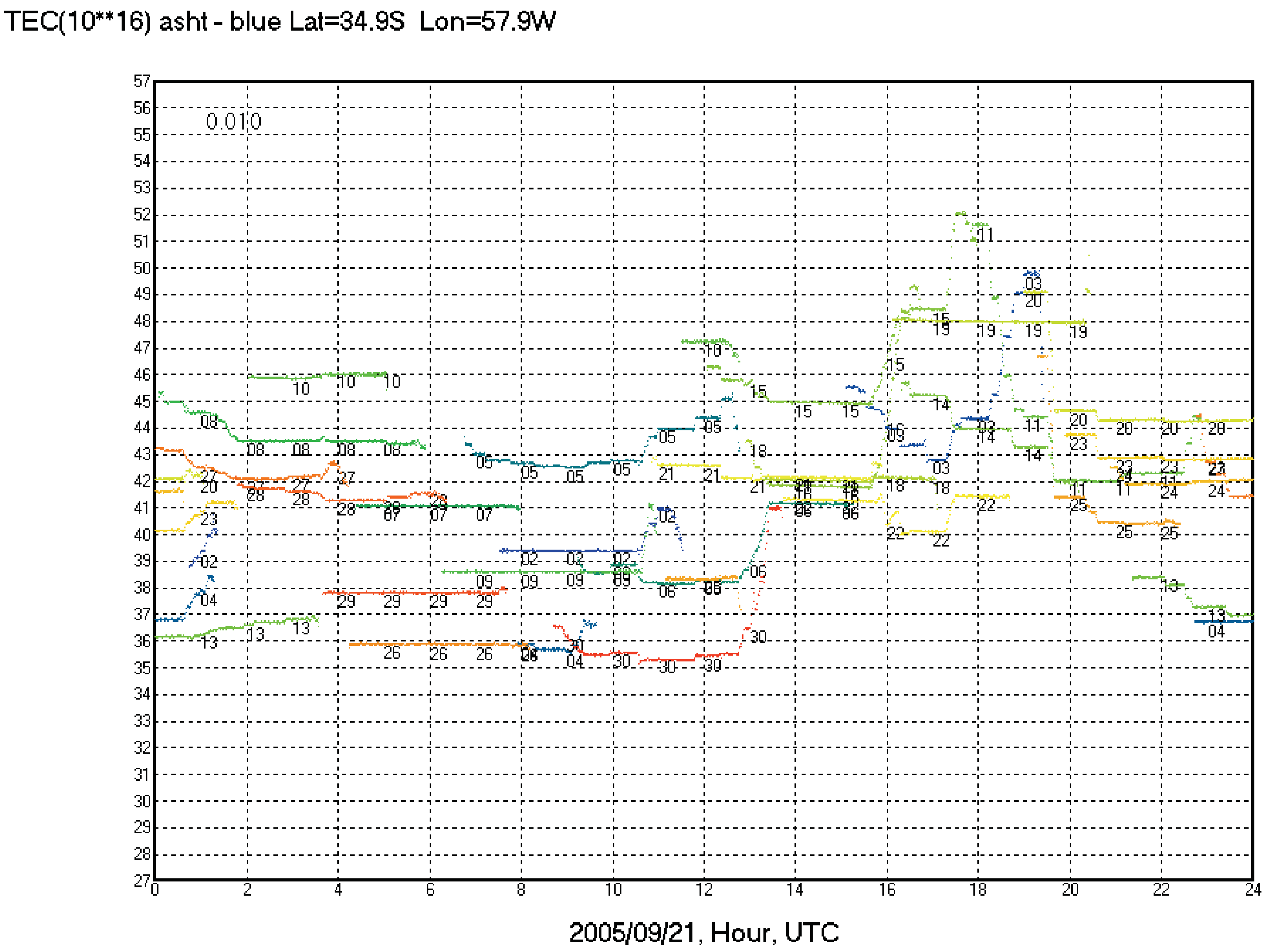
Spread will appear again, suggesting that its cause is more the way by which multipath is processed rather than multipath itself.



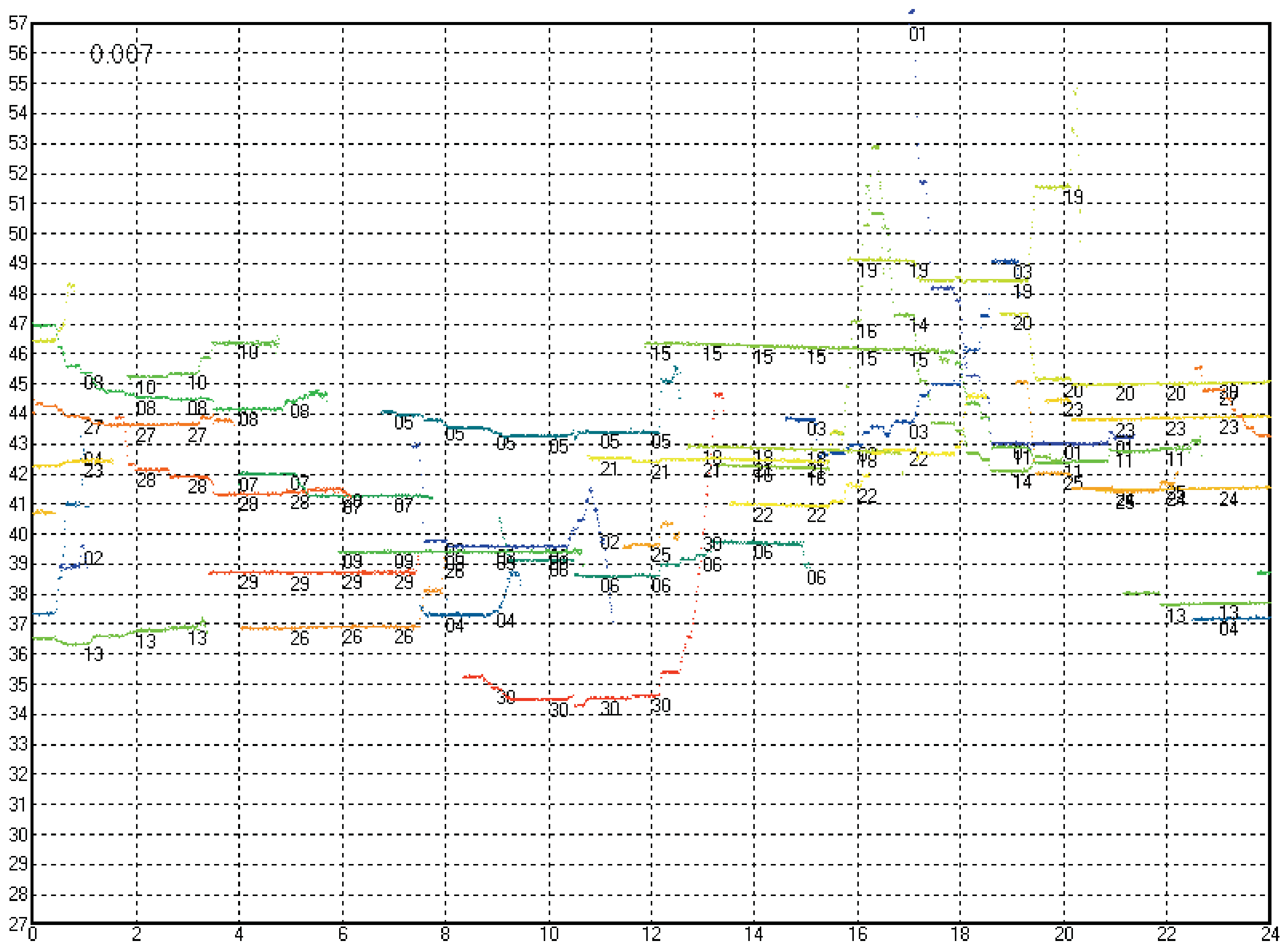
Split antenna, same multipath, different type of receiver



Split antenna, same multipath, different type of receiver



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



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).

Back to the system implementing calibration, consider the <u>***TEC*** expansion</u>

$$\boldsymbol{S = \underline{\Sigma c\ \Psi(P,t)} + [\,\beta, \gamma\,;\,\Omega\,]}$$

Possible approaches:

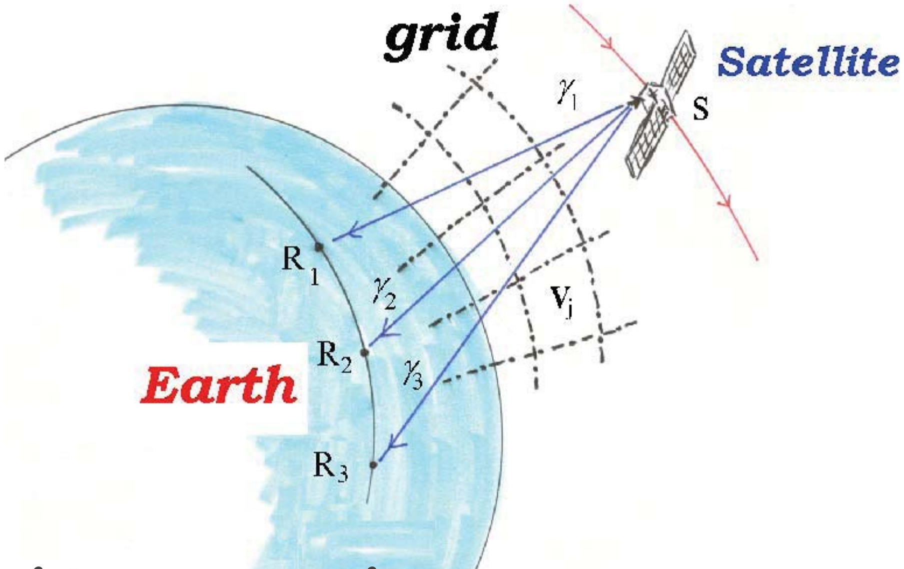
3D (Tomography)

Multi shell

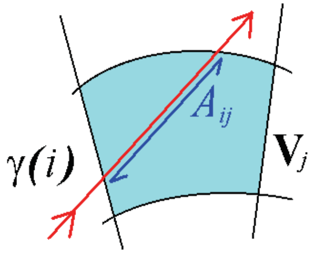
Thin shell

3D-4D approach (Tomography)

the ionosphere is divided in elements of volume (voxels) inside which $\boldsymbol{N_e}$ is constant.
Evolution with time of $\boldsymbol{N_e}$ is considered to improve the budget unknowns/observations.
Vertical behavour of $\boldsymbol{N_e}$ is expanded in Empirical Orthogonal Functions (EOF)



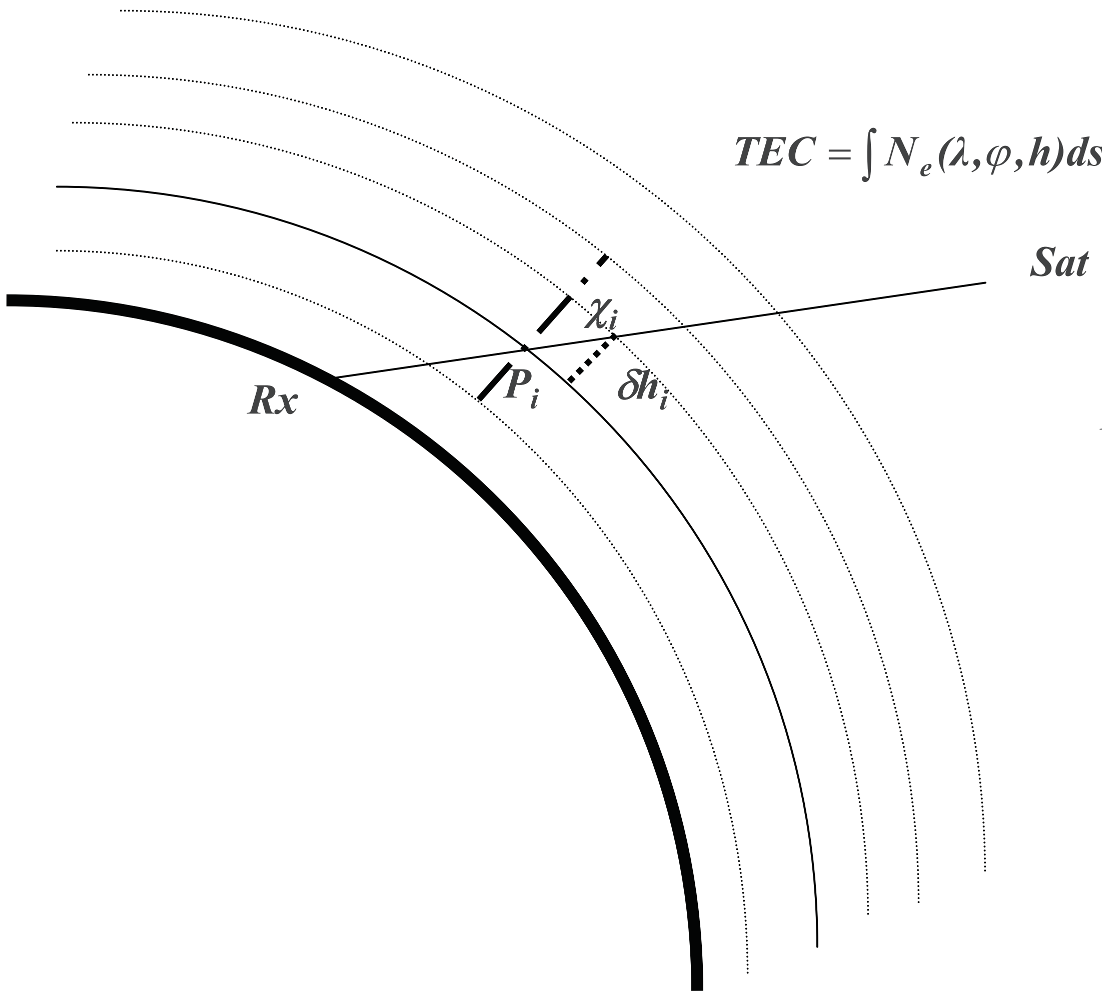
$$d_i = \int_{\gamma(i)} N(\mathbf{r},t)ds = \sum_j x_j \int_{\gamma(i)} b_j(\mathbf{r})ds \equiv \sum_j A_{ij} x_j$$



$$\underline{d} = A\underline{x} \quad \Rightarrow \quad \underline{x} = A^{-1}_{SVD}\underline{d}$$

3D: The multishell method

If many shells are used, this is exactly the method by which numerical integration is carried out. For each shell, a suitable 2D expansion in horizontal coordinates is assumed.



$$TEC = \int N_e(\lambda,\varphi,h)ds \approx \sum N_e(P_i)\delta s_i = \sum N_e(P_i)sec\chi_i\delta h_i$$

