TEC Evaluation from GNSS Measurements

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ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

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What did we learn about GNSS and TEC so far?

A lot of cool stuff but mainly…

- There are a lot of GNSS satellites and receivers available nowadays
- GNSS transmit signals on (at least) 2 different frequencies
- We can get code and phase observables from GNSS signals
- Ionosphere impacts on the propagation of GNSS signals from the satellite to the receiver
- We can use GNSS to derive TEC

But…

- It is not straightforward to measure TEC by means of GNSS signals
- There are “biases” affecting TEC measurements from GNSS

Goals to be reached in the next hour (or less if get bored)

- Understand how to use GNSS observables to retrieve TEC
- Understand what problems we have to face to do that
- Have a rough idea on how the problems can be solved (one of the possible solutions)
- Have the possibility to run a software capable of estimating TEC from GNSS measurements

Outline

- Ionosphere refractive index
- Total Electron Content
- Geometry-free linear combination of GNSS observables
- TEC calibration and mapping
- Ciraolo (Gigi) calibration technique
- Gigi’s software
- Live session (if we are on time)

The Appleton equation

To describe the refractive index of the ionosphere, *n*, we can refer to the Appleton equation:

$$n^2 = 1 - \frac{X}{1 - iZ - \frac{Y_T^2}{2(1-X-iZ)} \pm \sqrt{\frac{Y_T^2}{4(1-X-iZ)^2} + Y_L}}$$

$X = \frac{\omega_0^2}{\omega^2}$ — Electron plasma frequency

$Y = \frac{\omega_H}{\omega}$ — Electron gyro frequency

$Z = \frac{\nu}{\omega}$ — Collision frequency

$\omega = 2\pi f$

υ Can be neglected in most of the case → No Absorption

$$\omega_0 = \sqrt{\frac{Ne^2}{\varepsilon_0 m}} \qquad \omega_H = \frac{Be}{m}$$

$$B = 0 \;\Rightarrow\; n = \sqrt{1 - X}$$

The Appleton equation (GNSS frequencies)

The frequency of signals used for positioning has to be selected in order to make the refractive index as close as possible to unity (compatibly with international rules and status of art of technology).
Consider $N = 10^{12}\ e/m^3$ (a rather strong value) and $f = 1.5\ GHz$ (representative of GNSS frequencies)

$$n \approx 1 - (2 * 10^{-5})$$

For frequencies used in positioning, it can be used a first order approximation of the Appleton-Hartree formula

$$X = \frac{\omega_0^2}{\omega^2} \ll 1 \qquad Y = \frac{\omega_H}{\omega} \approx 0 \qquad Z = \frac{\nu}{\omega} \approx 0$$

$$n^2 = 1 - \frac{X}{1 - iZ - \frac{Y_T^2}{2(1-X-iZ)} \pm \sqrt{\frac{Y_T^2}{4(1-X-iZ)^2} + Y_L}} \Rightarrow n = \sqrt{1-X} \approx 1 - \frac{X}{2} = 1 - \frac{N_e e^2}{\varepsilon_0 m} = 1 - \frac{40.3 N_e}{f^2}$$

Electron density (N_e)

Total Electron Content

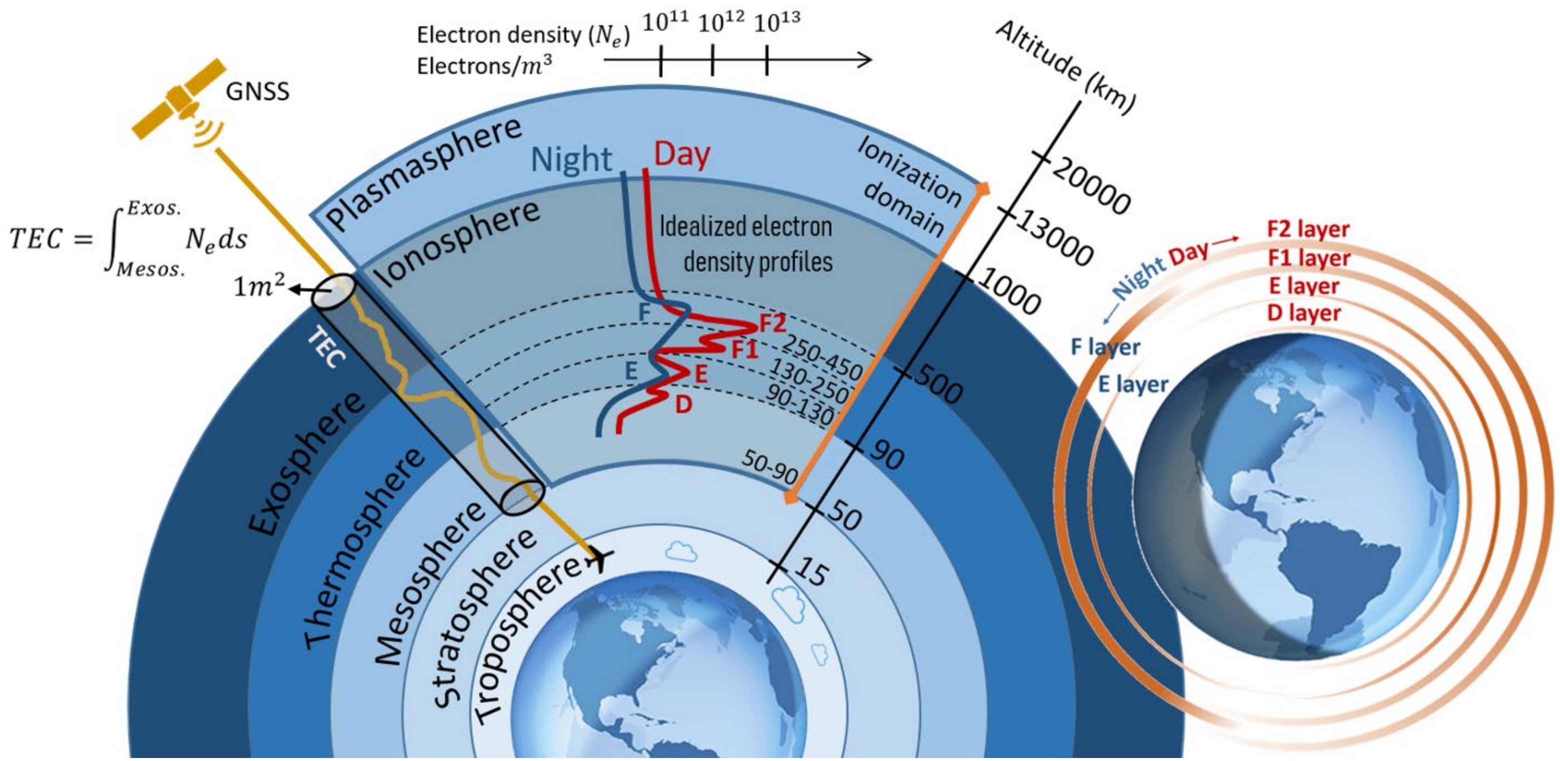
Using the 1st order expansion, the Optical Path of a GNSS signal travelling from the satellite to a ground receiver can be expressed as:

Geometric path

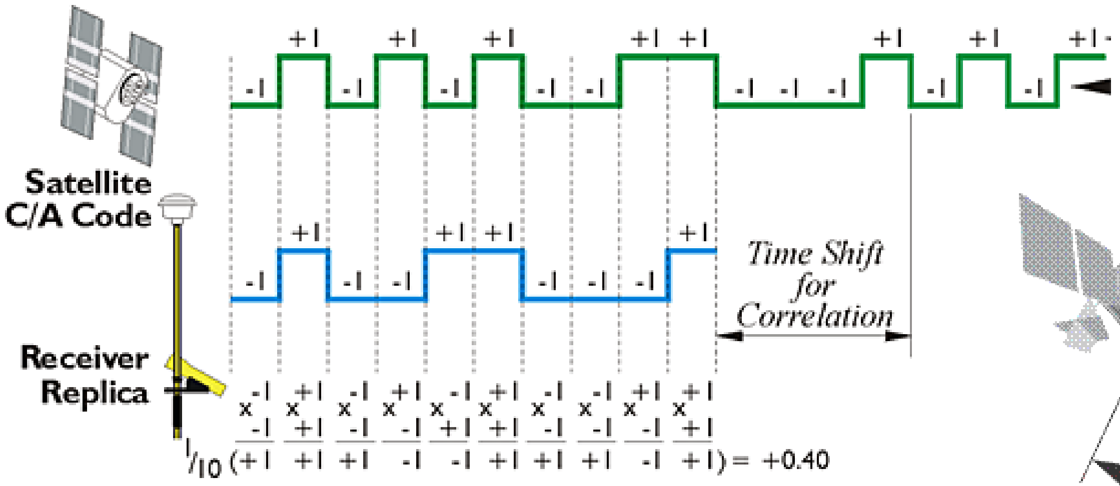
$$\Lambda = \int_{satellite}^{receiver} n\, ds = \int \left(1 - \frac{40.3 N_e}{f^2}\right) ds = S - \frac{40.3}{f^2} \int N_e ds = S - \frac{40.3}{f^2} STEC$$

