The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2333-16

Workshop on Science Applications of GNSS in Developing Countries (11-27 April), followed by the: Seminar on Development and Use of the Ionospheric NeQuick Model (30 April-1 May)

11 April - 1 May, 2012

GNNS Remote Sensing: Electron Density Profiling through Radio Occultation

NAVA Bruno

Abdus Salam International Centre For Theoretical Physics
Telecommunications ICT for Development Laboratory
(T/ICT4D), Via Beirut 7
Trieste
ITALY

GNSS Remote Sensing: Electron Density Profiling through Radio Occultation

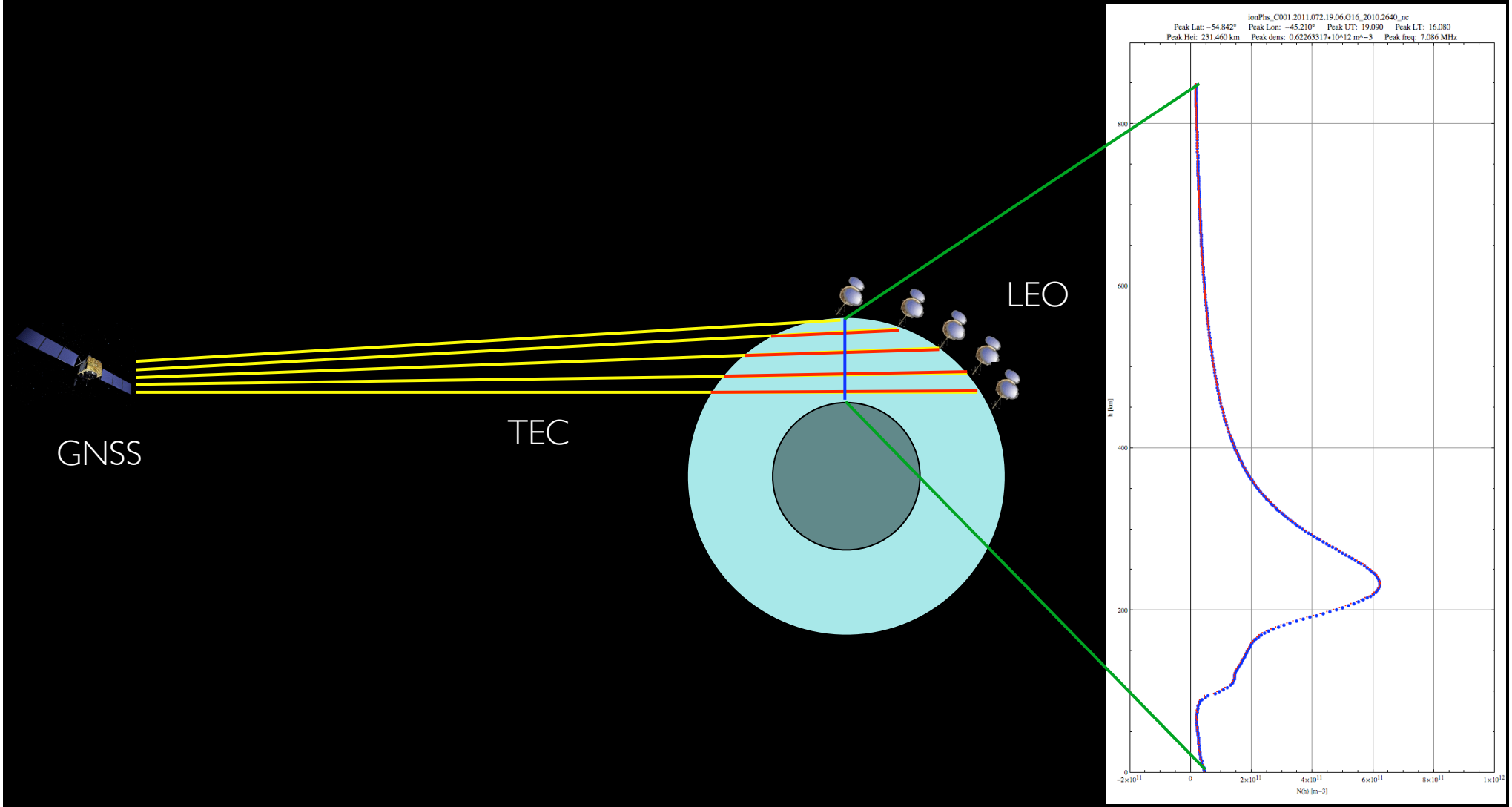
Bruno Nava
ICTP, Trieste, Italy

Workshop on Science Applications of GNSS in Developing Countries
Trieste, 11-27 April 2012

Outline

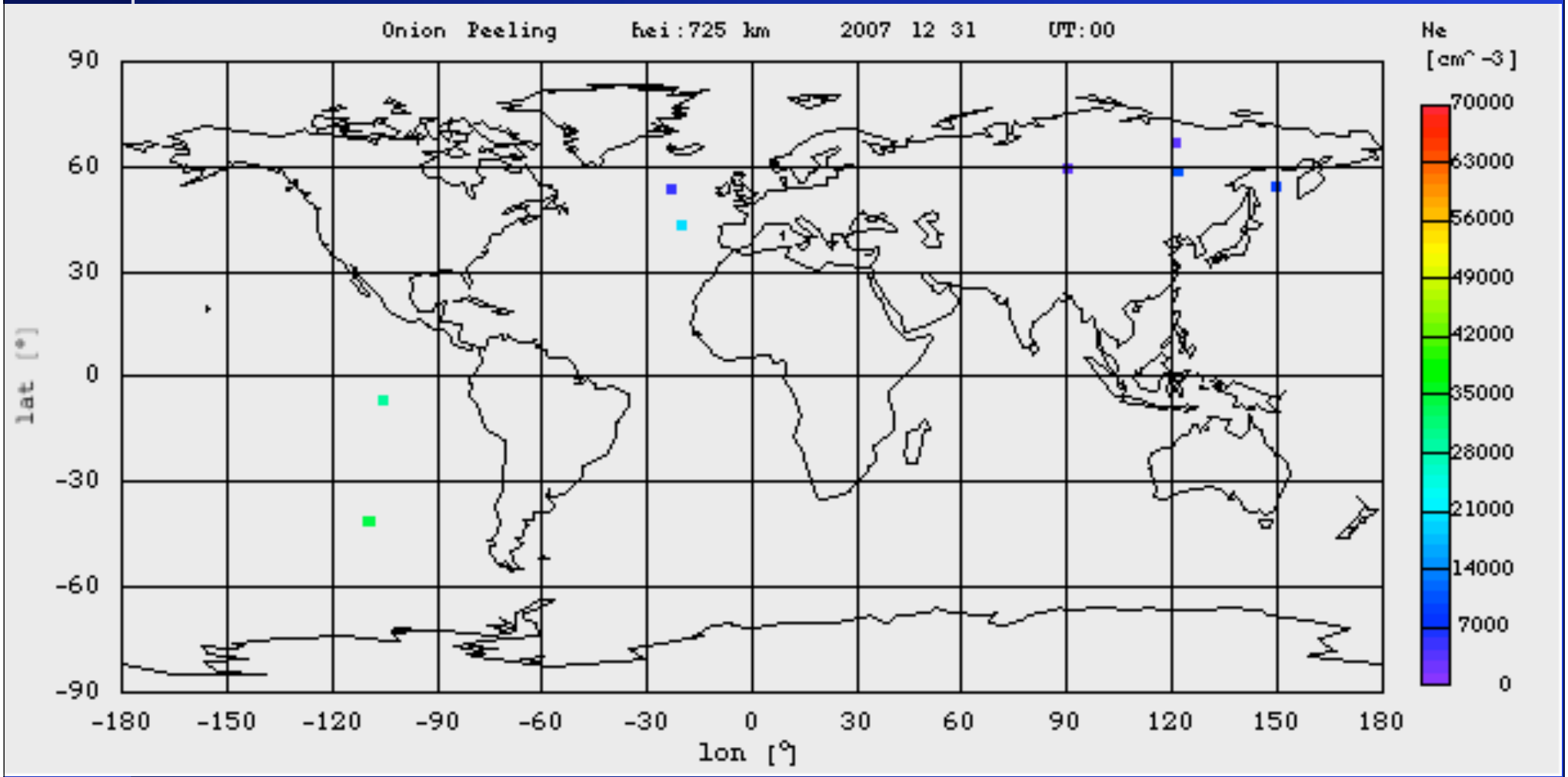
- RO data inversion
  - The Onion Peeling algorithm
    - TEC calibration
- The Onion Peeling algorithm validation
- Simulation results

GNSS RO data inversion



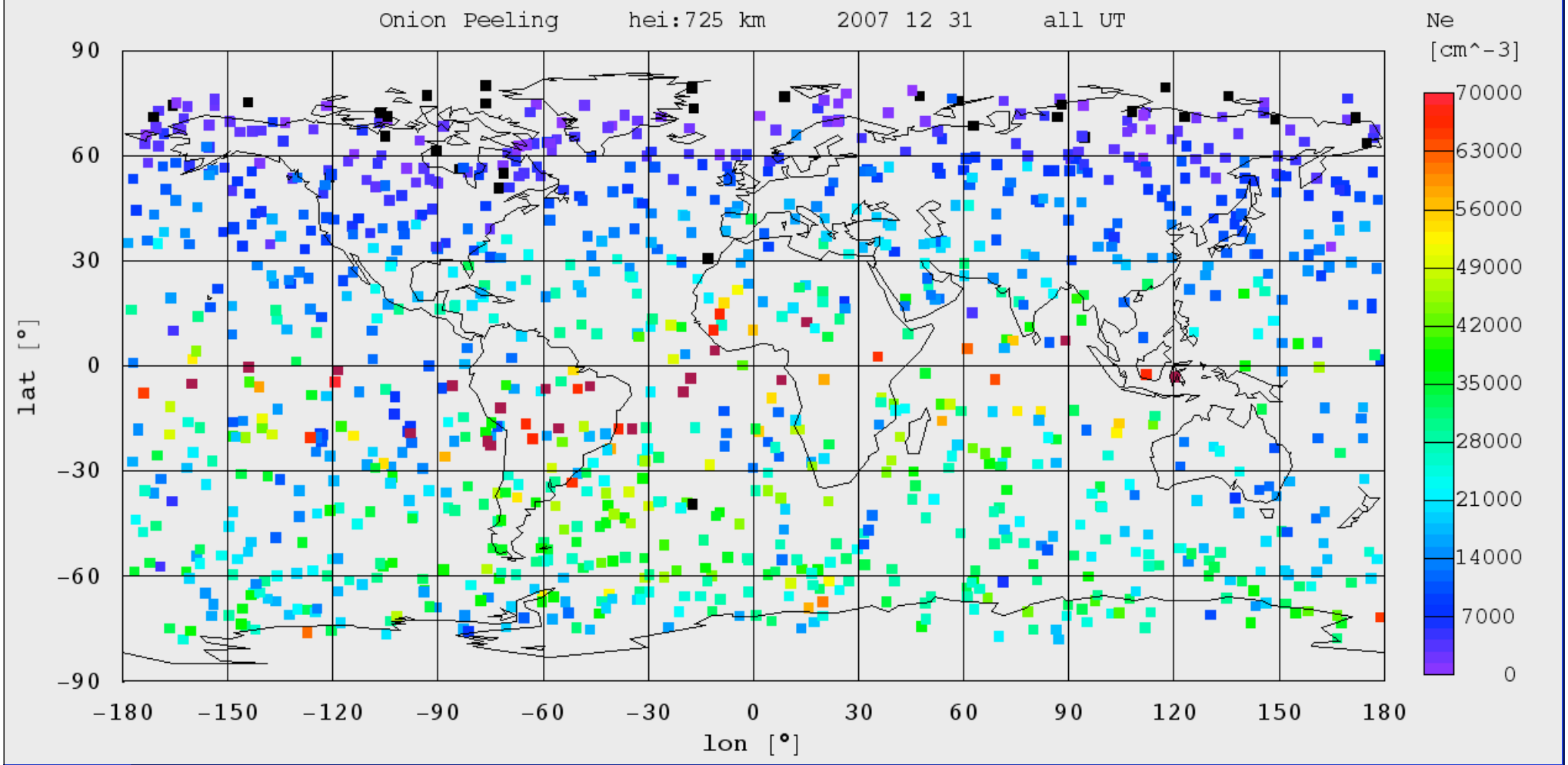
The importance of the RO data

RO derived Ne



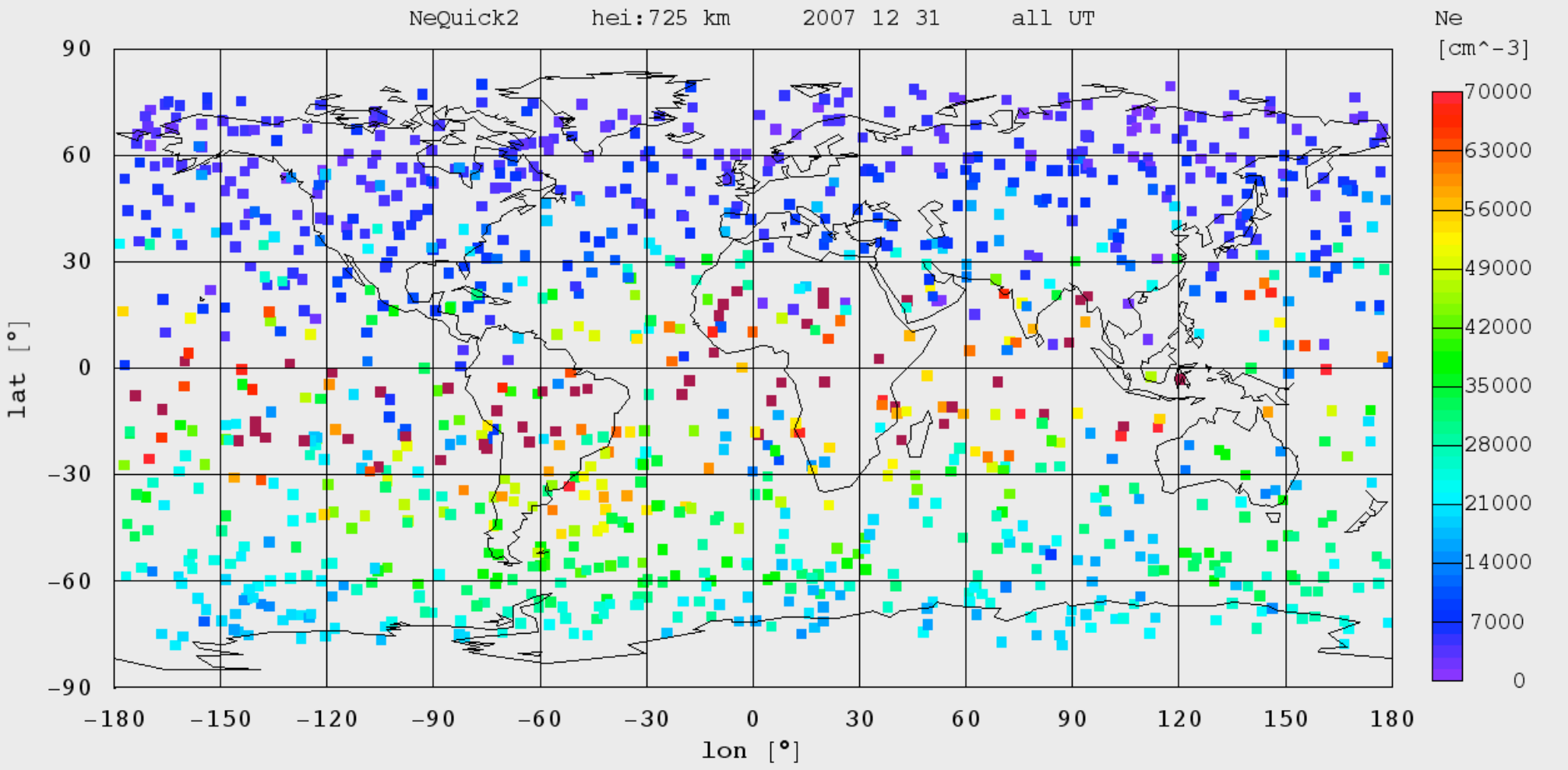
One hour RO data per frame

RO derived Ne



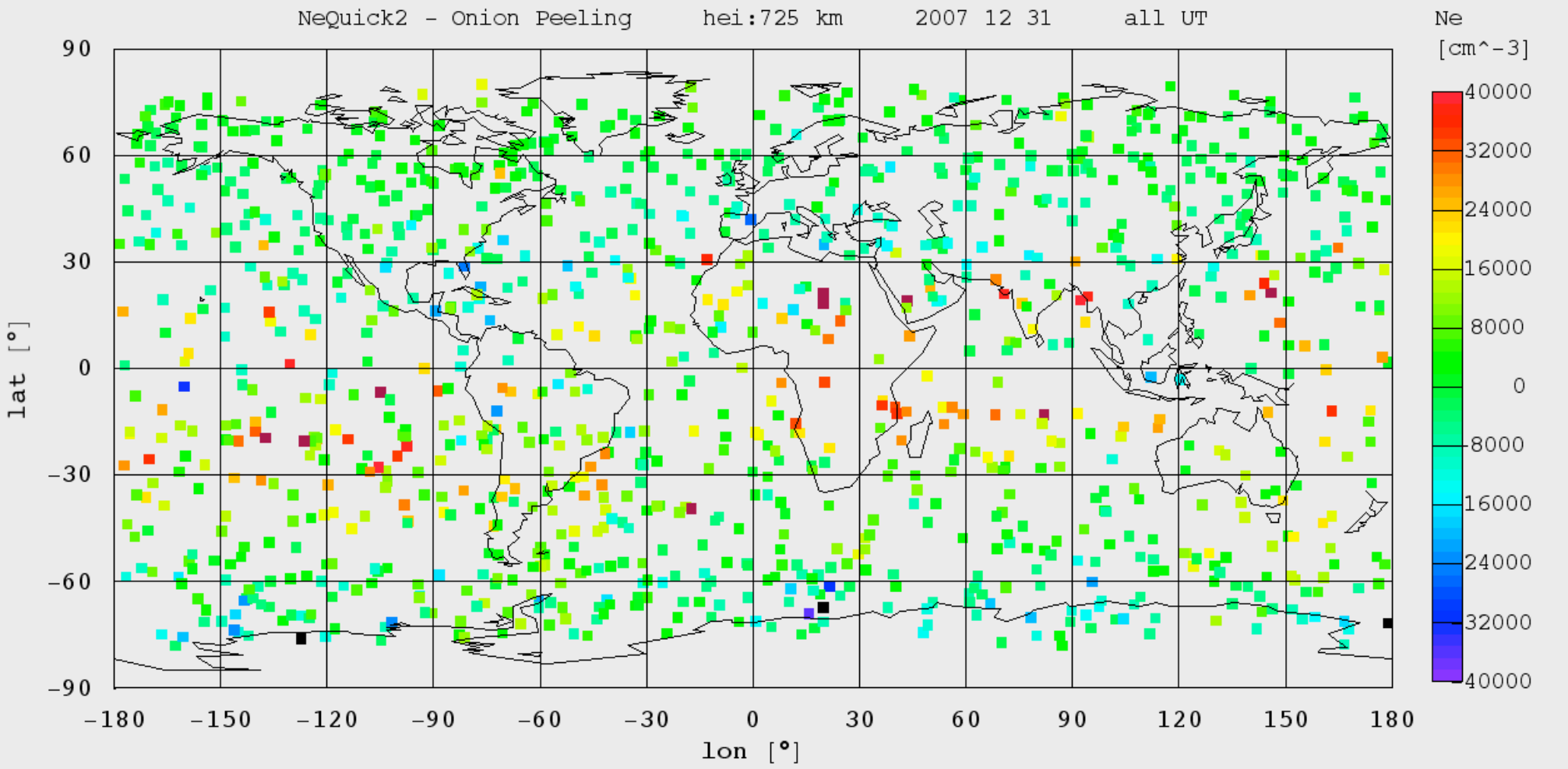
One day RO data (Onion Peeling)

RO derived Ne



One day RO data (NeQuick)

RO derived Ne difference

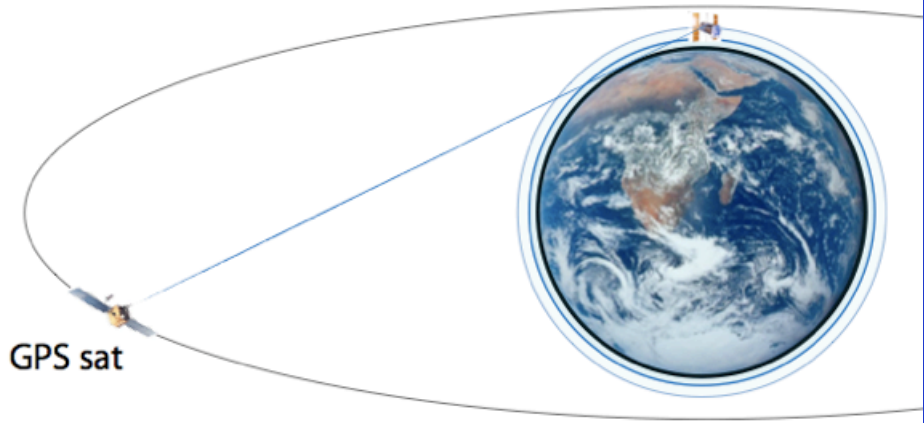


One day RO data (NeQuick - Onion Peeling)

The Onion Peeling algorithm

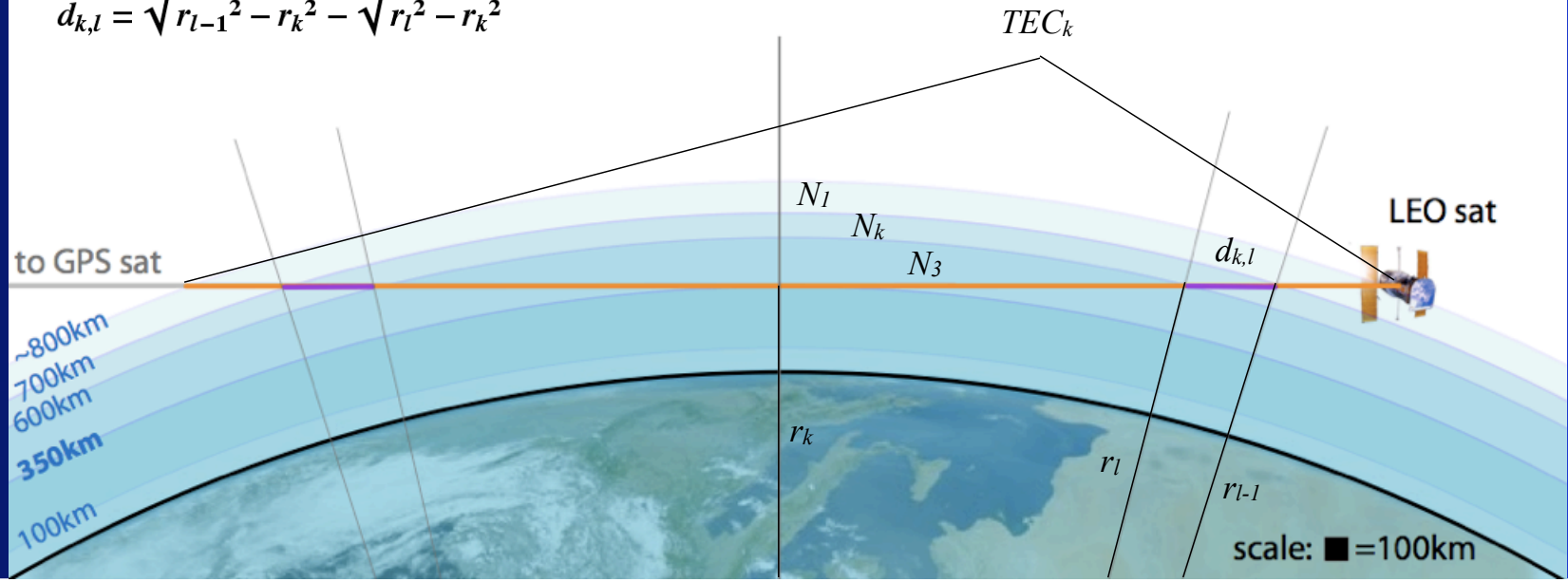
- The “Onion Peeling” algorithm is a procedure that permits to compute a vertical electron density profile if the slant TEC from a LEO to a GPS satellite are available for an occultation event.
- Since the ray bending in the ionosphere is small enough, the straight-line propagation from GPS to LEO satellites is assumed for the GPS signals.
- As required by the inversion technique adopted, the spherical symmetry for the electron density of the ionosphere has been assumed.
- To compute the (calibrated) TEC in the shell determined by the LEO orbit, excess phase measurements at L1 and L2 GPS frequencies during one occultation event are used: uncalibrated_TEC[TECU] = 9.52*(delayL1[m] - delayL2[m]).

The Onion Peeling algorithm

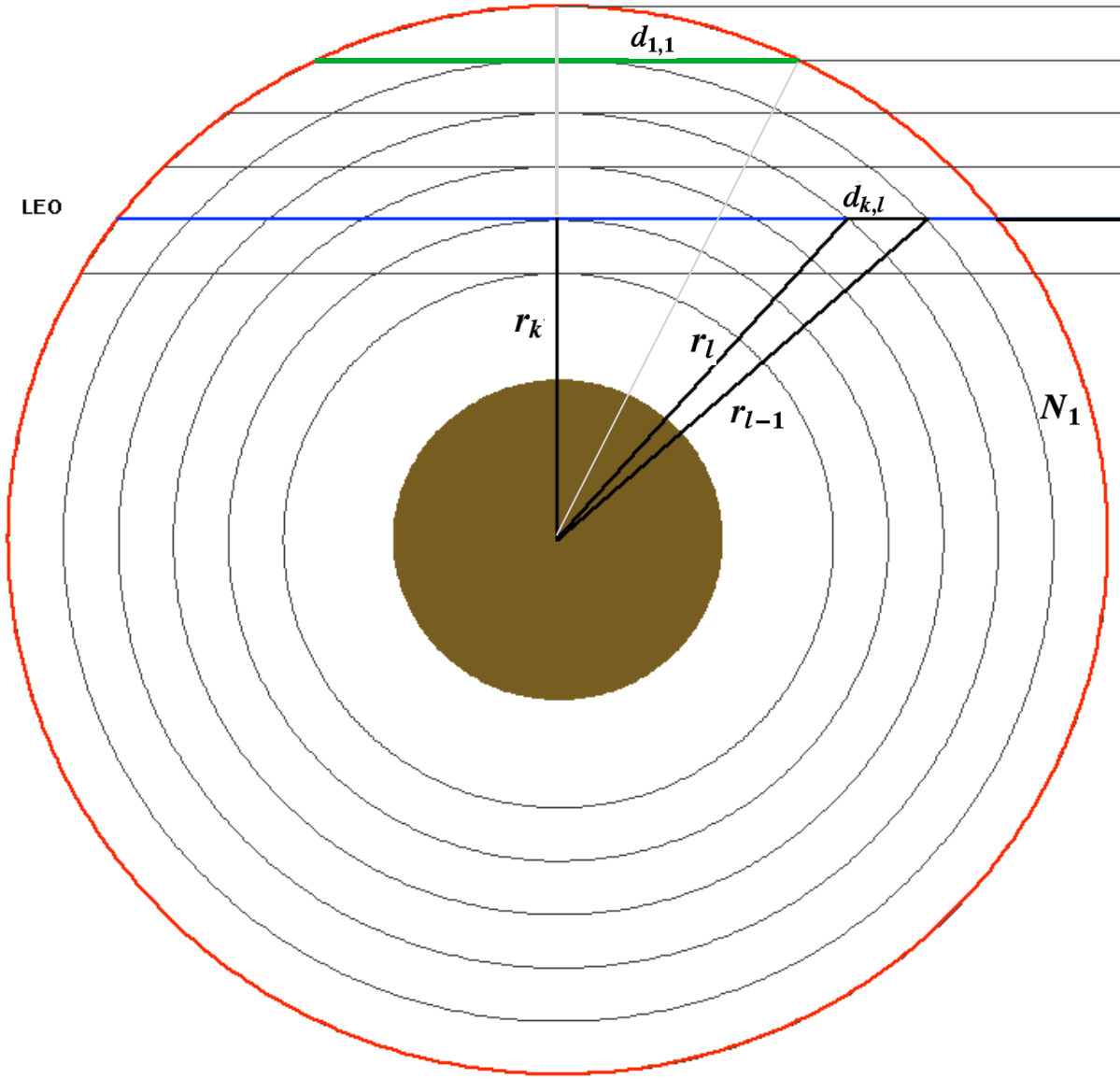


$$\mathrm{TEC}_k = 2\,(N_1\,d_{k,1} + N_2\,d_{k,2} + \ldots + N_k\,d_{k,k})$$

$$d_{k,l} = \sqrt{r_{l-1}^2 - r_k^2} - \sqrt{r_l^2 - r_k^2}$$



The Onion Peeling algorithm



$$TEC_1 = 2\,N_1\,d_{1,1}$$

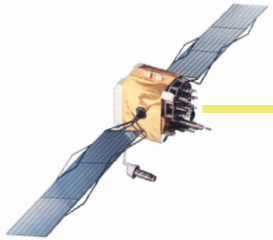
...

...

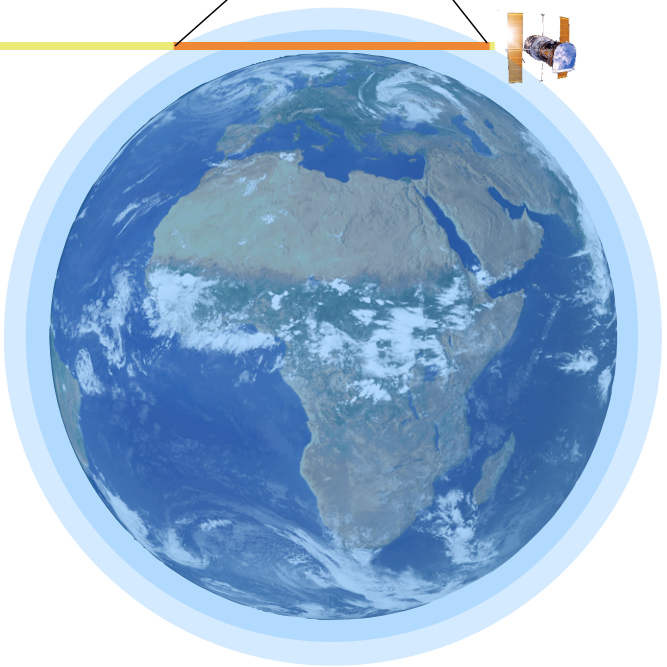
$$TEC_k = 2\,(N_1\,d_{k,1} + N_2\,d_{k,2} + \ldots + N_k\,d_{k,k})$$

