Tutorial 4

Solving navigation equations: Least squares and Kalman filter

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Contents

Navigation equations system and Least Squares solution

Exercise 1:

The measurement file **UPC11490.05O** has been collected by a receiver with fixed coordinates. Using navigation file **UPC11490.05N**, compute the **SPP solution** in static mode and check *by hand* the computation of the **Least Square solution** at time **t = 300** seconds.

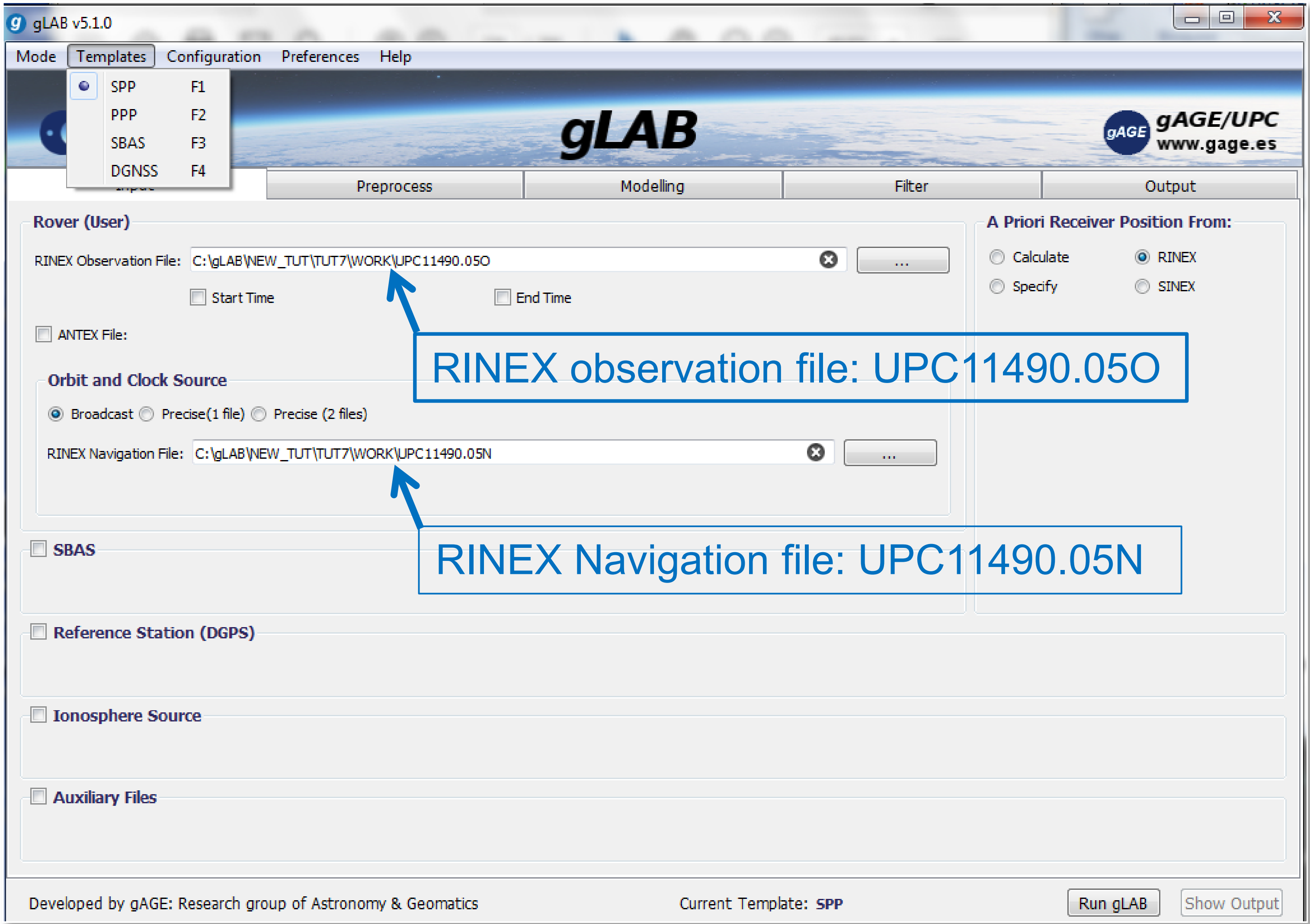
Complete the next steps:

1.- Use gLAB to compute the prefit-residuals, elevation and azimuth of all satellites at time t=300 sec.

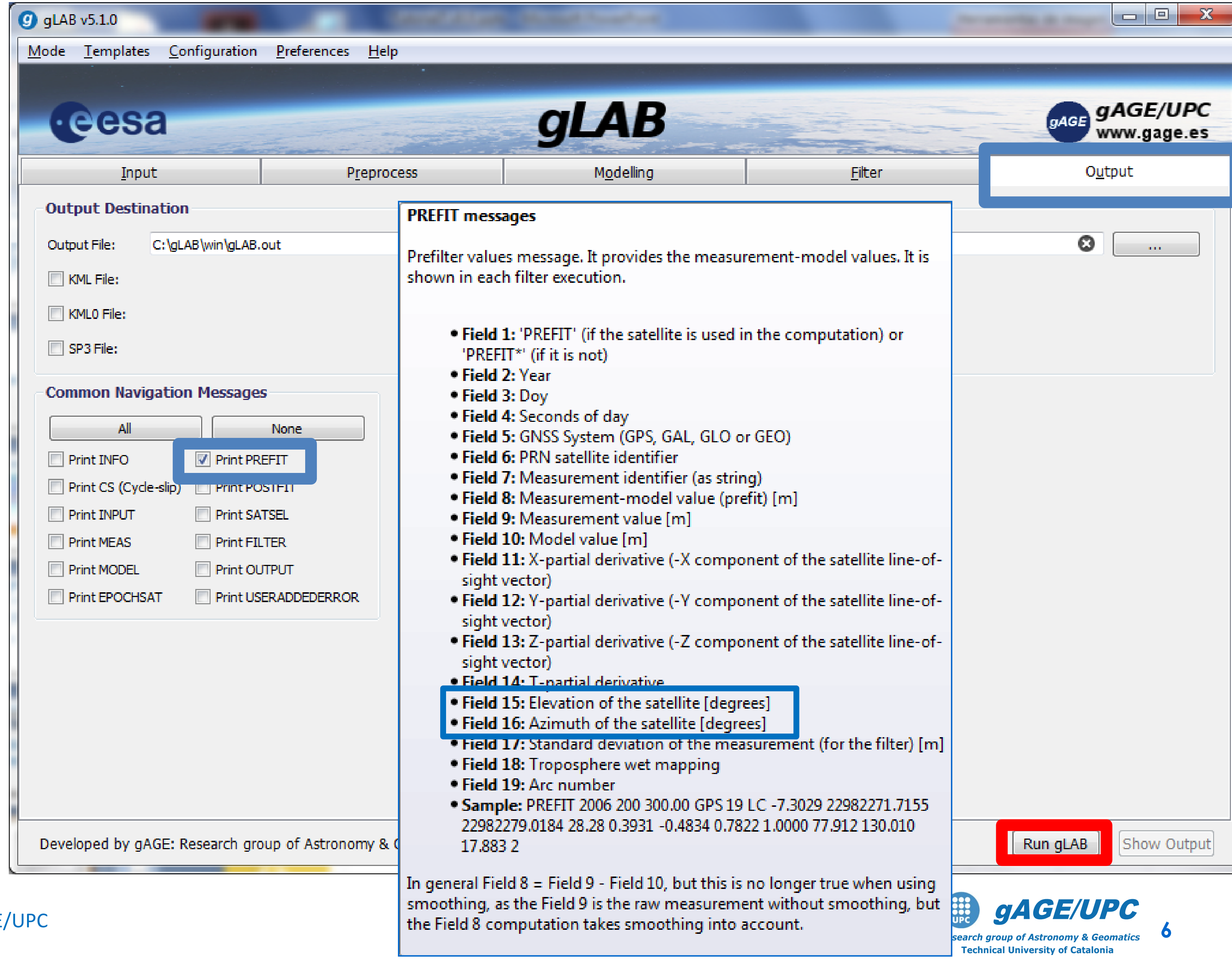
2.- Build up the navigation equations system to compute the solution in (ENU) coordinates. Solve the system with MATLAB (octave).

$$\begin{bmatrix} Prefit^1 \\ Prefit^2 \\ \cdots\cdots \\ Prefit^n \end{bmatrix} = \begin{bmatrix} -\cos el^1 \sin az^1 & -\cos el^1 \cos az^1 & -\sin el^1 & 1 \\ -\cos el^2 \sin az^2 & -\cos el^2 \cos az^2 & -\sin el^2 & 1 \\ & \cdots\cdots\cdots & & \\ -\cos el^n \sin az^n & -\cos el^n \cos az^n & -\sin el^n & 1 \end{bmatrix} \begin{bmatrix} \Delta e_{rec} \\ \Delta n_{rec} \\ \Delta u_{rec} \\ c\, dt_{rec} \end{bmatrix}$$

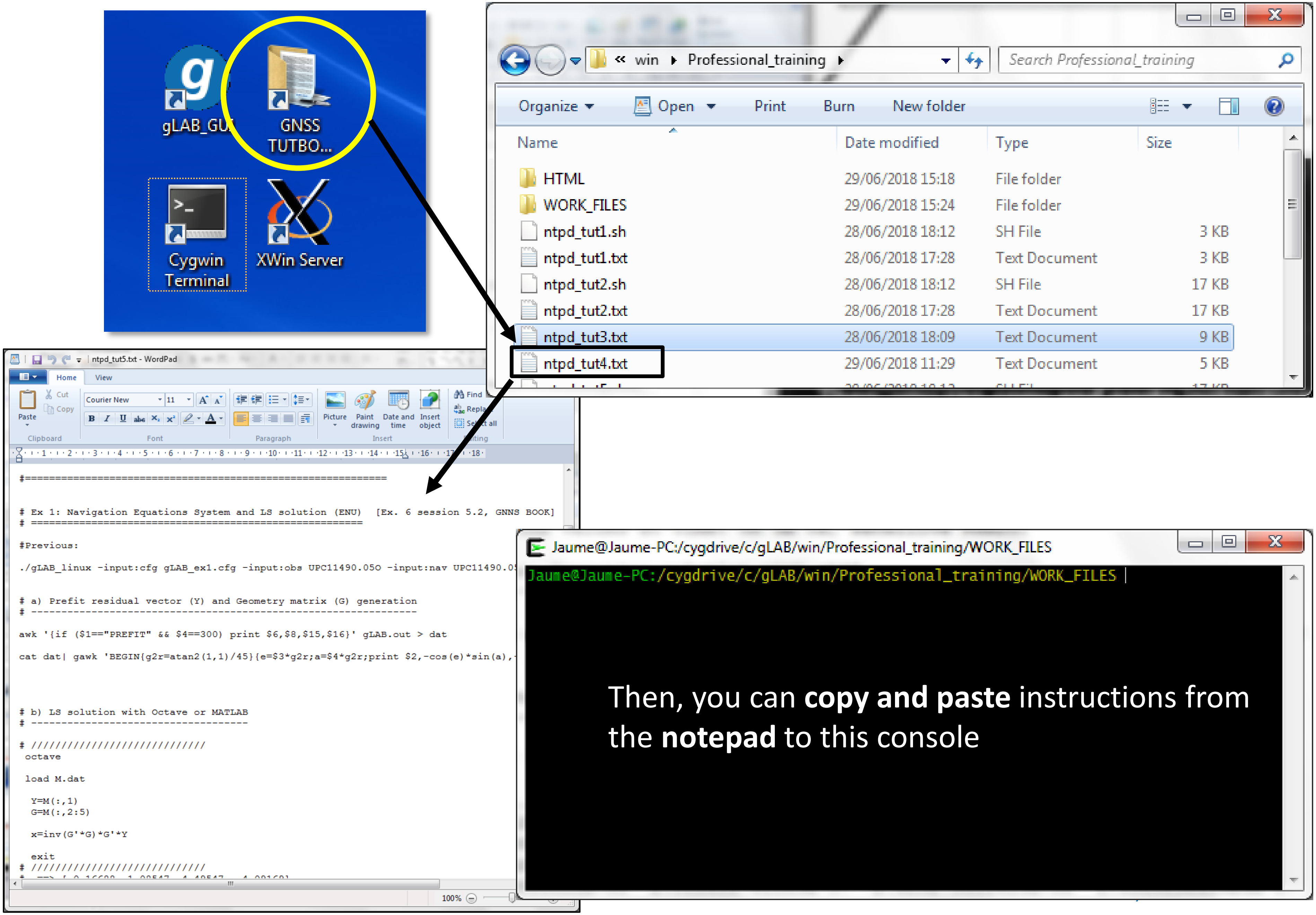
1.- Process the data files in de default SPP mode:



In the **Output** section, unselect all messages except "**print PREFIT**"



How to use the **notepad** ?