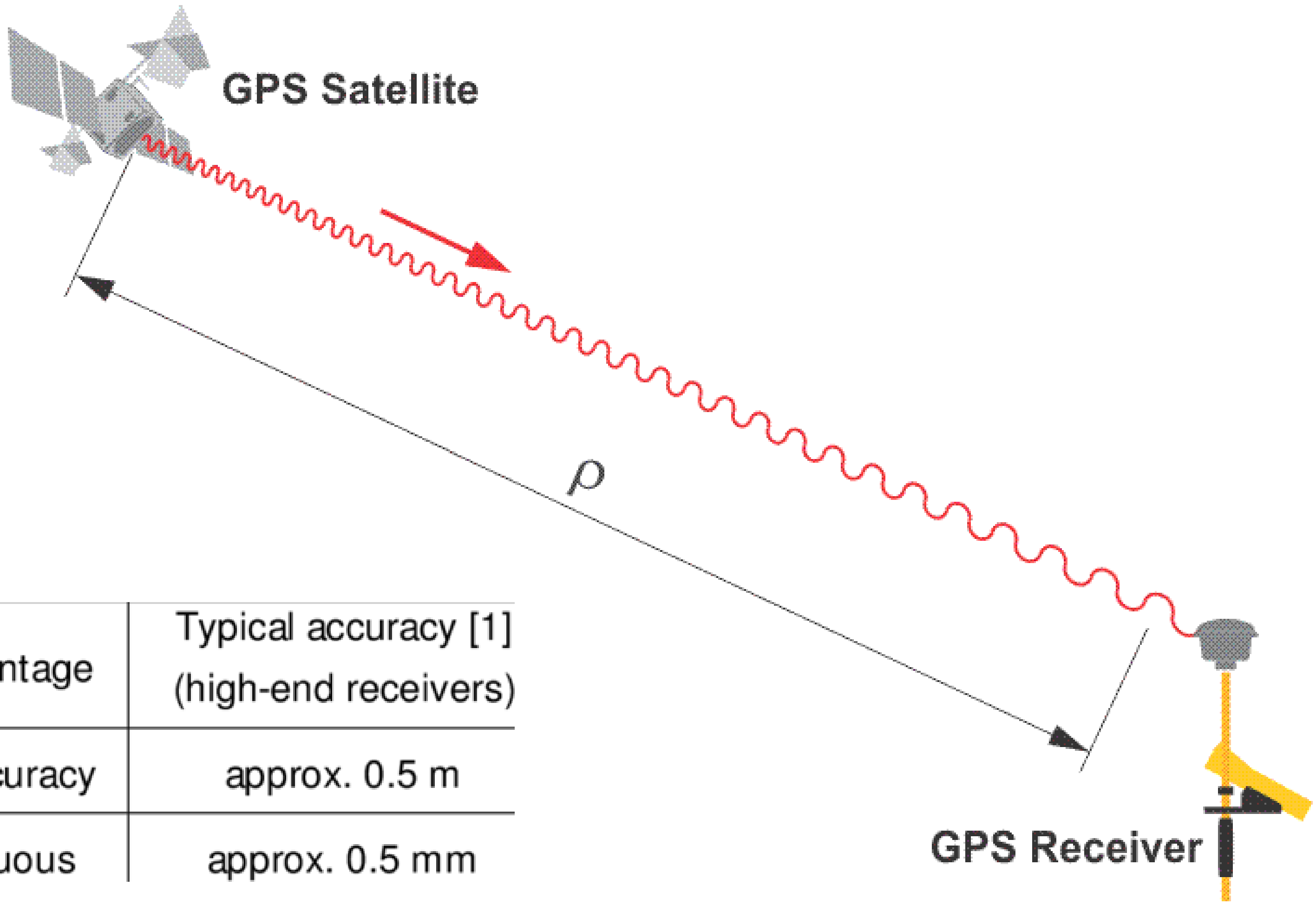
$$STEC = \int_{satellite}^{receiver} N_e ds$$

$$1\, TECU = 10^{16}\, e/m^2$$



Ionospheric Phase (L) and Code (d) Delays for GNSS





	Advantage	Disadvantage	Typical accuracy [1] (high-end receivers)
Code measurement	Unambiguous	Low accuracy	approx. 0.5 m
Carrier measurement	High accuracy	Ambiguous	approx. 0.5 mm

Linear Combination of GNSS Measurements

IONOSPHERE-FREE COMBINATION

$$\Phi_{\text{iono-free}} = \frac{f_1^2\ \Phi_{L_1} - f_2^2\ \Phi_{L_2}}{f_1^2 - f_2^2}$$

It removes the first order (up to 99.9%) ionospheric effect, which depends on the inverse square of the frequency

Positioning

Assessment of higher order ionospheric effects

GEOMETRY-FREE COMBINATION

$$\Phi_{LI} = \Phi_{L1} - \Phi_{L2}$$

It cancels the geometric part of the measurement, leaving all the frequency-dependent effects (i.e., ionospheric refraction, instrumental delays, wind-up) besides multipath and measurement noise

Estimation of Total electron content

Ionospheric Phase (L) and Code (d) Delays for GNSS

$$\mathrm{L}(cycles) = \frac{\Lambda}{\lambda} = \frac{1}{\lambda}\left(S - \frac{40.3}{f^2} STEC\right) = \frac{S}{\lambda} - \frac{40.3}{\lambda f^2} STEC = \frac{fS}{c} - \frac{40.3}{cf} STEC$$

$$\delta(seconds) = \frac{dL}{df} = \frac{S}{c} + \frac{40.3}{cf^2} STEC$$

$$\mathrm{L}(meters) = L(cycles) * \lambda = S - \frac{40.3}{f^2} STEC$$

$$\delta\,(meters) = \delta(seconds) * c = S + \frac{40.3}{f^2} STEC$$

Under the assumed approximation of the Appleton-Hartree formula:
distance measurements using phase delay and code delay provide with an estimation of actual distance S plus a ionospheric contribution which in absolute value is the same for phase and code, but with opposite sign.

Geometry free linear combination (ideal case)

$$L_1, P_1 = S \mp \frac{40.3\ STEC}{f_1^2}$$

$$L_2, P_2 = S \mp \frac{40.3\ STEC}{f_2^2}$$

How isolating ionospheric information? Solving the system provided by measurements at two frequencies f1 and f2 at advantage of the ionospheric investigator