$$d_{k,l} = \sqrt{r_{l-1}^2 - r_k^2} - \sqrt{r_l^2 - r_k^2}$$

TEC calibration

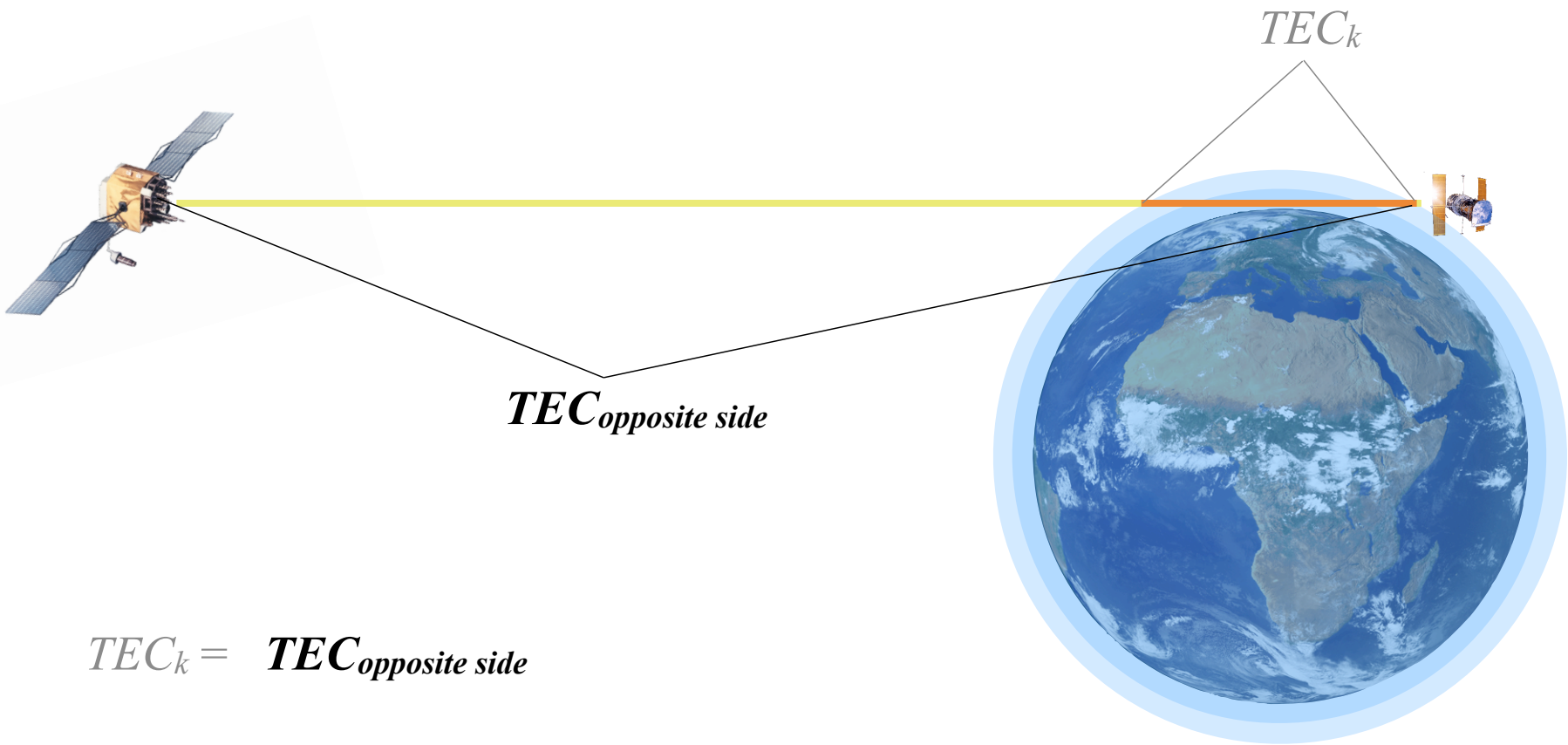


TEC_k



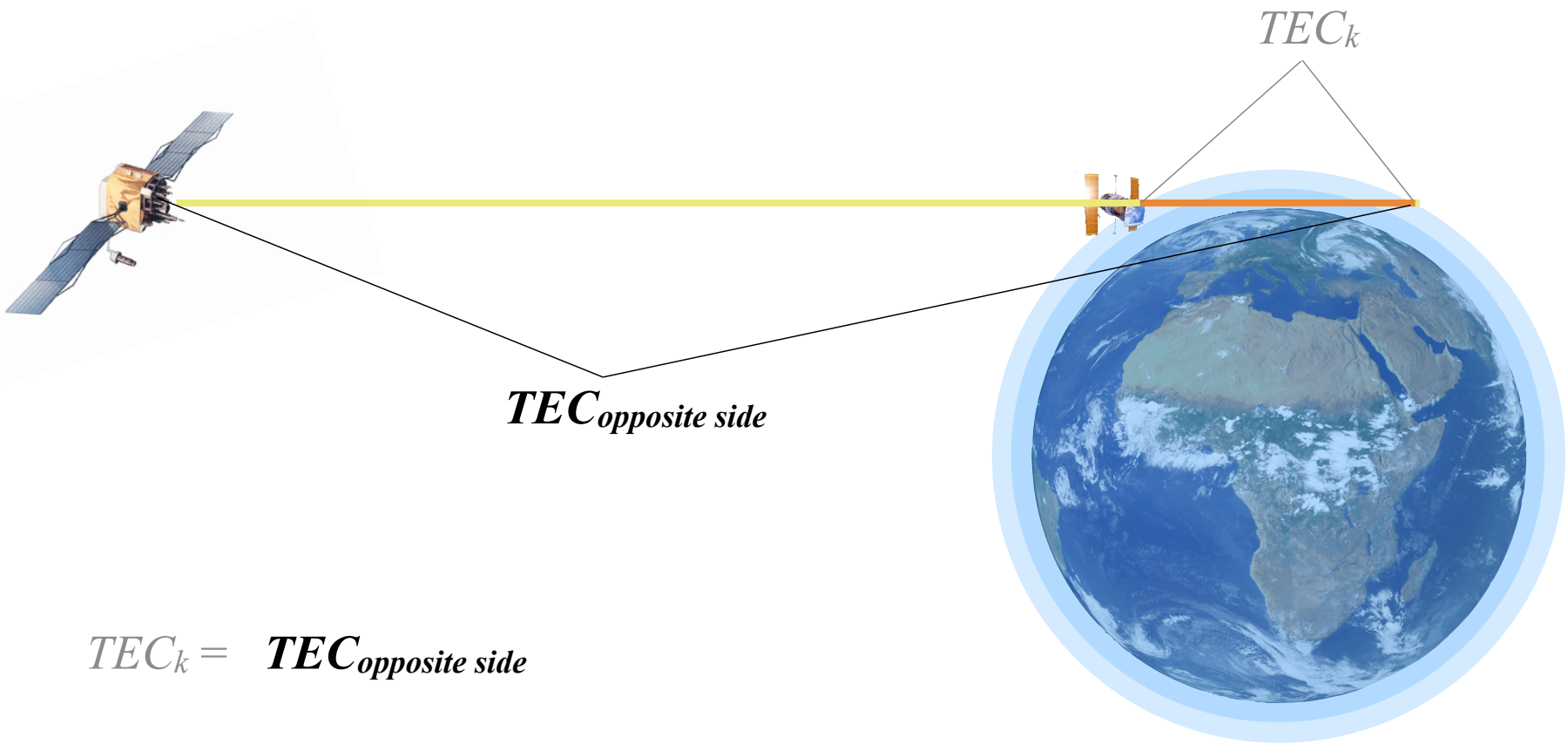
$TEC_k =$

TEC calibration



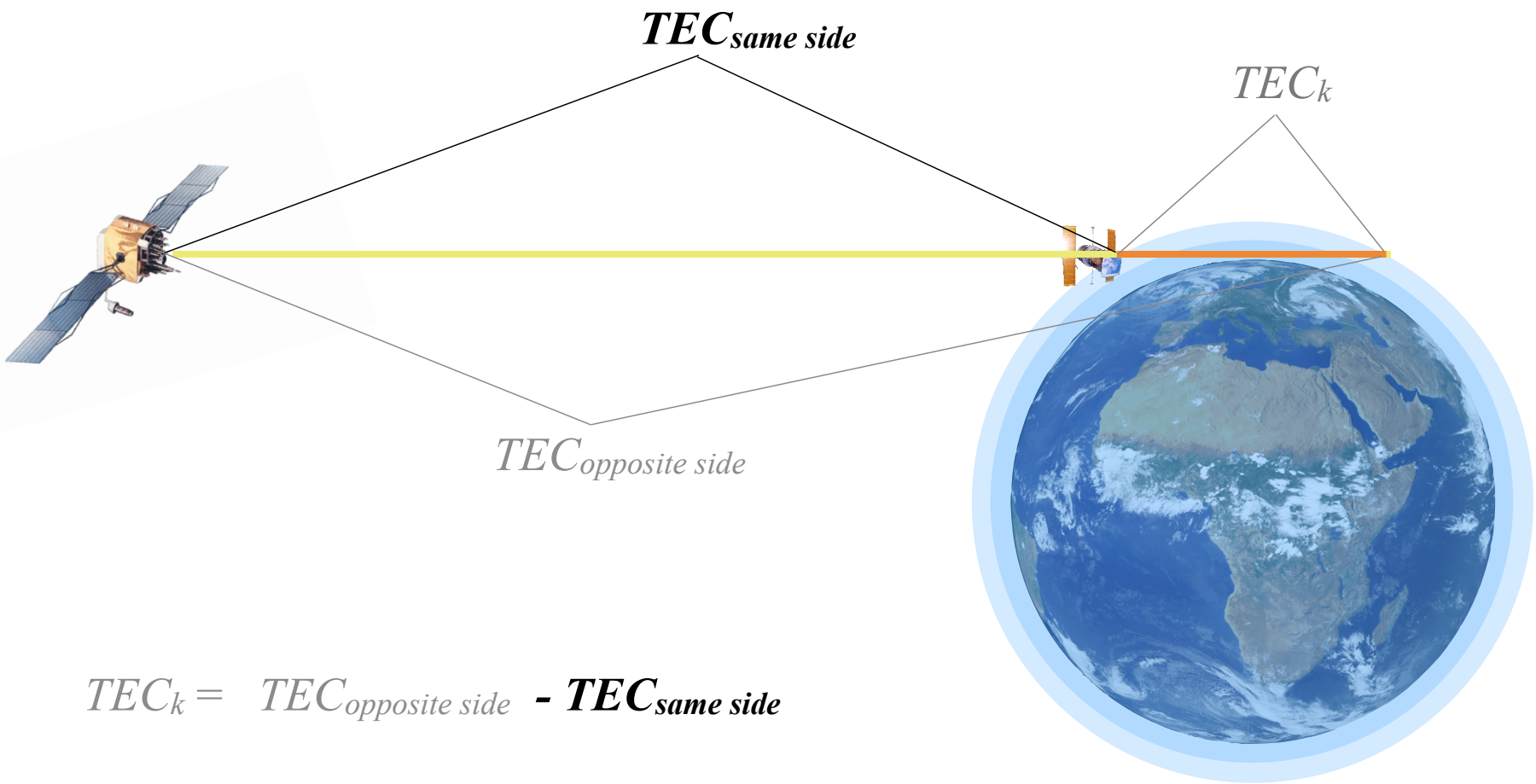
$$TEC_k = TEC_{opposite\ side}$$

TEC calibration



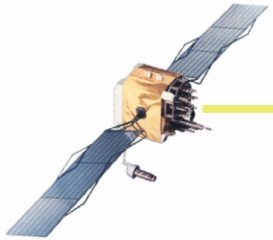
$TEC_k = TEC_{opposite\ side}$

TEC calibration

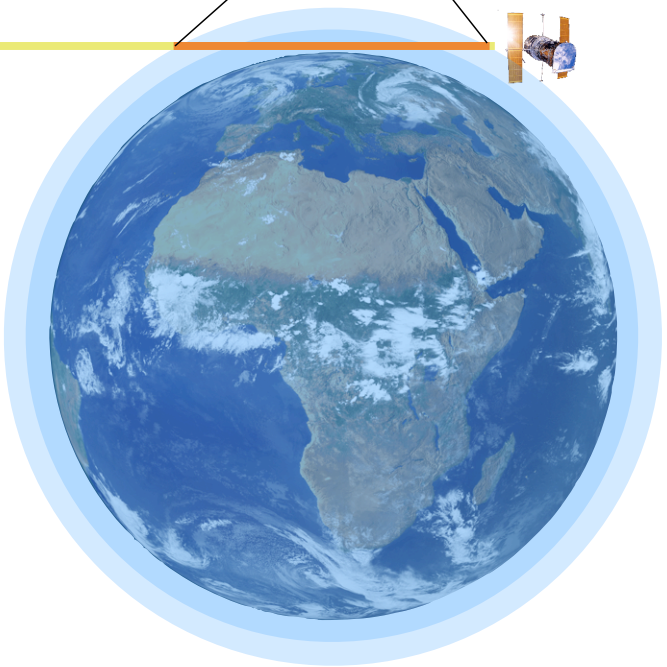


$$TEC_k = TEC_{opposite\ side} - TEC_{same\ side}$$

TEC calibration

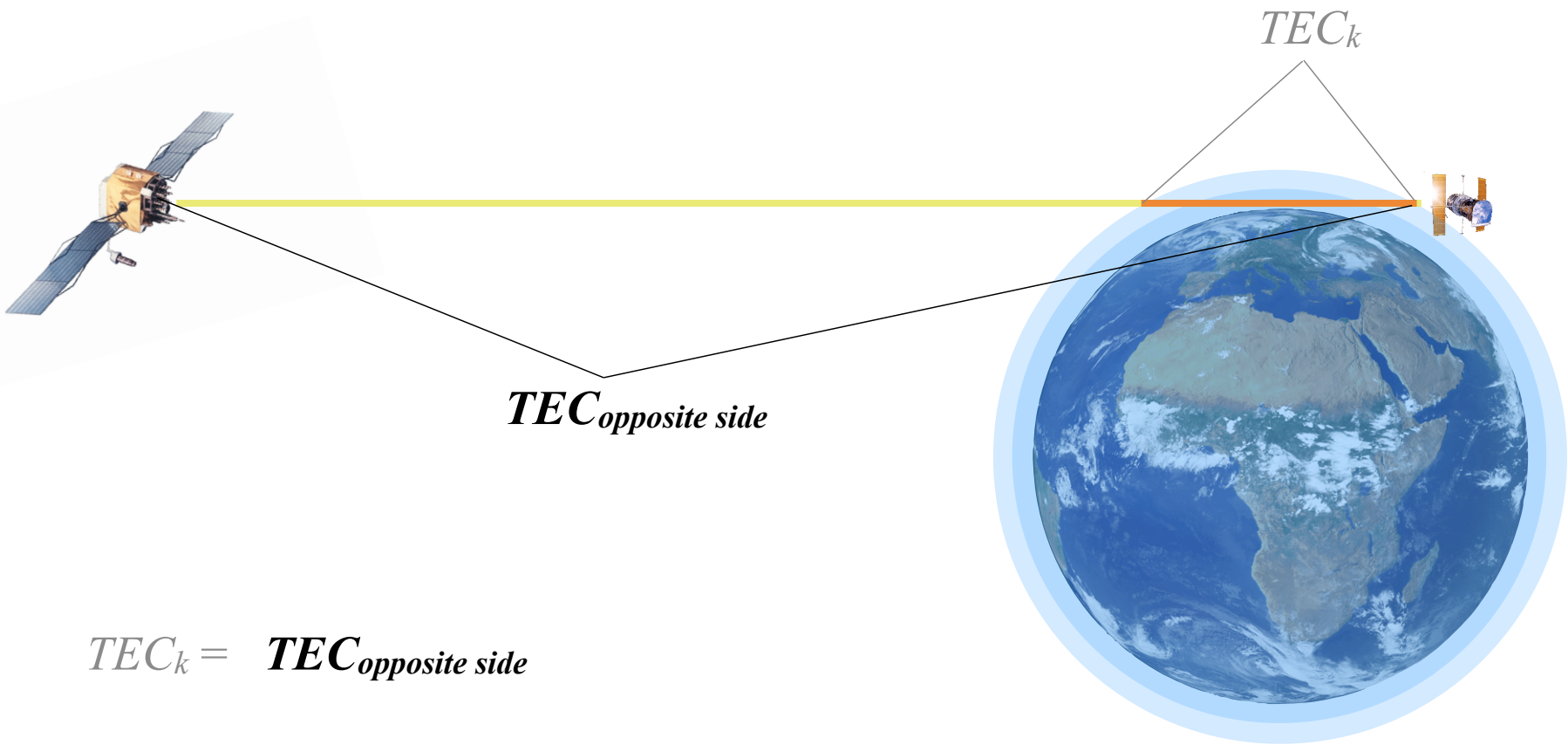


TEC_k



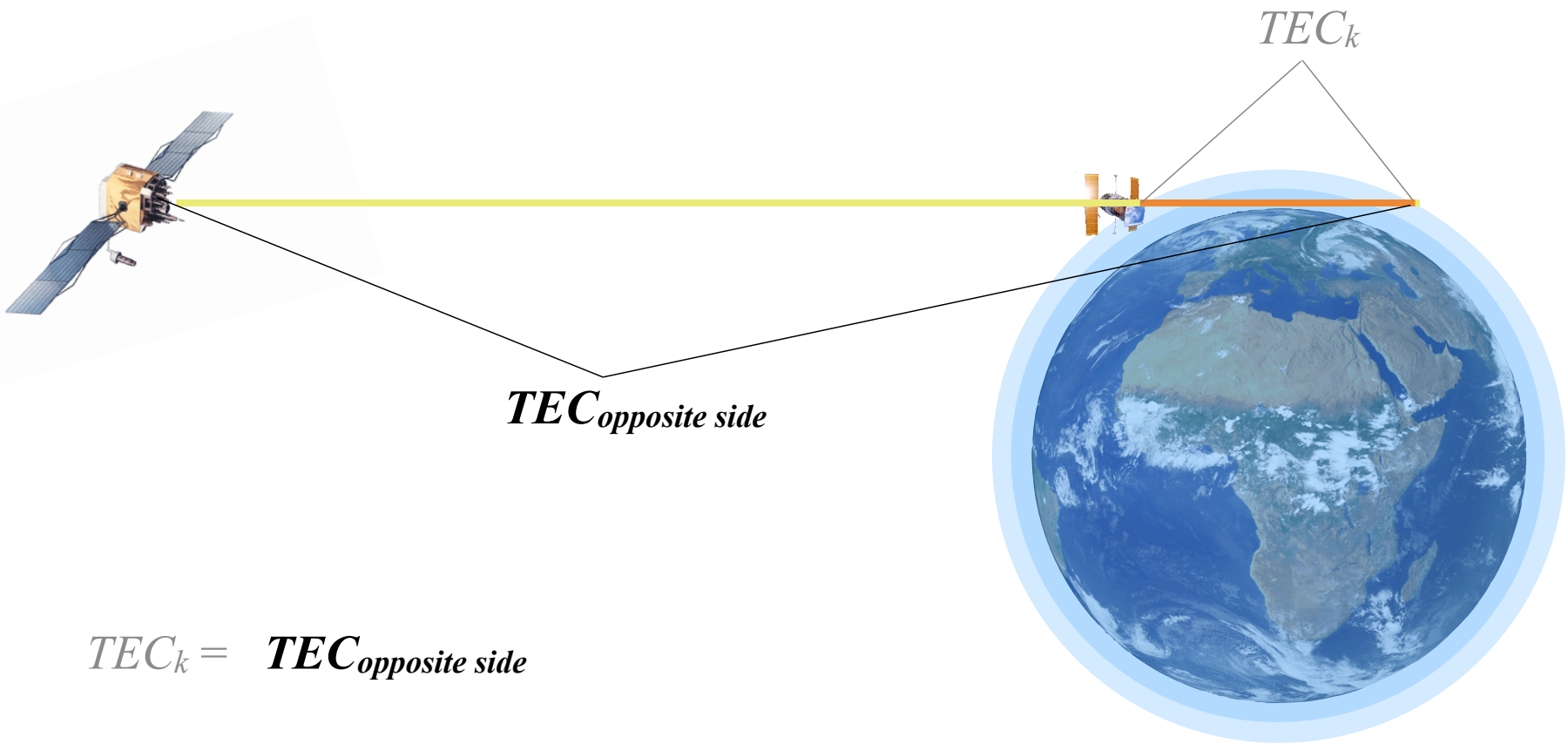
$TEC_k =$

TEC calibration



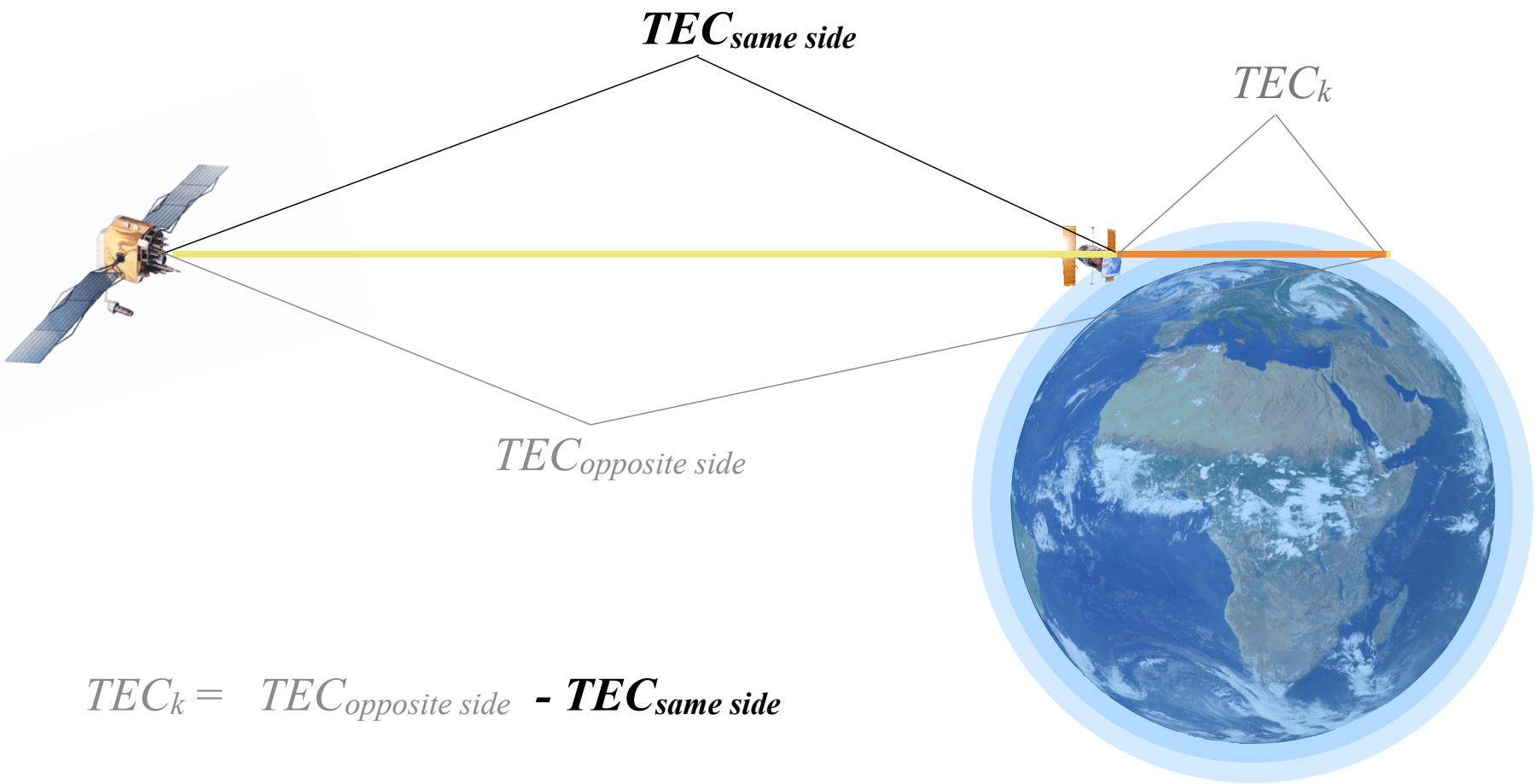
$$TEC_k = TEC_{opposite\ side}$$

TEC calibration



$TEC_k = TEC_{opposite\ side}$

TEC calibration

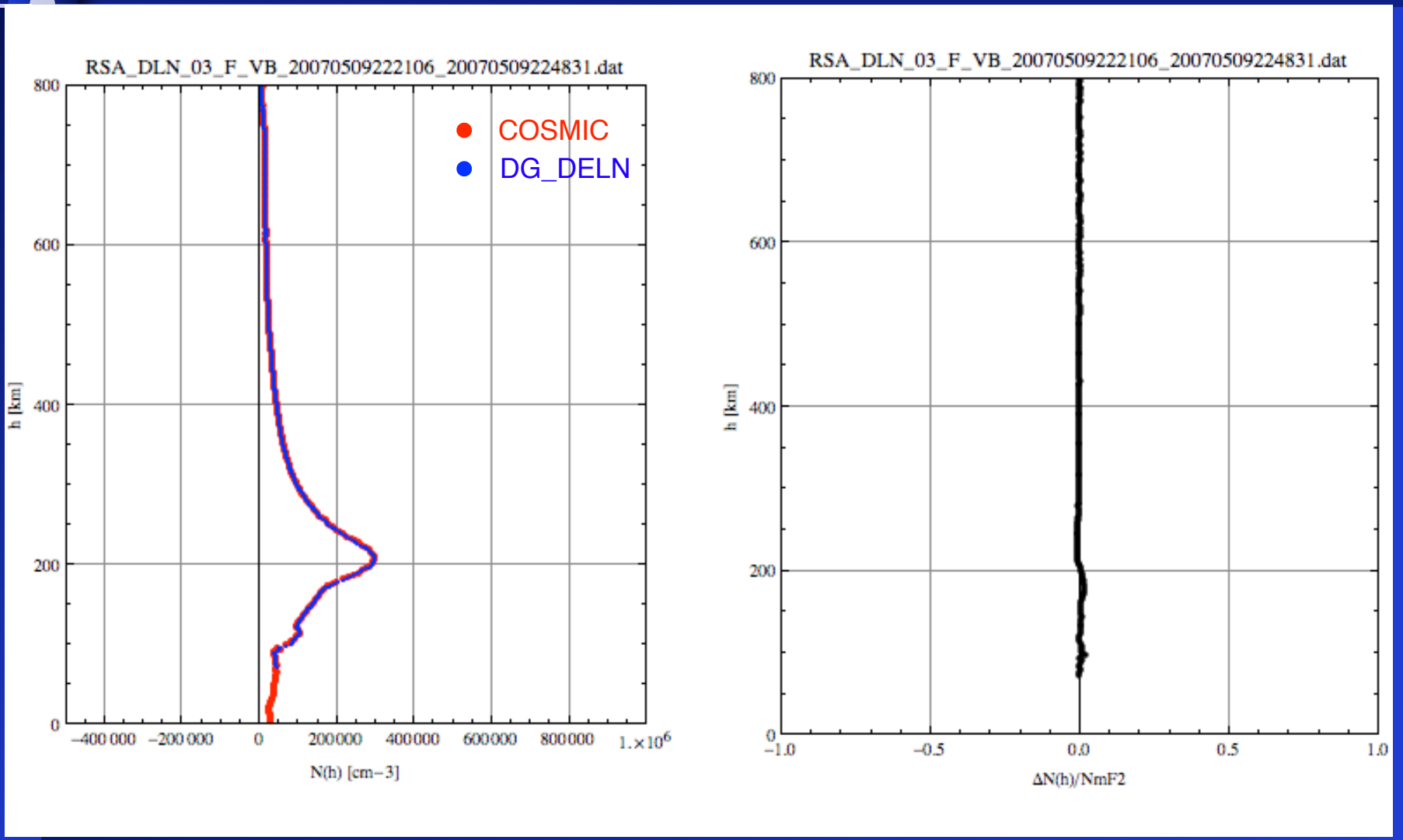


$$TEC_k = TEC_{opposite\ side} - TEC_{same\ side}$$

Some electron density profiles obtained applying the “onion peeling” algorithm*

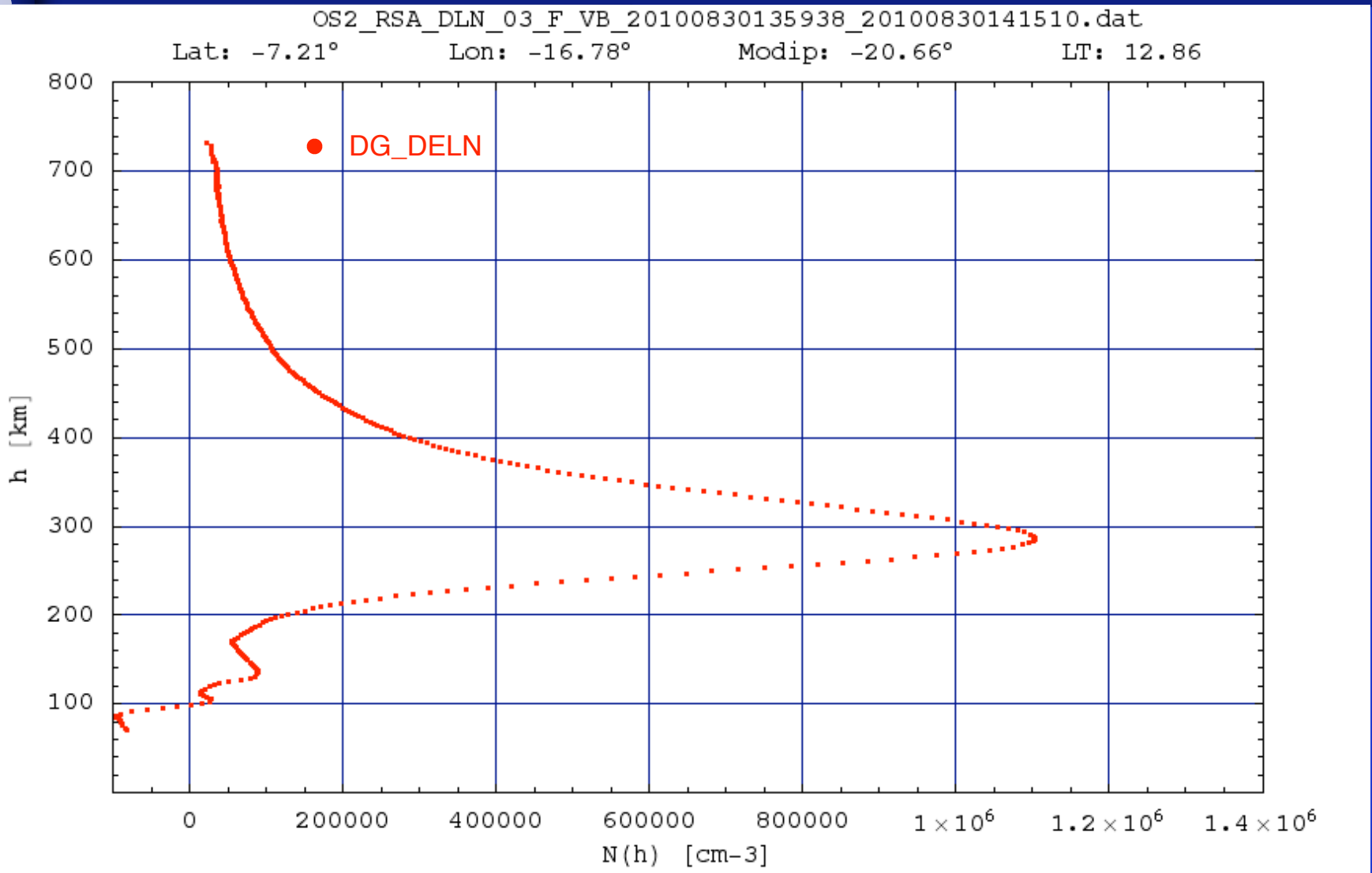
*implemented as DG_DELN SW

Onion peeling derived profile



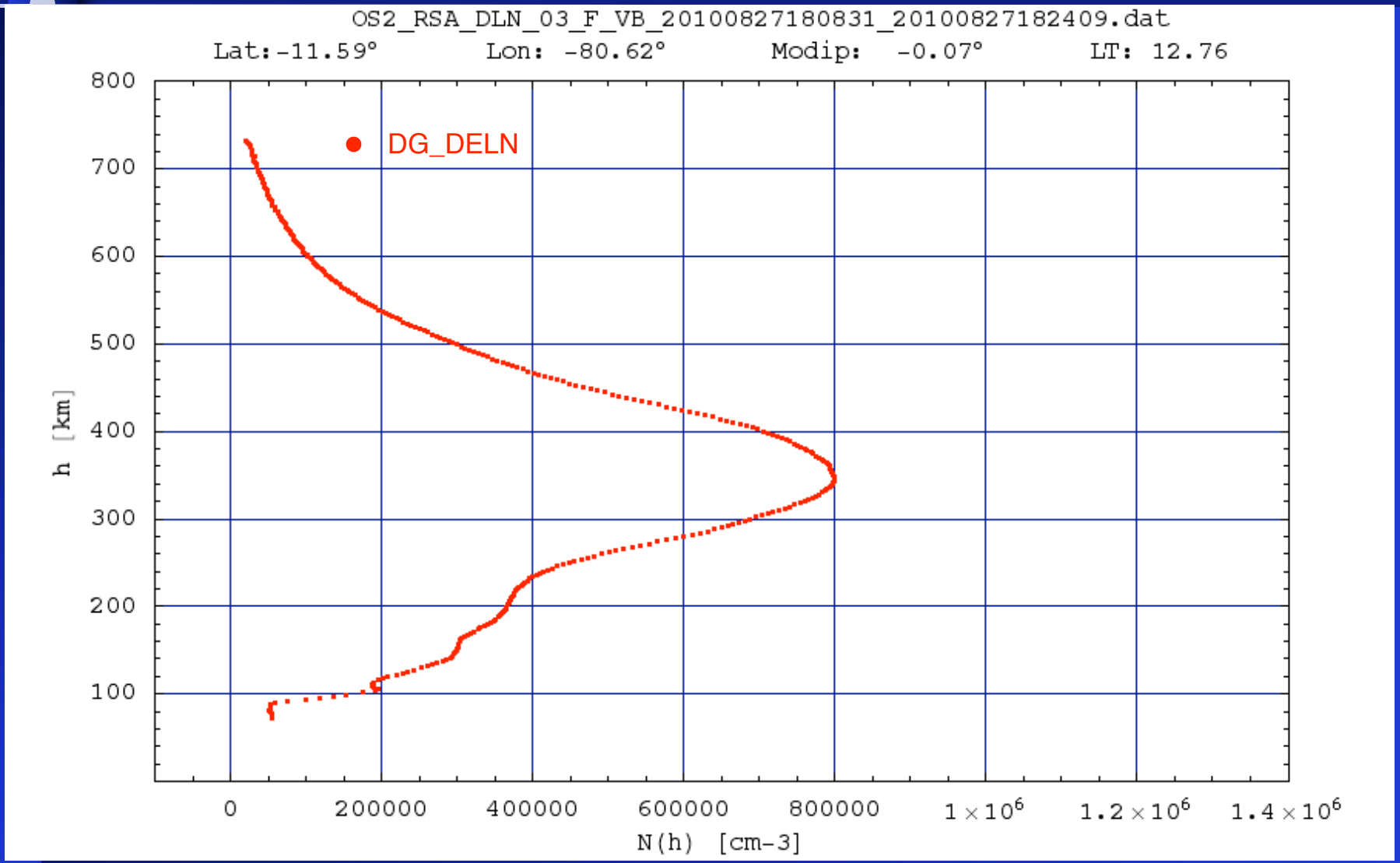
COSMIC data are used

Onion peeling derived profile



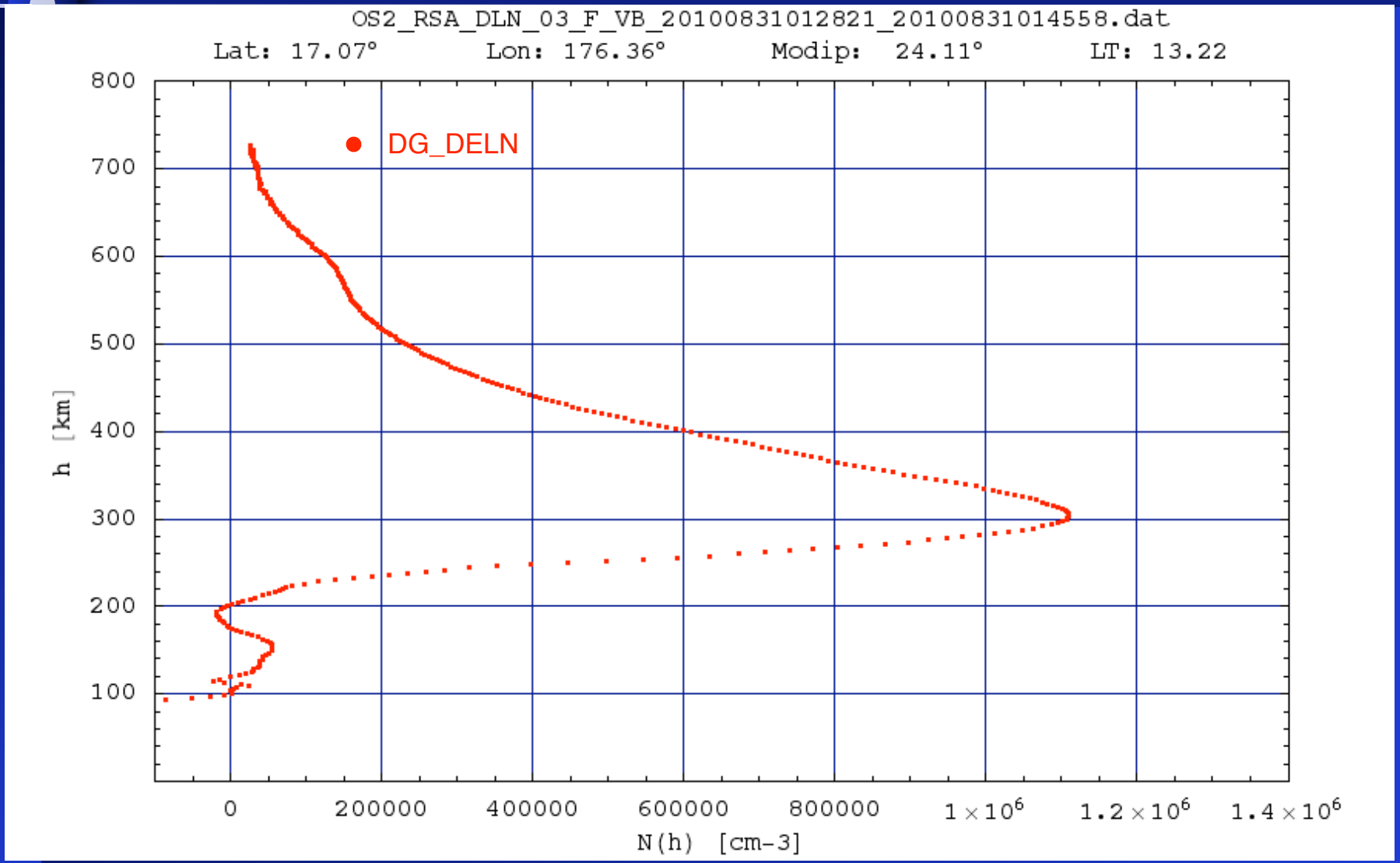
