GPS radio occultation data retrieval -- Ionospheric correction

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Outline

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II. Wave propagation fundamental
III. Ionospheric correction
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I. Why do we need to perform ionospheric corrections?

- GPS radio occultation (RO) technique has been used for retrieving Earth's profiles of refractivity, temperature, pressure and water vapor in the neutral atmosphere and electron density in the ionosphere for years. A variety of retrieval schemes and correction methods are hence developed to perform the retrieval.
- **Systematic errors exist and degrade the retrieval accuracy** of atmospheric parameters when the RO technique is implemented. The errors are caused by many factors, such as **large-scale horizontal gradients** [Ahmad and Tyler, 1999], **small-scale irregularity**, **super refraction**, **gravity wave** [Liou et al. 2002, 2003, 2004; Pavelyev et al., 2003], **multipath** [Igarashi et al., 2000], **reflected signals from surface** [Pavelyev et al., 2002], **oblateness of earth** [Syndergaard, 1998], and **ionospheric influence** [Syndergaard, 2000, 2002].
- **To reduce the ionospheric influence**, ionosphere-free linear combination is generally used to derive the neutral atmospheric parameters. Here, we consider only the systematic errors connected with the ionospheric influence. A new method (thereafter called **NCURO scheme**) is developed for the ionosphere calibration correction.

II. Wave propagation

1. Propagation delay of radio waves

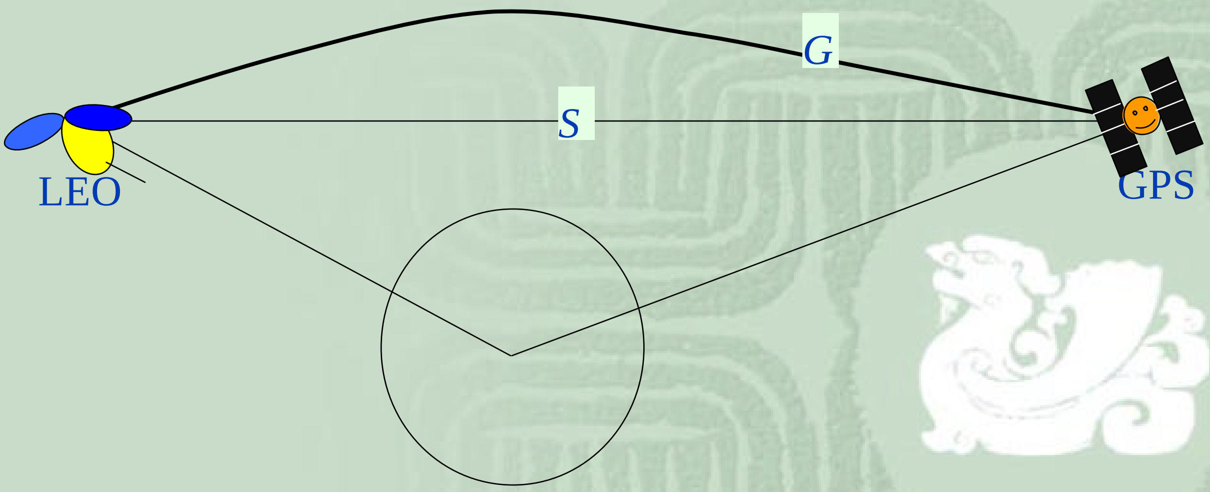
$$\text{Total Delay(TD)} = \int n ds - G = \int (n-1) ds + S - G$$

G: Length between Transmitter and Receiver

S: Length of Ray path

S-G : Geometric delay

$\int (n-1) ds$ **: Path delay**



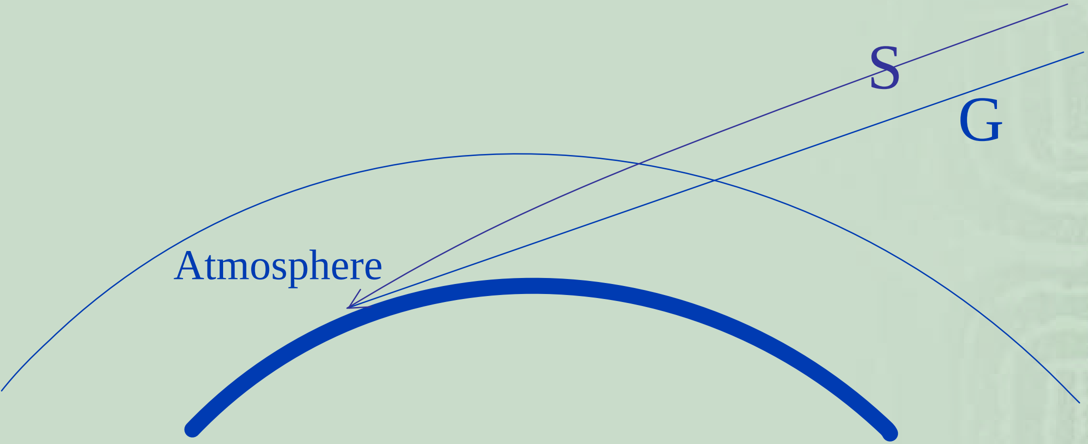
2. Refractive index n

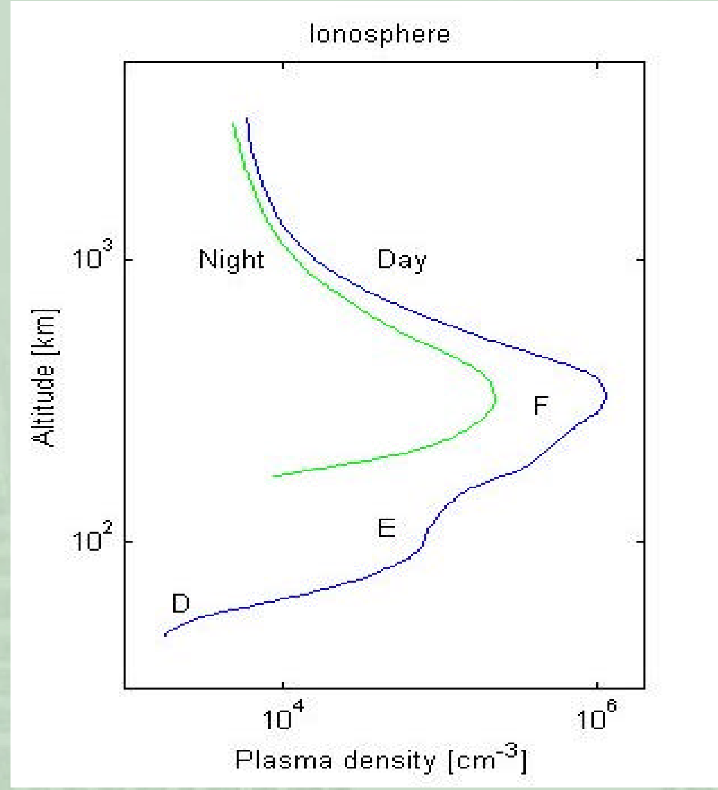
$$n = 1 + n^{Trop} + n^{I}$$

Ionosphere: $n^{I} = -\frac{40.3 n_e}{f^2}$

Neutral atmosphere: $10^6 n^{Trop} = N = k_1 \frac{P}{T} Z_d^{-1} + k_2^{'} \frac{e}{T} Z_w^{-1} + k_3 \frac{e}{T^2} Z_w^{-1}$

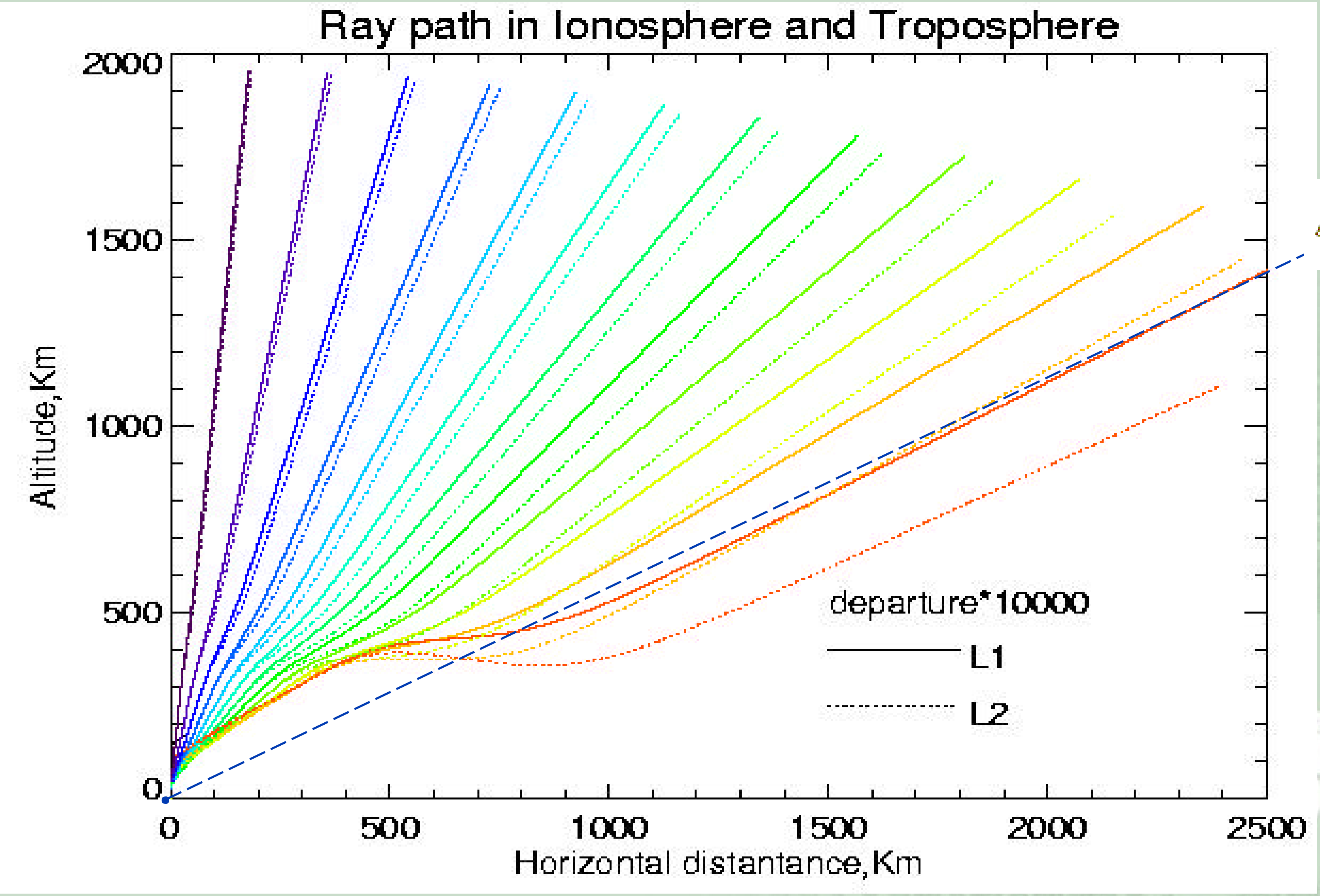
1. First 2 terms: induced dipole
2. 3rd term: permanent dipole moment of PW





