Ionosphere monitoring using NOAA's CORS network

Dru A. Smith, Ph.D.
National Geodetic Survey
National Oceanic and Atmospheric Administration

ION GNSS 2004
September 21-24, 2004
Long Beach, CA

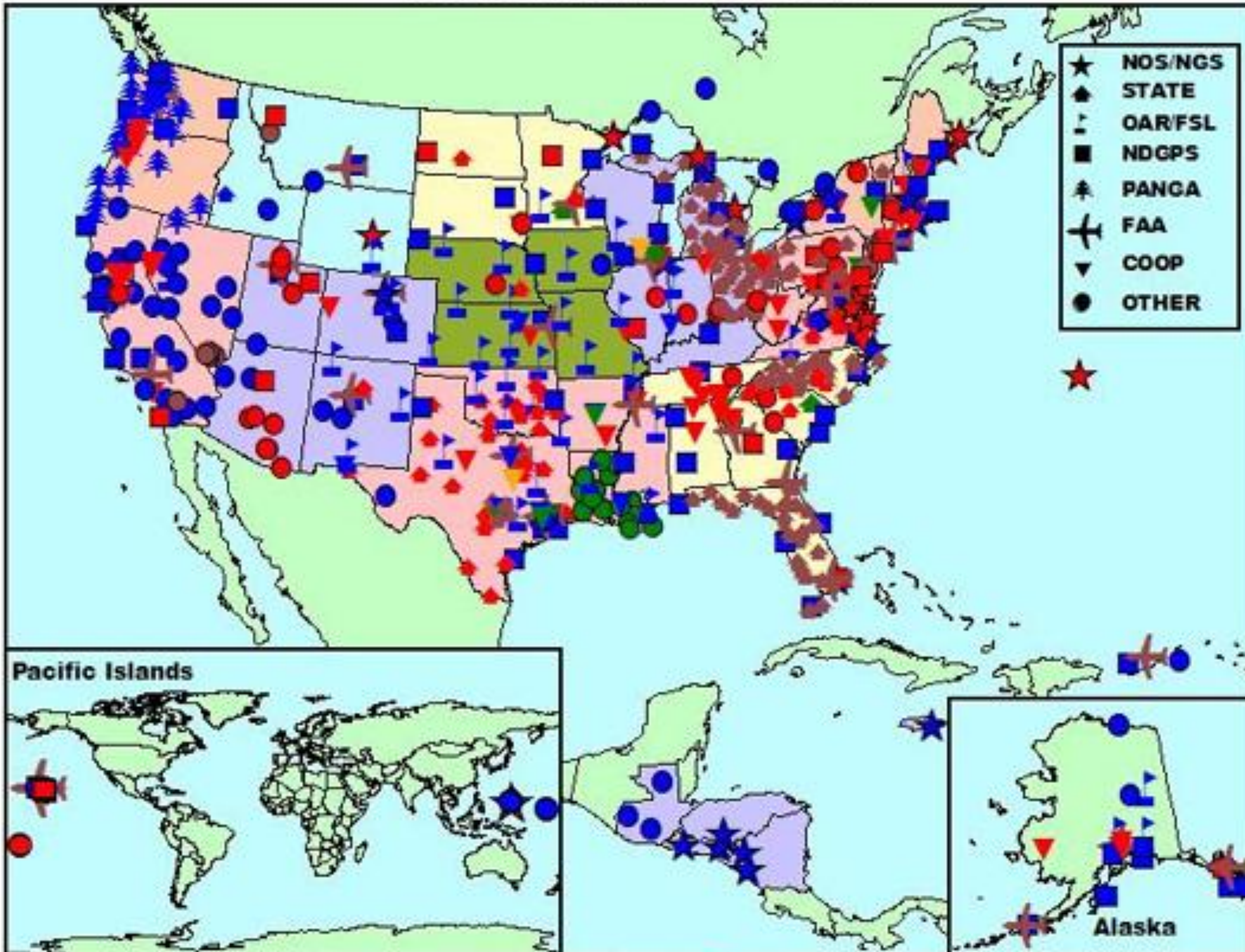
Topics of Discussion

- Geodetic need for Ionosphere
- Model/Equations
- Initial tests
- Full day solution
- Future directions

Geodetic need for ionosphere delays

- Frequency-dependent signals in GPS:
  - Ambiguities
  - Ionosphere
  - Multi-path (assumed zero initially)
- NOAA has developed an innovative new method for modeling <u>absolute</u> Ionosphere delays from <u>ambiguous</u> carrier phase data
- All data from NOAA's CORS network

CORS Coverage - June 2004

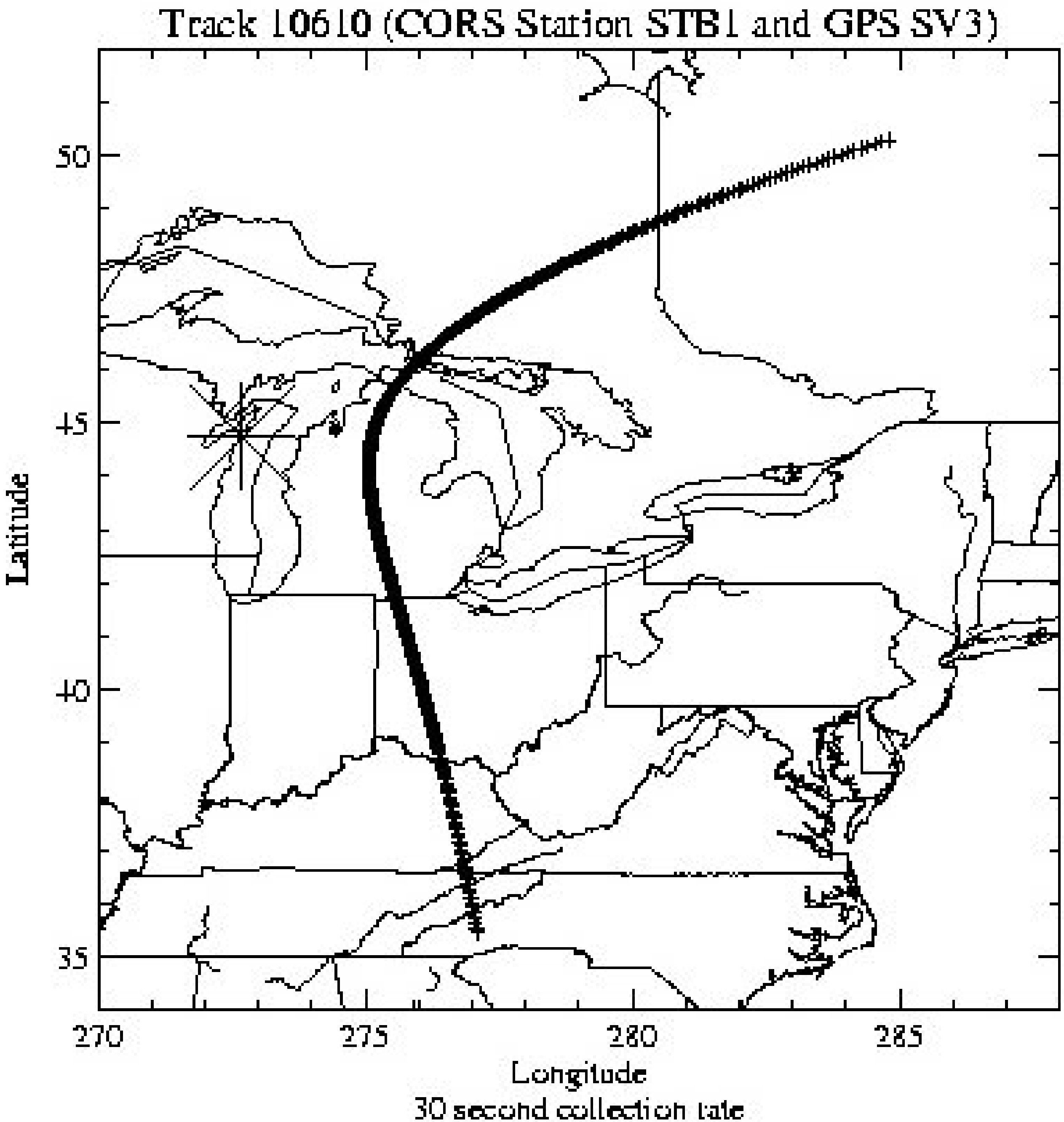


Symbol color denotes sampling rates: (1 sec) (5 sec) (10 sec) (15 sec) (30 sec)