Then, you can **copy and paste** instructions from the **notepad** to this console

2.- Pre-fit residual vector (y) and Geometry matrix (G) generation

2. 1. From gLAB.out file, print the pre-fit residual, the elevation and azimuth of all satellites at epoch t=300 sec:

Next "**awk**" sentence performs this selection:

```
awk '{if ($1=="PREFIT" && $4==300) print $6,$8,$15,$16}' gLAB.out > dat
```

```
gAGE@gAGE-PC:/cygdrive/c/gLAB/win/Professional_Training/WORK_FILES
/WORK_FILES
/WORK_FILES
/WORK_FILES
/WORK_FILES awk '{if ($1=="PREFIT" && $4==300) print $6,$8,$15,$16}' gLAB.out > dat
```

dat (t=300)			
PRN	Pre-fit	Elev (Deg)	Azim (deg)
25	-7,3516	32,97	-49,15
9	-5,3107	15,05	141,52
6	-7,4675	71,83	-144,91
1	-6,8946	30,40	-68,99
2	-6,5154	27,58	62,57
5	-5,2957	38,89	81,01
30	-10,313	72,25	25,35
14	-5,6687	32,79	-117,19

PREFIT messages

Prefilter values message. It provides the measurement-model values. It is shown in each filter execution.

- **Field 1:** 'PREFIT' (if the satellite is used in the computation) or 'PREFIT*' (if it is not)
- **Field 2:** Year
- **Field 3:** Doy
- **Field 4:** Seconds of day
- **Field 5:** [illegible]
- **Field 6:** PRN satellite identifier
- **Field 7:** Measurement identifier (as string)
- **Field 8:** Measurement-model value (prefit) [m]
- **Field 9:** Measurement value [m]
- **Field 10:** Model value [m]
- **Field 11:** X-partial derivative (-X component of the satellite line-of-sight vector)
- **Field 12:** Y-partial derivative (-Y component of the satellite line-of-sight vector)
- **Field 13:** Z-partial derivative (-Z component of the satellite line-of-sight vector)
- **Field 14:** T-partial derivative
- **Field 15:** Elevation of the satellite [degrees]
- **Field 16:** Azimuth of the satellite [degrees]
- **Field 17:** Standard deviation of the measurement (for the filter) [m]
- **Field 18:** Troposphere wet mapping
- **Field 19:** Arc number
- **Sample:** PREFIT 2006 200 300.00 GPS 19 LC -7.3029 22982271.7155 22982279.0184 28.28 0.3931 -0.4834 0.7822 1.0000 77.912 130.010 17.883 2

In general Field 8 = Field 9 - Field 10, but this is no longer true when using smoothing, as the Field 9 is the raw measurement without smoothing, but the Field 8 computation takes smoothing into account.

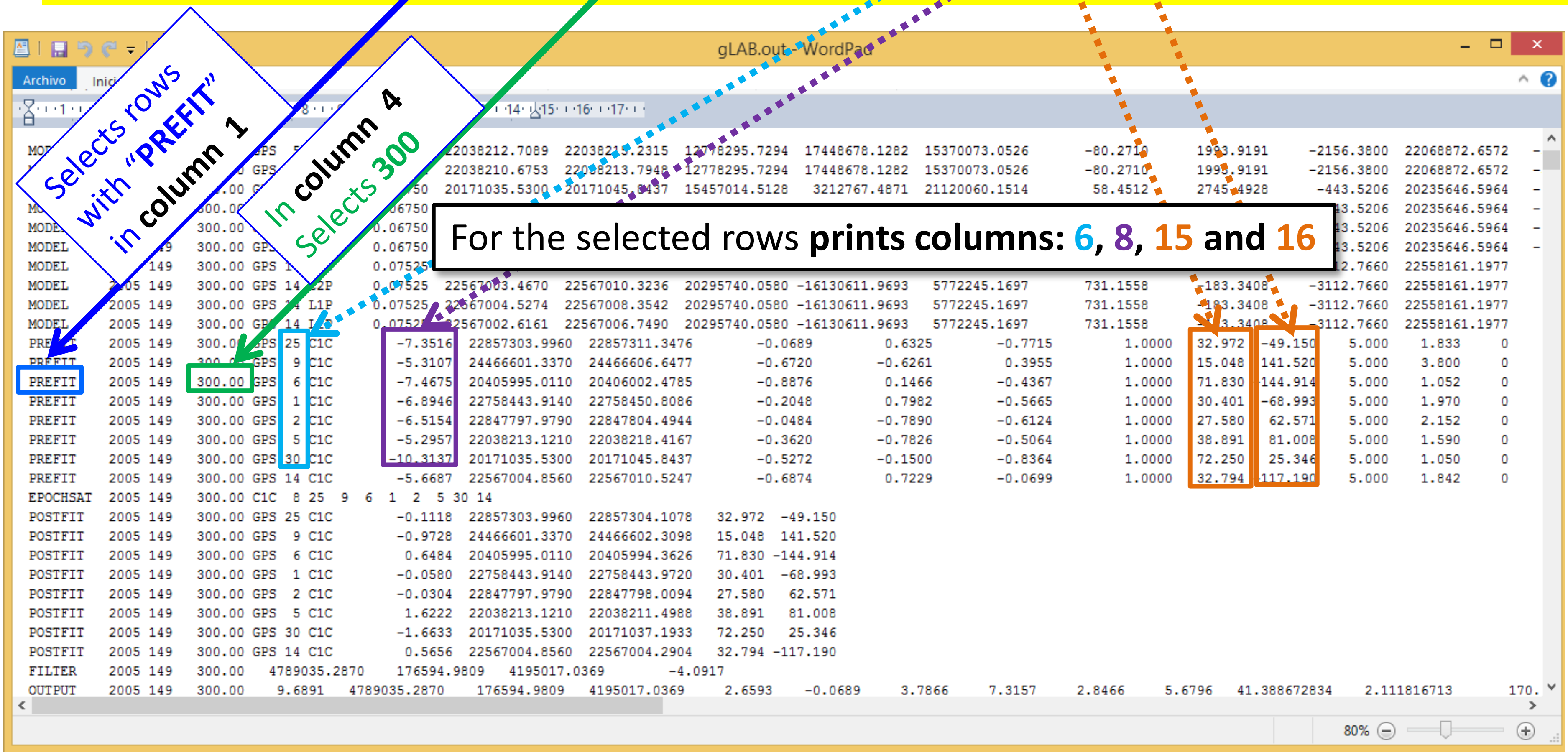
2.- Pre-fit residual vector (y) and Geometry matrix (G) generation

2. 1. From gLAB.out file, print the pre-fit residual, the elevation and azimuth of all satellites at epoch t=300 sec:

Next "**awk**" sentence performs this selection:

Selected values are sent to file "**dat**"

```
awk '{if ($1=="PREFIT" && $4==300) print $6,$8,$15,$16}' gLAB.out > dat
```



2.- Pre-fit residual vector (y) and Geometry matrix (G) generation

2.2. Using the previous "dat" file, build-up the navigation equations system:

dat			
PRN	Pre-fit	Elev (Deg)	Azim (deg)
25	-7,3516	32,97	-49,15
9	-5,3107	15,05	141,52
6	-7,4675	71,83	-144,91
1	-6,8946	30,40	-68,99
2	-6,5154	27,58	62,57
5	-5,2957	38,89	81,01
30	-10,313	72,25	25,35
14	-5,6687	32,79	-117,19

$$\begin{bmatrix} Prefit^1 \\ Prefit^2 \\ \cdots\cdots \\ Prefit^n \end{bmatrix} = \begin{bmatrix} -\cos el^1 \sin az^1 & -\cos el^1 \cos az^1 & -\sin el^1 & 1 \\ -\cos el^2 \sin az^2 & -\cos el^2 \cos az^2 & -\sin el^2 & 1 \\ & \cdots\cdots\cdots & & \\ -\cos el^n \sin az^n & -\cos el^n \cos az^n & -\sin el^n & 1 \end{bmatrix} \begin{bmatrix} \Delta e_{rec} \\ \Delta n_{rec} \\ \Delta u_{rec} \\ c\, dt_{rec} \end{bmatrix}$$

Execute next sentence in a single line

```
cat dat| gawk 'BEGIN{g2r=atan2(1,1)/45}{e=$3*g2r;a=$4*g2r;
    print $2,-cos(e)*sin(a),-cos(e)*cos(a),-sin(e),1}' > M.dat
```

y	G			
Pre-fit	-cos(e)*sin(a)	-cos(e)*cos(a)	-sin(e)	1
-7,3516	0,634592	-0,548732	-0,544229	1
-5,3107	-0,600904	0,755981	-0,259628	1
-7,4675	0,179246	0,255174	-0,950135	1
-6,8946	0,805180	-0,309192	-0,506049	1
-6,5154	-0,786722	-0,408303	-0,462987	1
-5,2957	-0,768776	-0,121652	-0,627841	1
-10,3137	-0,130507	-0,275518	-0,952396	1
-5,6687	0,747731	0,384117	-0,541620	1

Next, we will use MATLAB (octave) to solve this equations system by Least Squares

2.3. Computing the LS solution with octave (or MATLAB)

```
octave

load M.dat

y=M(:,1)

G=M(:,2:5)

x=inv(G'*G)*G'*y

exit
```

Jaume@Jaume-PC:/cygdrive/c/gLAB/...