http://www.oulu.fi/~spaceweb/textbook/ionosphere.html

Ray path of GPS signals received by ground-baseed receivers



Ionospheric refractivity

- Refractive index in the ionosphere is given by Appleten formula (Davies, 1965)

$$n_{\pm}^{2} = 1 - \frac{X}{1 - jZ - \dfrac{Y_T^2}{2(1 - X - jZ)} \pm \sqrt{\dfrac{Y_T^4}{4(1 - X - jZ)^2} + Y_L^2}}$$

$X = N_e e^2 / m e_0 w^2,\ Y_L = eB_L / mw,\ Y_T = eB_T / mw,\ Z = n / w,$

w is the carrier angle frequency,

N_e is the electron density, n is the collision frequency,

B_L is the component of the geomagnetic field along the ray direction,

B_T is the component of the geomagnetic field perpendicular the ray direction.

- For the propagation of high-frequency radio waves through the E and F regions of the ionosphere, Z is usually very small and can be neglected so that refractive index is given by (Davies, 1965):

$$n = 1 - \frac{1}{2}X \pm \frac{1}{2}XY\left|\cos q\right| - \frac{1}{8}X^2 - \frac{1}{4}XY^2(1+\cos^2 q) - i\frac{1}{2}XZ + \cdots$$

$$1 - 10^{-4} \pm \quad 10^{-7} \quad - \; 10^{-9} - \quad 10^{-10} \quad - i10^{-9}$$

X: is proportional to f^{-2} and a function of electron density.

Y: is proportional to f^{-1} and a function of magnetic field .

GPS signals are mainly right-hand circularly polarized, giving rise to either ordinary waves (southern geomagnetic hemisphere) or extraordinary waves (northern geomagnetic hemisphere) (Syndergaard, 2004).

III. Ionospheric correction

- Traditional ionospheric correction: Lc(t) & Lc(a)

$$e_{1,2}(p) = \frac{f_1^2 e_1(p) - f_2^2 e_2(p)}{f_1^2 - f_2^2}$$

- Syndergaard ionospheric correction: Lc(***Γ***)

$$\tilde{L}_C(a) = \frac{f_1^2 \tilde{L}_1 - f_2^2 \tilde{L}_2}{f_1^2 - f_2^2} \approx \tilde{r}_0 \mp \frac{K \langle B \rangle_0}{f_1 f_2 (f_1 + f_2)} E_0 + \frac{1}{2} \frac{C^2}{f_1^2 f_2^2} \Gamma$$

- NCURO ionospheric correction: Lc(NCU)

$$Lc_{NCURO}(a) = \left\{ \frac{f_1^2 \left(L_1(a) - G_1(a) \right) - f_2^2 \left(L_2(a) - G_2(a) \right)}{f_1^2 - f_2^2} \right\} +$$

$$\left\{ \frac{1}{2} \left(\frac{1}{D_{Gi}} + \frac{1}{D_{Li}} \right) \left(\triangle a_1 - \triangle a_{ION} \right)^2 \right\}$$

- Combination of Lc(t) & Lc(a)

$$e_{1,2}(t,a) = \frac{f_1^2 e_1(t,a) - f_2^2 \left[q e_2(t,a') + (1-q) f_2^2 e_2(t'',a) \right]}{f_1^2 - f_2^2}$$

1.Traditional ionospheric correction: Lc(t) & Lc(a)

[*Gorbunov and Kornblueh*, 2001]:

$$\boldsymbol{e}_{1,2}(p) = \frac{f_1^{\,2}\boldsymbol{e}_1(p) - f_2^{\,2}\boldsymbol{e}_2(p)}{f_1^{\,2} - f_2^{\,2}}$$

where ε can be the excess phase delay or the bending angle, *p* can be the impact (*a*) or the time (*t*), *f* is the carrier frequency of GPS signals, and subscripts 1 and 2 represent L1 and L2 signals, respectively. Here, the excess phase delays corrected as function of time and impact parameter are represented by Lc(*t*) and Lc(*a*), respectively.

2.Syndergaard ionospheric correction: Lc(*Γ*)

- Excess phase delay of GPS signals can be written as (Syndergaard, 2004)

$$L_i = \int_T^R n_i dl_i = \int_T^R \left(1 + 10^{-6} N_n - \frac{C}{f_i^2} N_e \pm \frac{K}{f_i^3} N_e B \left| \cos q \right| \right) dl_i$$

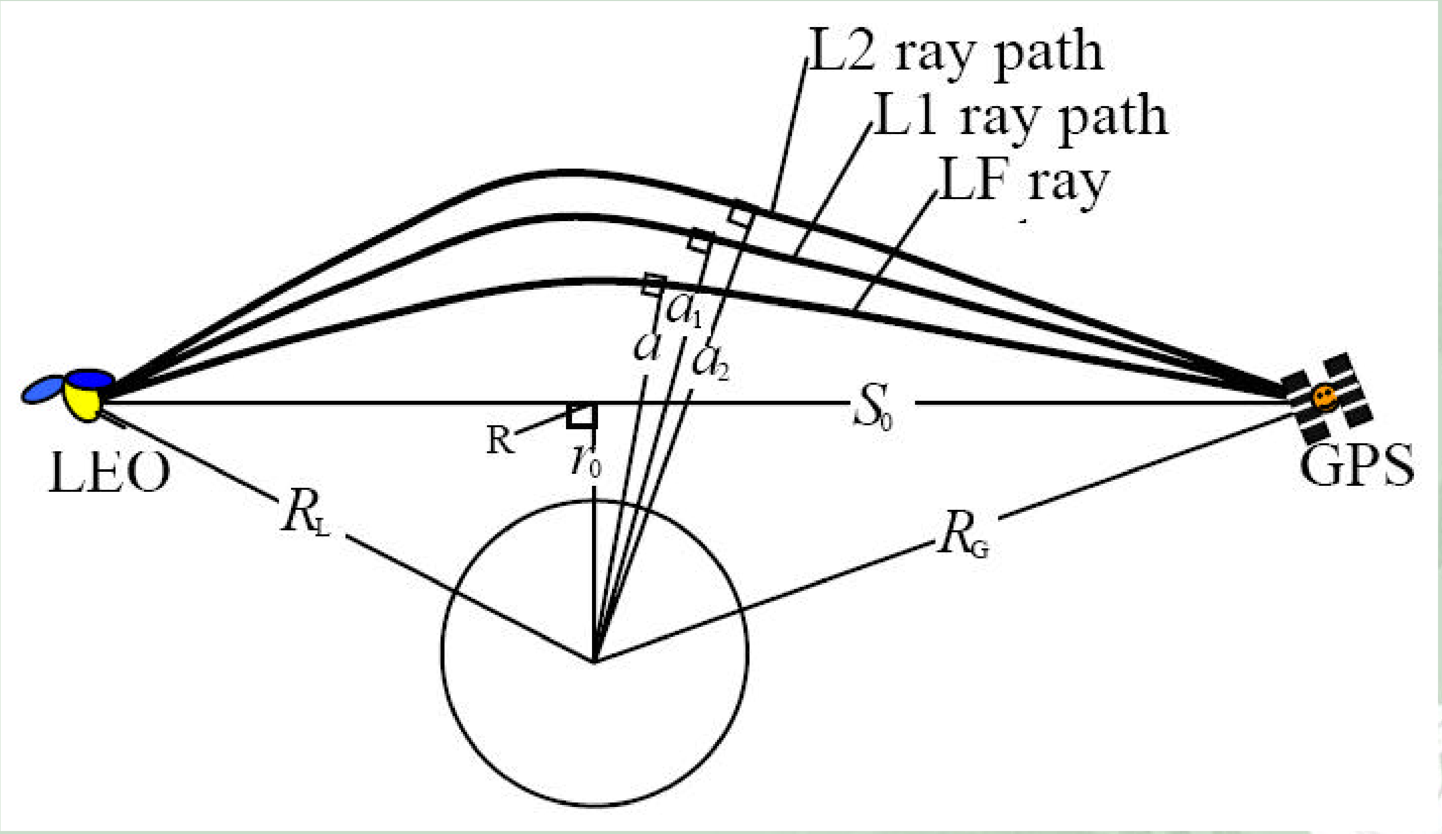
- Syndergaard(2004) derived the excess phase as

$$\tilde{L}_i \approx \tilde{r}_0 - \frac{C}{f_i^2} \pm \frac{K \langle B \rangle_0}{f_i^3} E_0 - \frac{1}{2} \frac{C^2}{f_i^4} \Gamma$$

$$E_i = \int_T^R N_e dl_i,\ \langle B \rangle_i = E_i^{-1} \int_T^R N_e B \left| \cos q \right| dl_i,\ \tilde{r}_i = \int_T^R \left(1 + 10^{-6} N_n \right) dl_i - \left| \vec{r}_R - \vec{r}_T \right|$$

Γ is geometric delay caused by ionospheric gradient refractivity and a function of N_e along the path.

