gAGE

gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain

Lecture 4
Satellite orbits and clocks

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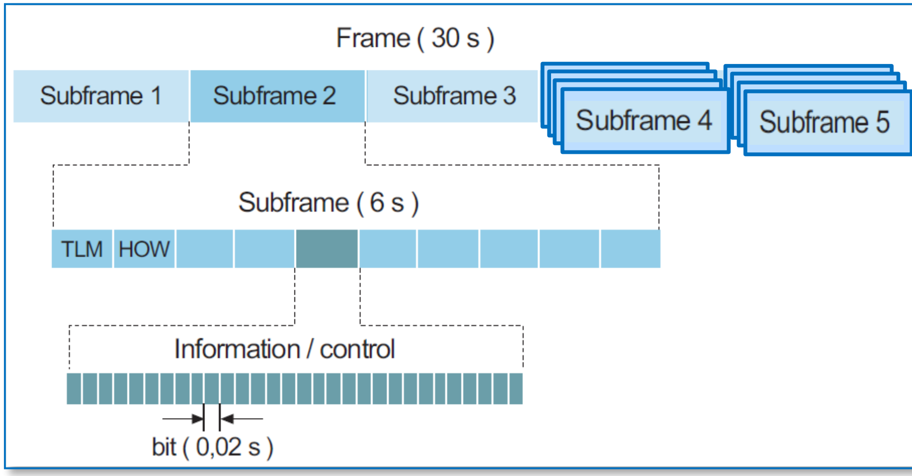
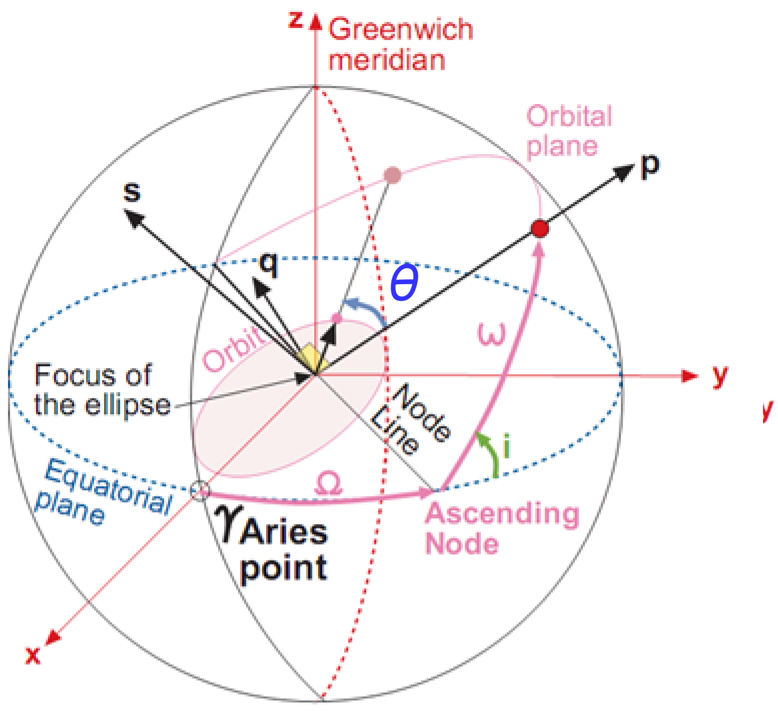
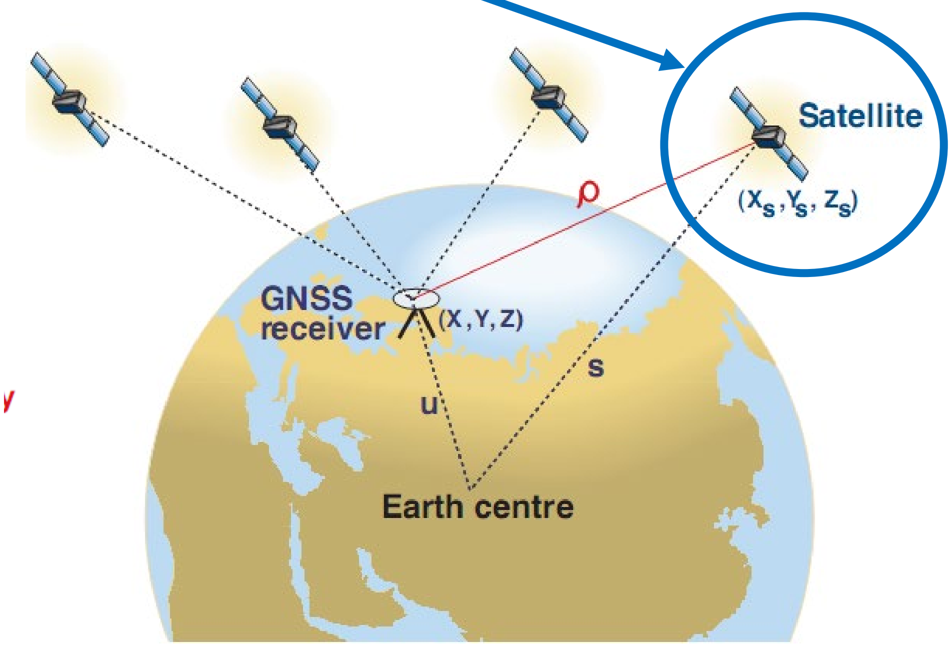
Contents

The GPS navigation message provides pseudo-Keplerian elements to compute satellite coordinates

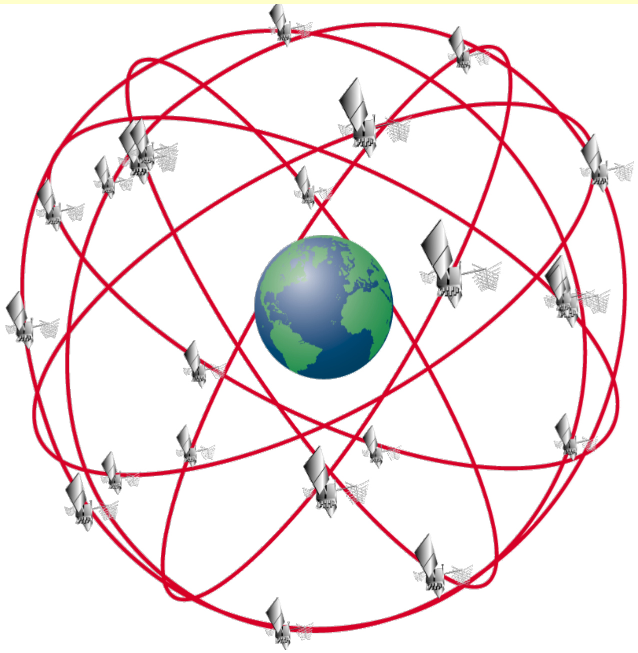


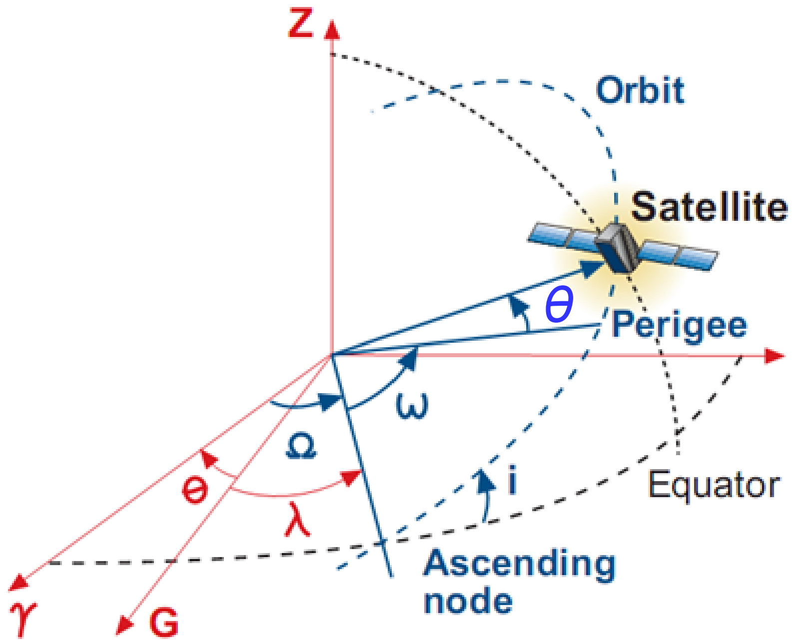




(X, Y, Z, Vx, Vy, Vz) → (a, e, i, Ω, ω, θ)

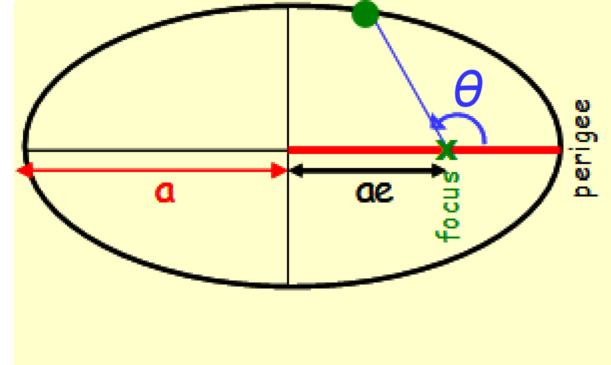
6 values are needed (X, Y, Z, Vx, Vy, Vz) to provide the position and velocity of a body. They can be mapped into the **six Keplerian elements** (a, e, i, Ω, ω, θ), which provides the "natural" representation of the orbit!

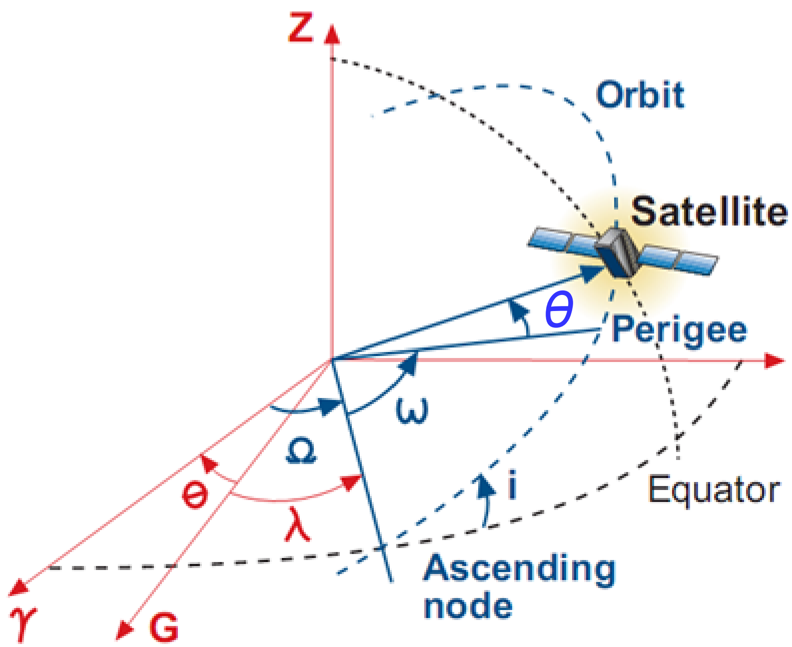




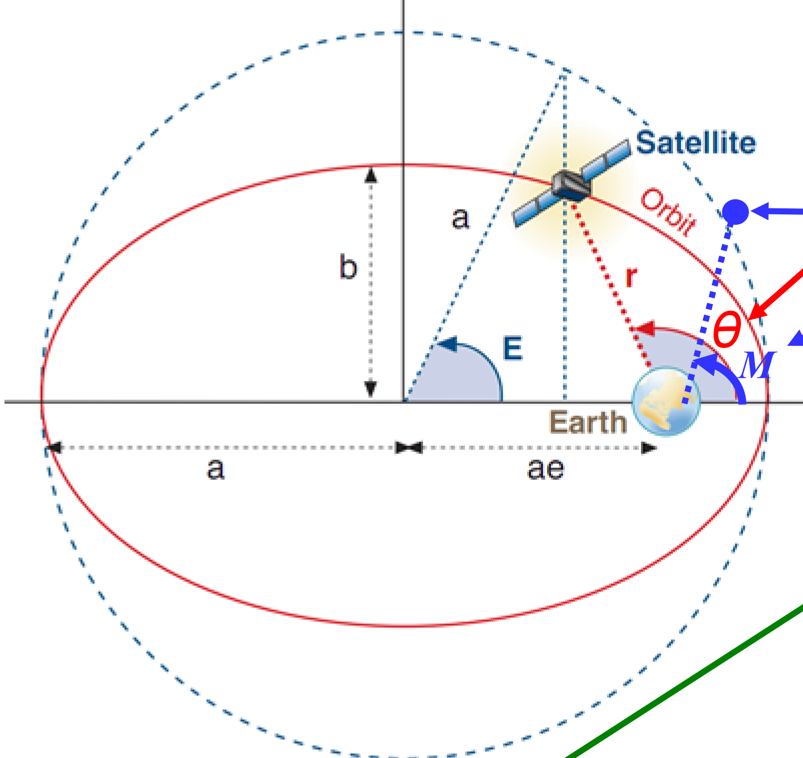
$(a, e, i, \Omega, \omega, \theta)$

- a, e: orbit shape
- i, Ω, ω: orbit orientation
- θ: position in the orbit





- **i** inclination
- **ω** argument of perigee
- **Ω** arg. ascending node (Aries)
- **λ** arg. ascending node (Greenwich)
- **θ** true anomaly
- **ϴ** sidereal time
- **ϒ** vernal equinox
- **G** Greenwich meridian