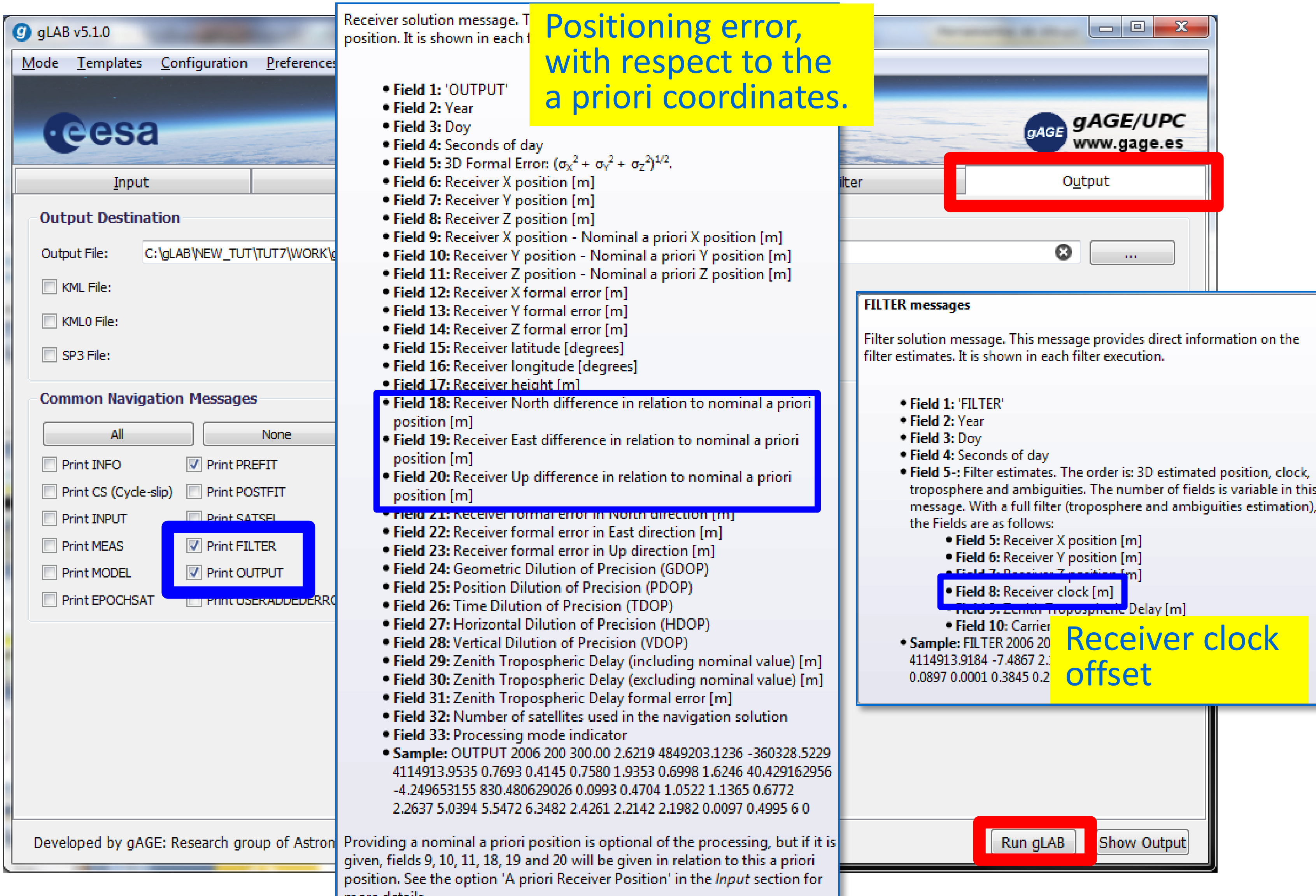
```
octave:1> load M.dat
octave:2> y=M(:,1)
y =

   -7.3516
   -5.3107
   -7.4675
   -6.8946
   -6.5154
   -5.2957
  -10.3137
   -5.6687

octave:3> G=M(:,2:5)
G =

   0.63459  -0.54873  -0.54423   1.00000
  -0.60090   0.75598  -0.25963   1.00000
   0.17925   0.25517  -0.95013   1.00000
   0.80518  -0.30919  -0.50605   1.00000
  -0.78672  -0.40830  -0.46299   1.00000
  -0.76878  -0.12165  -0.62784   1.00000
  -0.13051  -0.27552  -0.95240   1.00000
   0.74773   0.38412  -0.54162   1.00000

octave:4> x=inv(G'*G)*G'*y
x =

  -0.16688
   1.08547
   4.49547
  -4.09169

octave:5> |
```

Positioning error, regarding to the reference coordinates given in the header of RINEX file

	ΔEast	ΔNorth	ΔUp	dT
➔	[-0.16688	1.08547	4.49547	-4.09169]

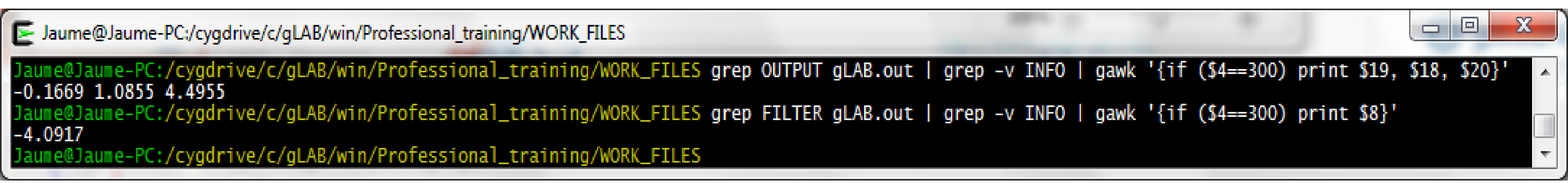
Receiver clock offset

2.4. Check results with gLAB



Checking gLAB values:

```
grep OUTPUT gLAB.out | grep -v INFO |
           gawk '{if ($4==300) print $19, $18, $20}'

              ➔ -0.1669  1.0855  4.4955


grep FILTER gLAB.out | grep -v INFO |
                      gawk '{if ($4==300) print $8}'

             ➔ -4.0917
```



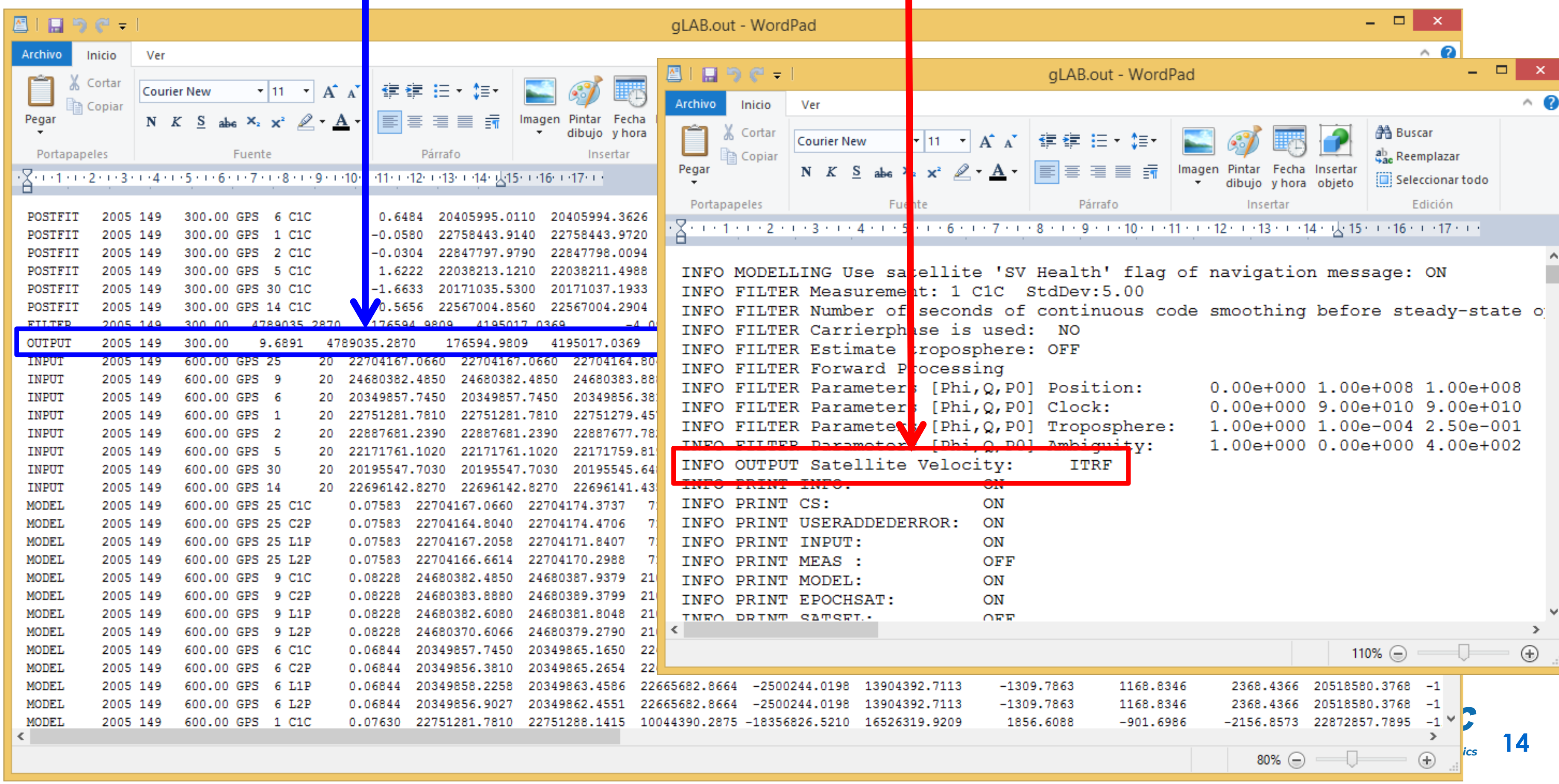
Checking gLAB values:

This is a "**pipe**": the output of the first "**grep**" is sent to the second one.

```
grep OUTPUT gLAB.out | grep -v INFO > results
```

Select rows containing "OUTPUT"
(in any of its columns)

Skip rows containing "INFO"
(in any of its columns)



Navigation equations system and least Squares solution

Exercise 2:

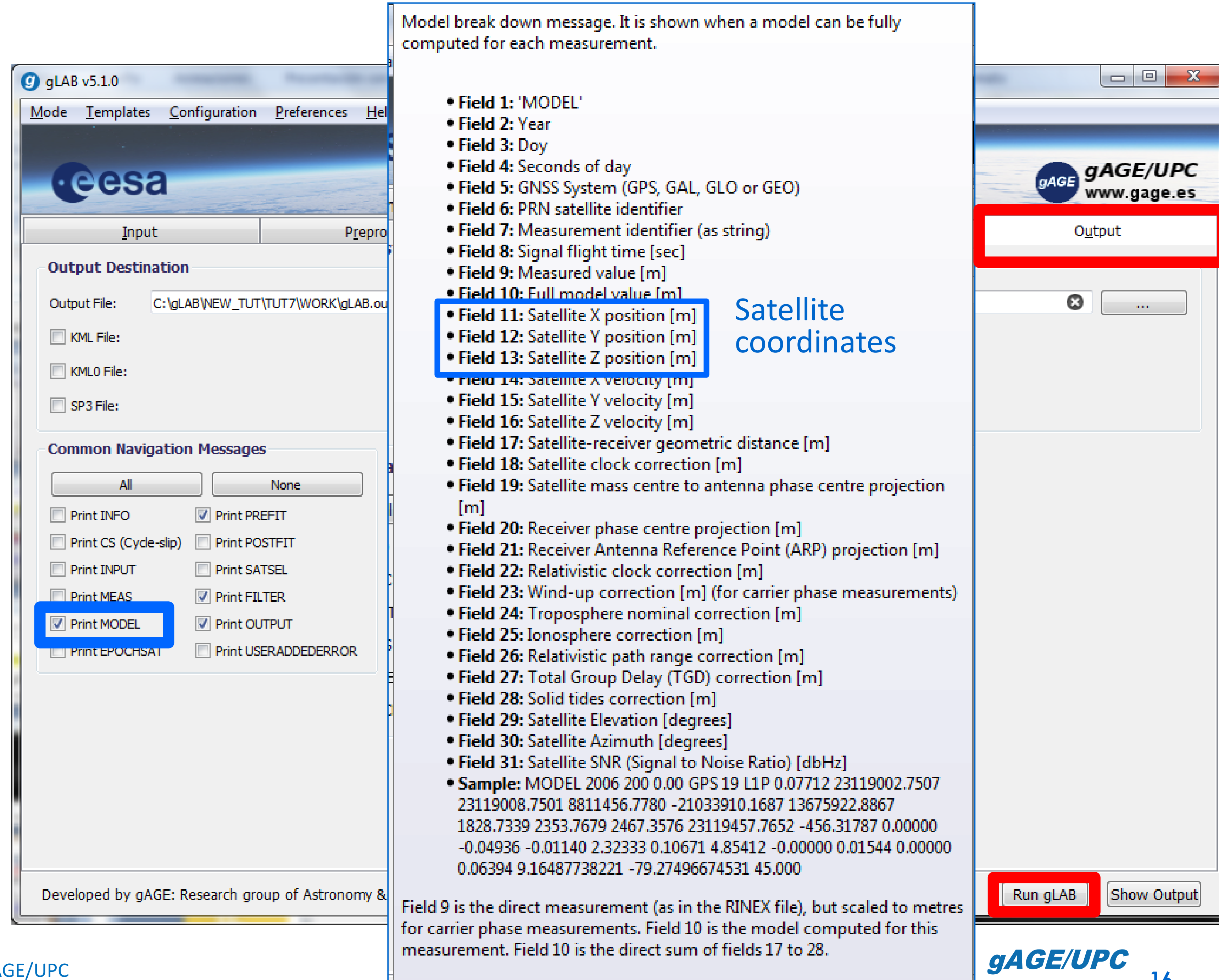
Repeat the previous exercise, but writing the system and computing the solution in (XYZ) coordinates.