Ray paths for L1, L2, and ionosphere-free LF



Syndergaard (2000) suggested that the fourth term can be calibrated by using the occultation observation data. The relation between ***Γ*** *(*geometric delay*)* and observation data is

$$\Gamma = Dz\left(\frac{dI}{da}\right)^2 + a\frac{dJ}{da} + 2C\left(\frac{1}{f_1^2}+\frac{1}{f_2^2}\right)(Dz)^2\left(\frac{dI}{da}\right)^2\frac{d^2I}{da^2}$$

$I = f_1^2 f_2^2 (L1 - L2)/[C(f_1^2 - f_2^2)],\ 1/D = 1/DG + 1/DL,$

$z = (1 - D(da/da)) - 1,$

J is calculated from double-Chapman model (Syndergaard, 2000).

The first term $Dz\left(\frac{dI}{da}\right)^2$ is proportional to $(\Delta TEC)^2$,

The second term $a\frac{dJ}{da}$ is proportional to $\int_T^R N_e^2 dl$,

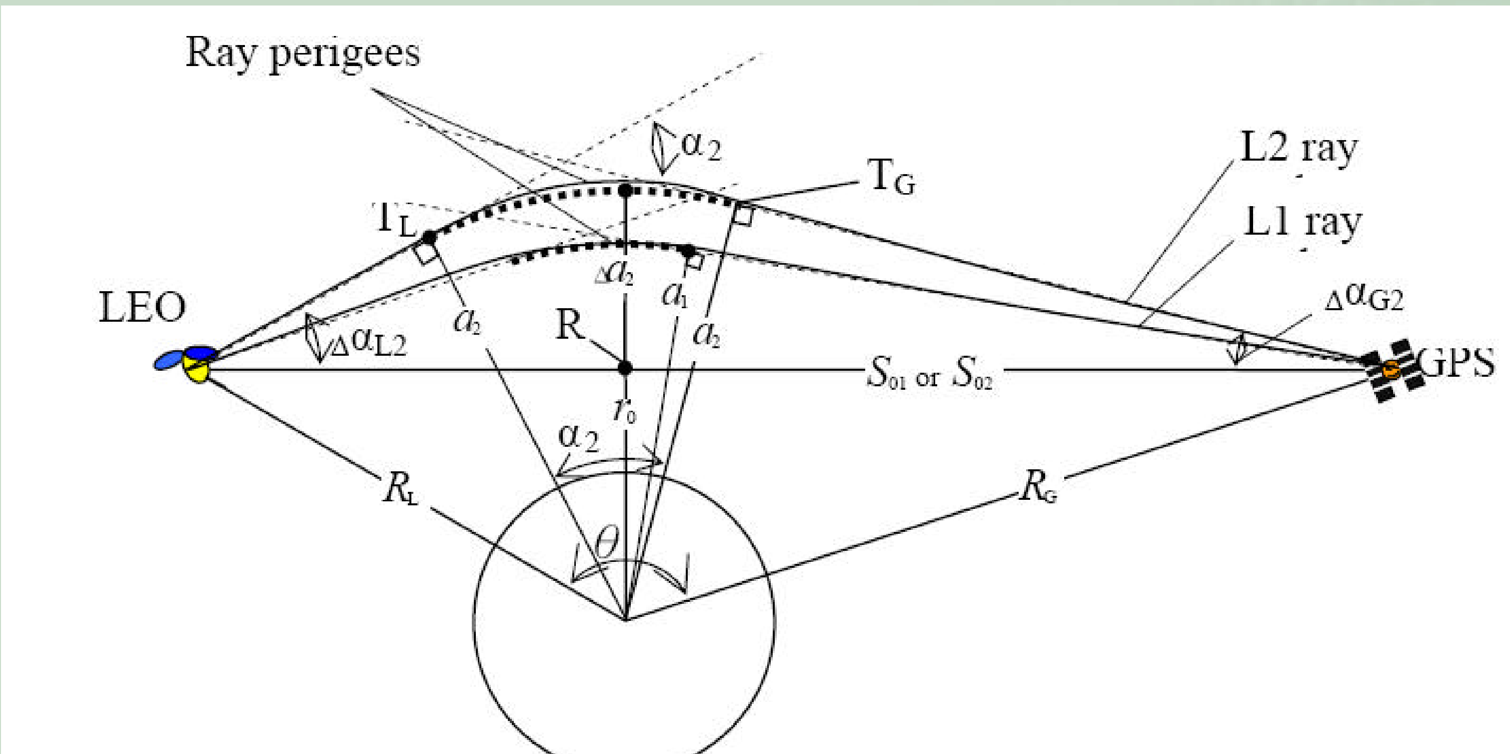
The third term $2C\left(\frac{1}{f_1^2}+\frac{1}{f_2^2}\right)(Dz)^2\left(\frac{dI}{da}\right)^2\frac{d^2I}{da^2}$ is proportional to $(\Delta TEC)^4$,

3.NCURO ionospheric correction: Lc(NCU)

- Pphase excess between GPS and LEO can be described by expression (Pavelyev et al, 2004)

$$L_i = \sqrt{r_G^2 - a^2} + \sqrt{r_L^2 - a^2} + aa(a) + \int_a^\infty a(a')da'$$

Blue color : Geometric delay, Red color : Path delay



- The bending angle can be approximated as

$$\triangle a \approx \triangle a \left(\frac{1}{D_{L0}} + \frac{1}{D_{G0}} \right) = \frac{\triangle a}{D_0}$$

- The geometric delay is written as

$$\begin{aligned} & G_i - S_{0i} \\ & = [D_{GRi}(1/2)(\triangle a_{Gi})^2 - r_{0i}(1/3)(\triangle a_{Gi})^3 + \cdots] \\ & + [D_{LRi}(1/2)(\triangle a_{Li})^2 - r_{0i}(1/3)(\triangle a_{Li})^3 + \cdots] \end{aligned}$$

- The higher order (>2) terms of bending angle are ignored

$$G_i - S_{0i} = 0.5(\triangle a_i)^2 \left(\frac{1}{D_{Gi}} + \frac{1}{D_{Li}} \right) = 0.5a^2(a_i) \left(\frac{1}{D_{Gi}} + \frac{1}{D_{Li}} \right)$$

The bending angle caused by electron density gradient is proportional to f^{-2} (Vorob'ev and Krasil'nikova, 1994), so the geometric delay caused by ionosphere would be proportional to f^{-4} , if the bending angle $\triangle a$ is very small, otherwise it would be proportional to ($\triangle a$ f^{-2})

- The result can also be proved from

$$G_{path} = \int_a^\infty a(a')da' = \int (dn/ndx)\sqrt{x^2 - a^2}\,dx$$

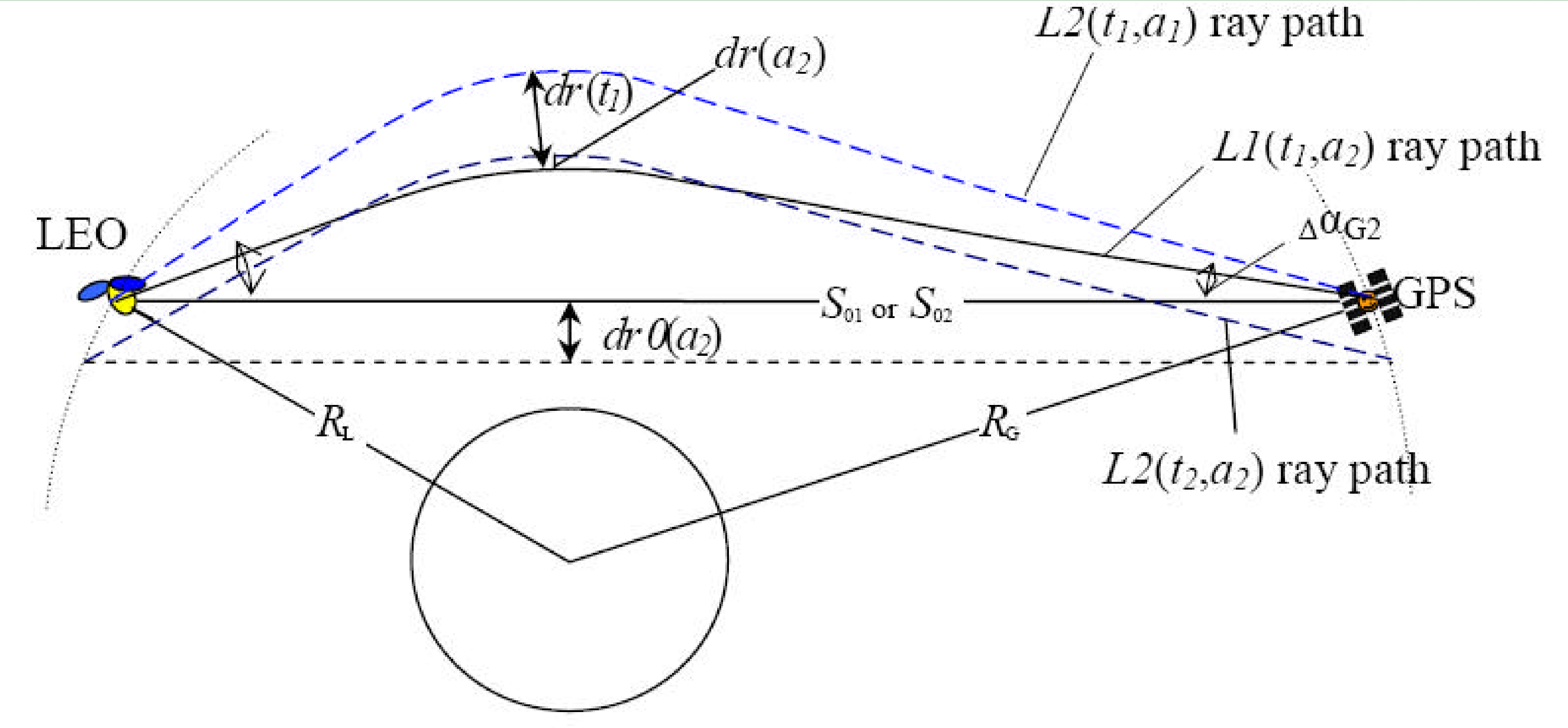
$$= \ln(n)\sqrt{x^2 - a^2} - \int \ln(n)\frac{x}{\sqrt{x^2 - a^2}}dx$$