$$DPD = L_1 - L_2 = I_1 - I_2$$

$$DGD = P_2 - P_1 = I_2 - I_1$$

$$I_1 - I_2 = 40.3\left(\frac{1}{f_2^2} - \frac{1}{f_1^2}\right) STEC$$

But in the real world…

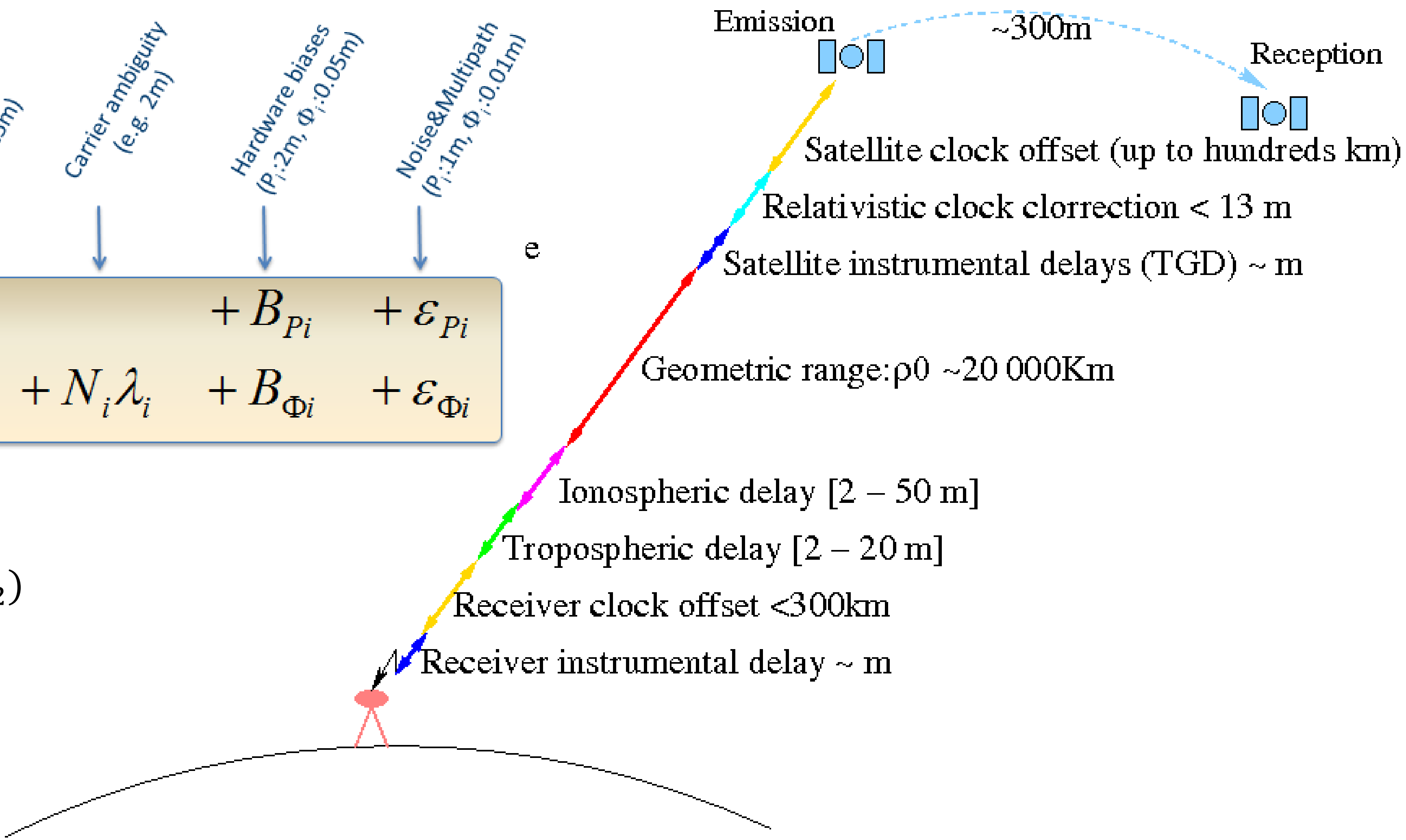
Code and Carrier phase measurements equations

Geometric range (e.g. 20000km) | Clock offset (e.g. 500km) | Troposphere (e.g. 3m) | Ionosphere (e.g. 15m) | Carrier ambiguity (e.g. 2m) | Hardware biases (P_i:2m, Φ_i:0.05m) | Noise&Multipath (P_i:1m, Φ_i:0.01m)

$$P_i = \rho + c\cdot dt + T + I_i + B_{Pi} + \varepsilon_{Pi}$$

$$\Phi_i = \rho + c\cdot dt + T - I_i + N_i\lambda_i + B_{\Phi i} + \varepsilon_{\Phi i}$$

i= $carrier\ frequency\ (e.g.\ L_1, L_2)$



The ionosphere will introduce a delay of the modulation (the code measurement will be larger than in vacuum), and an advance of the carrier phase (the carrier phase measurement will be smaller than in vacuum).

Geometry free linear combination

$$L_{\mathrm{arc}}[m] = L_1 - L_2 = I_1 - I_2 + \cancel{T_1 - T_2} + c\left(\tau_{1,\mathrm{R}} - \tau_{2,\mathrm{R}}\right) + c\left(\tau_{1,\mathrm{S}} - \tau_{2,\mathrm{S}}\right) + \lambda_1 N_1 + \lambda_2 N_2 + \epsilon_{\mathrm{L}}$$

Troposphere is assumed to be non-dispersive medium, so the tropospheric contribution is cancelled out

$$STEC = \left[40.3\left(\frac{1}{f_2^2} - \frac{1}{f_1^2}\right)\right]^{-1} * (I_1 - I_2) = k(I_1 - I_2)$$

$$L_{\mathrm{arc}}[TECu] = \mathrm{sTEC} + B_{\mathrm{R}} + B_{\mathrm{S}} + C_{\mathrm{arc}} + \varepsilon_L$$

$$B_{\mathrm{R}} = c\left(\tau_{1,\mathrm{R}} - \tau_{2,\mathrm{R}}\right)k \qquad B_{\mathrm{S}} = c\left(\tau_{1,\mathrm{S}} - \tau_{2,\mathrm{S}}\right)k$$

$$C_{\mathrm{arc}} = k(\lambda_1 N_1 + \lambda_2 N_2) \qquad \varepsilon_L = k\epsilon_{\mathrm{L}}$$

The meaning of **Arc** in radio observations, as a series of observations carried out with *continuity* from one station to one satellite**.** *Continuity***:** presence of satellite over the horizon of the station (astronomical arc) **,** no loss of lock for phase or code.

If not recoverable loss of lock occurs, two distinct arcs will be considered also if observations belong to the same "astronomical" arc.

Geometry free linear combination (phase vs code)

Phase observables GFLC

$$L_{\mathrm{arc}}[TECu] = \mathrm{sTEC} + B_{\mathrm{R}} + B_{\mathrm{S}} + C_{\mathrm{arc}} + \varepsilon_L$$

Less noisy wrt code observables

Relative measurement (ambiguity term)

Code observables GFLC

$$P = \mathrm{sTEC} + b_{\mathrm{R}} + b_{\mathrm{S}} + \varepsilon_{\mathrm{P}}$$

Noisier wrt phase observables

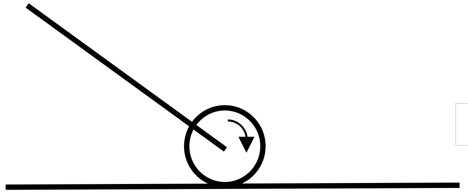
Absolute measurement (no ambiguity term)

Phase ambiguity

Measuring phase is like measuring distance with an odometer

Apart the initial ambiguity ***Ω***, the user can cumulate the cycles (***L***) of the incoming signal achieving very high resolution in the measurement of the distance. If some cycle is lost (**cycle slip, phase jump**), measurement re-starts with a new ambiguity

$$D = \Omega + L \cdot \lambda$$



$\lambda = 2\pi \cdot R$

(***R*** **radius of odometer)**

Geometry free linear combination (ambiguity resolution)

Phase observables GFLC

$$L_{\mathrm{arc}}[TECu] = \mathrm{sTEC} + B_{\mathrm{R}} + B_{\mathrm{S}} + C_{\mathrm{arc}} + \varepsilon_L$$

Code observables GFLC

$$P = \mathrm{sTEC} + b_{\mathrm{R}} + b_{\mathrm{S}} + \varepsilon_{\mathrm{P}}$$

$$\langle L_{\mathrm{arc}} - P \rangle_{\mathrm{arc}} = C_{\mathrm{arc}} + B_{\mathrm{R}} + B_{\mathrm{S}} - b_{\mathrm{R}} - b_{\mathrm{S}} - \langle \varepsilon_{\mathrm{P}} \rangle_{\mathrm{arc}}$$

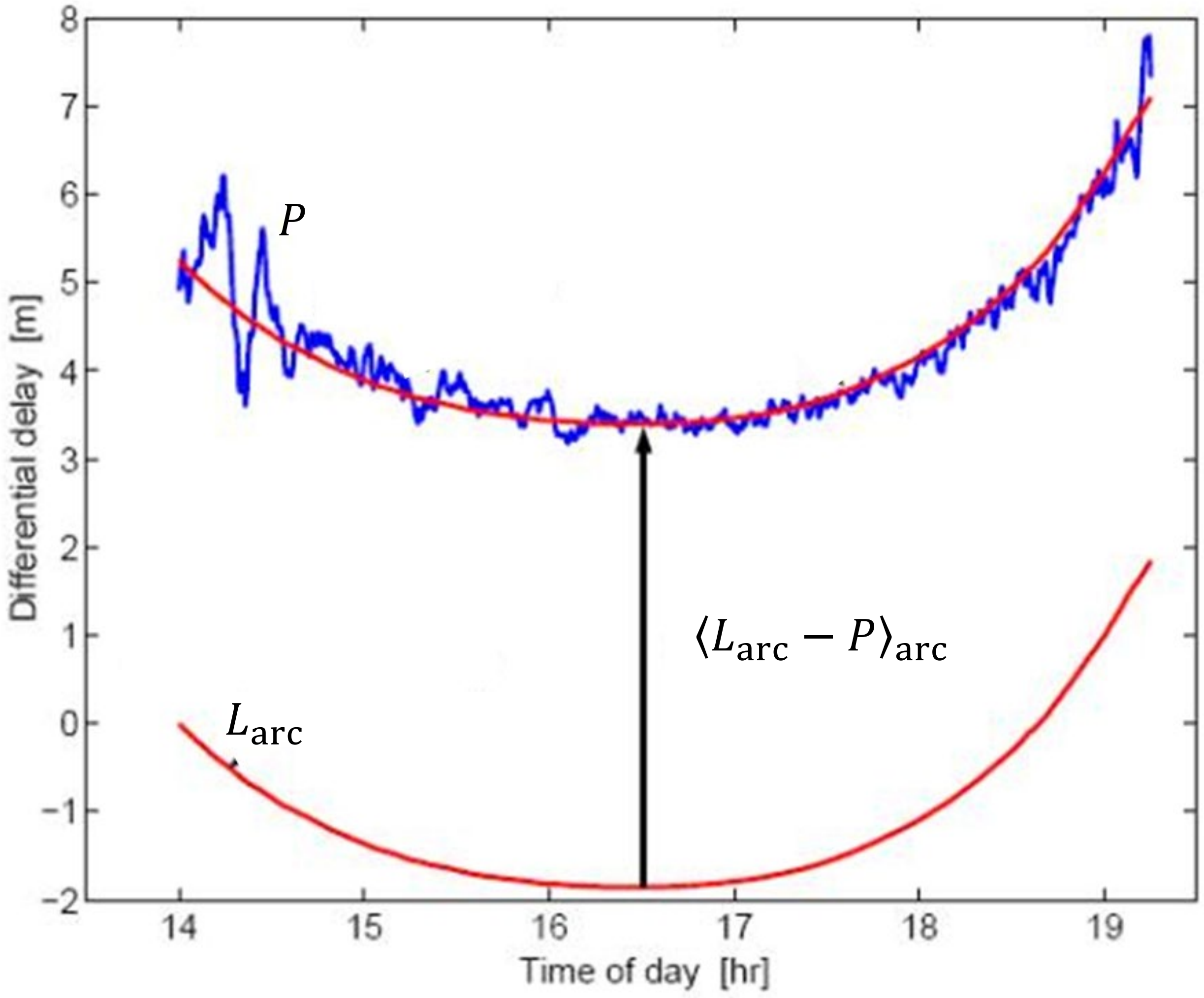
$\langle \quad \rangle$=*mean over an arc*