Complete the next steps:

1.- Use gLAB to compute the prefit-residuals and satellite **(x,y,z)** coordinates at time **t=300** seconds.

2.- Build up the navigation equations system to compute the solution in (XYZ) coordinates. Solve the system with MATLAB (octave).

$$
\begin{bmatrix} Prefit^1 \\ Prefit^2 \\ \ldots\ldots \\ Prefit^n \end{bmatrix}
=
\begin{bmatrix}
\frac{x_{0,rec}-x^{sat1}}{\rho_{0,rec}^{sat1}} & \frac{y_{0,rec}-y^{sat1}}{\rho_{0,rec}^{sat1}} & \frac{z_{0,rec}-z^{sat1}}{\rho_{0,rec}^{sat1}} & 1 \\
\frac{x_{0,rec}-x^{sat2}}{\rho_{0,rec}^{sat2}} & \frac{y_{0,rec}-y^{sat2}}{\rho_{0,rec}^{sat2}} & \frac{z_{0,rec}-z^{sat2}}{\rho_{0,rec}^{sat2}} & 1 \\
 & \ldots\ldots\ldots & & \\
\frac{x_{0,rec}-x^{sat\,n}}{\rho_{0,rec}^{sat\,n}} & \frac{y_{0,rec}-y^{sat\,n}}{\rho_{0,rec}^{sat\,n}} & \frac{z_{0,rec}-z^{sat\,n}}{\rho_{0,rec}^{sat\,n}} & 1
\end{bmatrix}
\begin{bmatrix} \Delta x_{rec} \\ \Delta y_{rec} \\ \Delta z_{rec} \\ c\,dt_{rec} \end{bmatrix}
$$



Model break down message. It is shown when a model can be fully computed for each measurement.

- **Field 1:** 'MODEL'
- **Field 2:** Year
- **Field 3:** Doy
- **Field 4:** Seconds of day
- **Field 5:** GNSS System (GPS, GAL, GLO or GEO)
- **Field 6:** PRN satellite identifier
- **Field 7:** Measurement identifier (as string)
- **Field 8:** Signal flight time [sec]
- **Field 9:** Measured value [m]
- **Field 10:** Full model value [m]
- **Field 11:** Satellite X position [m]
- **Field 12:** Satellite Y position [m]
- **Field 13:** Satellite Z position [m]
- **Field 14:** Satellite X velocity [m]
- **Field 15:** Satellite Y velocity [m]
- **Field 16:** Satellite Z velocity [m]
- **Field 17:** Satellite-receiver geometric distance [m]
- **Field 18:** Satellite clock correction [m]
- **Field 19:** Satellite mass centre to antenna phase centre projection [m]
- **Field 20:** Receiver phase centre projection [m]
- **Field 21:** Receiver Antenna Reference Point (ARP) projection [m]
- **Field 22:** Relativistic clock correction [m]
- **Field 23:** Wind-up correction [m] (for carrier phase measurements)
- **Field 24:** Troposphere nominal correction [m]
- **Field 25:** Ionosphere correction [m]
- **Field 26:** Relativistic path range correction [m]
- **Field 27:** Total Group Delay (TGD) correction [m]
- **Field 28:** Solid tides correction [m]
- **Field 29:** Satellite Elevation [degrees]
- **Field 30:** Satellite Azimuth [degrees]
- **Field 31:** Satellite SNR (Signal to Noise Ratio) [dbHz]
- **Sample:** MODEL 2006 200 0.00 GPS 19 L1P 0.07712 23119002.7507 23119008.7501 8811456.7780 -21033910.1687 13675922.8867 1828.7339 2353.7679 2467.3576 23119457.7652 -456.31787 0.00000 -0.04936 -0.01140 2.32333 0.10671 4.85412 -0.00000 0.01544 0.00000 0.06394 9.16487738221 -79.27496674531 45.000

Field 9 is the direct measurement (as in the RINEX file), but scaled to metres for carrier phase measurements. Field 10 is the model computed for this measurement. Field 10 is the direct sum of fields 17 to 28.

Satellite coordinates

```
Jaume@Jaume-PC:/cygdrive/c/gLAB/NEW_TUT/TUT7/WORK
     2.10           OBSERVATION DATA    GPS/GEO             RINEX VERSION / TYPE
B2AConv V2.0        gAGE/UPC            21-Dec-09 19:17     PGM / RUN BY / DATE
BIT 2 OF LLI (+4) FLAGS DATA COLLECTED UNDER "AS" CONDITION COMMENT
UPC1                                                        MARKER NAME
gAGE / UPC          gAGE / UPC                              OBSERVER / AGENCY
1                   NOVATEL  MILLENIUM  OEM-3               REC # / TYPE / VERS
1                   NOVATEL  PINWELL                        ANT # / TYPE
  4789032.6277   176595.0498  4195013.2503                  APPROX POSITION XYZ
        0.0000        0.0000        0.0000                  ANTENNA: DELTA H/E/N
     1     1                                                WAVELENGTH FACT L1/2
     6    C1    P2    L1    L2    D1    D2                  # / TYPES OF OBSERV
SNR is mapped to signal strength [0-9]
 L1 SNR:  >44  >35   >26   >17    >8    >0      n
    sig:    9    8     7     6     5     4      0         COMMENT
 L2 SNR:  >50  >42   >34   >26   >18    >8    >0   n/a    COMMENT
    sig:    9    8     7     6     5     4     3     0    COMMENT
     1                                                      INTERVAL
  2005     5    29     0     0    1.000000                  TIME OF FIRST OBS
  2005     5    29    23    59   58.000000                  TIME OF LAST OBS
                                                            END OF HEADER
  5  5 29  0  0  1.0000000  0  9G25G 9G 6G 1G21G 2G 5G30G14
  23014409.454    23014407.0624  120941560.43748  94240180.12946      2797.89748
      2180.13646
  24255343.500    24255342.1054  127462772.33948  99321651.17545     -3695.18948
     -2879.38745
  20470437.022    20470435.1684  107572939.39549  83823051.74446      1206.77349
       940.33646
  22776509.627    22776510.7274  119691395.32948  93266004.45346       413.23948
                                                                1,6        Top
```

$(x_{0,rec}, y_{0,rec}, z_{0,rec})$

Receiver coordinates to linearize the equations (*a priori*)

$$
\begin{bmatrix} Prefit^1 \\ Prefit^2 \\ \cdots\cdots \\ Prefit^n \end{bmatrix}
=
\begin{bmatrix}
\frac{x_{0,rec}-x^{sat1}}{\rho^{sat1}_{0,rec}} & \frac{y_{0,rec}-y^{sat1}}{\rho^{sat1}_{0,rec}} & \frac{z_{0,rec}-z^{sat1}}{\rho^{sat1}_{0,rec}} & 1 \\
\frac{x_{0,rec}-x^{sat2}}{\rho^{sat2}_{0,rec}} & \frac{y_{0,rec}-y^{sat2}}{\rho^{sat2}_{0,rec}} & \frac{z_{0,rec}-z^{sat2}}{\rho^{sat2}_{0,rec}} & 1 \\
 & \cdots\cdots\cdots & & \\
\frac{x_{0,rec}-x^{sat\,n}}{\rho^{sat\,n}_{0,rec}} & \frac{y_{0,rec}-y^{sat\,n}}{\rho^{sat\,n}_{0,rec}} & \frac{z_{0,rec}-z^{sat\,n}}{\rho^{sat\,n}_{0,rec}} & 1
\end{bmatrix}
\begin{bmatrix} \Delta x_{rec} \\ \Delta y_{rec} \\ \Delta z_{rec} \\ c\,dt_{rec} \end{bmatrix}
$$

$x_{0,rec}$ =4789032.6277
$y_{0,rec}$ = 176595.0498
$z_{0,rec}$ =4195013.2503

2.1 Pre-fit residual vector (y) and Geometry matrix (G) generation

```
grep "MODEL " gLAB.out | grep -v INFO | grep C1C |
 awk 'BEGIN{x=4789032.6277;y=176595.0498;z=4195013.2503}
  {if ($4==300)
   {r1=x-$11;r2=y-$12;r3=z-$13;r=sqrt(r1*r1+r2*r2+r3*r3);
                               print $9-$10,r1/r,r2/r,r3/r,1}}'>M.dat
```

$$
\begin{bmatrix} Prefit^1 \\ Prefit^2 \\ \cdots\cdots \\ Prefit^n \end{bmatrix} = \begin{bmatrix} \frac{x_{0,rec}-x^{sat1}}{\rho_{0,rec}^{sat1}} & \frac{y_{0,rec}-y^{sat1}}{\rho_{0,rec}^{sat1}} & \frac{z_{0,rec}-z^{sat1}}{\rho_{0,rec}^{sat1}} & 1 \\ \frac{x_{0,rec}-x^{sat2}}{\rho_{0,rec}^{sat2}} & \frac{y_{0,rec}-y^{sat2}}{\rho_{0,rec}^{sat2}} & \frac{z_{0,rec}-z^{sat2}}{\rho_{0,rec}^{sat2}} & 1 \\ & \cdots\cdots\cdots & & \\ \frac{x_{0,rec}-x^{sat\,n}}{\rho_{0,rec}^{sat\,n}} & \frac{y_{0,rec}-y^{sat\,n}}{\rho_{0,rec}^{sat\,n}} & \frac{z_{0,rec}-z^{sat\,n}}{\rho_{0,rec}^{sat\,n}} & 1 \end{bmatrix} \begin{bmatrix} \Delta x_{rec} \\ \Delta y_{rec} \\ \Delta z_{rec} \\ c\,dt_{rec} \end{bmatrix}
$$

y	M			
Pre-fit	$\frac{x_{0,rec}-x^{sat1}}{\rho_{0,rec}^{sat1}}$	$\frac{y_{0,rec}-y^{sat1}}{\rho_{0,rec}^{sat1}}$	$\frac{z_{0,rec}-z^{sat1}}{\rho_{0,rec}^{sat1}}$	1
-7,3516	-0,068854	0,632491	-0,771501	1
-5,3107	-0,671994	-0,626096	0,395511	1
-7,4675	-0,887550	0,146645	-0,436749	1
-6,8946	-0,204785	0,79818	-0,566544	1
-6,5154	-0,048353	-0,789036	-0,612441	1
-5,2957	-0,362015	-0,782645	-0,506372	1
-10,3137	-0,527188	-0,150041	-0,836398	1
-5,6687	-0,687410	0,722896	-0,069918	1