Perigee

True anomaly $\theta(t)$

Fictitious body moving at velocity $n=2\pi/P=constant$

➔ Mean anomaly $M(t)$

T_0 : time of passage by satellite's perigee

$$t \rightarrow \begin{bmatrix} T_0 \\ n=\dfrac{2\pi}{P} \\ \mu, a, e \end{bmatrix} \rightarrow \theta(t) \longleftrightarrow$$

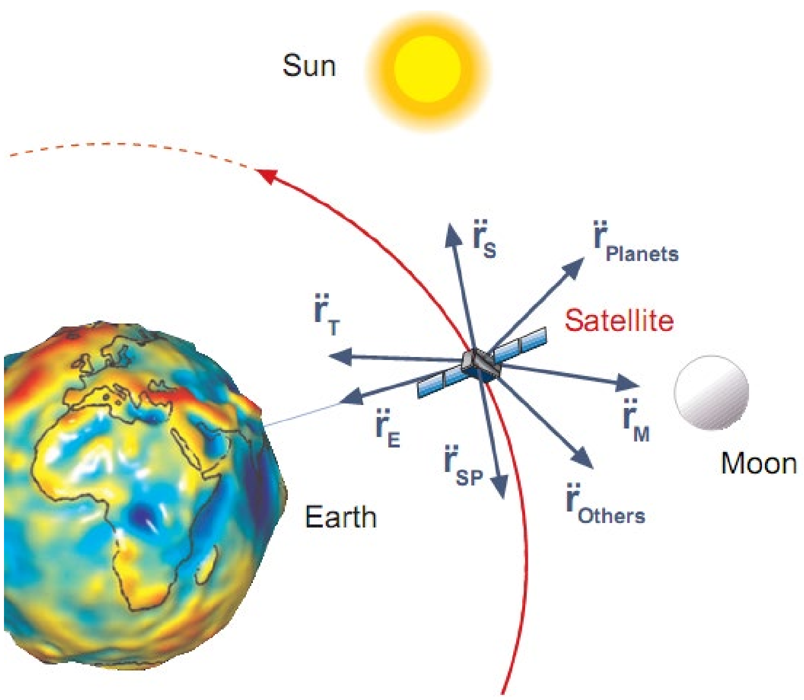
$$M(t) = n(t - T_0) = \sqrt{\frac{\mu}{a^3}}(t - T_0)$$

$$E(t) = M(t) + e \sin E(t)$$

$$\theta(t) = 2 \cdot atan\left[\sqrt{\frac{1+e}{1-e}} \tan\left(\frac{E(t)}{2}\right)\right]$$

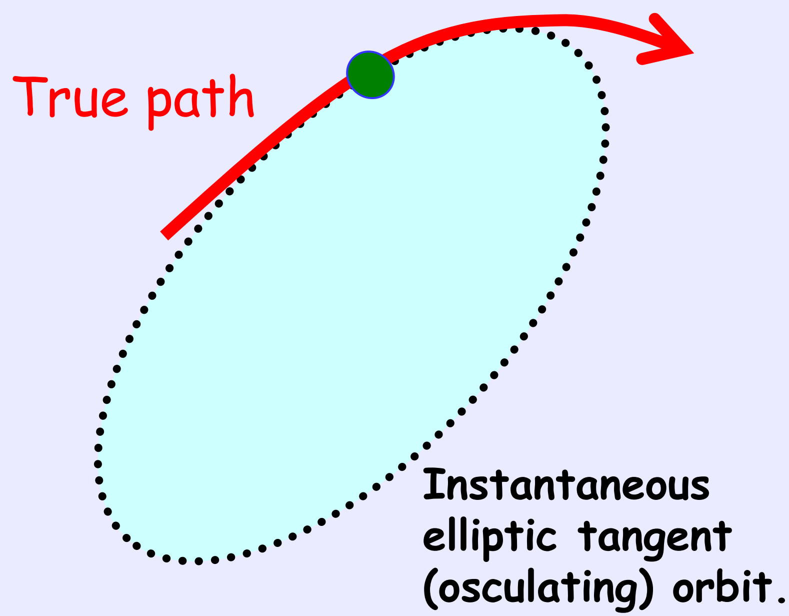
Contents

Due to the non-spherical nature of gravitational potential, the attraction of the Sun and Moon, the solar radiation pressure, etc., **the true satellite path deviates from the elliptic orbit**.



At any time an elliptical orbit tangent to the true path can be defined. This is the "osculating orbit", whose Keplerian elements vary with time "t":

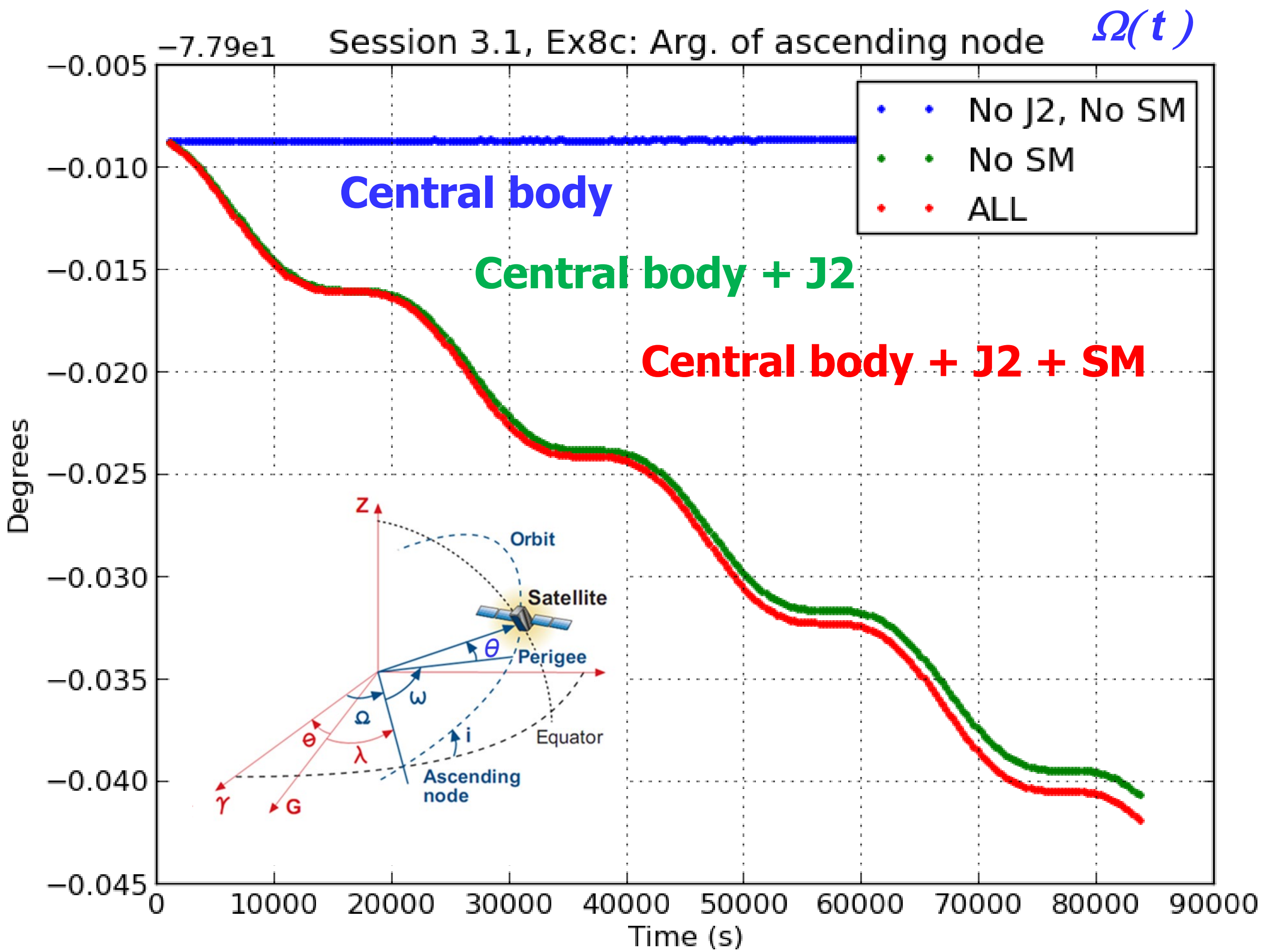
$$a(t),\ e(t),\ i(t),\ \Omega(t), \omega(t),\ \theta(t)$$

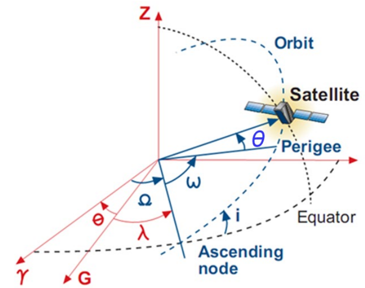


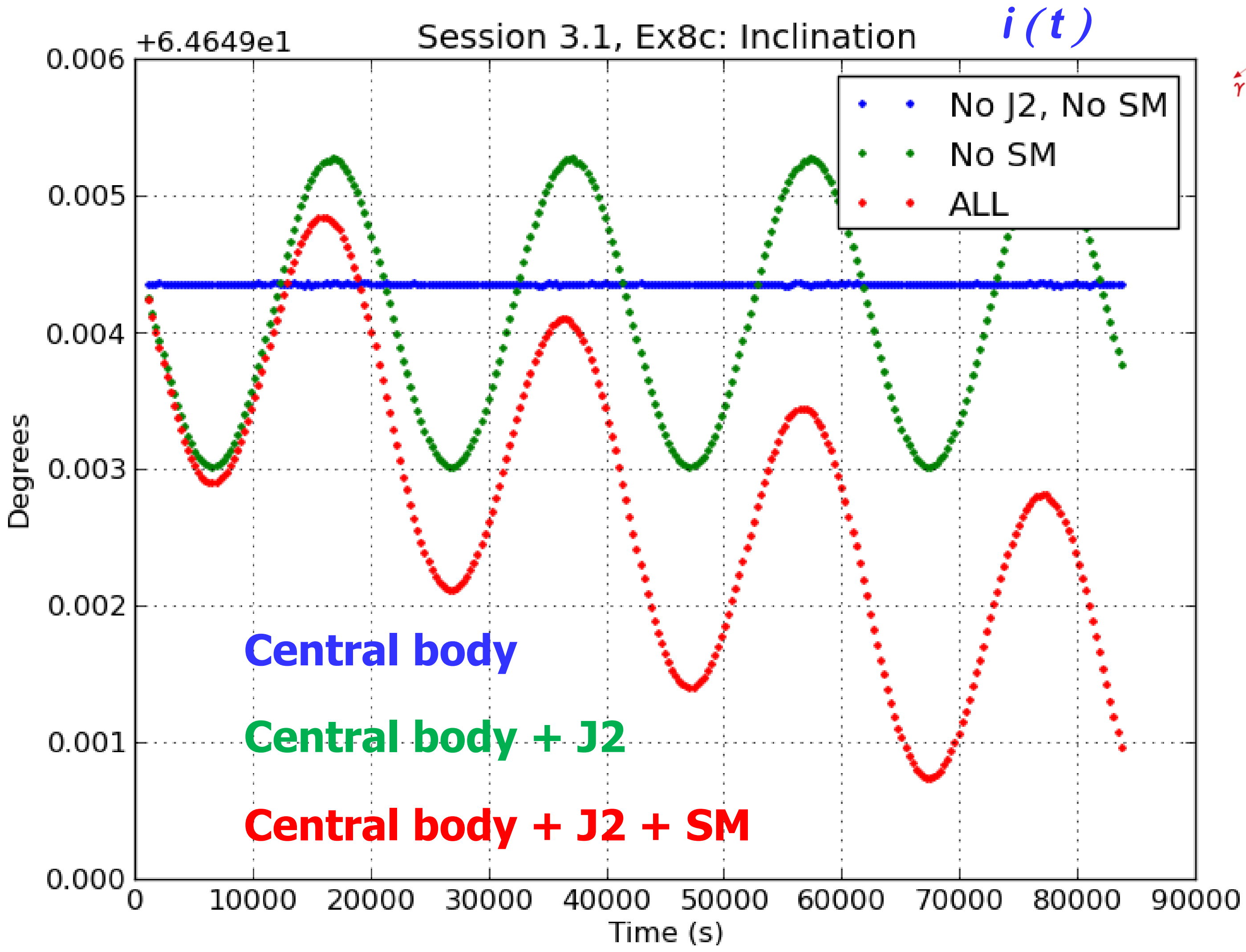
Different magnitudes of perturbation and their effects on GPS orbits