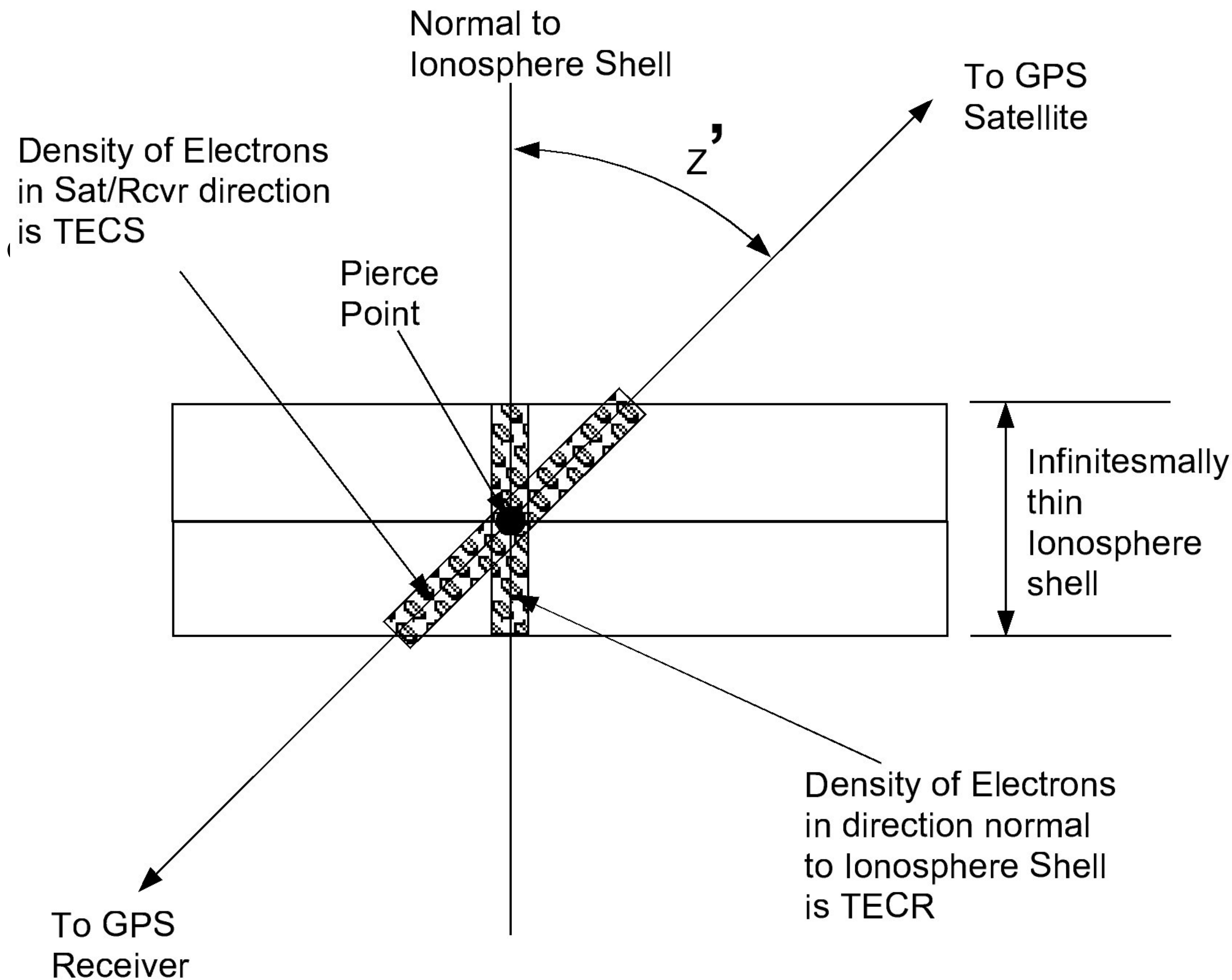
Craig 6/04/2004

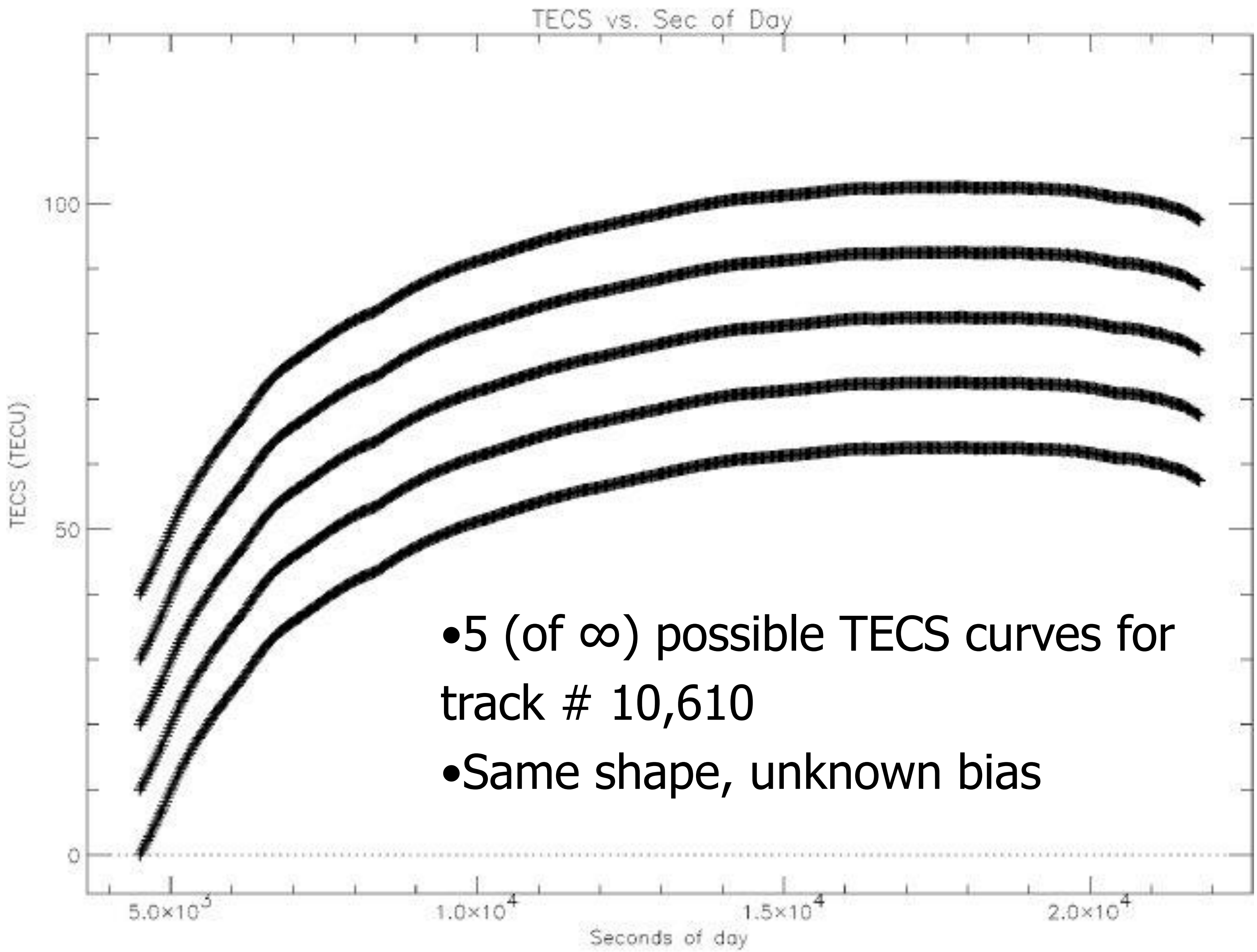
Assumptions and model

- 2-D “condensed” TEC shell (epoch = pierce point)
- Focus on *fast*, *accurate* ionosphere delays; not on realistic 4-D electron distribution
- Mapping pierce points without loss of lock yields a track
- CORS yields about 20,000 tracks every day



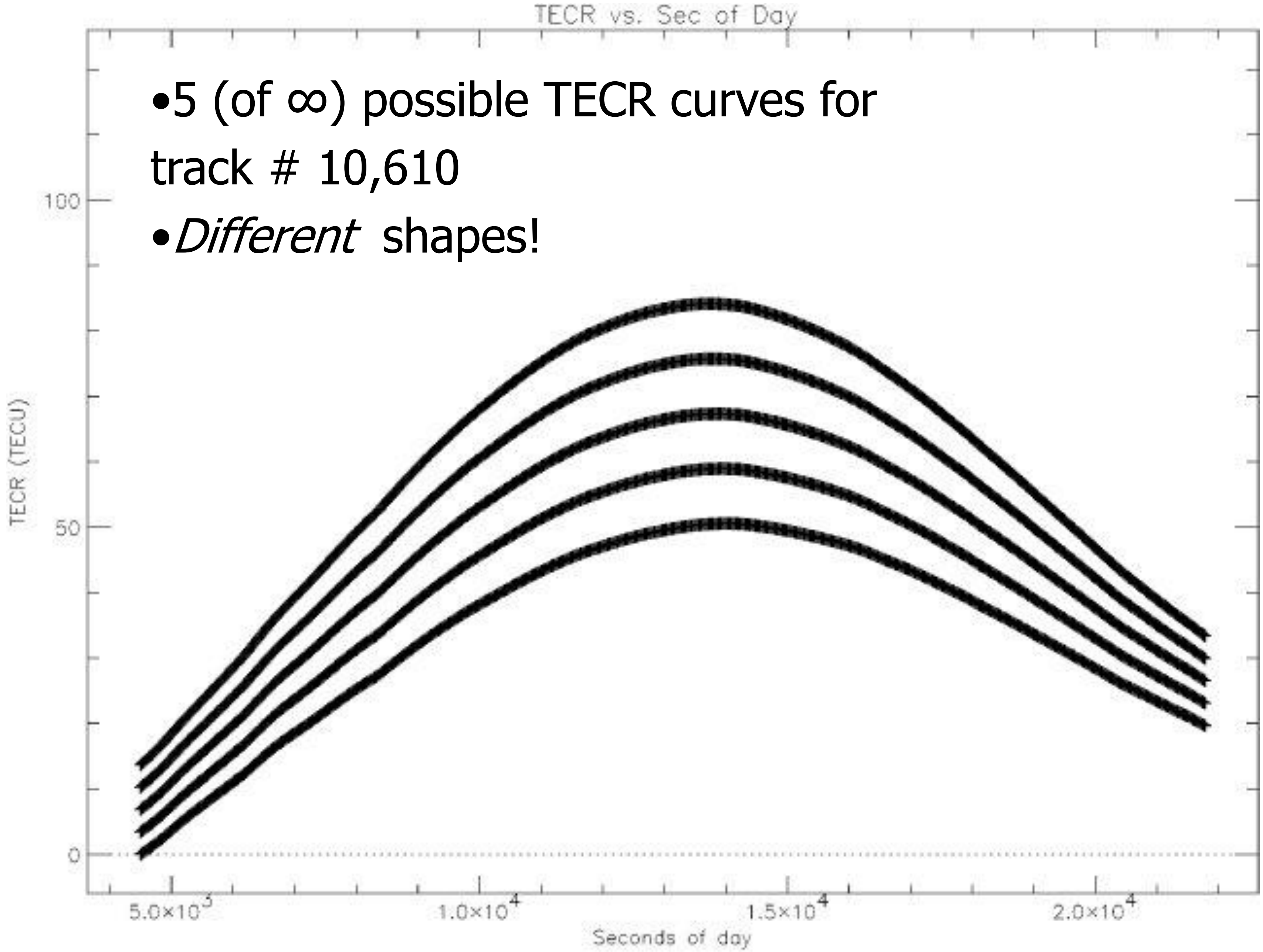
Track 10610 (CORS Station STB1 and GPS SV3)
50
45
40
35
Latitude
270
275
280
285
Longitude
30 second collection rate


Normal to
Ionosphere Shell
To GPS
Satellite
z'
Density of Electrons
in Sat/Rcvr direction
is TECS
Pierce
Point
Infinitesmally
thin
Ionosphere
shell
Density of Electrons
in direction normal
to Ionosphere Shell
is TECR
To GPS
Receiver


TECS vs. Sec of Day
TECS (TECU)
100
50
0
5.0×10^3
1.0×10^4
1.5×10^4
2.0×10^4
Seconds of day
•5 (of ∞) possible TECS curves for track # 10,610
•Same shape, unknown bias

•5 (of ∞) possible TECR curves for track # 10,610

•*Different* shapes!

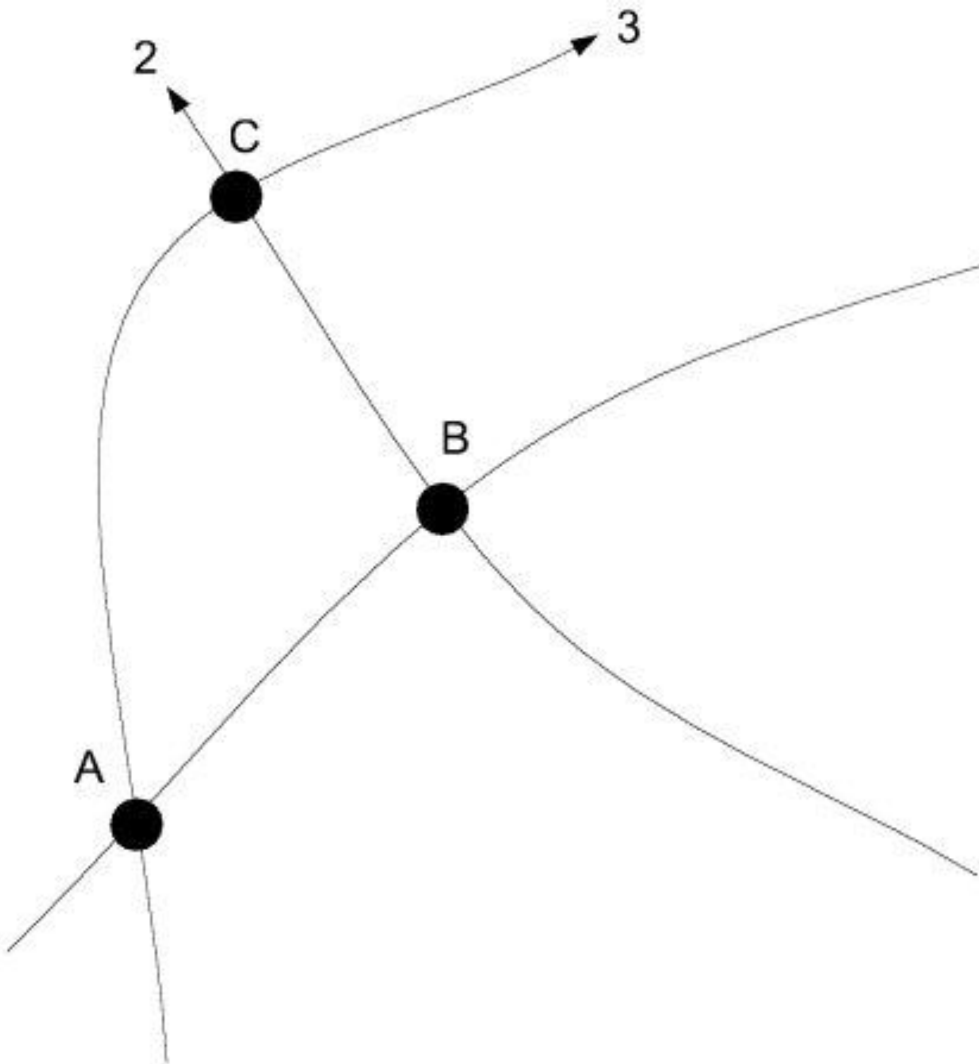


Solving for biases with crossovers

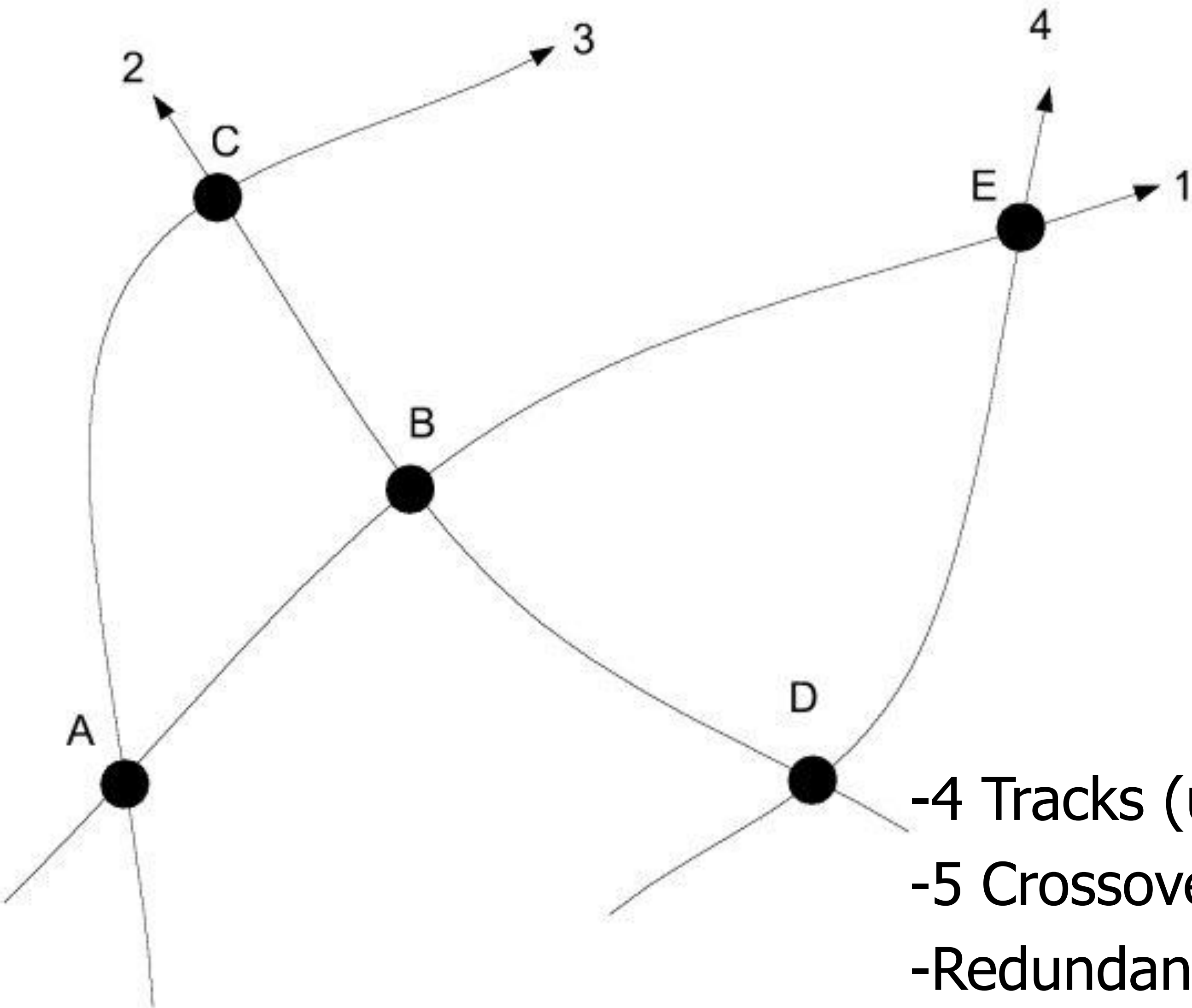
- Solve:
  - 1 TECS bias per track
- Consider two tracks that pierce the ionosphere at the same place, at the same time (i.e. a "crossover")
  - $TECS(\phi,\lambda,t,\text{track a}) \neq TECS(\phi,\lambda,t,\text{track b})$
  - $TECR(\phi,\lambda,t,\text{track a}) = TECR(\phi,\lambda,t,\text{track b})$