$x_{0,rec}$ =4789032.6277
$y_{0,rec}$ = 176595.0498
$z_{0,rec}$ =4195013.2503

Checking gLAB equations values with gLAB:

```
grep "PREFIT " gLAB.out | grep -v INFO |
         gawk '{if ($4==300) print $8,$11,$12,$13, $14}'
```

y	M			
Pre-fit	**Previous computations**			
-7,3516	-0,068854	0,632491	-0,771501	1
-5,3107	-0,671994	-0,626096	0,395511	1
-7,4675	-0,887550	0,146645	-0,436749	1
-6,8946	-0,204785	0,79818	-0,566544	1
-6,5154	-0,048353	-0,789036	-0,612441	1
-5,2957	-0,362015	-0,782645	-0,506372	1
-10,3137	-0,527188	-0,150041	-0,836398	1
-5,6687	-0,687410	0,722896	-0,069918	1

y	M			
Pre-fit	**From gLAB**			
-7,3516	-0,0689	0,6325	-0,7715	1
-5,3107	-0,6720	-0,6261	0,3955	1
-7,4675	-0,8876	0,1466	-0,4367	1
-6,8946	-0,2048	0,7982	-0,5665	1
-6,5154	-0,0484	-0,7890	-0,6124	1
-5,2957	-0,3620	-0,7826	-0,5064	1
-10,3137	-0,5272	-0,1500	-0,8364	1
-5,6687	-0,6874	0,7229	-0,0699	1

2.3. Computing the LS solution with octave (or MATLAB)

```
octave

load M.dat

y=M(:,1)

G=M(:,2:5)

x=inv(G'*G)*G'*y

exit
```

```
Jaume@Jaume-PC:/cygdrive/c/gLAB/N...
octave:1> load M.dat
octave:2> y=M(:,1)
y =

   -7.3516
   -5.3107
   -7.4675
   -6.8946
   -6.5154
   -5.2957
  -10.3137
   -5.6687

octave:3>  G=M(:,2:5)
G =

  -0.068854   0.632491  -0.771501   1.000000
  -0.671994  -0.626096   0.395511   1.000000
  -0.887550   0.146645  -0.436749   1.000000
  -0.204785   0.798180  -0.566544   1.000000
  -0.048353  -0.789036  -0.612441   1.000000
  -0.362015  -0.782645  -0.506372   1.000000
  -0.527188  -0.150041  -0.836398   1.000000
  -0.687410   0.722896  -0.069918   1.000000

octave:4>  x=inv(G'*G)*G'*y
x =

   2.659322
  -0.068950
   3.786600
  -4.091713

octave:5> exit
```

Positioning error, with respect to the a priori coordinates given in the header of RINEX file:

	ΔX	ΔY	ΔZ	dT
➔	[2.659322	-0.068950	3.786600	-4.091713]

Receiver clock offset

Finally, the receiver coordinates are:

$$(x,y,z)=(x_{0,rec},\, x_{0,rec},\, x_{0,rec})+(\Delta x,\, \Delta y,\, \Delta z)$$

$$=(4789032.6277,\ 176595.0498,\ 4195013.2503)+(2.659322,-0.068950,3.786600)$$

$$=(4789035.2870,176594.9808,4195017.0369)$$

Navigation equations system and Kalman Filter

Exercise 3:

The measurement file **UPC11490.05O** has been collected by a receiver with fixed coordinates. Using navigation file **UPC11490.05N**, compute the **SPP solution** in static mode and check *by hand* the computation of the Kalman filter solution for the first three epochs (i.e. t = 300, t = 600 and t = 900 seconds).

Complete the next steps:

1. Set the default configuration of gLAB for the SPP mode. Then, in section [Filter], **select [Static] in the Receiver Kinematics option**. To process the data, click Run button.

2. Write the Kalman filter equations. Check the configuration parameters applied by gLAB and compute by hand the solution for the first three epochs in file (i.e. t = 300, t = 600 and t = 900 s).

*Note: Use prefit-residuals vector **y**(k) and design matrix **G**(k) from gLAB*

Kalman filter (see kalman.f)

Measurements

$$\mathbf{y}_k, \mathbf{R}_k$$

Estimation

$$\hat{\mathbf{x}}_k = \mathbf{P}_k \left[\mathbf{G}_k^{\mathrm{T}} \mathbf{R}_k^{-1} \mathbf{y}_k + \left(\mathbf{P}_k^{-} \right)^{-1} \hat{\mathbf{x}}_k^{-} \right]$$

$$\mathbf{P}_k = \left[\mathbf{G}_k^{\mathrm{T}} \mathbf{R}_k^{-1} \mathbf{G}_k + \left(\mathbf{P}_k^{-} \right)^{-1} \right]^{-1}$$

Prediction

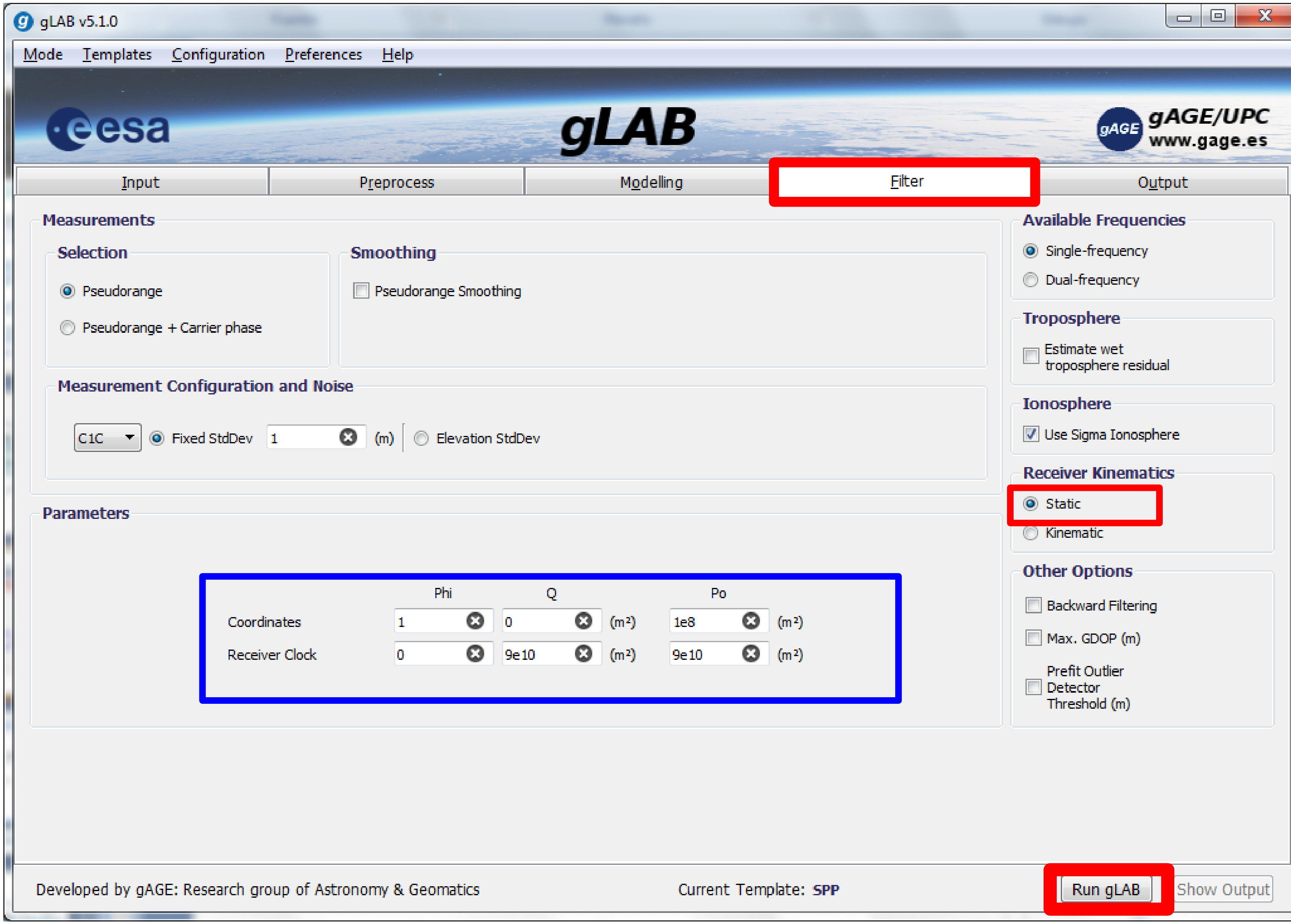
$$\hat{\mathbf{x}}_{k+1}^{-} = \Phi_k \hat{\mathbf{x}}_k$$

$$\mathbf{P}_{k+1}^{-} = \Phi_k \mathbf{P}_k \Phi_k^{\mathrm{T}} + \mathbf{Q}_k$$

$$\hat{\mathbf{x}}_0, \mathbf{P}_0$$

Initialization

$$\hat{\mathbf{x}}_k, \mathbf{P}_k$$


gLAB v5.1.0
Mode
Templates
Configuration
Preferences
Help
esa
gLAB
gAGE
gAGE/UPC
www.gage.es
Input
Preprocess
Modelling
Filter
Output
Measurements
Selection
Pseudorange
Pseudorange + Carrier phase
Smoothing
Pseudorange Smoothing
Measurement Configuration and Noise
C1C
Fixed StdDev
1
(m)
Elevation StdDev
Parameters
Phi
Q
Po
Coordinates
1
0
(m²)
1e8
(m²)
Receiver Clock
0
9e10
(m²)
9e10
(m²)
Available Frequencies
Single-frequency
Dual-frequency
Troposphere
Estimate wet troposphere residual
Ionosphere
Use Sigma Ionosphere
Receiver Kinematics
Static
Kinematic
Other Options
Backward Filtering
Max. GDOP (m)
Prefit Outlier Detector Threshold (m)
Developed by gAGE: Research group of Astronomy & Geomatics
Current Template: SPP
Run gLAB
Show Output

Filter configuration: From previous gLAB panel, it follows:

i. Filter configuration (according to gLAB):

- Initialisation:

  $\widehat{\mathtt{x}}\mathtt{0} \equiv \widehat{x}(0) = (0,0,0,0),$

  $\mathtt{P0} \equiv \mathbf{P}(0) = \sigma_0^2\,\mathbf{I}$, with $\sigma_0 = 3\cdot 10^5$m. (see comment [*])

- Process noise $\mathbf{Q}$ and transition matrices $\mathbf{\Phi}$:

$$\mathtt{Q} \equiv \boldsymbol{Q}(k) = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma_{dt}^2 \end{bmatrix}, \quad \Phi \equiv \mathbf{\Phi}(k) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