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

δh_i increment in height

δs_i increment in arc length

$\delta s_i = \delta h_i \sec \chi_i$

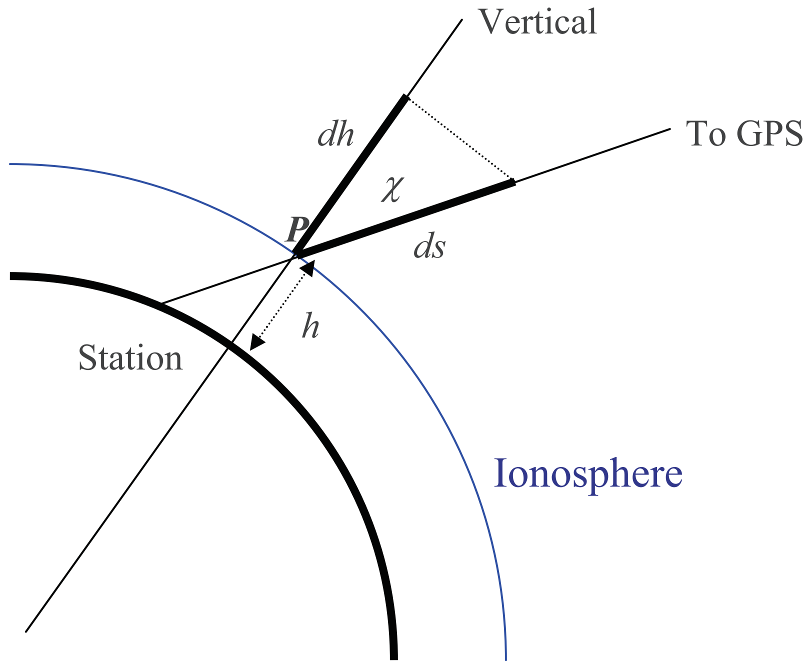
Reducing down the number of shells, and in principle the expected accuracy,

take only one **(thin) shell at some reference height *h***

$$S = V(P) \sec \chi + [\beta + \gamma, \Omega]$$

V(P) is the ***TEC*** along the vertical of the ionospheric point ***P***

V(P) is a 2D function of horizontal coordinates

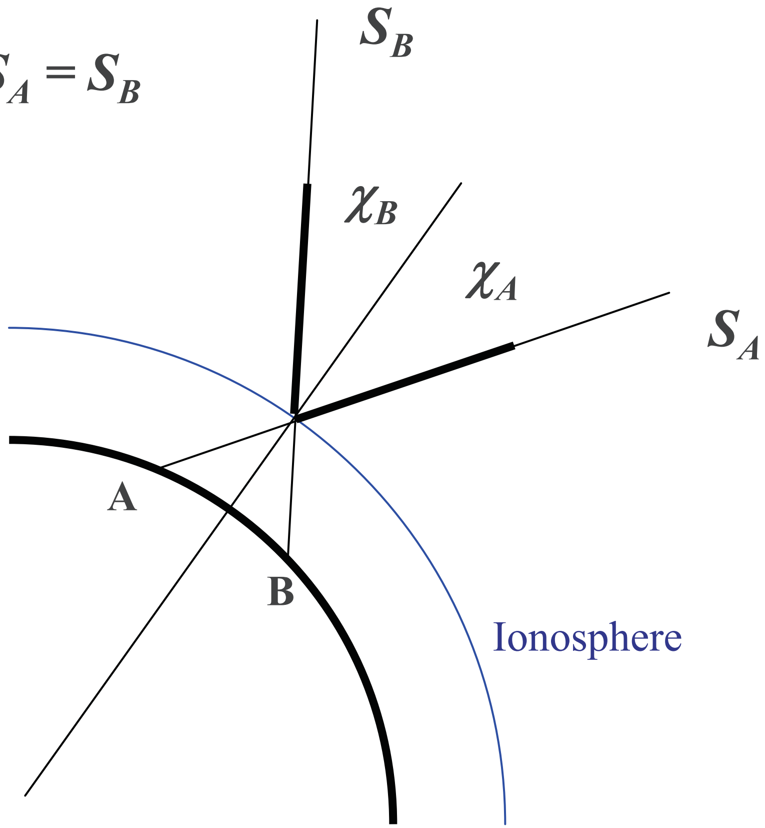


The thin shell assumption is self-evidently poor:

TEC is the same for rays passing through the same ionospheric point,

disregarding at all gradients

If $\chi_A = \chi_B$ then $\boldsymbol{S}_A = \boldsymbol{S}_B$



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

Given satellite and station positions, using an artificial ionosphere (*):

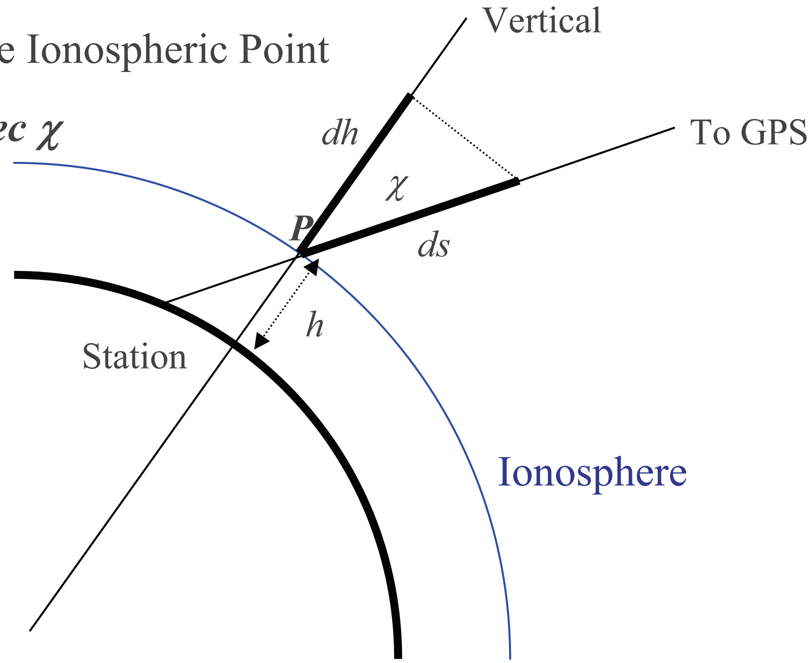
Compute χ

Compute Slant ***S***

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

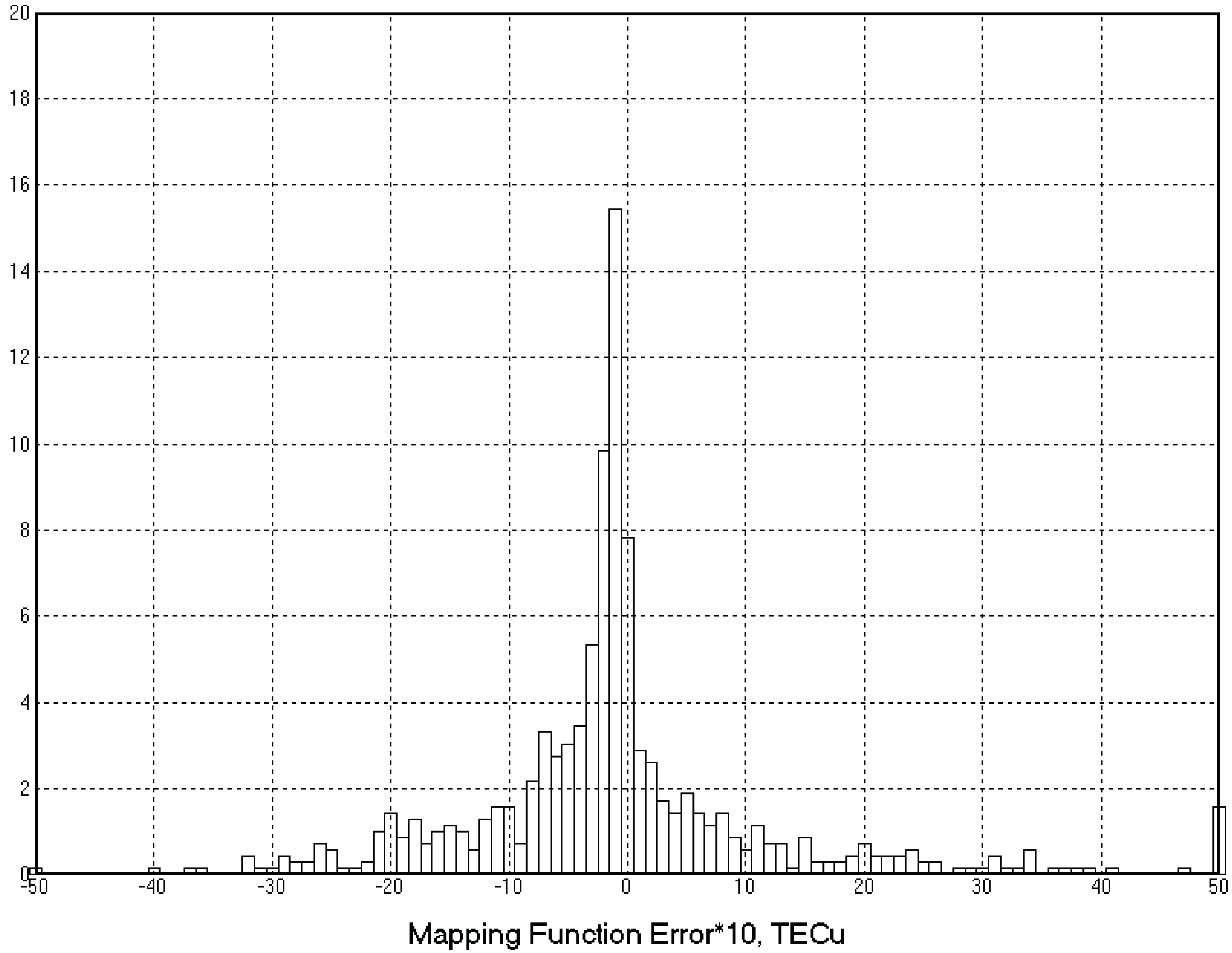
Error: $S - V \sec \chi$

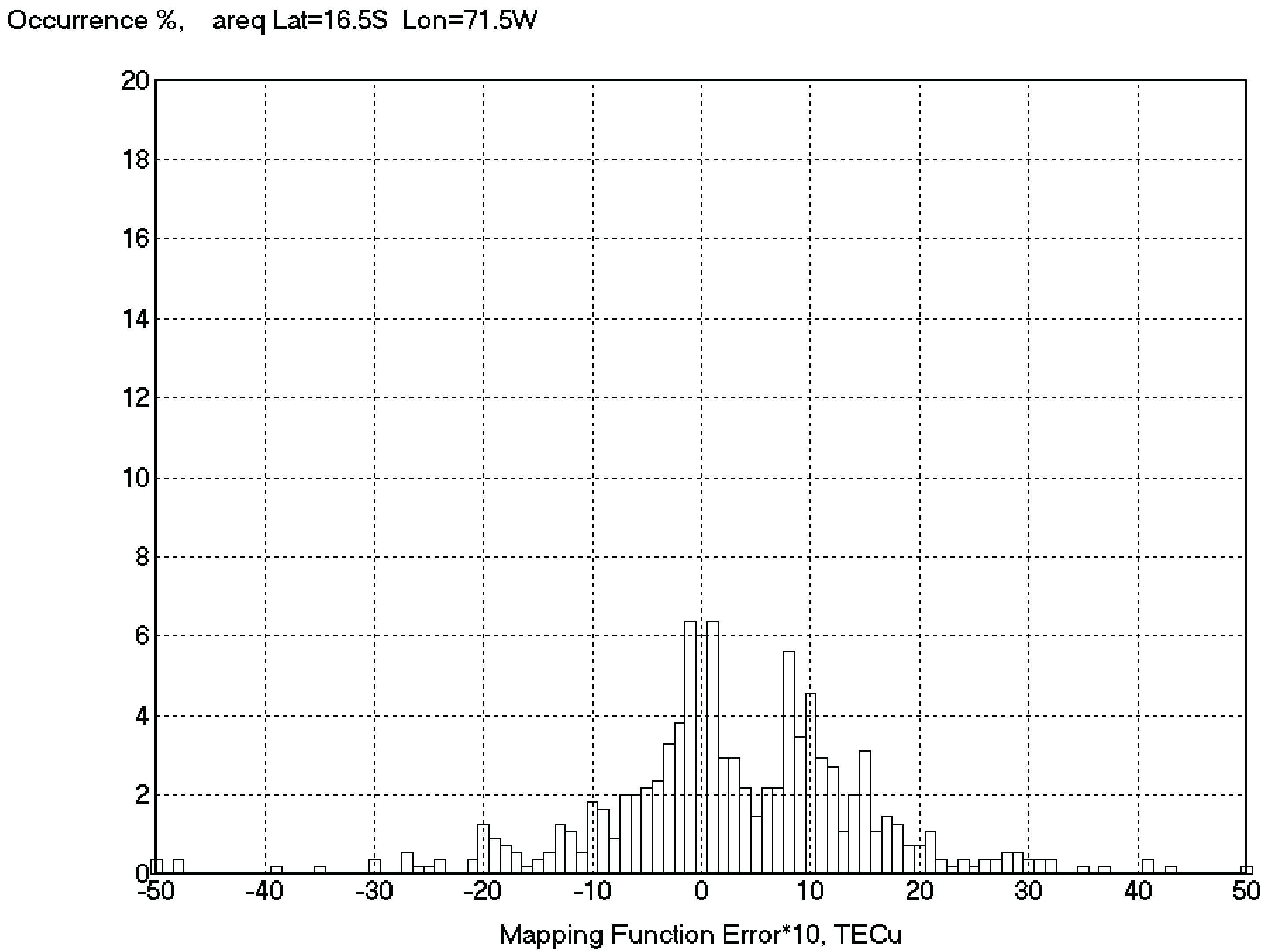
Plot Error distribution



(*) Keep in mind for the following, where it will be better explained

Occurrence %,   ajac Lat=41.9N Lon=8.8E




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

Shall we discard the thin shell approach?

A new interpretation

For a given ray, rearrange ***TEC*** definition using **sec** χ_{REF} at a given reference height

$$TEC = \int N_e ds = \int N_e sec\chi dh = sec\chi_{REF} \int N_e \frac{sec\chi}{sec\chi_{REF}} dh = sec\chi_{REF} V_{eq}$$

$$V_{Eq} = \int N_e \frac{sec\chi}{sec\chi_{REF}} ds \qquad \boxed{TEC = sec\chi_{REF} V_{eq}}$$

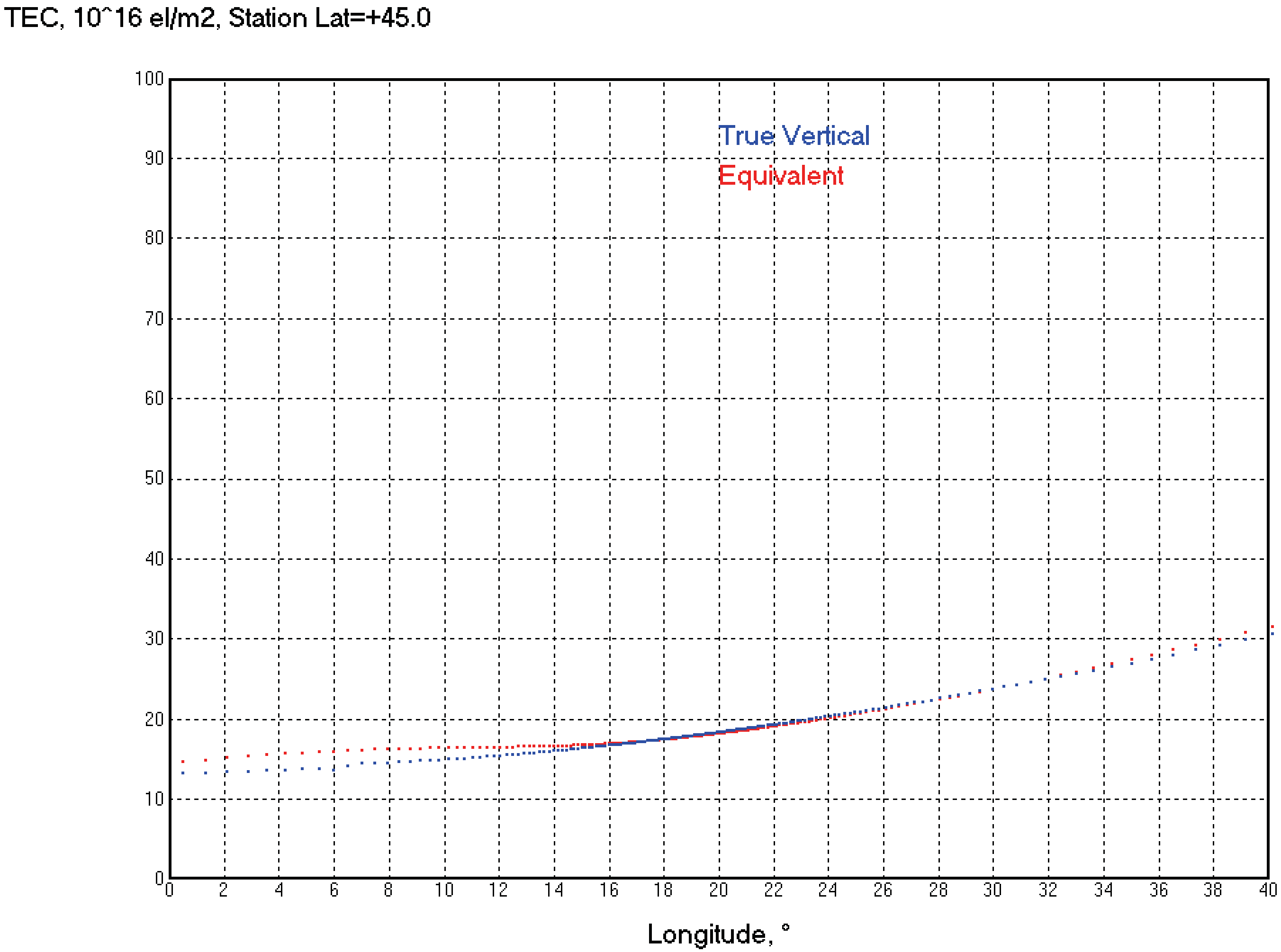
The expression is formally identical to the mapping function approximation,

but it is **exact** provided V_{Eq}, a 2D Function (elevation/azimut or displacement of horizontal coordinates from the station) is not interpreted as the vertical ***TEC***.