Using Crossovers

- By itself, one crossover has:
  - 1 condition (TECR equality)
  - 2 unknowns (TECS biases for 2 tracks)
  - Thus, unsolvable as is
- Need conditions ≥ unknowns
- Closed polygons is the solution



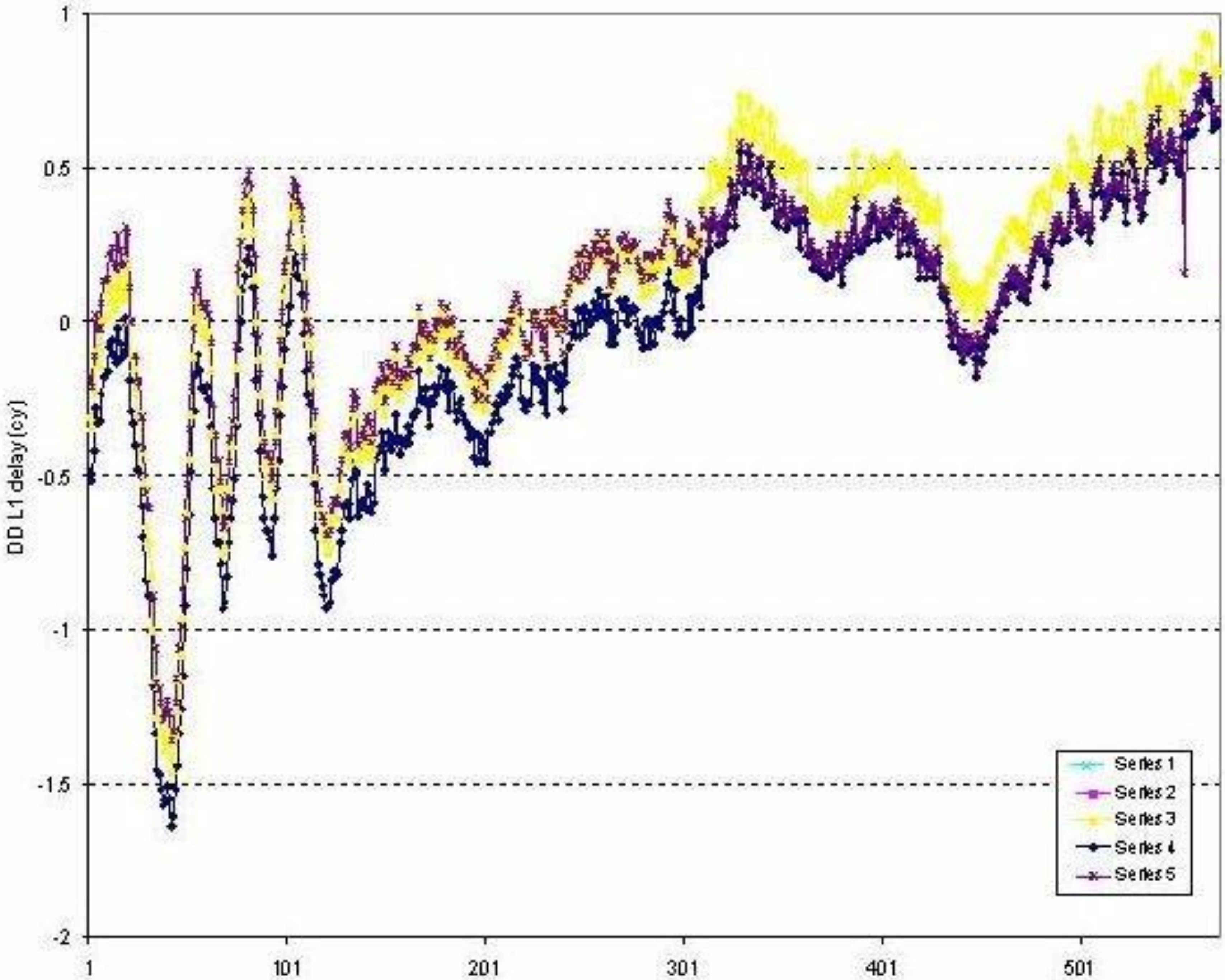
- 3 Tracks
- Crossovers A,B,C occur in sequential order
- Not as rare as it looks
- Forms a “closed polygon” of tracks
- *Uniquely* solvable in *absolute* TECS space



-4 Tracks (unknowns)
-5 Crossovers (conditions)
-Redundancy = Least Squares
Adjustment in *absolute* TECS space

Initial Tests

- Small “tracknets” of 10-12 tracks formed
- Proof-of-concept
- Absolute delays converted to double difference delays
- DD delays good to 0.1   0.01 TECUs against “truth” (Ambiguity resolving software)



DD L1 delay (cy)
1
0.5
0
-0.5
-1
-1.5
-2
1
101
201
301
401
501
Series 1
Series 2
Series 3
Series 4
Series 5

Full day solution

- Day 193 (July 12) of 2002
- 307 CORS stations
- 16,896 Crossovers (conditions)
- 8298 Tracks (unknowns)

Full day solution

- Unzip/read hundreds of RINEX.gz files
  - 2 hours
- Clean 11 Million data pts (cycle slips, etc)
  - 30 min
- Solve 8298 x 16896 sparse linear system
  - 30 seconds to get 8298 biases
  - 10 minutes to get σ_{bias}

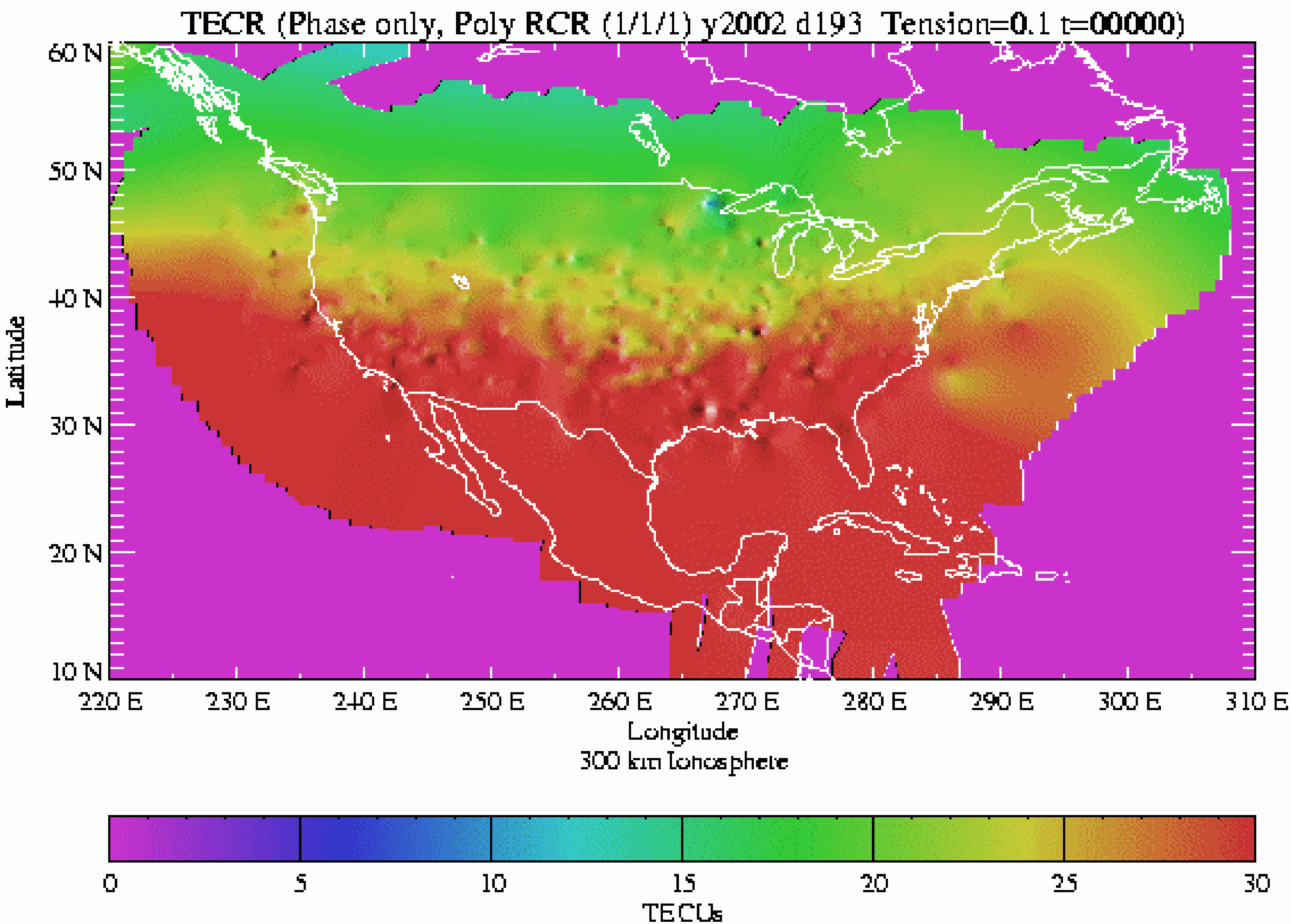
Full day solution (cont)

- Post Fit Crossover stats (TECUs)
  - -0.004   0.51 (Min -3.7; Max +4.0)

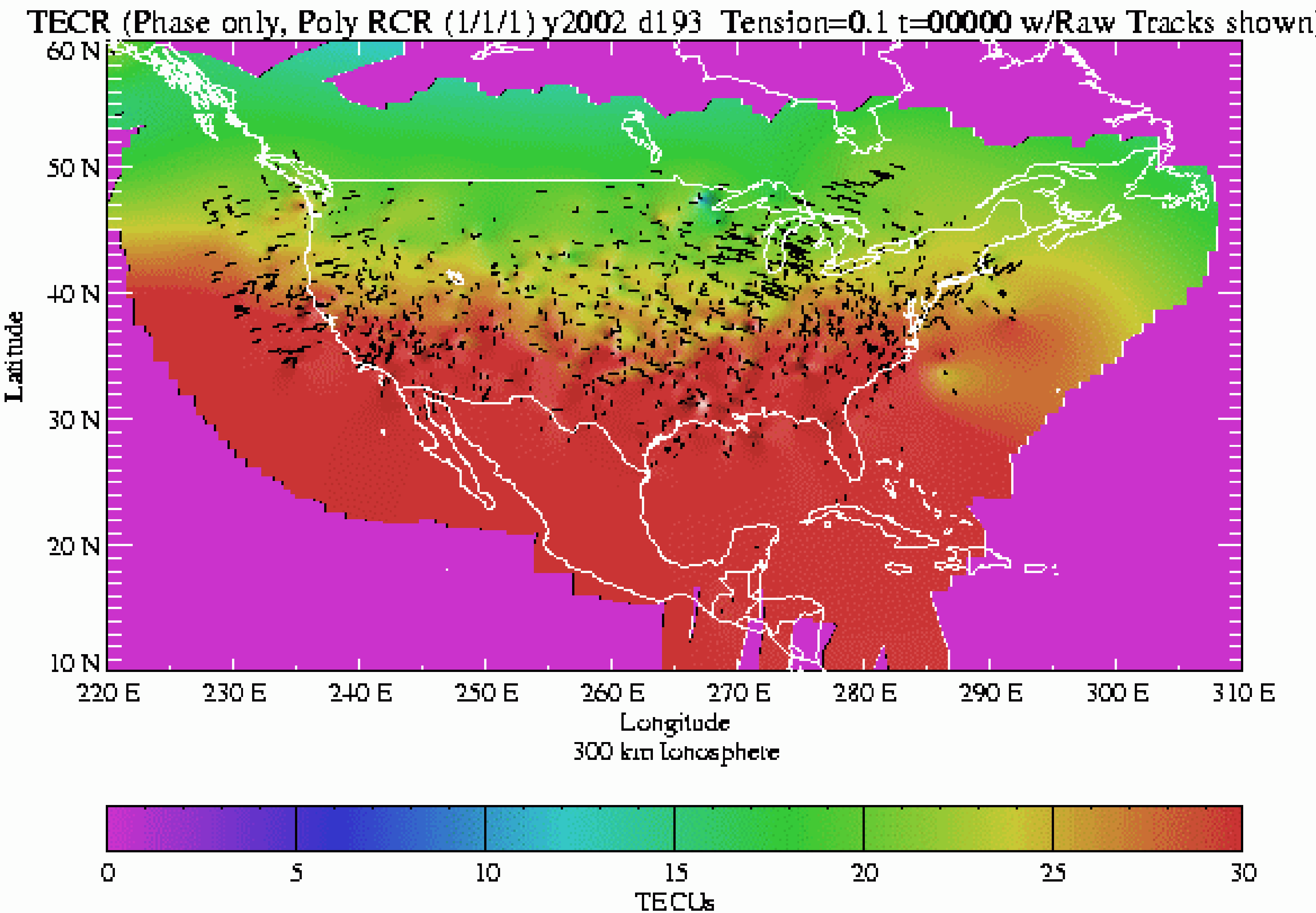
- A-posteriori σ_{bias} estimates:
  - Ave(σ_{bias}) =   1.1 TECU (Min 0.22, Max 10.7)

Full day solution Animations

- Animation without tracks
  - gif
  - avi
- Animation with tracks
  - gif
  - avi