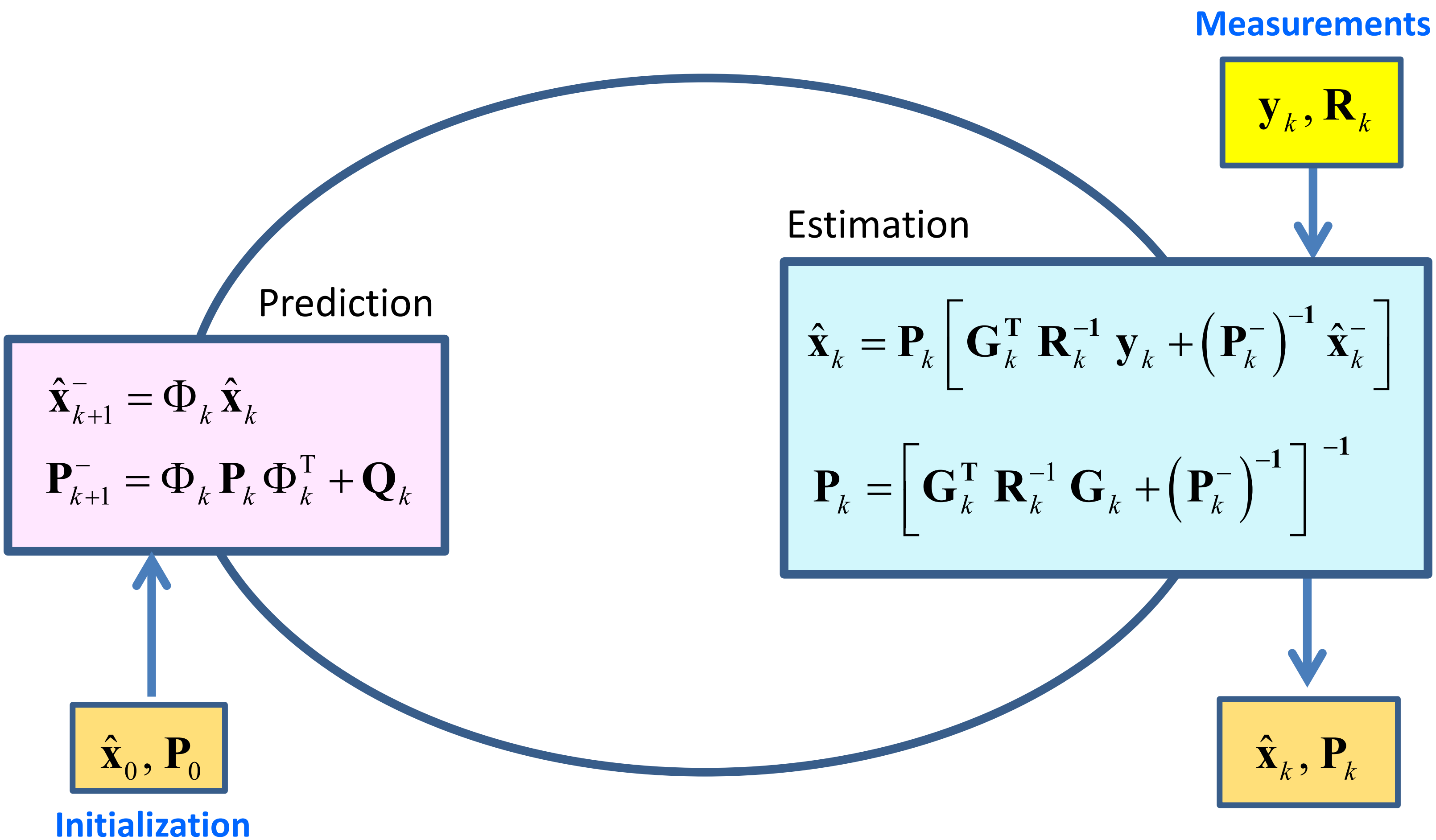
  with $\sigma_{dt} = 3\cdot 10^5$m.

- Measurement covariance matrix:

  $\mathtt{Rk} \equiv \mathbf{R}(k) = \sigma_y^2\,\mathbf{I}$, with $\sigma_y = 1\,$m.

[*]: By default, gLAB takes **P0** as: σ_0=1 $\cdot 10^4$ m (coord.) and σ_0=3 $\cdot 10^5$ m (clock),
But the results will be basically the same.
(we use here σ_0=3 $\cdot 10^5$ m for coordinates and clock to easier computations)

Kalman filter (see kalman.f)



ii. Kalman filter iterations:

k=1:

Prediction

$$x1^{-} = \Phi \cdot \widehat{x}0$$

$$P1^{-} = \Phi \cdot P0 \cdot \Phi^{T} + Q$$

Estimation

$$P1 = \left[G1^{T} \cdot R1^{-1} \cdot G1 + (P1^{-})^{-1}\right]^{-1}$$

$$\widehat{x}1 = P1 \cdot \left[G1^{T} \cdot R1^{-1} \cdot y1 + (P1^{-})^{-1} \cdot x1^{-}\right]$$

k=2:

Prediction

$$x2^{-} = \Phi \cdot \widehat{x}1$$

$$P2^{-} = \Phi \cdot P1 \cdot \Phi^{T} + Q$$

Estimation

$$P2 = \left[G2^{T} \cdot R2^{-1} \cdot G2 + (P2^{-})^{-1}\right]^{-1}$$

$$\widehat{x}2 = P2 \cdot \left[G2^{T} \cdot R2^{-1} \cdot y2 + (P2^{-})^{-1} \cdot x2^{-}\right]$$

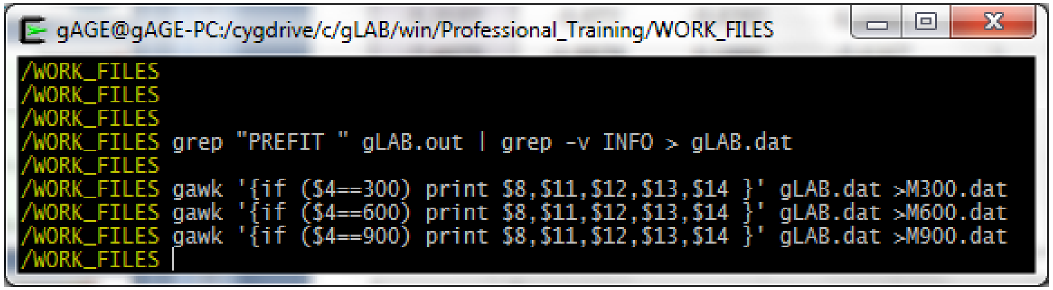
k=3:

...

Computation of pre-fit residuals an geometry matrix using gLAB (see previous exercise)

```
grep "PREFIT " gLAB.out | grep -v INFO > gLAB.dat

gawk '{if ($4==300) print $8,$11,$12,$13,$14 }' gLAB.dat >M300.dat
gawk '{if ($4==600) print $8,$11,$12,$13,$14 }' gLAB.dat >M600.dat
gawk '{if ($4==900) print $8,$11,$12,$13,$14 }' gLAB.dat >M900.dat
```

y300	M300			
Pre-fit				1
-7,3516	-0,0689	0,6325	-0,7715	1
-5,3107	-0,672	-0,6261	0,3955	1
-7,4675	-0,8876	0,1466	-0,4367	1
-6,8946	-0,2048	0,7982	-0,5665	1
-6,5154	-0,0484	-0,7890	-0,6124	1
-5,2957	-0,362	-0,7826	-0,5064	1
-10,3137	-0,5272	-0,1500	-0,8364	1
-5,6687	-0,6874	0,7229	-0,0699	1



y600	M600			
Pre-fit				1
-7,3077	-0,1017	0,6223	-0,7761	1
-5,4529	-0,6574	-0,6196	0,4289	1
-7,4200	-0,8712	0,1305	-0,4732	1
-6,3605	-0,2298	0,8103	-0,5391	1
-7,1679	-0,0198	-0,7741	-0,6327	1
-5,4569	-0,3589	-0,8043	-0,4735	1
-10,1605	-0,5277	-0,1904	-0,8278	1
-5,6403	-0,6925	0,7209	-0,0281	1

y900	M900			
Pre-fit				1
-6,8505	-0,1351	0,6124	-0,7789	1
-3,6943	-0,6418	-0,6128	0,4612	1
-7,0965	-0,8537	0,1131	-0,5084	1
-6,6825	-0,2535	0,8219	-0,5101	1
-7,3007	0,0096	-0,7590	-0,6510	1
-5,6064	-0,3561	-0,8245	-0,4398	1
-9,7147	-0,5288	-0,2302	-0,8170	1
-5,0505	-0,6959	0,7180	0,0136	1

i. Loading data files in octave and filter configuration

```
octave

load M300.dat
load M600.dat
load M900.dat

x0=[0 0 0 0]'
sigma0=3e5
P0=(sigma0)^2*eye(4,4)

sig_dt=3e5
Q=zeros(4,4)
Q(4,4)=(sig_dt)^2

fi=eye(4,4)
fi(4,4)=0
```

```
Jaume@Portatil_Jaume:/cygdrive/c/gLAB/wi...
ining/WORK_FILES octave
octave:1> load M300.dat
octave:2> load M600.dat
octave:3> load M900.dat
octave:4> x0=[0 0 0 0]'
x0 =

   0
   0
   0
   0

octave:5> sigma0=3e5
sigma0 =  300000
octave:6> P0=(sigma0)^2*eye(4,4)
P0 =

Diagonal Matrix

   9.0000e+10            0            0            0
            0   9.0000e+10            0            0
            0            0   9.0000e+10            0
            0            0            0   9.0000e+10

octave:7> sig_dt=3e5
sig_dt =  300000
octave:8> Q=zeros(4,4)
Q =

   0   0   0   0
   0   0   0   0
   0   0   0   0
   0   0   0   0

octave:9> Q(4,4)=(sig_dt)^2
Q =

   0.0000e+00   0.0000e+00   0.0000e+00   0.0000e+00
   0.0000e+00   0.0000e+00   0.0000e+00   0.0000e+00
   0.0000e+00   0.0000e+00   0.0000e+00   0.0000e+00
   0.0000e+00   0.0000e+00   0.0000e+00   9.0000e+10

octave:10> fi=eye(4,4)
fi =

Diagonal Matrix

   1   0   0   0
   0   1   0   0
   0   0   1   0
   0   0   0   1

octave:11> fi(4,4)=0
fi =

Diagonal Matrix

   1   0   0   0
   0   1   0   0
   0   0   1   0
   0   0   0   0

octave:12>
```

```
y1=M300(:,1);
G1=M300(:,2:5);
sigma_y=1
R1=(sigma_y)^2*eye(size(y1),size(y1))

y2=M600(:,1);
G2=M600(:,2:5);
sigma_y=1
R2=(sigma_y)^2*eye(size(y2),size(y2))

y3=M900(:,1);
G3=M900(:,2:5);
sigma_y=1
R3=(sigma_y)^2*eye(size(y3),size(y3))
```

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```
octave:12> Y1=M300(:,1);
octave:13> G1=M300(:,2:5);
octave:14> sigma_y=1
sigma_y =  1
octave:15> R1=(sigma_y)^2*eye(size(Y1),size(Y1))
R1 =

Diagonal Matrix

   1   0   0   0   0   0   0   0
   0   1   0   0   0   0   0   0
   0   0   1   0   0   0   0   0
   0   0   0   1   0   0   0   0
   0   0   0   0   1   0   0   0
   0   0   0   0   0   1   0   0
   0   0   0   0   0   0   1   0
   0   0   0   0   0   0   0   1

octave:16> Y2=M600(:,1);
octave:17> G2=M600(:,2:5);
octave:18> sigma_y=1
sigma_y =  1
octave:19> R2=(sigma_y)^2*eye(size(Y2),size(Y2))
R2 =