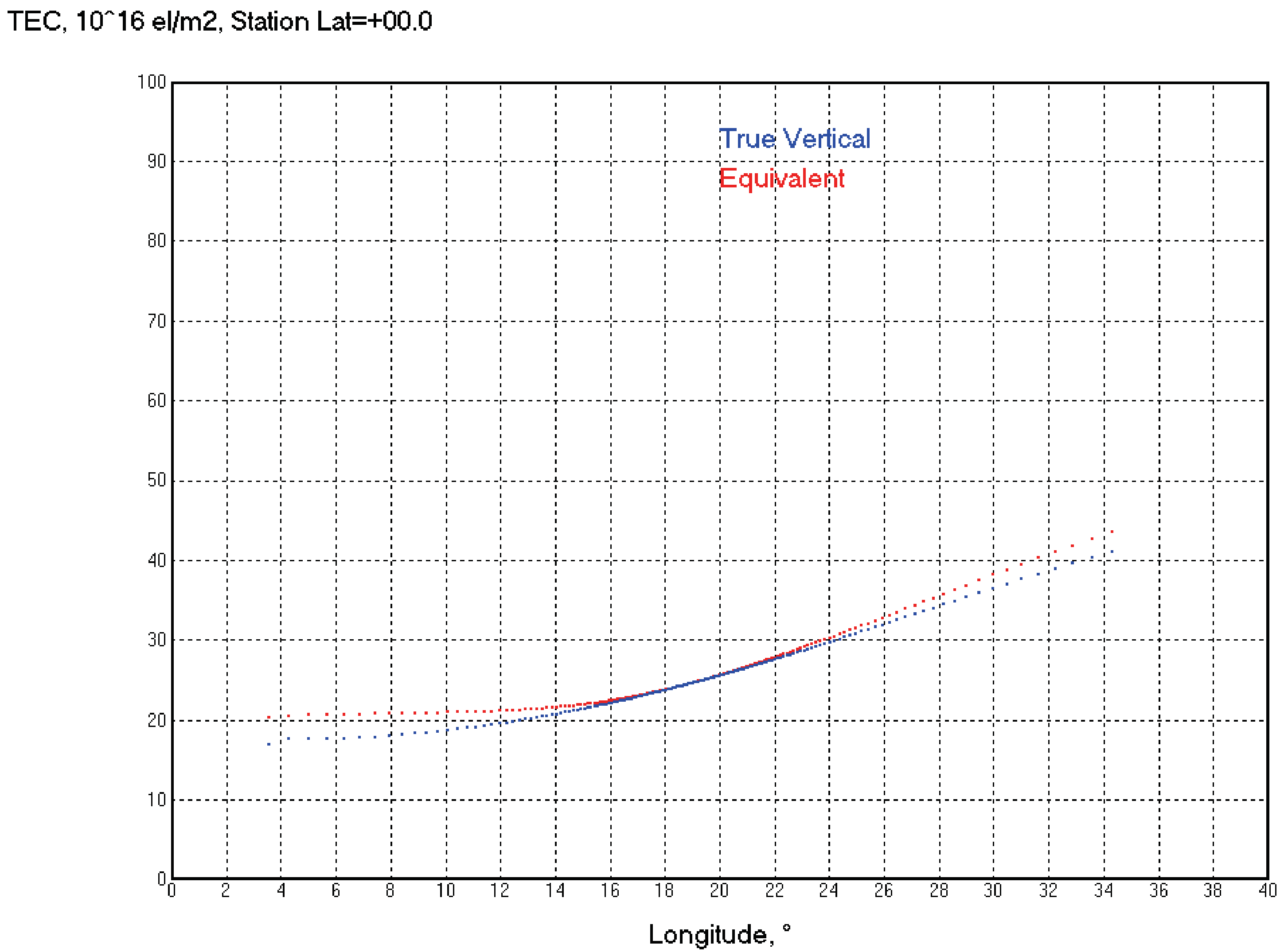
V_{Eq} will change for stations in different locations, **so its use is limited to the calibration performed by the single station solution**.

Calibration requires a relationship correlating the various slants: for the single station solution the properly interpreted mapping function does not implies errors other than the capability to map V_{Eq} in satisfactory way.

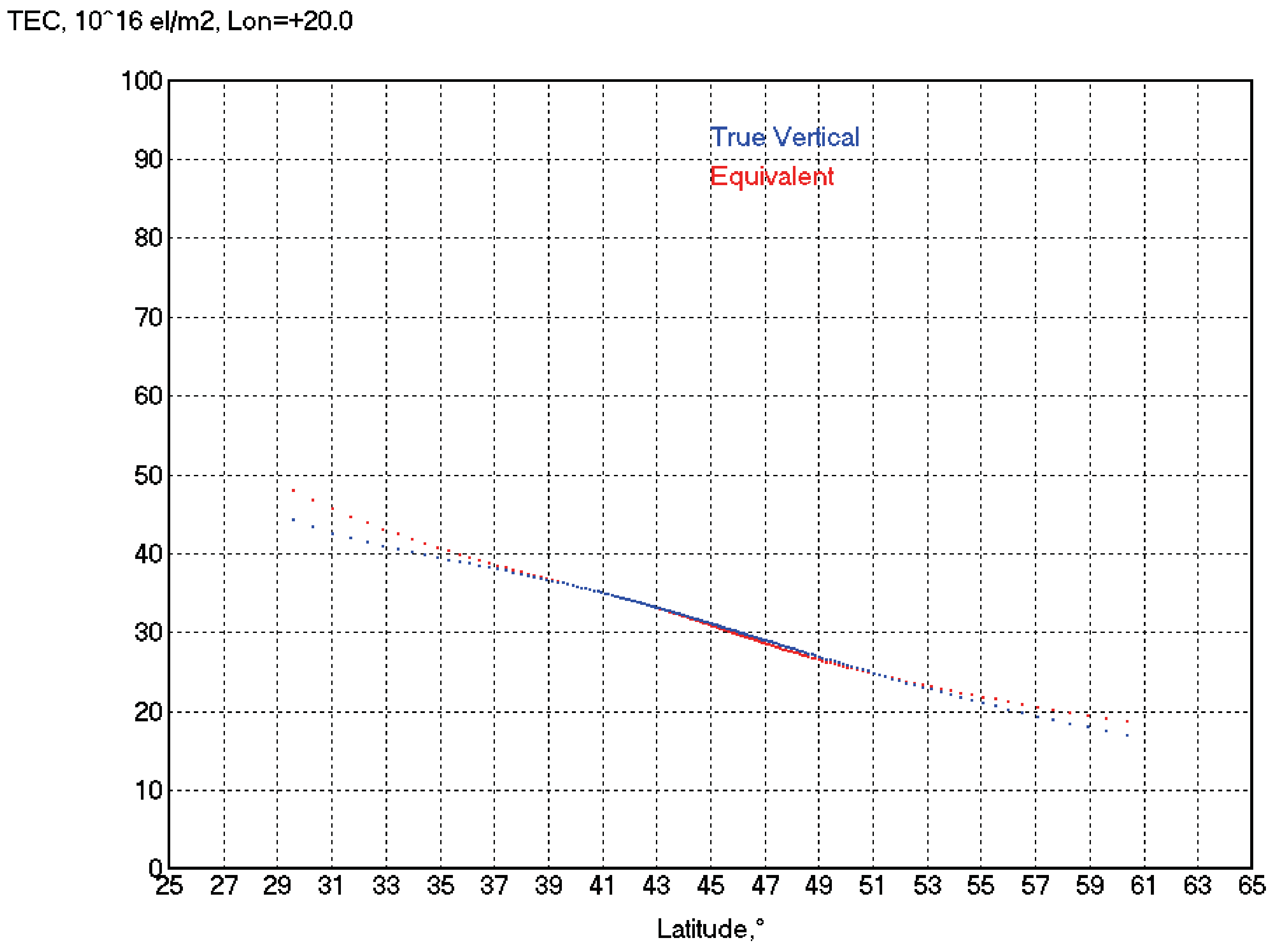
Comparison of True and Equivalent Vertical TEC vs longitude at given latitude



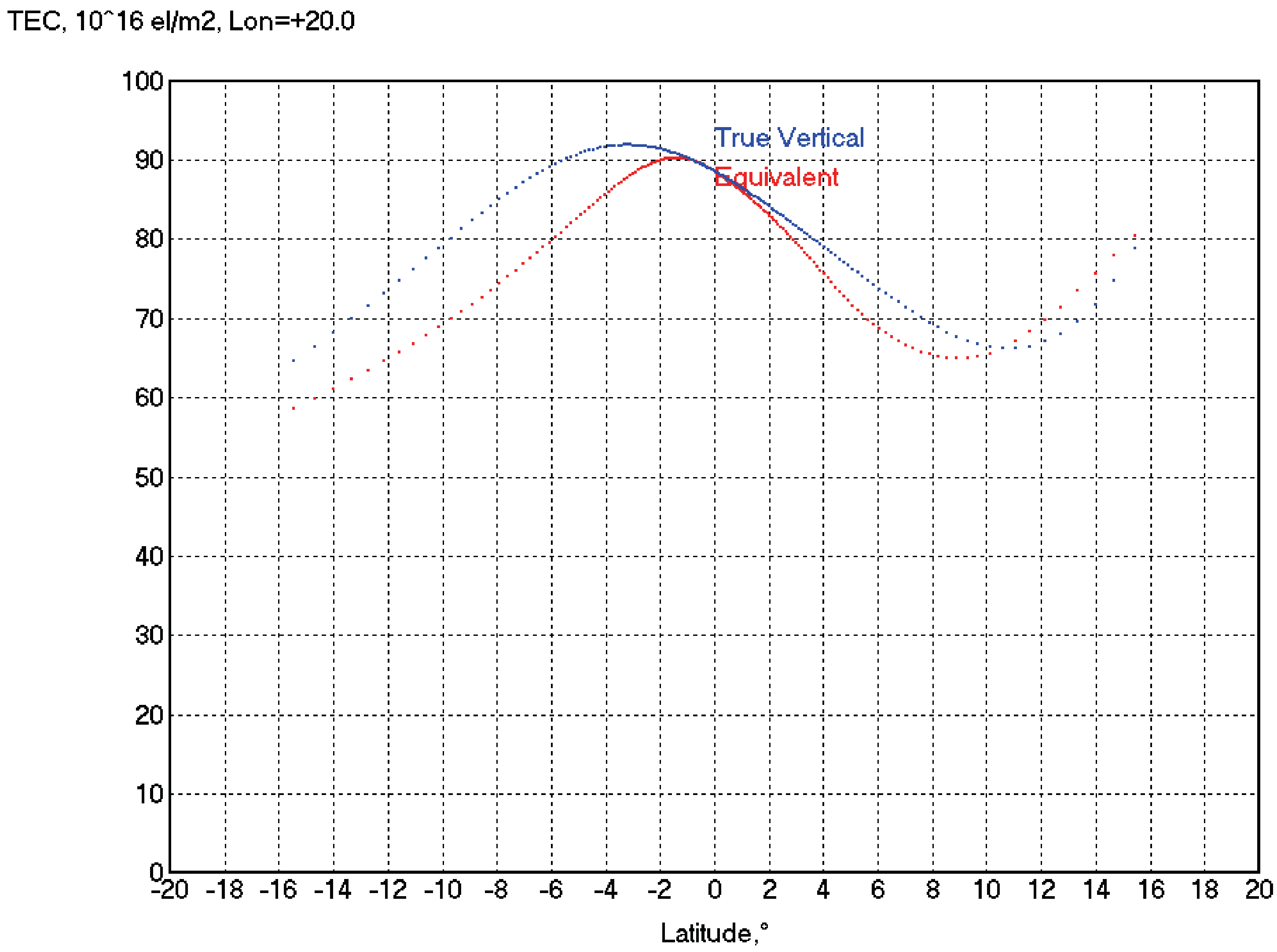
Comparison of True and Equivalent Vertical TEC vs longitude at given latitude



Comparison of True and Equivalent Vertical TEC vs longitude at given longitude



Comparison of True and Equivalent Vertical TEC vs longitude at given longitude



The choice of the calibration method

Aiming to

a simple solution (thin shell)

avoiding the problems of slants leveled to code $\boldsymbol{S_L}$

mitigating the errors of mapping function

It is natural to select a **single station** solution using **phase slants** $\boldsymbol{S_P}$

Notes about $\boldsymbol{V_{Eq}}$ 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°

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

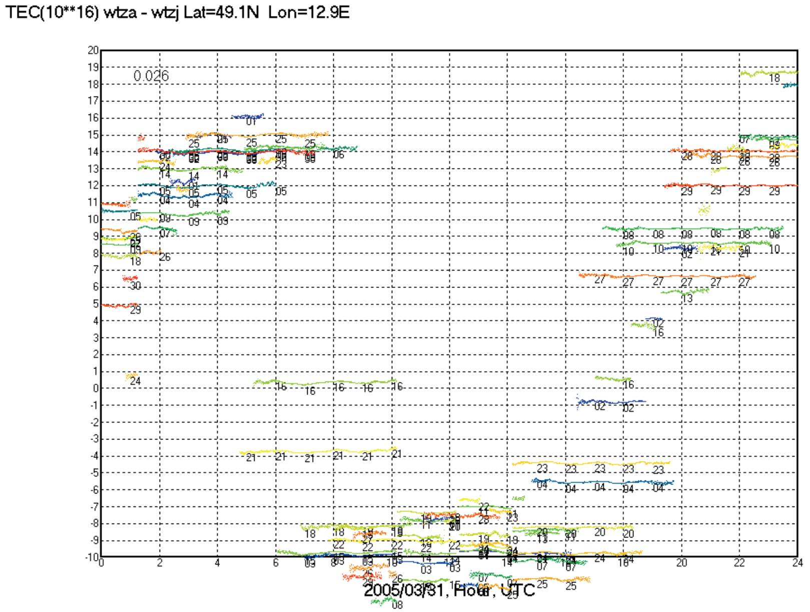
$$R_{ijt} = S_{ijt} - \Sigma_n c^{(t)}{}_n p_n (l_{ijt}, f_{ijt}) \sec \chi_{ijt} - \Omega_{Arc}$$

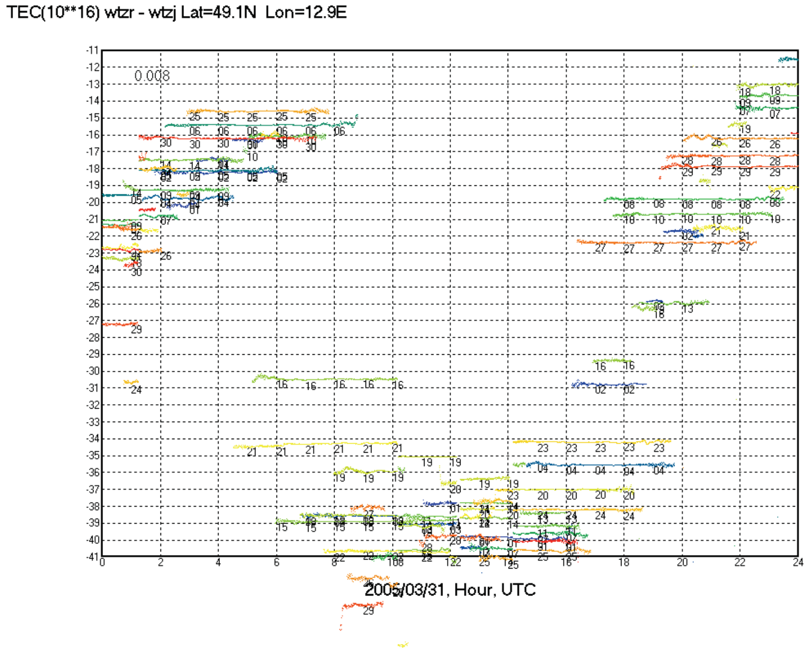
Small residuals mean good internal consistency, but do not help in asserting the accuracy of the method.