ROSA data are used

Onion peeling derived profile



ROSA data are used

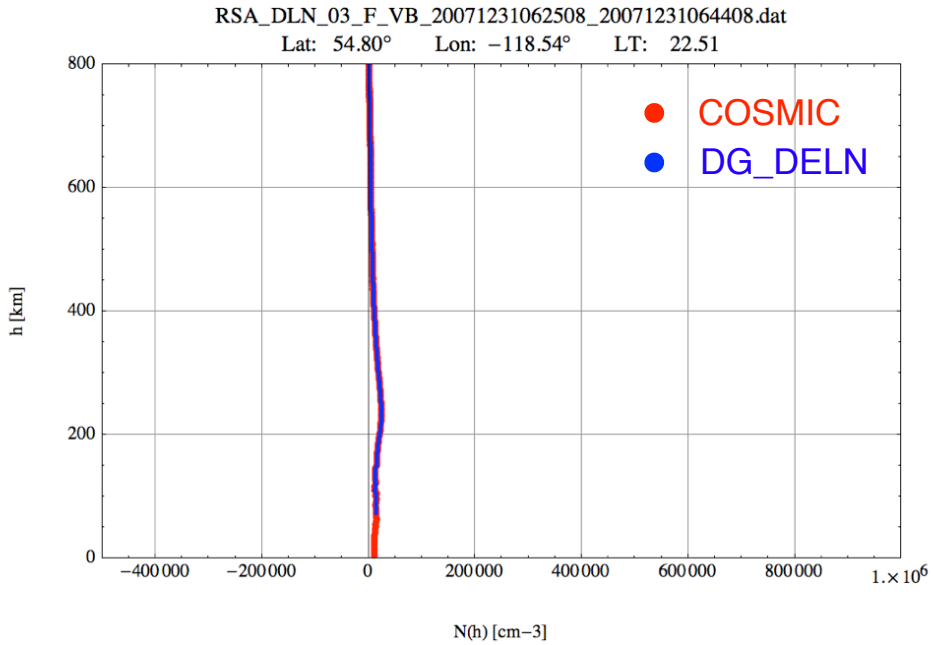
Onion peeling derived profile

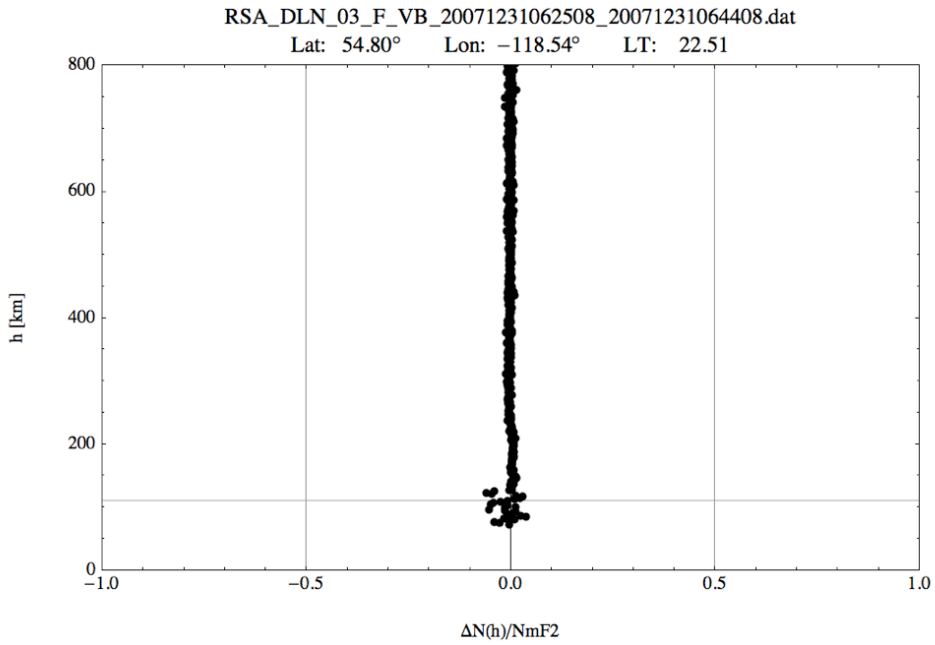


ROSA data are used

Some “interesting” results

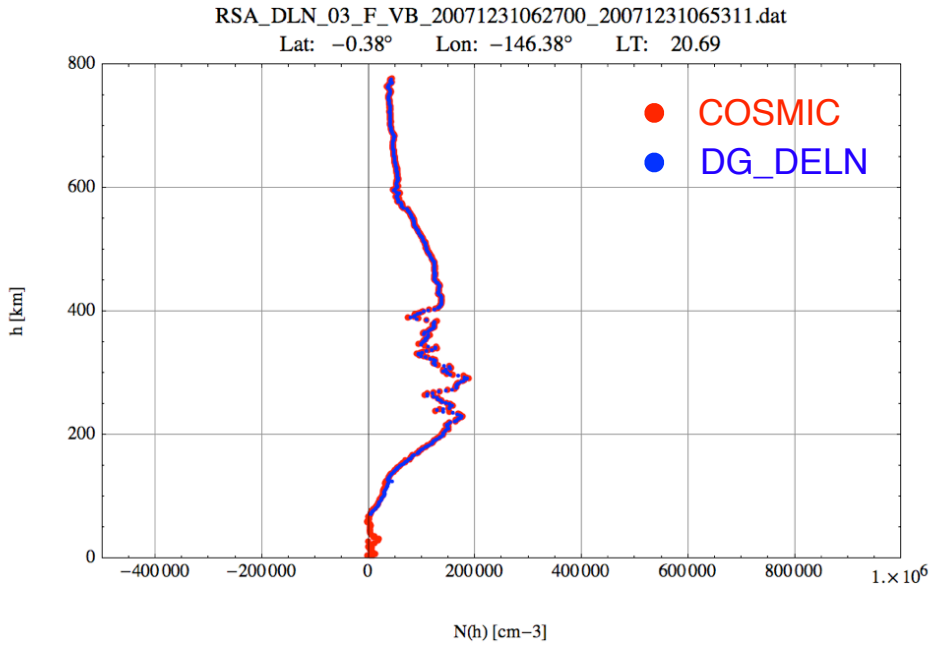
Profile example 1

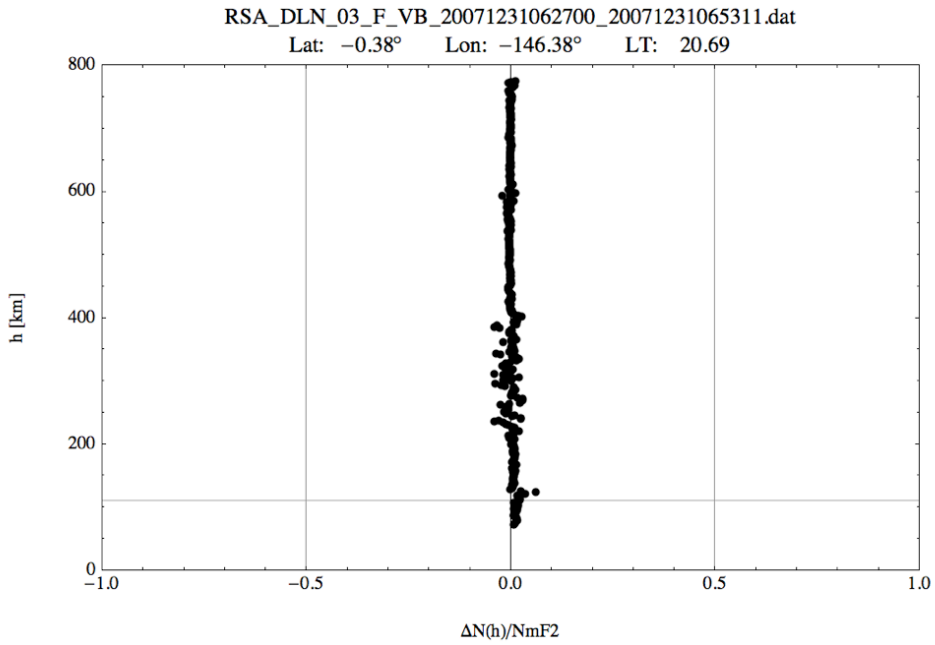




COSMIC data are used

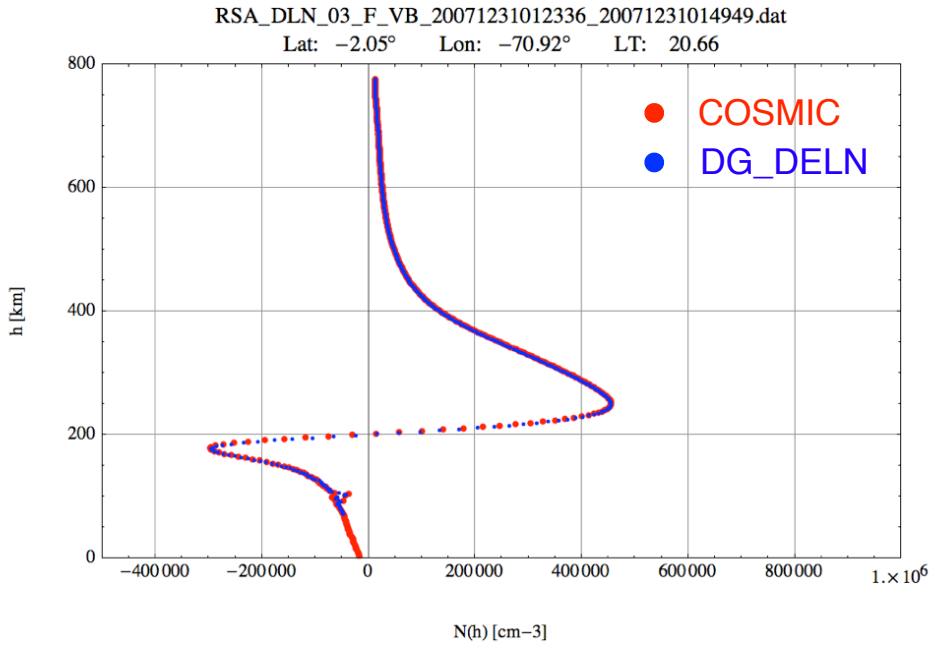
Profile example 2

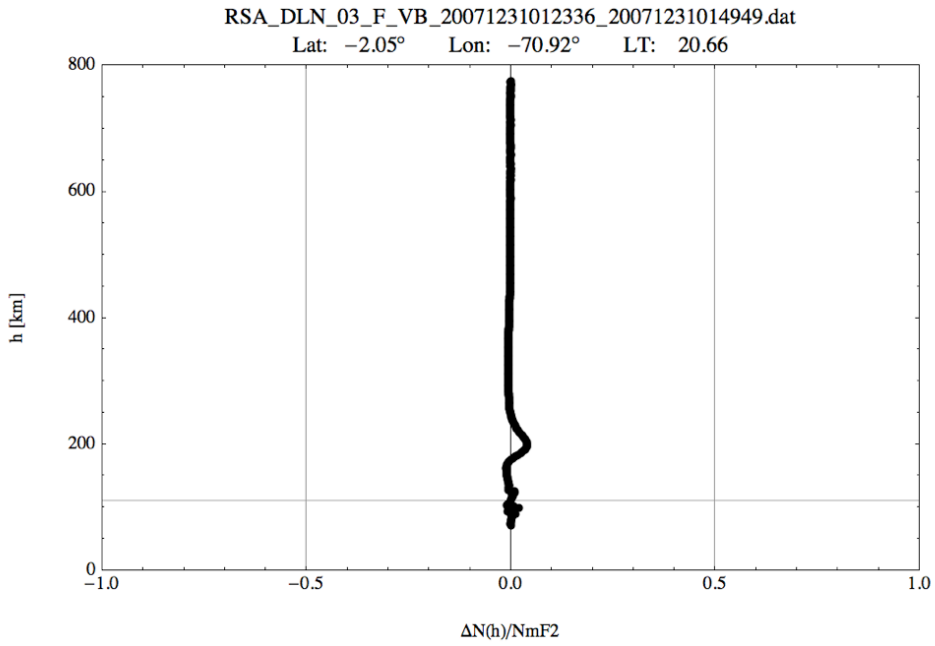




COSMIC data are used

Profile example 3

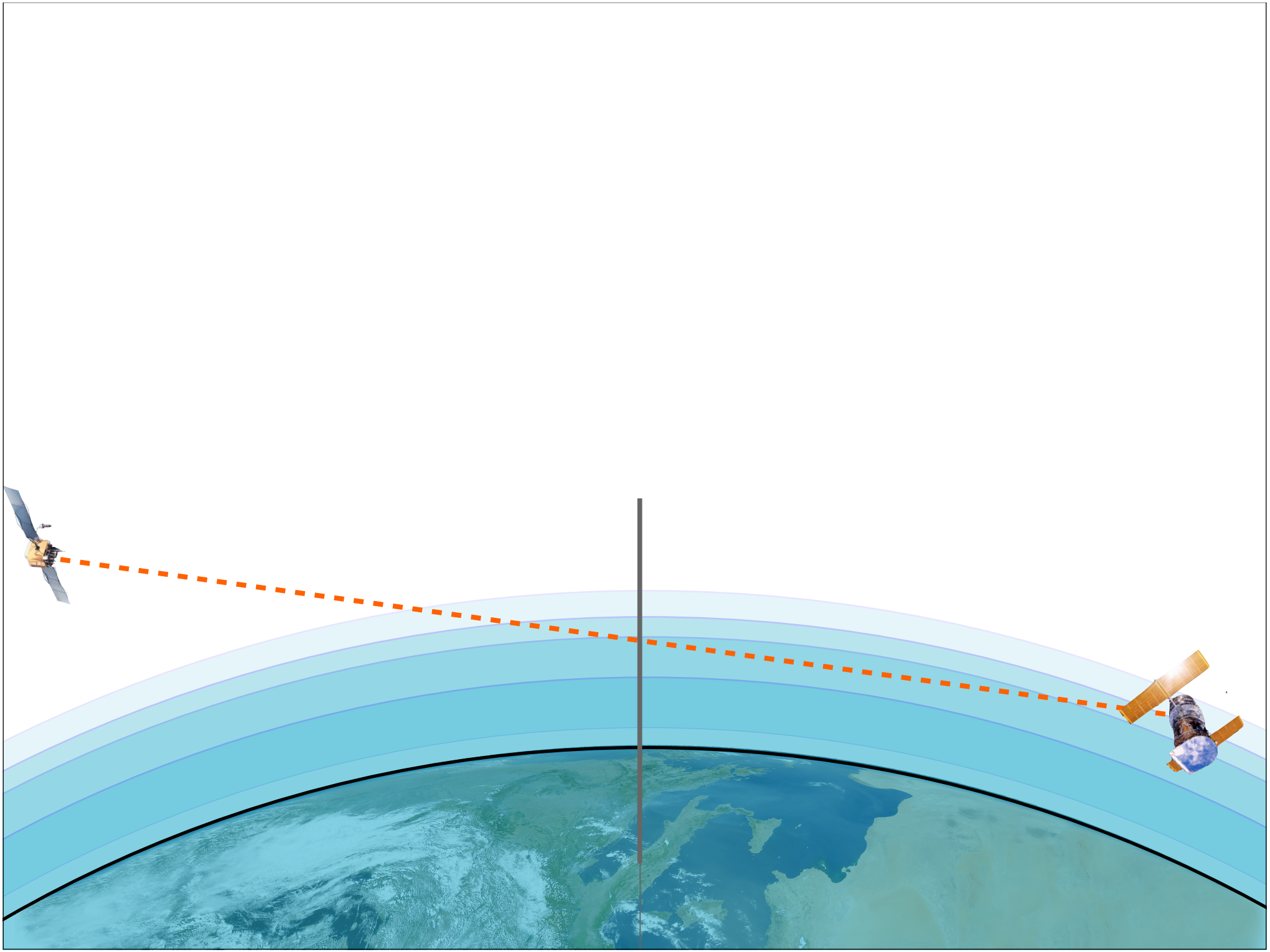


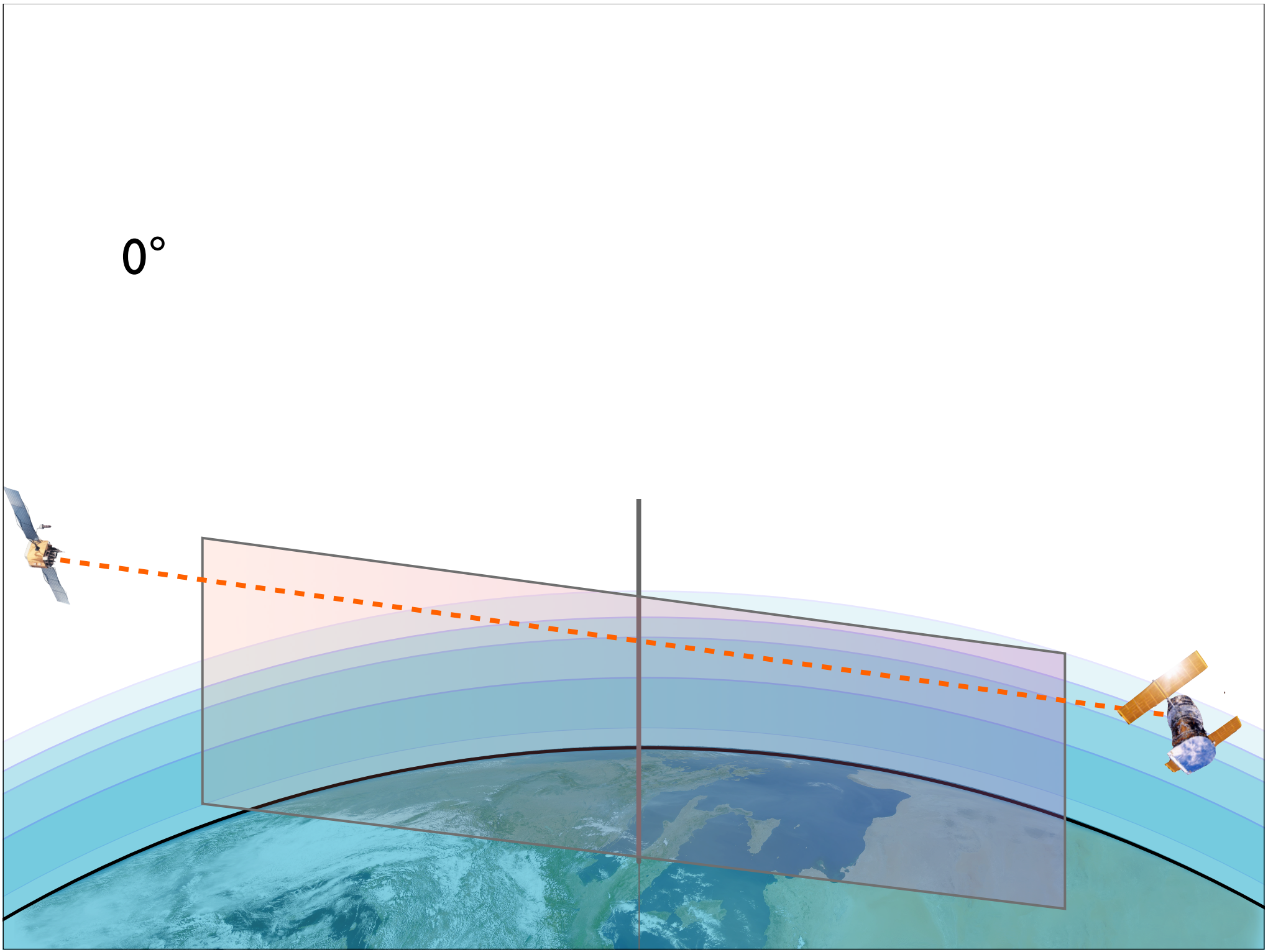


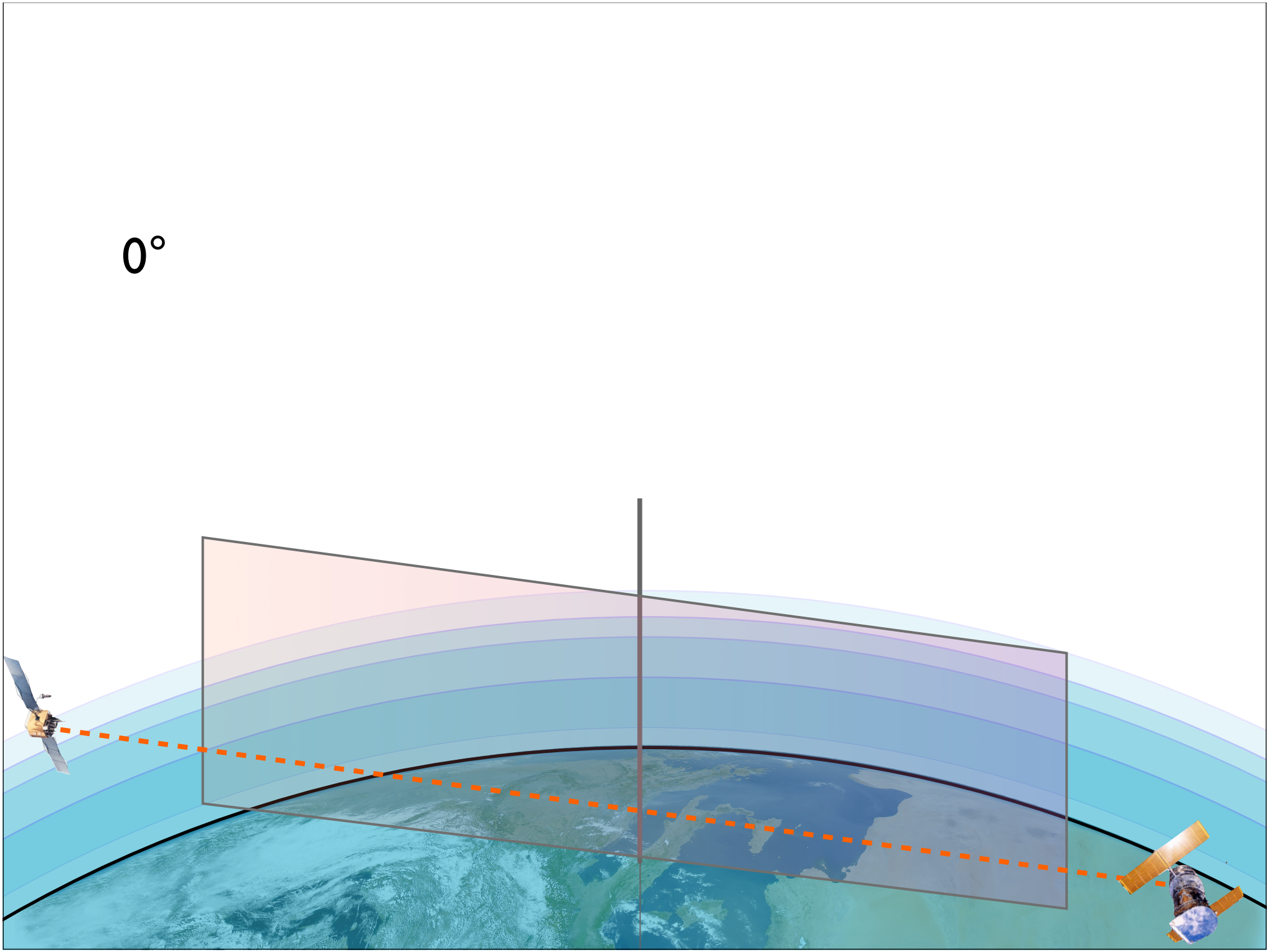
COSMIC data are used

The spherical symmetry assumption for the electron density of the ionosphere: effects on the reconstructed profiles.

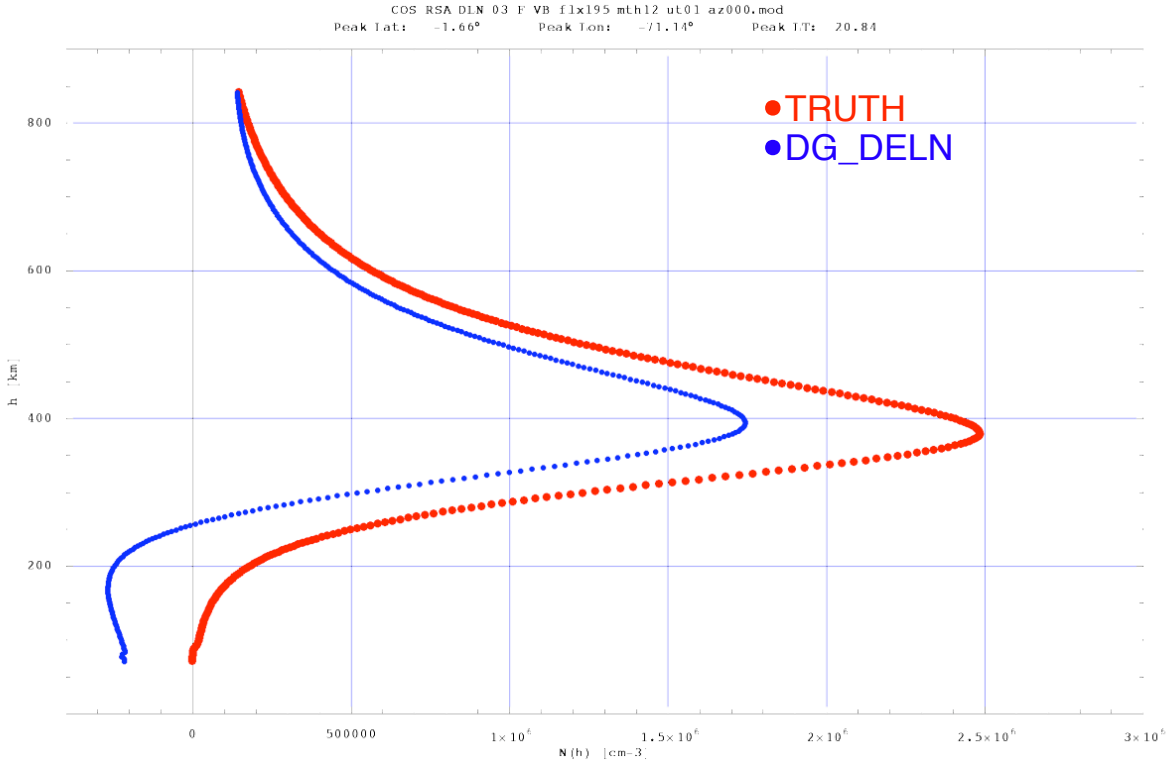
SIMULATION RESULTS

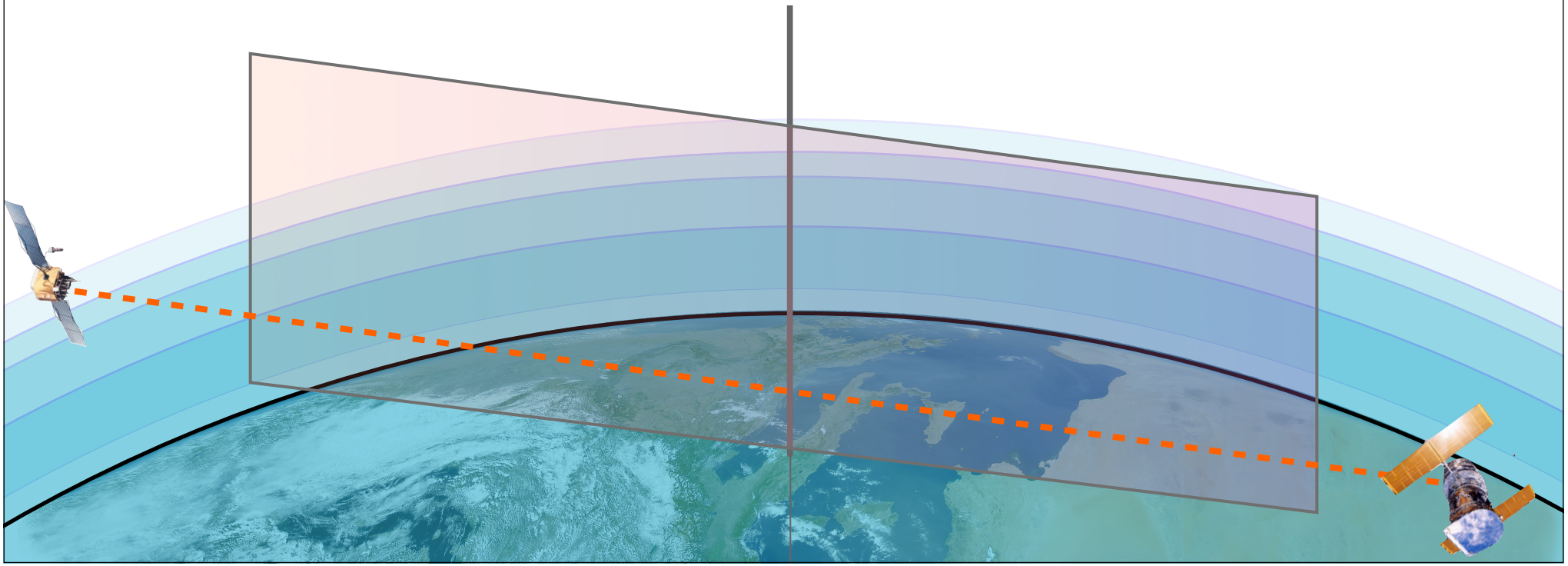



0°

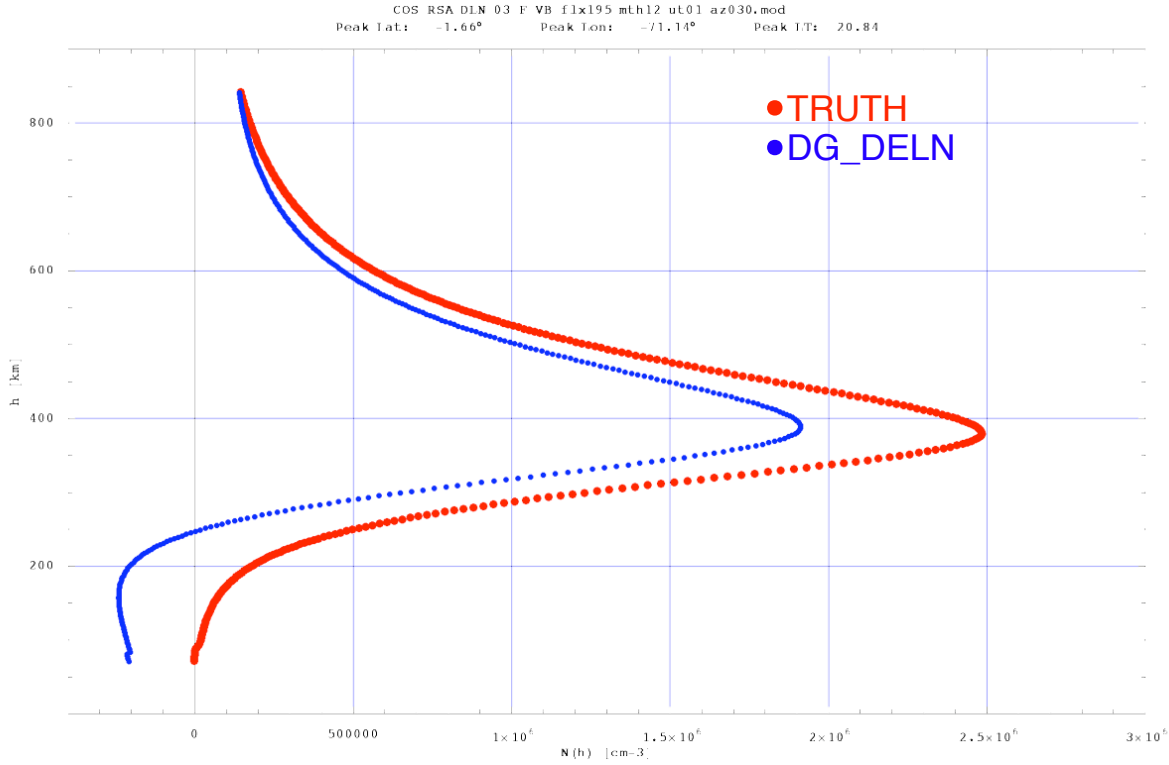

0°

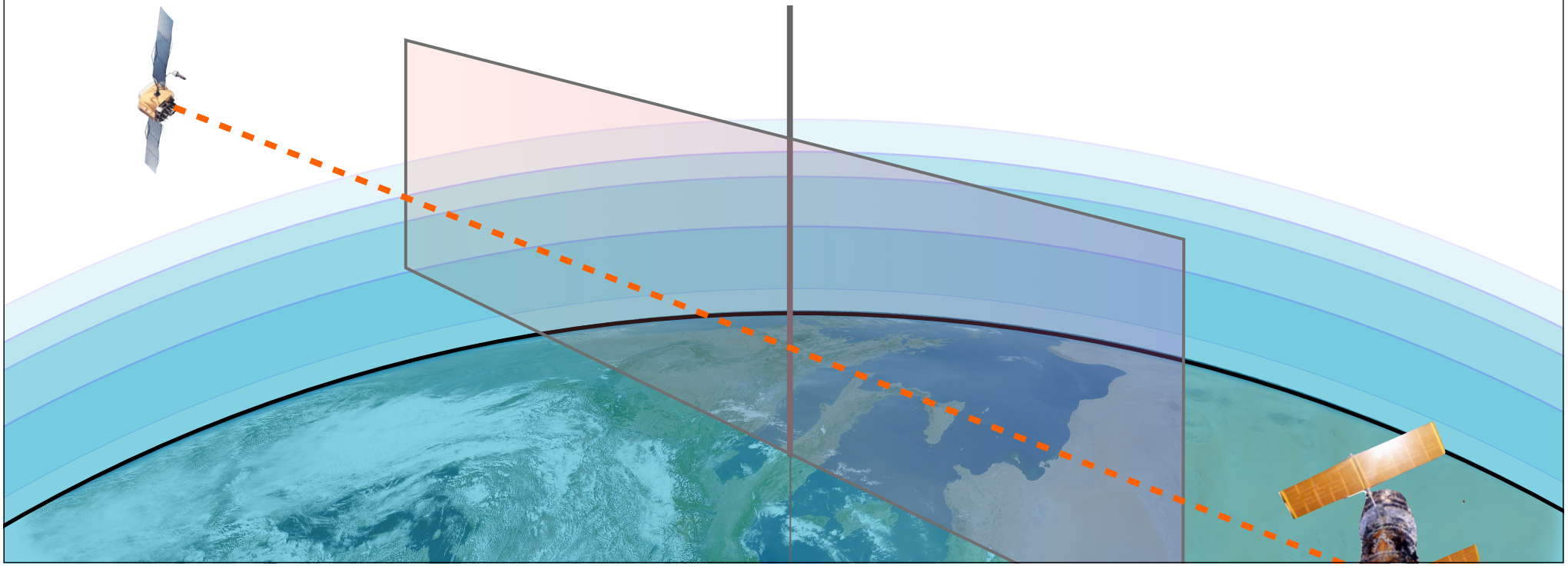
0°


COS RSA DLN 03 F VB flx195 mth12 ut01 az000.mod
Peak Lat: -1.66°
Peak Lon: -71.14°
Peak LT: 20.84
TRUTH
DG_DELN
800
600
400
200
h [km]
0
500000
1×10^6
1.5×10^6
2×10^6
2.5×10^6
3×10^6
N(h) [cm-3]