$$L_{\mathrm{arc}} - \langle L_{\mathrm{arc}} - P \rangle_{\mathrm{arc}} = \tilde{L}_{\mathrm{arc}} = \mathrm{sTEC} + b_{\mathrm{R}} + b_{\mathrm{S}} + \langle \varepsilon_{\mathrm{P}} \rangle_{\mathrm{arc}}$$

multipath + other non-zero mean errors

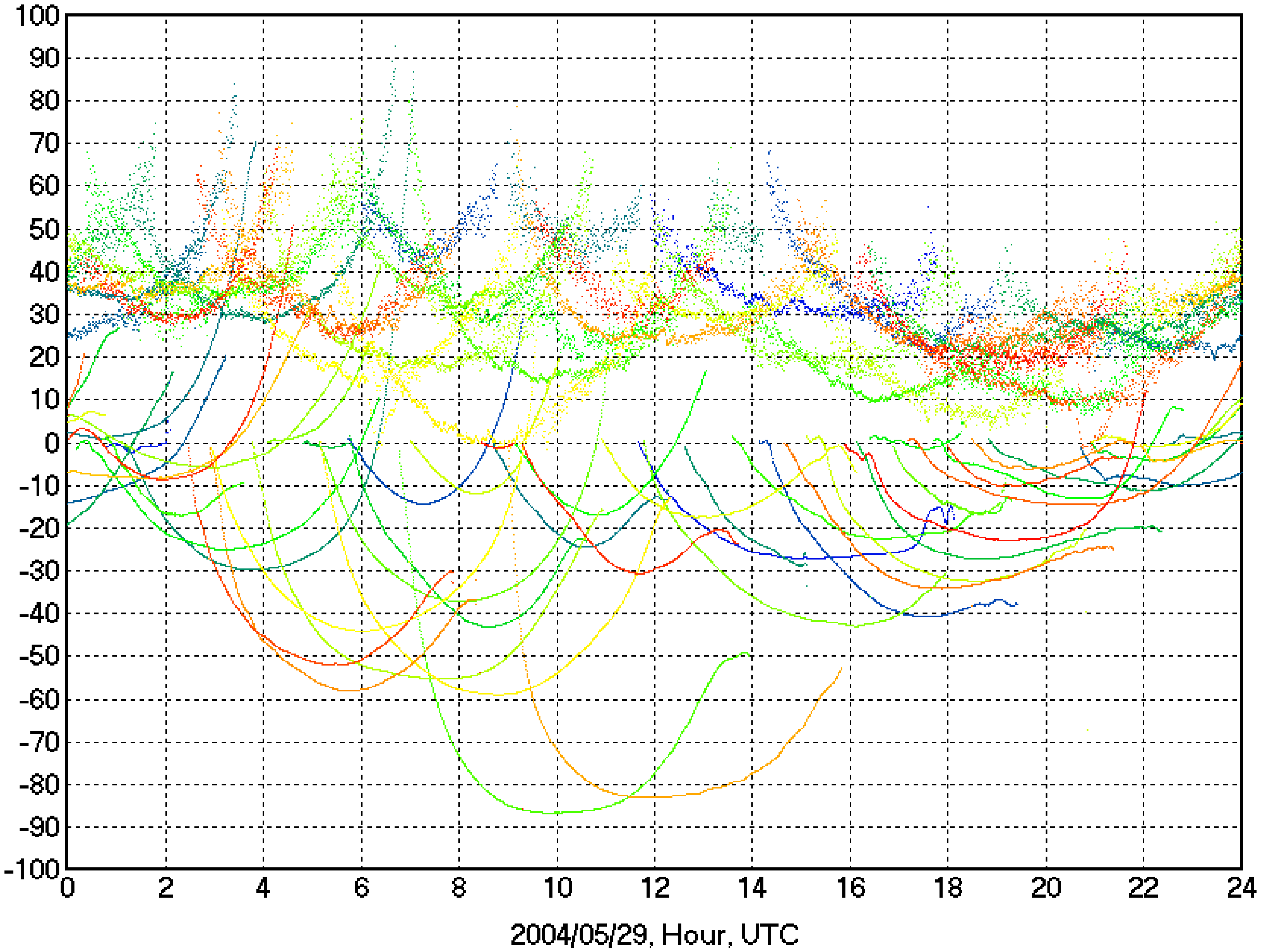
Geometry free linear combination (ambiguity resolution)

$$L_{\mathrm{arc}} - \langle L_{\mathrm{arc}} - P \rangle_{\mathrm{arc}} = \tilde{L}_{\mathrm{arc}} = \mathrm{sTEC} + b_{\mathrm{R}} + b_{\mathrm{S}} + \langle \varepsilon_{\mathrm{P}} \rangle_{\mathrm{arc}}$$



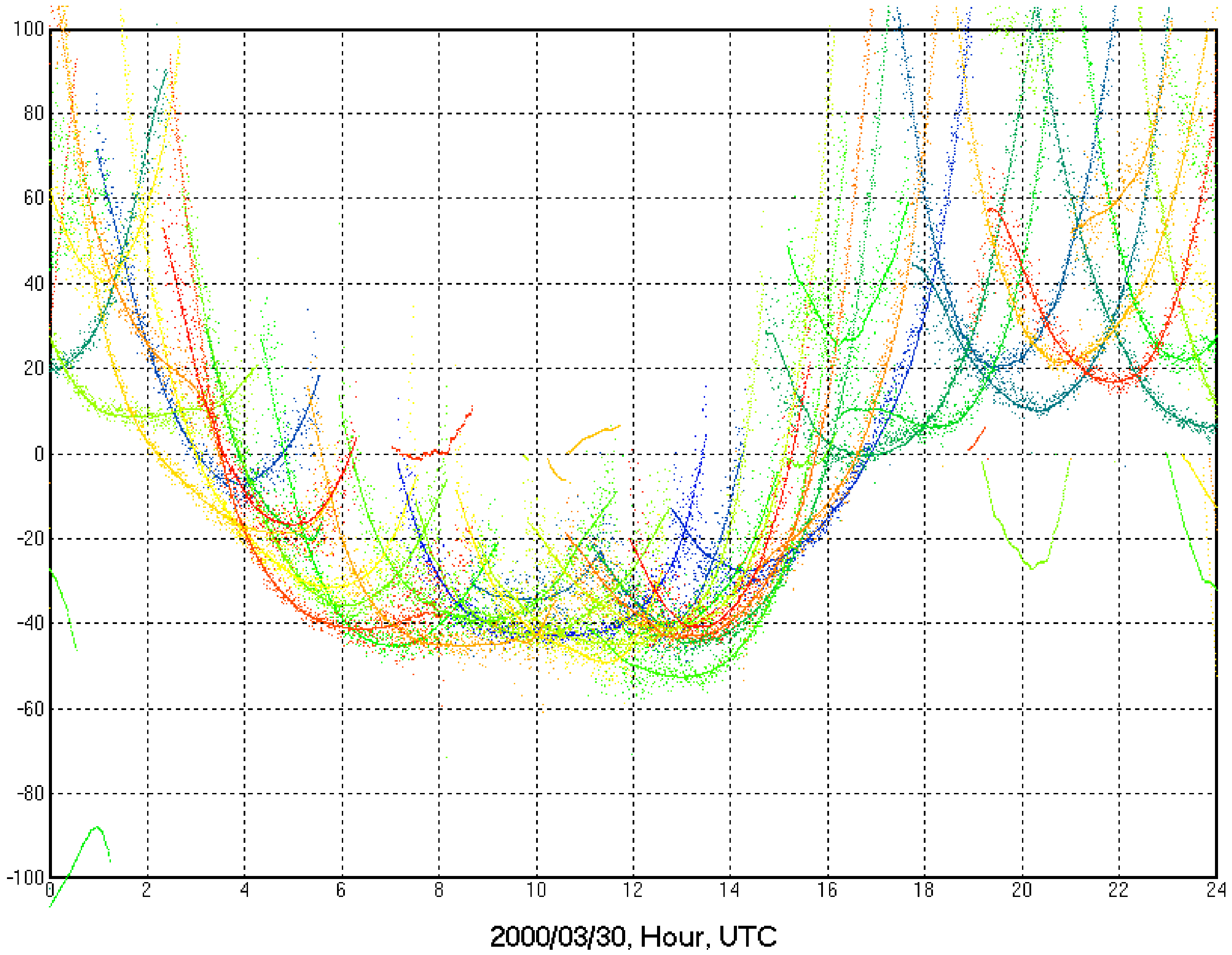
Geometry free linear combination (ambiguity resolution)