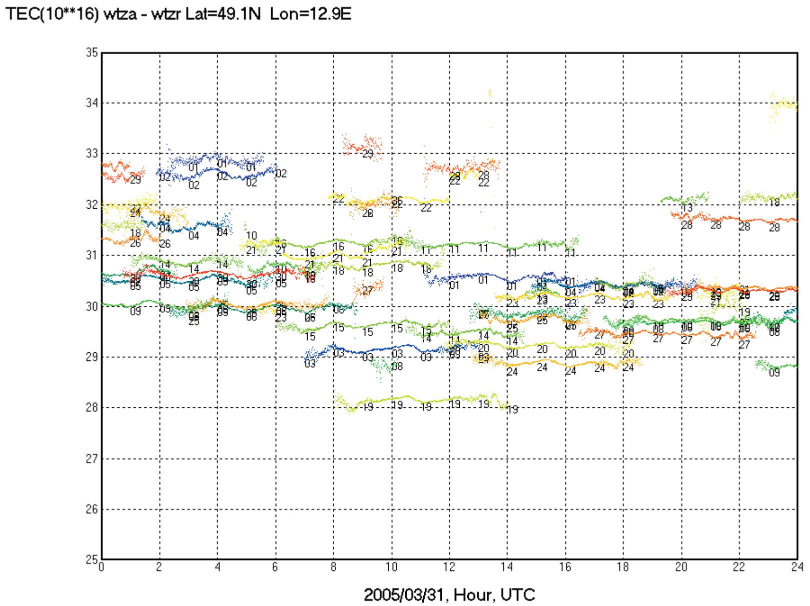
3) External consistency, namely the comparison with completely independent observations, should be the only way to assert the accuracy.
Possible observations: Incoherent Scatter Radar (**ISR**), Two-Frequency Radar Altimeter (**RA-2**). Problems: very few ***ISR***'s, **RA-2** needs its own calibration.

Only possibility: using artificial truth data obtained using ionospheric models

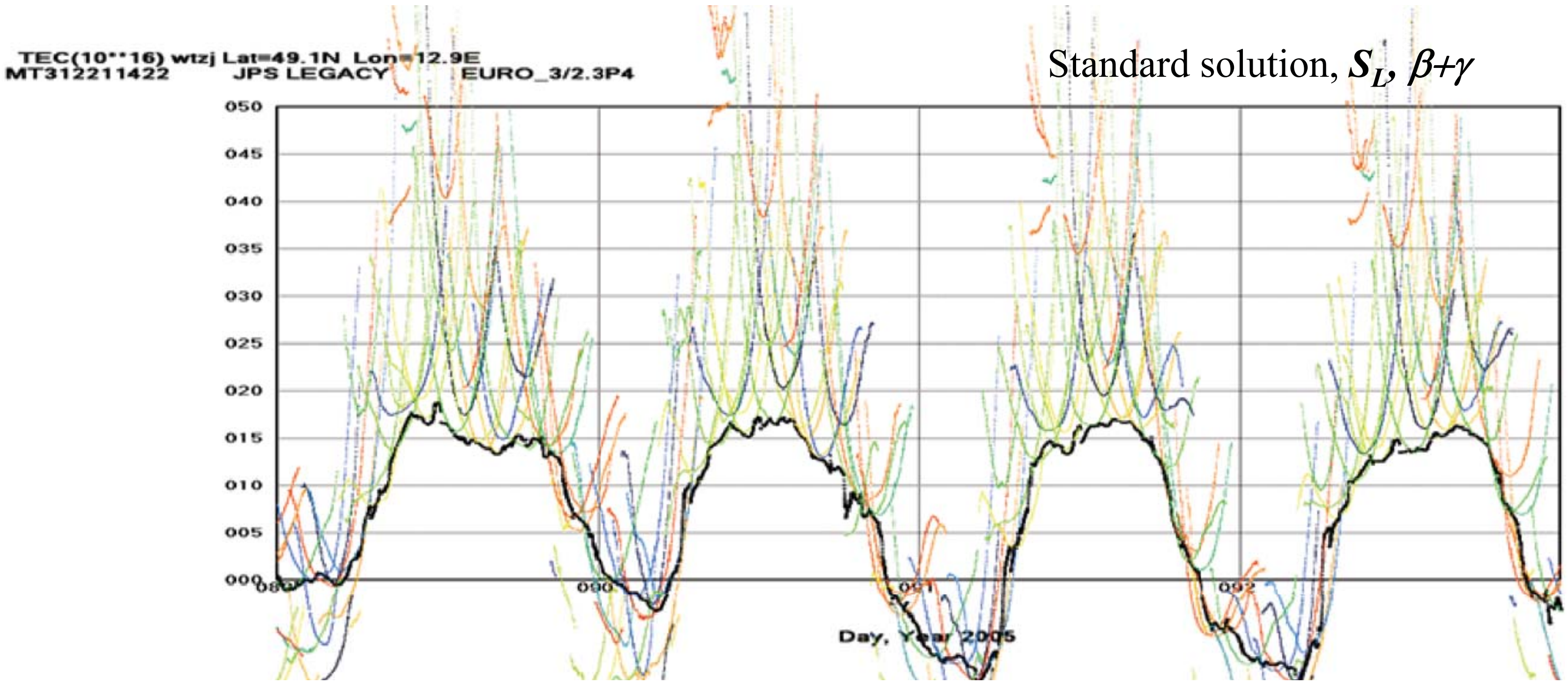
A first look: worth adopting the above procedure for calibration?







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
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035
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000
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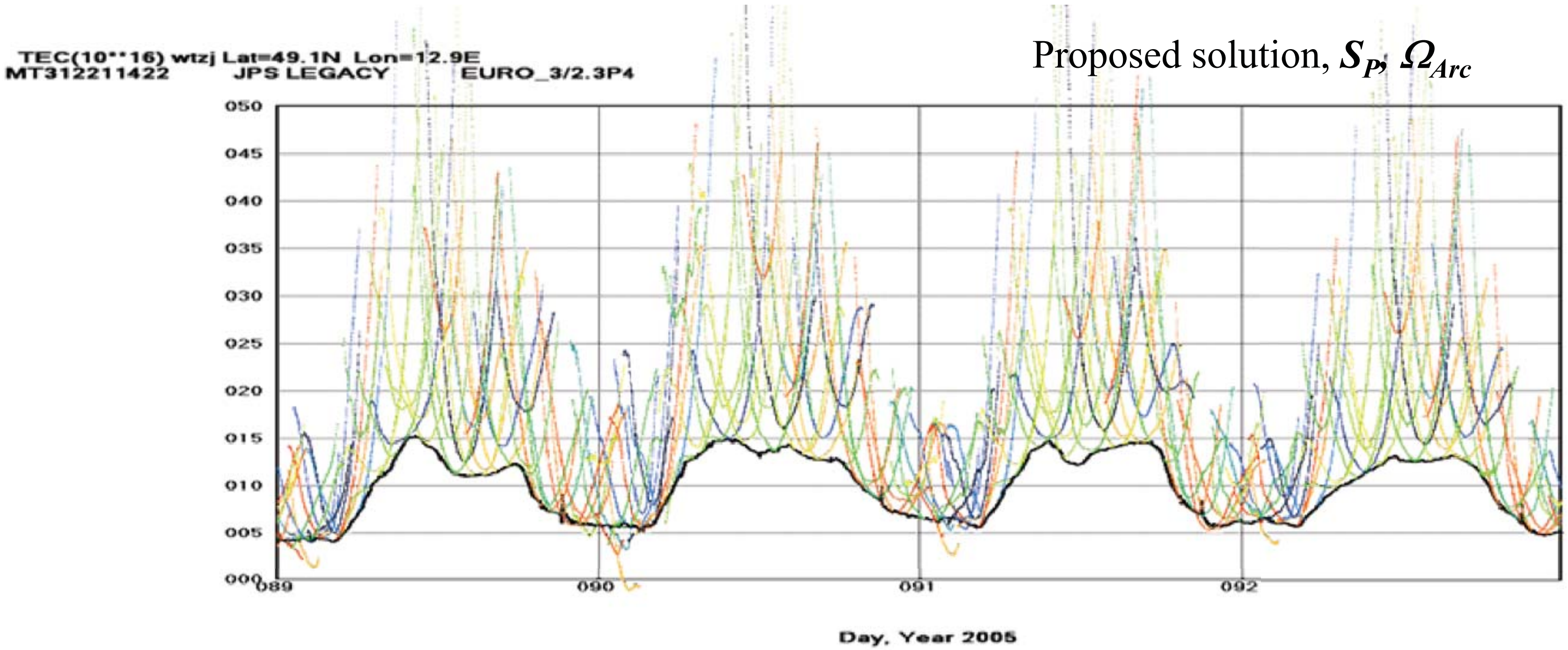
090
091
092
Day, Year 2005


TEC(10**16) wtzj Lat=49.1N Lon=12.9E
MT312211422 JPS LEGACY EURO_3/2.3P4
Proposed solution, S_P, Ω_{Arc}
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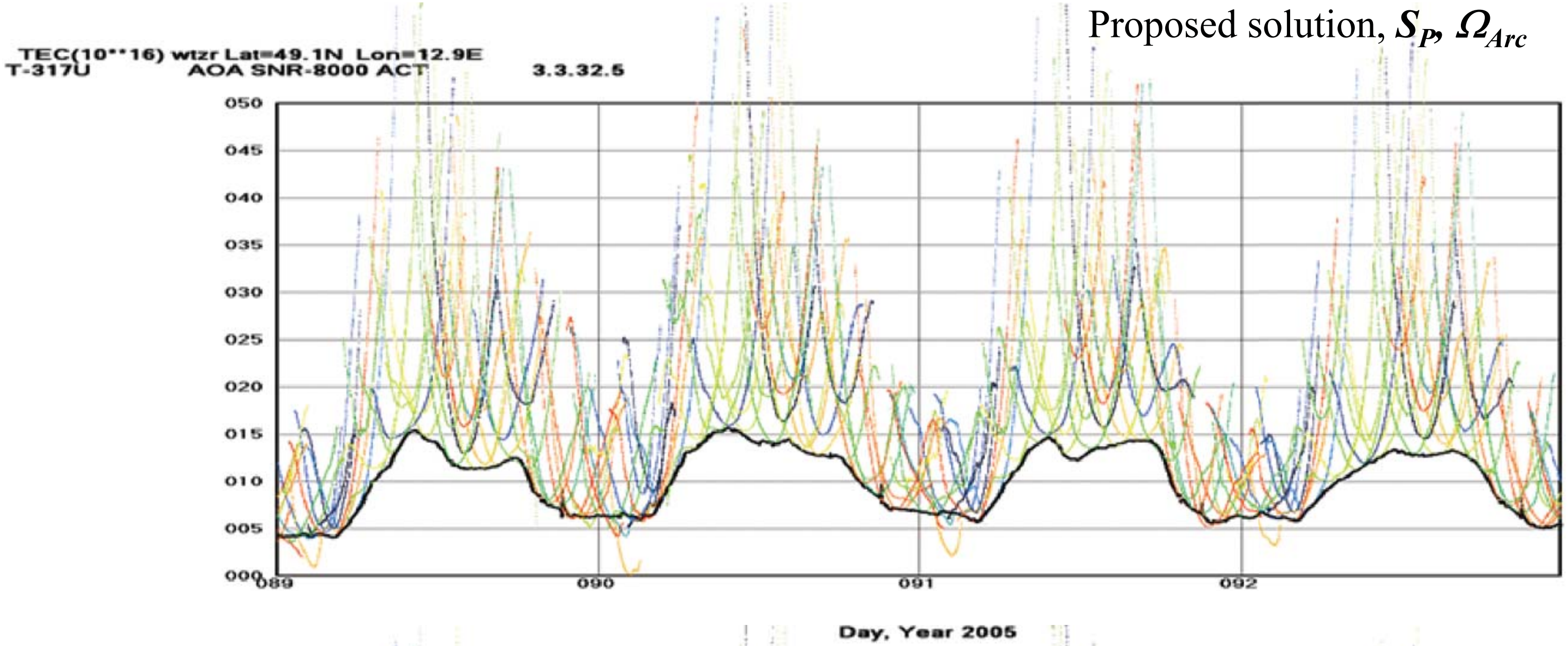
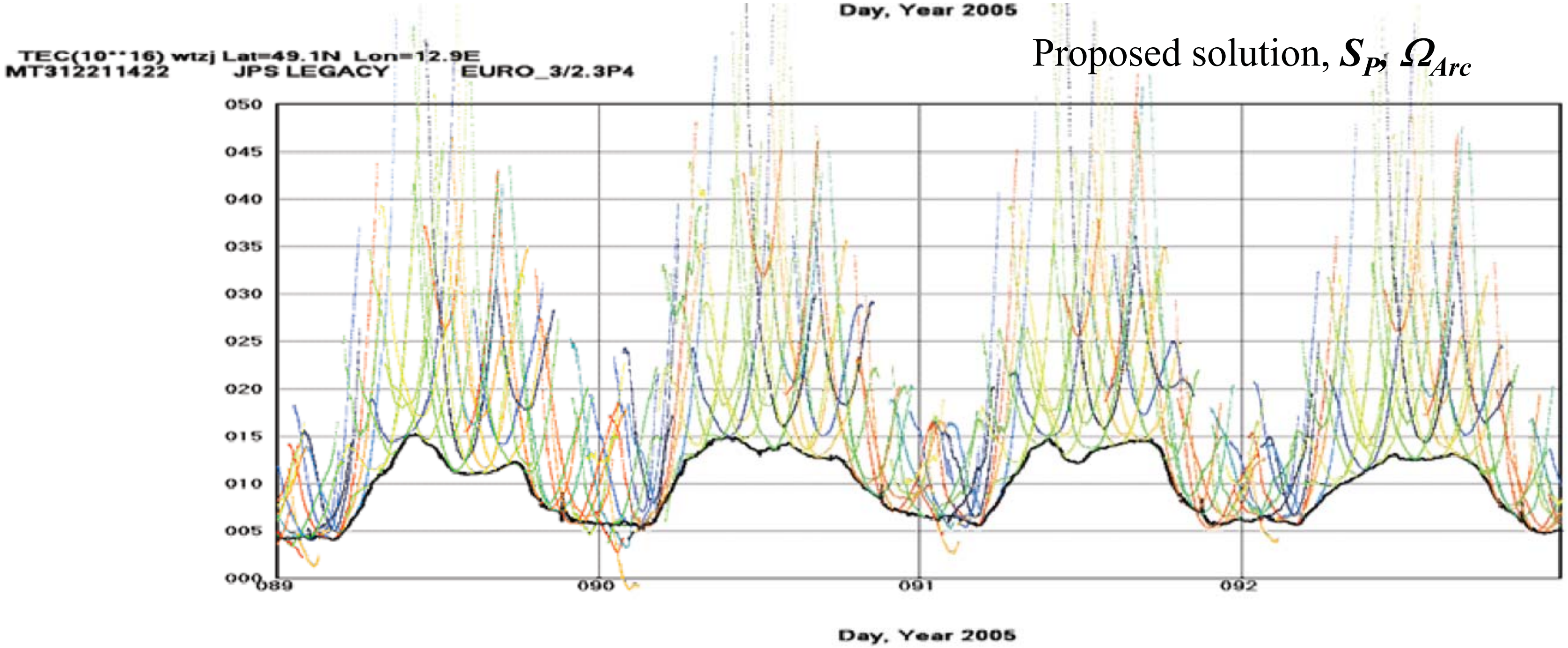
Day, Year 2005