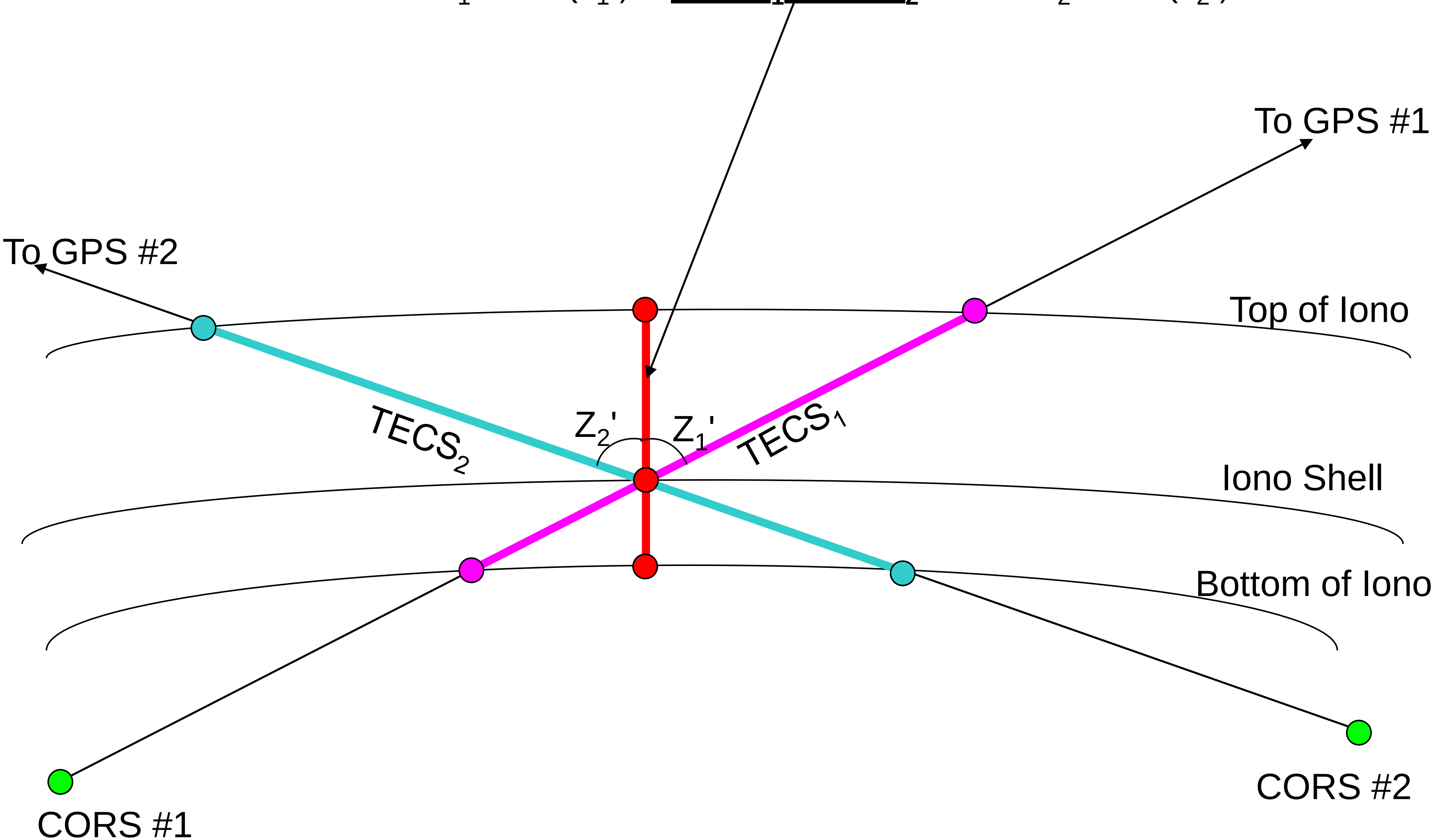
TECR (Phase only, Poly RCR (1/1/1) y2002 d193 Tension=0.1 t=00000)
60 N
50 N
40 N
30 N
20 N
10 N
Latitude
220 E
230 E
240 E
250 E
260 E
270 E
280 E
290 E
300 E
310 E
Longitude
300 km Ionosphere
0
5
10
15
20
25
30
TECUs


TECR (Phase only, Poly RCR (1/1/1) y2002 d193 Tension=0.1 t=00000 w/Raw Tracks shown)
60 N
50 N
40 N
30 N
20 N
10 N
Latitude
220 E
230 E
240 E
250 E
260 E
270 E
280 E
290 E
300 E
310 E
Longitude
300 km Ionosphere
0
5
10
15
20
25
30
TECUs

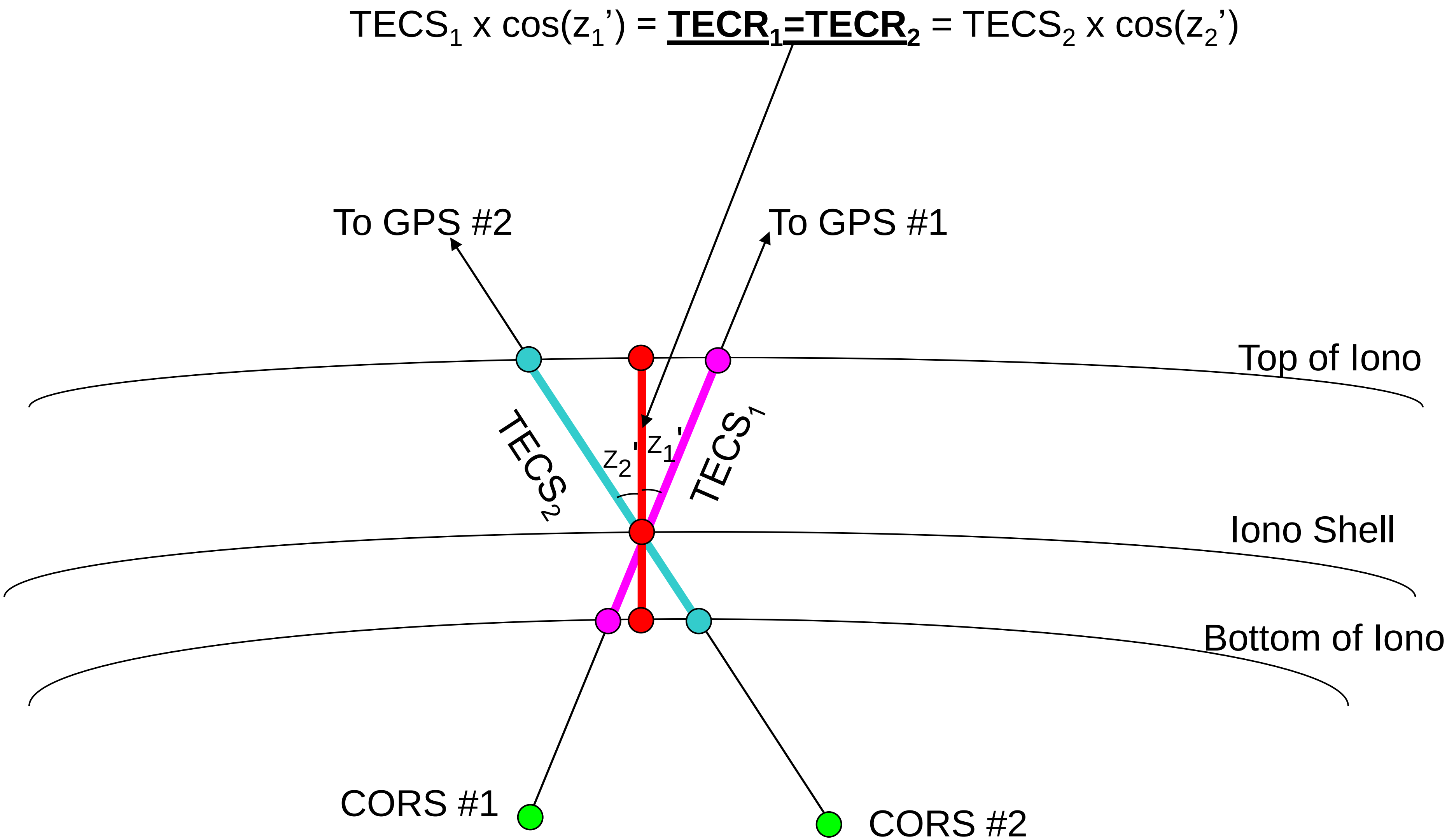
Full day solution (cont)

- Average a-posteriori σ_{bias} of 1.1 TECU reasonable, but larger than hoped for
- Sub-TECU crossover residuals show tight "locking" or consistency of tracknet
- Overall noise in grids needs improvement
- General conclusion:
  - "Promising" but not by any means "done"
  - Initial analysis indicates **<u>near-horizon crossovers are the primary error source</u>** (TECS=TECR/cos z' unreliable)

$TECS_1 \times \cos(z_1') = \underline{\mathbf{TECR_1 = TECR_2}} = TECS_2 \times \cos(z_2')$



“Large” z’ makes the TECR equality questionable



"Small" z' makes the TECR equality more reliable

Latest Results

- Ohio State University compared various Ionosphere estimates at Ohio CORS stations
- Crossovers restricted to 40 degrees above the horizon
  - Avoids erroneous biases from low-elevation crossovers
  - Reduces number of tracks immediately solvable from tracknets (unsolved tracks need interpolation from nearby solved tracks)

Report for NOAA/NGS

On:

Accuracy analysis of various NGS ionosphere estimation models

Dorota Grejner-Brzezinska, Pawel Wielgosz, Israel Kashani

Department Of Civil & Environmental Engineering & Geodetic Science
The Ohio State University
470 Hitchcock Hall, 2070 Neil Avenue, Columbus, OH 43210
Tel: 614-292-0169;   Fax: 614-292-2957
Email: dbrzezinska@osu.edu
Email: kashani.1@osu.edu
Email: wielgosz.1@osu.edu

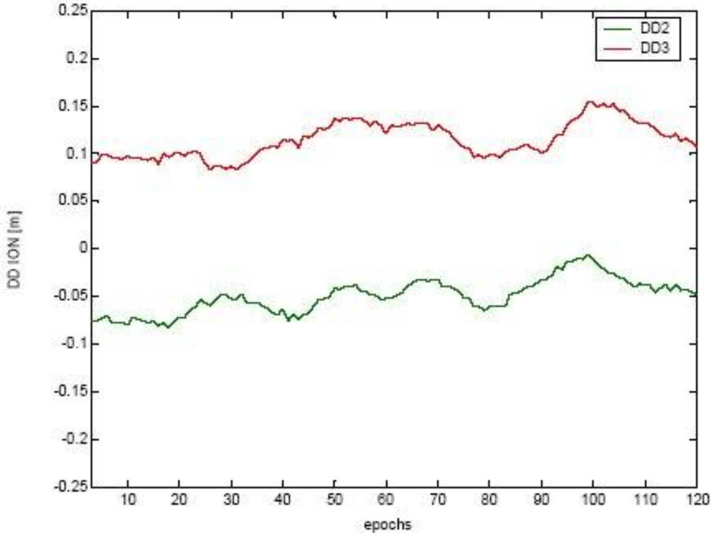


Fig. 22 NGSa DD iono (day-time)

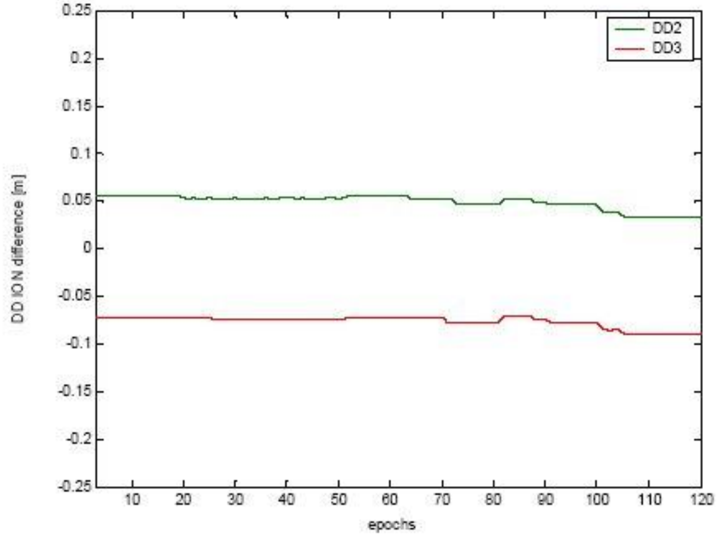


Fig. 23 NGSa DD iono differences from the "truth" (day-time)

This model

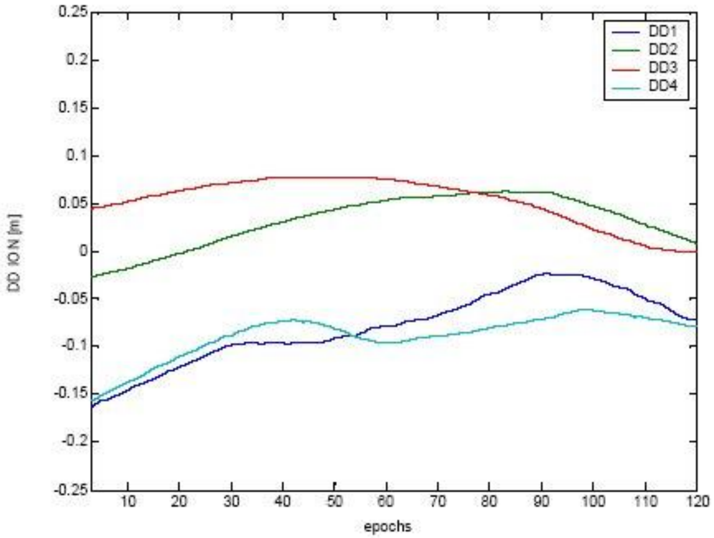


Fig. 24 NGSb DD iono (day-time)