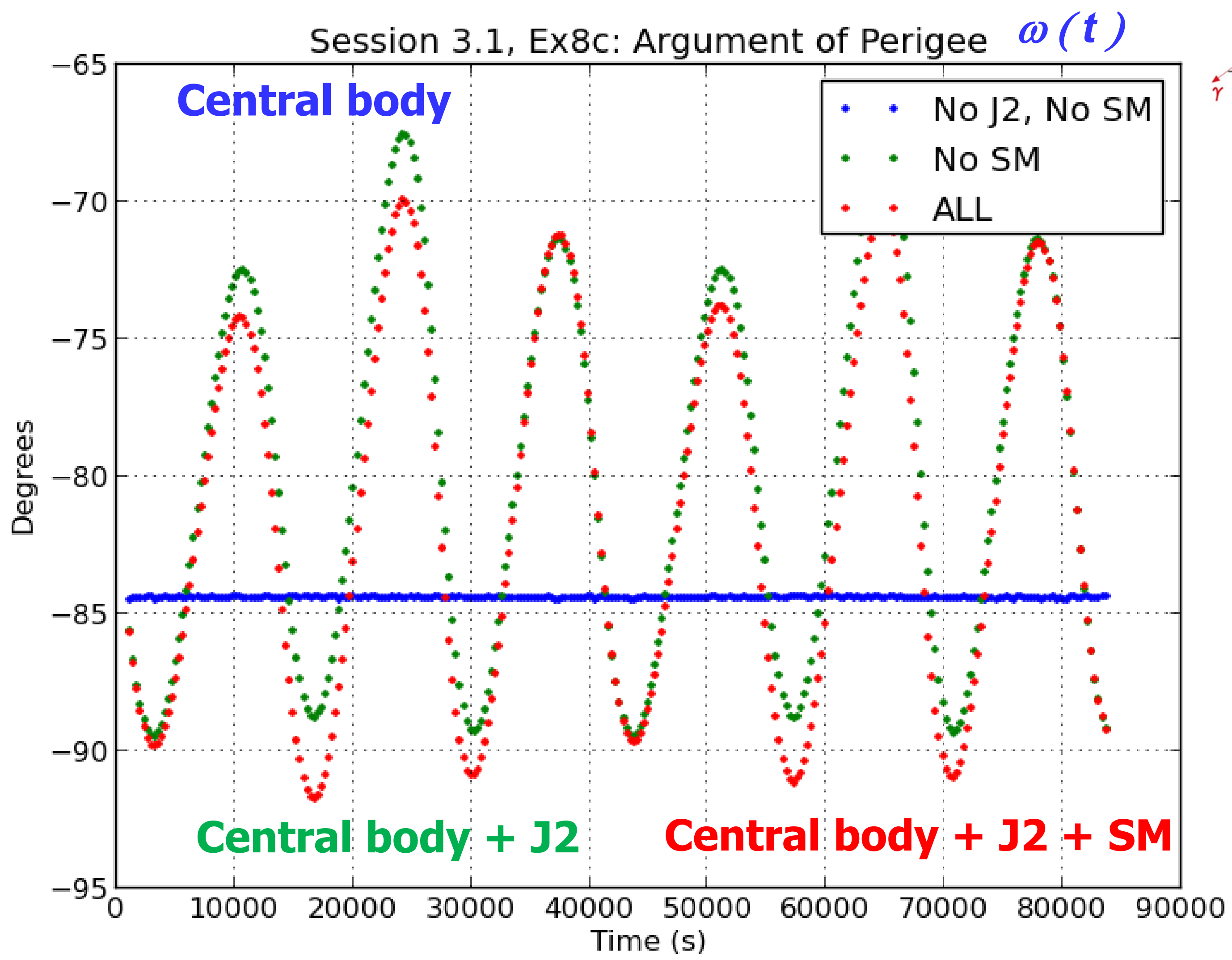
Perturbation	Acceleration (m/s^2)	Orbital effect in 3 hours	Orbital effect in 3 days
Central force (as a reference)	0.56		
J_2	$5 \cdot 10^{-5}$	2 km	14 km
Rest of the harmonics	$3 \cdot 10^{-7}$	50–80 m	100–1500 m
Solar + Moon grav.	$5 \cdot 10^{-6}$	5–150 m	1000–3000 m
Tidal effects	$1 \cdot 10^{-9}$	–	0.5–1.0 m
Solar rad. pressure	$1 \cdot 10^{-7}$	5–10 m	100–800 m

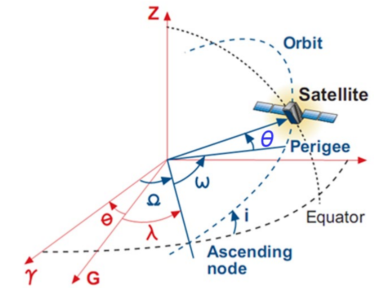
GLONASS Broadcast orbit integration terms


Ω(t)
Session 3.1, Ex8c: Arg. of ascending node
−7.79e1
No J2, No SM
No SM
ALL
Central body
Central body + J2
Central body + J2 + SM
Degrees
Time (s)
−0.005
−0.010
−0.015
−0.020
−0.025
−0.030
−0.035
−0.040
−0.045
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
Z
Orbit
Satellite
θ
Perigee
ω
Ω
Θ
λ
i
Equator
Ascending node
γ
G


Z
Orbit
Satellite
θ
Perigee
ω
Ω
Θ
λ
i
Equator
Ascending node
γ
G


i (t)
Session 3.1, Ex8c: Inclination
+6.4649e1
0.006
0.005
0.004
0.003
0.002
0.001
0.000
Degrees
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
Time (s)
No J2, No SM
No SM
ALL
Central body
Central body + J2
Central body + J2 + SM


Session 3.1, Ex8c: Argument of Perigee
ω(t)
Central body
No J2, No SM
No SM
ALL
Degrees
Time (s)
Central body + J2
Central body + J2 + SM


Z
Orbit
Satellite
θ
Perigee
ω
Ω
Θ
λ
i
Equator
Ascending node
γ
G

Calculation of osculating orbital elements from position and velocity (rv2osc.f)

$$\boxed{(x, y, z, v_x, v_y, v_z) \Rightarrow (a, e, i, \Omega, \omega, M)}$$

$$\boldsymbol{c} = \boldsymbol{r} \times \boldsymbol{v} \Rightarrow p = \frac{c^2}{\mu} \Rightarrow p$$

$$\frac{\mathrm{v}^2}{2} - \frac{\mu}{r} = -\frac{\mu}{2\,a} \Rightarrow a$$

$$\mathrm{a} = p\,\frac{1}{1-e^2} \Rightarrow e$$

$$i = arccos\left(\frac{\mathrm{c}_z}{c}\right) \Rightarrow i$$

$$\Omega = \mathrm{arc}tan\left(-\frac{\mathrm{c}_x}{\mathrm{c}_y}\right) \Rightarrow \Omega$$

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \boldsymbol{R_3}(-\Omega)\boldsymbol{R_1}(-i)\boldsymbol{R_3}(-\omega)\begin{pmatrix} \mathrm{r}\cos\theta \\ \mathrm{r}\sin\theta \\ 0 \end{pmatrix} = \mathrm{r}\begin{pmatrix} \cos\Omega\cdot\cos(\omega+\theta) - \sin\Omega\cdot\cos\mathrm{i}\cdot\sin(\omega+\theta) \\ \sin\Omega\cdot\cos(\omega+\theta) + \cos\Omega\cdot\cos\mathrm{i}\cdot\sin(\omega+\theta) \\ \sin\mathrm{i}\cdot\sin(\omega+\theta) \end{pmatrix} \Rightarrow (\omega+\theta)$$

$$\mathrm{r} = \frac{p}{1+\mathrm{e}\cdot\cos\theta} \Rightarrow \omega, \theta$$

$$\tan\left(\frac{\theta}{2}\right) = \sqrt{\frac{1+\mathrm{e}}{1-\mathrm{e}}}\tan\left(\frac{\mathrm{E}}{2}\right)$$

$$M = E - e\sin E \Rightarrow M$$

Calculation of position and velocity from osculating orbital elements (osc2rv.f)

$$\boxed{(a, e, i, \Omega, \omega, t - T_0) \Rightarrow (x, y, z, v_x, v_y, v_z)}$$

$$M = n(t - T_0) = \sqrt{\frac{\mu}{a^3}}(t - T_0) \Rightarrow M$$

$$M = E - e \sin E \Rightarrow E$$

$$r = a\,(1 - e \cos E) \Rightarrow r$$

$$\tan\left(\frac{\theta}{2}\right) = \sqrt{\frac{1+\mathrm{e}}{1-\mathrm{e}}}\tan\left(\frac{\mathrm{E}}{2}\right) \Rightarrow \theta$$

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \boldsymbol{R}\begin{pmatrix} \mathrm{r}\cos\theta \\ \mathrm{r}\sin\theta \\ 0 \end{pmatrix} \qquad \begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} = \frac{na^2}{r}\left\{\vec{\boldsymbol{Q}}\sqrt{1-e^2}\cos E - \vec{\boldsymbol{P}}\sin E\right\}$$

Where:

$$\boldsymbol{R} = \boldsymbol{R_3}(-\Omega)\boldsymbol{R_1}(-i)\boldsymbol{R_3}(-\omega)$$

$$= \begin{pmatrix} \cos\Omega & -\sin\Omega & 0 \\ \sin\Omega & \cos\Omega & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos i & -\sin i \\ 0 & \sin i & \cos i \end{pmatrix}\begin{pmatrix} \cos\omega & -\sin\omega & 0 \\ \sin\omega & \cos\omega & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} P_x & Q_x & S_x \\ P_y & Q_y & S_y \\ P_z & Q_z & S_z \end{pmatrix} = [\vec{\boldsymbol{P}} \quad \vec{\boldsymbol{Q}} \quad \vec{\boldsymbol{S}}]$$

Exercise: Orbital elements variation:

File 1995-10-18.eci contains the precise position and velocities of GPS satellites every 5 minutes for October 18th, 1995 in a Earth-Centred Inertial system (ECI) **[from JPL/NASA server: ftp://sideshow.jpl.nasa.gov/pub/gipsy_products]**

a) Use program "**rv2osc**" to compute the instantaneous orbital eleme $(X, Y, Z, Vx, Vy, Vz) \rightarrow (a, e, i, \Omega, \omega, \theta)$

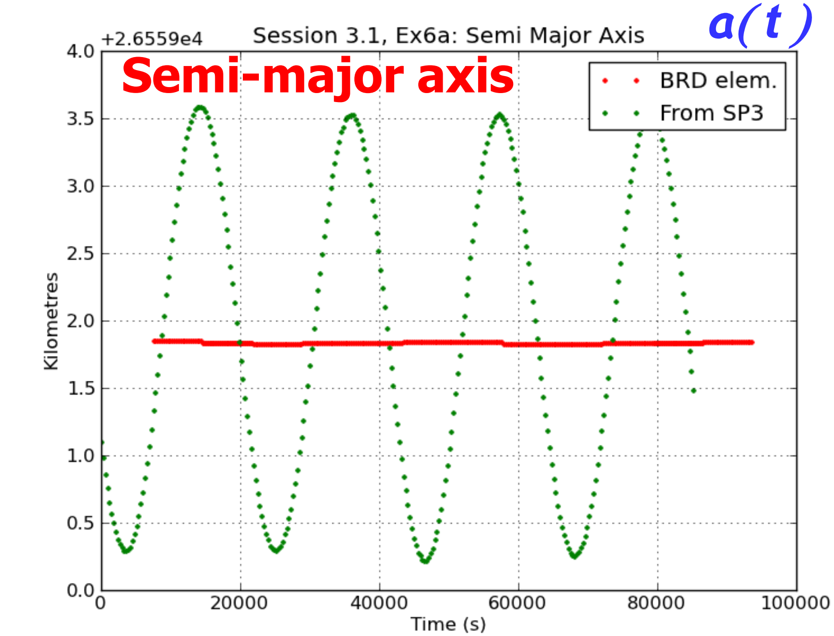
b) Plot the orbital elements in function of time to show their variation: $a(t), e(t), i(t), \Omega(t), \omega(t), \theta(t)$