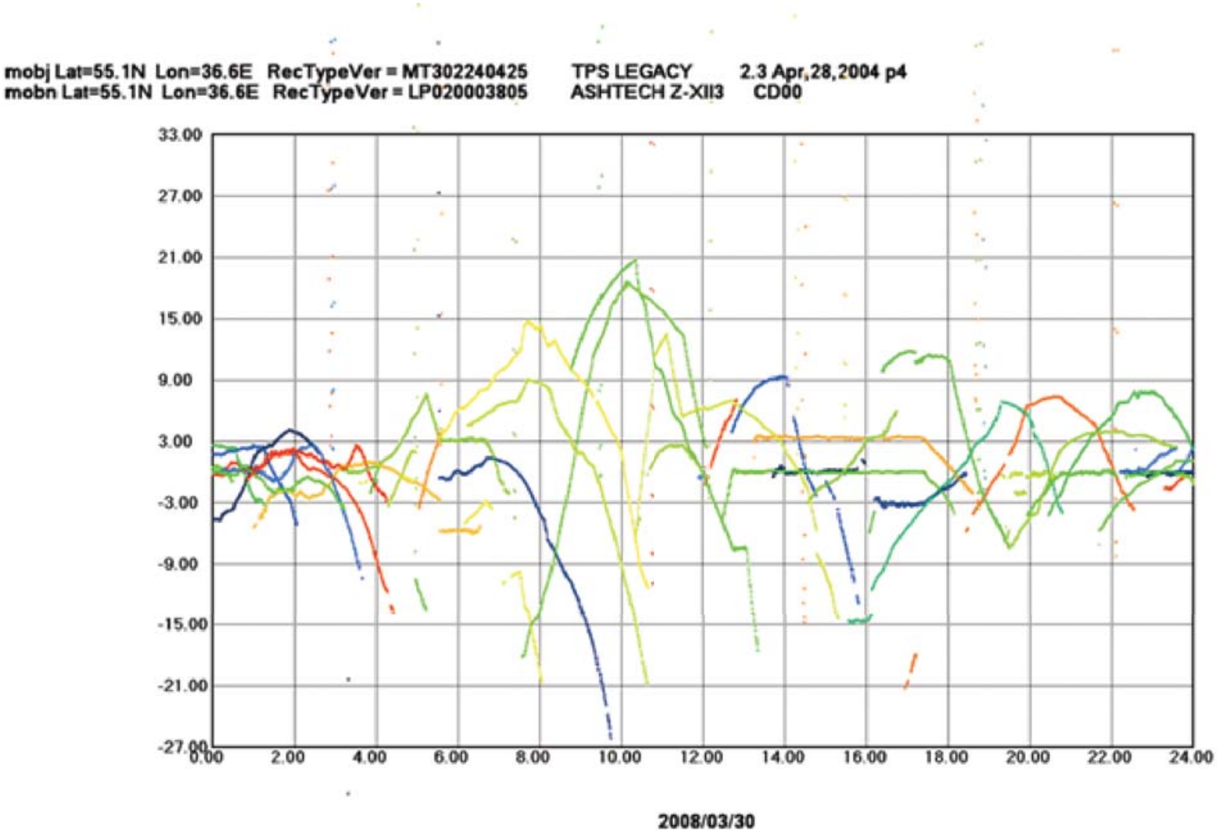
Proposed solution, S_P, Ω_{Arc}

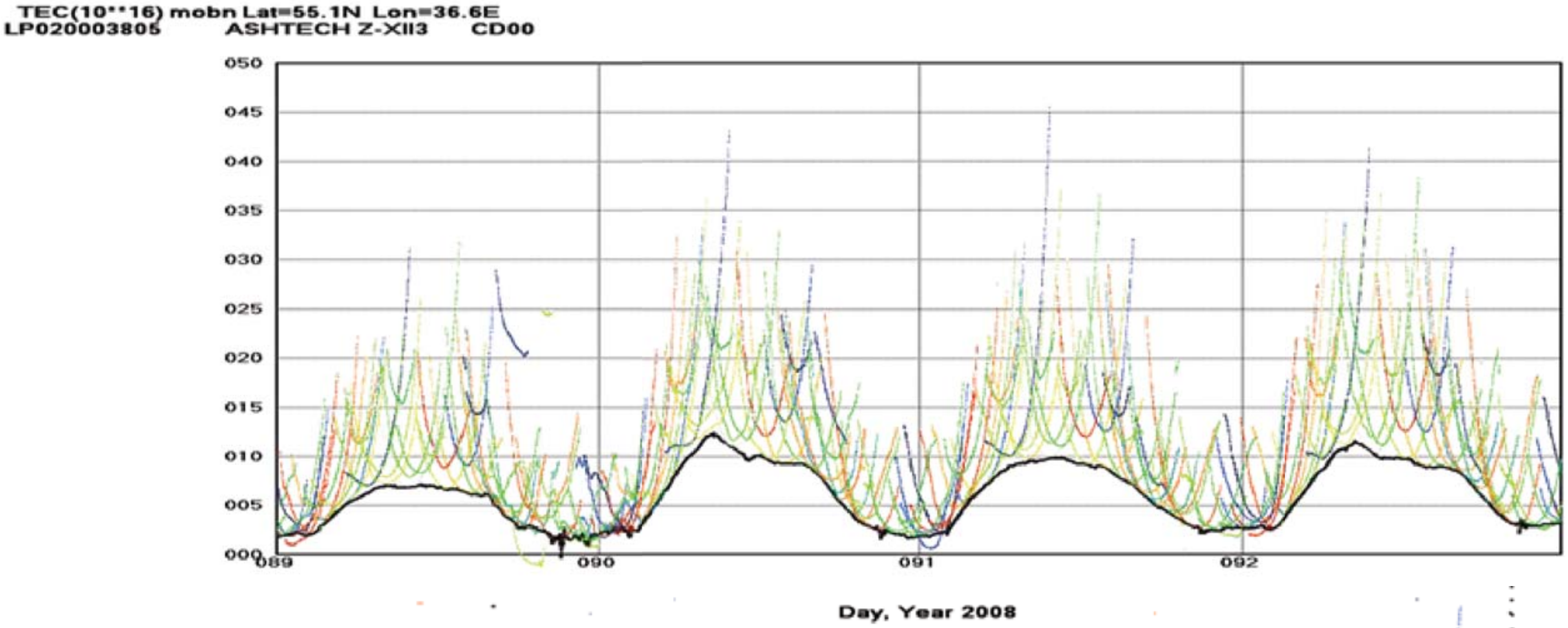


Proposed solution, S_P, Ω_{Arc}



Will it work everytime? Yes, provided phase slants $\boldsymbol{S_P}$ are reliable. For some pair of stations (namely $\boldsymbol{S_P}$ [*mobj*] - $\boldsymbol{S_P}$ [*mobn*]), the situation looks like here, showing that, for at least one of them, observations are not reliable. Still, no a priori way exists to know what is going wrong. For the present sample, the solutions of individual stations (next slide) show that the problem arises with "***mobj***".




TEC(10**16) mobn Lat=55.1N Lon=36.6E
LP020003805 ASHTECH Z-XII3 CD00
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090
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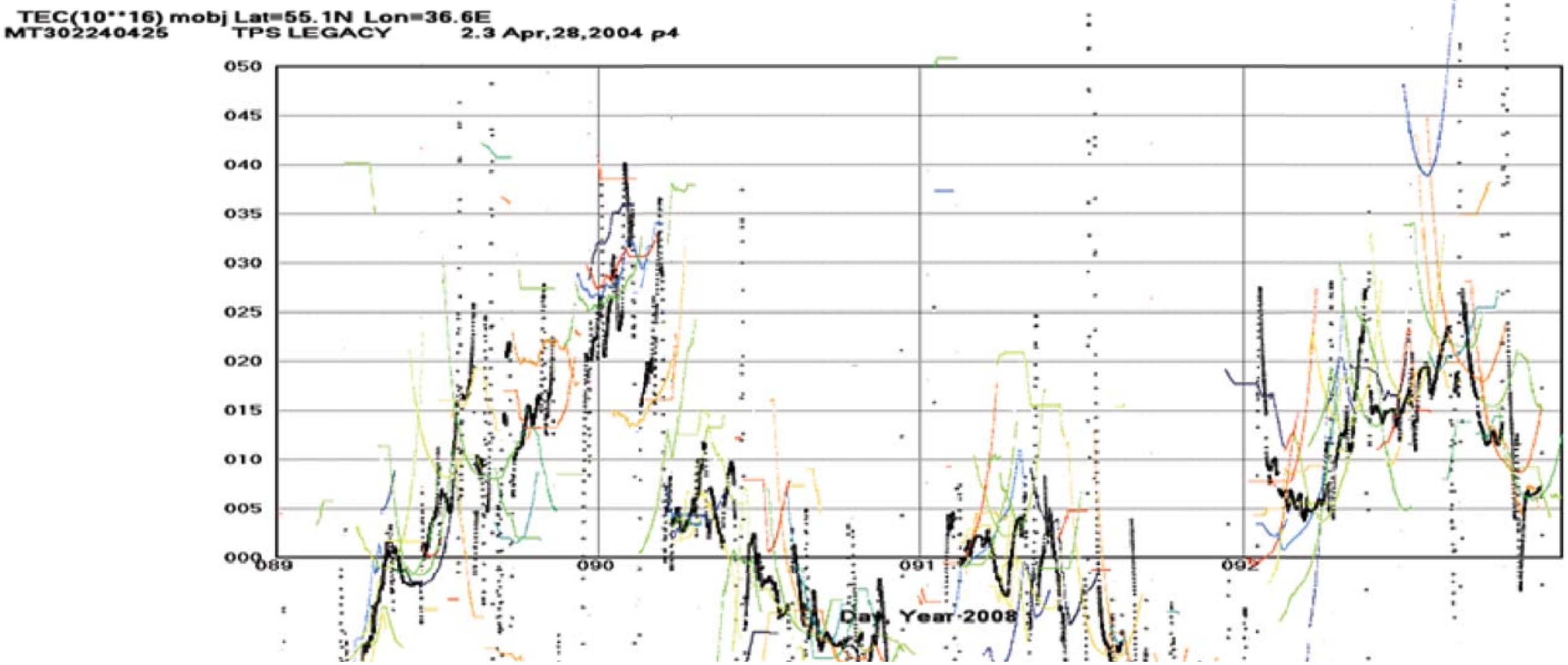
Day, Year 2008


TEC(10**16) mobj Lat=55.1N Lon=36.6E
MT302240425 TPS LEGACY 2.3 Apr,28,2004 p4
050
045
040
035
030
025
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000
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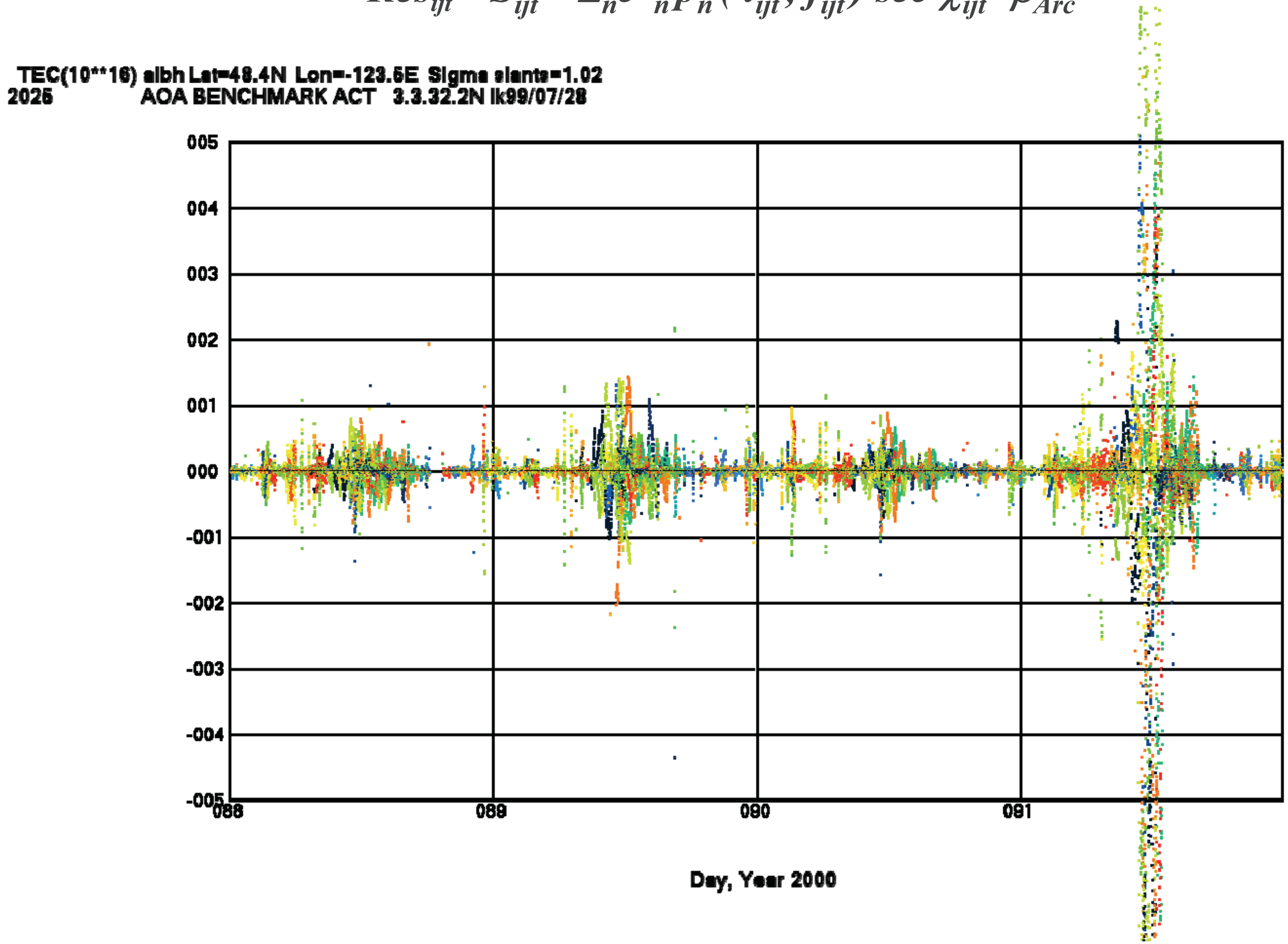
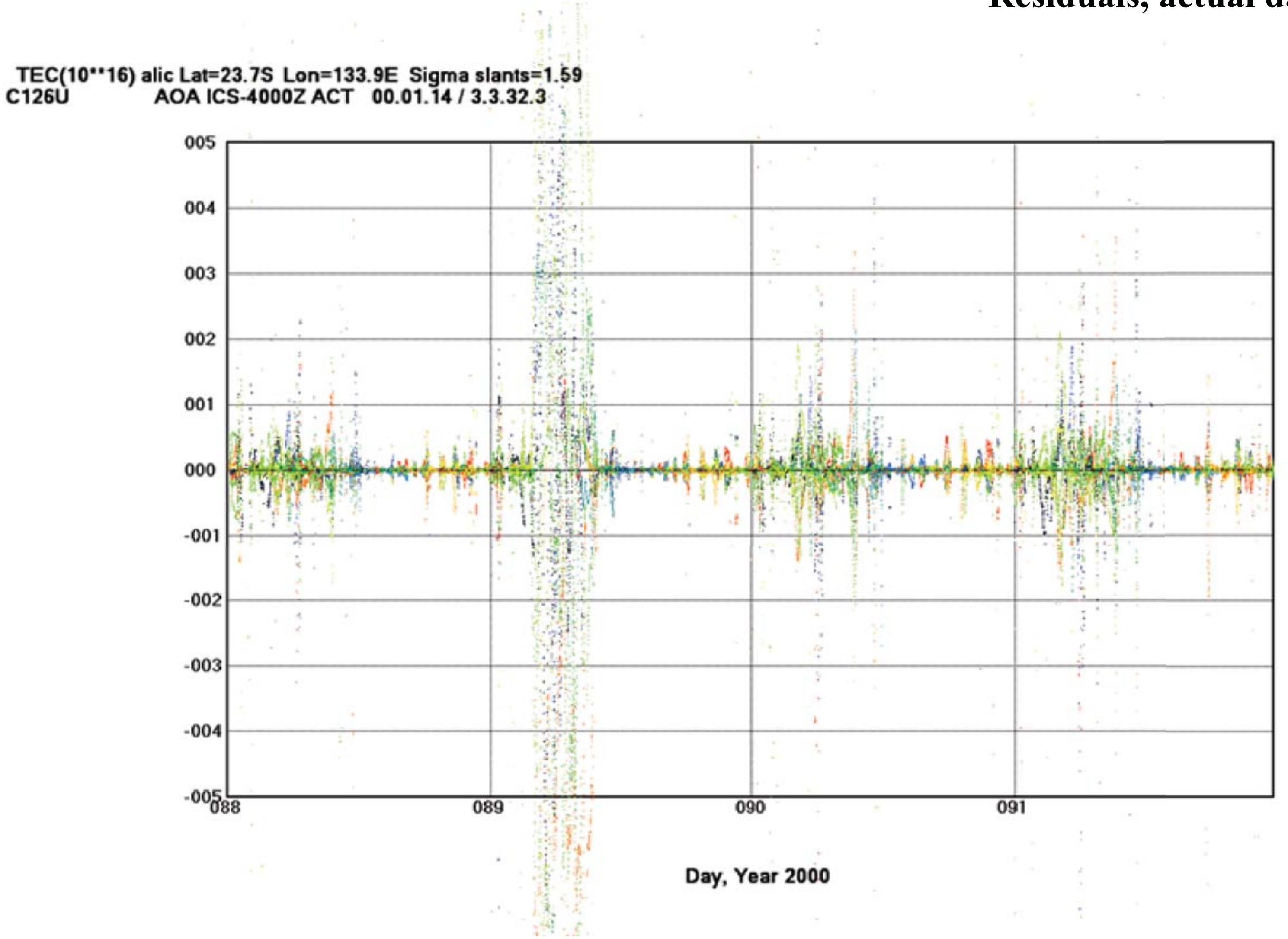
Day, Year 2008