$$L_{\mathrm{arc}} - \langle L_{\mathrm{arc}} - P \rangle_{\mathrm{arc}} = \tilde{L}_{\mathrm{arc}} = \mathrm{sTEC} + b_{\mathrm{R}} + b_{\mathrm{S}} + \langle \varepsilon_{\mathrm{P}} \rangle_{\mathrm{arc}}$$

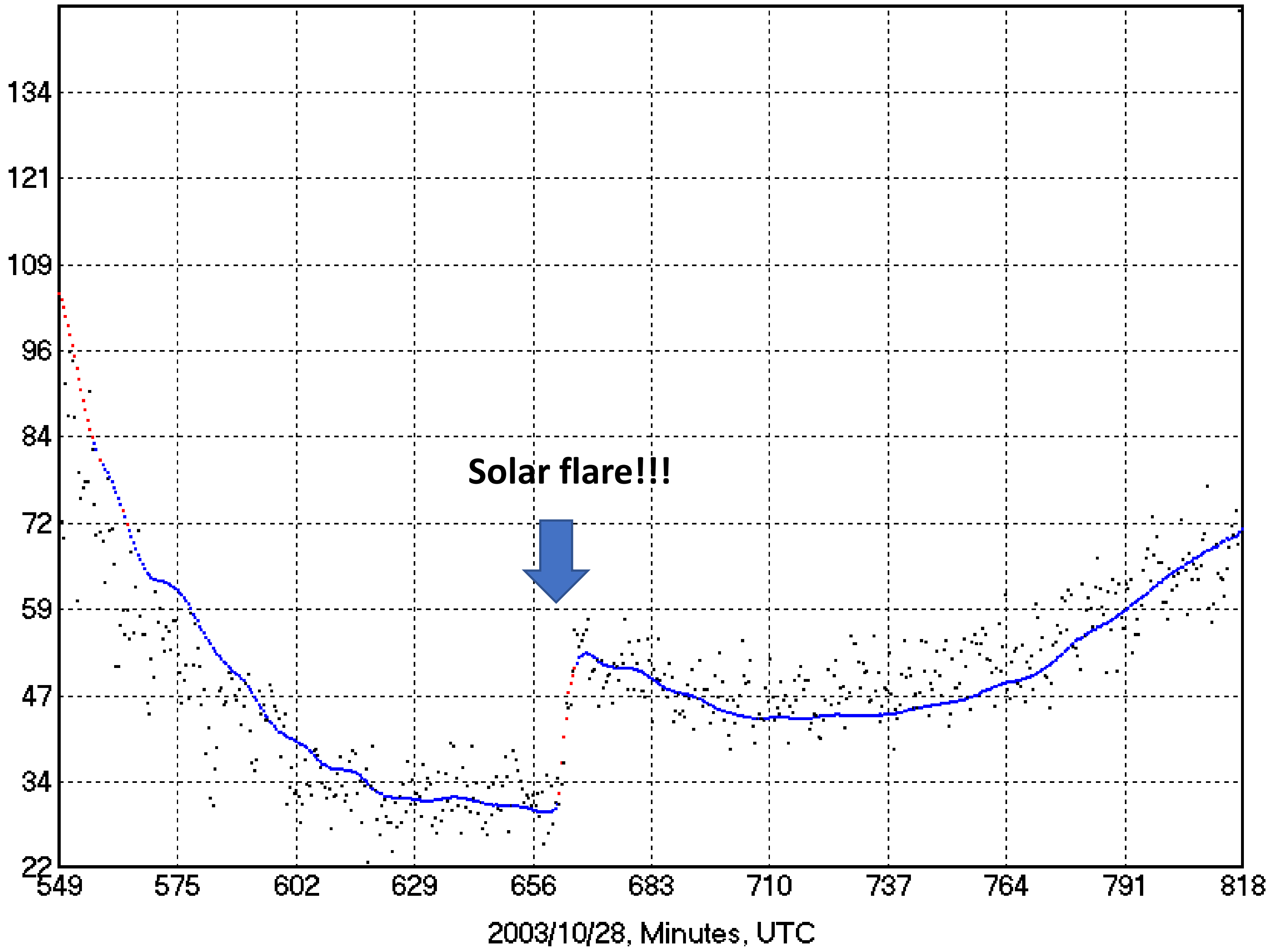


Geometry free linear combination (ambiguity resolution)

$$L_{\text{arc}} - \langle L_{\text{arc}} - P \rangle_{\text{arc}} = \tilde{L}_{\text{arc}} = \text{sTEC} + b_{\text{R}} + b_{\text{S}} + \langle \varepsilon_{\text{P}} \rangle_{\text{arc}}$$



Phase jump (cycle slips?)



Calibration and Mapping

Task of the calibration

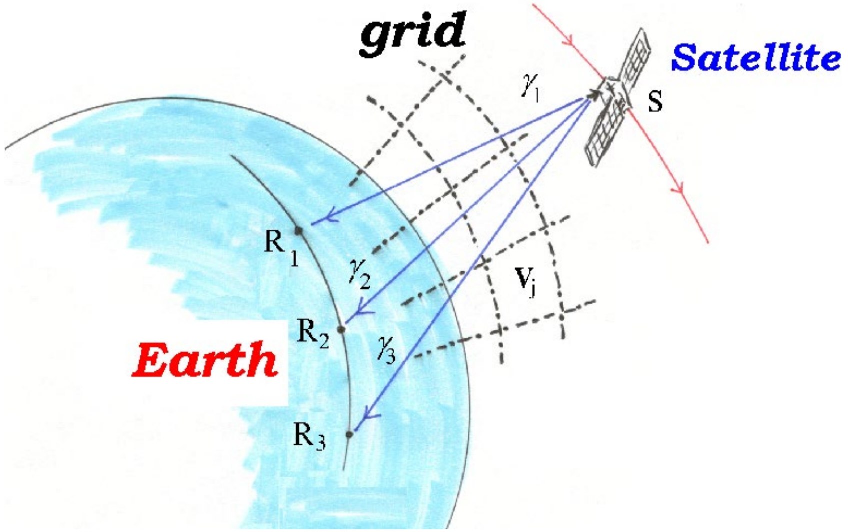
Isolate TEC from other terms

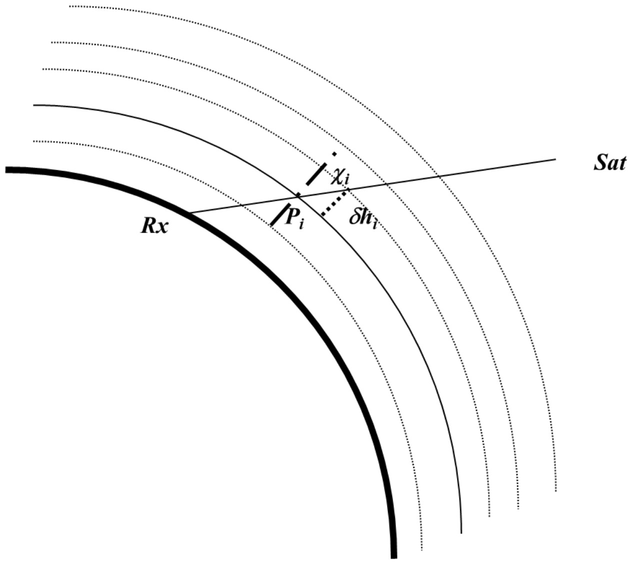
The only way to proceed is assuming that TEC from all available observations from generic station R_j to generic satellite S_i can be expanded using proper base functions of time and position $\Psi(P,t)$.