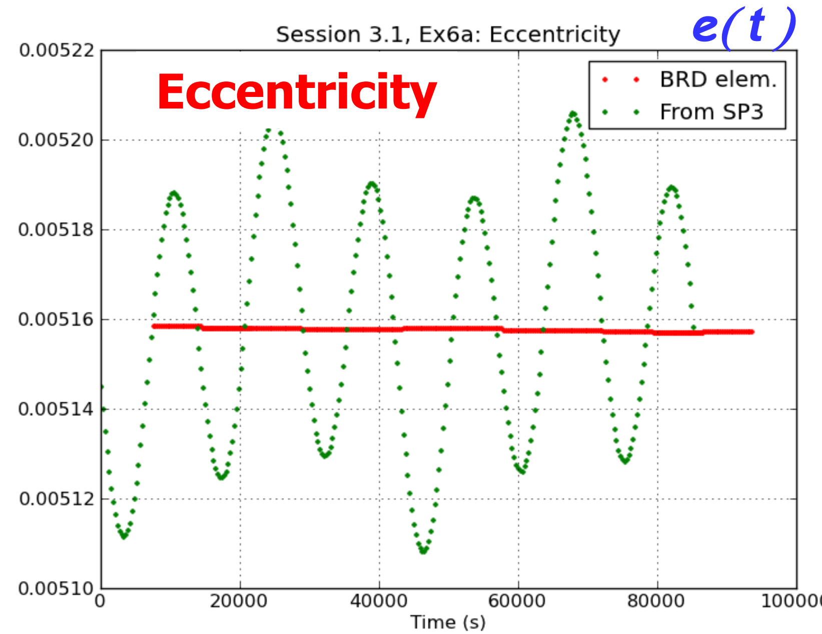
c) Compare with the broadcast orbital elements

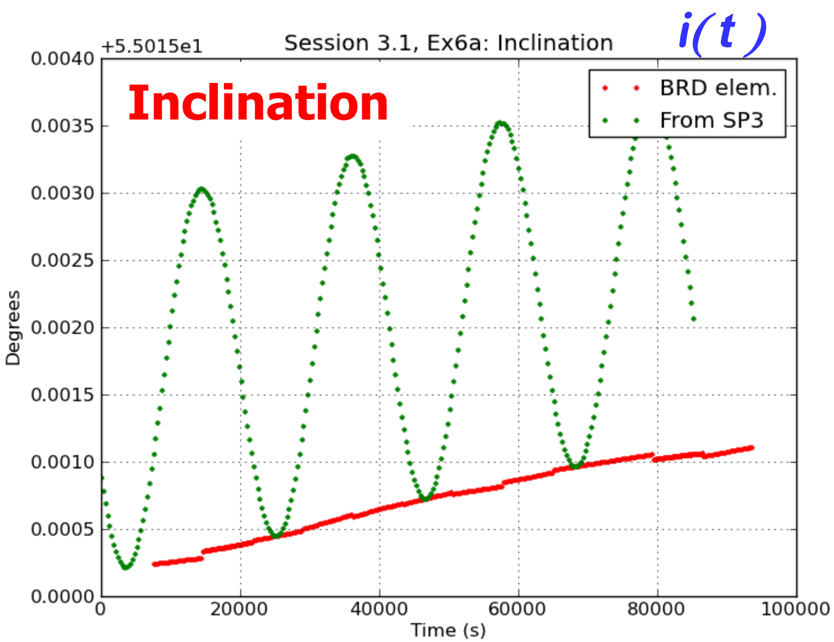
Solution:

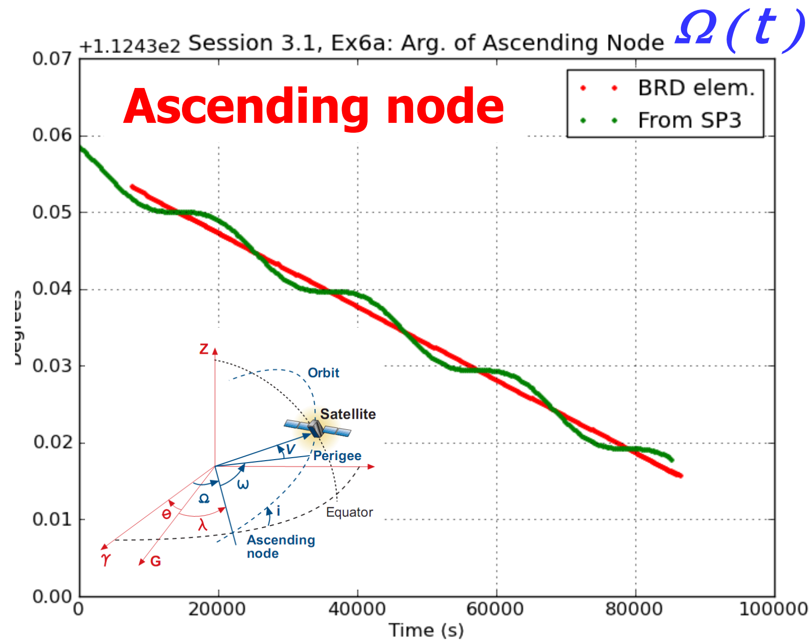
a) cat 1995-10-18.eci|rv2osc> orb.dat

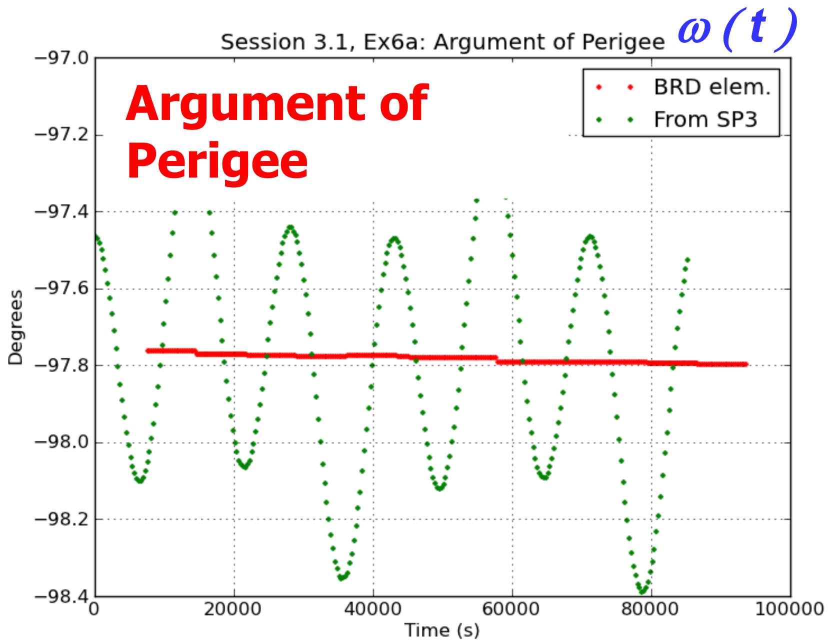
b) See the following plots


a(t)
Session 3.1, Ex6a: Semi Major Axis
Semi-major axis
+2.6559e4
Kilometres
Time (s)
BRD elem.
From SP3

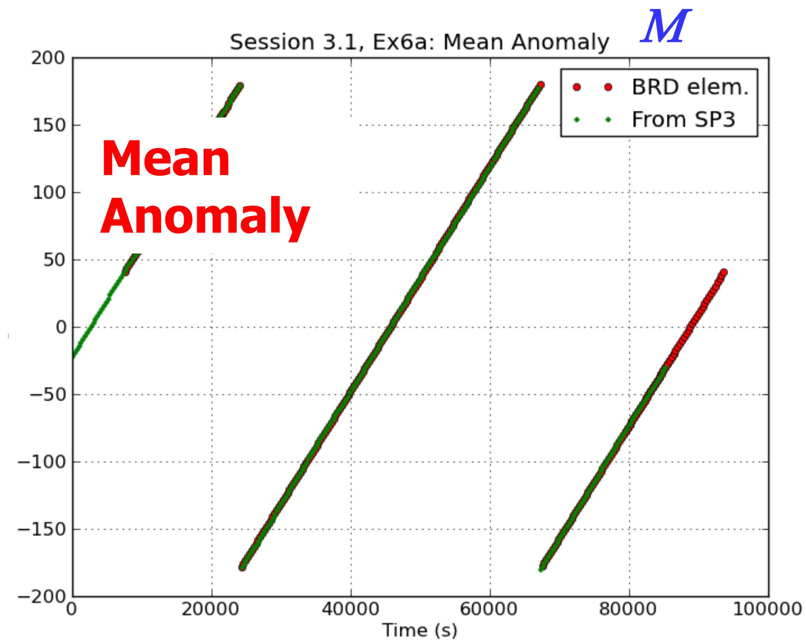

e(t)
Session 3.1, Ex6a: Eccentricity
Eccentricity
Time (s)
BRD elem.
From SP3


i(t)
Session 3.1, Ex6a: Inclination
Inclination
+5.5015e1
Degrees
Time (s)
BRD elem.
From SP3

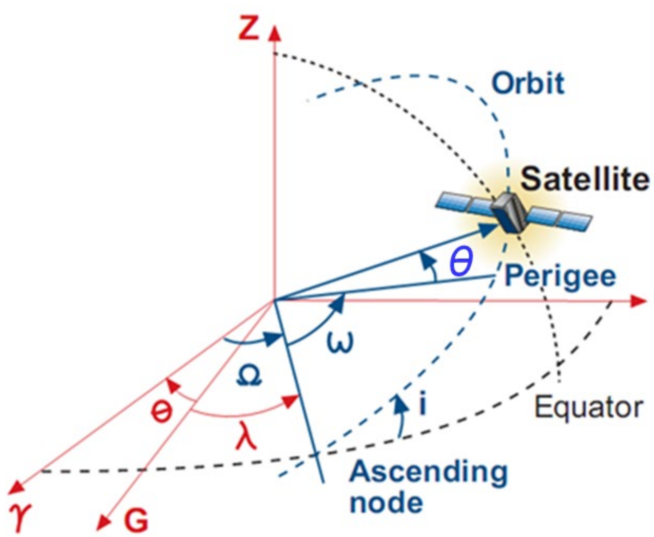

Ω(t)
Session 3.1, Ex6a: Arg. of Ascending Node
Ascending node
+1.1243e2
Time (s)
BRD elem.
From SP3
Z
Orbit
Satellite
Perigee
Equator
Ascending node
γ
G



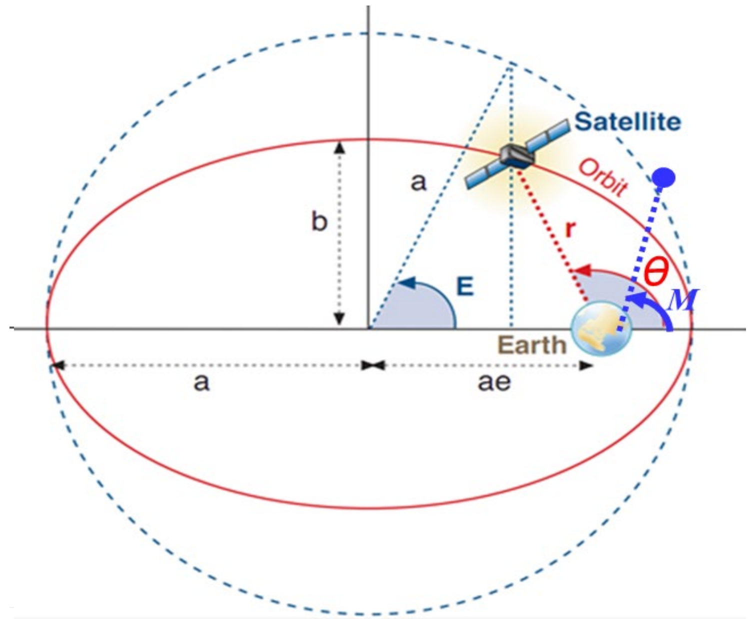
$\omega(t)$
Session 3.1, Ex6a: Argument of Perigee
Argument of Perigee
BRD elem.
From SP3
Degrees
Time (s)