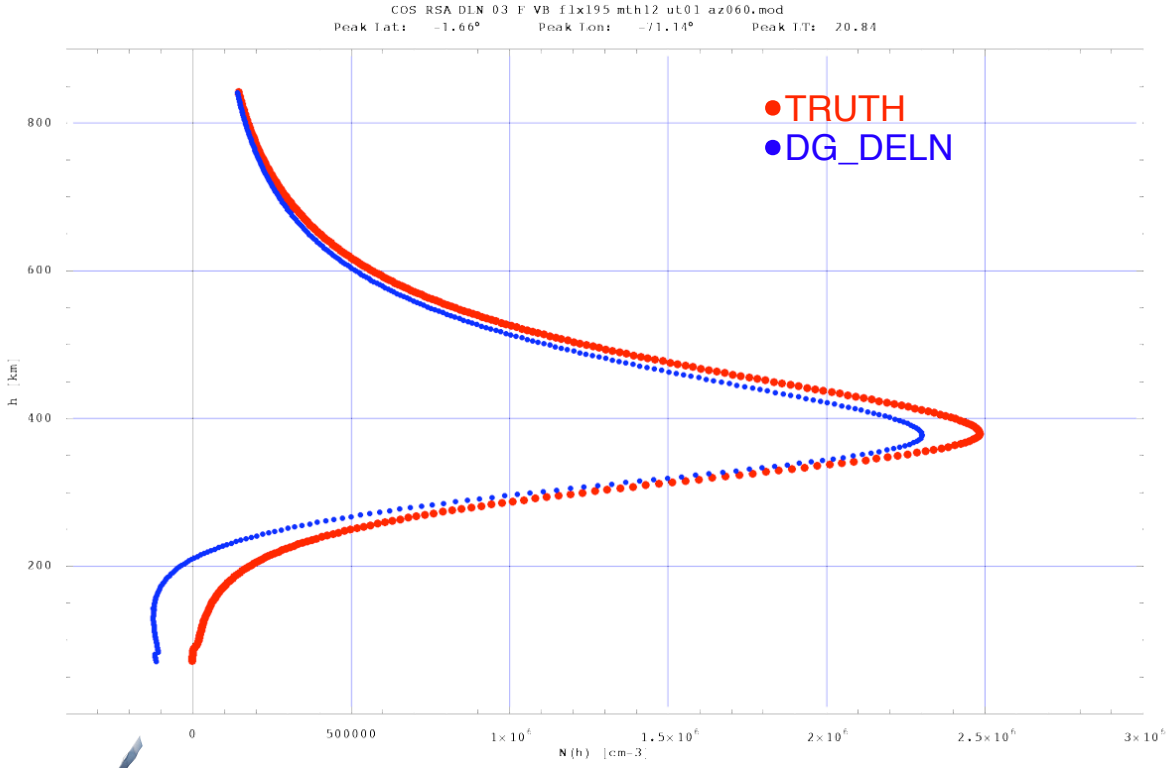


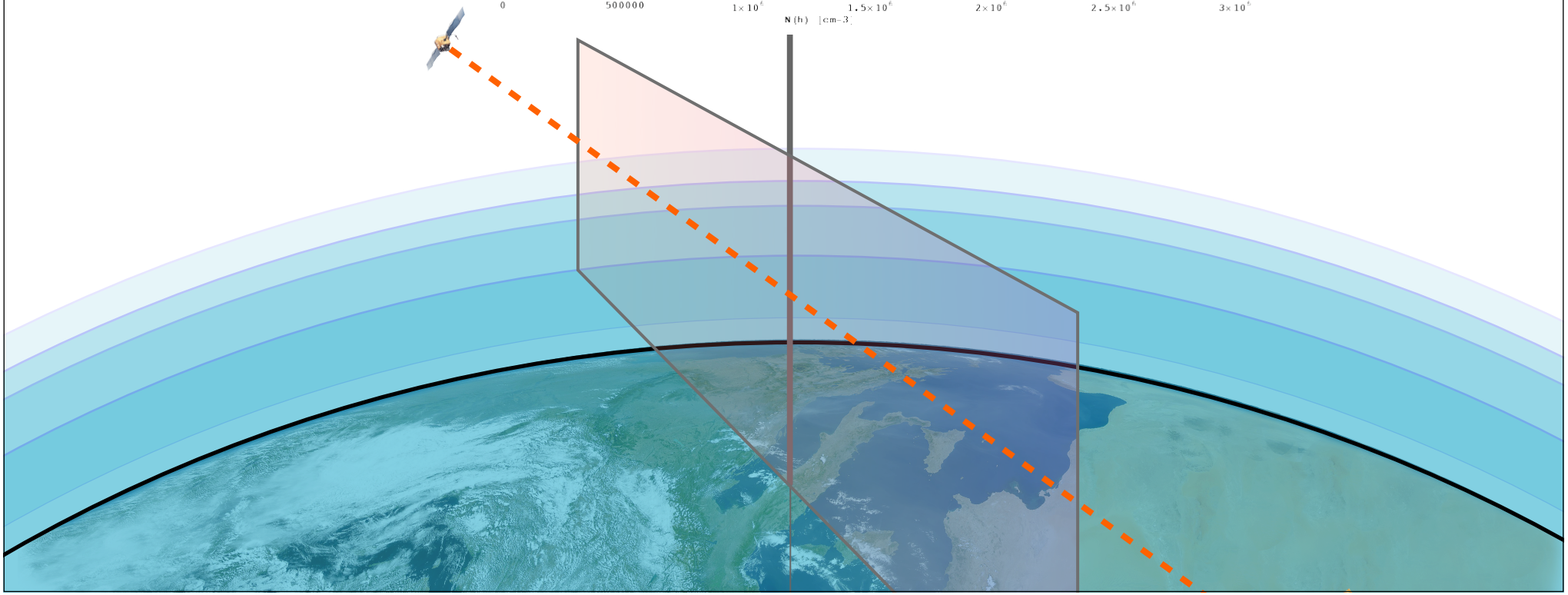
30°


COS RSA DLN 03 F VB flx195 mth12 ut01 az030.mod
Peak Lat: -1.66° Peak Lon: -71.14° Peak LT: 20.84
TRUTH
DG_DELN
800
600
400
200
h [km]
0
500000
1×10^6
1.5×10^6
2×10^6
2.5×10^6
3×10^6
N(h) [cm-3]

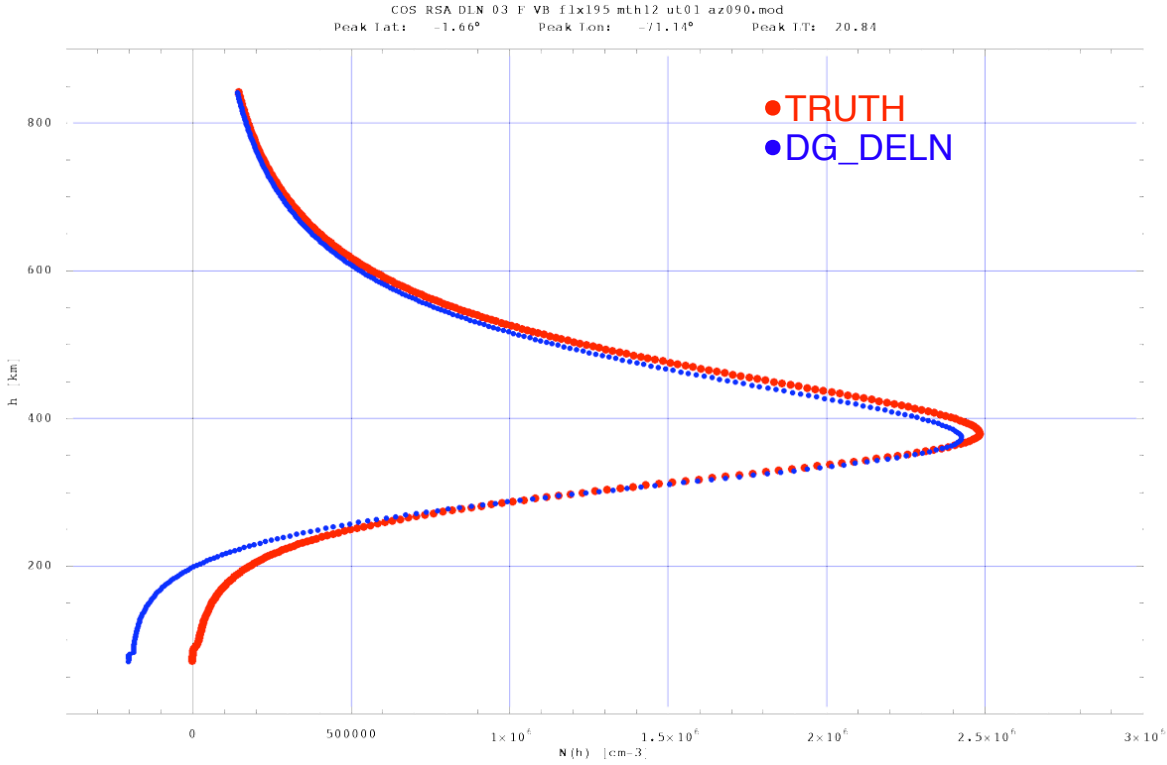


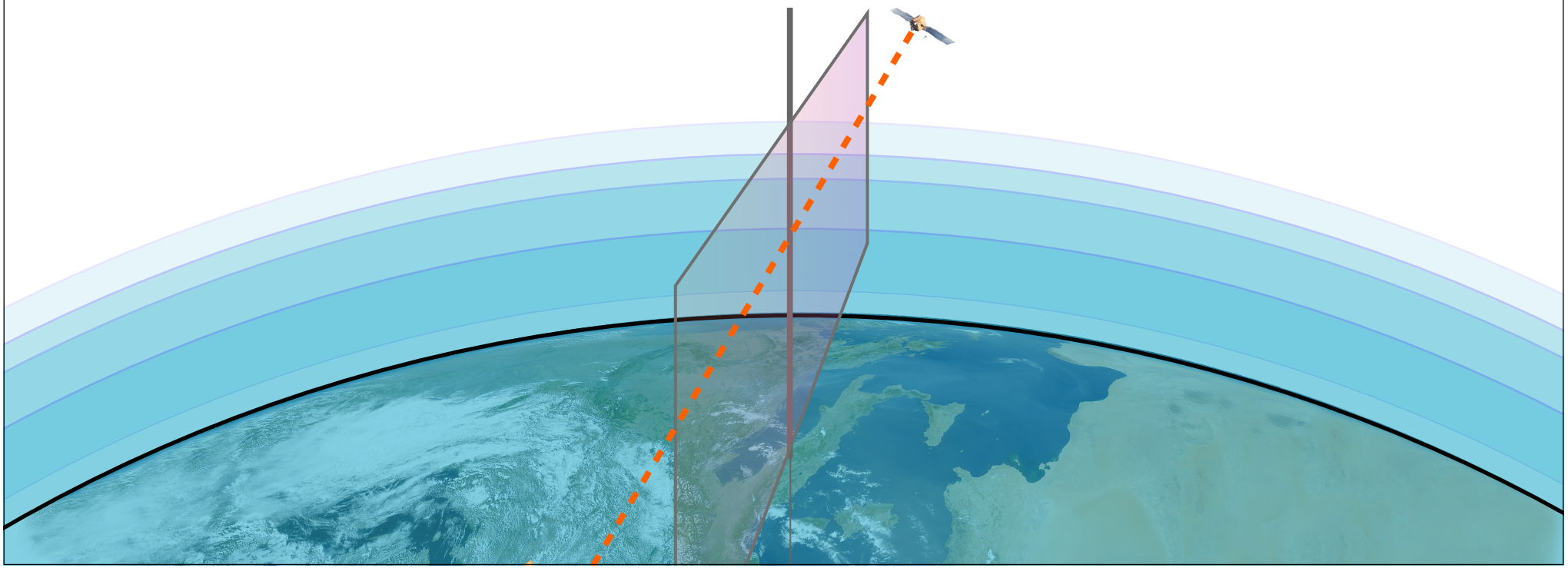
60°


COS RSA DLN 03 F VB flx195 mth12 ut01 az060.mod
Peak Lat: -1.66° Peak Lon: -71.14° Peak LT: 20.84
TRUTH
DG_DELN
800
600
400
200
h [km]
0
500000
1×10^6
1.5×10^6
2×10^6
2.5×10^6
3×10^6
N(h) [cm-3]

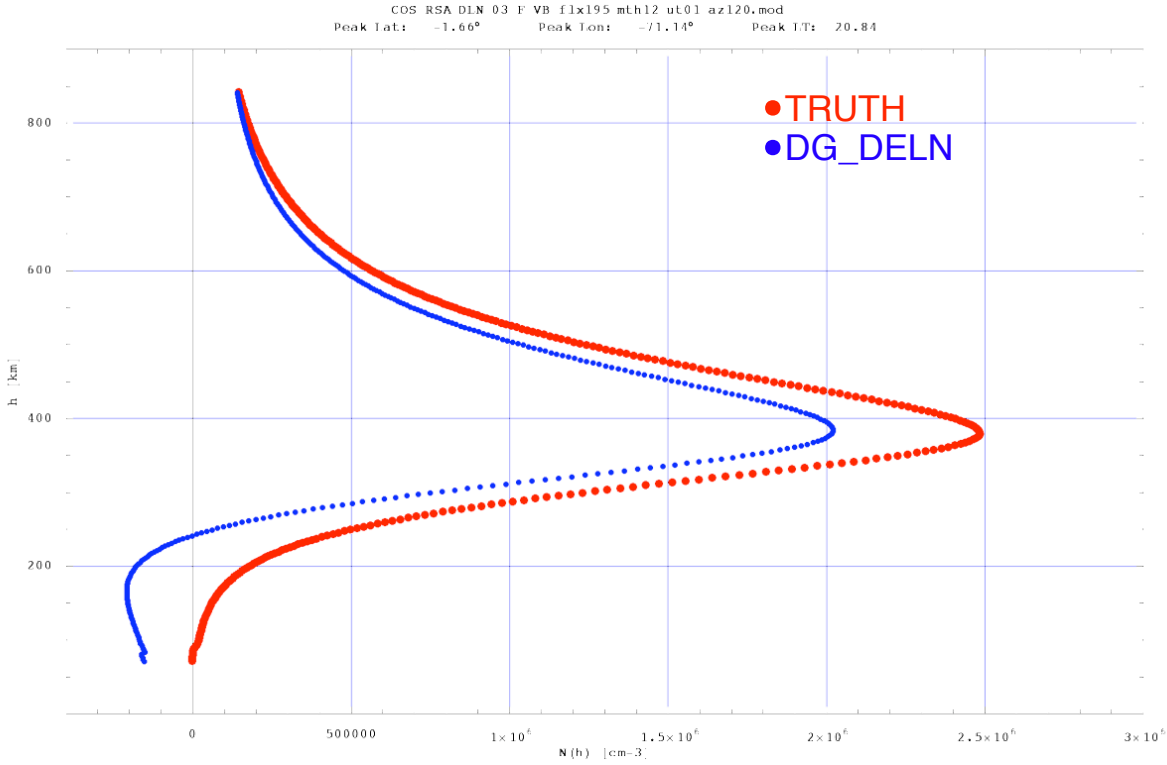


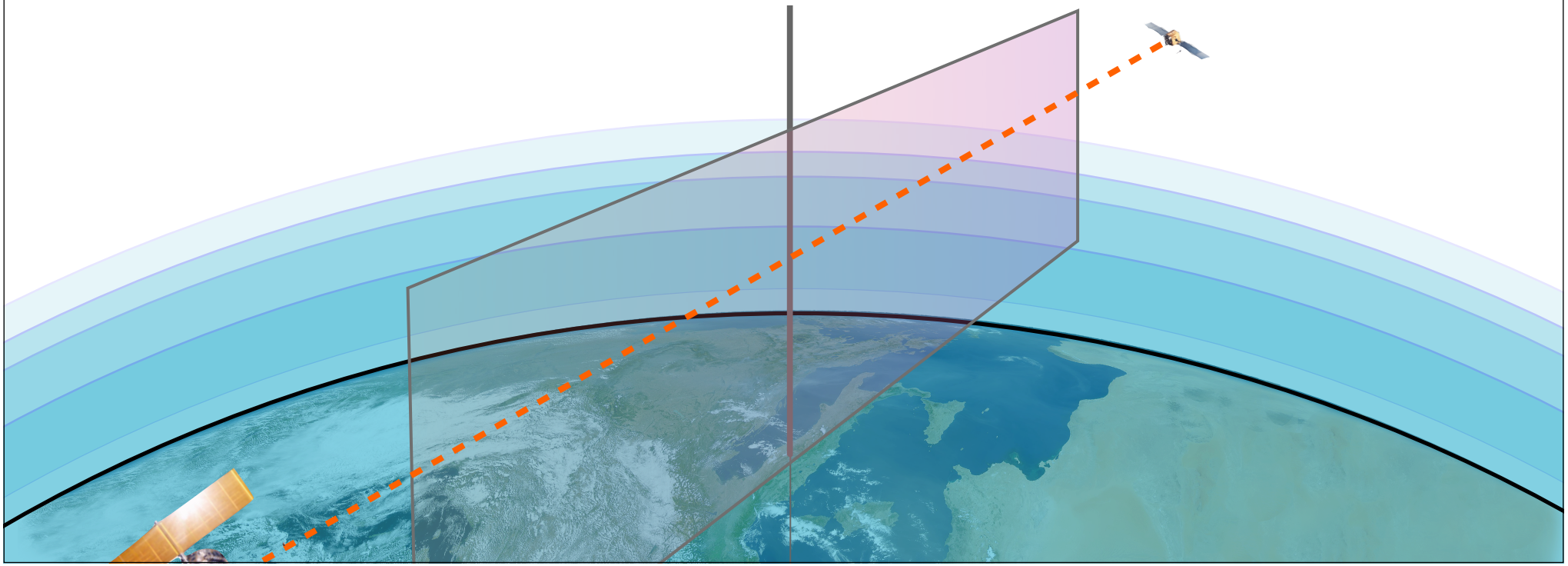
90°


COS RSA DLN 03 F VB flx195 mth12 ut01 az090.mod
Peak Lat: -1.66°
Peak Lon: -71.14°
Peak LT: 20.84
TRUTH
DG_DELN
800
600
400
200
h [km]
0
500000
1×10^6
1.5×10^6
2×10^6
2.5×10^6
3×10^6
N(h) [cm-3]

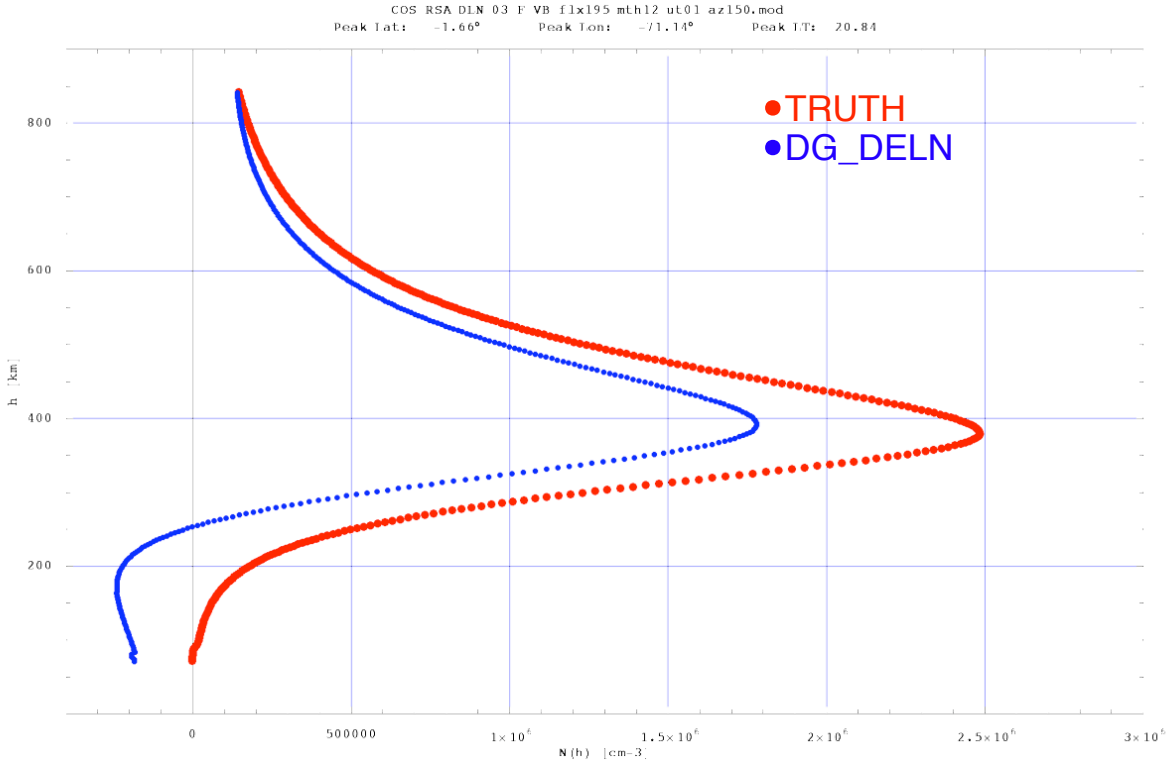


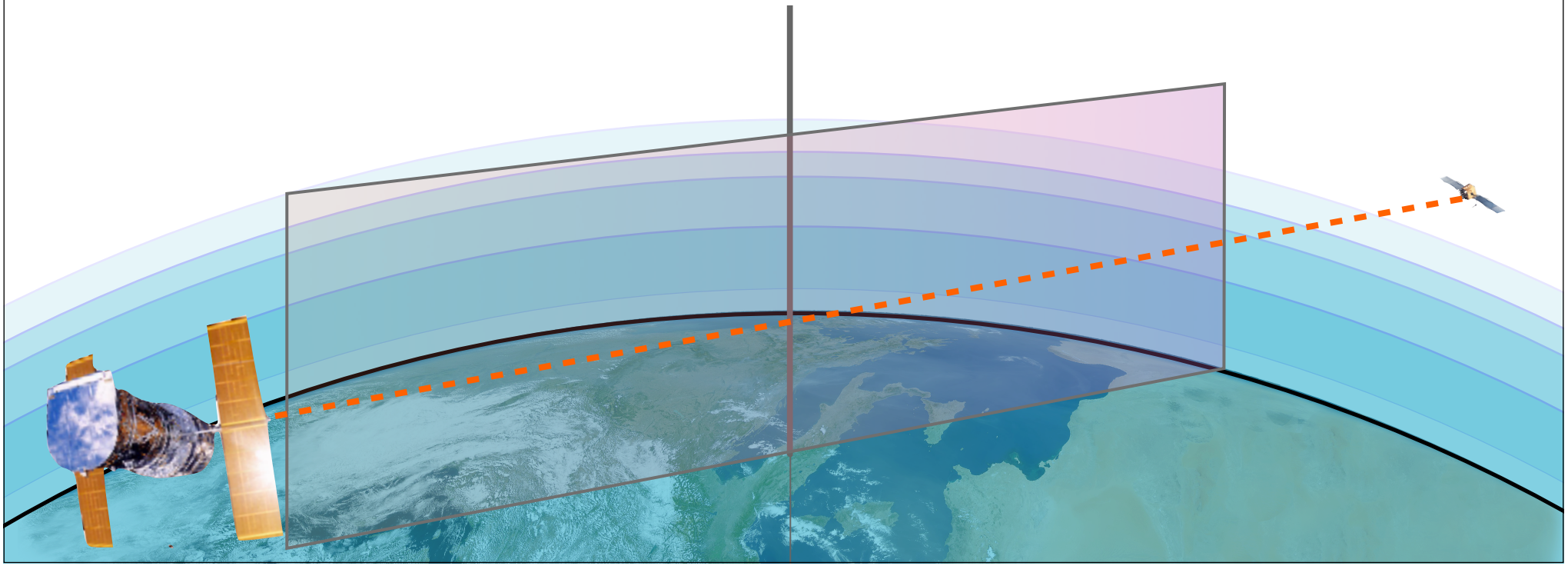
120°


COS RSA DLN 03 F VB flx195 mth12 ut01 az120.mod
Peak Lat: -1.66° Peak Lon: -71.14° Peak LT: 20.84
TRUTH
DG_DELN
800
600
400
200
h [km]
0
500000
1×10^6
1.5×10^6
2×10^6
2.5×10^6
3×10^6
N(h) [cm-3]

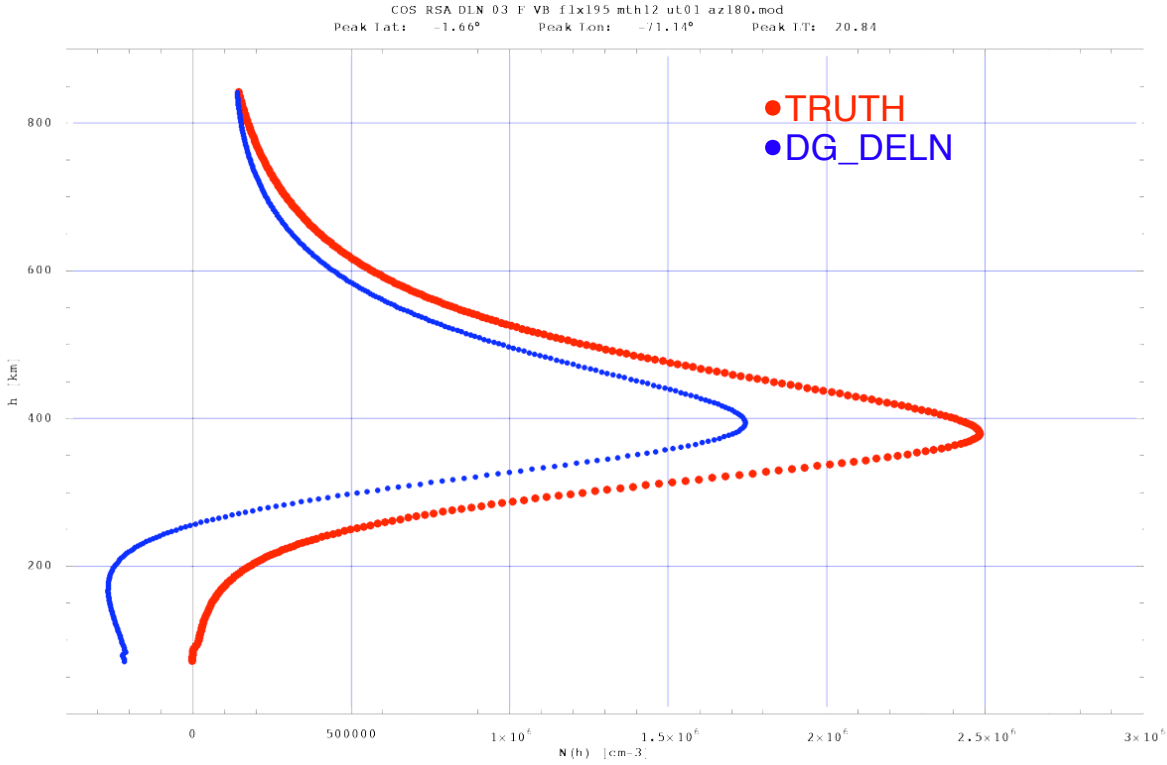


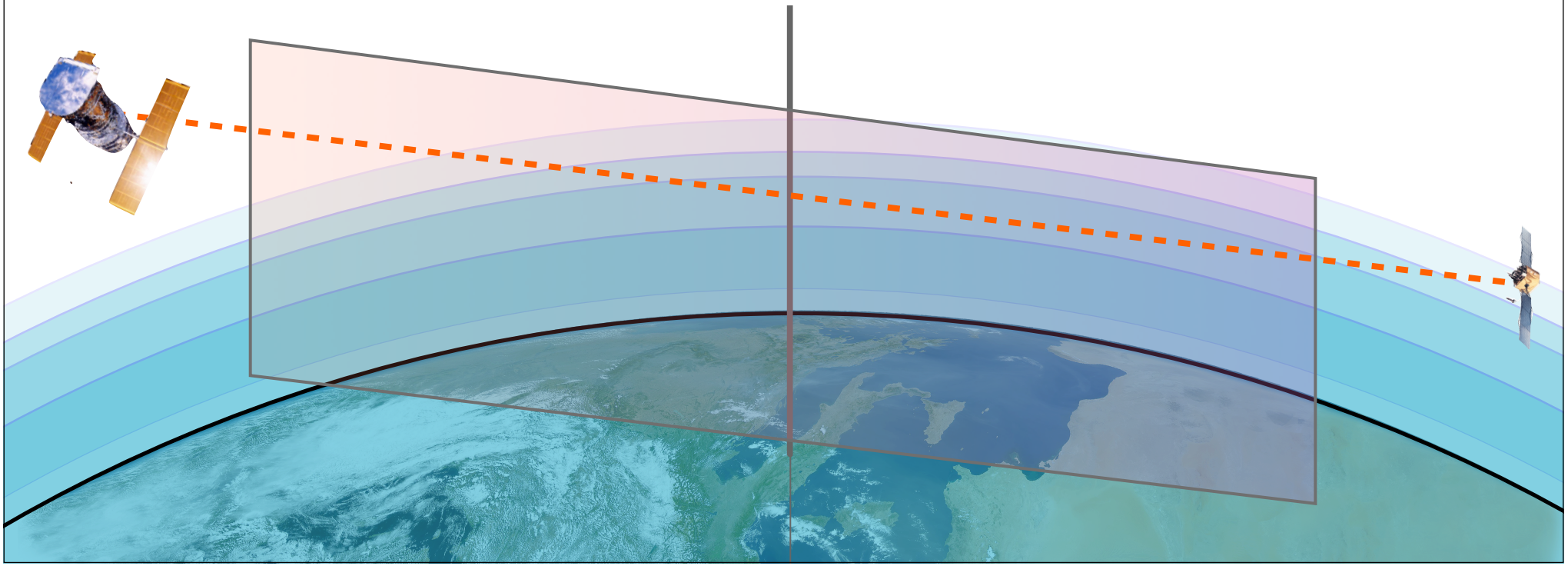
150°


COS RSA DLN 03 F VB flx195 mth12 ut01 az150.mod
Peak Lat: -1.66°
Peak Lon: -71.14°
Peak LT: 20.84
TRUTH
DG_DELN
800
600
400
200
h [km]
0
500000
1×10^6
1.5×10^6
2×10^6
2.5×10^6
3×10^6
N(h) [cm-3]

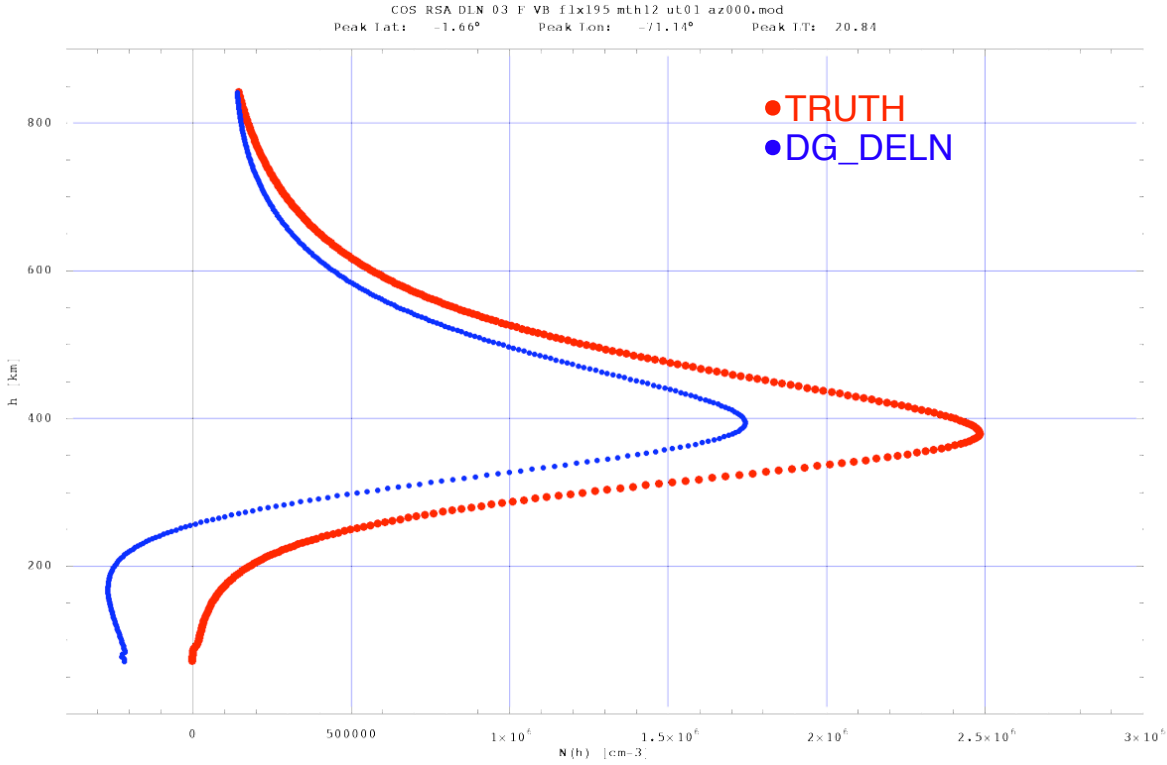


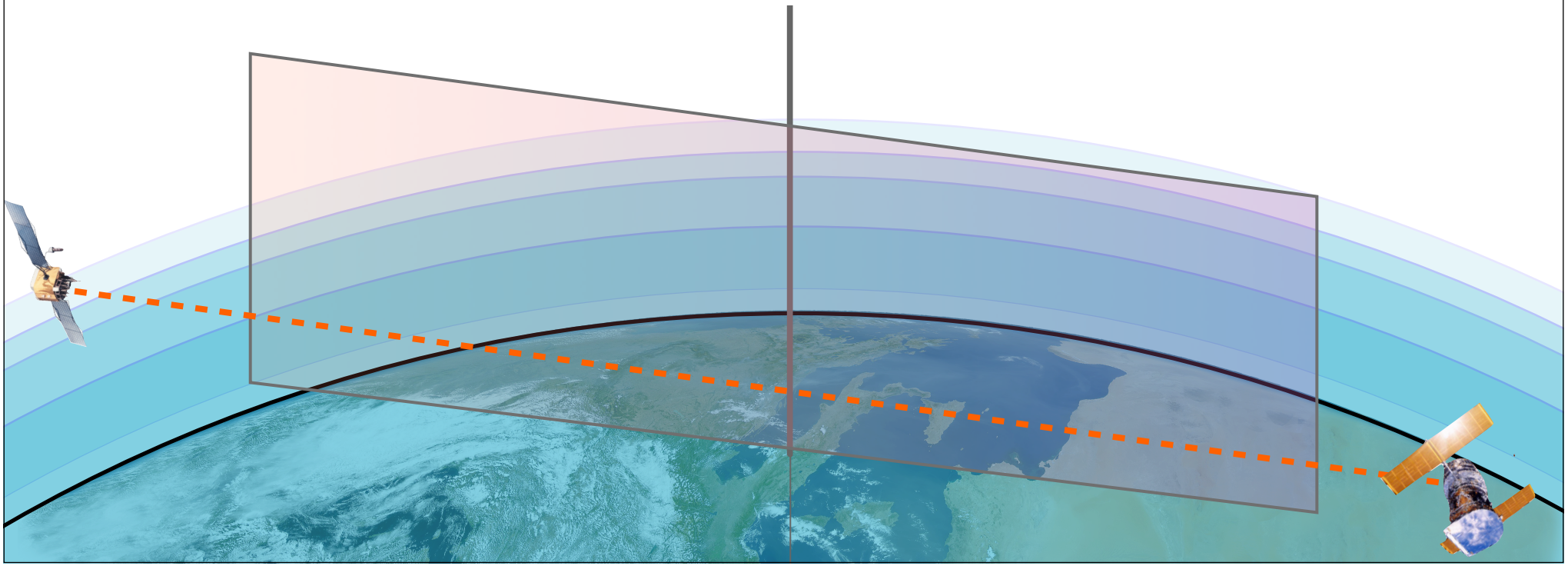
180°


COS RSA DLN 03 F VB flx195 mth12 ut01 az180.mod
Peak Lat: -1.66°
Peak Lon: -71.14°
Peak LT: 20.84
TRUTH
DG_DELN
800
600
400
200
h [km]
0
500000
1×10^6
1.5×10^6
2×10^6
2.5×10^6
3×10^6
N(h) [cm-3]