This representation of TEC is the so-called **TEC Mapping**, achievable in several ways (integrated 3D electron density, or 2D shell, …)

$$TEC(R_j, S_i, t) = \sum_k c_k \psi_k(P,t)$$

Global many days
Global single day
Regional many days
Regional single day
Single station many days
Single station one day





TEC Calibration (de-biasing)

$$L_{\mathrm{arc}} - \langle L_{\mathrm{arc}} - P \rangle_{\mathrm{arc}} = \tilde{L}_{\mathrm{arc}} = \mathrm{sTEC} + b_{\mathrm{R}} + b_{\mathrm{S}} + \langle \varepsilon_{\mathrm{P}} \rangle_{\mathrm{arc}}$$

$\langle \varepsilon_{\mathrm{P}} \rangle_{\mathrm{arc}} \approx 0$

$b_{\mathrm{R}}, b_{\mathrm{S}}$ evaluated independently every now and then

$b_{\mathrm{R}}, b_{\mathrm{S}}$ can be taken from **IGS Ionosphere** Associate Analysis **Centers** (IAACs)

$\tilde{L}_{\mathrm{arc}} = \mathrm{sTEC} + \beta_{arc}$

$\beta_{arc} = b_{\mathrm{R}} + b_{\mathrm{S}} + \langle \varepsilon_{\mathrm{P}} \rangle_{\mathrm{arc}}$
to be evaluated arc by arc

Gg calibration technique (see e.g. Ciraolo et al., 2007; Cesaroni et al., 2015; Cesaroni et al., 2021)

$\sum_{j=sat} b_r^j = 0$

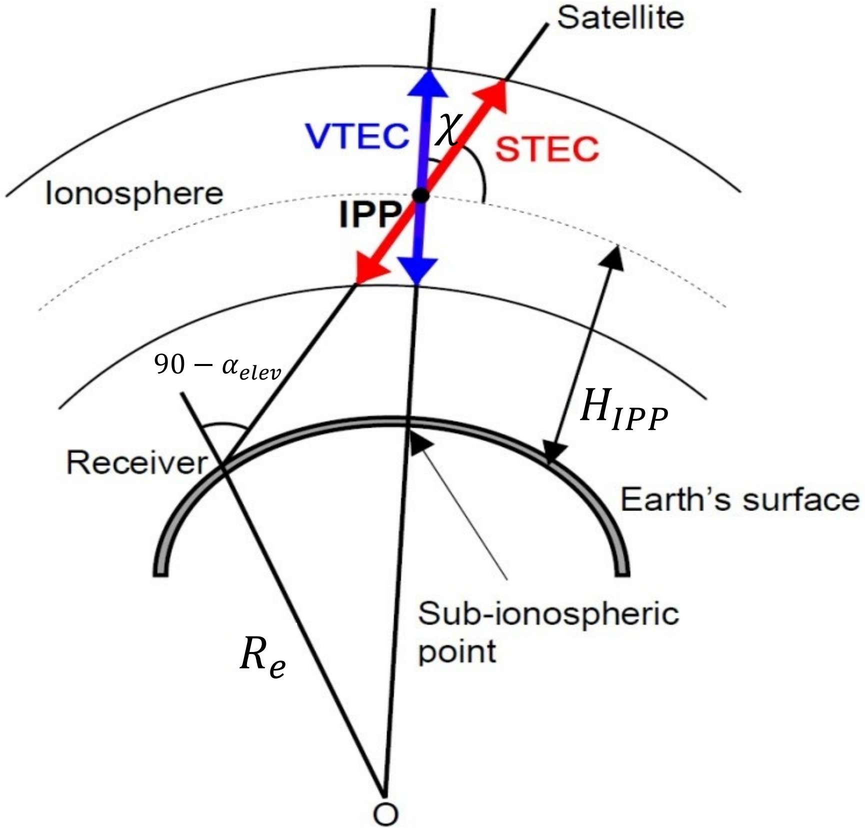
$\tilde{L}_{\mathrm{arc}} = \tilde{L}_{\mathrm{arc}}(\varphi, \lambda, H, t)$
Global or regional TEC model

$b_{\mathrm{R}}, b_{\mathrm{S}}$ evaluated independentely

Single day – single station approach (Gg technique)

$$\tilde{L}_{\mathrm{arc}}(R_j, S_i, t) = \mathrm{sTEC}(R_j, S_i, t) + \beta_{arc}$$

Once selected some method of mapping has been assumed, the coefficients ***c*** of TEC expansion become a new set of unknowns to be estimated together with the “biasing” terms using standard minimization algorithms



$$\tilde{L}_{\mathrm{arc}}(R_j, S_i, t) = \sum_k c_k \psi_k(P, t) + \beta_{arc}$$

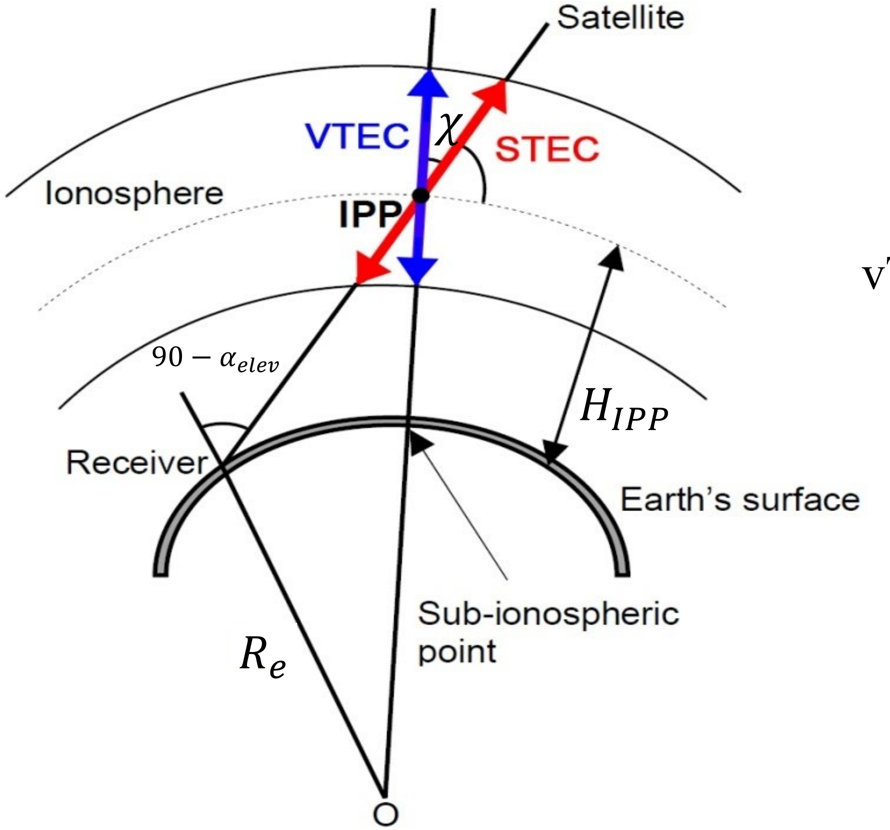
$$F(\alpha_{\mathrm{elev}}) = \frac{1}{\sqrt{1 - \left(\frac{R_{\mathrm{e}} \cos \alpha_{\mathrm{elev}}}{R_{\mathrm{e}} + H_{\mathrm{IPP}}}\right)^2}},$$

$$STEC = VTEC \cdot \sec \chi = VTEC \cdot F_{(\alpha_{elev})}$$

Single day – single station approach (Gg technique)

$$sTEC = vTEC(\phi_1, \phi_2) \cdot \sec\chi$$

where $vTEC(\phi_1, \phi_2)$ is the unknown describing a surface in the reference frame defined by a couple (ϕ_1, ϕ_2)·over the thin shell (bi-dimensional)



$$\tilde{L}_{\mathrm{arc}} = \sec\chi \sum_n c_n p_n(\mathrm{LT}, \mathrm{Modip}) + \beta_{\mathrm{arc}}$$