M
Session 3.1, Ex6a: Mean Anomaly
Mean Anomaly
BRD elem.
From SP3
Time (s)



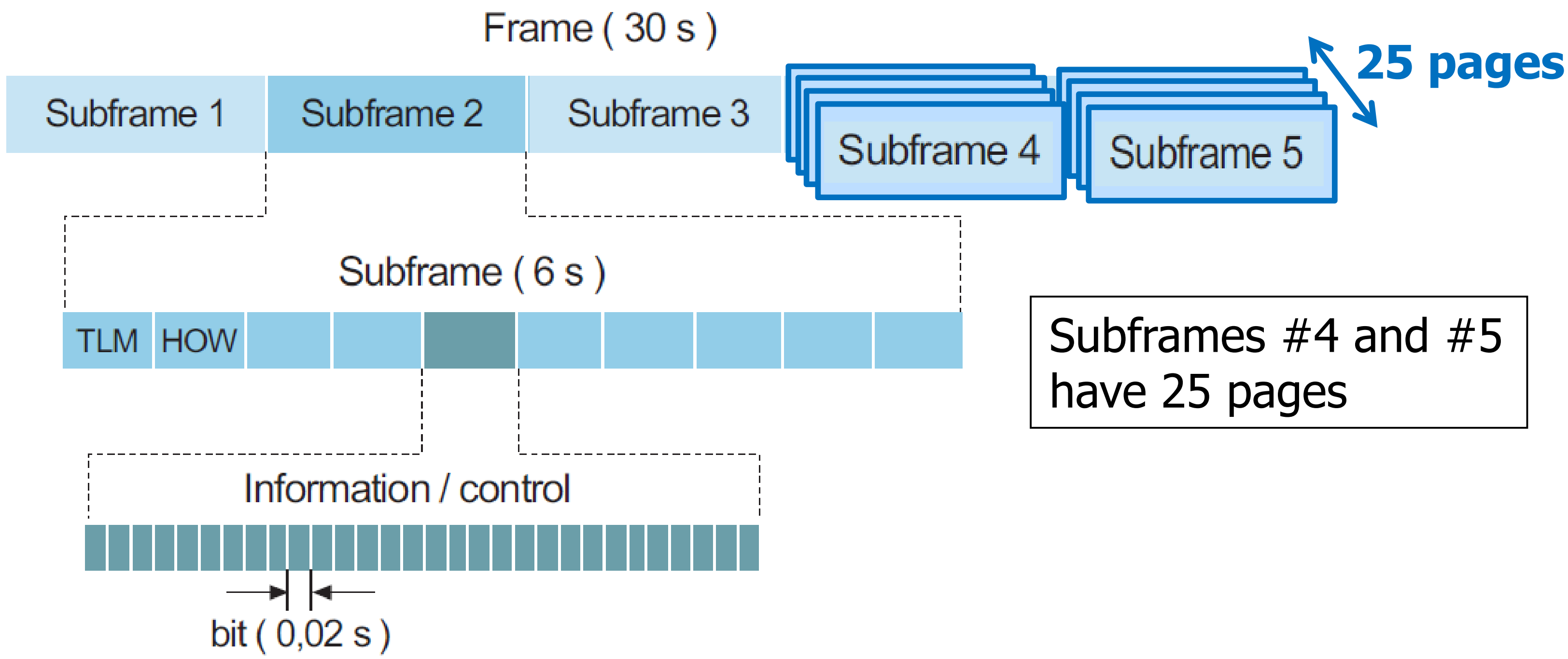
Z
Orbit
Satellite
θ
Perigee
ω
Ω
Θ
λ
i
Equator
Ascending node
γ
G



Satellite
Orbit
a
b
r
E
θ
M
Earth
a
ae

Contents

GPS navigation message



Subframes #4 and #5 have 25 pages

One Master Frame includes All 25 pages of Subframes #4 and #5 ➔ 25 x 30s = **12.5 min**

Subframe 1 contains information about the parameters to be applied to **satellite clock** status for its correction. These values are polynomial coefficients that allow time onboard to be converted to GPS time. The subframe also contains information on satellite health condition.

Subframes 2 and 3 contain **satellite ephemerides**.

Subframe 4 provides **ionospheric model** parameters (in order to adjust for ionospheric refraction), UTC information, part of the **almanac**, and indications whether the A/S is activated or not (which transforms the P code into encrypted Y code).

Subframe 5 contains data from the **almanac** and on constellation status. It allows rapid identification of the satellite from which the signal comes. A total of 25 frames are needed to complete the almanac.

Ephemeris in navigation message

Parameter	Explanation
$IODE$	Series number of ephemerides data
t_{oe}	Ephemerides reference epoch
$\sqrt{a}$	Square root of semi-major axis
e	Eccentricity
M_o	Mean anomaly at reference epoch
ω	Argument of perigee
i_o	Inclination at reference epoch
Ω	Ascending node's right ascension
Δn	Mean motion difference
$\dot{i}$	rate of inclination angle
$\dot{\Omega}$	Rate of node's right ascension
c_{uc}, c_{us}	Latitude argument correction
c_{rc}, c_{rs}	Orbital radius correction
c_{ic}, c_{is}	Inclination correction

In order to calculate WGS84 satellite coordinates, you should apply de following algorithm [GPS/SPS-SS, table 2-15] (see in the book FORTRAN subroutine orbit.f)

RINEX ephemeris file

```
     2              NAVIGATION DATA     GPS                 RINEX VERSION/ TYPE
XPRINT v1.1         gAGE                00/08/17 09:31:37   PGM / RUN BY / DATE
gAGE BROADCAST EPHEMERIS FILE                               COMMENT
   +1.7695E-08 +2.2352E-08 -1.1921E-07 -1.1921E-07          ION ALPHA
   +1.1878E+05 +1.4746E+05 -1.3107E+05 -3.2768E+05          ION BETA
   +1.955777406693E-08+1.598721155460E-14   405504     1064 DELTA_UTC: A0,A1,T,W
    13                                                      LEAP SECONDS
                                                            END OF HEADER

03 00  5 30 10  0 40.0+7.855705916882E-06+3.524291969370E-12+0.000000000000E+00
   +1.010000000000E+02+6.500000000000E+01+5.456298524109E-09+5.530285585107E-01  Mo
   +3.475695848465E-06+1.308503560722E-03+2.641230821609E-06+5.153678266525E+03  e, √a
   +2.088000000000E+05+1.117587089539E-08+7.472176136643E-01-1.862645149231E-09  TOE, Ω
   +9.412719852649E-01+3.163750000000E+02+1.125448382894E+00-8.826796182859E-09  io, ω
   +1.239337382719E-10+1.000000000000E+00+1.064000000000E+03+0.000000000000E+00
   +4.000000000000E+00+0.000000000000E+00-4.190951585770E-09+6.130000000000E+02  TGD
   +2.044980000000E+05+0.000000000000E+00+0.000000000000E+00+0.000000000000E+00

06 00  5 30 10  0  0.0+1.636799424887E-06+0.000000000000E+00+0.000000000000E+00
   +6.000000000000E+01+5.100000000000E+01+5.198073527168E-09-5.601816471398E-01
   +2.635642886162E-06+6.763593177311E-03+2.468004822731E-06+5.153726325989E+03
   +2.088000000000E+05+1.862645149231E-08+7.894129138508E-01+8.195638656616E-08
   +9.487675576456E-01+3.229687500000E+02-2.409256713064E+00-8.734292400447E-09
   +4.714481929846E-11+1.000000000000E+00+1.064000000000E+03+0.000000000000E+00
```

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3.1. Computation of satellite coordinates from navigation message (orbit.f)

- **Computation of t_k time since ephemerids reference epoch t_{oe} (t and t_{oe} are given in GPS seconds of week):**

$$\boxed{t_k = t - t_{oe}}$$

- **Computation of mean anomaly M_k for t_k,**

$$\boxed{M_k = M_0 + \left(\frac{\sqrt{\mu}}{\sqrt{a^3}} + \Delta n\right) t_k}$$

- **Iterative resolution of Kepler's equation in order to compute eccentric anomaly E_k :**

$$\boxed{M_k = E_k - e \sin E_k}$$

- **Calculation of true anomaly θ_k :**

$$\boxed{\theta_k = \arctan\left(\frac{\sqrt{1-e^2}\sin E_K}{\cos E_k - e}\right)}$$

- **Computation of latitude argument u_k from perigee argument ω, true anomaly θ_k and corrections c_{uc} and c_{us}:**

$$\boxed{u_k = \omega + \theta_k + c_{uc} cos\ 2(\omega + \theta_k) + c_{us}\ sin\ 2(\omega + \theta_k)}$$

- **Computation of radial distance r_k taking into consideration corrections c_{rc} and c_{rs}:**

$$r_k = a(1 - 2\cos E_k) + c_{rc}\cos 2(\omega + \theta_k) + c_{rs}\sin 2(\omega + \theta_k)$$

- **Calculation of orbital plane inclination i_k from inclination i_o at reference epoch t_{oe} and corrections c_{ic} and c_{is} :**

$$i_k = i_0 + i \cdot t_k + c_{ic}\cos 2(\omega + \theta_k) + c_{is}\sin 2(\omega + \theta_k)$$

- **Computation of ascending node longitude λ_k (wrt Greenwich), from RAAN at start of GPS week Ω_0, corrected from apparent variation of sidereal time at Greenwich between start of week and reference time $t_k = t - t_{oe}$, and also corrected from change of ascending node longitude since reference epoch t_{oe}.**

$$\lambda_k = \Omega_0 + \left(\dot{\Omega} - \omega_E\right)t_k - \omega_E t_{OE}$$

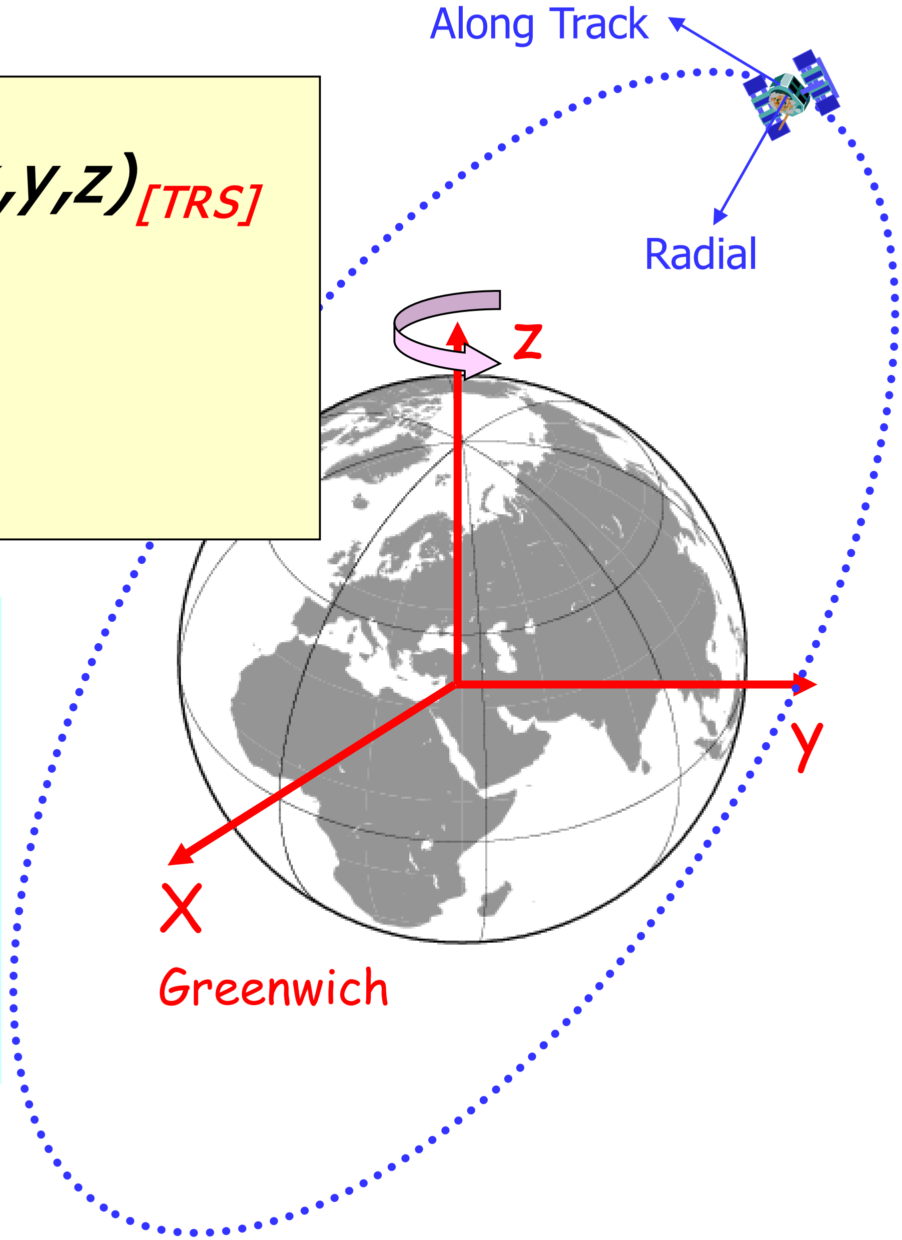
- **Calculation of coordinates in Conventional Terrestrial System (CTS) applying three rotations (around u_k, i_k , λ_k) :**

$$\begin{bmatrix} X_k \\ Y_k \\ Z_k \end{bmatrix} = \boldsymbol{R_3}(-\lambda_k) \cdot \boldsymbol{R_1}(-i_k) \cdot \boldsymbol{R_3}(-u_k) \begin{bmatrix} r_k \\ 0 \\ 0 \end{bmatrix}$$