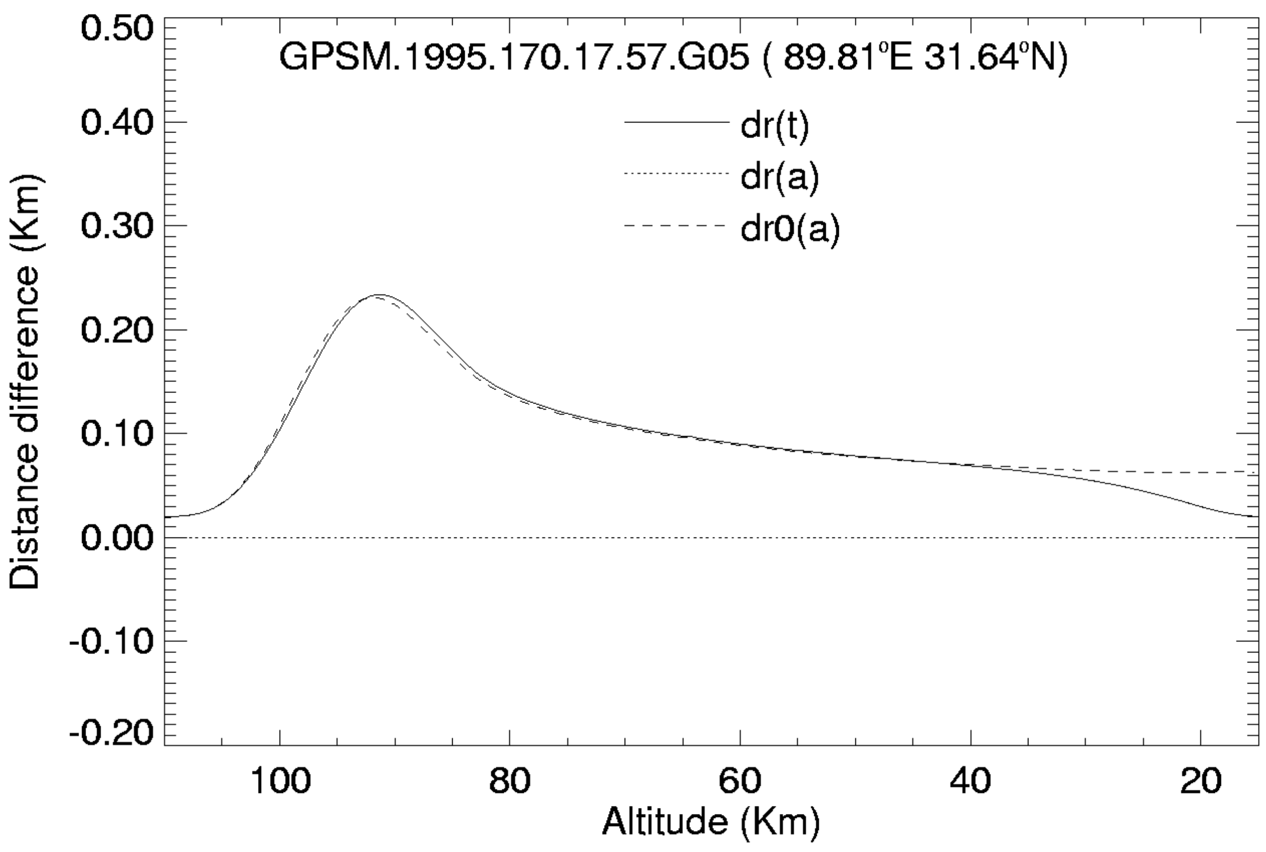
- Where n is equal to 1 for GPS and LEO position. The refractivity index $n = 1 + N_{ion+neu}$, if $N_{ion+neu}$ is very small compared to 1, $\ln(n) \sim N_{ion+neu}$ and $X \sim r$ so the Eq.(15) could be rewritten as

$$G_{path} = \int \frac{N(r)r}{\sqrt{r^2 - a^2}}dr = \int N ds_0$$

4. Combination of Lc(t) & Lc(a)

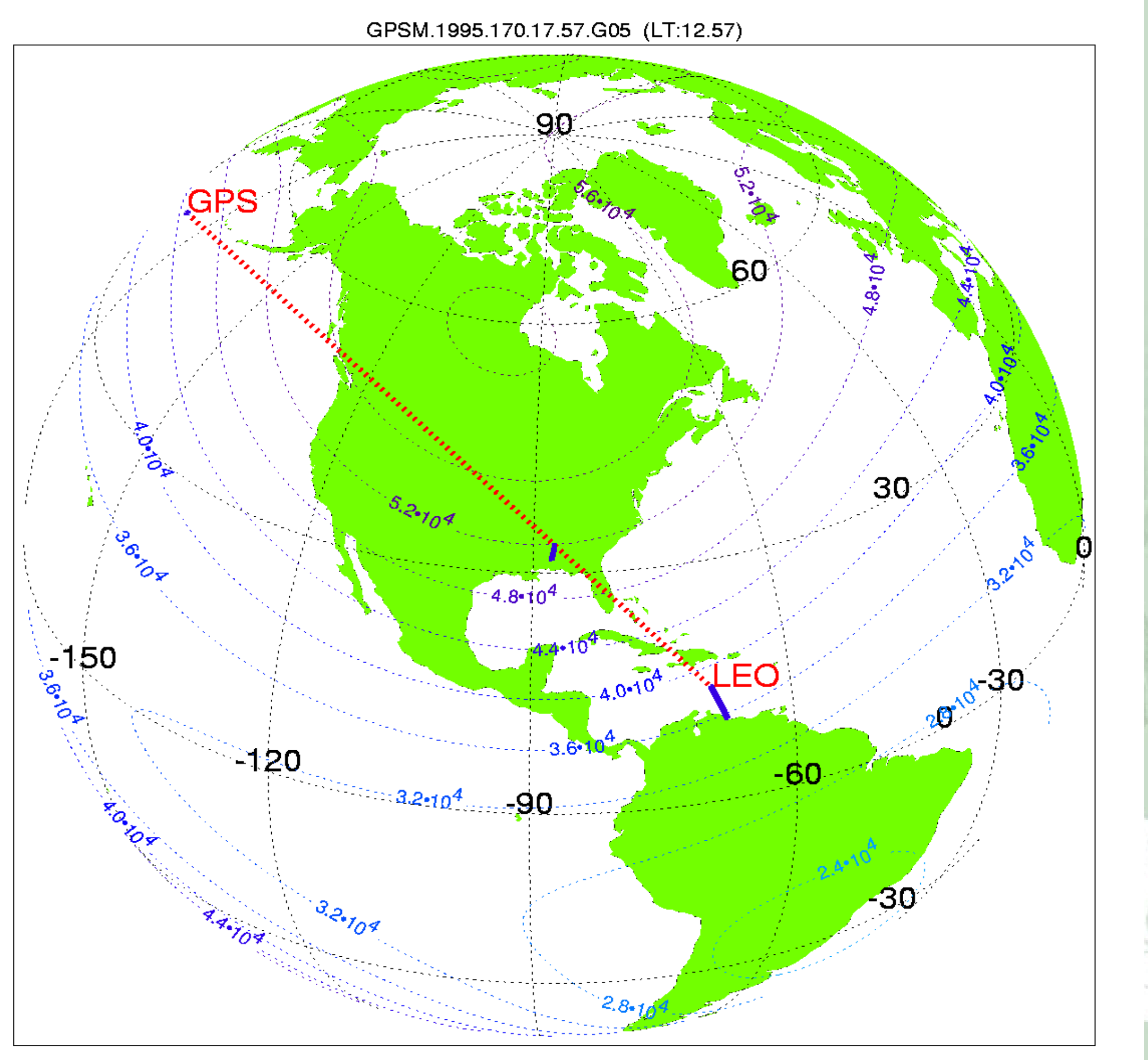
$$e_{1,2}(t,a) = \frac{f_1^2 e_1(t,a) - f_2^2\left[q e_2(t,a') + (1-q) f_2^2 e_2(t'',a)\right]}{f_1^2 - f_2^2}$$