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

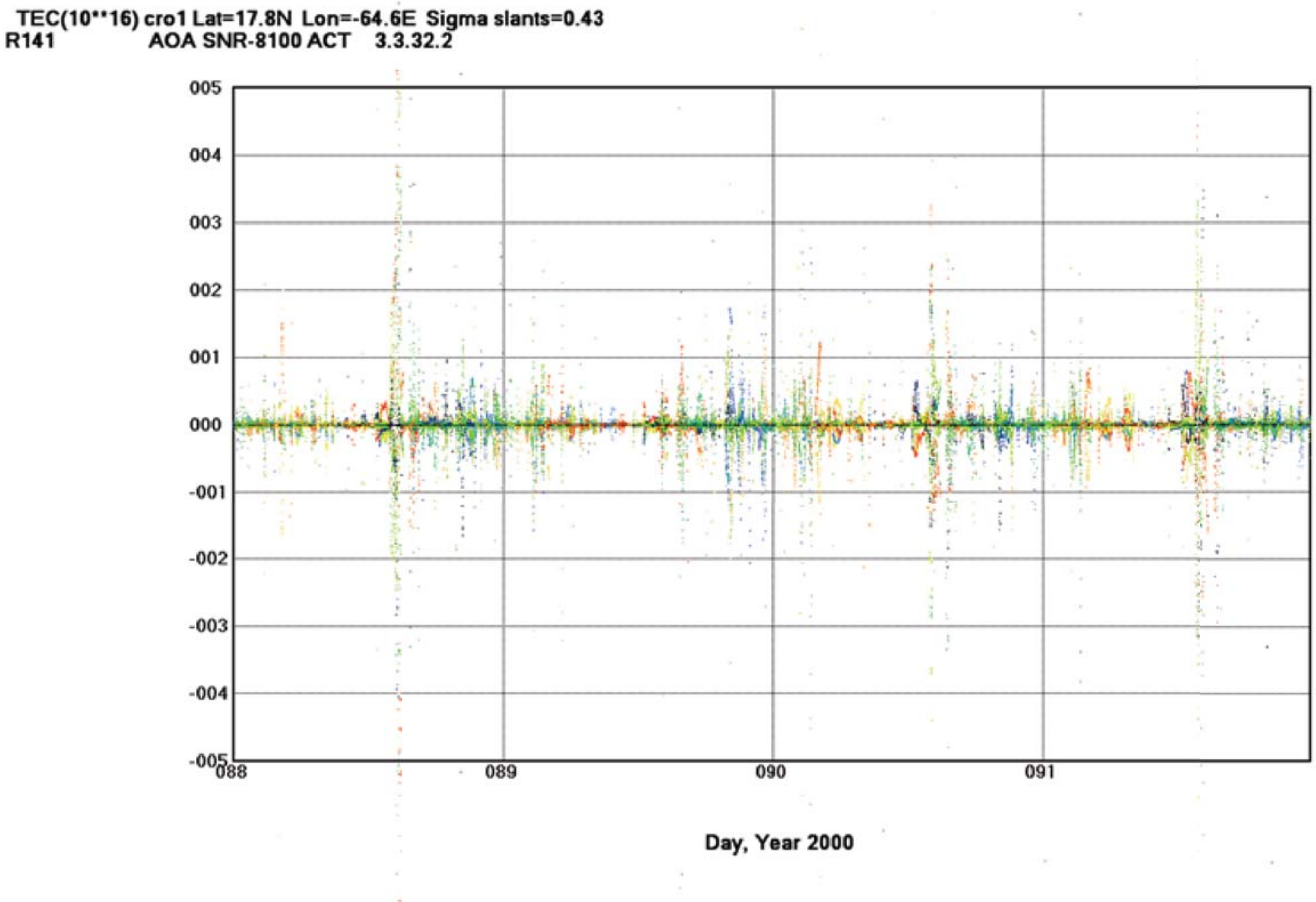
$$Res_{ijt} = S_{ijt} - \Sigma_n c^t{}_n p_n(l_{ijt}, f_{ijt}) \sec \chi_{ijt} - \beta_{Arc}$$



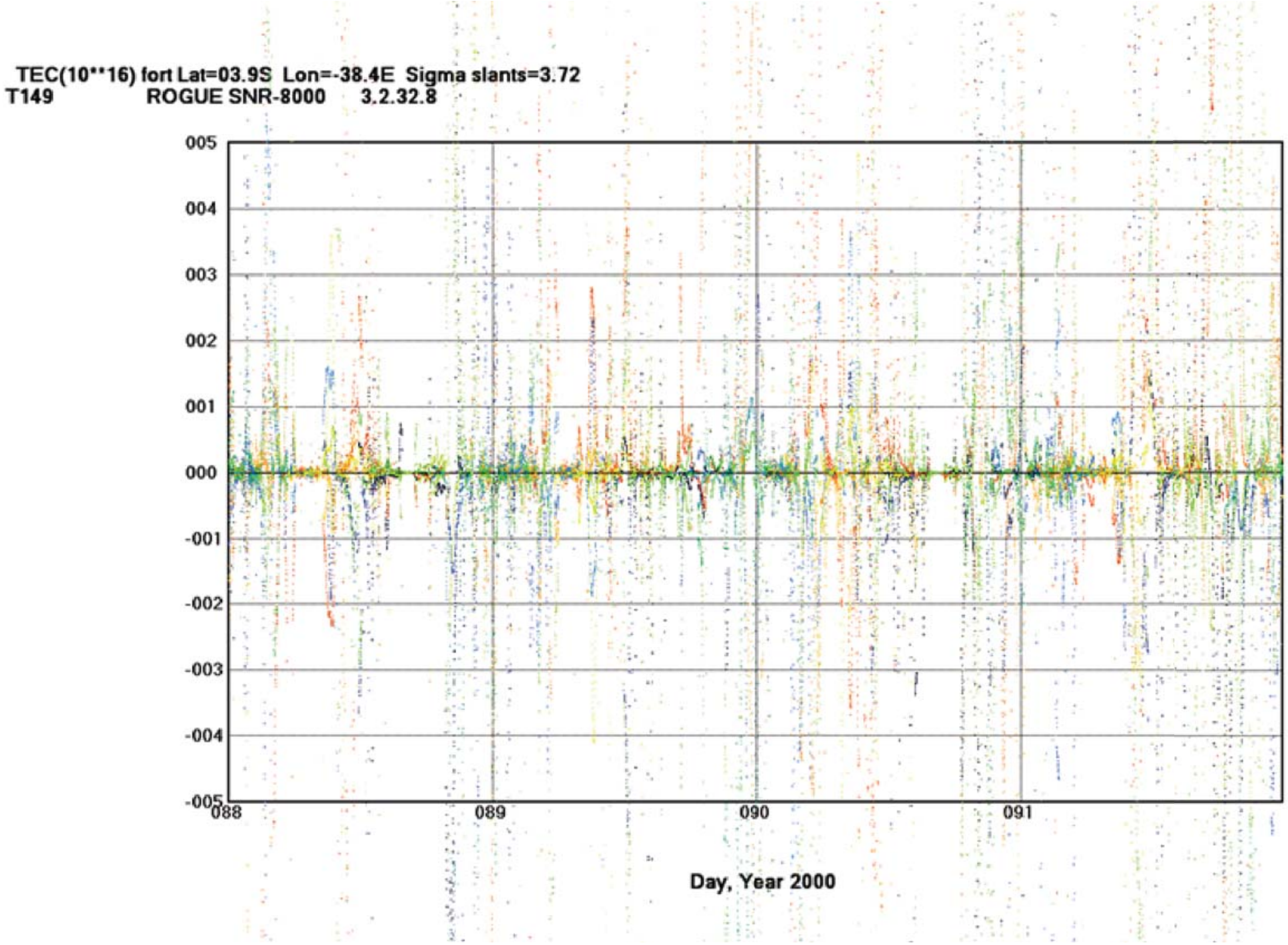
Residuals, actual data



Residuals, actual data



Residuals, actual data



Sigma of the sample residuals shown 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.

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

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

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

$\boldsymbol{\delta s_i}$ increment in arc length

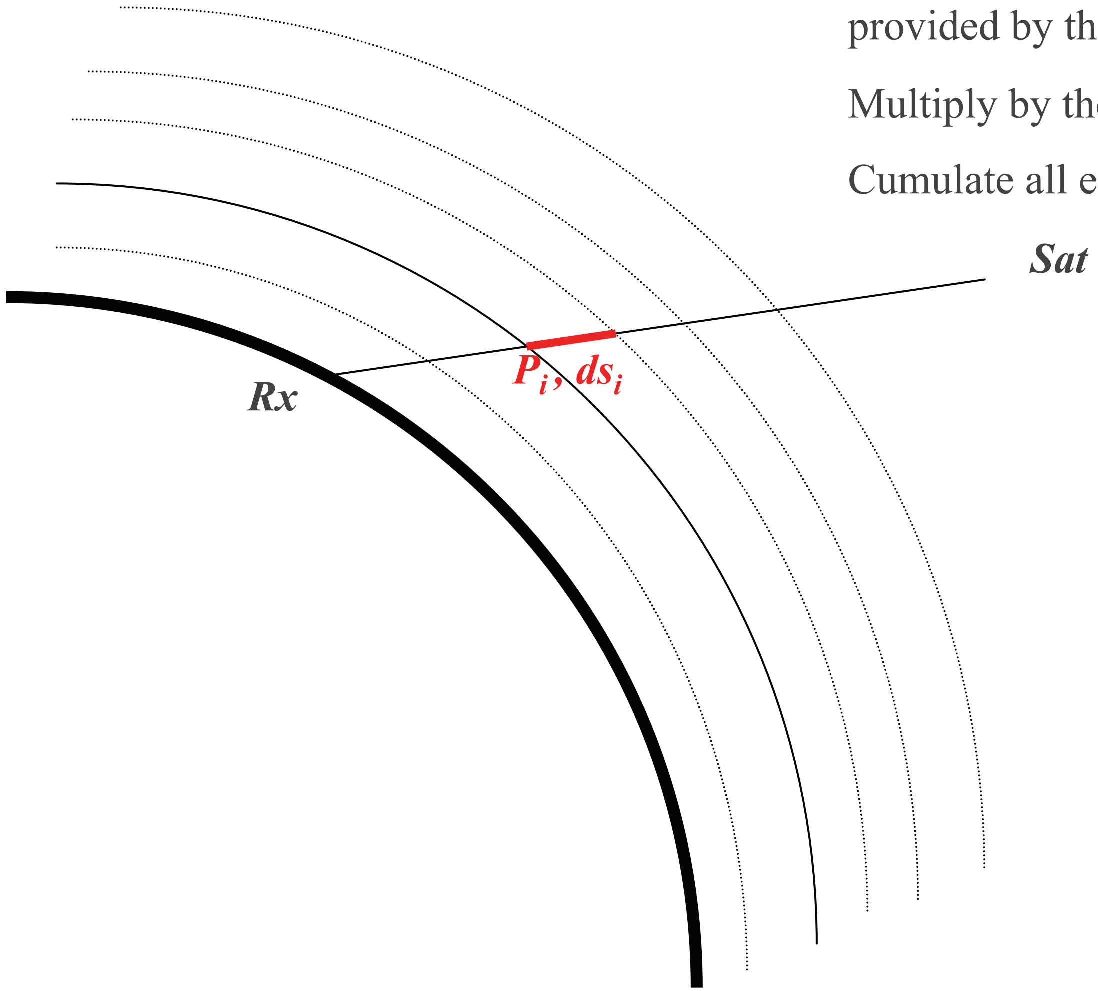
Model TEC computation

Divide the path in elements $\boldsymbol{\delta s_i}$

At each point $\boldsymbol{P_i}$ compute the electron density $\boldsymbol{N_e(P_i)}$ provided by the model

Multiply by the element length $\boldsymbol{\delta s_i}$

Cumulate all elements



Generation of artificial truth data

Given all slants actually observed and archived

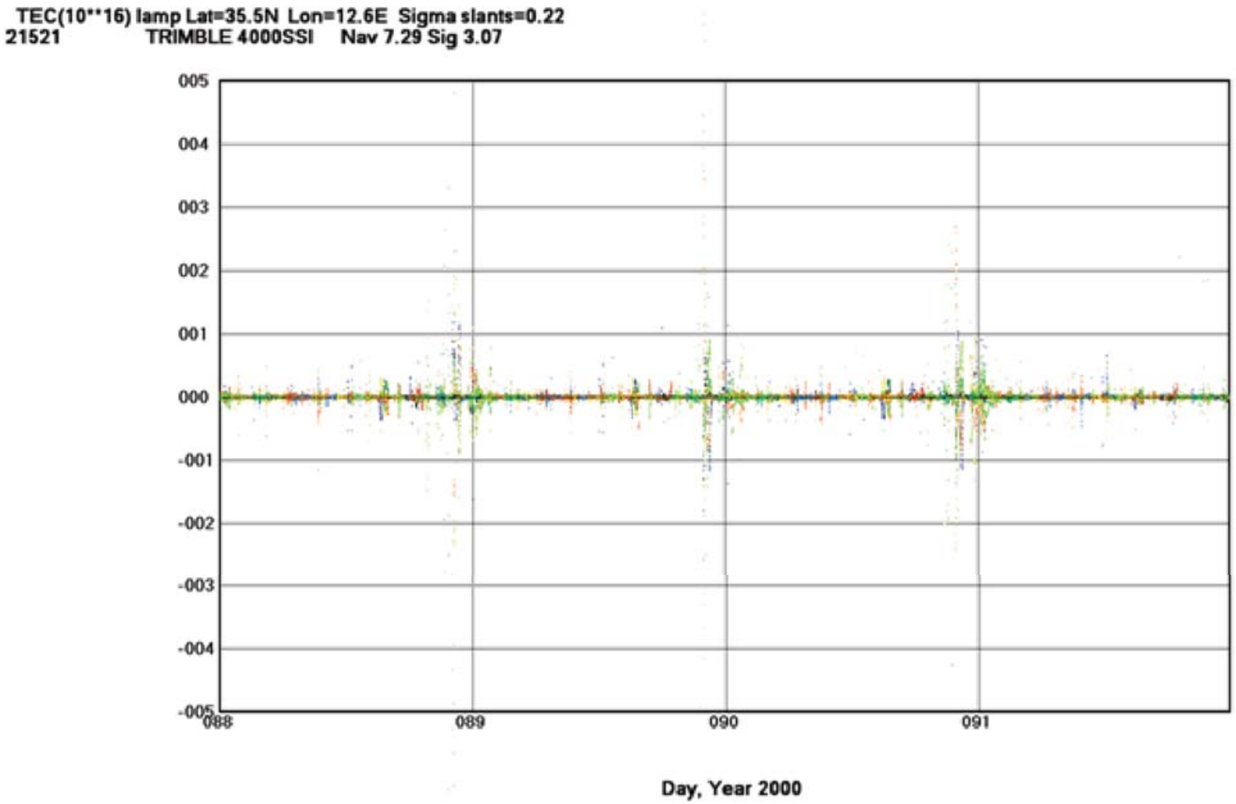
in a (quasi) complete set of IGS stations (≈ 200 per day)
for year 2000
for days 88-91 (March 28-31)