Diagonal Matrix

   1   0   0   0   0   0   0   0
   0   1   0   0   0   0   0   0
   0   0   1   0   0   0   0   0
   0   0   0   1   0   0   0   0
   0   0   0   0   1   0   0   0
   0   0   0   0   0   1   0   0
   0   0   0   0   0   0   1   0
   0   0   0   0   0   0   0   1

octave:20> Y3=M900(:,1);
octave:21> G3=M900(:,2:5);
octave:22> sigma_y=1
sigma_y =  1
octave:23> R3=(sigma_y)^2*eye(size(Y3),size(Y3))
R3 =

Diagonal Matrix

   1   0   0   0   0   0   0   0
   0   1   0   0   0   0   0   0
   0   0   1   0   0   0   0   0
   0   0   0   1   0   0   0   0
   0   0   0   0   1   0   0   0
   0   0   0   0   0   1   0   0
   0   0   0   0   0   0   1   0
   0   0   0   0   0   0   0   1
```

ii. Computations:

- **First iteration (t=300)**

```
x1_=fi*x0
P1_=fi*P0*fi'+Q

P1=inv(G1'*inv(R1)*G1+inv(P1_))
x1=P1*(G1'*inv(R1)*y1+inv(P1_)*x1_)
```

- **Second iteration (t=600)**

```
x2_=fi*x1
P2_=fi*P1*fi'+Q

P2=inv(G2'*inv(R2)*G2+inv(P2_))
x2=P2*(G2'*inv(R2)*y2+inv(P2_)*x2_)
```

- **Third iteration (t=900)**

```
x3_=fi*x2
P3_=fi*P2*fi'+Q

P3=inv(G3'*inv(R3)*G3+inv(P3_))
x3=P3*(G3'*inv(R3)*y3+inv(P3_)*x3_)

exit
```

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```
octave:24>  x1_=fi*x0
x1_ =

   0
   0
   0
   0

octave:25> P1_=fi*P0*fi'+Q
P1_ =

   9.0000e+10   0.0000e+00   0.0000e+00   0.0000e+00
   0.0000e+00   9.0000e+10   0.0000e+00   0.0000e+00
   0.0000e+00   0.0000e+00   9.0000e+10   0.0000e+00
   0.0000e+00   0.0000e+00   0.0000e+00   9.0000e+10

octave:26> P1=inv(G1'*inv(R1)*G1+inv(P1_))
P1 =

   2.14078   0.11270   0.92176   1.31834
   0.11270   0.32412   0.13636   0.10867
   0.92176   0.13636   1.29029   0.94834
   1.31834   0.10867   0.94834   1.09910

octave:27> x1=P1*(G1'*inv(R1)*Y1+inv(P1_)*x1_)
x1 =

   2.659434
  -0.069009
   3.786612
  -4.091662

octave:28> x2_=fi*x1
x2_ =

   2.65943
  -0.06901
   3.78661
  -0.00000

octave:29> P2_=fi*P1*fi'+Q
P2_ =

   2.1408e+00   1.1270e-01   9.2176e-01   0.0000e+00
   1.1270e-01   3.2412e-01   1.3636e-01   0.0000e+00
   9.2176e-01   1.3636e-01   1.2903e+00   0.0000e+00
   0.0000e+00   0.0000e+00   0.0000e+00   9.0000e+10

octave:30> P2=inv(G2'*inv(R2)*G2+inv(P2_))
P2 =

   1.079337   0.062567   0.442905   0.651389
   0.062567   0.161736   0.065505   0.056361
   0.442905   0.065505   0.611456   0.446232
   0.651389   0.056361   0.446232   0.592655

octave:31> x2=P2*(G2'*inv(R2)*Y2+inv(P2_)*x2_)
x2 =

   2.48617
   0.12145
   3.63518
  -4.28497
```

```
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octave:24>  x1_=fi*x0
x1_ =

   0
   0
   0
   0

octave:25> P1_=fi*P0*fi'+Q
P1_ =

   9.0000e+10   0.0000e+00   0.0000e+00   0.0000e+00
   0.0000e+00   9.0000e+10   0.0000e+00   0.0000e+00
   0.0000e+00   0.0000e+00   9.0000e+10   0.0000e+00
   0.0000e+00   0.0000e+00   0.0000e+00   9.0000e+10

octave:26> P1=inv(G1'*inv(R1)*G1+inv(P1_))
P1 =

   2.14078   0.11270   0.92176   1.31834
   0.11270   0.32412   0.13636   0.10867
   0.92176   0.13636   1.29029   0.94834
   1.31834   0.10867   0.94834   1.09910

octave:27> x1=P1*(G1'*inv(R1)*Y1+inv(P1_)*x1_)
x1 =

   2.659434
  -0.069009
   3.786612
  -4.091662

octave:28> x2_=fi*x1
x2_ =

   2.65943
  -0.06901
   3.78661
  -0.00000

octave:29> P2_=fi*P1*fi'+Q
P2_ =

   2.1408e+00   1.1270e-01   9.2176e-01   0.0000e+00
   1.1270e-01   3.2412e-01   1.3636e-01   0.0000e+00
   9.2176e-01   1.3636e-01   1.2903e+00   0.0000e+00
   0.0000e+00   0.0000e+00   0.0000e+00   9.0000e+10

octave:30> P2=inv(G2'*inv(R2)*G2+inv(P2_))
P2 =

   1.079337   0.062567   0.442905   0.651389
   0.062567   0.161736   0.065505   0.056361
   0.442905   0.065505   0.611456   0.446232
   0.651389   0.056361   0.446232   0.592655

octave:31> x2=P2*(G2'*inv(R2)*Y2+inv(P2_)*x2_)
x2 =

   2.48617
   0.12145
   3.63518
  -4.28497
```
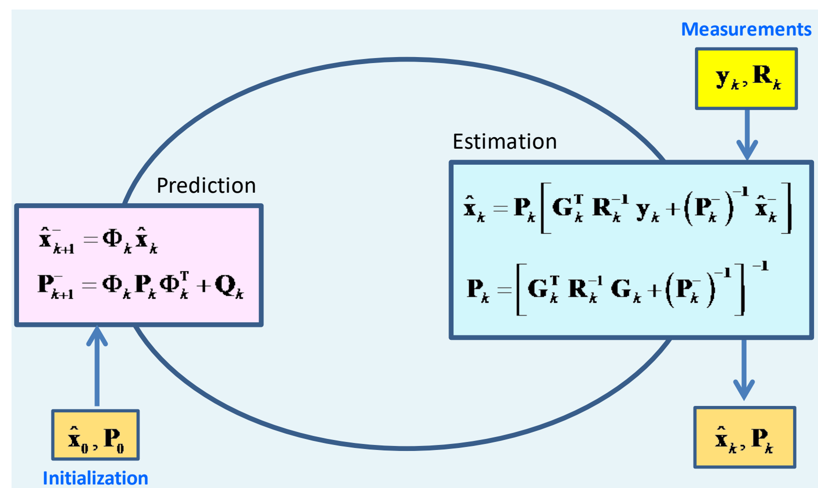

```
Jaume@Portatil_Jaume:/cygdrive/c/gLAB...

octave:32> x3_=fi*x2
x3_ =

   2.48617
   0.12145
   3.63518
  -0.00000

octave:33> P3_=fi*P2*fi'+Q
P3_ =

   1.0793e+00   6.2567e-02   4.4290e-01   0.0000e+00
   6.2567e-02   1.6174e-01   6.5505e-02   0.0000e+00
   4.4290e-01   6.5505e-02   6.1146e-01   0.0000e+00
   0.0000e+00   0.0000e+00   0.0000e+00   9.0000e+10

octave:34> P3=inv(G3'*inv(R3)*G3+inv(P3_))
P3 =

   0.724451   0.045809   0.283082   0.428130
   0.045809   0.107696   0.041886   0.038868
   0.283082   0.041886   0.386279   0.279090
   0.428130   0.038868   0.279090   0.423394

octave:35> x3=P3*(G3'*inv(R3)*Y3+inv(P3_)*x3_)
x3 =

   2.29035
   0.17603
   3.86966
  -3.94417

octave:36> exit
```



Cross-checking results with gLAB:

Coordinates (x,y,z)

```
grep OUTPUT gLAB.out | grep -v INFO > gLAB.tmp1

gawk '{if ($4==300) print $9,$10,$11}' gLAB.tmp1
                              ➔ 2.6593 -0.0689 3.7866
gawk '{if ($4==600) print $9,$10,$11}' gLAB.tmp1
                              ➔ 2.4861  0.1214 3.6351
gawk '{if ($4==900) print $9,$10,$11}' gLAB.tmp1
                              ➔ 2.2904  0.1760 3.8697
```

Clock (dt)

```
grep FILTER gLAB.out | grep -v INFO > gLAB.tmp2

gawk '{if ($4==300) print $8}' gLAB.tmp2  ➔ -4.0917
gawk '{if ($4==600) print $8}' gLAB.tmp2  ➔ -4.2850
gawk '{if ($4==900) print $8}' gLAB.tmp2  ➔ -3.9442
```

Homework. Predicted Accuracy: Dilution Of Precision

Exercise 4:

Using navigation file **UPC11490.05N**, compute the **Dilution Of Precision** at time **t = 300** seconds: GDOP, PDOP, TDOP, HDOP, VDOP.

Complete the next steps:

1.- Using previous results of exercises 1 and 2, compute the Geometry matrix $\mathbf{G}$ in (x,y,z,t) and (e,n,u,t) coordinates at **t = 300** seconds :

$$\mathbf{G}_{xyzt} = \begin{bmatrix} \frac{x_{0,rec} - x^{sat\,1}}{\rho_{0,rec}^{sat\,1}} & \frac{y_{0,rec} - y^{sat\,1}}{\rho_{0,rec}^{sat\,1}} & \frac{z_{0,rec} - z^{sat\,1}}{\rho_{0,rec}^{sat\,1}} & 1 \\ \frac{x_{0,rec} - x^{sat\,2}}{\rho_{0,rec}^{sat\,2}} & \frac{y_{0,rec} - y^{sat\,2}}{\rho_{0,rec}^{sat\,2}} & \frac{z_{0,rec} - z^{sat\,2}}{\rho_{0,rec}^{sat\,2}} & 1 \\ & \cdots\cdots\cdots & & \\ \frac{x_{0,rec} - x^{sat\,n}}{\rho_{0,rec}^{sat\,n}} & \frac{y_{0,rec} - y^{sat\,n}}{\rho_{0,rec}^{sat\,n}} & \frac{z_{0,rec} - z^{sat\,n}}{\rho_{0,rec}^{sat\,n}} & 1 \end{bmatrix}$$

$$\mathbf{G}_{enut} = \begin{bmatrix} -\cos el^1 \sin az^1 & -\cos el^1 \cos az^1 & -\sin el^1 & 1 \\ -\cos el^2 \sin az^2 & -\cos el^2 \cos az^2 & -\sin el^2 & 1 \\ & \cdots\cdots\cdots & & \\ -\cos el^n \sin az^n & -\cos el^n \cos az^n & -\sin el^n & 1 \end{bmatrix}$$