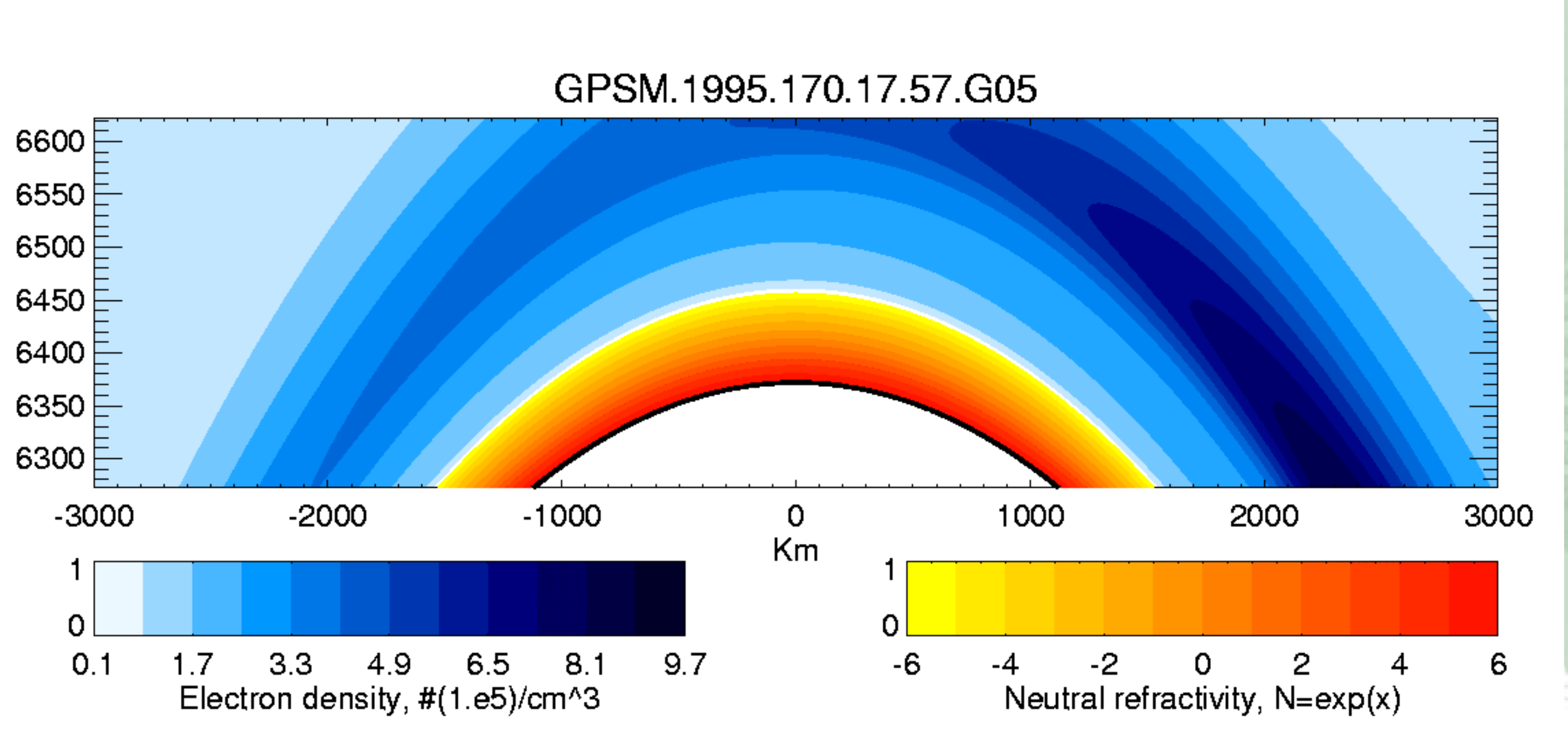
GPSM.1995.170.17.57.G05 (89.81°E 31.64°N)
dr(t)
dr(a)
dr0(a)
Distance difference (Km)
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
100
80
60
40
20
Altitude (Km)

IV. Results and Comparisons



Geographic locations of occultation event, and GPS and LEO satellites

The refractivity calculated from IRI2001 and NRLMSIS-00



Electron density distribution from the IRI2001 model

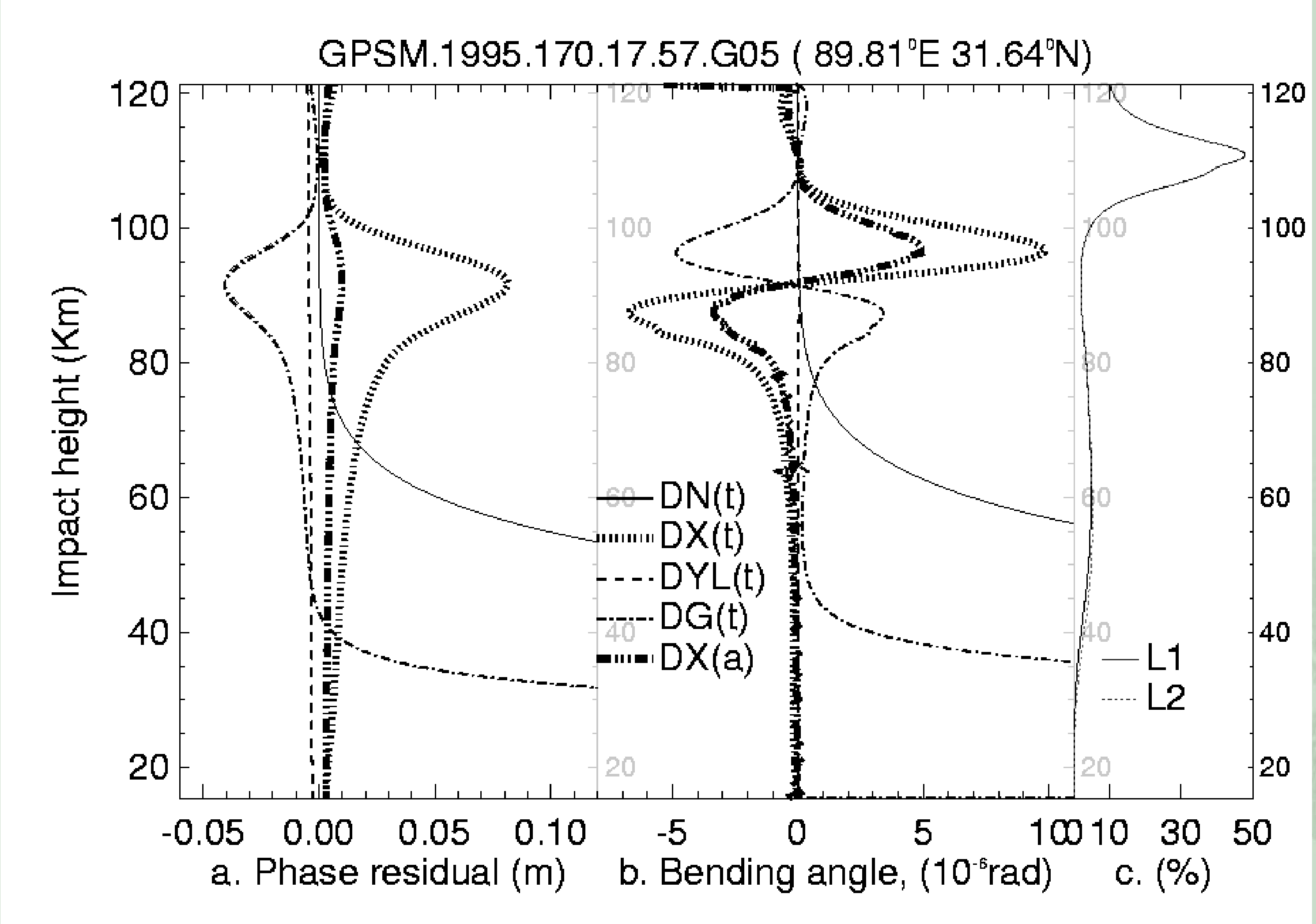
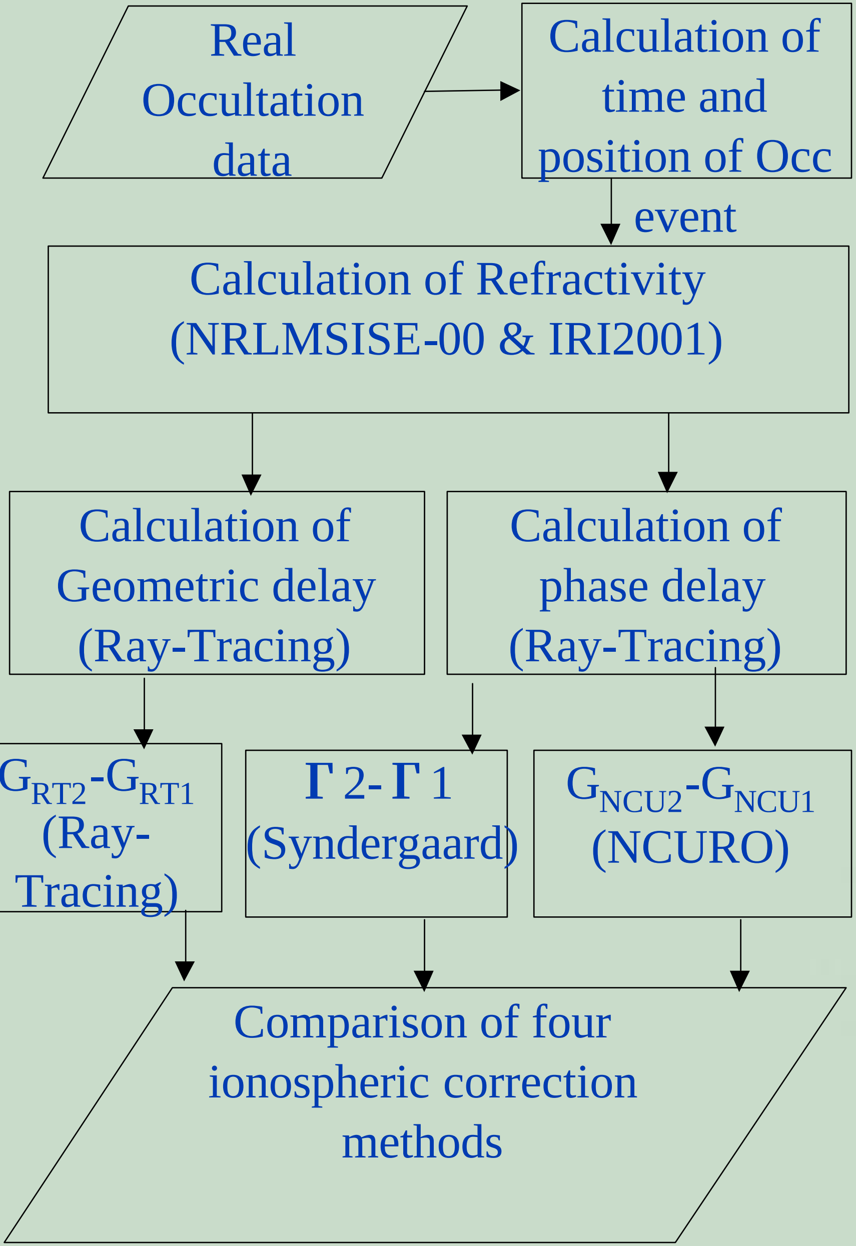
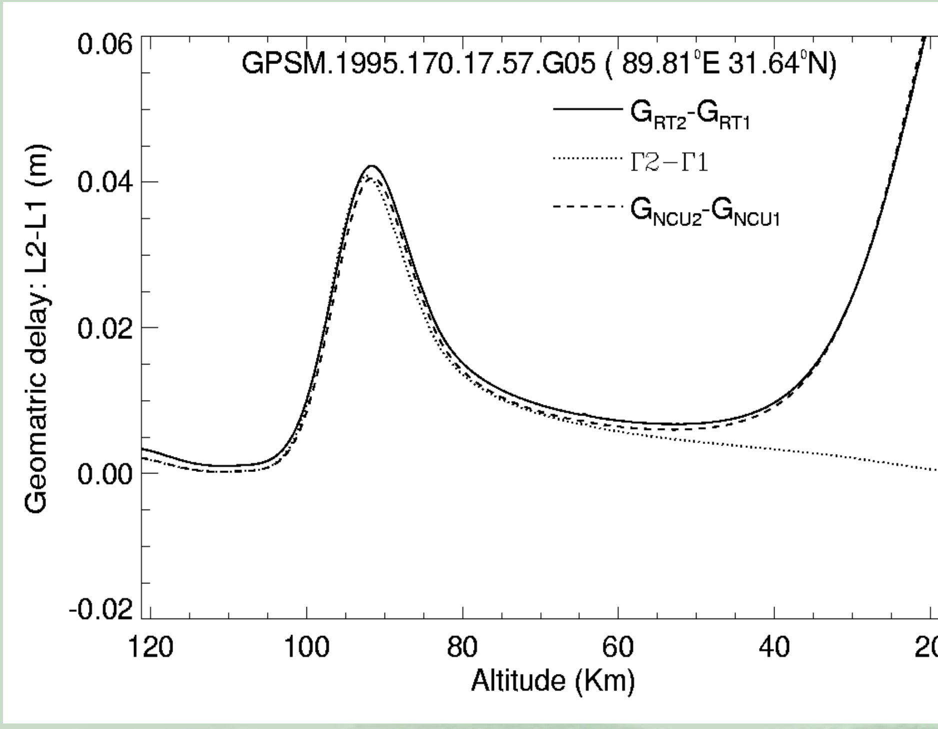