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

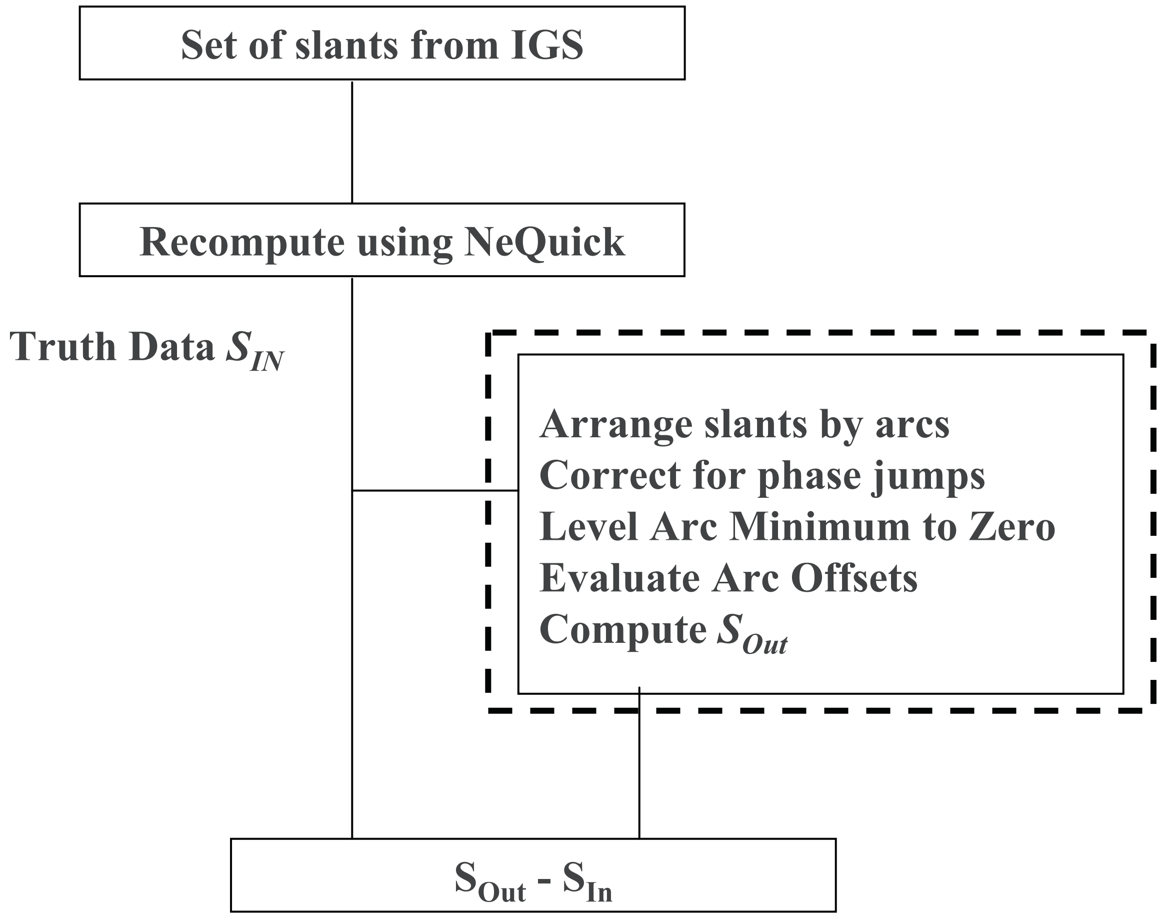
Therefore:

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



Testing the calibration procedure



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

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

Remark about highlighted arc:

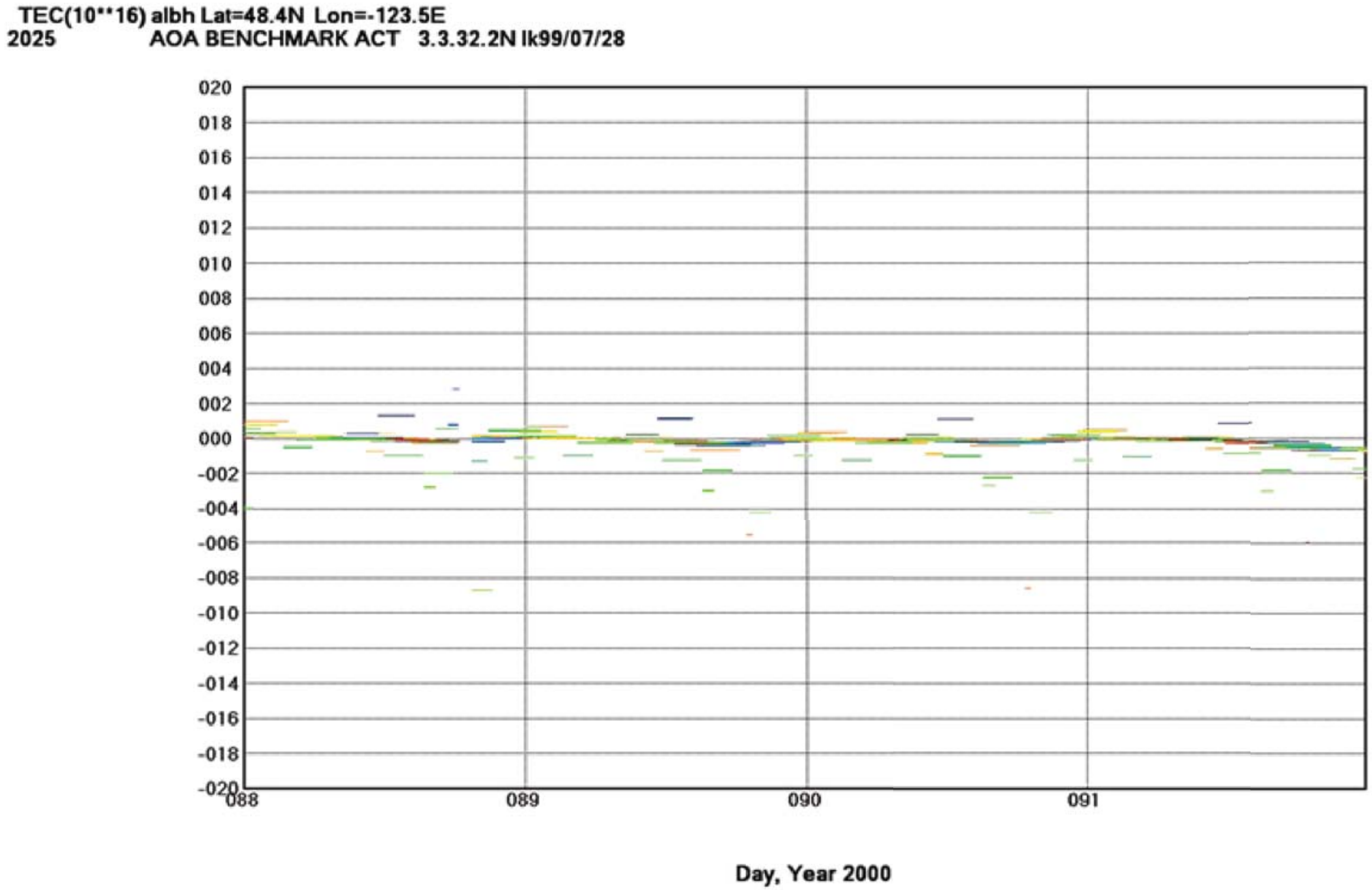
errors show a weakness of the solution**.**

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

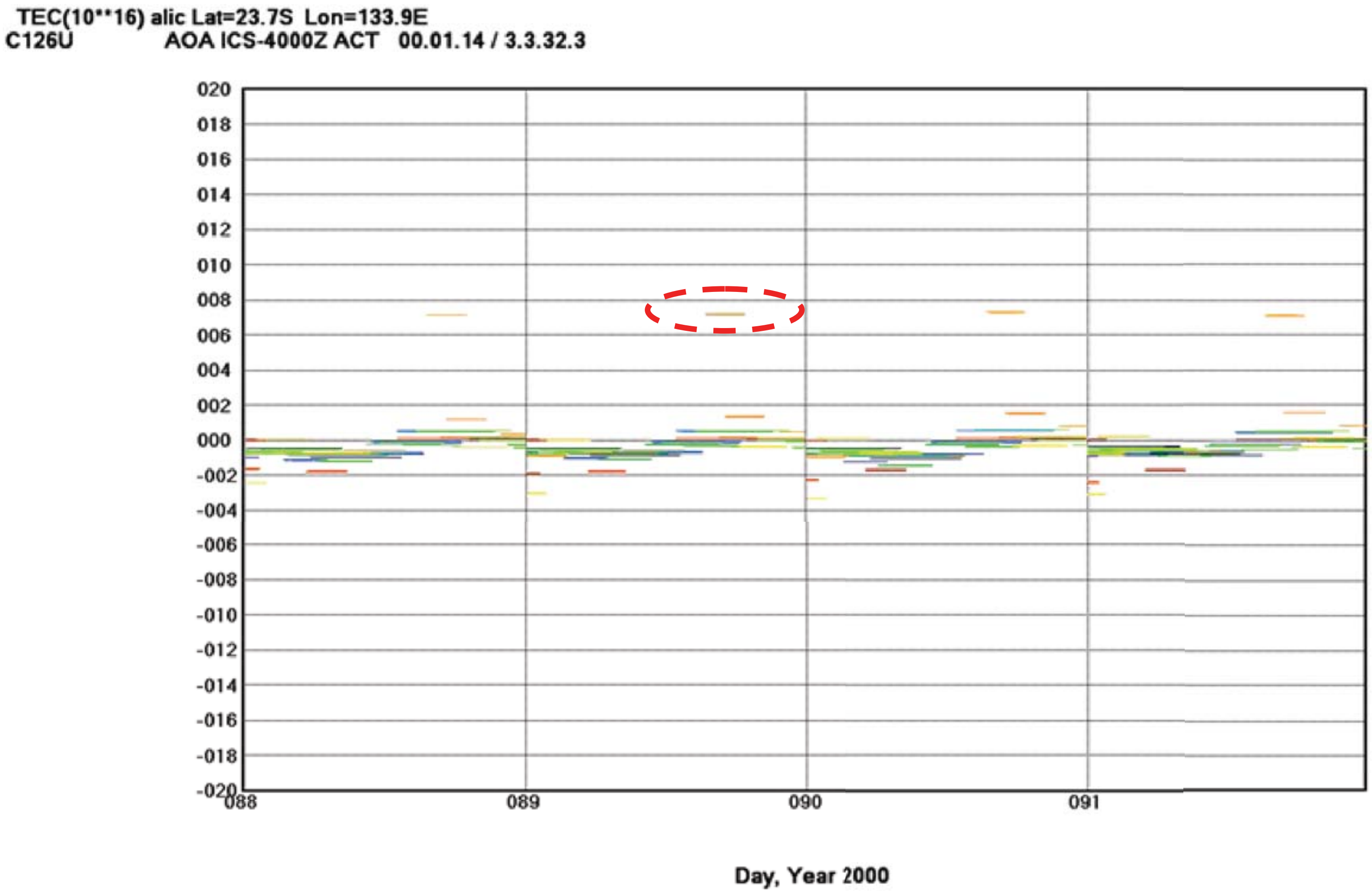
Processing real data, there is no chance to know if the subject arc is ill-calibrated (unless in presence of very strong errors)