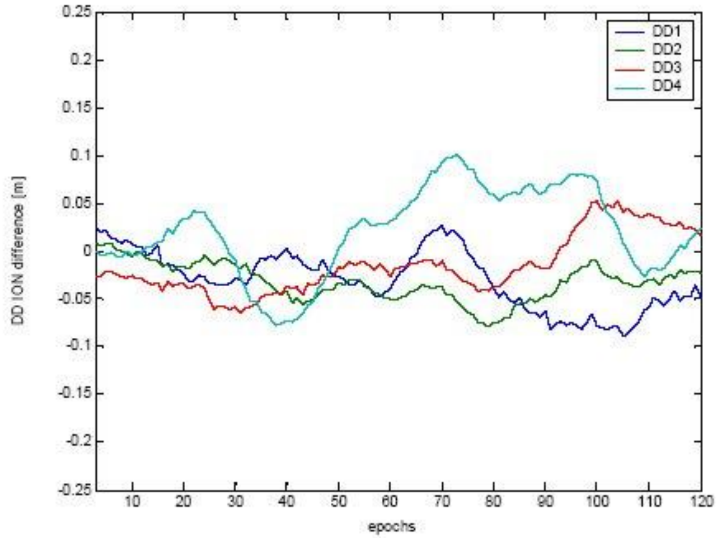


Fig. 25 NGSb DD iono differences from the "truth" (day-time)

NOAA's "Magic" model

Summary and Conclusions

- With certain assumptions, a model for the ionosphere can be computed as an entire network
  - to ~1 TECU (absolute)
  - to ~0.3 0.06 TECU (5 cm   1 mm on L1) agreement with Double Difference estimates, subject to cycle-slip fixing
- Interpolation can yield   5 cm (L1) biases from nearby tracks

Summary and Conclusions (cont)

- Further sensitivity studies:
  - Removing near-horizon crossovers (nearly done)
  - Shell height
  - CORS thinning
- Independent tests forthcoming:
  - Against other ionosphere models
  - In ambiguity resolving software
- Production:
  - Daily solutions expected to begin in Fall 2004

```
     2.10           OBSERVATION DATA    G (GPS)             RINEX VERSION / TYPE
teqc  2000Jul20     CORS-ADM Account    20040108 05:18:03UTCPGM / RUN BY / DATE
dqua                                                        MARKER NAME
xxx                                                         MARKER NUMBER
CORS/NGS/NOAA       OAR/FSL                                 OBSERVER / AGENCY
3735A20424          TRIMBLE   4000SSI   7.19                REC # / TYPE / VERS
3328A68603          TRM14532.00                             ANT # / TYPE
  -395445.7142 -5271710.3365  3556709.0313                  APPROX POSITION XYZ
        0.0000        0.0000        0.0000                  ANTENNA: DELTA H/E/N
     1     1                                                WAVELENGTH FACT L1/2
     8    C1    L1    L2    P1    P2    D1    D2    I1      # / TYPES OF OBSERV
    30.0000                                                 INTERVAL
Forced Modulo Decimation to 30 seconds                      COMMENT
  2004     1     7     0     0    0.0000000     GPS         TIME OF FIRST OBS
This is an IINEX file, not strictly RINEX.                  COMMENT
The difference is that an I1 variable, representing         COMMENT
the computed Ionosphere delay on L1, in cycles of L1,       COMMENT
has been introduced.  This value should generally           COMMENT
always be positive.                                         COMMENT
I1 was computed by Dru Smith, NOAA/NGS with the following   COMMENT
parameters (see D. Smith for details):                      COMMENT
Year = 2004 Day of Year = 007                               COMMENT
Shell Height (km) = 0300                                    COMMENT
Track Cleaning Criteria Index     : 001                     COMMENT
Crossover Spacing Criteria Index  : 001                     COMMENT
Tracknet Formation Criteria Index : 009                     COMMENT
LSA Weighting Scheme Index        : 004                     COMMENT
Flag for post-LSA interpolation   : 000                     COMMENT
                                                            END OF HEADER
 04  1  7  0  0  0.0000000  0  9G 5G13G24G 6G17G10G 4G30G29  0  0  0 0.000000000
  21696356.31340  10363943.65748   8142514.00747         0.00000  21696361.84440
     -4100.07840         0.00000      15.799
  25107871.38340   3708841.58542   2259556.02945         0.00000  25107875.26240
     -3307.67240         0.00000  -99999.000
  21512358.68840  18328193.84048  14366529.97347         0.00000  21512363.50440
     -3686.29740         0.00000  -99999.000
  23862591.76640  -1725935.55946  -1150692.59045         0.00000  23862597.87140
       706.65640         0.00000      24.278
  21126131.32040   3655026.98748   2892249.13247         0.00000  21126136.67640
     -1809.82840         0.00000       9.850
  20301784.44540  -5022796.20048  -3846505.25347         0.00000  20301789.52040
     -1548.39140         0.00000  -99999.000
  24034690.15640  41863677.08547  32692773.82046         0.00000  24034694.44540
     -4906.23440         0.00000  -99999.000
  21762273.85940   -282123.29347   -147989.82246         0.00000  21762278.34840
     -1713.00040         0.00000      16.644
  24560456.50840    -45620.85743         0.00000         0.00000         0.00000
       704.09440         0.00000  -99999.000
```

Contact Information

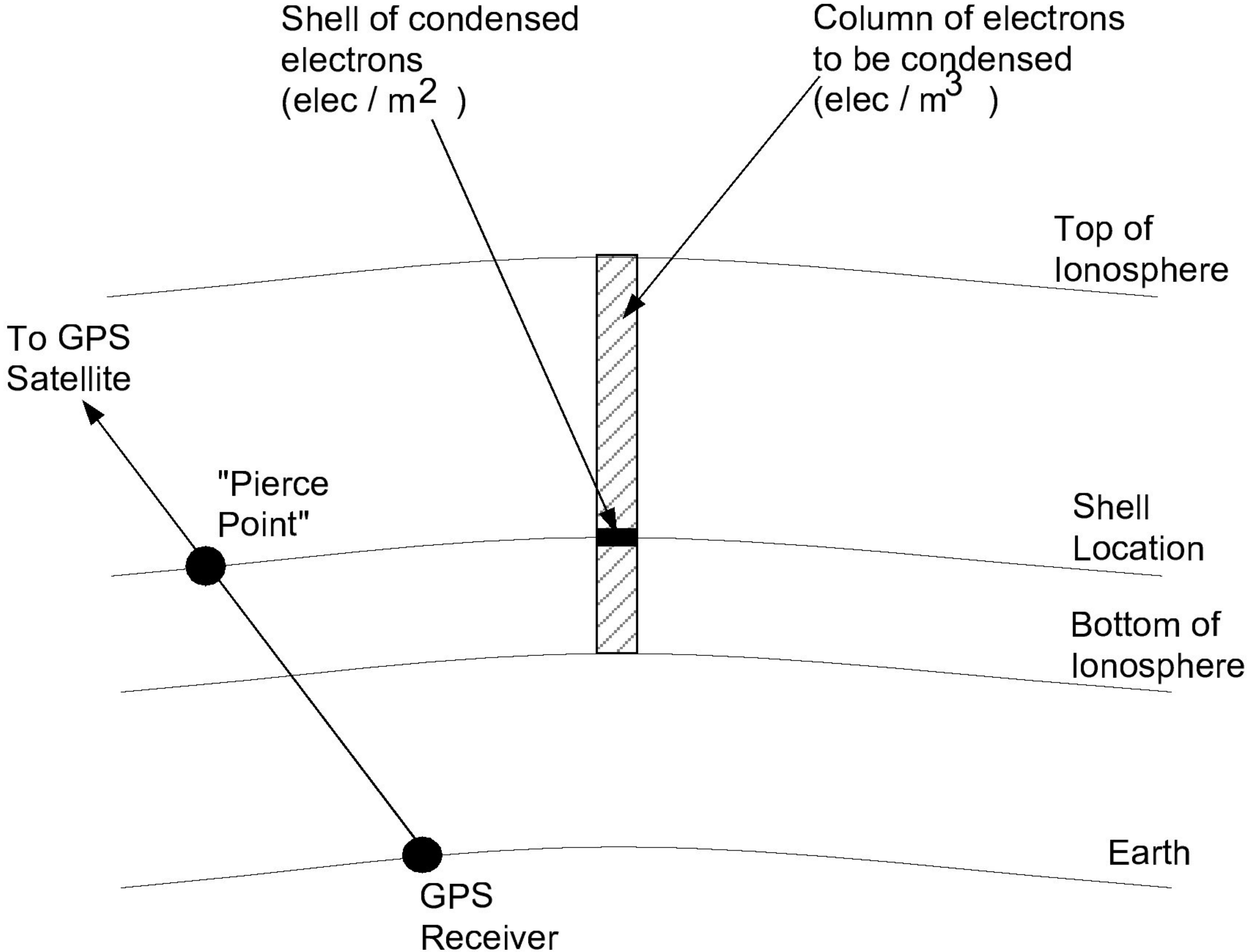
- Dr. Dru A. Smith
- 301-713-3202 x 149
- Fax: 301-713-4172
- Dru.Smith@noaa.gov

Questions?

Extra Slides

CORS Network

- ***Currently 400+ 24/7 receivers***
  - Dual frequency, carrier-phase
  - Multi-agency
  - Administered by NGS
  - All 50 states, Central America, others
  - *Ideally suited to serve as an ionosphere monitoring network for geodetic applications in the USA*



Shell of condensed electrons (elec / m2)
Column of electrons to be condensed (elec / m3)
Top of Ionosphere
To GPS Satellite
"Pierce Point"
Shell Location
Bottom of Ionosphere
Earth
GPS Receiver

Pierce Points and Tracks

- A pierce point occurs at ionosphere shell for each data epoch
- Mapping pierce points without loss of lock yields a track
- CORS yields about 20,000 tracks every day

TECS and TECR

- TECS is the TEC value seen in the satellite-receiver direction
- TECR is the vertical TEC value at the shell
  - TECS = TECR / cos z’
    - Questionable usefulness at low elevation angles

Equations

$$^{i}R_k = b_k + {}^{i}r + c({}^{i}\delta t) + {}^{i}T + {}^{i}I_k\,(+{}^{i}m_k) = \lambda_k\, {}^{i}\Phi_k^{\mathrm{RINEX}} \qquad \text{(biased range, m, epoch "i", freq "k")}$$

$$I_k = -\frac{40.3}{f_k^2} TECS \qquad \text{(m)}$$

$$\therefore \quad \lambda_1\, {}^{i}\Phi_1^{\mathrm{RINEX}} - \lambda_2\, {}^{i}\Phi_2^{\mathrm{RINEX}} = (b_1 - b_2) + ({}^{i}I_1 - {}^{i}I_2)$$

$$\therefore \quad {}^{i}TECS = \left(\frac{1}{40.3}\right)\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right)^{-1} \left[\lambda_1\, {}^{i}\Phi_1^{\mathrm{RINEX}} - \lambda_2\, {}^{i}\Phi_2^{\mathrm{RINEX}}\right]$$

$$- \left(\frac{1}{40.3}\right)\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right)^{-1} (b_1 - b_2)$$

$$\therefore \quad {}^{i,j}\Delta TECS = {}^{j}TECS - {}^{i}TECS$$

$$= \left(\frac{1}{40.3}\right)\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right)^{-1} \left(\lambda_1\, {}^{i,j}\Delta\Phi_1^{\mathrm{RINEX}} - \lambda_2\, {}^{i,j}\Delta\Phi_2^{\mathrm{RINEX}}\right)$$

Implications of Equations

- Knowing ΔTECS:
  - Shape of "TECS vs time" curve known
  - Absolute level unknown
- Single, unknown bias per "track"

$\Delta TECR$ vs $\Delta TECS$

$${}^{i}TECS = {}^{i}TECR / \cos {}^{i}z'$$

$${}^{i,j}\Delta TECR = {}^{j}TECR - {}^{i}TECR$$

$$\therefore \quad {}^{i,j}\Delta TECR = {}^{i,j}\Delta TECS \cos {}^{j}z' + {}^{i}TECS \left(\cos {}^{j}z' - \cos {}^{i}z'\right)$$

Implications

- Epoch-dependent cos z' in TECR:
  - Shape of "TECR vs time" curve is *unknown*
  - Absolute level unknown

Closed Polygons

- Altimetry or Leveling (ΔH & H-equality):
  - # conditions = # vertices – 1
- Ionosphere (ΔTECS & TECR-equality)
  - # conditions = # vertices
- Any time that a closed polygon is formed on the ionosphere "shell" we have:
  - # Conditions = # Unknowns