2.- Compute GDOP, PDOP, TDOP, HDOP, VDOP at time **t = 300**

- *Geometric Dilution Of Precision:*

$$\mathrm{GDOP} = \sqrt{q_{xx} + q_{yy} + q_{zz} + q_{tt}}$$

- *Position Dilution Of Precision:*

$$\mathrm{PDOP} = \sqrt{q_{xx} + q_{yy} + q_{zz}}$$

- *Time Dilution Of Precision:*

$$\mathrm{TDOP} = \sqrt{q_{tt}}$$

$$\mathbf{Q}_{xyzt} = (\mathbf{G}_{xyzt}^T \mathbf{G}_{xyzt})^{-1} = \begin{pmatrix} q_{xx} & q_{xy} & q_{xz} & q_{xt} \\ q_{xy} & q_{yy} & q_{yz} & q_{yt} \\ q_{xz} & q_{yz} & q_{zz} & q_{zt} \\ q_{xt} & q_{yt} & q_{zt} & q_{tt} \end{pmatrix}$$

- *Horizontal Dilution Of Precision:*

$$\mathrm{HDOP} = \sqrt{q_{ee} + q_{nn}}$$

- *Vertical Dilution Of Precision:*

$$\mathrm{VDOP} = \sqrt{q_{uu}}$$

$$\mathbf{Q}_{enut} = (\mathbf{G}_{enut}^T \mathbf{G}_{enut})^{-1} = \begin{pmatrix} q_{ee} & q_{en} & q_{eu} & q_{et} \\ q_{en} & q_{nn} & q_{na} & q_{nt} \\ q_{eu} & q_{nu} & q_{uu} & q_{ut} \\ q_{et} & q_{nt} & q_{ut} & q_{tt} \end{pmatrix}$$

3.- Check the coordinate transformation

Let $\mathbf{R}$ be the transformation matrix of (e,n,u,t) coordinates to (x,y,z,t)

$$\mathbf{R} = \begin{pmatrix} -\sin\lambda & -\sin\varphi\cos\lambda & \cos\varphi\cos\lambda & 0 \\ \cos\lambda & -\sin\varphi\sin\lambda & \cos\varphi\sin\lambda & 0 \\ 0 & \cos\varphi & \sin\varphi & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Verify that the estimated coordinates in exercises 1 and 2 fulfill next relationship:

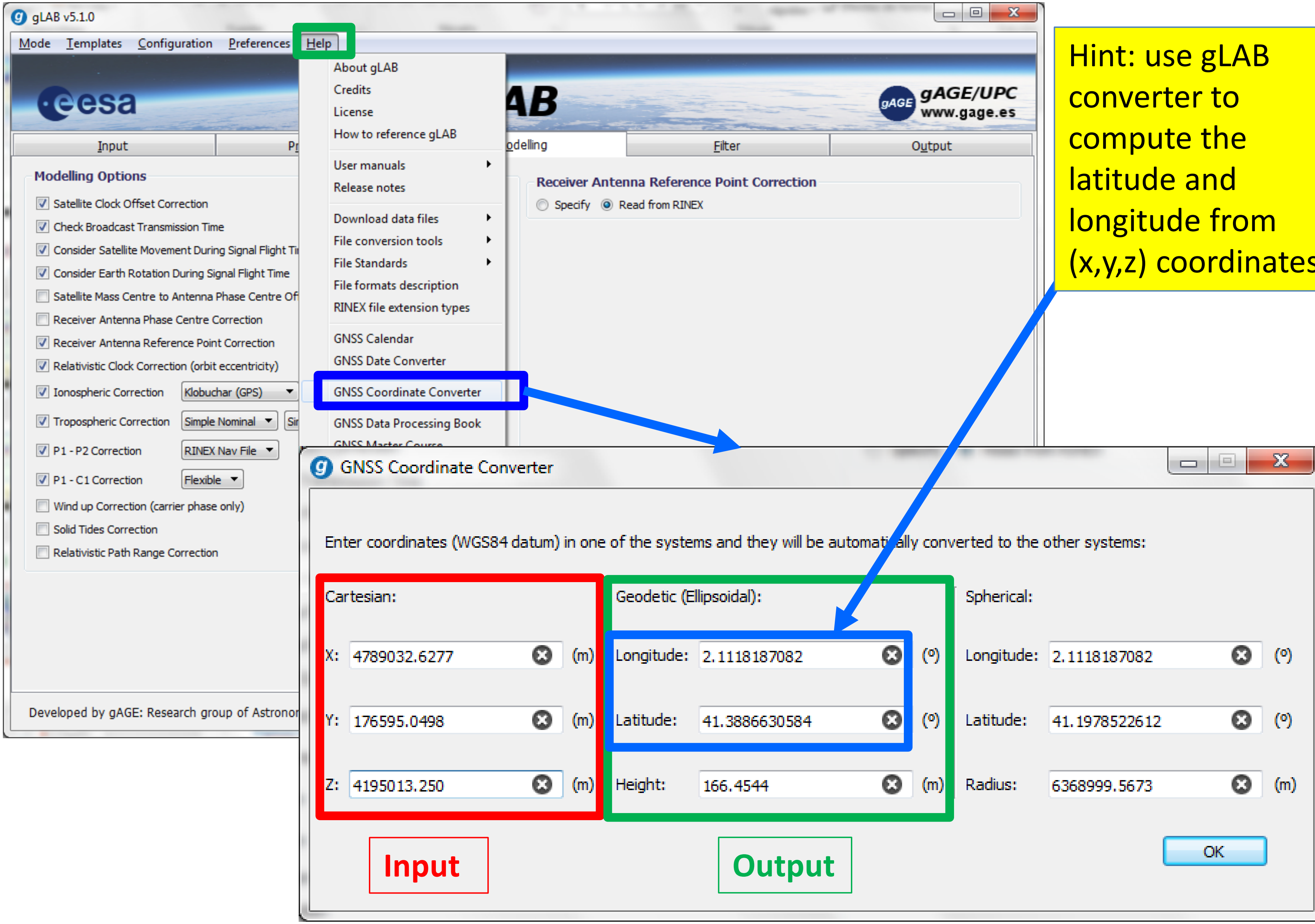
$$\mathbf{R} \begin{pmatrix} e \\ n \\ u \\ t \end{pmatrix} = \begin{pmatrix} x \\ y \\ z \\ t \end{pmatrix}$$

Verify the transformation:

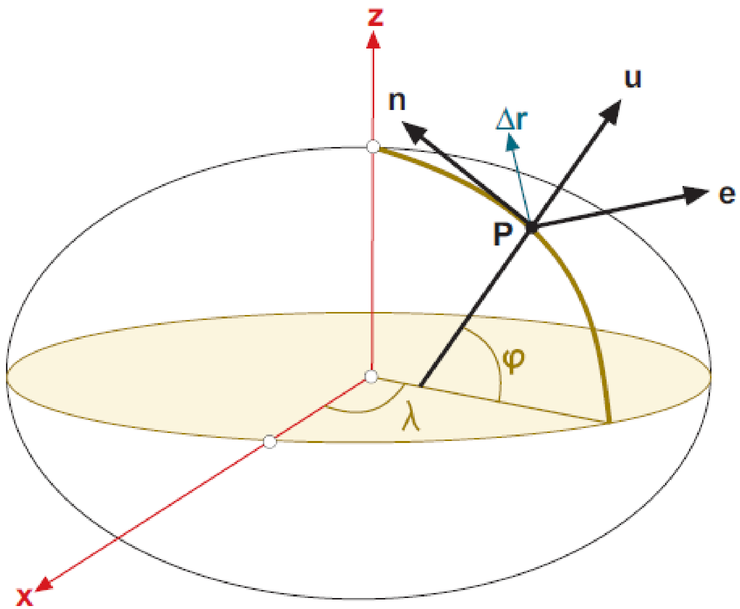
$$\mathbf{Q}_{enut} = \mathbf{R}^T \mathbf{Q}_{xyzt}\,\mathbf{R}$$

Justify the matrix $\mathbf{R}$ and previous expressions. Crosscheck results with gLAB.

Hint: use gLAB converter to compute the latitude and longitude from (x,y,z) coordinates



From ECEF (x,y,z) to Local (e,n,u) coordinates



$$\begin{bmatrix} \Delta \mathrm{e} \\ \Delta \mathrm{n} \\ \Delta \mathrm{u} \end{bmatrix} = \mathbf{R}_1[\pi/2-\varphi]\,\mathbf{R}_3[\pi/2+\lambda] \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix}$$

$$\hat{\mathbf{e}} = (-\sin\lambda\,,\ \cos\lambda\,,\ 0)$$
$$\hat{\mathbf{n}} = (-\cos\lambda\sin\varphi\,,\ -\sin\lambda\sin\varphi\,,\ \cos\varphi)$$
$$\hat{\mathbf{u}} = (\cos\lambda\cos\varphi\,,\ \sin\lambda\ \cos\varphi\,,\ \sin\varphi)$$

$$\begin{bmatrix} \Delta \mathrm{e} \\ \Delta \mathrm{n} \\ \Delta \mathrm{u} \end{bmatrix} = \begin{bmatrix} -\sin\lambda & \cos\lambda & 0 \\ -\cos\lambda\sin\varphi & -\sin\lambda\sin\varphi & \cos\varphi \\ \cos\lambda\cos\varphi & \sin\lambda\cos\varphi & \sin\varphi \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix}$$

Thank you

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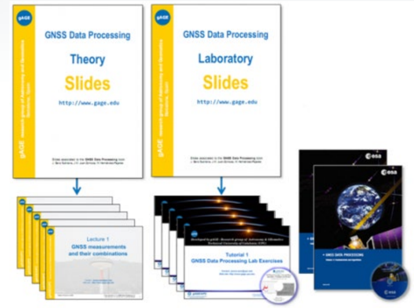

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  - About the course
  - **GNSS Data Processing: Theory Slides (Full compendium)**
    - Lecture 0: Introduction
    - Lecture 1: GNSS measurements and their combinations
    - Lecture 2: Satellite orbits and clocks computation accuracy
    - Lecture 3: Position estimation with pseudoranges
    - Lecture 4: Introduction to DGNSS
    - Lecture 5: Precise positioning with carrier phase (PPP)
    - Lecture 6: Differential positioning with code pseudoranges
    - Lecture 7: Carrier based differential positioning. Ambiguity resolution techniques
  - **GNSS Data Processing: Laboratory Exercises (Full compendium)**
    - Tutorial 0: UNIX enviroment, tools and skills. GNSS standard file formats [Format files decription]
    - Tutorial 1: GNSS data processing laboratory exercises
    - Tutorial 2: Measurement analysis and error budget
    - Tutorial 3: Differential positioning with code measurements
    - Tutorial 4: Carrier ambiguity fixing
    - Tutorial 5: Analysis of propagation effects from GNSS observables based on laboratory exercises
    - Tutorial 6: Differential positioning and carrier ambiguity fixing
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    - CDROM zipped tar file. How to install the CDROM [Linux]
    - CDROM ISO. How to install the CDROM [Linux]
  - Associated **Software and Data Files (Windows)**
    - **Instalable Toolkit (*gLAB* + Cygwin)**
    - **Data Files**
    - How to install the Software
  - **Bootable USB stick (Linux live)**
    - ***gAGE-GLUE*** (to buid-up a botable USB stick). How to burn the gAGE-GLUE. **How to use the bootable USB stick.**
    - **How to start-up the laboratory session.**
  - **Useful tools for Windows:** Windows users can install the next ports of Linux tools (instead of Cygwin) at gnuwin32.sourceforge.net/packages.html:

About us

gAGE is a research group of the Technical University of Catalonia (UPC). UPC is a public university located in Barcelona, Spain.

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- Master Of Science (ENAC)
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jaume.sanz
Password: *
••••••••
Log in

- Log in using OpenID
- Request new password

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