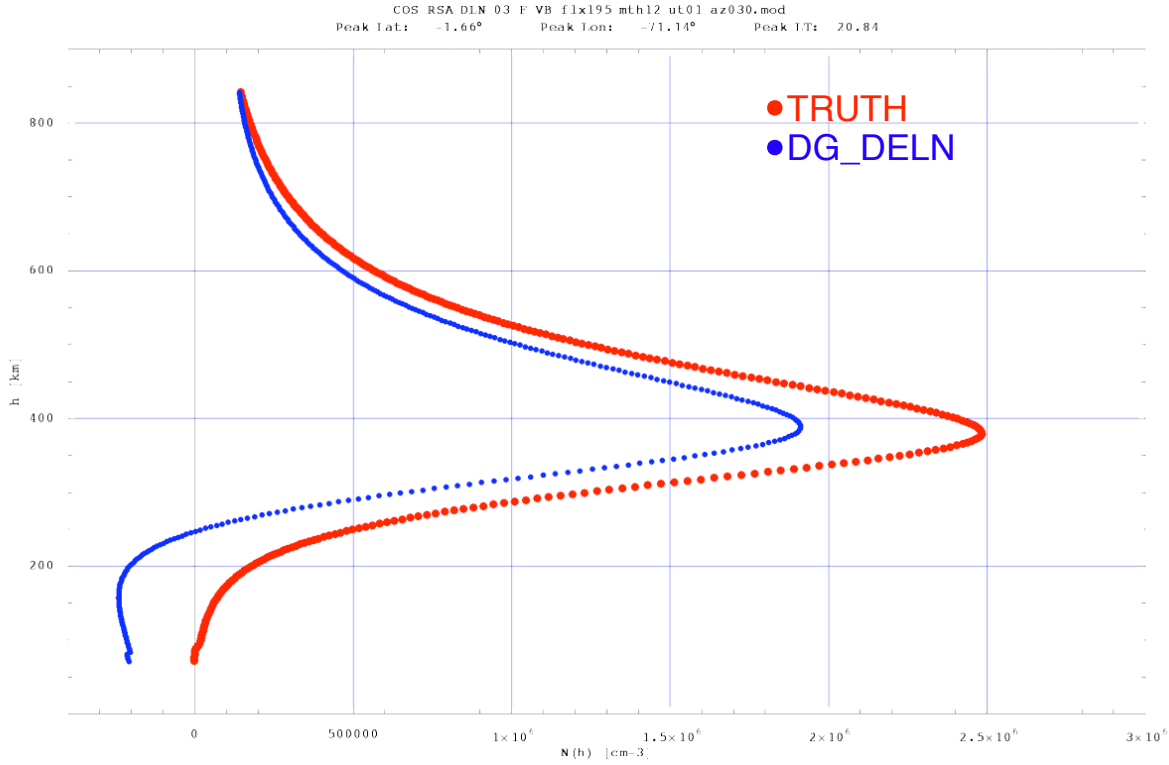


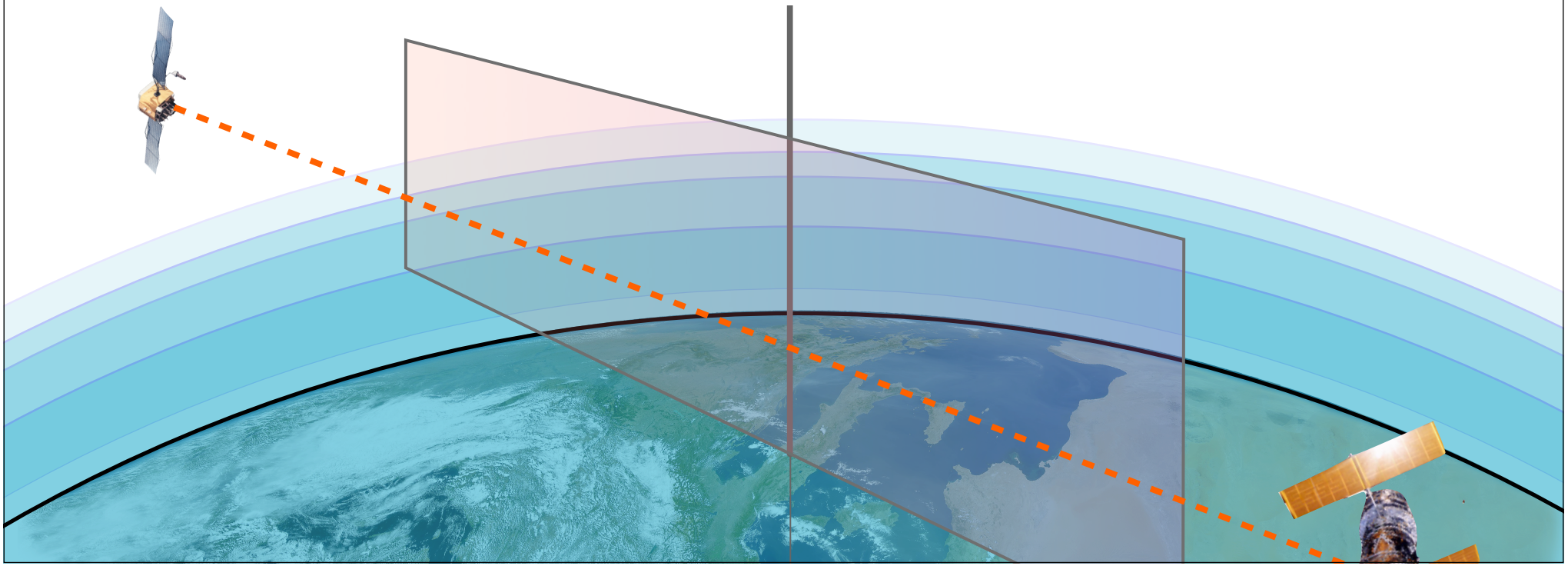
0°


COS RSA DLN 03 F VB flx195 mth12 ut01 az000.mod
Peak Lat: -1.66°
Peak Lon: -71.14°
Peak LT: 20.84
TRUTH
DG_DELN
800
600
400
200
h [km]
0
500000
1×10^6
1.5×10^6
2×10^6
2.5×10^6
3×10^6
N(h) [cm-3]

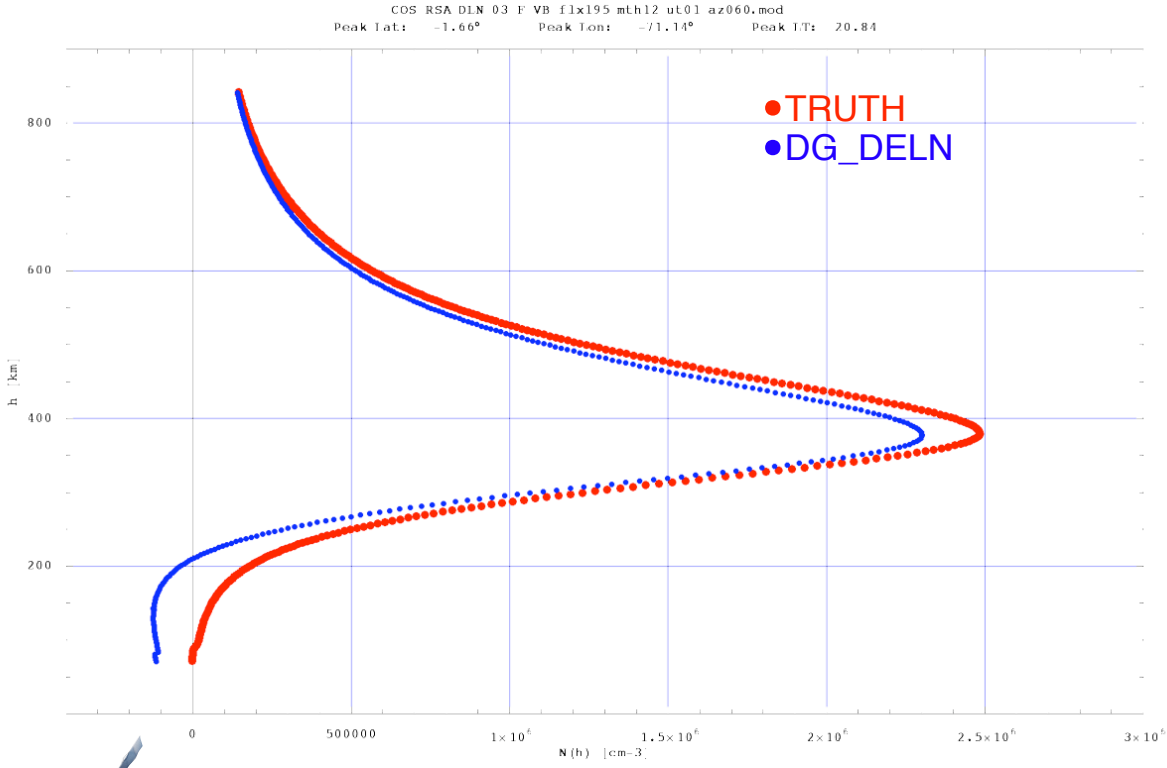


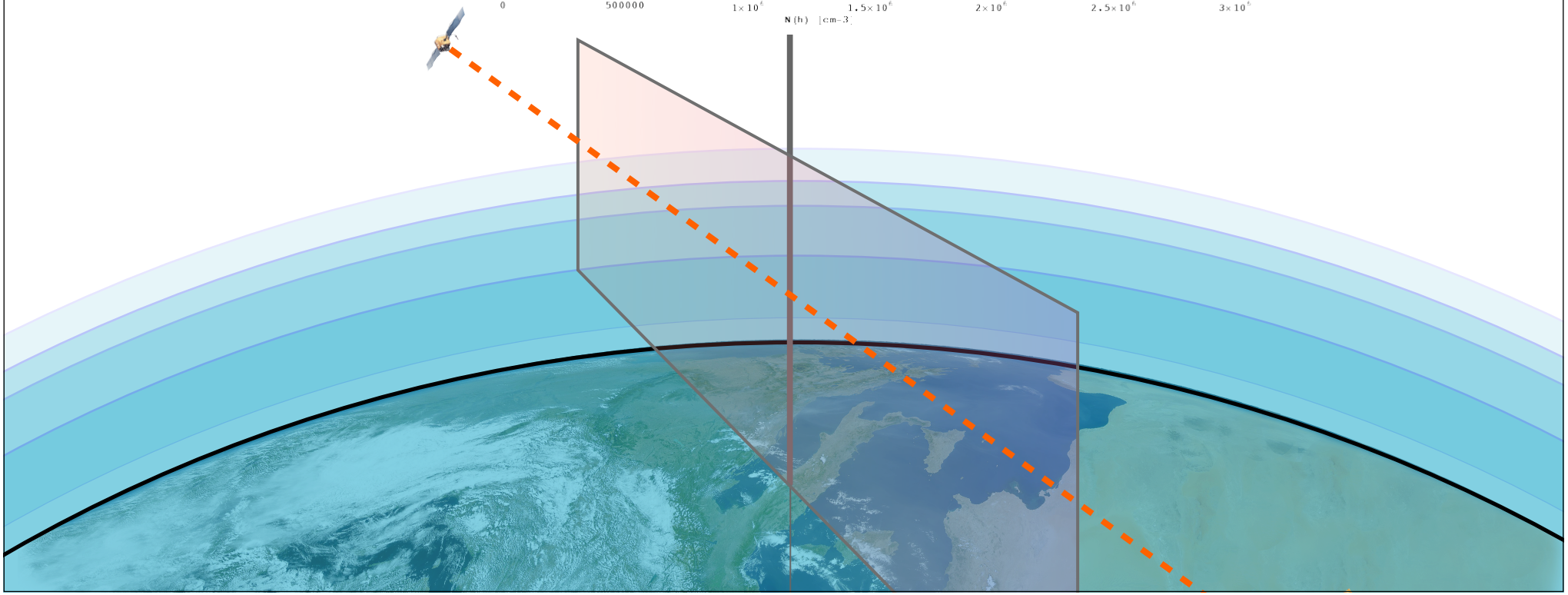
30°


COS RSA DLN 03 F VB flx195 mth12 ut01 az030.mod
Peak Lat: -1.66° Peak Lon: -71.14° Peak LT: 20.84
TRUTH
DG_DELN
800
600
400
200
h [km]
0
500000
1×10^6
1.5×10^6
2×10^6
2.5×10^6
3×10^6
N(h) [cm-3]

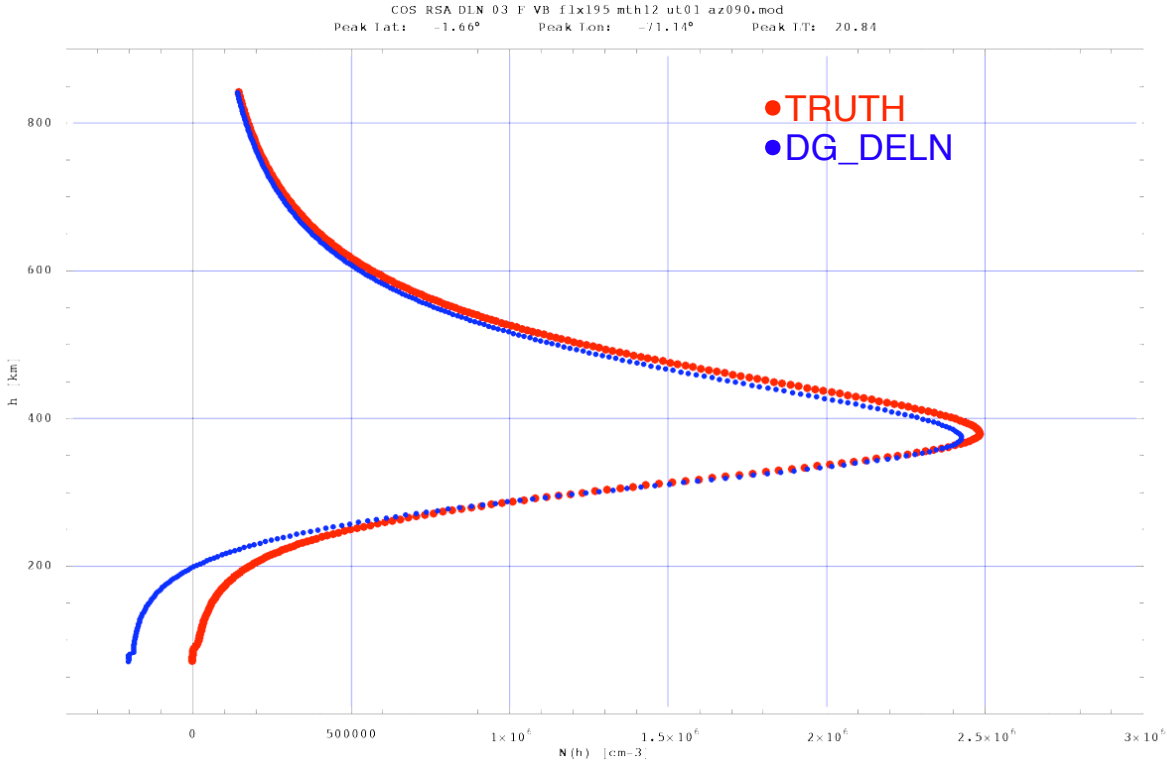


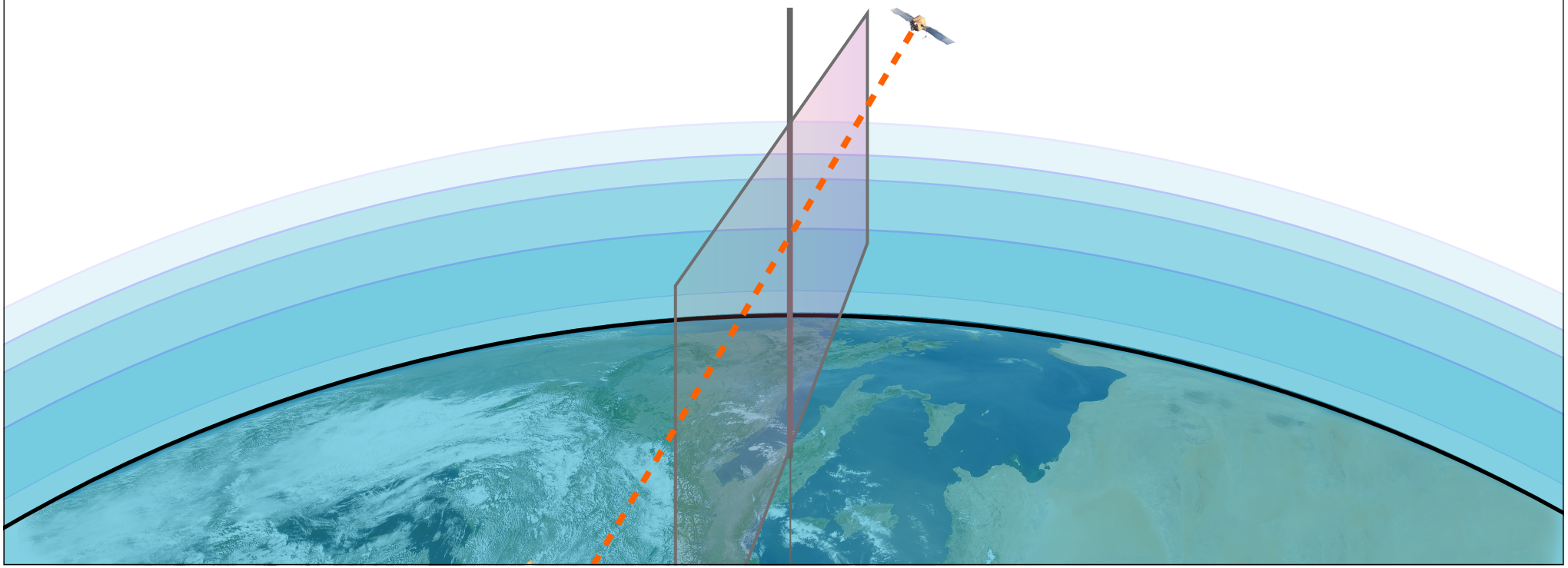
60°


COS RSA DLN 03 F VB flx195 mth12 ut01 az060.mod
Peak Lat: -1.66° Peak Lon: -71.14° Peak LT: 20.84
TRUTH
DG_DELN
800
600
400
200
h [km]
0
500000
1×10^6
1.5×10^6
2×10^6
2.5×10^6
3×10^6
N(h) [cm-3]

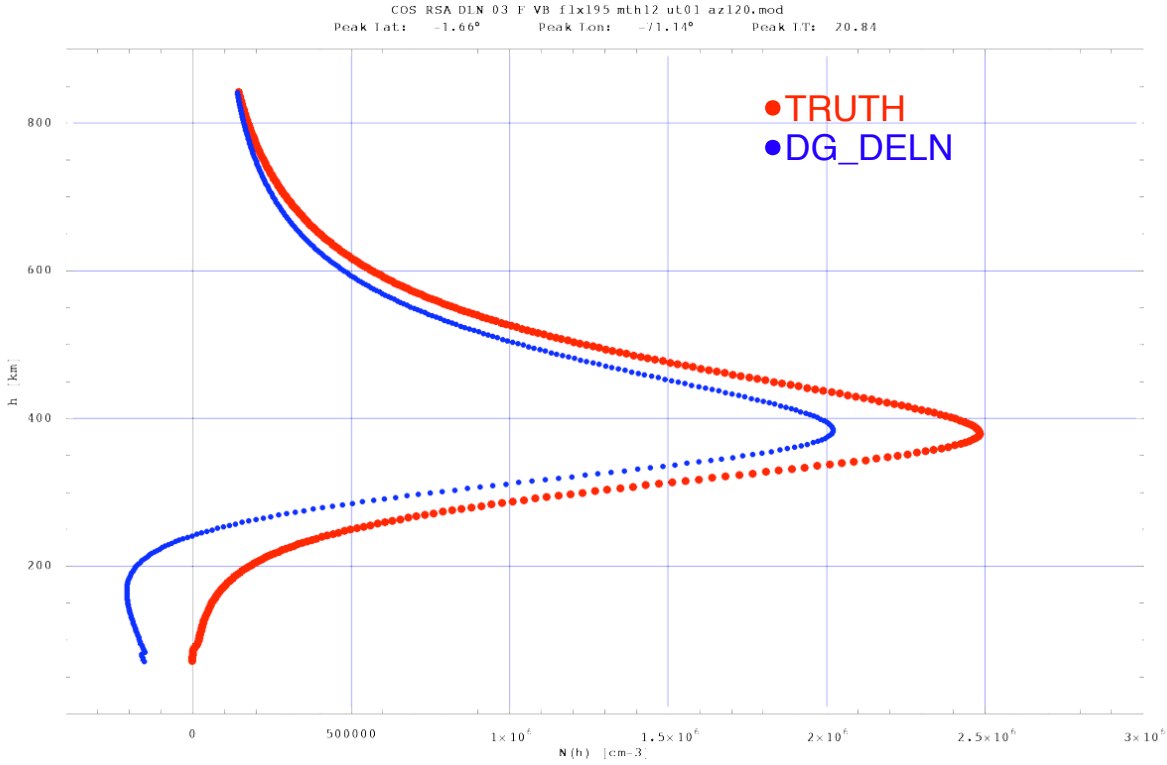


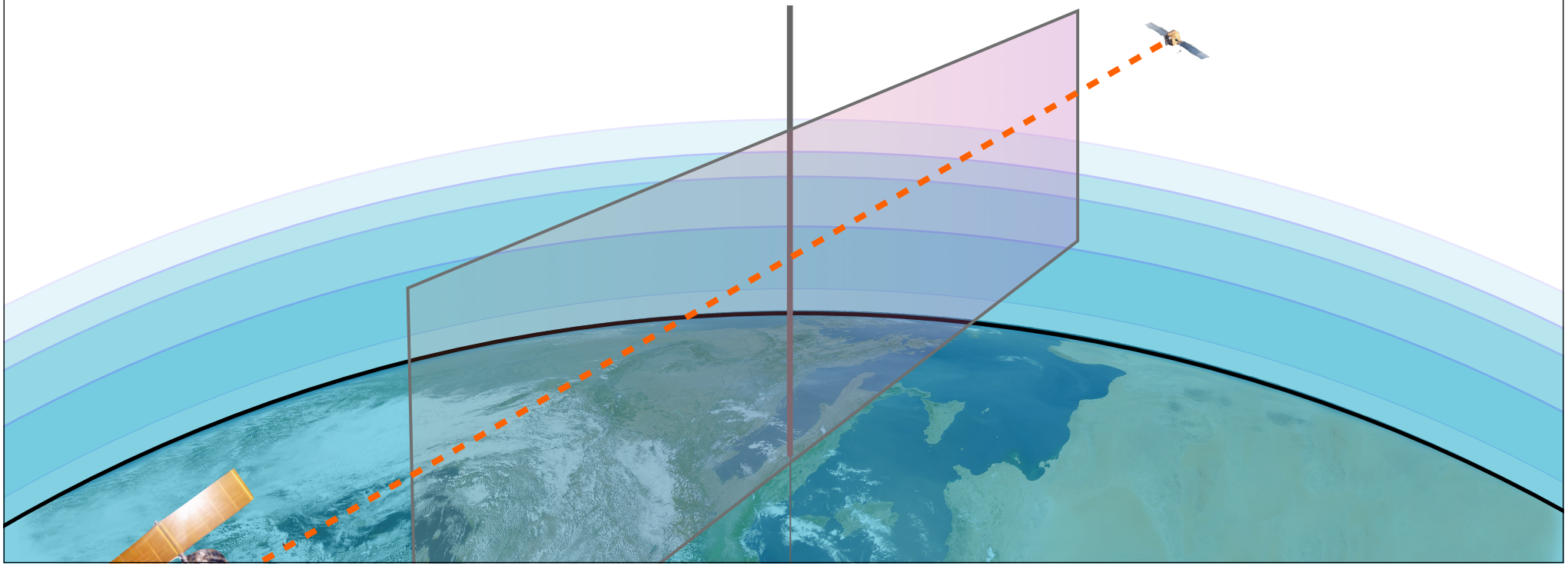
90°


COS RSA DLN 03 F VB flx195 mth12 ut01 az090.mod
Peak Lat: -1.66°
Peak Lon: -71.14°
Peak LT: 20.84
TRUTH
DG_DELN
800
600
400
200
h [km]
0
500000
1×10^6
1.5×10^6
2×10^6
2.5×10^6
3×10^6
N(h) [cm-3]

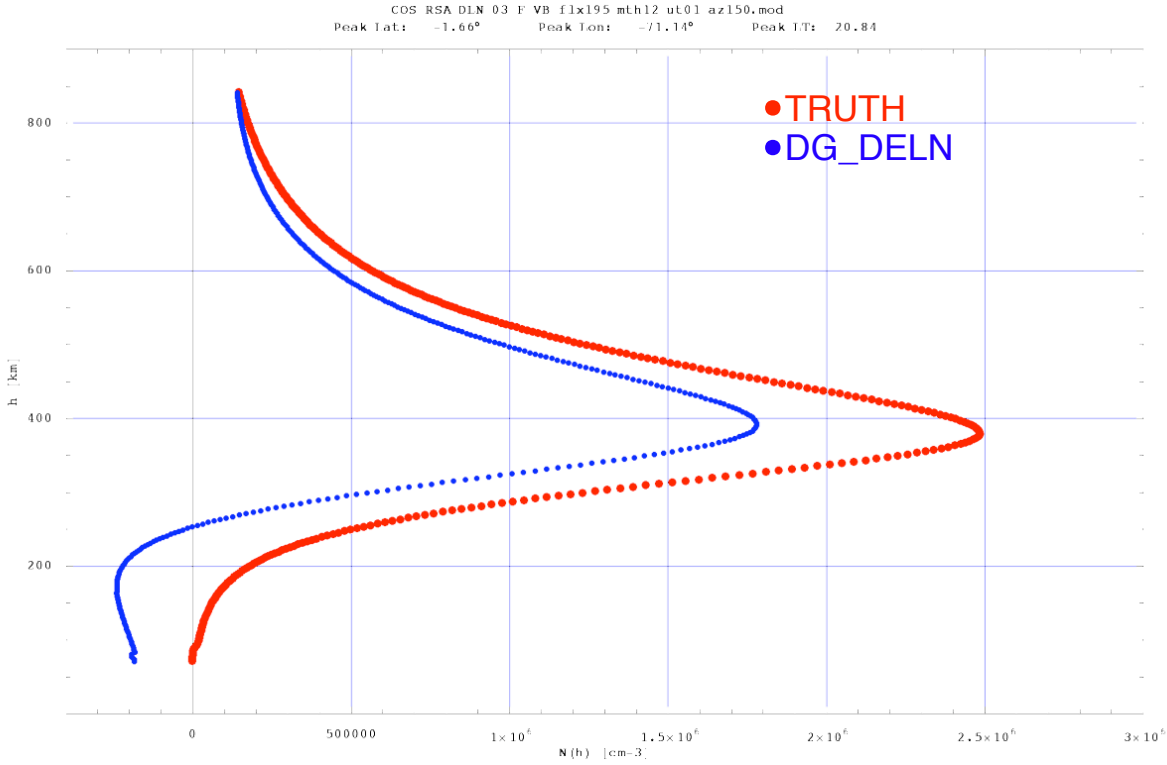


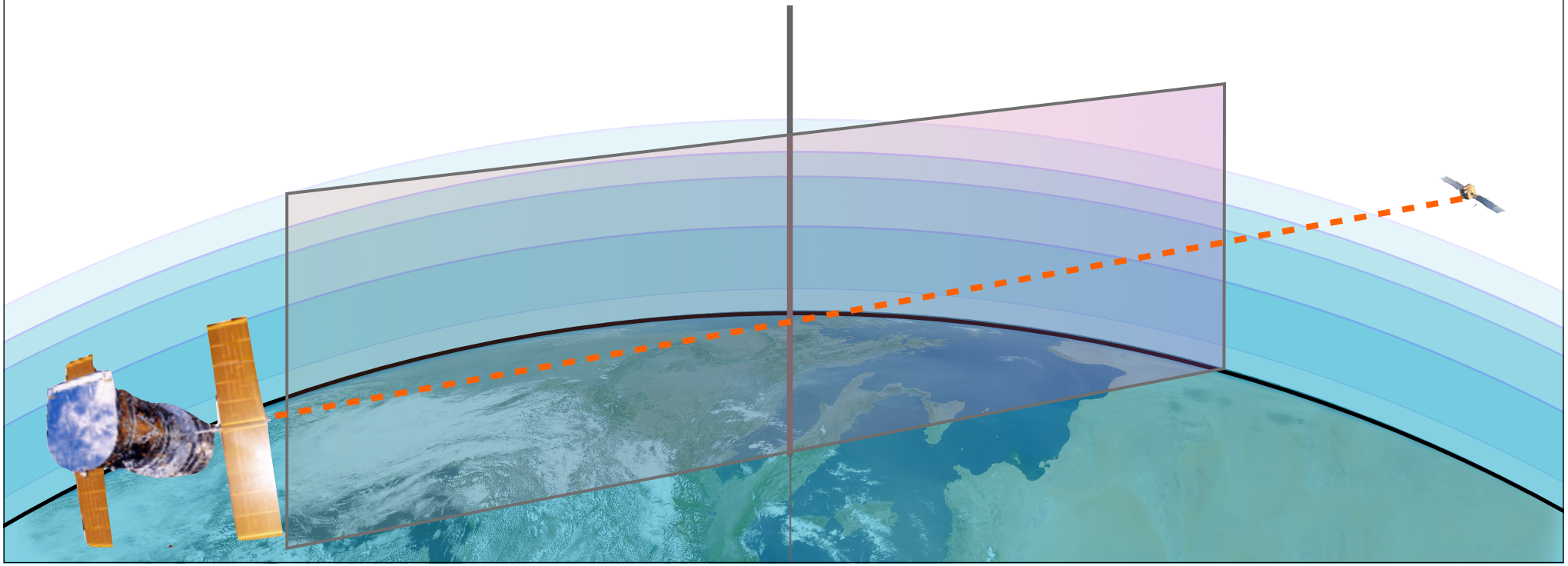
120°


COS RSA DLN 03 F VB flx195 mth12 ut01 az120.mod
Peak Lat: -1.66° Peak Lon: -71.14° Peak LT: 20.84
TRUTH
DG_DELN
800
600
400
200
h [km]
0
500000
1×10^6
1.5×10^6
2×10^6
2.5×10^6
3×10^6
N(h) [cm-3]