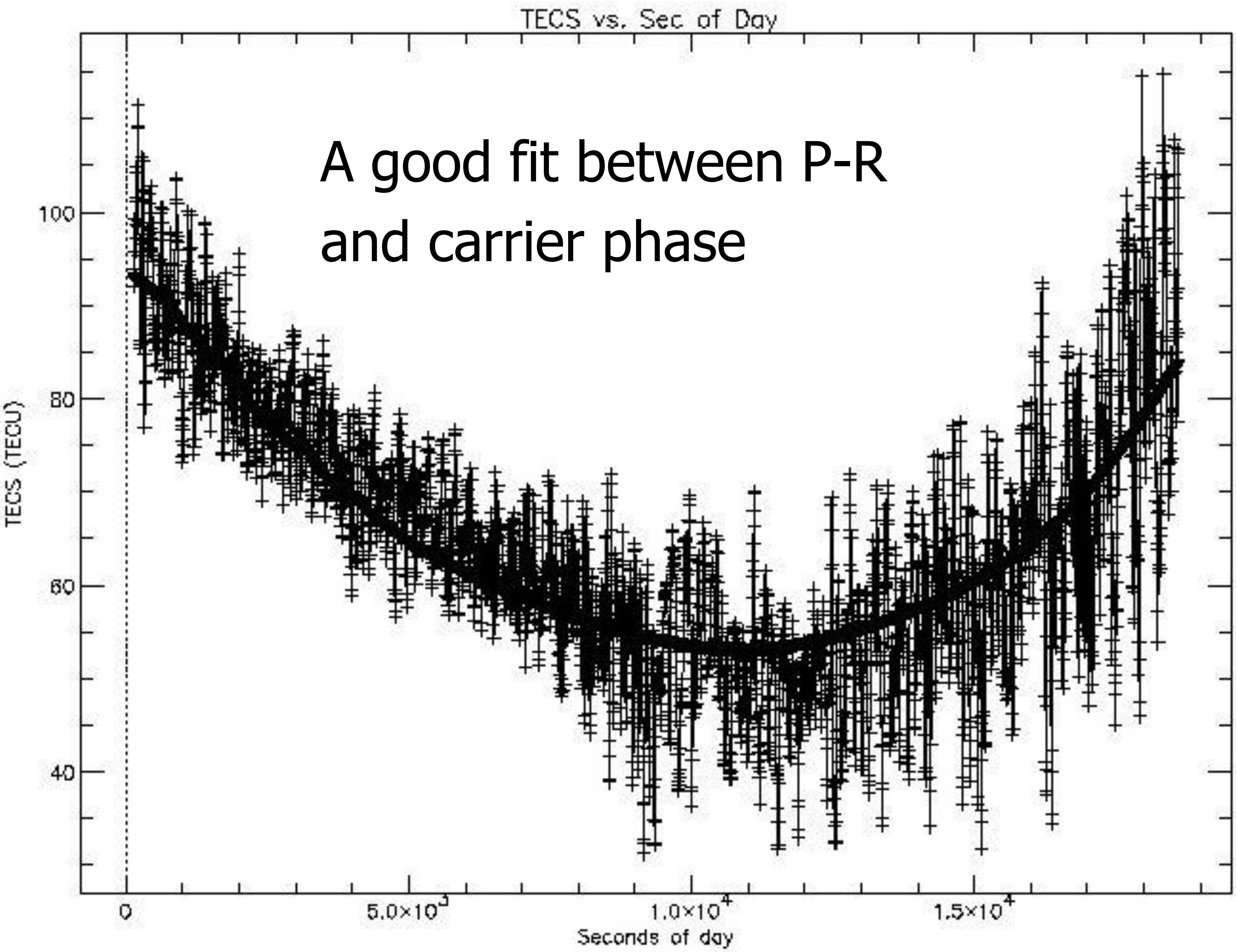
Polygon Crossover Equations

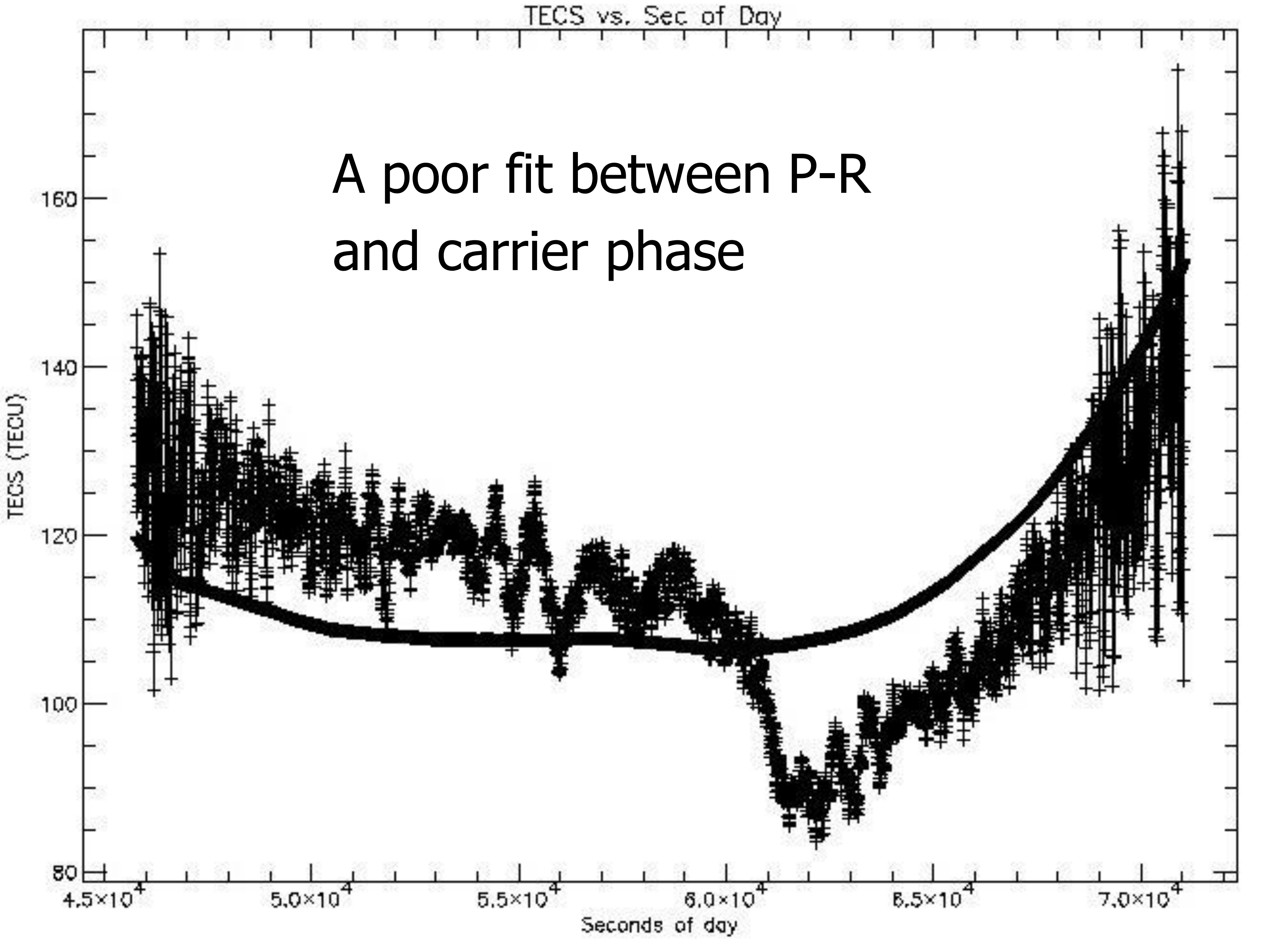
$$\begin{bmatrix} {}^{A}_{1}\Delta TECS \cos {}^{A}_{1}z' - {}^{A}_{3}\Delta TECS \cos {}^{A}_{3}z' \\ {}^{B}_{1}\Delta TECS \cos {}^{B}_{1}z' - {}^{B}_{2}\Delta TECS \cos {}^{B}_{2}z' \\ {}^{C}_{2}\Delta TECS \cos {}^{C}_{2}z' - {}^{C}_{3}\Delta TECS \cos {}^{C}_{3}z' \end{bmatrix}$$

$$= \begin{bmatrix} -\cos {}^{A}_{1}z' & 0 & +\cos {}^{A}_{3}z' \\ -\cos {}^{B}_{1}z' & +\cos {}^{B}_{2}z' & 0 \\ 0 & -\cos {}^{C}_{2}z' & +\cos {}^{C}_{3}z' \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}$$

Polygon Crossover Equations

- The existence of the cos z' values on the RHS allows for matrix inversion
  - (as opposed to +1,0 and -1 for altimetry)
- Solvability
- Can we have redundancy?
  - YES


TECS vs. Sec of Day
A good fit between P-R
and carrier phase
TECS (TECU)
100
80
60
40
0
5.0×10^3
1.0×10^4
1.5×10^4
Seconds of day



TECS vs. Sec of Day
A poor fit between P-R
and carrier phase
TECS (TECU)
160
140
120
100
80
4.5×10^4
5.0×10^4
5.5×10^4
6.0×10^4
6.5×10^4
7.0×10^4
Seconds of day

Initial Tests

- Parameters:
  - Shell height = 300 km
  - Crossover definition: 0.1 x 0.1 x 1 min
  - Cut-off angle: 10 (for data and crossovers)

Initial Tests (all contain the 4 base tracks)

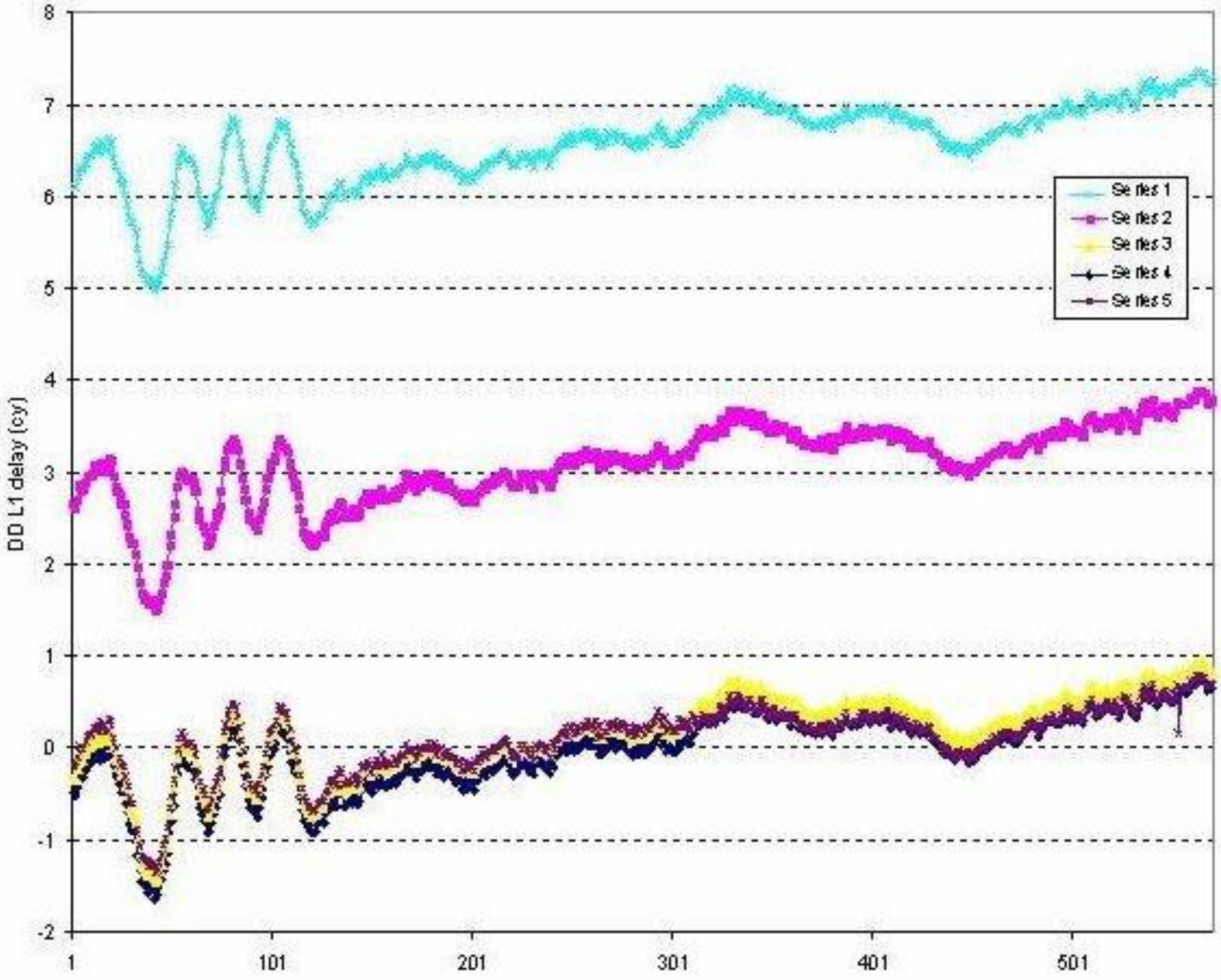
- Solution 1 (smallest tracknet possible containing the 4 base tracks)
  - 8 tracks, No polygons, PR-fit 6 of 8 tracks
- Solution 2
  - 10 tracks, 2 polygons, PR-fit 7 of 10 tracks
- Solution 3
  - 10 tracks, 2 polygons, no PR-fitting
- Solution 4
  - 10 tracks, 2 polygons, PR-fit 1 of 10 tracks

Formal σ_{bias} estimates for first tracknet tests (in TECU)

Track #	Soln 1 (PR fit to 6 of 8; no polygons)	Soln 2 (PR fit to 7 of 10; 2 polygons)	Soln 3 (No PR fit; 2 polygons)	Soln 4 (PR fit to 1 of 10; 2 polygons)
4300 (base)	3.5	2.9	0.1	1.2
4303 (base)	8.8	4.7	0.2	2.1
9484 (base)	9.3	4.6	0.2	2.0
9487 (base)	9.4	3.1	0.1	1.3
2253	13.6	5.9	0.3	2.5
10146	9.7	3.3	0.1	1.4
11416	6.5	4.9	0.2	2.0
12565	6.1	3.9	0.2	1.6
2224	-	4.3	0.2	1.7
11580	-	3.0	0.1	1.2

Initial Tests (cont)

- Individual ionosphere delays for each SV/CORS combo were estimated:
  - I_{4300}(SV1/GODE), I_{4303}(SV2/GODE), I_{9484}(SV1/RED1), I_{9487}(SV2/RED1) all estimated individually (as well as for all other tracks in the tracknet)
- Double Difference delays were then computed:
  - $I_{DD}=(I_{4300}-I_{9484})-(I_{4303}-I_{9487})$ computed and compared to independent estimates from NGS ambiguity resolving software



8
7
6
5
4
3
2
1
0
-1
-2
DD L1 delay (cy)
1
101
201
301
401
501
Series 1
Series 2
Series 3
Series 4
Series 5

First tracknet tests

- Pseudo-range fitting tends to bias the tracknet
- Better fit to Double Difference estimated ionosphere by using just polygons and no P-R fitting

Full day solution (cont)

- Interpolation from tracks to grids and/or other tracks:
  - Track-to-grid-to-Track
    - Useful for grid-distributed Ionosphere model and animations
    - 0.00   0.38 TECU (6 cm on L1)
  - Track-to-Track
    - Useful for RINEX-distributed Ionosphere model
    - 0.00   0.25 TECU (5 cm on L1)

- Full day solution was gridded and animated

Example 2. 17:00-18:00 UT (day-time)

The “truth” DD ionospheric delays are presented in figure 14 with the corresponding satellite elevation map in figure 15. Figures 16–25 represents the derived DD ionosphere form each method and the difference from the “truth” (in pairs). The mean and standard deviation of the ionospheric residuals from the “truth” are shown in Table 2.