Figure shows the effectiveness of ionospheric corrections by various delay components. We begin with model simulations. Four delay components are considered and caused by neutral atmosphere along ray path (DN); electron density along ray path (DX, a contribution from the second term of the equation (3)); the third term of equation (3) (DYL); and bending effect of ray path (DG).

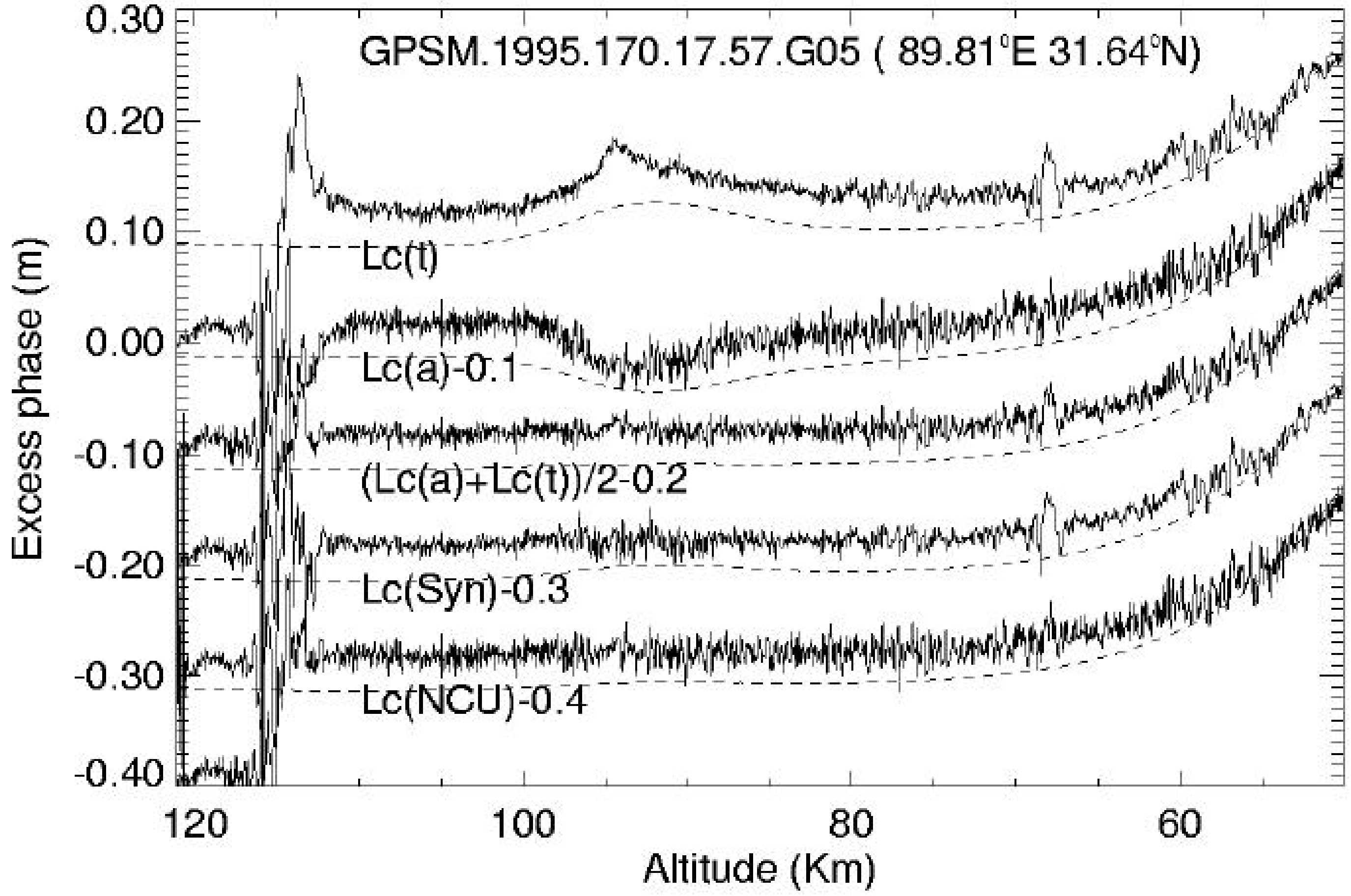
Comparison of Geometric delays





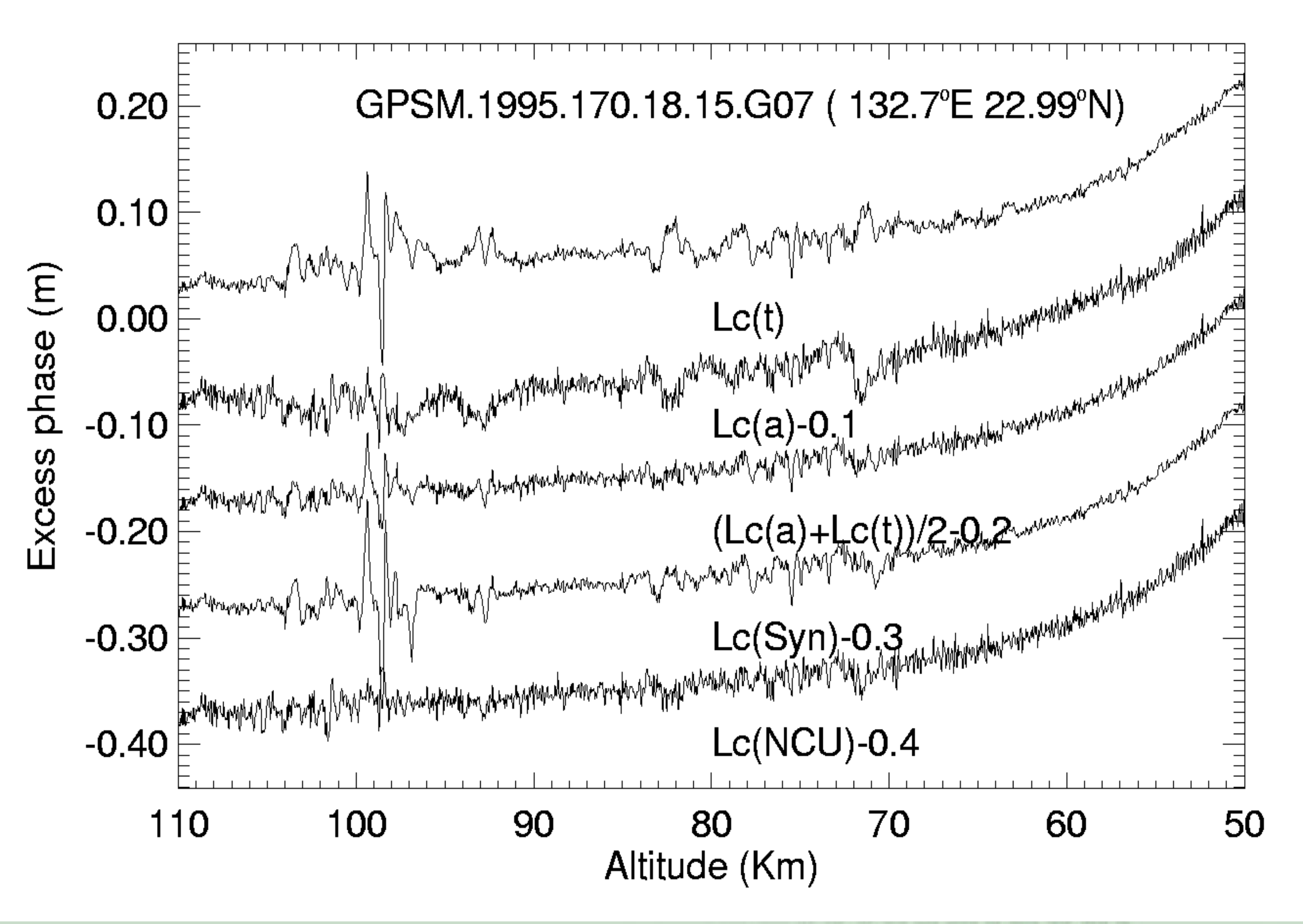