$t \longrightarrow$ **Orbit.f** $\longrightarrow (x,y,z)_{[TRS]}$

$\uparrow$

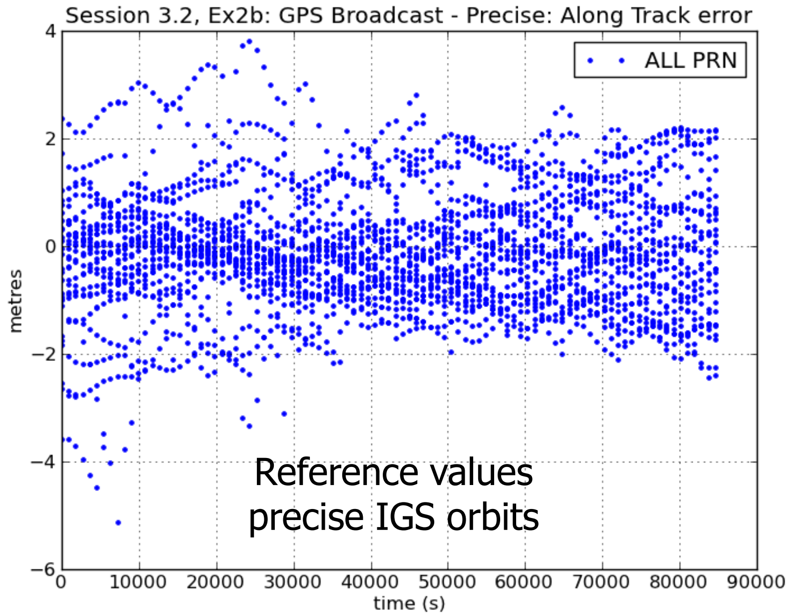
Navigation message (ephemeris)

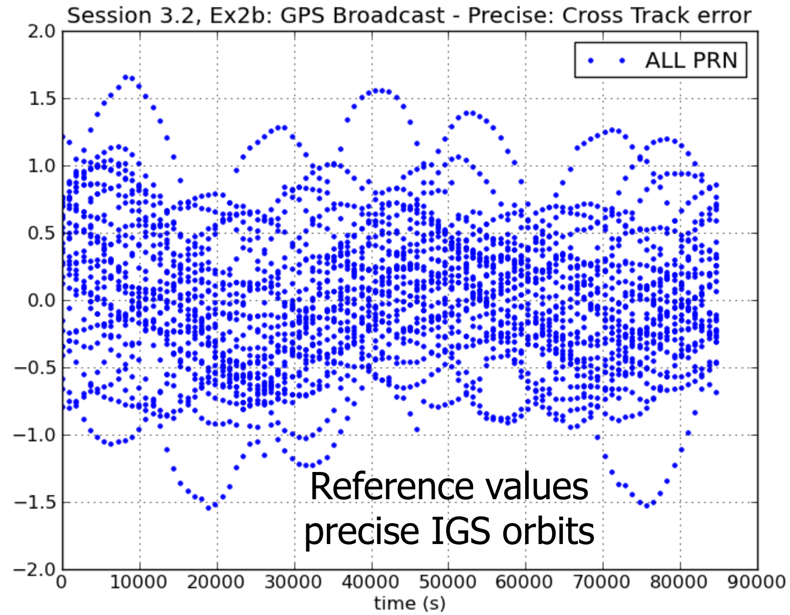


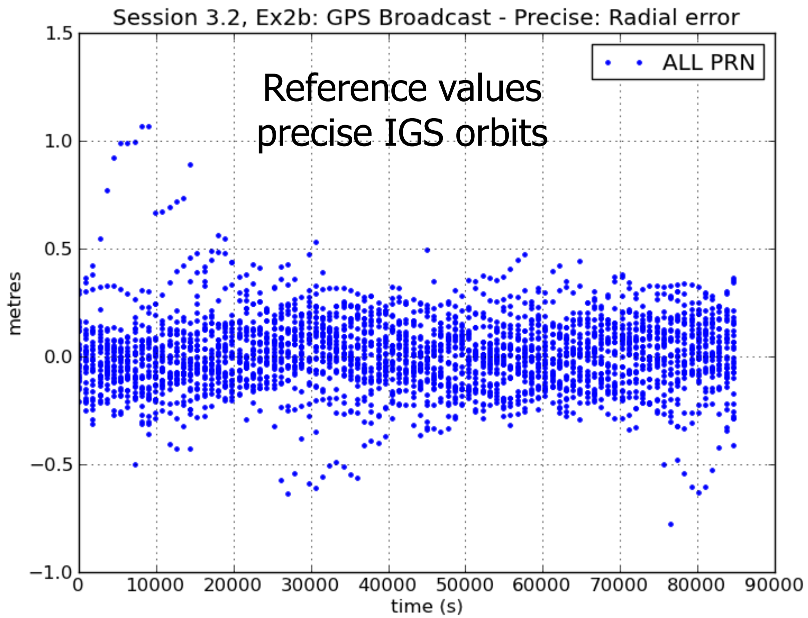
Conventional Terrestrial Reference System **(TRS):**

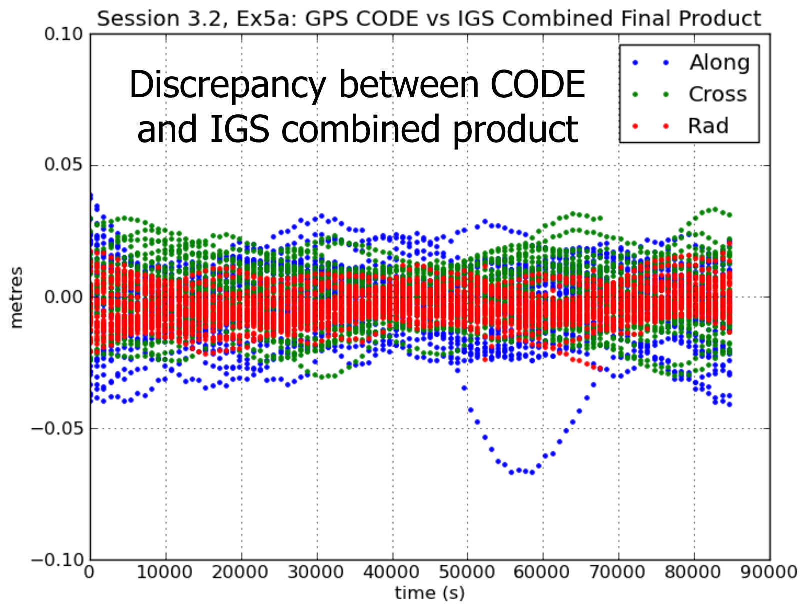
Earth Centered, Earth-Fixed (ECEF) ➔

the reference system rotates with Earth.