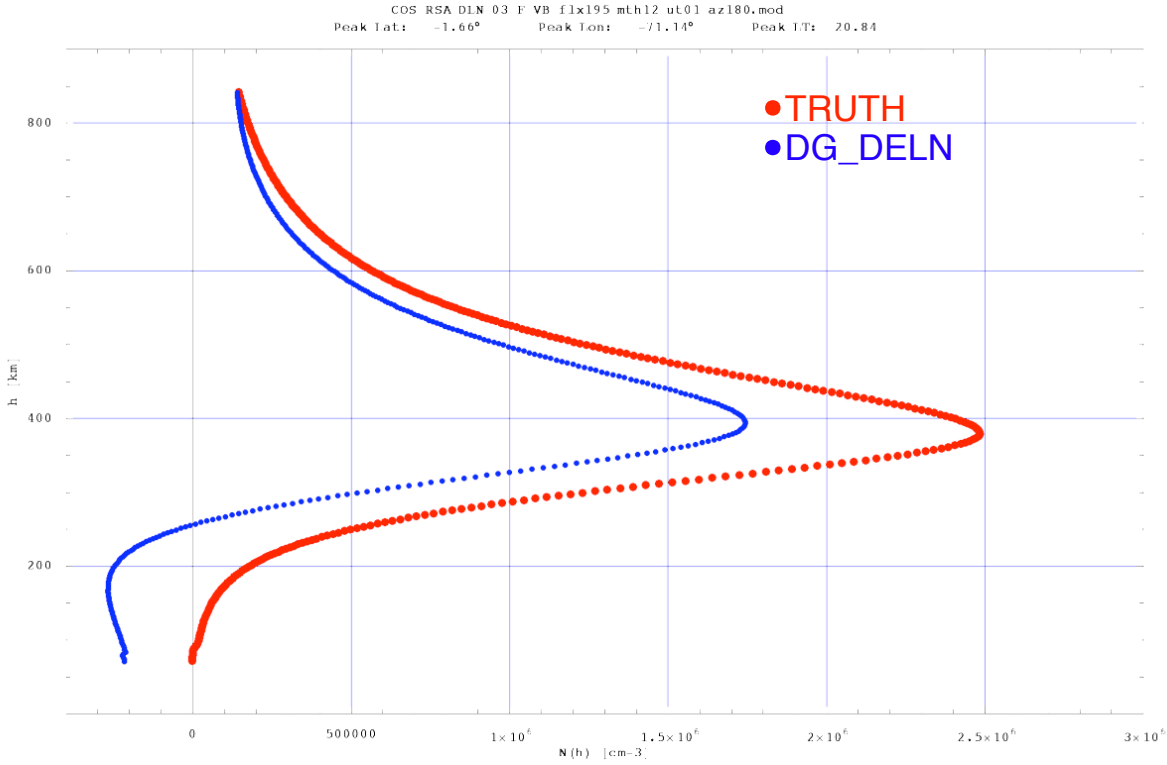


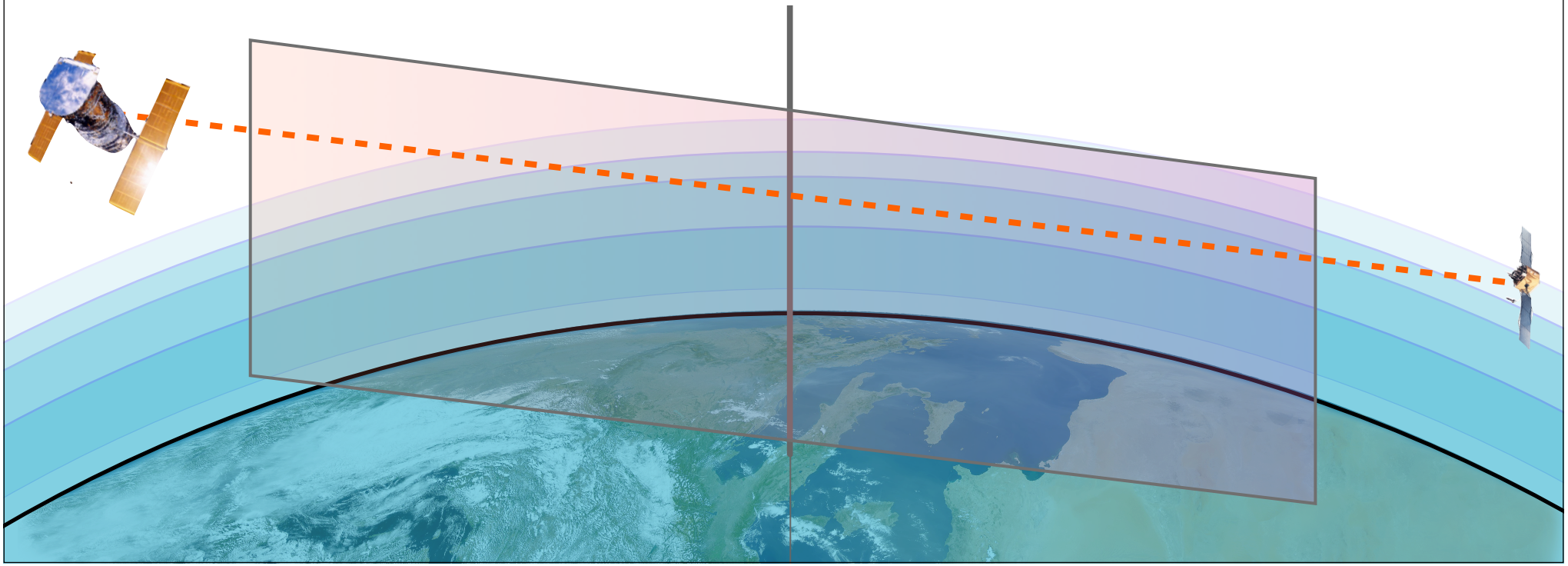
150°


COS RSA DLN 03 F VB flx195 mth12 ut01 az150.mod
Peak Lat: -1.66°
Peak Lon: -71.14°
Peak LT: 20.84
TRUTH
DG_DELN
800
600
400
200
h [km]
0
500000
1×10^6
1.5×10^6
2×10^6
2.5×10^6
3×10^6
N(h) [cm-3]



180°

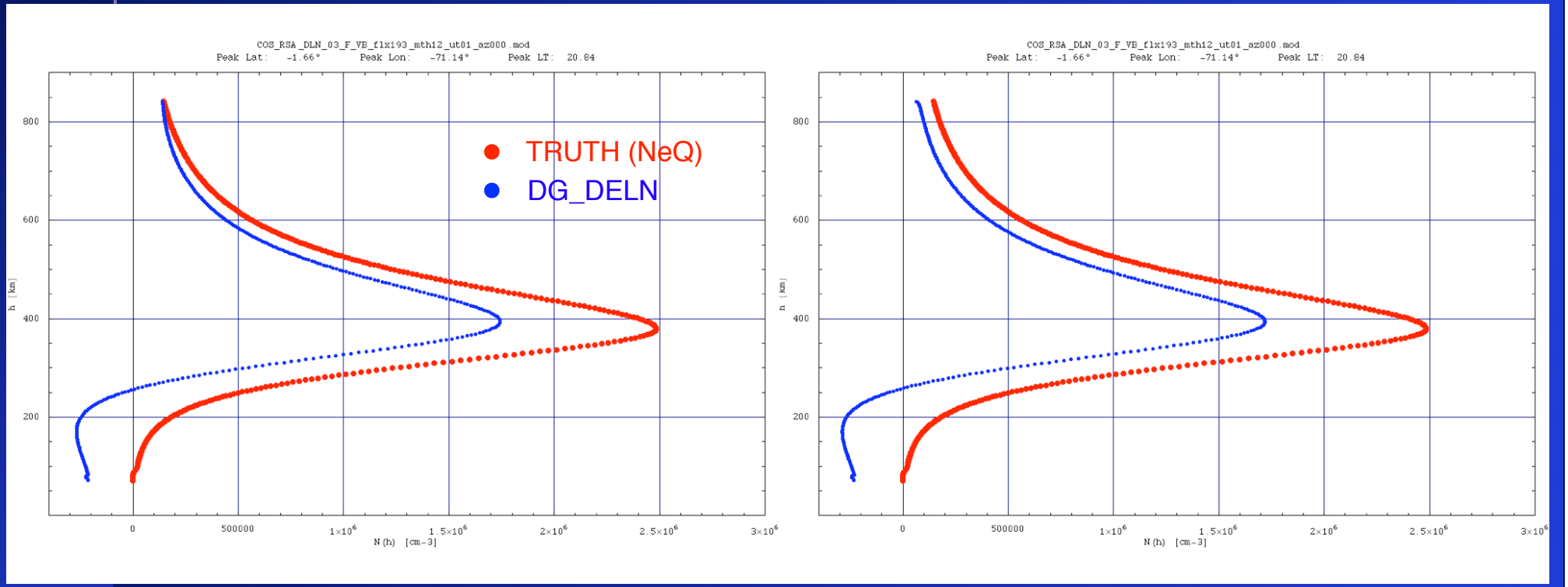

COS RSA DLN 03 F VB flx195 mth12 ut01 az180.mod
Peak Lat: -1.66°
Peak Lon: -71.14°
Peak LT: 20.84
TRUTH
DG_DELN
800
600
400
200
h [km]
0
500000
1×10^6
1.5×10^6
2×10^6
2.5×10^6
3×10^6
N(h) [cm-3]



The role of the “same side” (auxiliary) data in TEC calibration

SIMULATION RESULTS

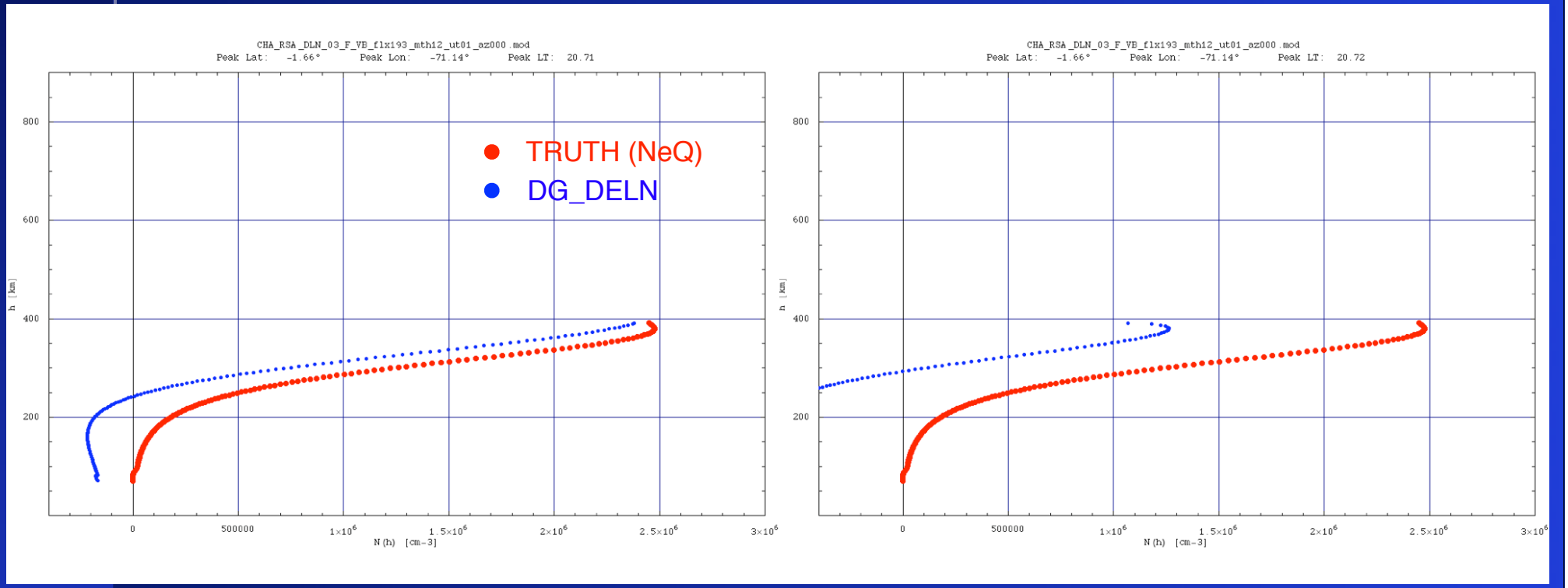
TEC calibration (COSMIC like sat.)



WITH auxiliary data

WITHOUT auxiliary data

TEC calibration (CHAMP like sat.)



WITH auxiliary data

WITHOUT auxiliary data

Onion Peeling validation

A test case

Day: 31 Dec. 2007

True satellite orbits (GPS + COSMIC)

Synthetic ionosphere
(TEC from 3D electron density)

Onion Peeling
vs
True profile
(NeQuick)

High & Low solar activity

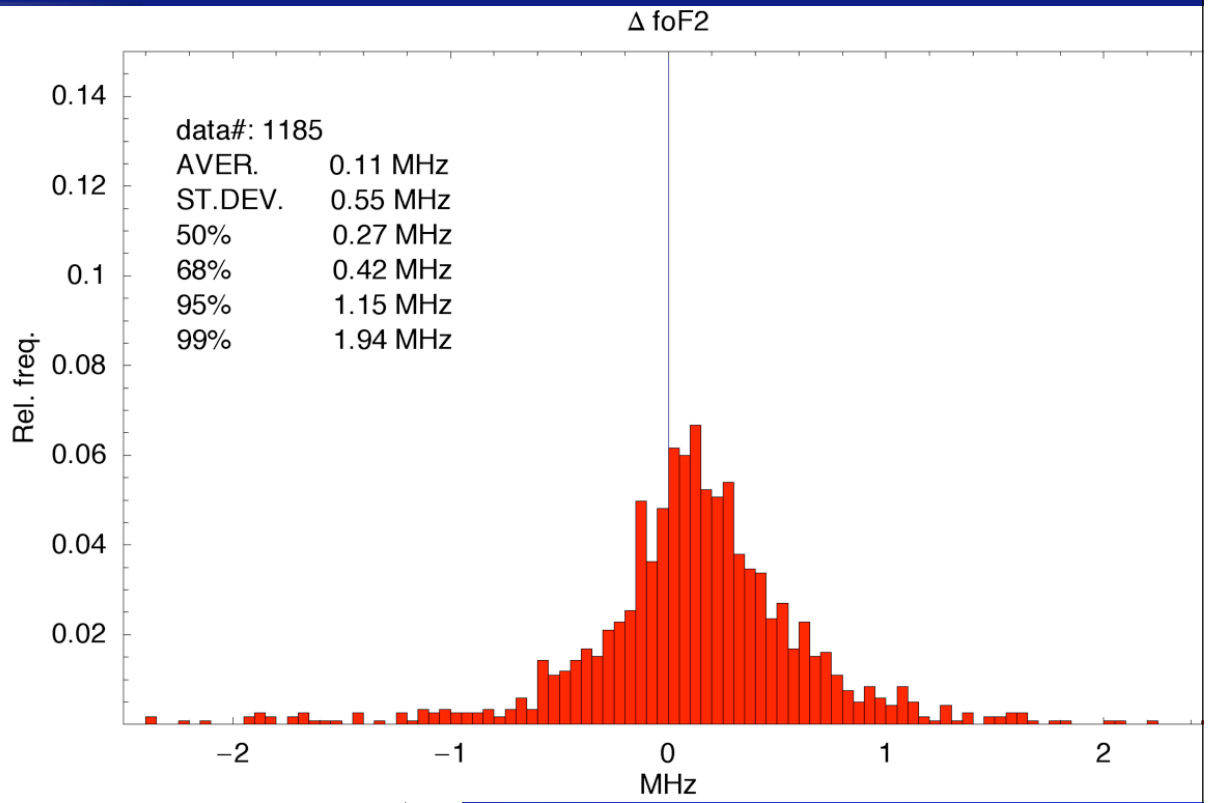
True ionosphere
(excess phase @ L1,L2)

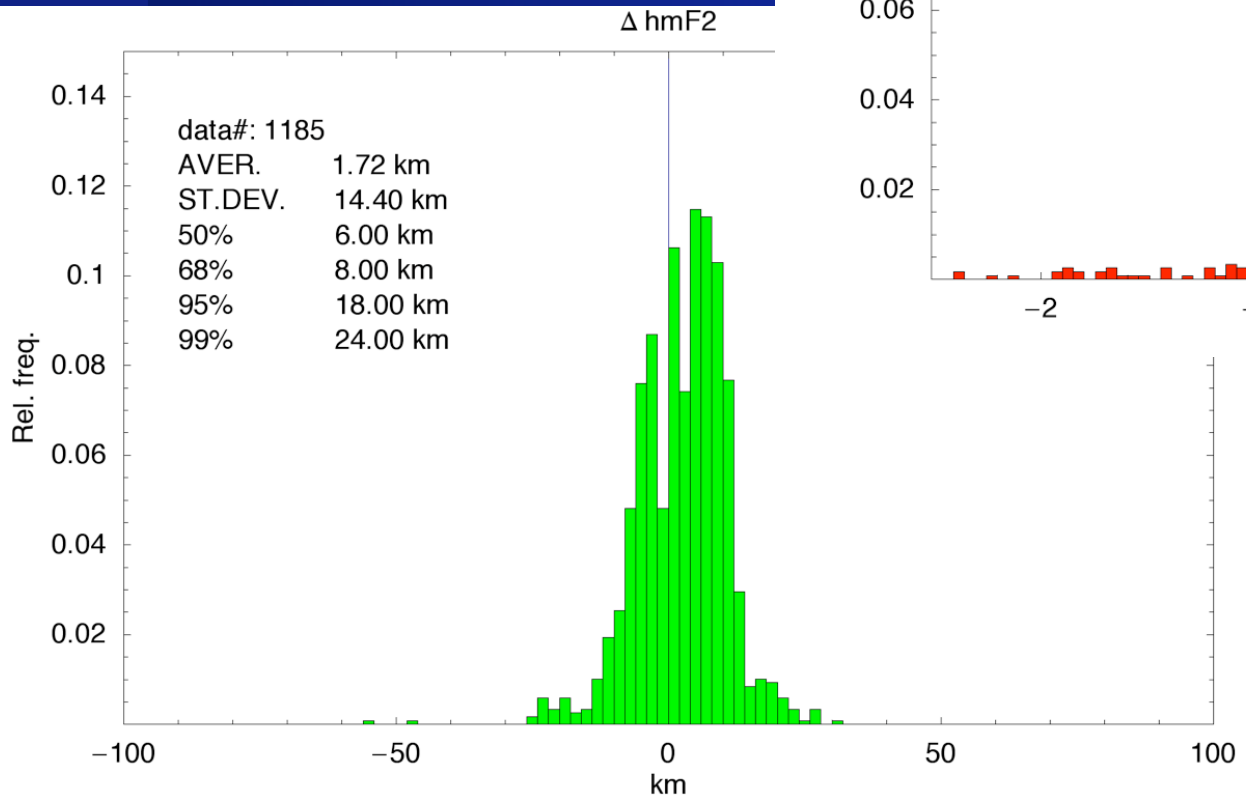
Onion Peeling
vs
True profile
(Ionosonde)

Onion Peeling performance analyzed in
terms of foF2 & hmF2 error statistics

Simulation results (HSA)

foF2 and hmF2 errors statistics





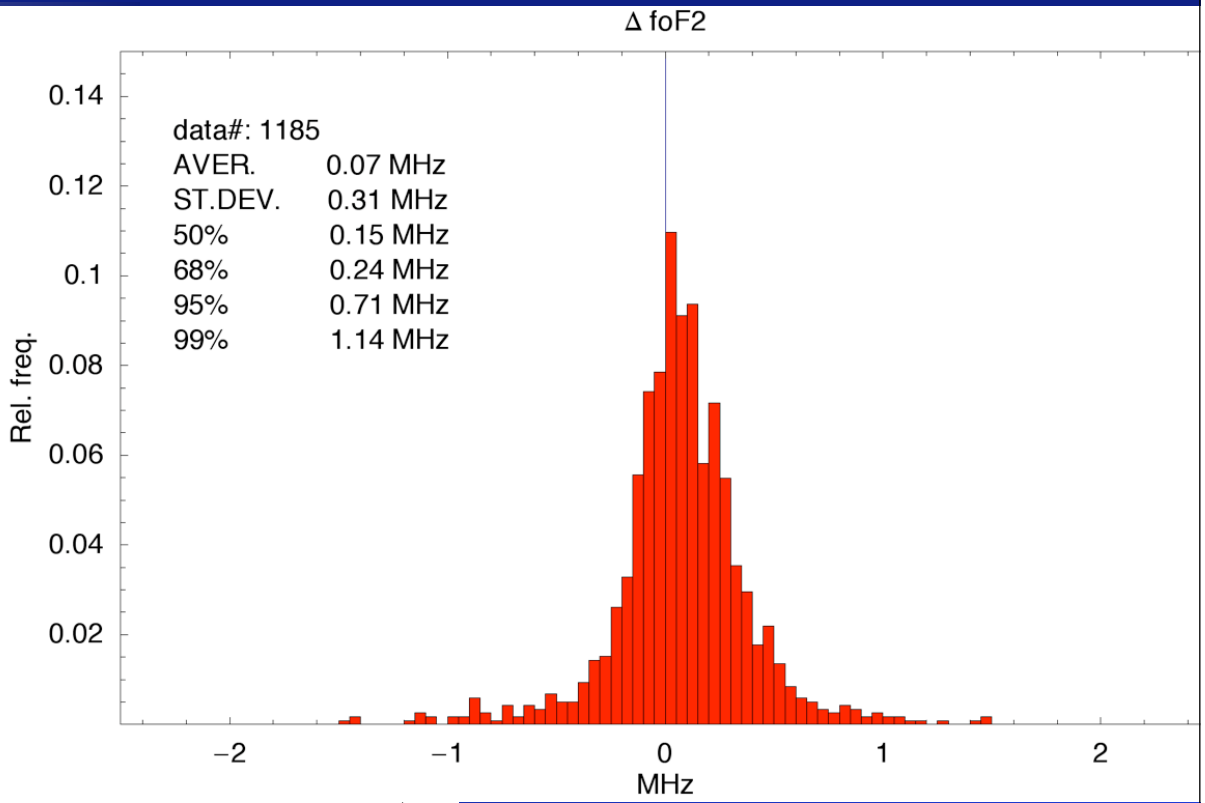
Co-location criteria for true profile and Onion Peeling derived profile

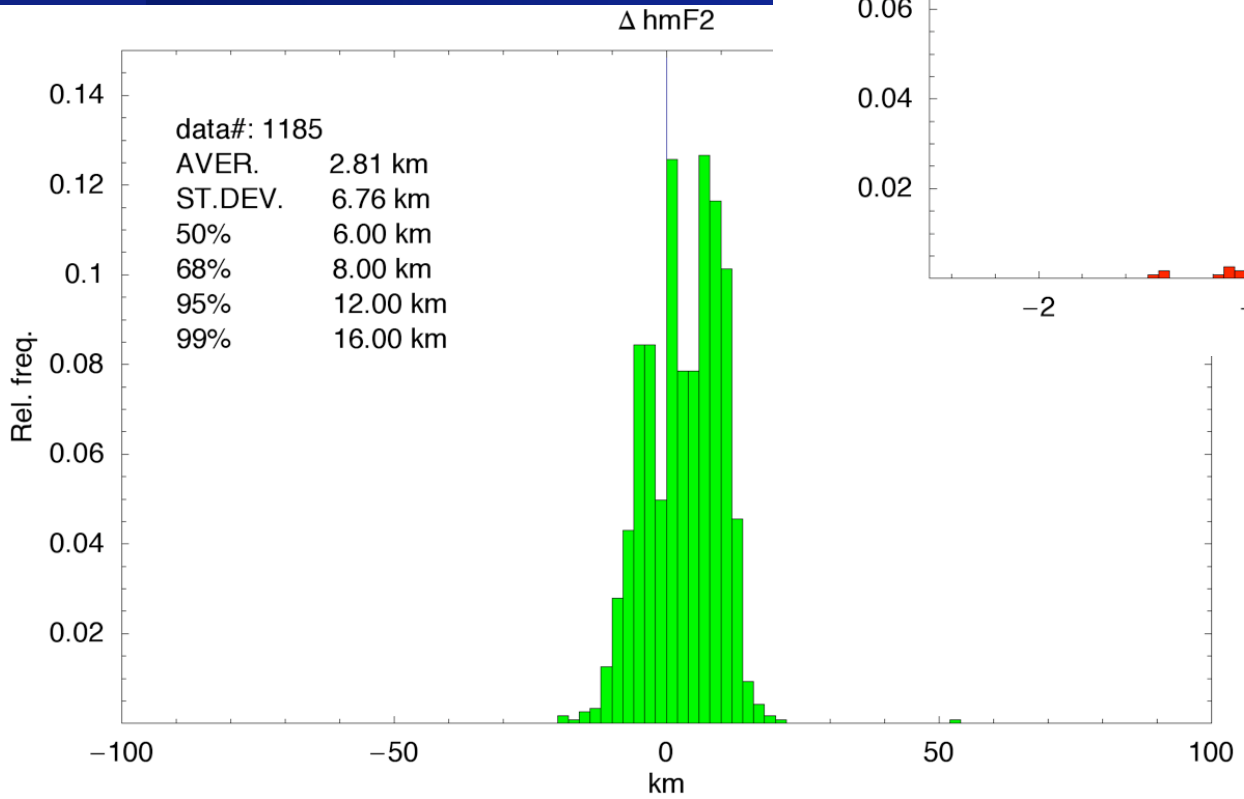
↓

exact matching

Simulation results (LSA)

foF2 and hmF2 errors statistics





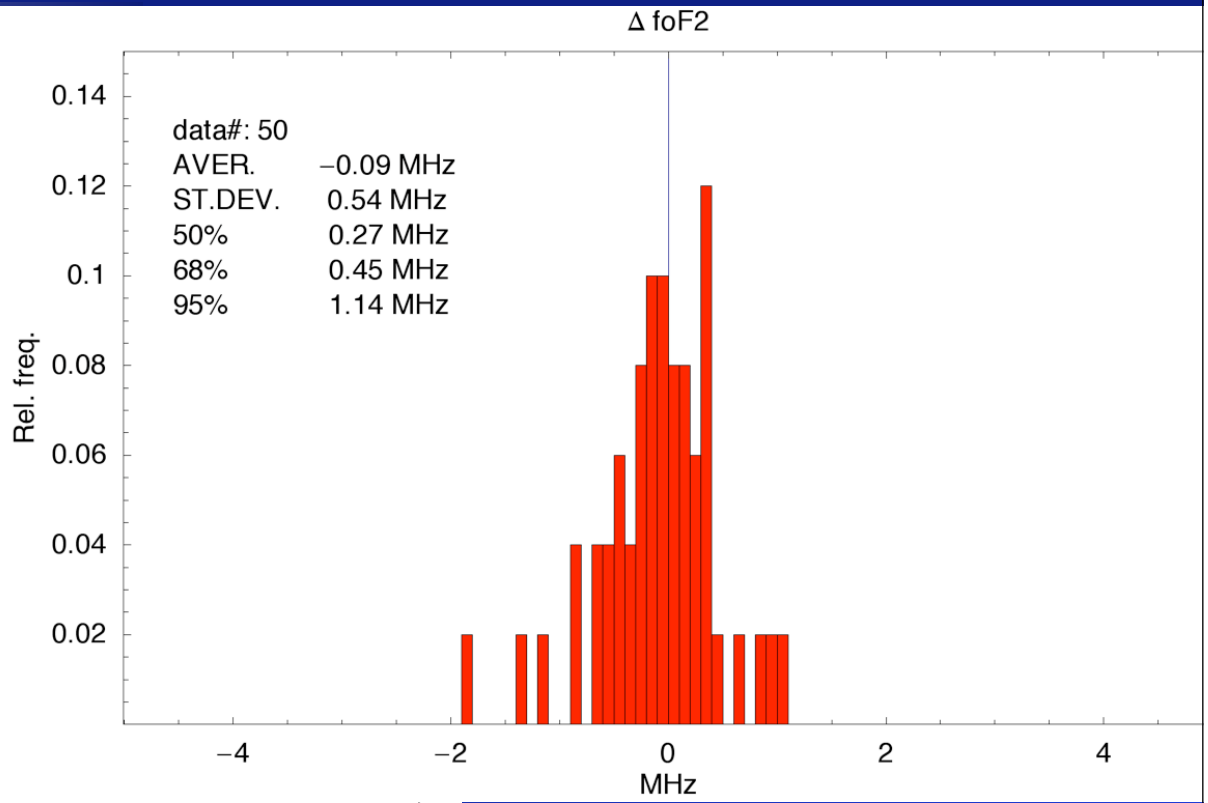
Co-location criteria for true profile and Onion Peeling derived profile

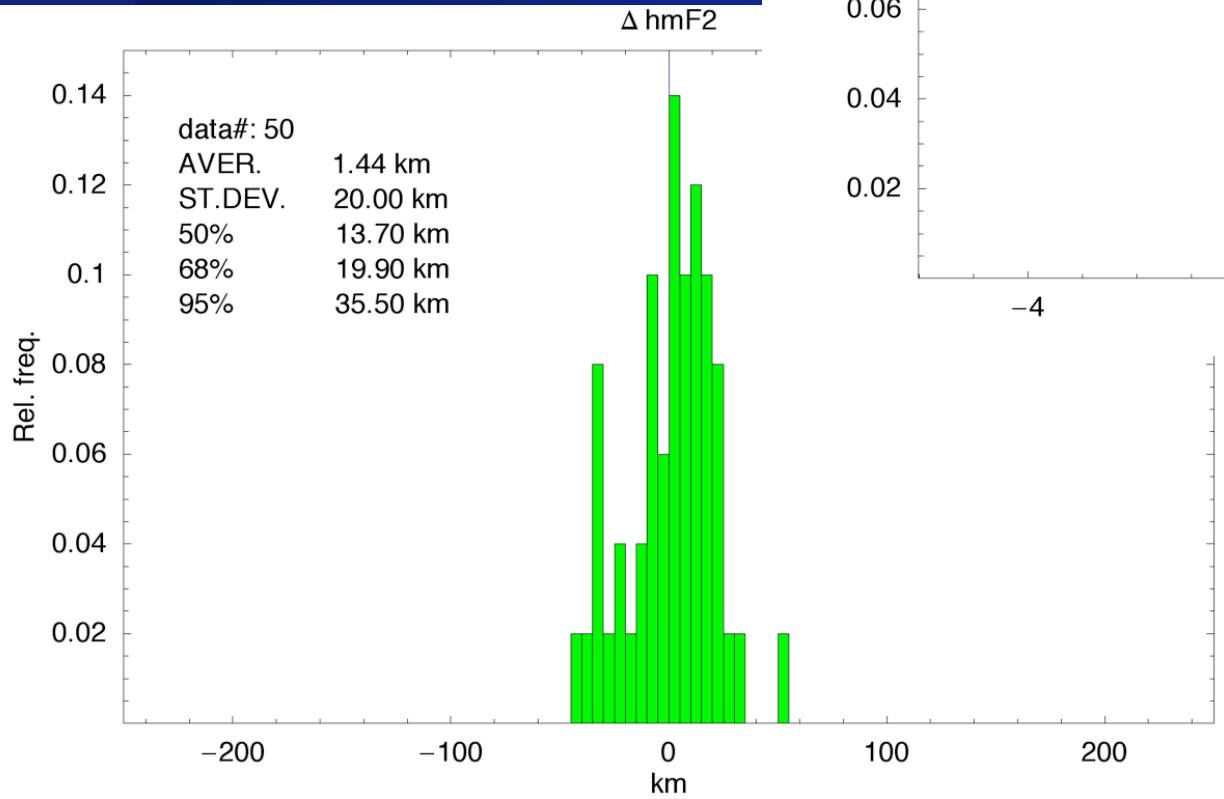
↓

exact matching

Experimental data (LSA)

foF2 and hmF2 errors statistics





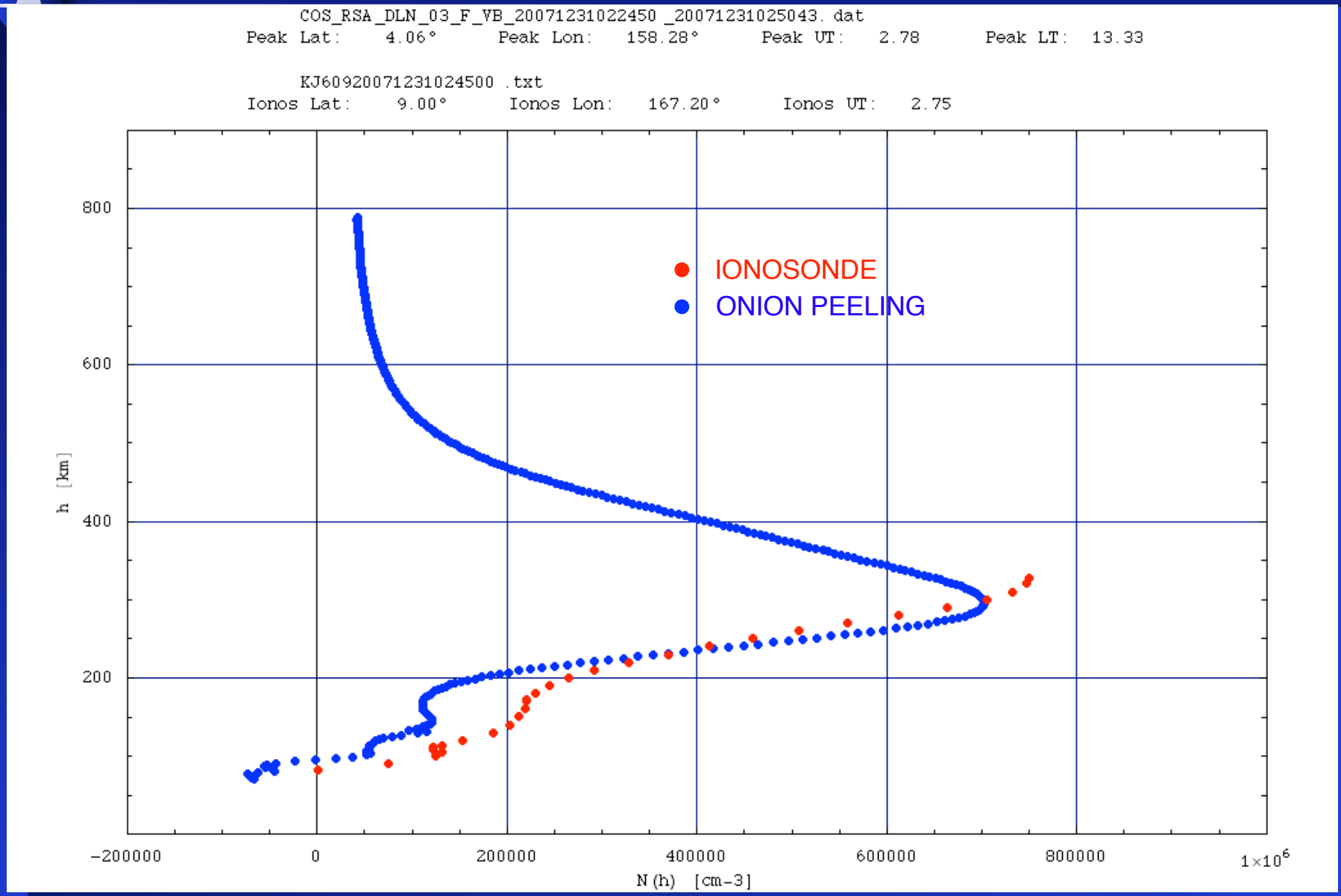
Co-location criteria for true profile and Onion Peeling derived profile