The results from the RT approach are shown by solid curve (GRT2-GRT1), from the Syndergaard method by dot curve (Γ2-Γ1) and from the NCURO scheme by dash curves (GNCU2-GNCU1)

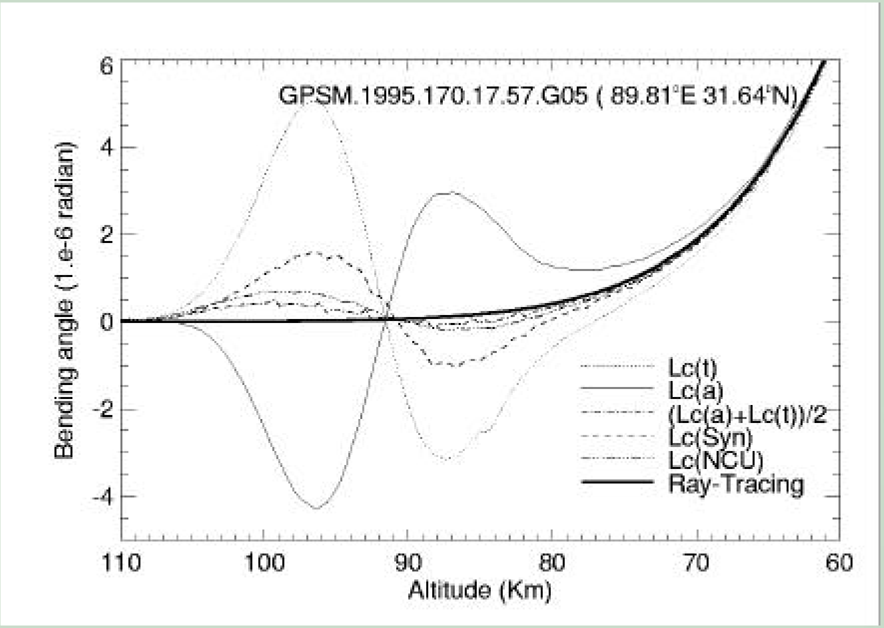
Excess phase delays from five ionospheric calibration methods

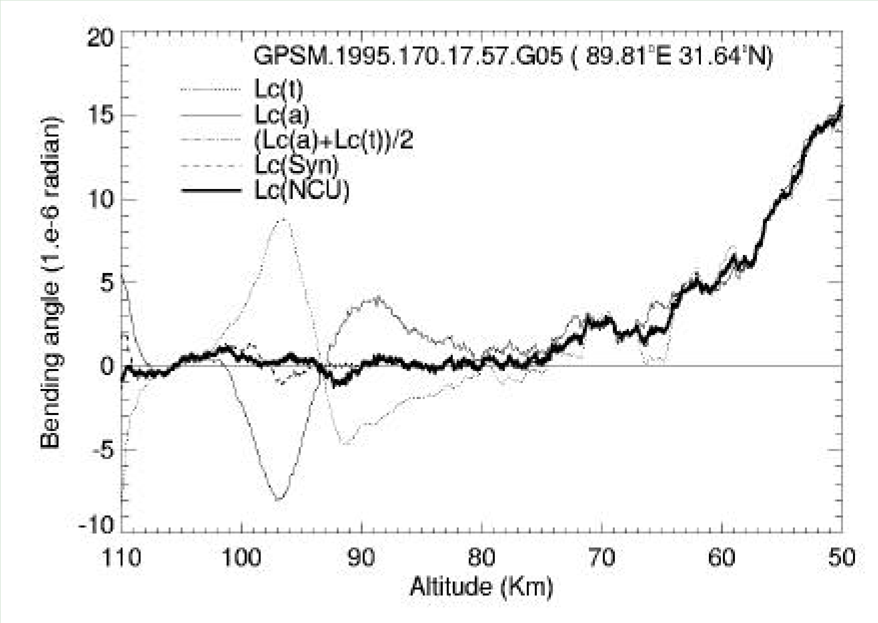


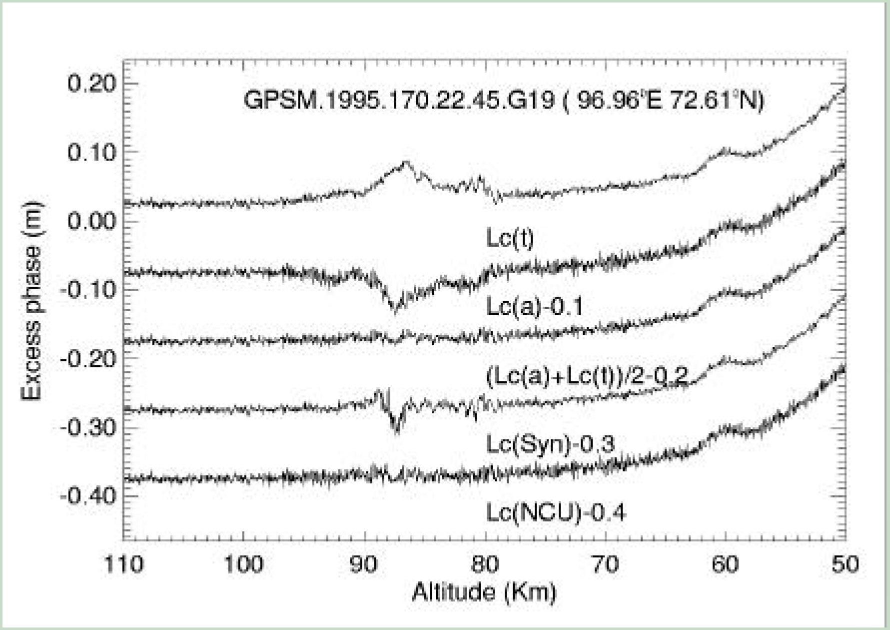
Solid curves are retrieved from occultation observation data, and dash curves are retrieved from simulations.

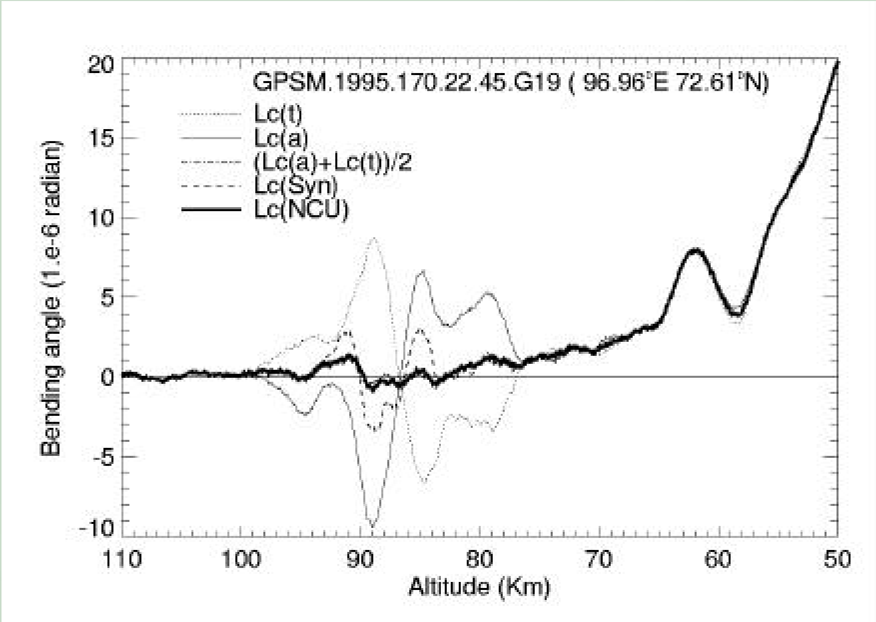
Excess phase delays from five ionospheric calibration methods