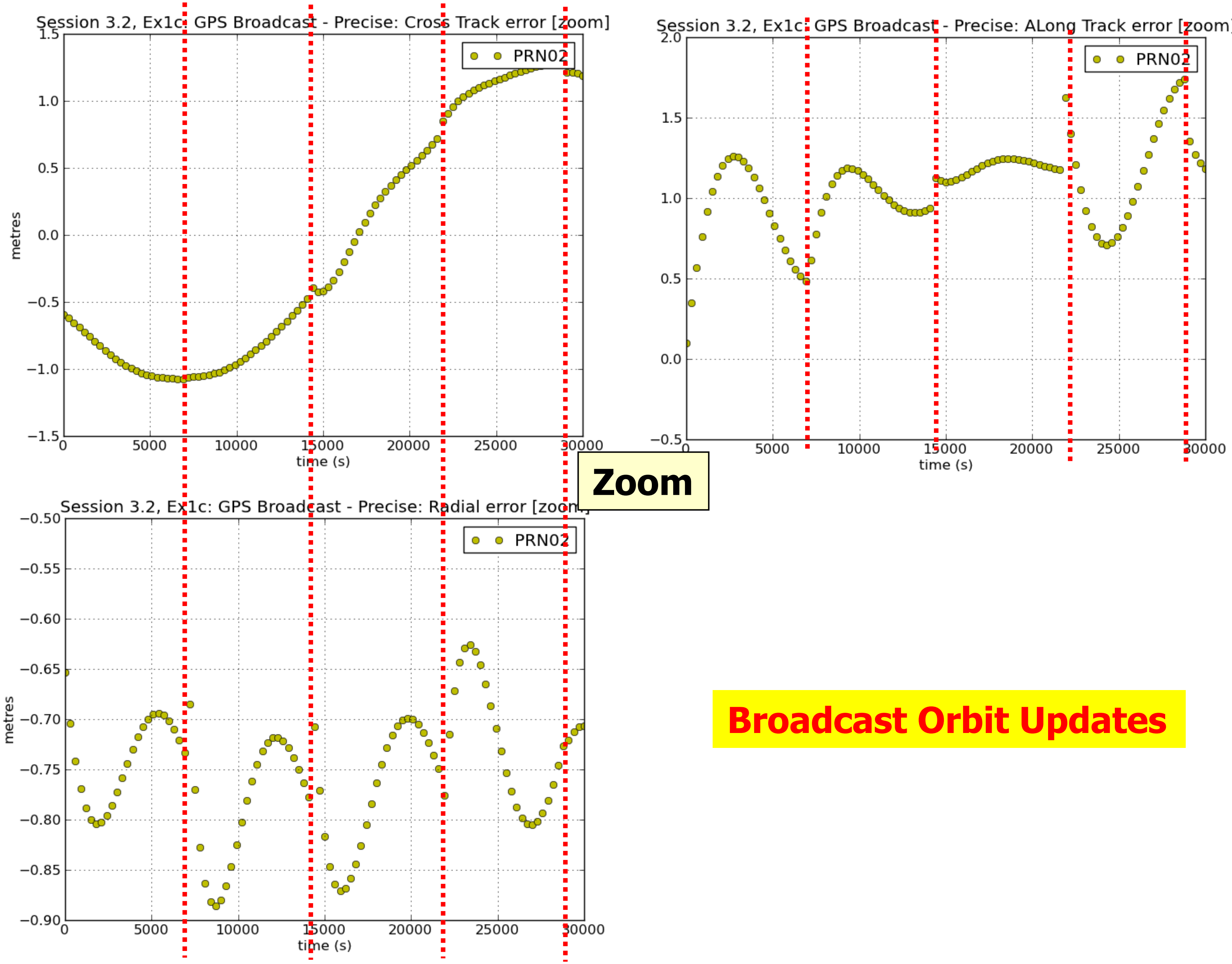








Antenna Phase Centre Correction has been applied



Broadcast Orbit Updates

Contents

3.2 Computation of satellite coordinates from precise products.

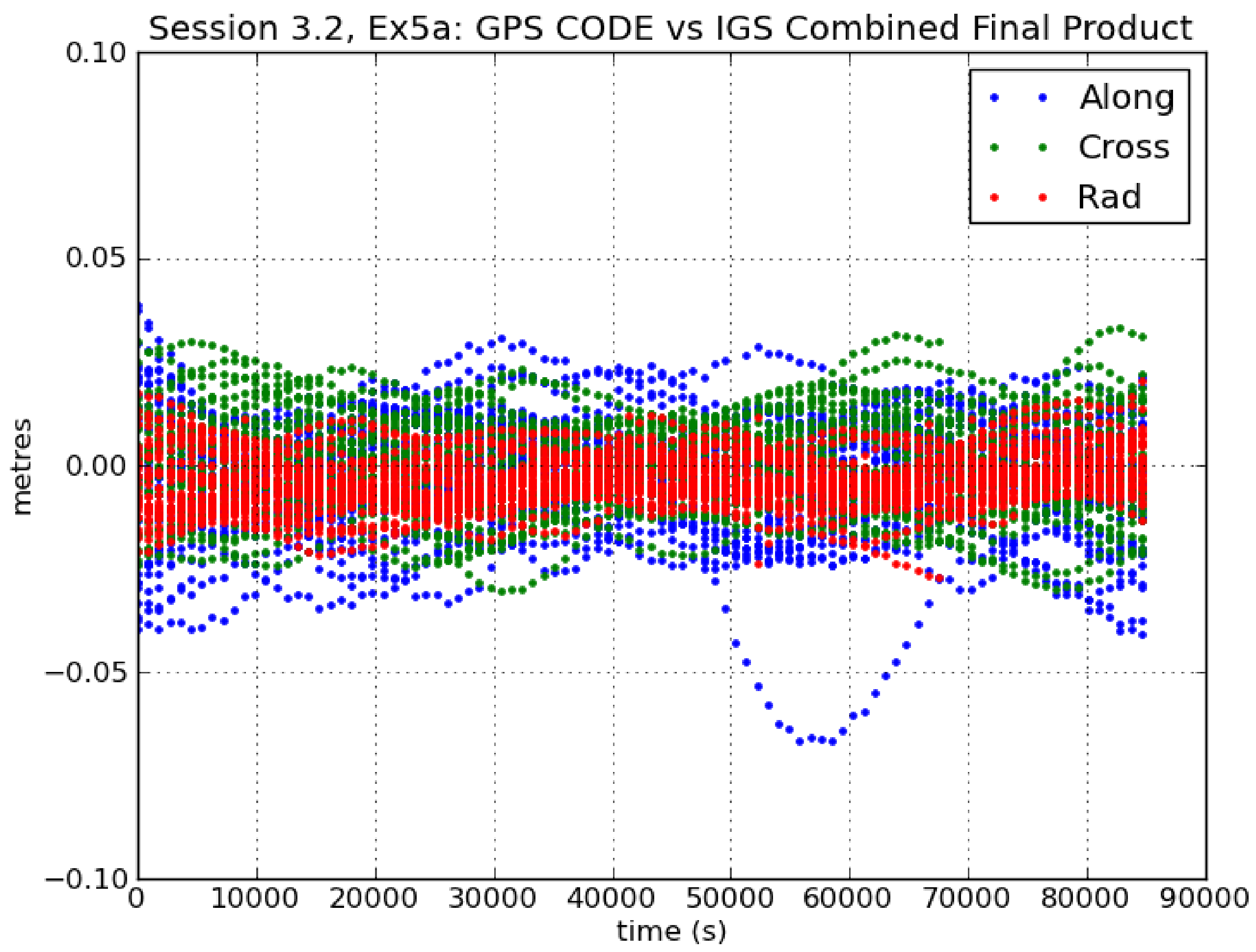
Precise orbits for GPS satellites can be found on the International GNSS Service (IGS) server **`http://igscb.jpl.nasa.gov`**

Orbits are given by (x,y,z) coordinates with a sampling rate of 15 minutes. The satellite coordinates between epochs can be computed by polynomial **interpolation**. A 10th-order polynomial is enough for a centimetre level of accuracy with 15 min data.

$$
\begin{aligned}
P_n(x) &= \sum_{i=1}^{n} y_i \frac{\prod_{j\neq i}(x-x_j)}{\prod_{j\neq i}(x_i-x_j)} \\
&= y_1 \frac{x-x_2}{x_1-x_2}\cdots\frac{x-x_n}{x_1-x_n}+\cdots \\
&\quad + y_i \frac{x-x_1}{x_i-x_1}\cdots\frac{x-x_{i-1}}{x_i-x_{i-1}}\frac{x-x_{i+1}}{x_i-x_{i+1}}\cdots\frac{x-x_n}{x_i-x_n}+\cdots \\
&\quad + y_n \frac{x-x_1}{x_n-x_1}\cdots\frac{x-x_{n-1}}{x_n-x_{n-1}}
\end{aligned}
$$

IGS orbit and clock products (for PPP):

Discrepancy between CODE and IGS combined product.



Contents

GPS Satellite Clock computation: Broadcast message

$$dt^{sat} = a_0 + a_1(t - t_0) + a_2(t - t_0)^2$$

t0 a0 a1 a2

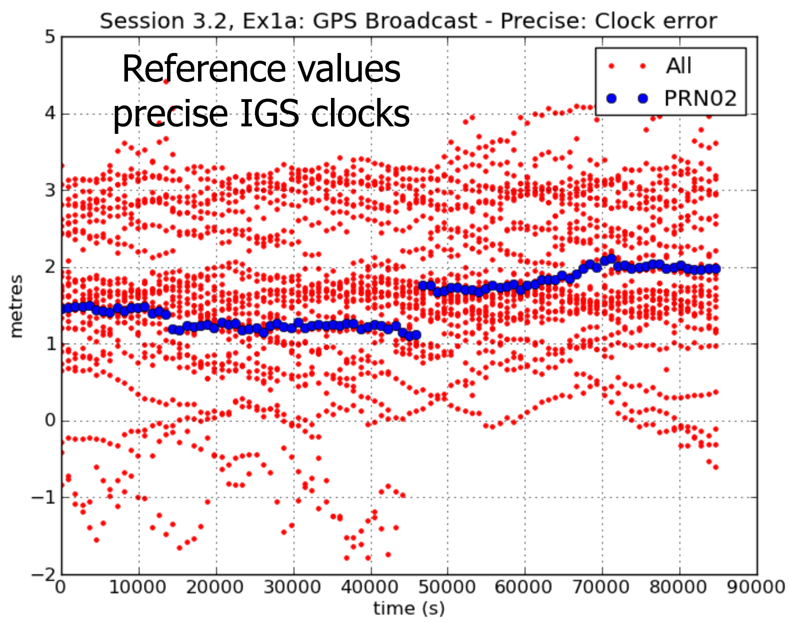
YY MM DD H M S

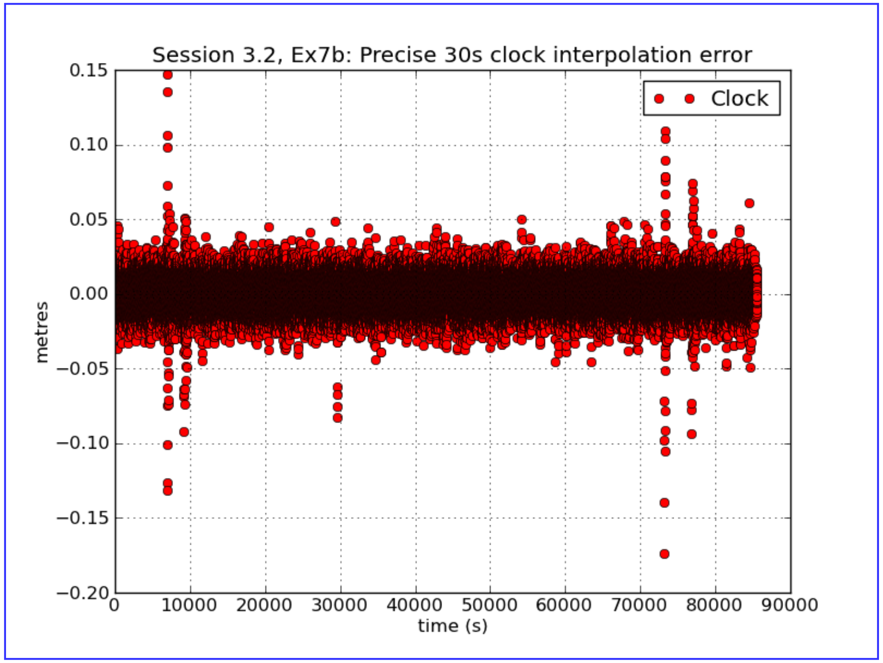
PRN

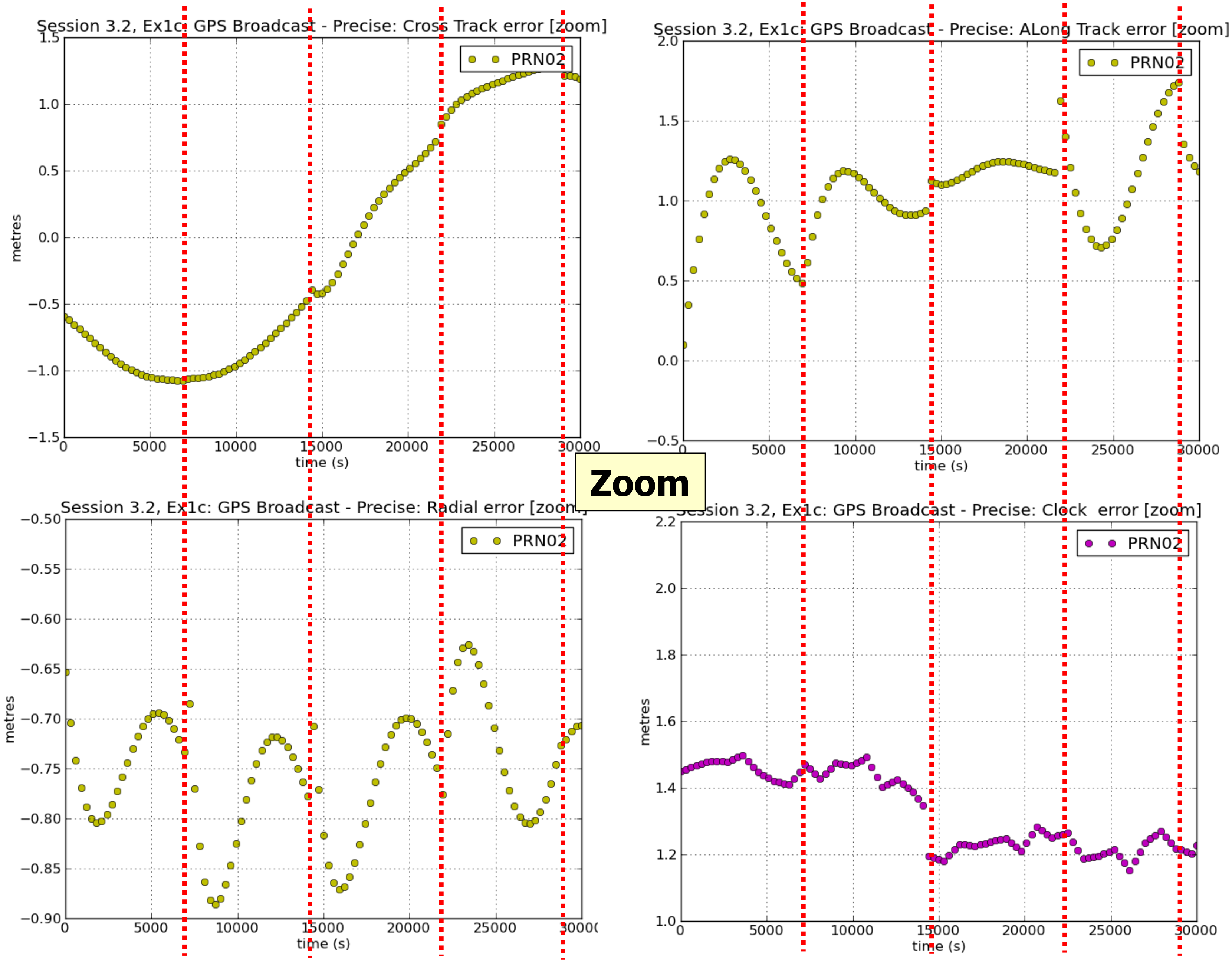
```
 2              NAVIGATION DATA     GPS                 RINEX VERSION / TYPE
srx/v1.8.1.4        BAI                 95/10/19 03:18:35   PGM / RUN BY / DATE
CASA                                                        COMMENT
 -2444431.2031 -4428688.6270  3875750.1442                  COMMENT
                                                            END OF HEADER
14 95 10 18 00 51 44.0 1.129414886236D-05 1.136868377216D-13 0.000000000000D+00
    1.730000000000D+02-5.175000000000D+01 4.375182243902D-09-5.836427291652D-01
   -2.712011337280D-06 2.427505562082D-03 8.568167686462D-06 5.153718931198D+03
    2.623040000000D+05 4.470348358154D-08 1.698435481558D+00 1.676380634308D-08
    9.636381916043D-01 2.153437500000D+02 3.056960010495D+00-8.030691653399D-09
   -5.178787145843D-11 1.000000000000D+00 8.230000000000D+02 0.000000000000D+00
    3.200000000000D+01 0.000000000000D+00 1.396983861923D-09 1.730000000000D+02
    2.592180000000D+05 0.000000000000D+00 0.000000000000D+00 0.000000000000D+00
```