vTEC is expanded as a polynomial linear in LT and of the fourth-order in Modip

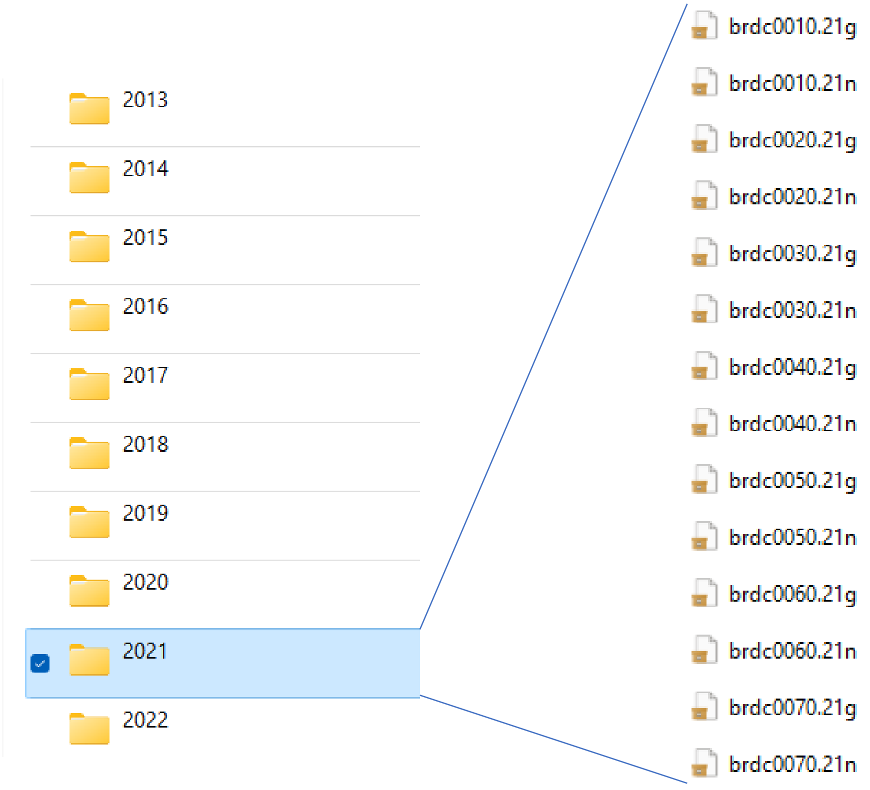
$$\mathrm{Modip} = \arctan\left(\frac{I}{\sqrt{\cos\varphi}}\right)$$

I: Magnetic dip at 350 km

φ: Geographic latitude

Gg software – overview

ingr	Station(s) directory(ies)
OutPut	Output directory
Calibration_settings.txt	File containing the calibration settings (see next slides)
crx2rnx.exe	Hatanaka decompression software (not mandatory)
GNSS_calibration.exe	Executable file
LonLats.dip	Modip lookup table
prepare_RINEX_for_cal.m	MATLAB script to organize input files (not mandatory)
read_ciraolo_output_fast_STEC.m	MATLAB script to read output files (not mandatory)



Gg calibration software is a windows package capable of evaluating single-station calibrated TEC from daily RINEX (v2.11) observational (ssssdoy0.yyo) and navigational (brdcdoy0.yyn/g) files from GPS and GLONASS satellites.

A new (Python) version of the software capable of processing GALILEO satellites will be available in the next future

Gg software – RINEX obs files (v 2.11)

```
     2.11           OBSERVATION DATA    G (GPS)             RINEX VERSION / TYPE
teqc  2016Apr1                          20220103 10:03:19UTCPGM / RUN BY / DATE
Linux 2.4.21-27.ELsmp|Opteron|gcc|Linux x86_64|=+           COMMENT
teqc  2019Feb25                         20220103 10:03:12UTCCOMMENT
Linux 2.6.32-573.12.1.x86_64|x86_64|gcc -static|Linux 64|=+ COMMENT
BIT 2 OF LLI FLAGS DATA COLLECTED UNDER A/S CONDITION       COMMENT
INGR                                                        MARKER NAME
Giuseppe_Casula     INGV                                    OBSERVER / AGENCY
495176              LEICA GRX1200+GNSS  9.20/6.404          REC # / TYPE / VERS
103144              LEIAT504        NONE                    ANT # / TYPE
  4646743.0089  1031406.1366  4231452.7511                  APPROX POSITION XYZ
        0.0000        0.0000        0.0000                  ANTENNA: DELTA H/E/N
     1     1                                                WAVELENGTH FACT L1/2
     6    L1    L2    C1    P2    S1    S2                  # / TYPES OF OBSERV
    30.0000                                                 INTERVAL
Forced Modulo Decimation to 30 seconds                      COMMENT
SPIDER                                                      COMMENT
Made by Spider v4.0.1                                       COMMENT
Project creator:                                            COMMENT
DAnastasio-Selvaggi                                         COMMENT
 SNR is mapped to RINEX snr flag value [0-9]                COMMENT
  L1 & L2: min(max(int(snr dBHz/6), 0), 9)                  COMMENT
  2022     1     1     0     0    0.0000000     GPS         TIME OF FIRST OBS
                                                            END OF HEADER
 22  1  1  0  0  0.0000000  0  8G32G23G21G08G10G16G01G27
 125160945.675 7  97528002.27147  23817336.360    23817334.140          43.400
        43.450
 120474269.007 7  93876044.88846  22925487.360    22925484.220          44.250
        41.650
 117805562.767 7  91796539.74646  22417650.580    22417646.040          45.800
        41.600
 109799902.880 8  85558367.14648  20894226.300    20894224.900          49.700
        49.700
 110595504.787 8  86178319.11648  21045624.060    21045622.460          50.800
        50.800
 120303830.786 7  93743230.52946  22893058.300    22893054.420          44.850
        40.200
 128382932.311 5 100038654.89545  24430460.160    24430458.120          35.000
        35.100
 106285891.940 8  82820170.27248  20225530.200    20225528.200          50.900
        50.950
 22  1  1  0  0 30.0000000  0  8G32G23G21G08G10G16G01G27
 125076168.884 6  97461942.45247  23801203.460    23801201.880          41.950
        42.000
 120564314.405 7  93946210.12546  22942622.380    22942619.080          44.050
```

- RINEX type/version
- Comments (ignored by the software)
- Station ID
- Position of the receiver in ECEF coordinates (WGS84)
- Number and type of GNSS observables available in the file
- Sampling time of the observables
- Time of the first observables
- End of header line
- YY MM DD HH MM SS.sss   #sat in view at that particular epoch   PRN
- Observations block

Gg software – RINEX nav files (v 2.11)

```
     2.11           N: GPS NAV DATA                         RINEX VERSION / TYPE
teqc  2019Feb25     BKG Frankfurt       20220105 09:17:40UTCPGM / RUN BY / DATE
Linux 2.6.32-573.12.1.x86_64|x86_64|gcc -static|Linux 64|=+ COMMENT
Converto v3.5.6     IGN                 20220105 000521 UTC COMMENT
Linux 2.6.32-573.12.1.x86_64|x86_64|gcc|Linux 64|=+         COMMENT
Concatenated RINEX files (31)                               COMMENT
                                                            END OF HEADER
 1 22  1  4  0  0  0.0 4.665437154472D-04-1.000444171950D-11 0.000000000000D+00
    7.300000000000D+01-4.275000000000D+01 4.347323940635D-09-5.174246376131D-01
   -2.102926373482D-06 1.122187799774D-02-4.135072231293D-07 5.153668924332D+03
    1.728000000000D+05 5.587935447693D-09-1.159150957942D+00 1.192092895508D-07
    9.863567403002D-01 3.972812500000D+02 8.845144020666D-01-8.498925442930D-09
   -1.964367538078D-10 1.000000000000D+00 2.191000000000D+03 0.000000000000D+00
    2.000000000000D+00 0.000000000000D+00 5.122274160385D-09 7.300000000000D+01
    1.656180000000D+05 4.000000000000D+00
 1 22  1  4  2  0  0.0 4.664720036089D-04-1.000444171950D-11 0.000000000000D+00
    7.400000000000D+01-2.246875000000D+01 4.259105980288D-09 5.327547024575D-01
   -1.041218638420D-06 1.122482249048D-02-1.564621925354D-07 5.153674575806D+03
    1.800000000000D+05-3.725290298462D-08-1.159212006976D+00 1.117587089539D-07
    9.863553037147D-01 3.930312500000D+02 8.845155153473D-01-8.485710606765D-09
   -2.196520065306D-10 1.000000000000D+00 2.191000000000D+03 0.000000000000D+00
    2.000000000000D+00 0.000000000000D+00 5.122274160385D-09 7.400000000000D+01
    1.728180000000D+05 4.000000000000D+00
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    7.500000000000D+01-6.875000000000D+00 4.368396246952D-09 1.583143868868D+00
   -5.085021257401D-07 1.122385857161D-02-4.153698682785D-07 5.153669784546D+03
    1.872000000000D+05-2.533197402954D-07-1.159273638252D+00 7.264316082001D-08
    9.863543220967D-01 4.028437500000D+02 8.843068183799D-01-8.386063598924D-09
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    2.000000000000D+00 0.000000000000D+00
    1.800180000000D+05 4.000000000000D+00
 1 22  1  4 22  0  0.0 4.657572135329D-04-
    1.700000000000D+01 6.968750000000D+00
    5.103647708893D-07 1.122514088638D-02-
    2.520000000000D+05 2.402812242508D-07-
    9.863576955857D-01 3.972812500000D+02
    3.571577341961D-13 1.000000000000D+00
    2.000000000000D+00 0.000000000000D+00
    2.471880000000D+05 4.000000000000D+00
```
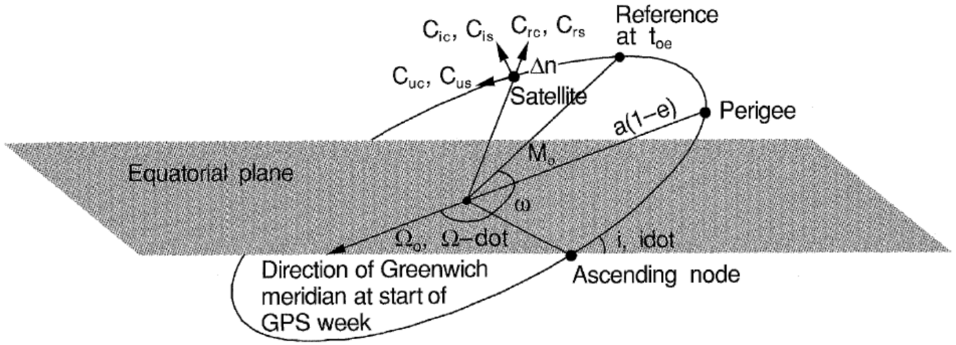