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

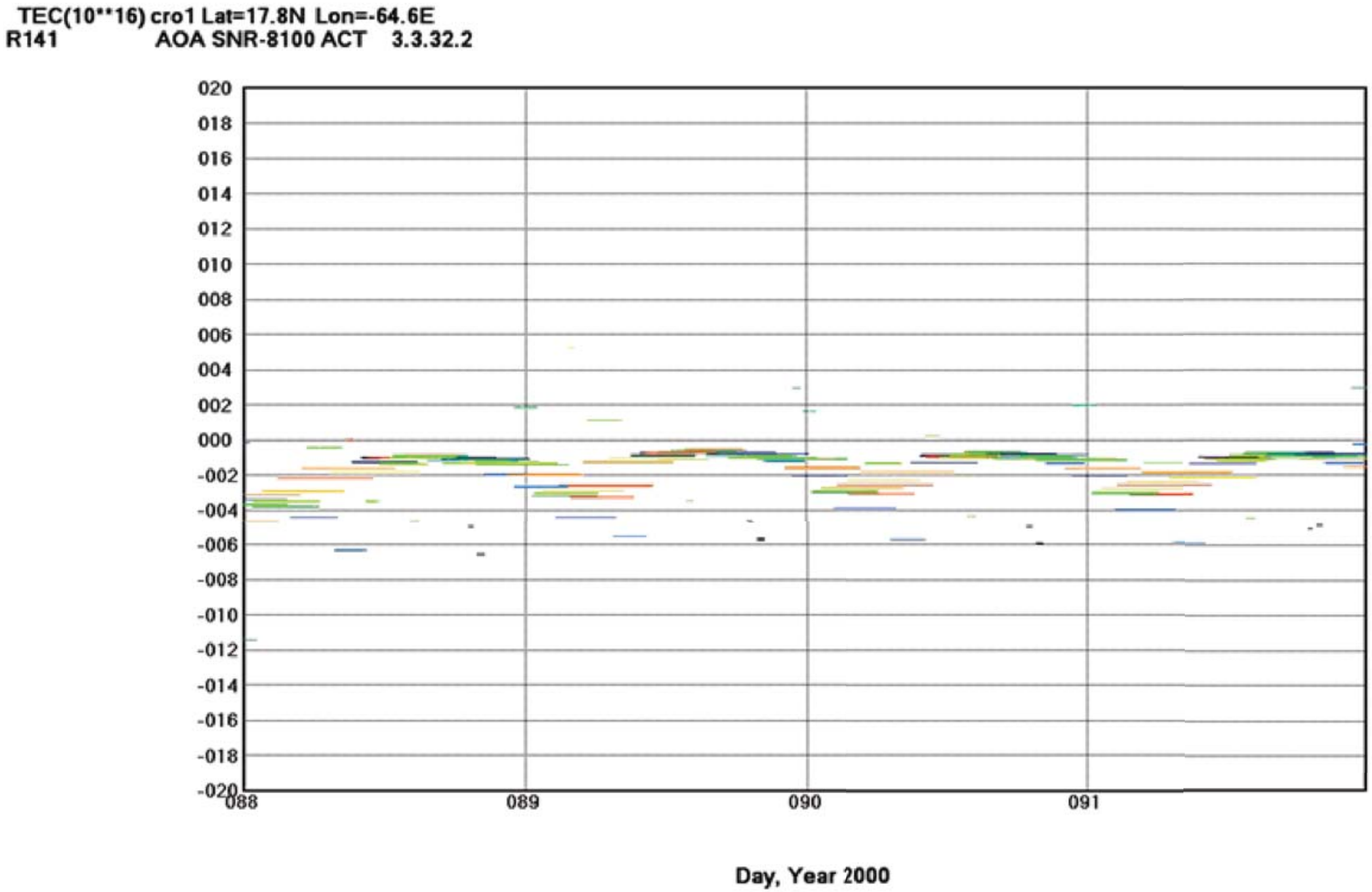
$Slant_{Out}$-$Slant_{In}$, TECu



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

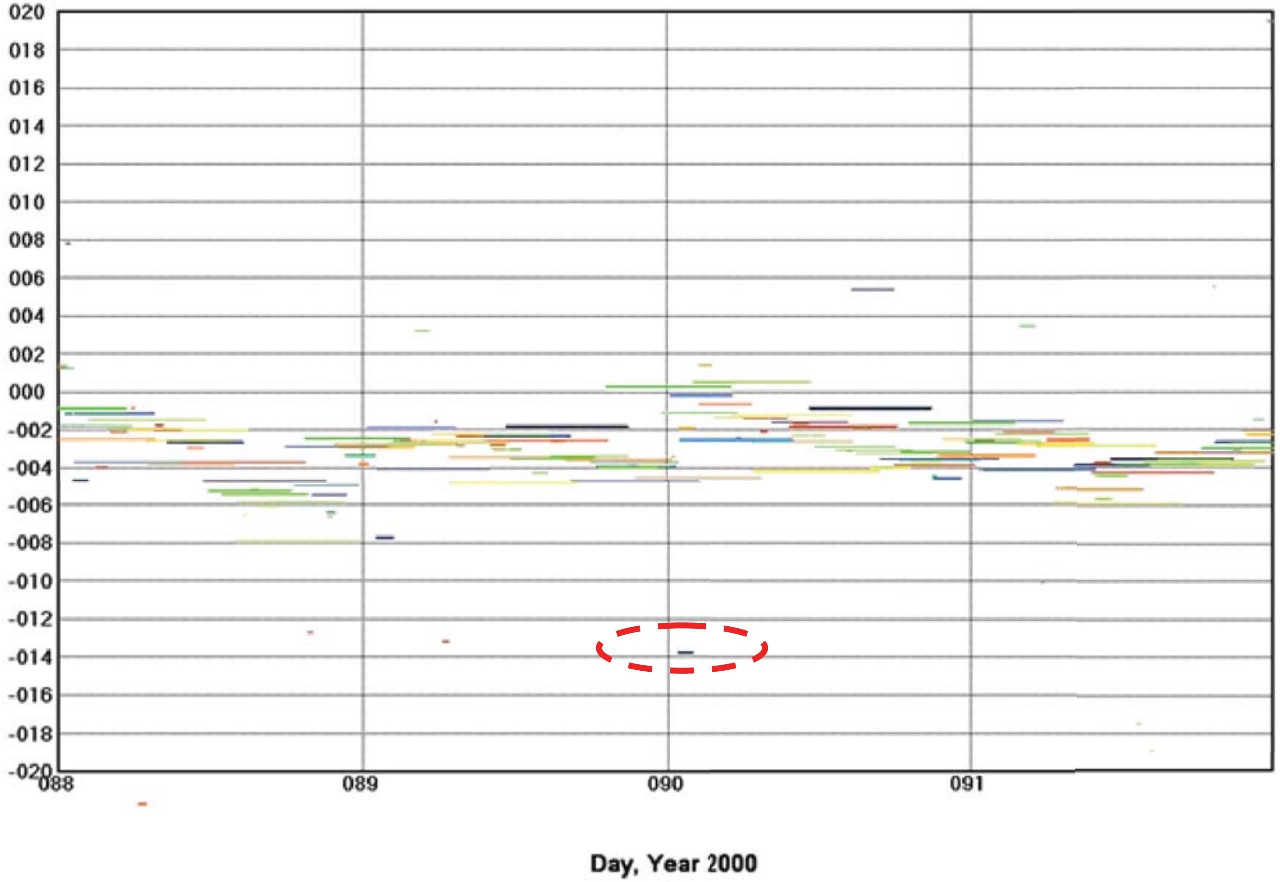


Slant$_{Out}$-Slant$_{In}$, TECu

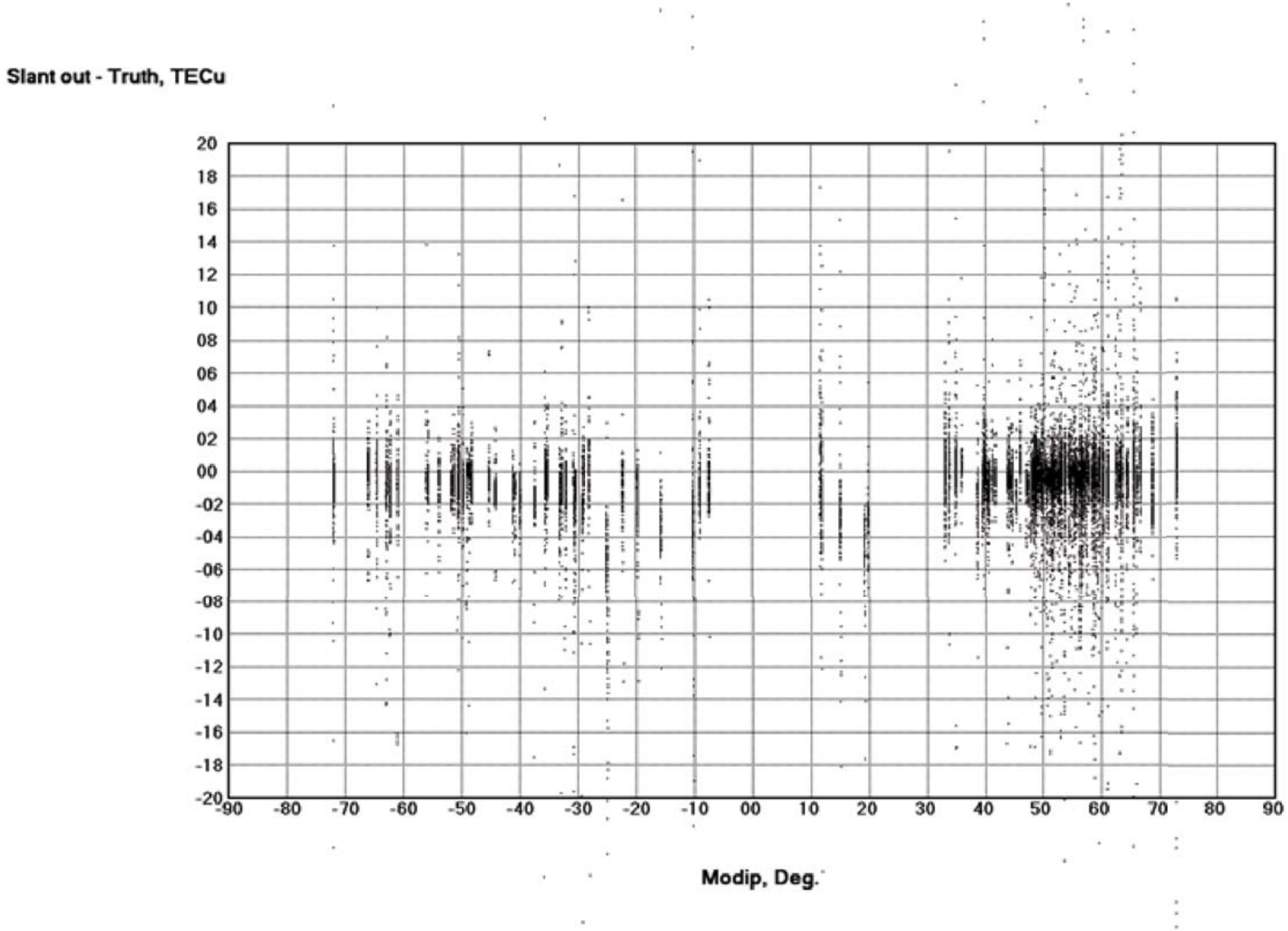


Slant$_{Out}$-Slant$_{In}$, TECu

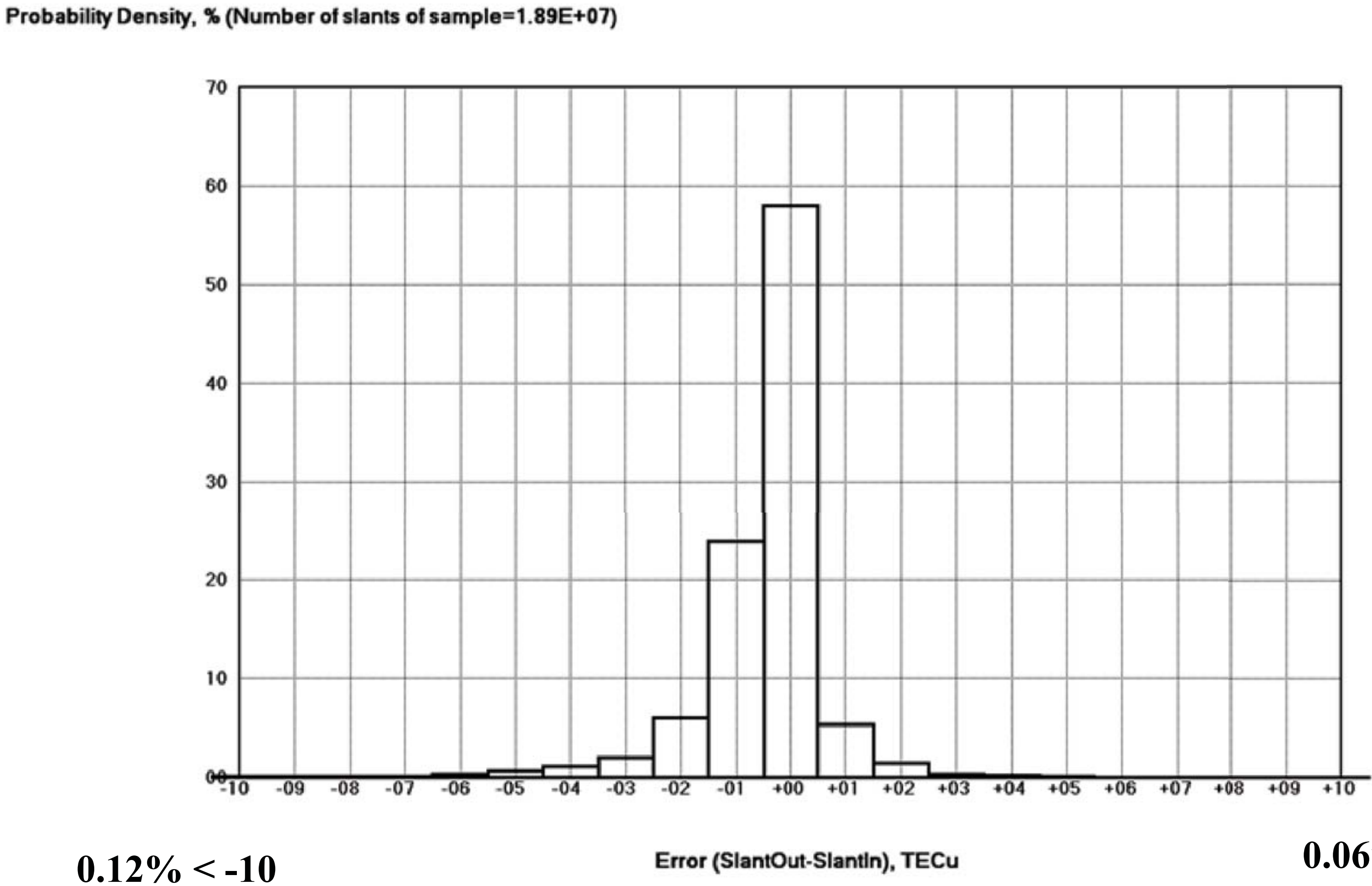
TEC(10**16) fort Lat=03.9S Lon=-38.4E
T149 ROGUE SNR-8000 3.2.32.8



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



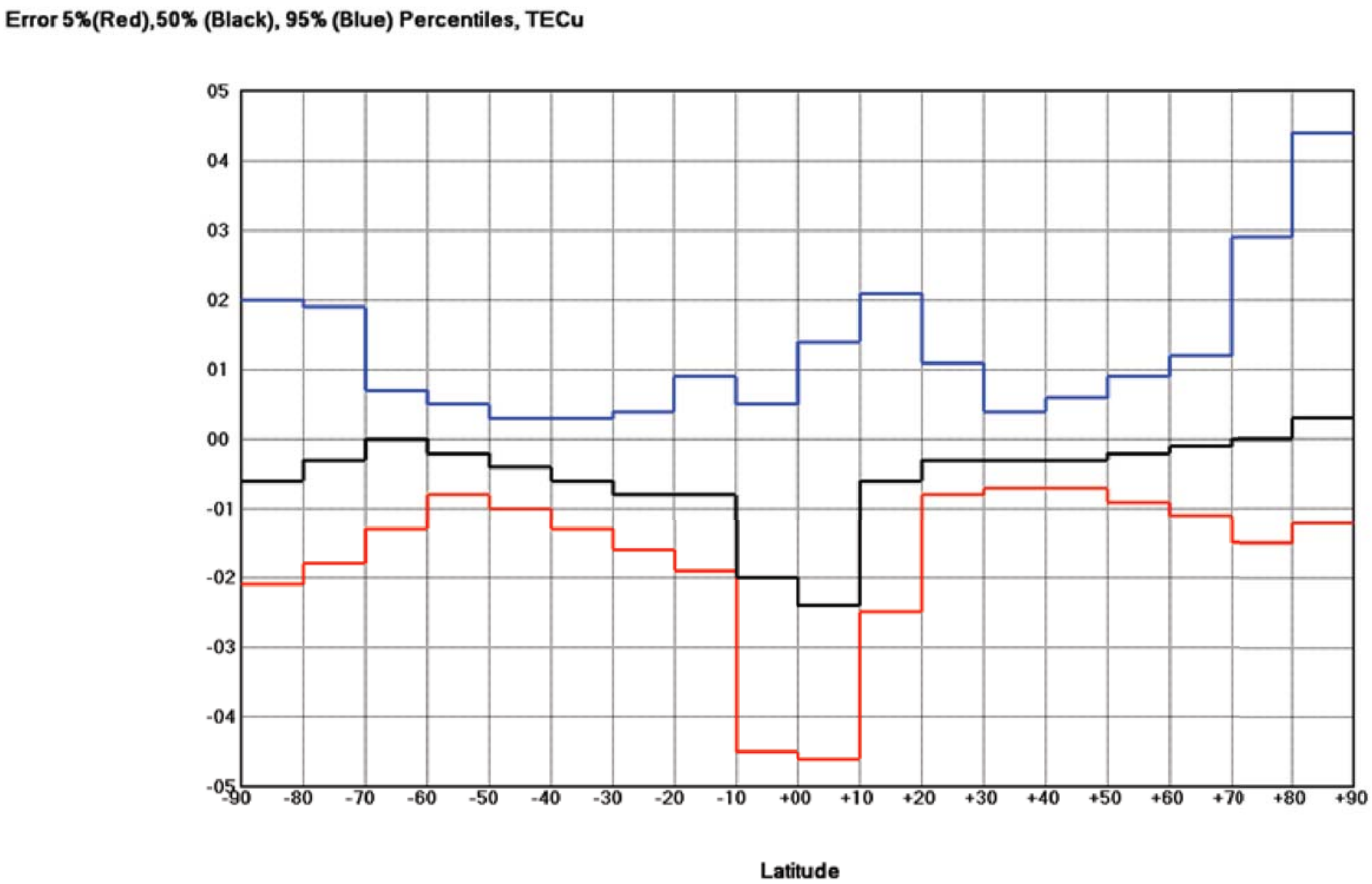
An overall look to the errors: $S_{Out} - S_{In}$, probability density



0.12% < -10

0.067 % > 10

Error's behavior vs latitude: percentiles, whole set



Can we assert that **processing actual data** the resulting errors will be the same as above?

NO

Other significant contributions arise from

Wrong reconstruction of arc continuity

Inadequacy of the $\boldsymbol{V_{Eq}}$ model (low or high latitudes, storms)

Possible improvements:

using a variable in time and space Az to achieve a more realistic situation

not taking into account of lacking observations to limit errors only to the calibration

Conclusions

Plans for the future:

investigating the reported facts in relation to their behavior in time and their dependence on the antenna environment and the type of receiver used (possibly de-coupling them: a task for owners of at least two receivers).

A wish:

that other colleagues investigate this topic in order to understand it better

and

Have a good (non negative) TEC

when back to Africa !!