↓

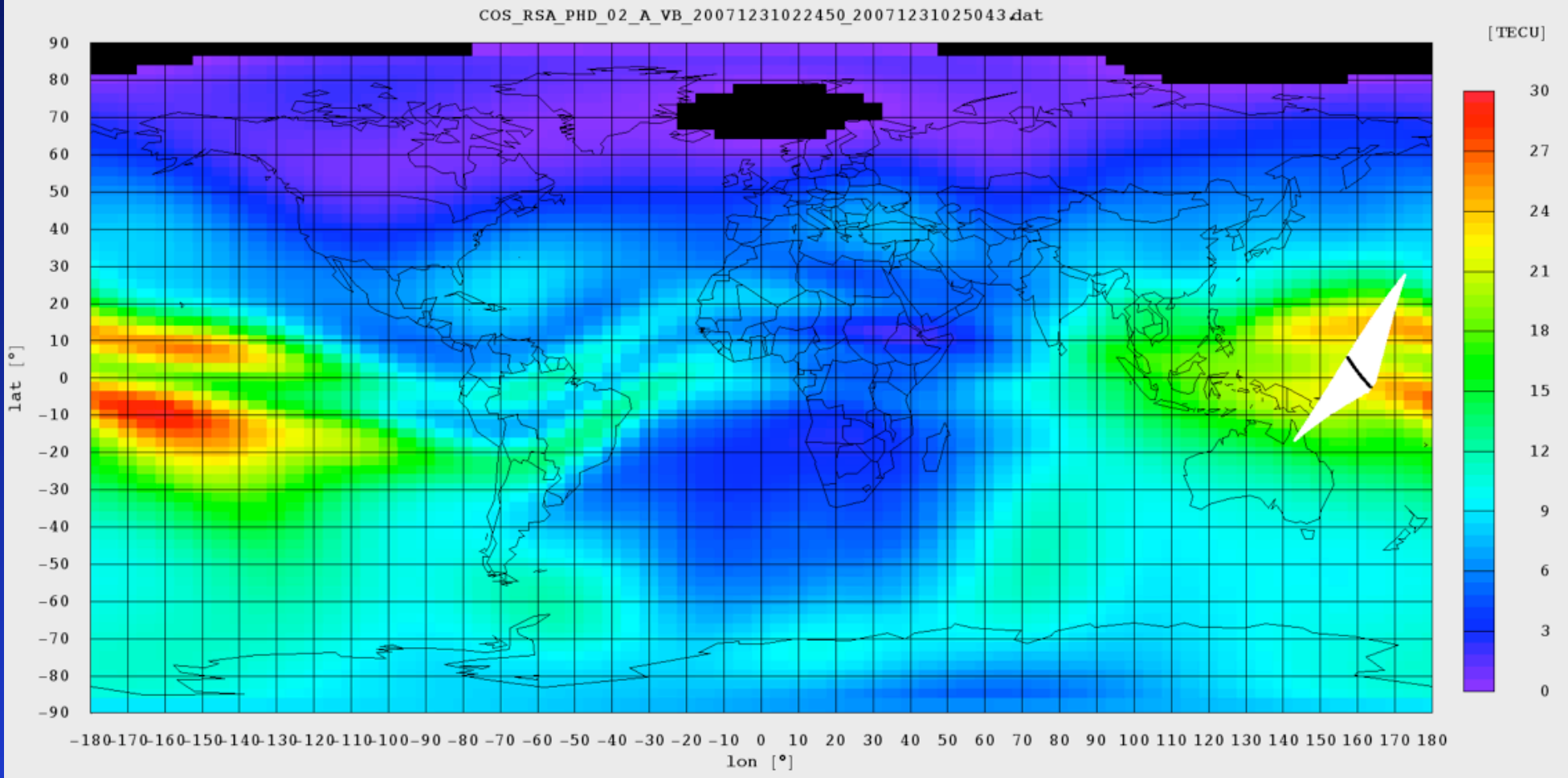
Delta Time < 15 min
Delta Lat < 5°
Delta Lon < 10°

Electron density profiles (examples)

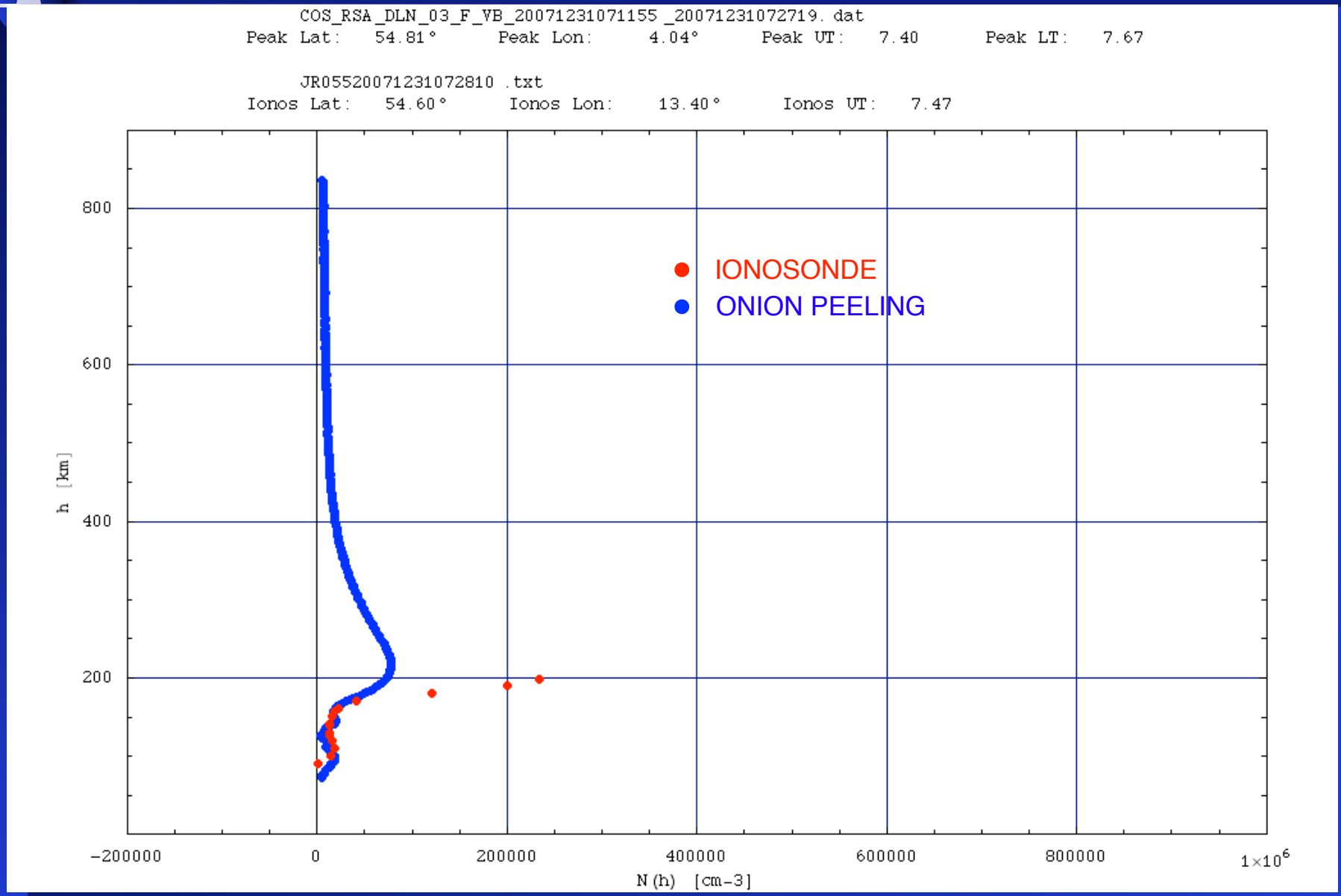
Profile 1


COS_RSA_DLN_03_F_VB_20071231022450 _20071231025043. dat
Peak Lat: 4.06° Peak Lon: 158.28° Peak UT: 2.78 Peak LT: 13.33
KJ609200712310245 00 .txt
Ionos Lat: 9.00° Ionos Lon: 167.20° Ionos UT: 2.75
IONOSONDE
ONION PEELING
h [km]
800
600
400
200
−200000
0
200000
400000
600000
800000
1×10^6
N(h) [cm-3]

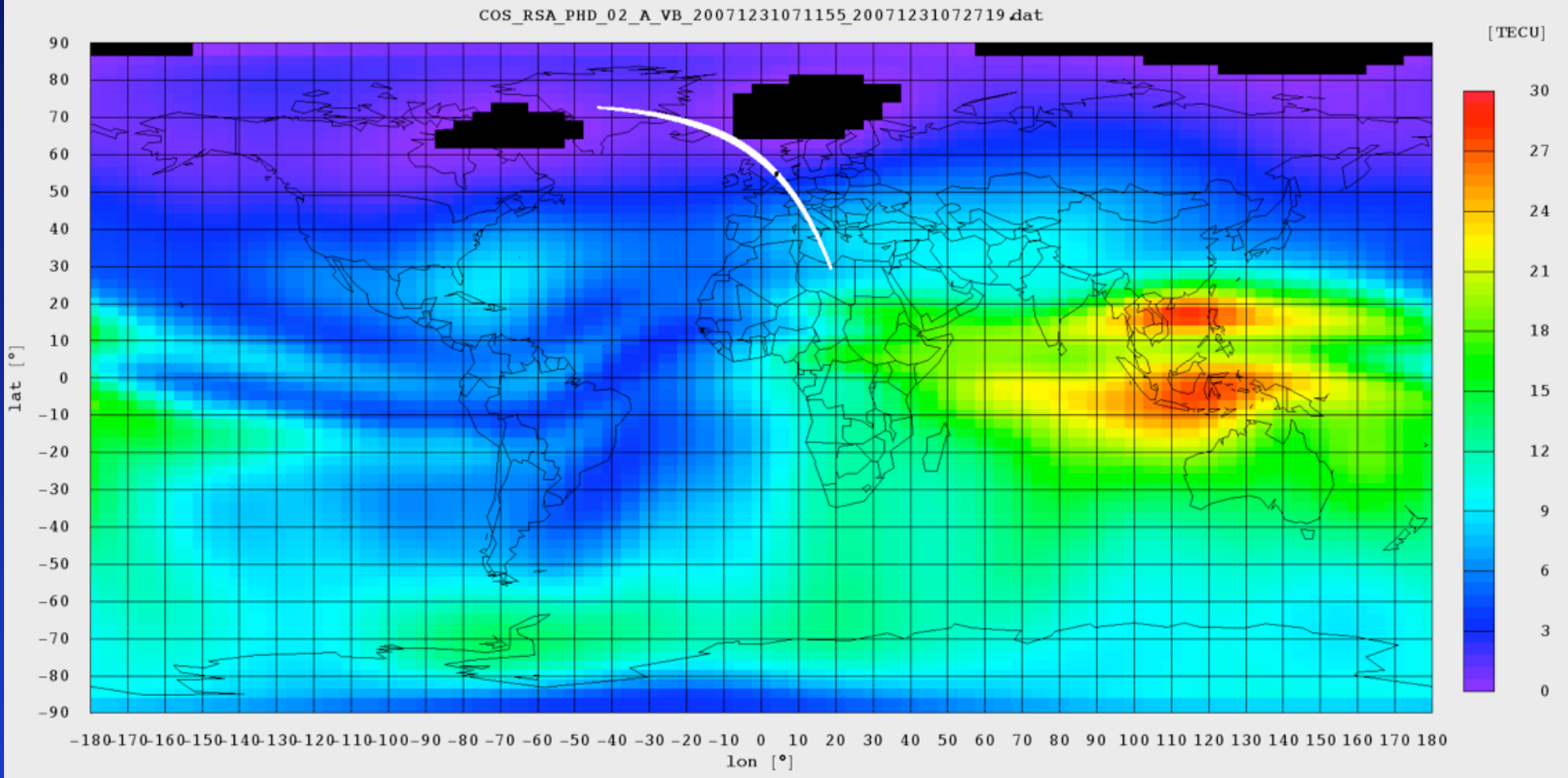
VTEC map 1


COS_RSA_PHD_02_A_VB_20071231022450_20071231025043.dat
[TECU]
30
27
24
21
18
15
12
9
6
3
0
lat [°]
90 80 70 60 50 40 30 20 10 0 -10 -20 -30 -40 -50 -60 -70 -80 -90
-180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
lon [°]

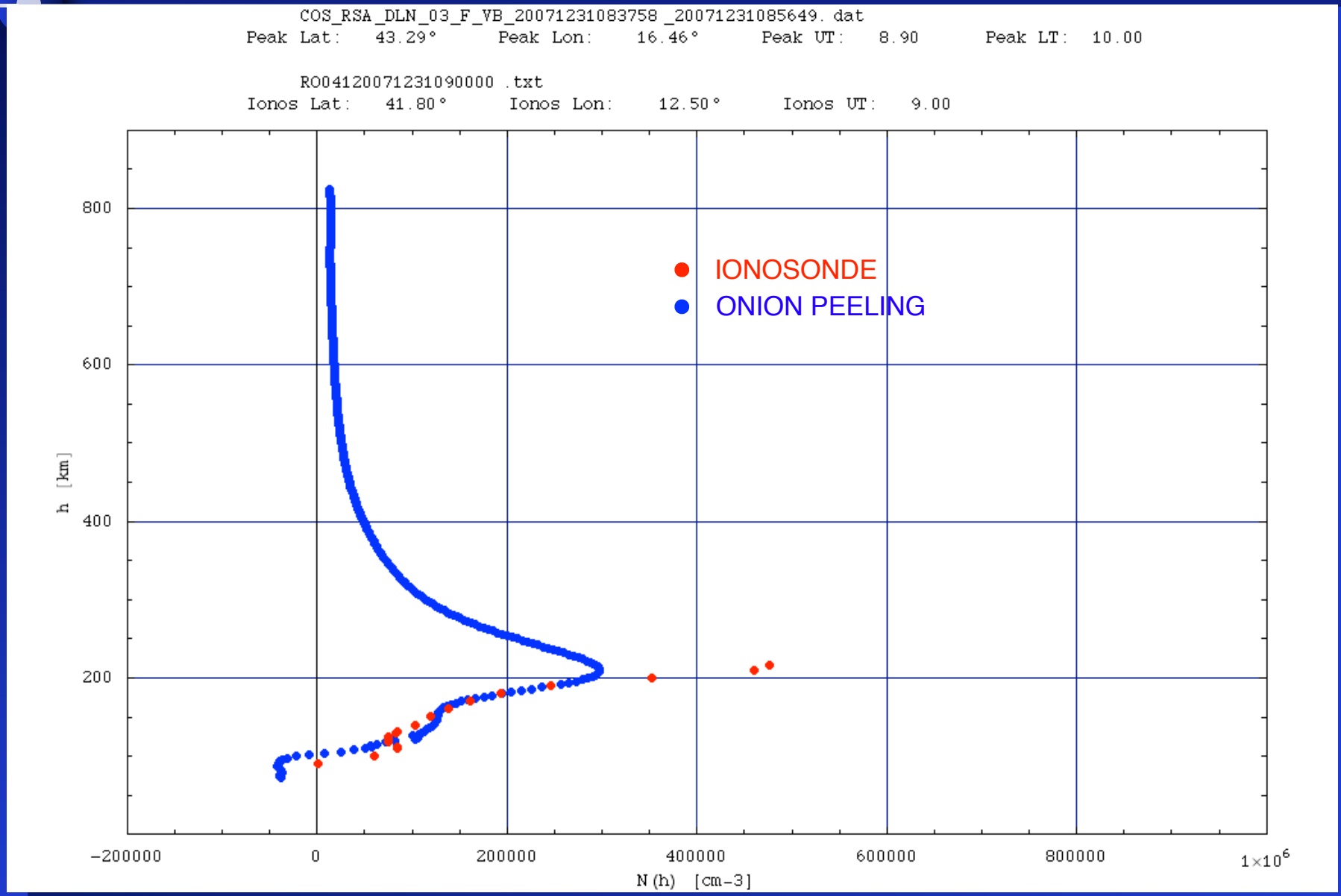
Profile 2


COS_RSA_DLN_03_F_VB_20071231071155_20071231072719.dat
Peak Lat: 54.81° Peak Lon: 4.04° Peak UT: 7.40 Peak LT: 7.67
JR055200712310728l0.txt
Ionos Lat: 54.60° Ionos Lon: 13.40° Ionos UT: 7.47
IONOSONDE
ONION PEELING
h [km]
800
600
400
200
−200000
0
200000
400000
600000
800000
1×10^6
N(h) [cm-3]

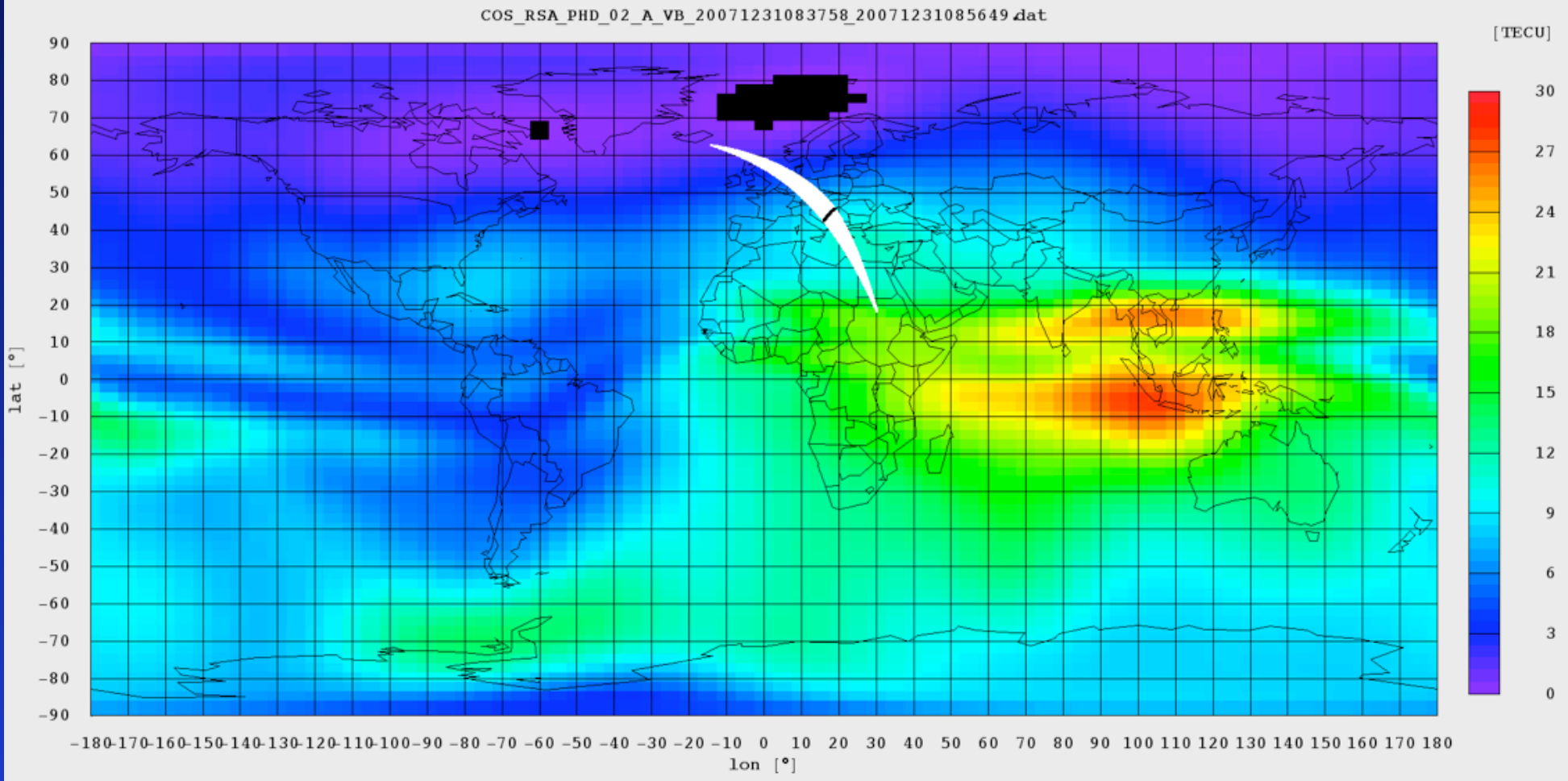
VTEC map 2


COS_RSA_PHD_02_A_VB_20071231071155_20071231072719.dat
[TECU]
30
27
24
21
18
15
12
9
6
3
0
lat [°]
90 80 70 60 50 40 30 20 10 0 -10 -20 -30 -40 -50 -60 -70 -80 -90
-180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
lon [°]

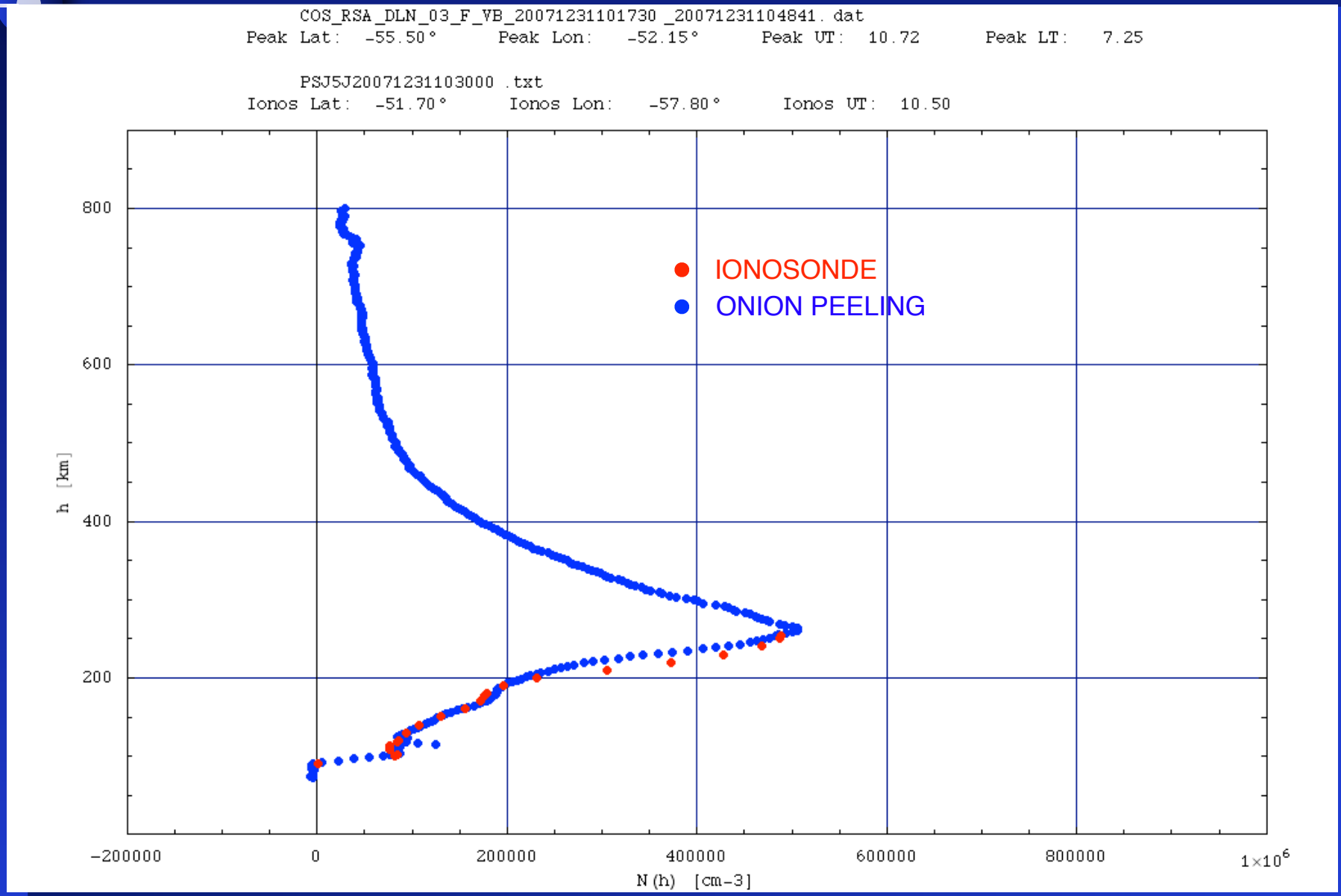
Profile 3


COS_RSA_DLN_03_F_VB_20071231083758_20071231085649.dat
Peak Lat: 43.29° Peak Lon: 16.46° Peak UT: 8.90 Peak LT: 10.00
RO04120071231090000.txt
Ionos Lat: 41.80° Ionos Lon: 12.50° Ionos UT: 9.00
IONOSONDE
ONION PEELING
h [km]
800
600
400
200
−200000
0
200000
400000
600000
800000
1×10^6
N(h) [cm-3]

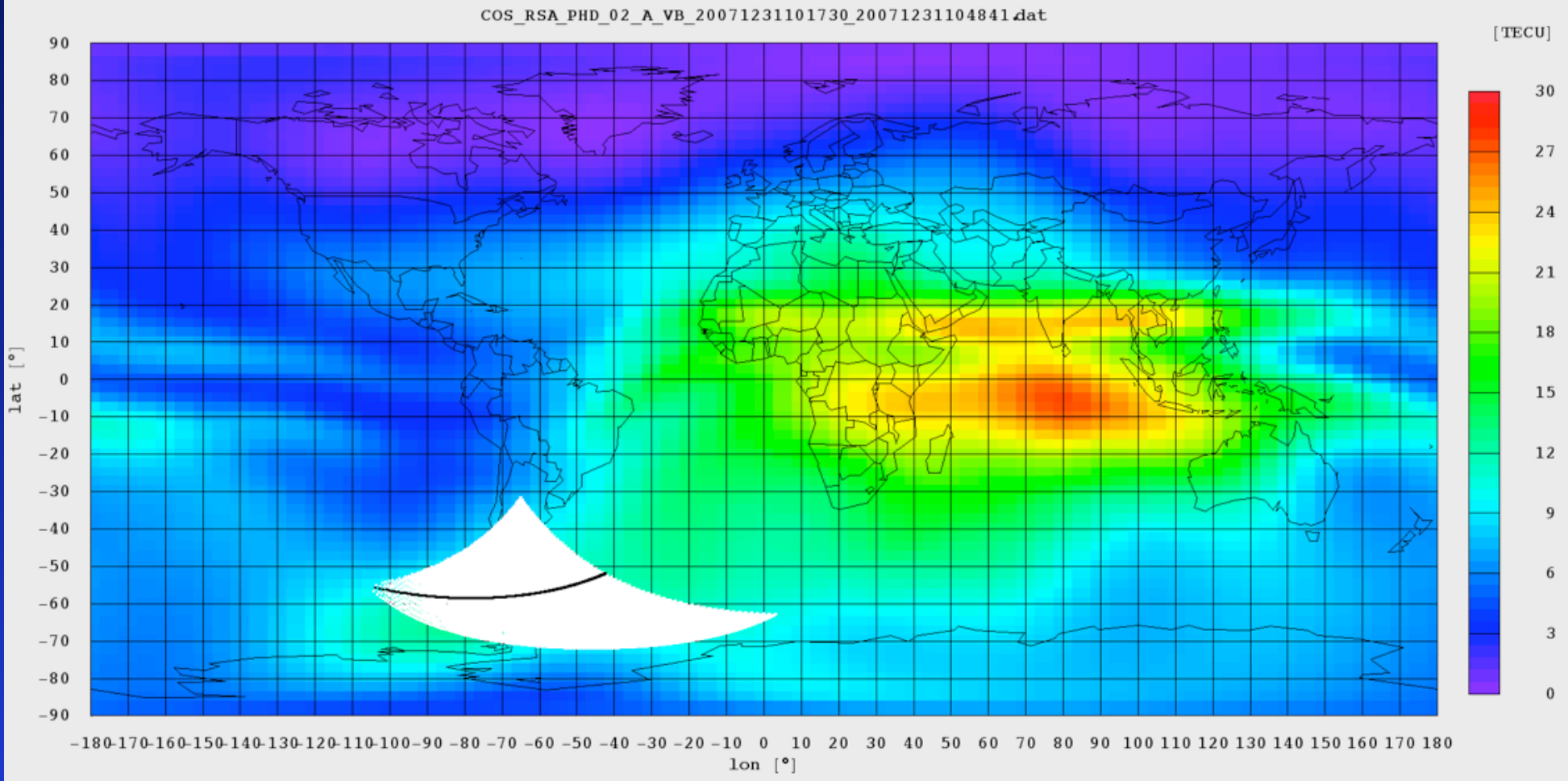
VTEC map 3


COS_RSA_PHD_02_A_VB_20071231083758_20071231085649.dat
[TECU]
30
27
24
21
18
15
12
9
6
3
0
lat [°]
90 80 70 60 50 40 30 20 10 0 -10 -20 -30 -40 -50 -60 -70 -80 -90
-180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
lon [°]

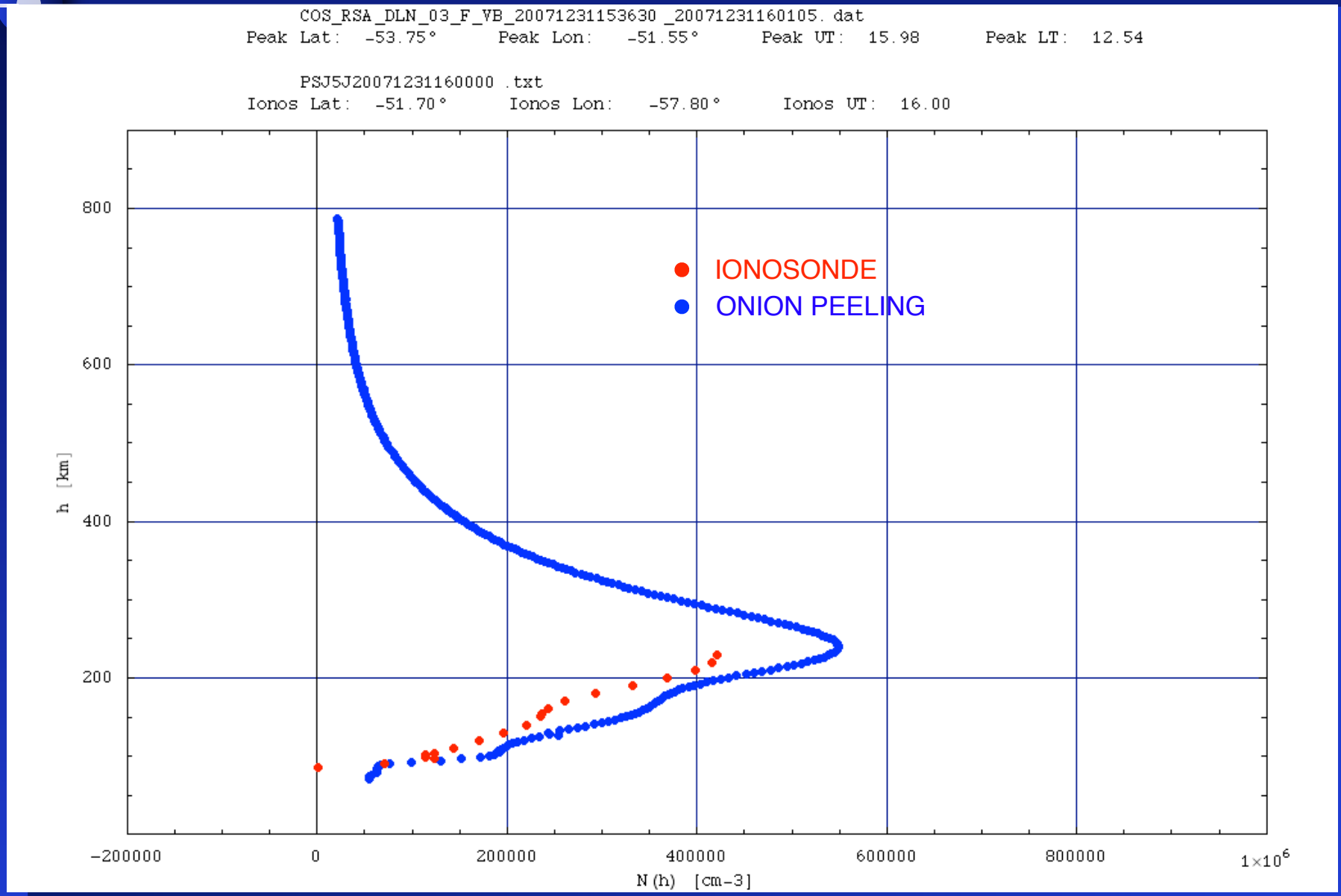
Profile 4


COS_RSA_DLN_03_F_VB_20071231101730 _20071231104841. dat
Peak Lat: -55.50° Peak Lon: -52.15° Peak UT: 10.72 Peak LT: 7.25
PSJ5J20071231103000 .txt
Ionos Lat: -51.70° Ionos Lon: -57.80° Ionos UT: 10.50
IONOSONDE
ONION PEELING
h [km]
800
600
400
200
−200000
0
200000
400000
600000
800000
1×10^6
N(h) [cm-3]

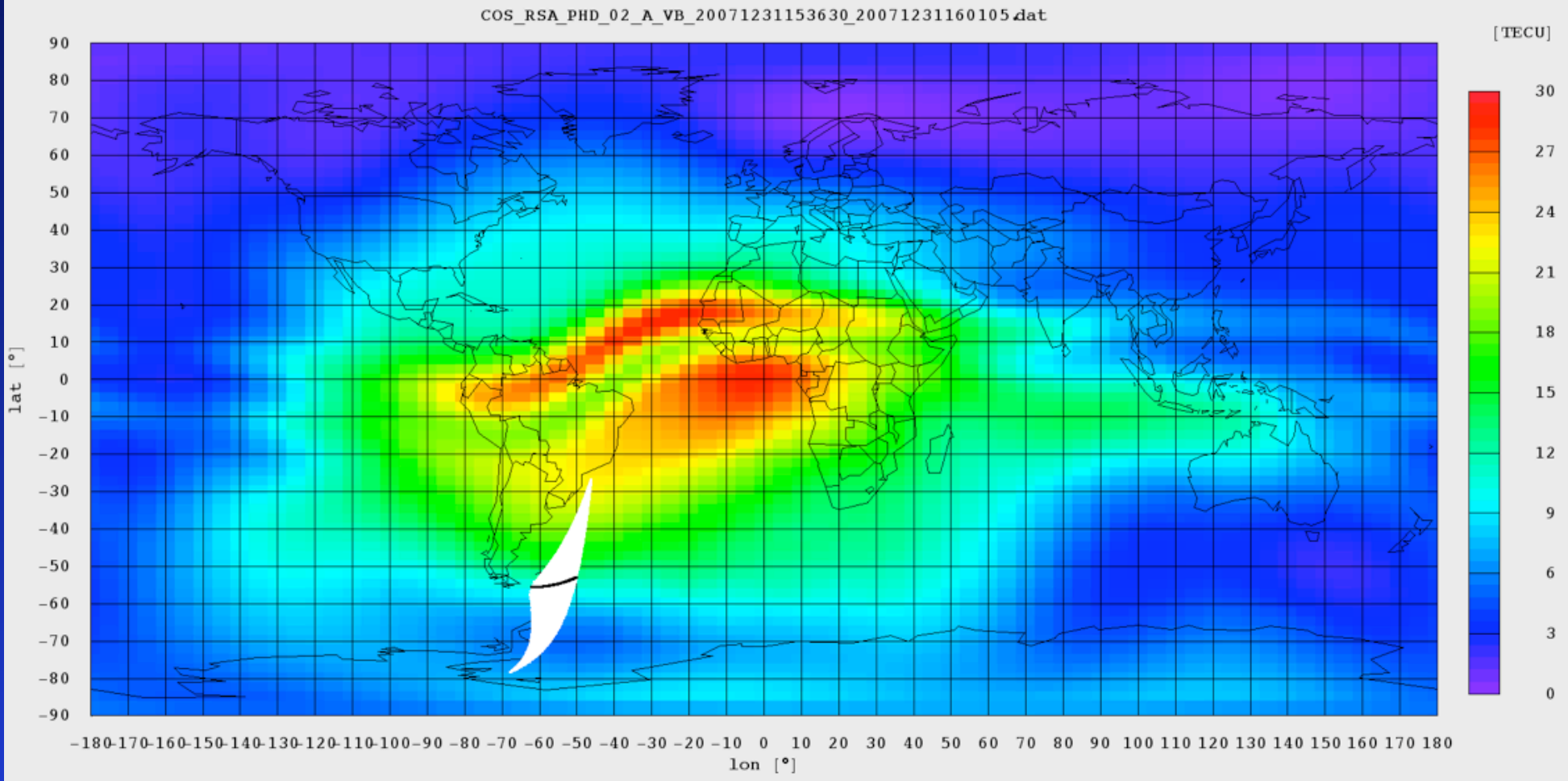
VTEC map 4


COS_RSA_PHD_02_A_VB_20071231101730_20071231104841.dat
[TECU]
30
27
24
21
18
15
12
9
6
3
0
lat [°]
90 80 70 60 50 40 30 20 10 0 -10 -20 -30 -40 -50 -60 -70 -80 -90
-180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
lon [°]