RINEX type/version

Date and time

Orbital parameters




```
+------------------------------------------------------------------------------+
|                                 TABLE A4                                     |
|           GPS NAVIGATION MESSAGE FILE - DATA RECORD DESCRIPTION              |
+--------------------+------------------------------------------+--------------+
|    OBS. RECORD     | DESCRIPTION                              |   FORMAT     |
+--------------------+------------------------------------------+--------------+
|PRN / EPOCH / SV CLK| - Satellite PRN number                   |     I2,      |
|                    | - Epoch: Toc - Time of Clock             |              |
|                    |         year (2 digits, padded with 0    |              |
|                    |               if necessary)              |  1X,I2.2,    |
|                    |         month                            |   1X,I2,     |
|                    |         day                              |   1X,I2,     |
|                    |         hour                             |   1X,I2,     |
|                    |         minute                           |   1X,I2,     |
|                    |         second                           |    F5.1,     |
|                    | - SV clock bias       (seconds)          |  3D19.12     |
|                    | - SV clock drift      (sec/sec)          |              |
|                    | - SV clock drift rate (sec/sec2)         |     *)       |
+--------------------+------------------------------------------+--------------+
| BROADCAST ORBIT - 1| - IODE Issue of Data, Ephemeris          | 3X,4D19.12   |
|                    | - Crs                 (meters)           |              |
|                    | - Delta n             (radians/sec)      |              |
|                    | - M0                  (radians)          |              |
+--------------------+------------------------------------------+--------------+
| BROADCAST ORBIT - 2| - Cuc                 (radians)          | 3X,4D19.12   |
|                    | - e Eccentricity                         |              |
|                    | - Cus                 (radians)          |              |
|                    | - sqrt(A)             (sqrt(m))          |              |
+--------------------+------------------------------------------+--------------+
| BROADCAST ORBIT - 3| - Toe Time of Ephemeris                  | 3X,4D19.12   |
|                    |                       (sec of GPS week)  |              |
|                    | - Cic                 (radians)          |              |
|                    | - OMEGA               (radians)          |              |
|                    | - CIS                 (radians)          |              |
+--------------------+------------------------------------------+--------------+
| BROADCAST ORBIT - 4| - i0                  (radians)          | 3X,4D19.12   |
|                    | - Crc                 (meters)           |              |
|                    | - omega               (radians)          |              |
|                    | - OMEGA DOT           (radians/sec)      |              |
+--------------------+------------------------------------------+--------------+
| BROADCAST ORBIT - 5| - IDOT                (radians/sec)      | 3X,4D19.12   |
|                    | - Codes on L2 channel                    |              |
|                    | - GPS Week # (to go with TOE)            |              |
|                    |   Continuous number, not mod(1024)!      |              |
|                    | - L2 P data flag                         |              |
+--------------------+------------------------------------------+--------------+
| BROADCAST ORBIT - 6| - SV accuracy         (meters)           | 3X,4D19.12   |
|                    | - SV health       (bits 17-22 w 3 sf 1)  |              |
|                    | - TGD                 (seconds)          |              |
|                    | - IODC Issue of Data, Clock              |              |
+--------------------+------------------------------------------+--------------+
| BROADCAST ORBIT - 7| - Transmission time of message       **) | 3X,4D19.12   |
|                    |        (sec of GPS week, derived e.g.    |              |
|                    |    from Z-count in Hand Over Word (HOW)  |              |
|                    | - Fit interval        (hours)            |              |
|                    |        (see ICD-GPS-200, 20.3.4.4)       |              |
|                    |   Zero if not known                      |              |
|                    | - spare                                  |              |
|                    | - spare                                  |              |
+--------------------+------------------------------------------+--------------+
```

Gg software – Calibration settings file

Output Sampling Time, Minutes	0	Out Sampling time (0 for the same resolution of the input Rinex files)
Output Minimum Elevation, Deg	20	Elevation mask (data «below» this value will not appear in the output files)
Solution: Arcs(A), Hardware biases (B)	A	Not implemented in this version (maintain «A»)
Select Output Format	3	Format of the output files (3 if you want to use the MATLAB scripts)
Folder of BRDC files	C:\...	Folder in which you put the BRDC files
Disable Rejection of First and Last Day	False	Maintain «FALSE» for reliable solutions
Shell Height	350	Height of the ionospheric thin shell in km
Discard GLONASS	False	Set «TRUE» if you want to ignore GLONASS observations

Gg software – Output files

00000	Z00	000.000	90.000	-063.243	+17.621	+005.29	+005.29
00000	G01	034.739	72.035	-062.664	+18.307	+004.05	+003.87
00000	G03	140.776	27.940	-059.881	+13.480	+018.04	+009.88
00000	G07	233.164	63.521	-064.475	+16.627	+007.58	+006.87
00000	G14	326.331	25.006	-066.710	+22.305	+004.76	+002.43
00000	G17	283.745	26.685	-068.815	+18.727	+007.34	+003.90
00000	G21	034.265	40.255	-061.197	+20.322	+005.54	+003.82
00000	G30	288.242	51.517	-065.577	+18.232	+005.27	+004.25
00000	R19	006.021	38.160	-062.832	+21.151	+003.33	+002.21
00000	R20	269.494	51.845	-065.661	+17.480	+006.16	+004.99
00015	Z00	000.000	90.000	-063.243	+17.621	+005.31	+005.31
00015	G01	034.565	71.913	-062.662	+18.315	+004.04	+003.86
00015	G03	140.674	28.013	-059.882	+13.496	+017.88	+009.80
00015	G07	232.913	63.447	-064.475	+16.619	+007.59	+006.88
00015	G14	326.395	25.088	-066.694	+22.294	+004.75	+002.43
00015	G17	283.870	26.714	-068.807	+18.737	+007.32	+003.89
00015	G21	034.242	40.151	-061.191	+20.333	+005.54	+003.81
00015	G30	288.057	51.561	-065.575	+18.224	+005.27	+004.26
00015	R19	006.099	38.045	-062.825	+21.165	+003.31	+002.20
00015	R20	269.739	51.863	-065.660	+17.490	+006.16	+004.99
00030	Z00	000.000	90.000	-063.243	+17.621	+005.32	+005.32
00030	G01	034.393	71.790	-062.661	+18.322	+004.03	+003.85
00030	G03	140.571	28.085	-059.883	+13.513	+017.74	+009.74
00030	G07	232.664	63.372	-064.474	+16.611	+007.61	+006.89
00030	G14	326.458	25.170	-066.677	+22.283	+004.75	+002.44
00030	G17	283.996	26.743	-068.798	+18.748	+007.33	+003.90
00030	G21	034.220	40.048	-061.185	+20.343	+005.54	+003.81
00030	G30	287.871	51.605	-065.574	+18.216	+005.28	+004.27
00030	R19	006.176	37.929	-062.818	+21.178	+003.38	+002.24
00030	R20	269.986	51.881	-065.658	+17.500	+006.16	+004.99

- Seconds since the beginning of the day
- Satellite (G for GPS, R for GLONASS)
- Azimuth
- Elevation
- Longitude of the IPP
- Latitude of the IPP
- STEC
- VTEC

Gg software

Let’s go for a live session!!!!

https://www.dropbox.com/sh/5ti51wl52e977ns/AACxxaCm8eBrveQHTW4xyFM_a?dl=0