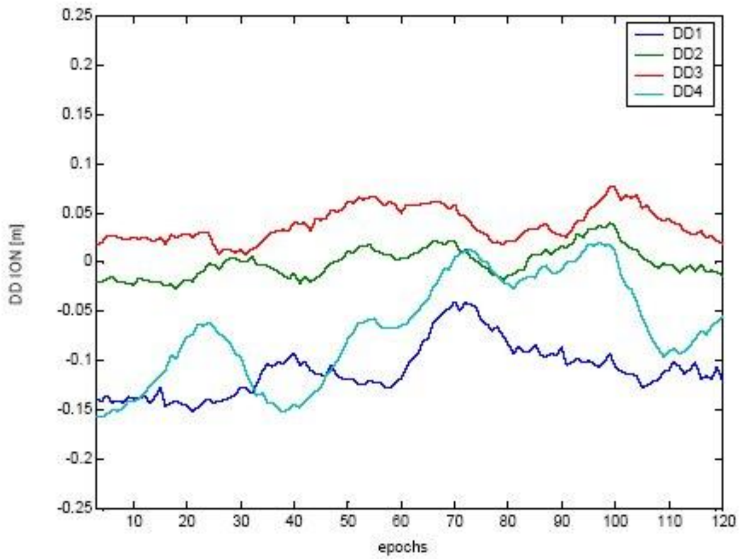


Fig. 14 “Truth” DD iono (day-time)

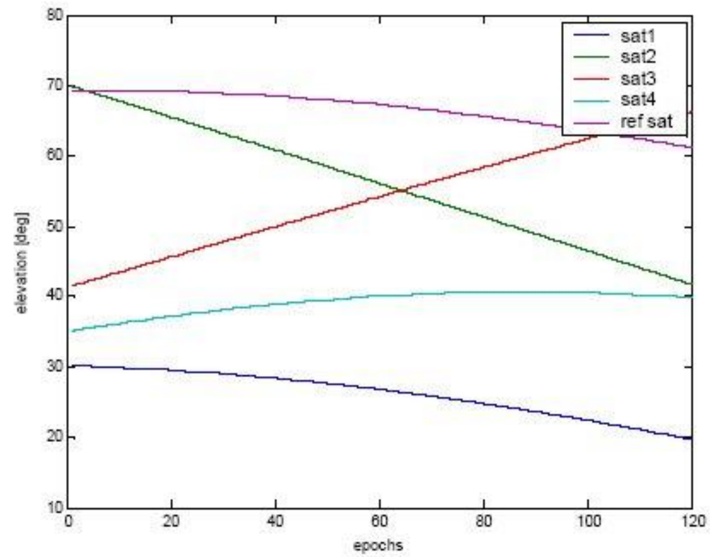


Fig. 15 Satellite elevations

“Truth” (Iono after ambiguity fixing)

Smith, D.A., Ionosphere from CORS, COSPAR 2004

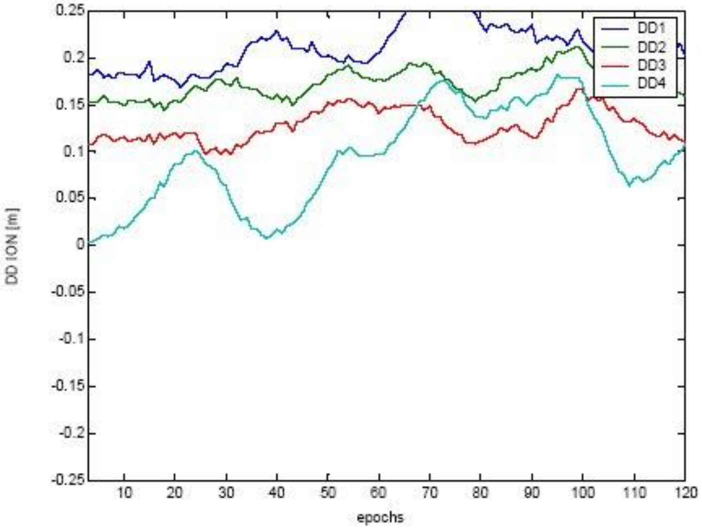


Fig. 16 P4 DD iono (day-time)

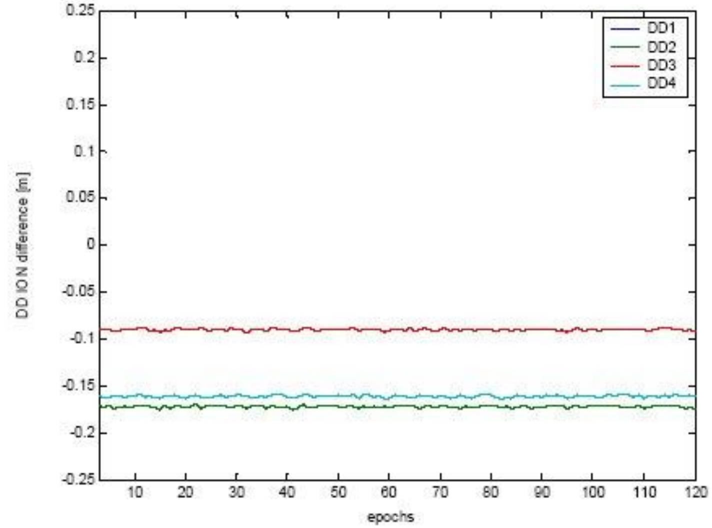


Fig. 17 P4 DD iono differences from the "truth" (day-time)

Smoothed Pseudorange Estimates

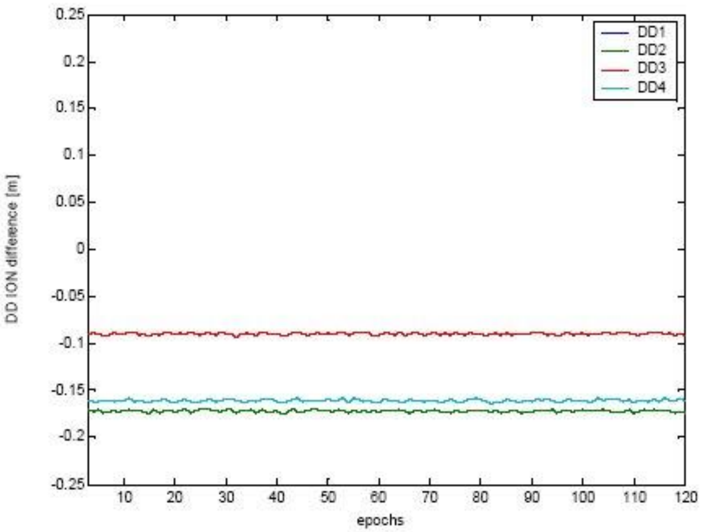


Fig. 18 GIM DD iono (day-time)

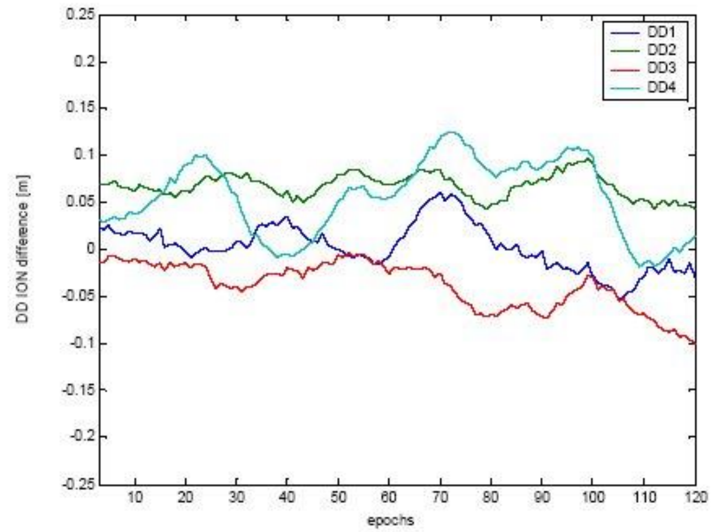
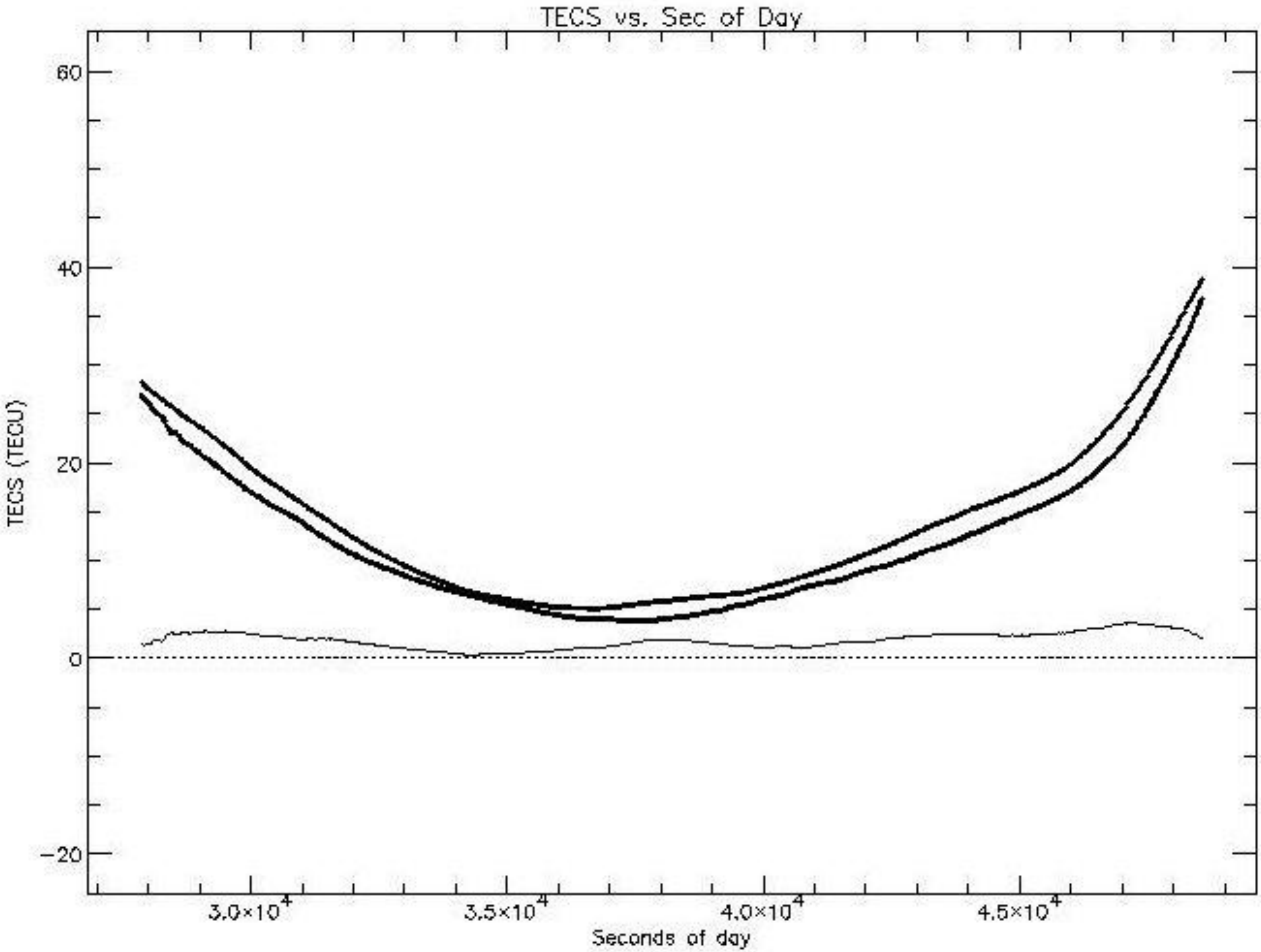
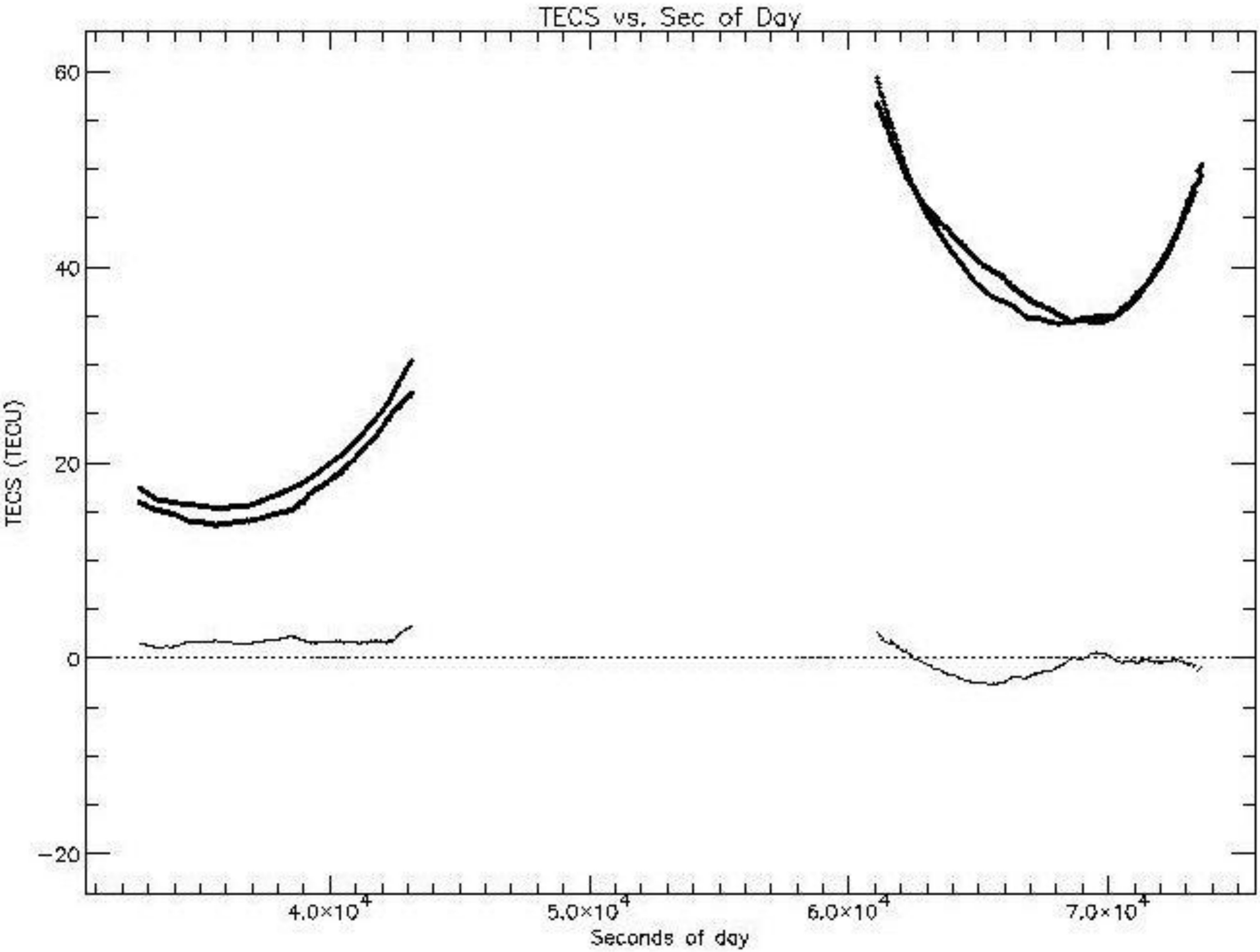