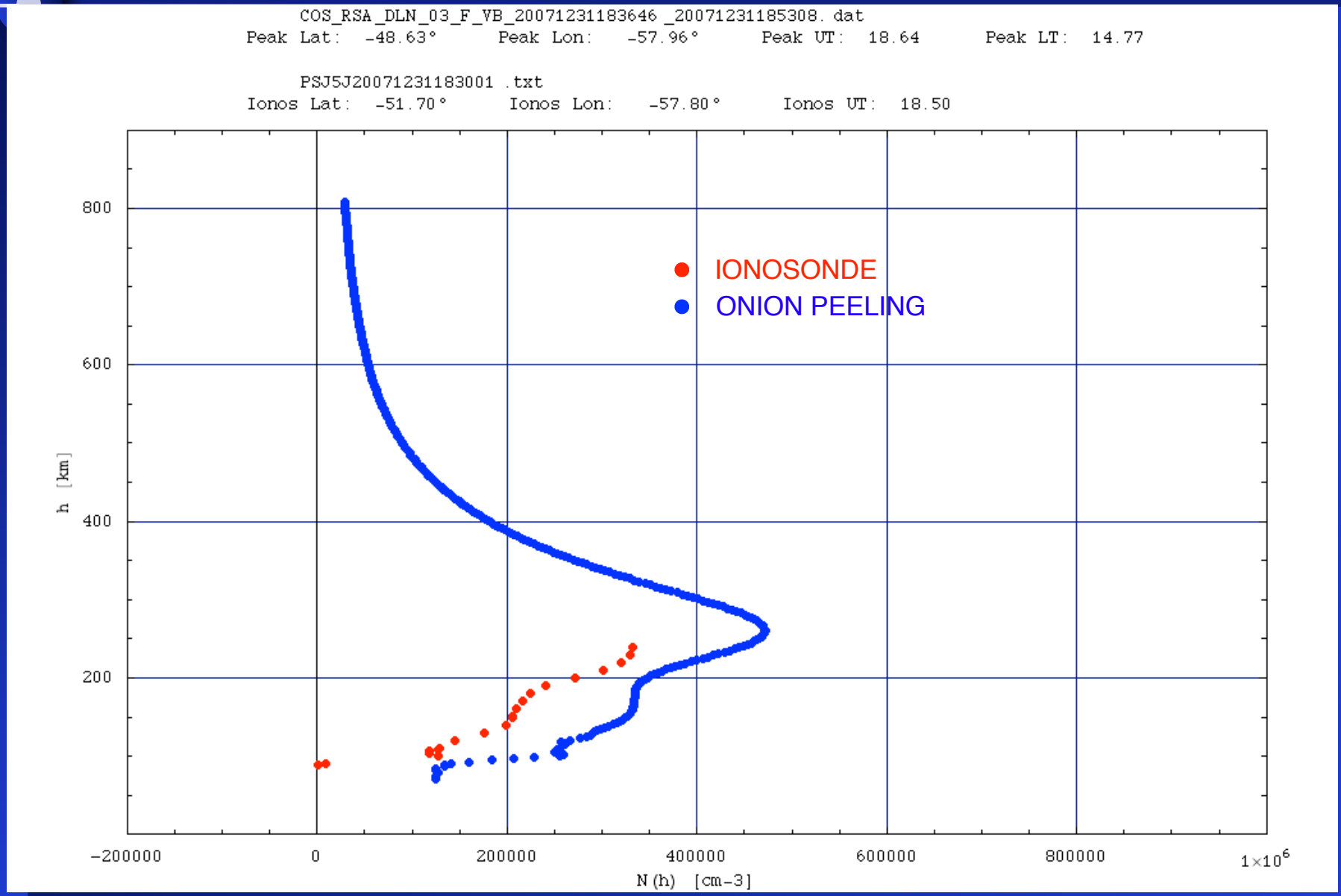
Profile 5


COS_RSA_DLN_03_F_VB_20071231153630 _20071231160105. dat
Peak Lat: -53.75° Peak Lon: -51.55° Peak UT: 15.98 Peak LT: 12.54
PSJ5J20071231160000 .txt
Ionos Lat: -51.70° Ionos Lon: -57.80° Ionos UT: 16.00
IONOSONDE
ONION PEELING
800
600
400
200
h [km]
−200000
0
200000
400000
600000
800000
1×10^6
N(h) [cm-3]

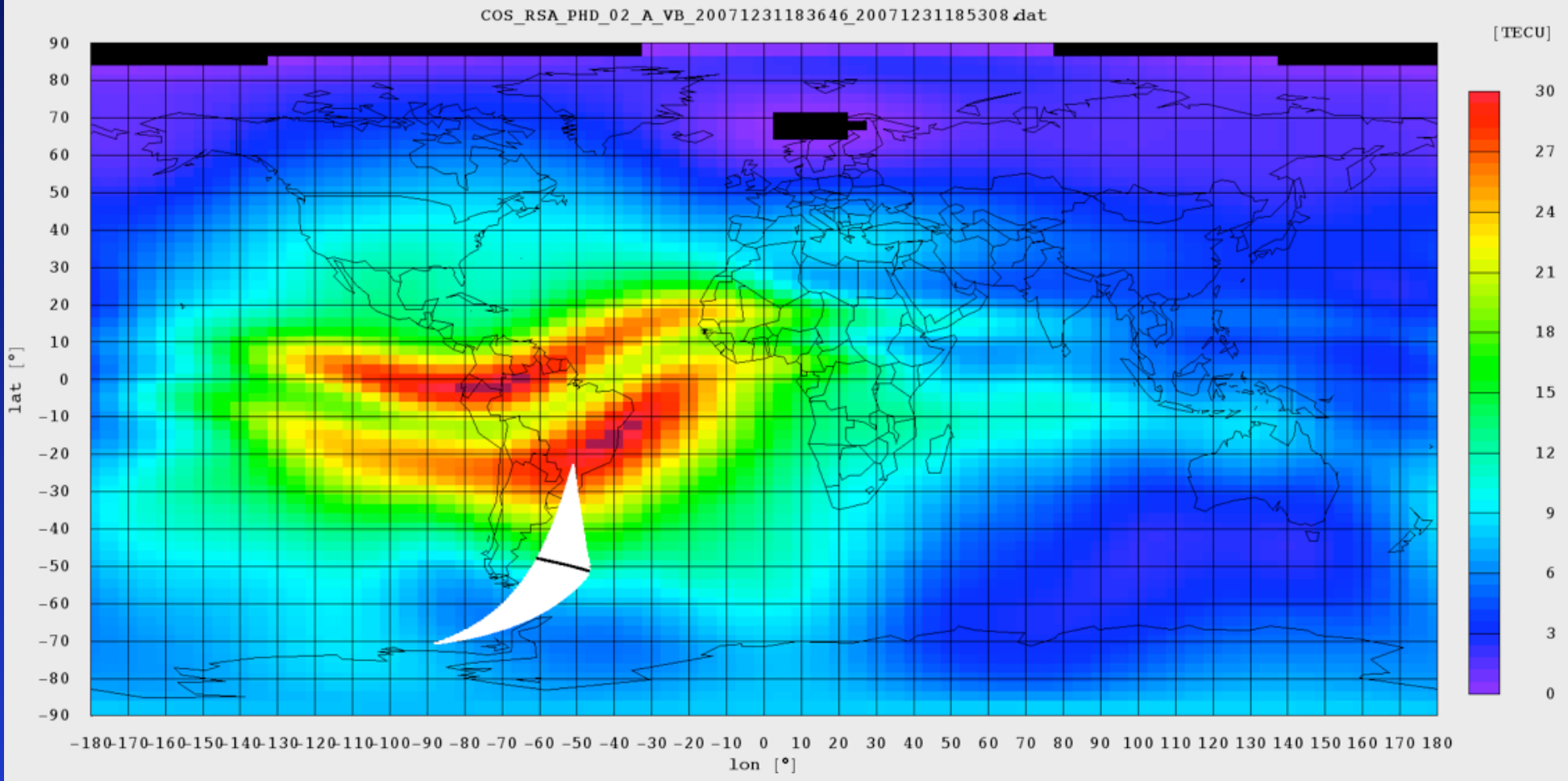
VTEC map 5


COS_RSA_PHD_02_A_VB_20071231153630_20071231160105.dat
[TECU]
30
27
24
21
18
15
12
9
6
3
0
lat [°]
90 80 70 60 50 40 30 20 10 0 -10 -20 -30 -40 -50 -60 -70 -80 -90
-180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
lon [°]

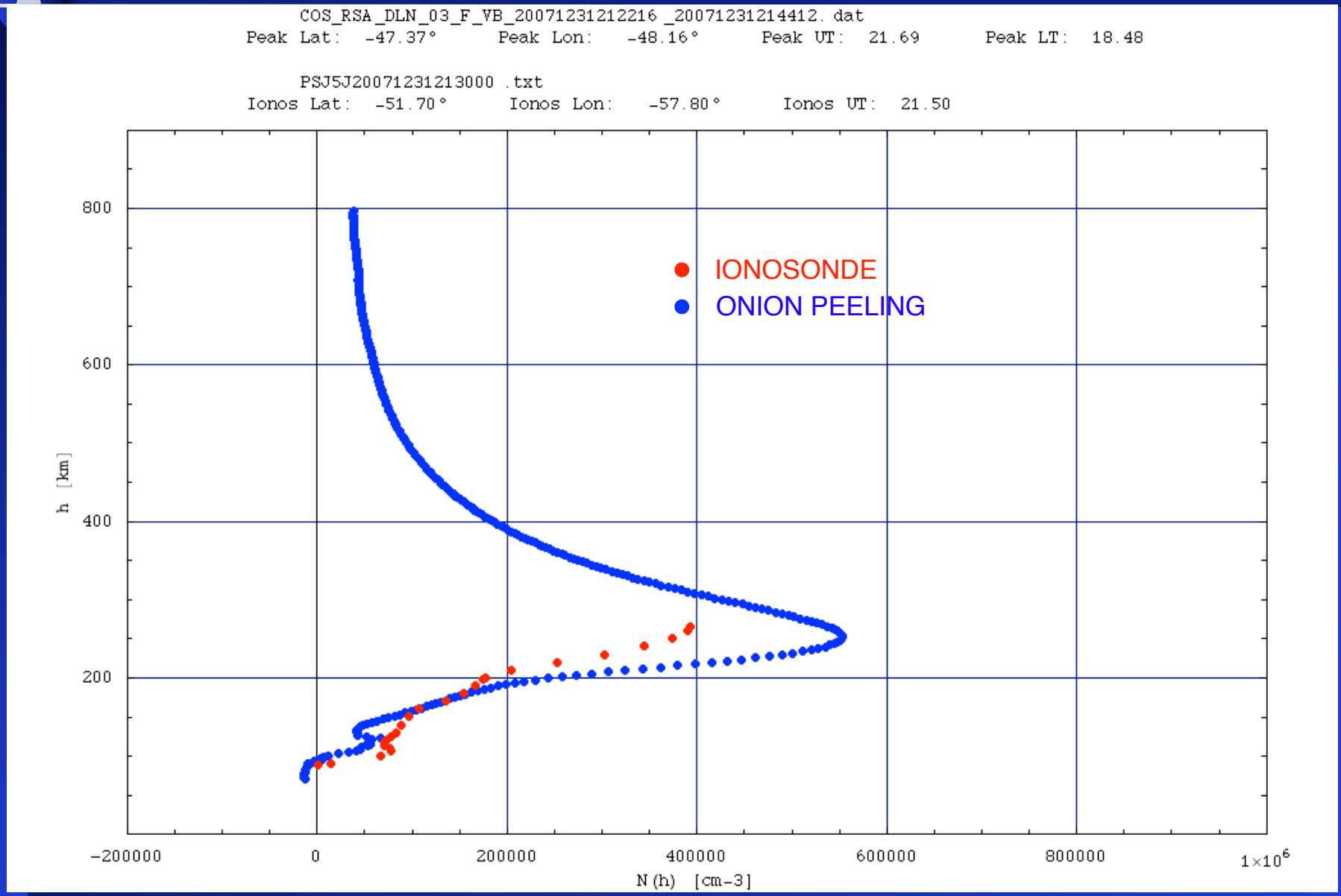
Profile 6


COS_RSA_DLN_03_F_VB_20071231183646 _20071231185308. dat
Peak Lat: -48.63° Peak Lon: -57.96° Peak UT: 18.64 Peak LT: 14.77
PSJ5J20071231183001 .txt
Ionos Lat: -51.70° Ionos Lon: -57.80° Ionos UT: 18.50
IONOSONDE
ONION PEELING
h [km]
800
600
400
200
−200000
0
200000
400000
600000
800000
1×10^6
N(h) [cm-3]

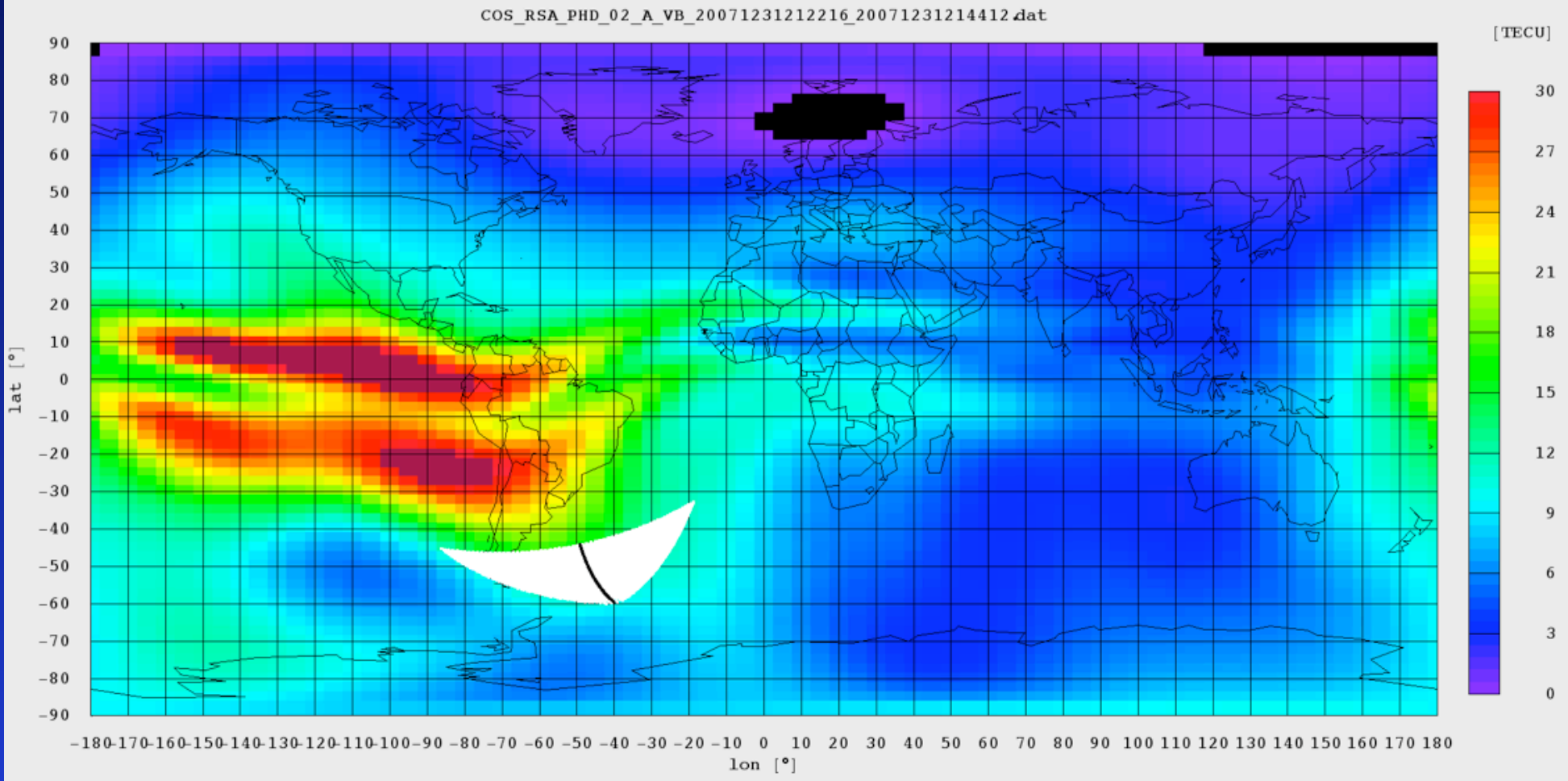
VTEC map 6


COS_RSA_PHD_02_A_VB_20071231183646_20071231185308.dat
[TECU]
30
27
24
21
18
15
12
9
6
3
0
lat [°]
90 80 70 60 50 40 30 20 10 0 -10 -20 -30 -40 -50 -60 -70 -80 -90
-180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
lon [°]

Profile 7

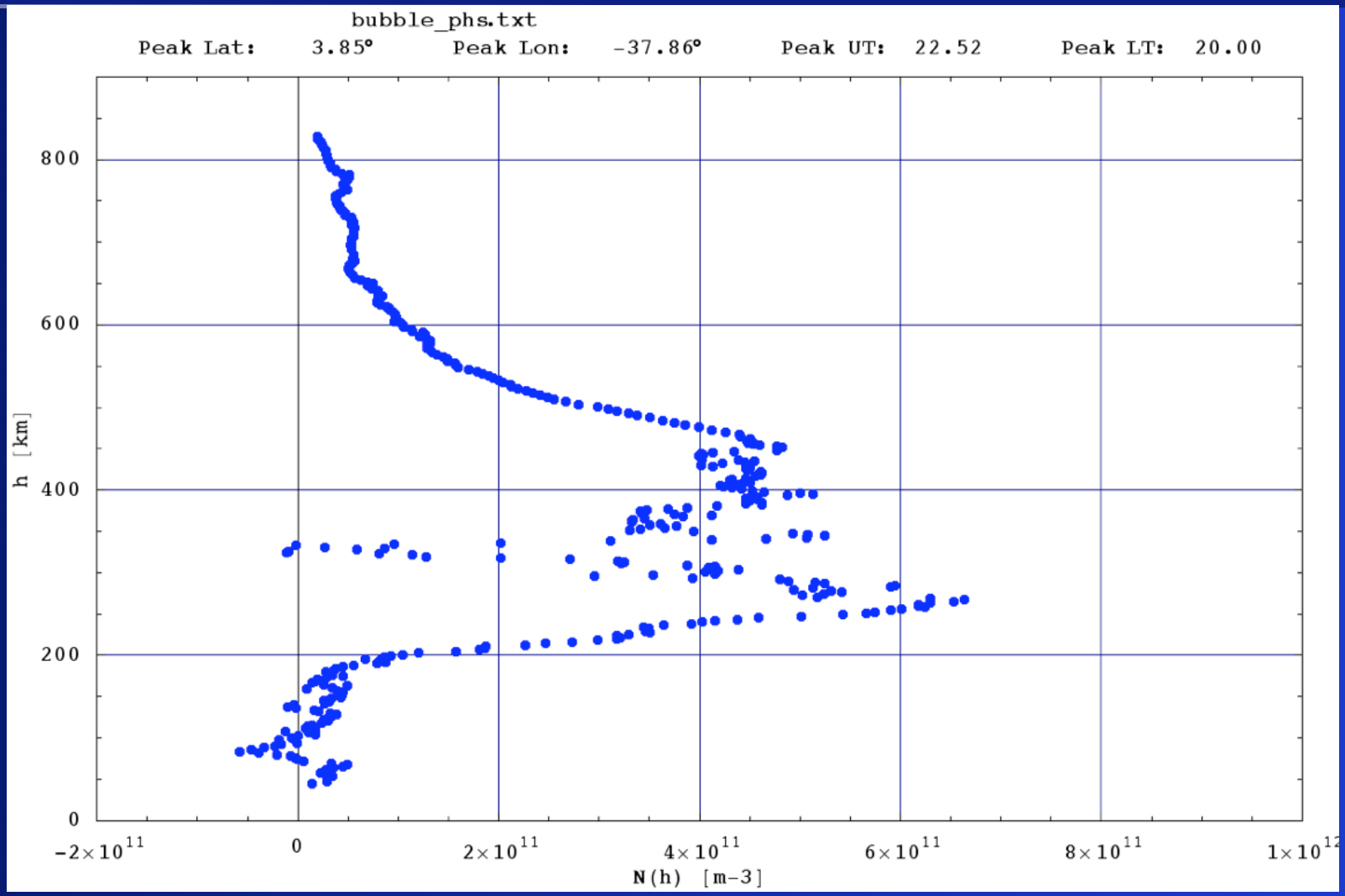

COS_RSA_DLN_03_F_VB_20071231212216 _20071231214412. dat
Peak Lat: -47.37° Peak Lon: -48.16° Peak UT: 21.69 Peak LT: 18.48
PSJ5J20071231213000 .txt
Ionos Lat: -51.70° Ionos Lon: -57.80° Ionos UT: 21.50
IONOSONDE
ONION PEELING
h [km]
800
600
400
200
−200000
0
200000
400000
600000
800000
1×10^6
N(h) [cm-3]

VTEC map 7


COS_RSA_PHD_02_A_VB_20071231212216_20071231214412.dat
[TECU]
30
27
24
21
18
15
12
9
6
3
0
lat [°]
90 80 70 60 50 40 30 20 10 0 -10 -20 -30 -40 -50 -60 -70 -80 -90
-180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
lon [°]

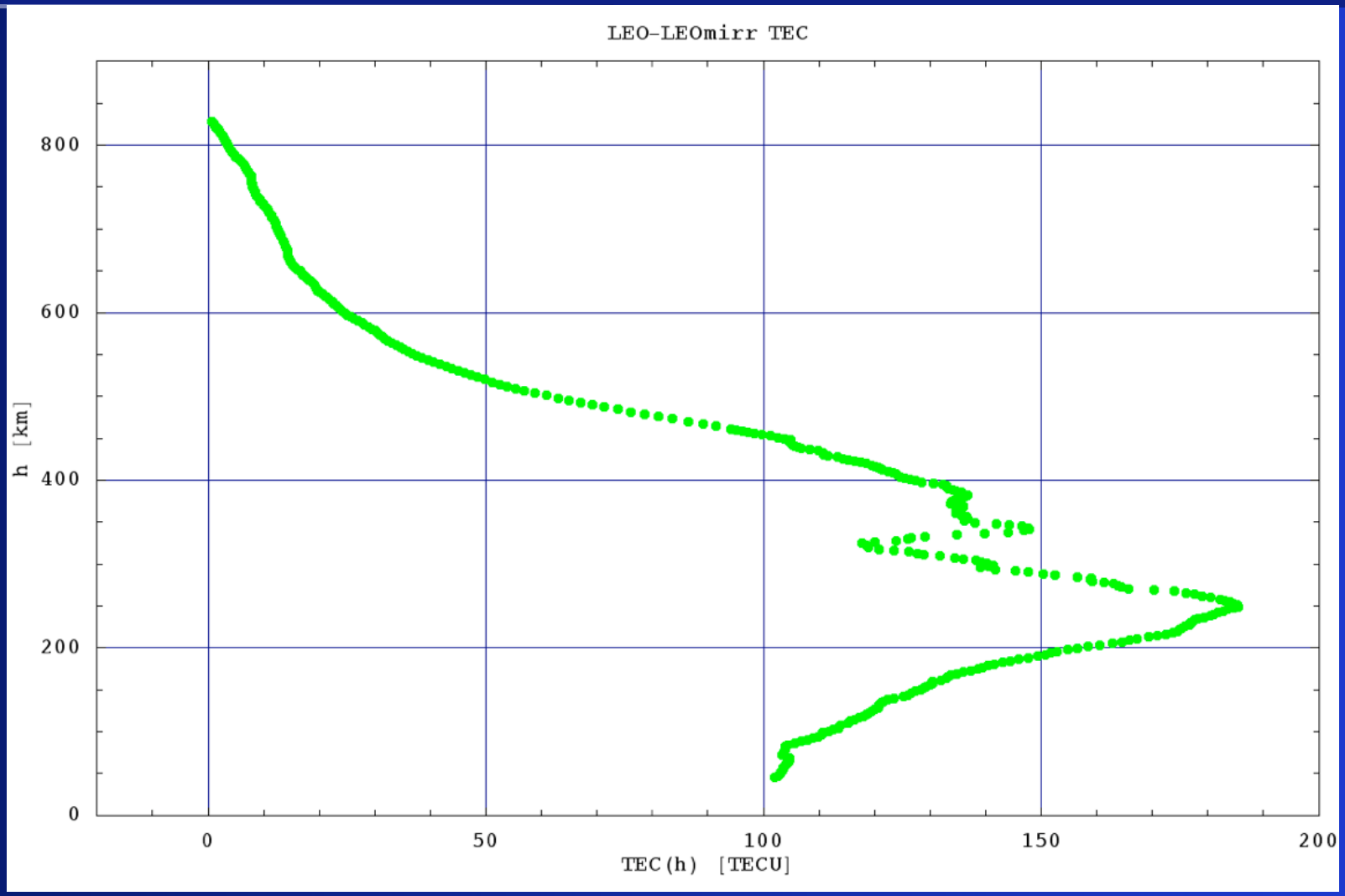
Depletion signatures in RO data

“Vertical” electron density profile



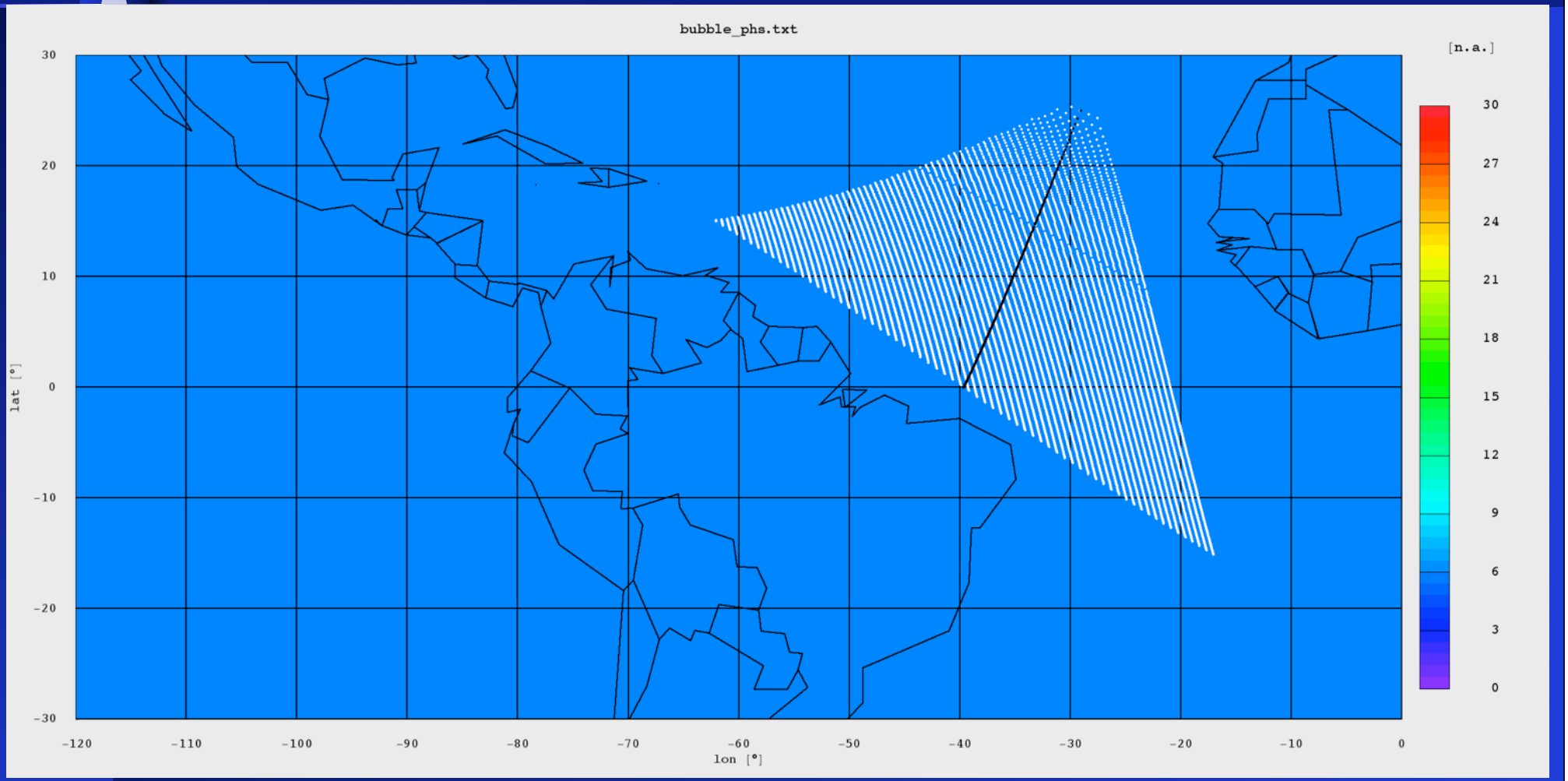
“Vertical” electron density profile obtained inverting RO data using the Onion Peeling algorithm

Profile of Leo-Leo_mirr TEC



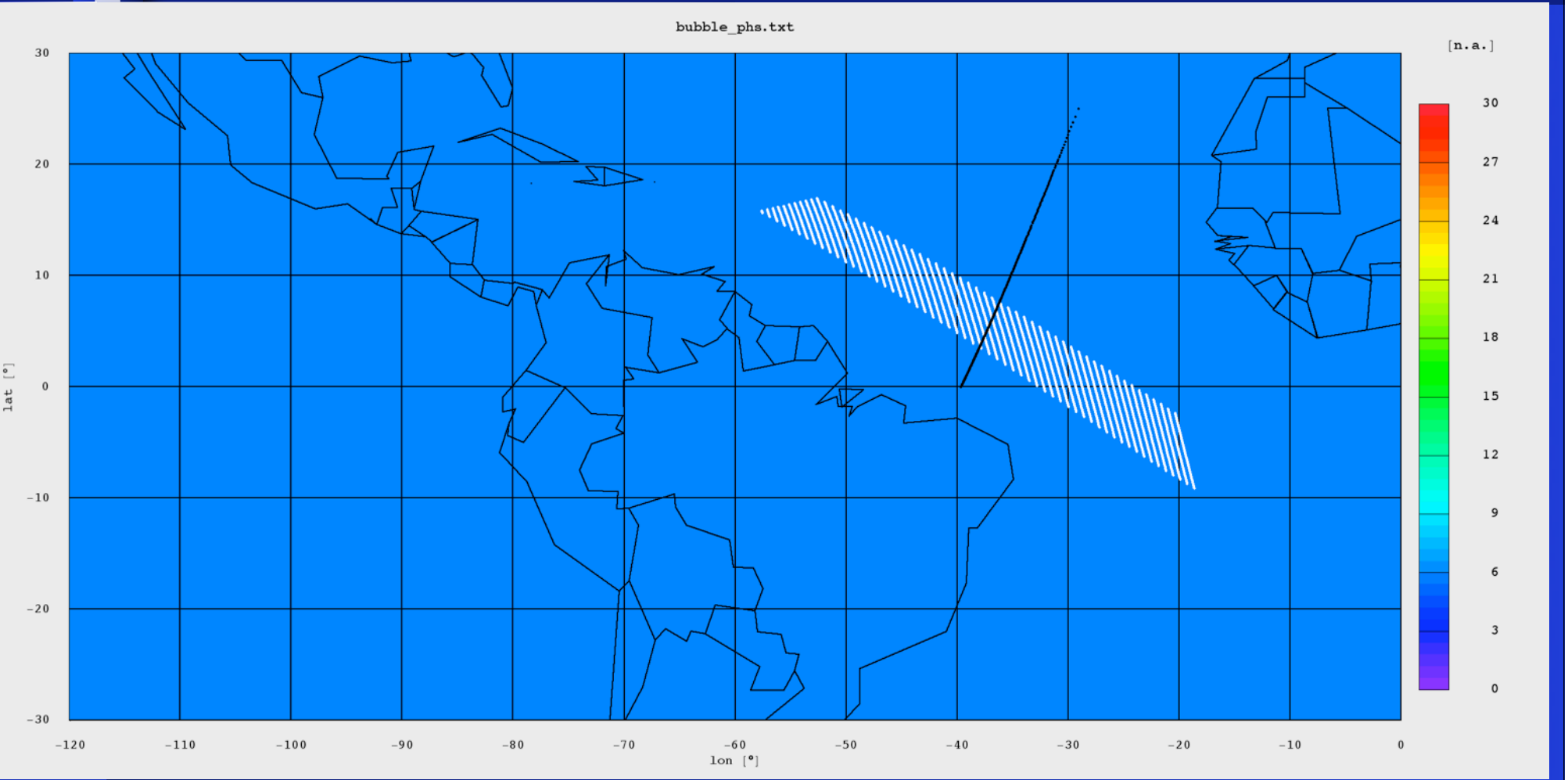
"Vertical" profile of the TEC between the Leo and its mirrored position with respect to the ray perigee.

Occultation geometry



Projection on the Earth surface of the links between the Leo and its “mirrored” position with respect to the ray perigee.

Occultation geometry



Projection on the Earth surface of the links between the Leo and its “mirrored” position with respect to the ray perigee. Ray perigee heights from 250 to 450 km.

Conclusions

- RO data, inverted with the Onion Peeling algorithm, are able to provide good representations of the ionosphere electron density ("vertical" electron density profiles).
- Global coverage.
- When the assumption of spherical symmetry for the electron density of the ionosphere fails, errors could appear in the retrieved profiles.

Acknowledgments

The authors are grateful to our BC Colleagues, La Plata University, La Plata, to K. Alazo of IGA, Cuba and to the ASI (Italian Space Agency) in relation to ROSA (Radio Occultation Sounder for Atmosphere) project, under which part of the SW to invert RO data has been developed.

Thank you for your attention