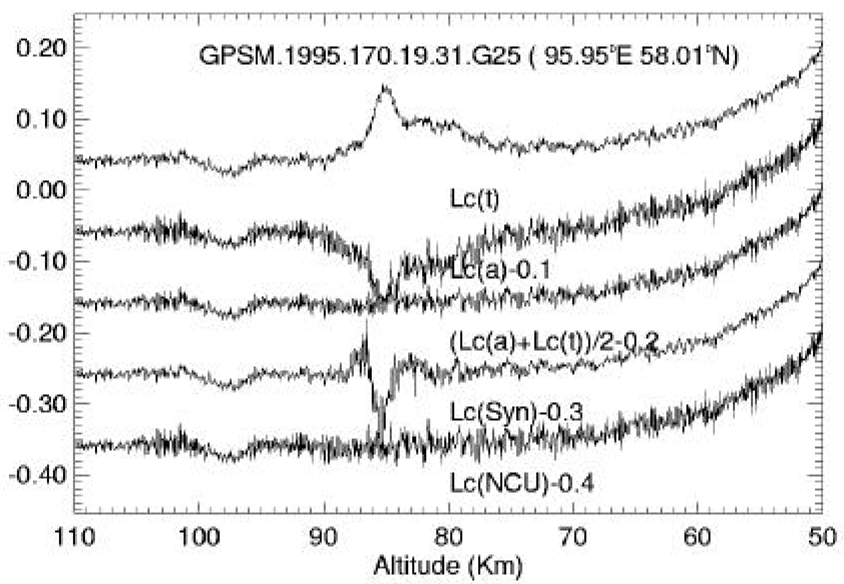



GPSM.1995.170.17.57.G05 (89.81°E 31.64°N)
Bending angle (1.e-6 radian)
Altitude (Km)
Lc(t)
Lc(a)
(Lc(a)+Lc(t))/2
Lc(Syn)
Lc(NCU)
Ray-Tracing

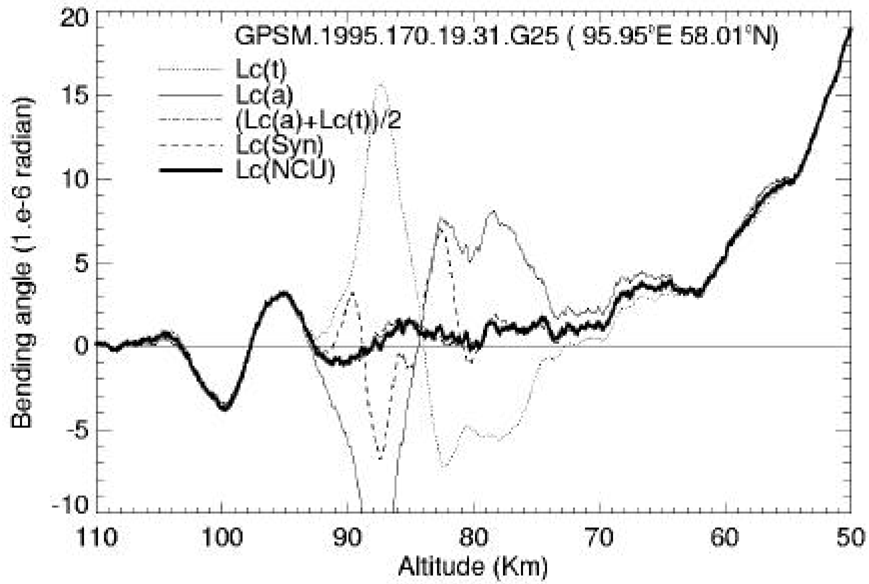

GPSM.1995.170.17.57.G05 (89.81°E 31.64°N)
Bending angle (1.e-6 radian)
Altitude (Km)
Lc(t)
Lc(a)
(Lc(a)+Lc(t))/2
Lc(Syn)
Lc(NCU)


GPSM.1995.170.22.45.G19 (96.96°E 72.61°N)
Excess phase (m)
Lc(t)
Lc(a)-0.1
(Lc(a)+Lc(t))/2-0.2
Lc(Syn)-0.3
Lc(NCU)-0.4
Altitude (Km)

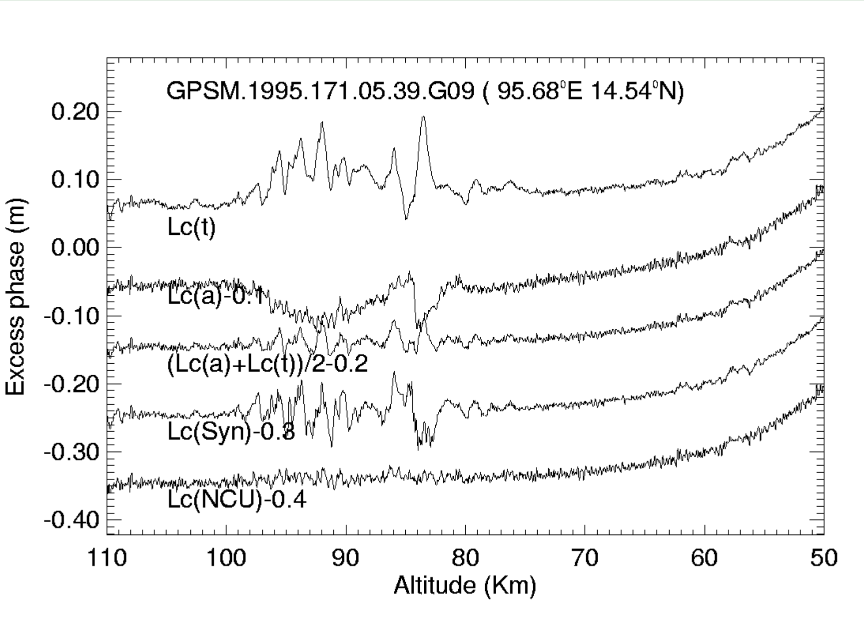

GPSM.1995.170.22.45.G19 (96.96°E 72.61°N)
Lc(t)
Lc(a)
(Lc(a)+Lc(t))/2
Lc(Syn)
Lc(NCU)
Bending angle (1.e-6 radian)
Altitude (Km)

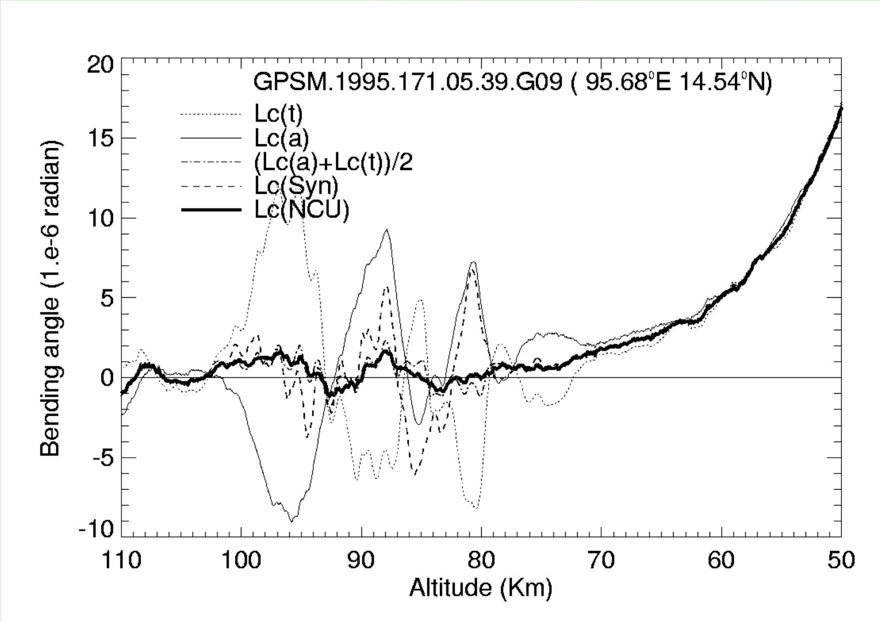


GPSM.1995.170.19.31.G25 (95.95°E 58.01°N)
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
Lc(t)
Lc(a)-0.1
(Lc(a)+Lc(t))/2-0.2
Lc(Syn)-0.3
Lc(NCU)-0.4
110
100
90
80
70
60
50
Altitude (Km)



GPSM.1995.170.19.31.G25 (95.95°E 58.01°N)
Lc(t)
Lc(a)
(Lc(a)+Lc(t))/2
Lc(Syn)
Lc(NCU)
Bending angle (1.e-6 radian)
20
15
10
5
0
-5
-10
110
100
90
80
70
60
50
Altitude (Km)


GPSM.1995.171.05.39.G09 (95.68°E 14.54°N)
Excess phase (m)
Altitude (Km)
Lc(t)
Lc(a)-0.1
(Lc(a)+Lc(t))/2-0.2
Lc(Syn)-0.3
Lc(NCU)-0.4


GPSM.1995.171.05.39.G09 (95.68°E 14.54°N)
Bending angle (1.e-6 radian)
Altitude (Km)
Lc(t)
Lc(a)
(Lc(a)+Lc(t))/2
Lc(Syn)
Lc(NCU)

V. Conclusions

- Simulation is performed to study the ionospheric correction. We show that the correction with the same impact performs better than that with the same signal received time. Nevertheless, the geometric delay caused by ionosphere at some altitudes cannot be corrected appropriately by the traditional ionosphere-free combination.
- It is shown that ray path delay and geometric delay can be corrected separately. The equations to characterize the delays are derived and implemented in the presented NCURO approach. The performance of the NCURO scheme appears to be superior to the ionospheric correction methods in the literature by use of theoretical RT simulations and experimental data comparisons.

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