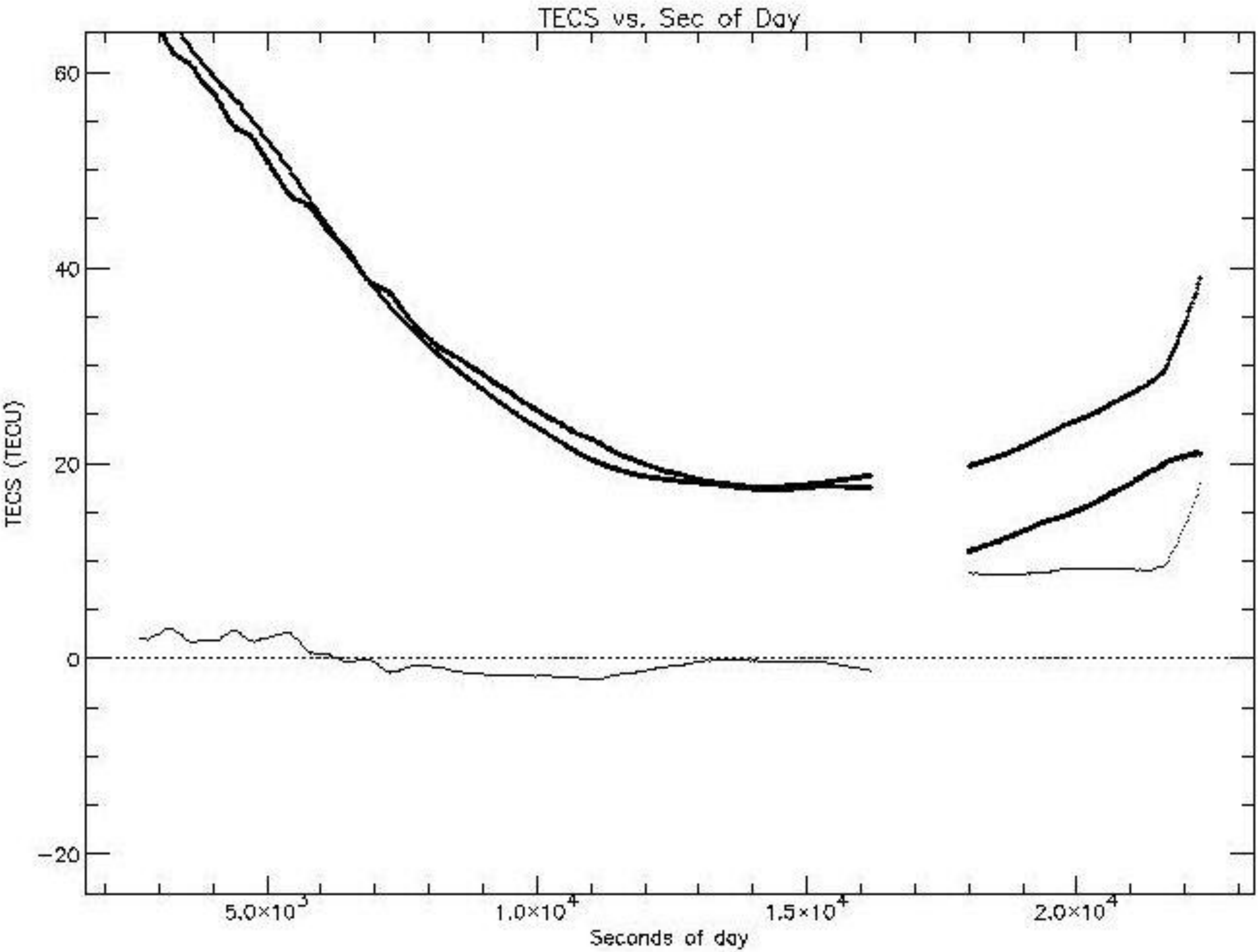
Fig. 19 GIM DD iono differences from the "truth" (day-time)

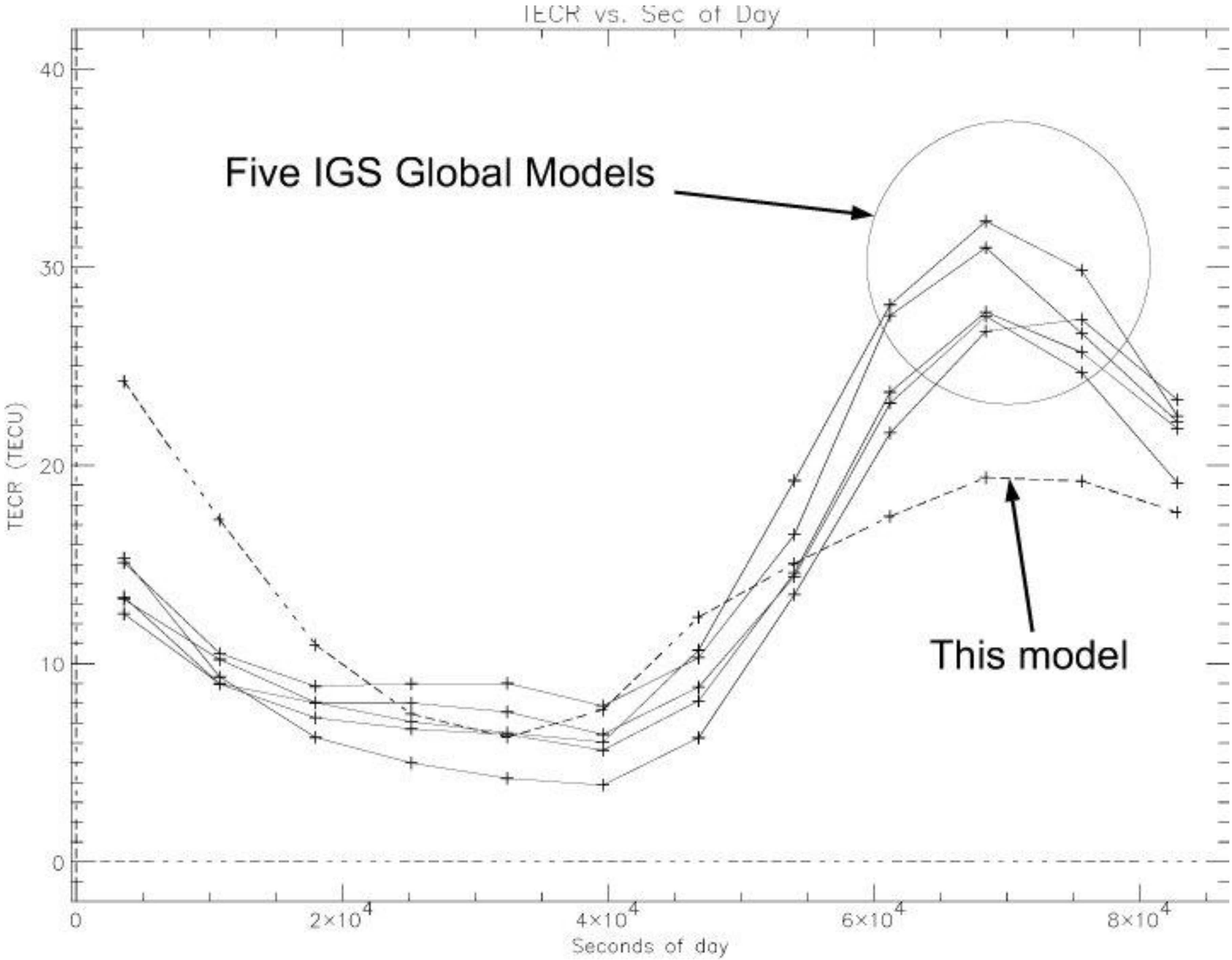
OSU's MPGPS method

```
     2.10           OBSERVATION DATA    G (GPS)             RINEX VERSION / TYPE
teqc  2000Jul20     CORS-ADM Account    20040108 05:18:03UTCPGM / RUN BY / DATE
dqua                                                        MARKER NAME
xxx                                                         MARKER NUMBER
CORS/NGS/NOAA       OAR/FSL                                 OBSERVER / AGENCY
3735A20424          TRIMBLE   4000SSI   7.19                REC # / TYPE / VERS
3328A68603          TRM14532.00                             ANT # / TYPE
  -395445.7142 -5271710.3365  3556709.0313                  APPROX POSITION XYZ
        0.0000        0.0000        0.0000                  ANTENNA: DELTA H/E/N
     1     1                                                WAVELENGTH FACT L1/2
     8    C1    L1    L2    P1    P2    D1    D2    I1      # / TYPES OF OBSERV
   30.0000                                                  INTERVAL
Forced Modulo Decimation to 30 seconds                      COMMENT
  2004     1     7     0     0    0.0000000     GPS         TIME OF FIRST OBS
This is an IINEX file, not strictly RINEX.                  COMMENT
The difference is that an I1 variable, representing         COMMENT
the computed Ionosphere delay on L1, in cycles of L1,       COMMENT
has been introduced.  This value should generally           COMMENT
always be positive.                                         COMMENT
I1 was computed by Dru Smith, NOAA/NGS with the following   COMMENT
parameters (see D. Smith for details):                      COMMENT
Year = 2004 Day of Year = 007                               COMMENT
Shell Height (km) = 0300                                    COMMENT
Track Cleaning Criteria Index     : 001                     COMMENT
Crossover Spacing Criteria Index  : 001                     COMMENT
Tracknet Formation Criteria Index : 009                     COMMENT
LSA Weighting Scheme Index        : 004                     COMMENT
Flag for post-LSA interpolation   : 000                     COMMENT
                                                            END OF HEADER
 04  1  7  0  0  0.0000000  0  9G 5G13G24G 6G17G10G 4G30G29  0  0  0 0.000000000
  21696356.31340  10363943.65748   8142514.00747         0.00000  21696361.84440
     -4100.07840         0.00000         15.799
  25107871.38340   3708841.58542   2259556.02945         0.00000  25107875.26240
     -3307.67240         0.00000     -99999.000
  21512358.68840  18328193.84048  14366529.97347         0.00000  21512363.50440
     -3686.29740         0.00000     -99999.000
  23862591.76640  -1725935.55946  -1150692.59045         0.00000  23862597.87140
       706.65640         0.00000         24.278
  21126131.32040   3655026.98748   2892249.13247         0.00000  21126136.67640
     -1809.82840         0.00000          9.850
  20301784.44540  -5022796.20048  -3846505.25347         0.00000  20301789.52040
     -1548.39140         0.00000     -99999.000
  24034690.15640  41863677.08547  32692773.82046         0.00000  24034694.44540
     -4906.23440         0.00000     -99999.000
  21762273.85940   -282123.29347   -147989.82246         0.00000  21762278.34840
     -1713.00040         0.00000         16.644
  24560456.50840    -45620.85743         0.00000         0.00000         0.00000
       704.09440         0.00000     -99999.000
```


TECS vs. Sec of Day
60
40
20
0
-20
TECS (TECU)
3.0×10^4
3.5×10^4
4.0×10^4
4.5×10^4
Seconds of day


TECS vs. Sec of Day
60
40
20
0
−20
TECS (TECU)
4.0×10^4
5.0×10^4
6.0×10^4
7.0×10^4
Seconds of day


TECS vs. Sec of Day
60
40
20
0
−20
TECS (TECU)
5.0×10^3
1.0×10^4
1.5×10^4
2.0×10^4
Seconds of day



TECR vs. Sec of Day
Five IGS Global Models
This model
TECR (TECU)
Seconds of day
0
10
20
30
40
0
2×10^4
4×10^4
6×10^4
8×10^4