GPS Satellite Clock computation: Broadcast message

SA=off







Broadcast Orbit & Clock Updates

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Contents

Computation of satellite clocks from precise products

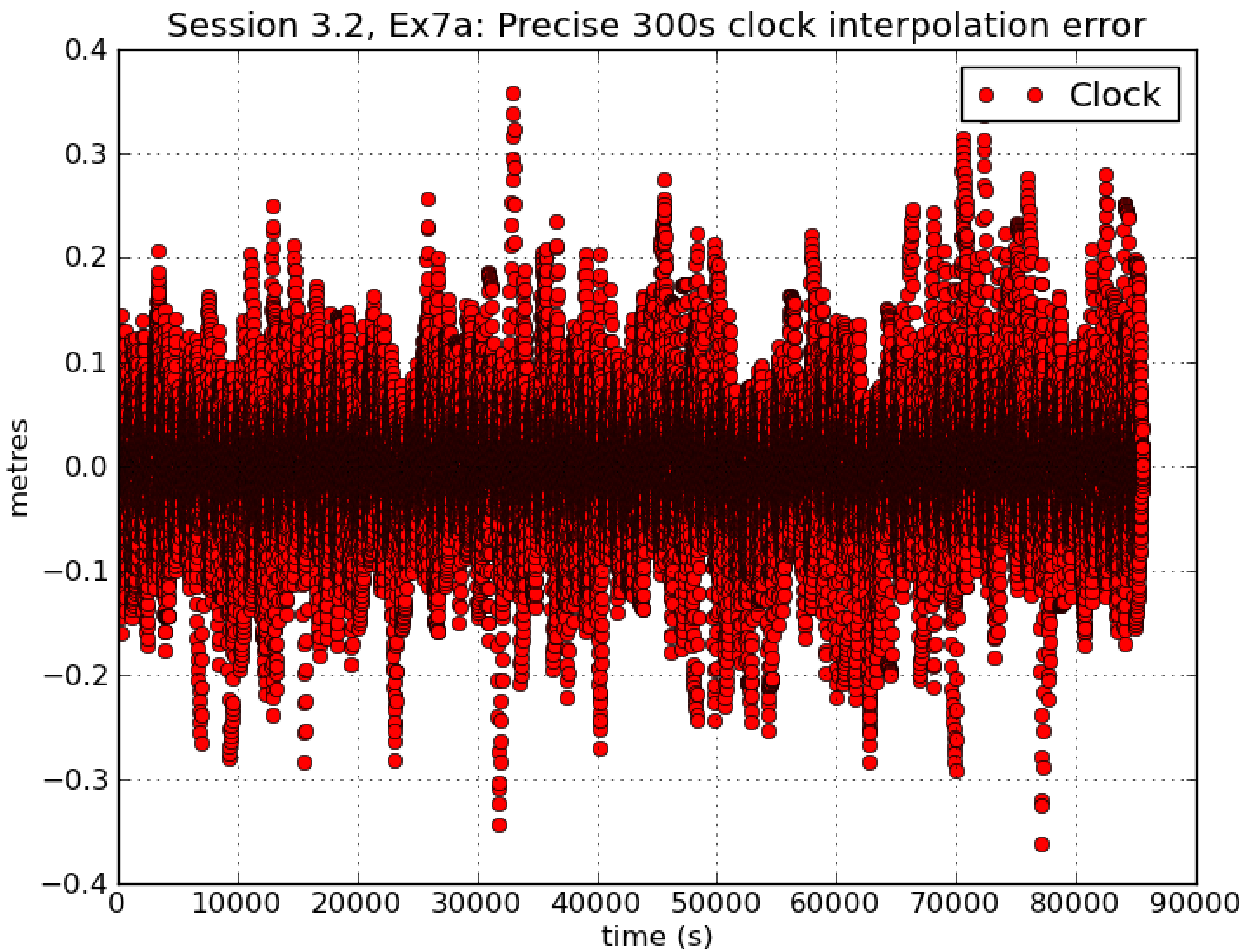
Precise clocks for GPS satellites can be found on the International GNSS Service (IGS) server **http://igscb.jpl.nasa.gov**

They are providing precise orbits and clock files with a sampling rate of 15 min (SP3 files), as well as precise clock files with a sample rate of 5 min and 30 s (CLK files).

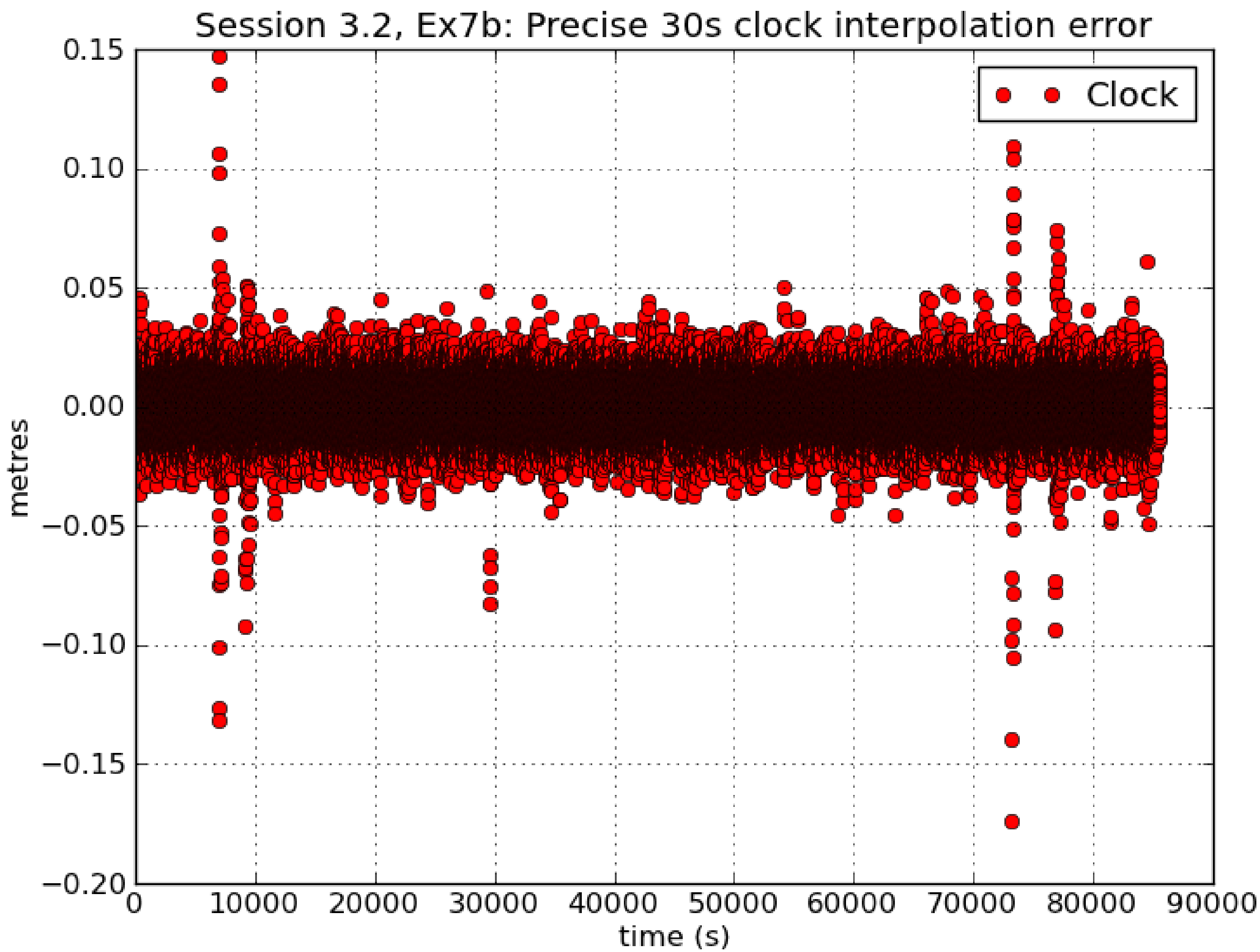
Some centres also provide GPS satellite clocks with a 5 s sampling rate, like the les obtained from the Crustal Dynamics Data Information System (CDDIS) site.

Stable clocks with a sampling rate of 30 s or higher can be interpolated with a first-order polynomial to a few centimetres of accuracy. Clocks with a lower sampling rate should not be interpolated, because clocks evolve as random walk processes.

Precise Clock Interpolation: 300s samples



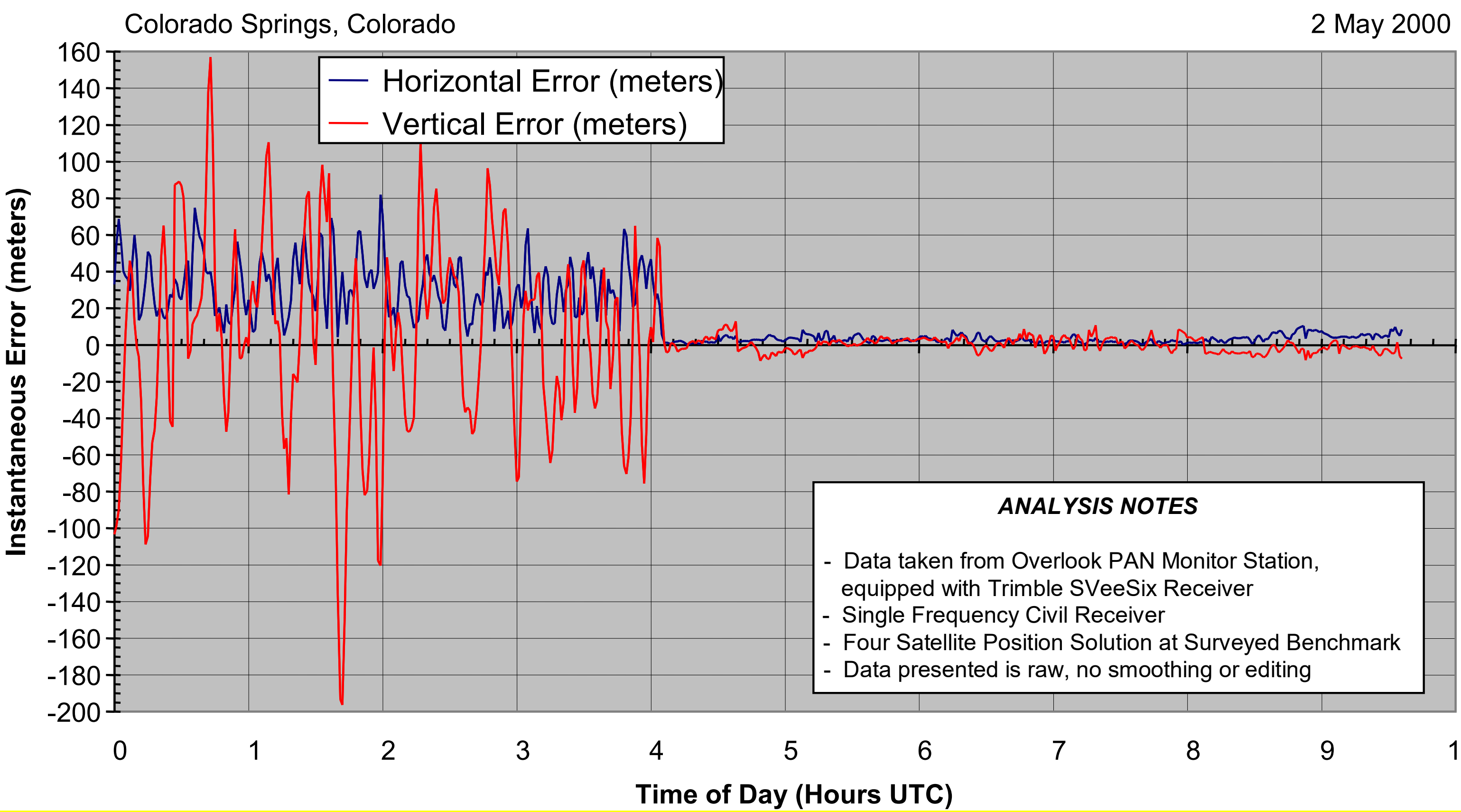
Precise Clock Interpolation: 30s samples



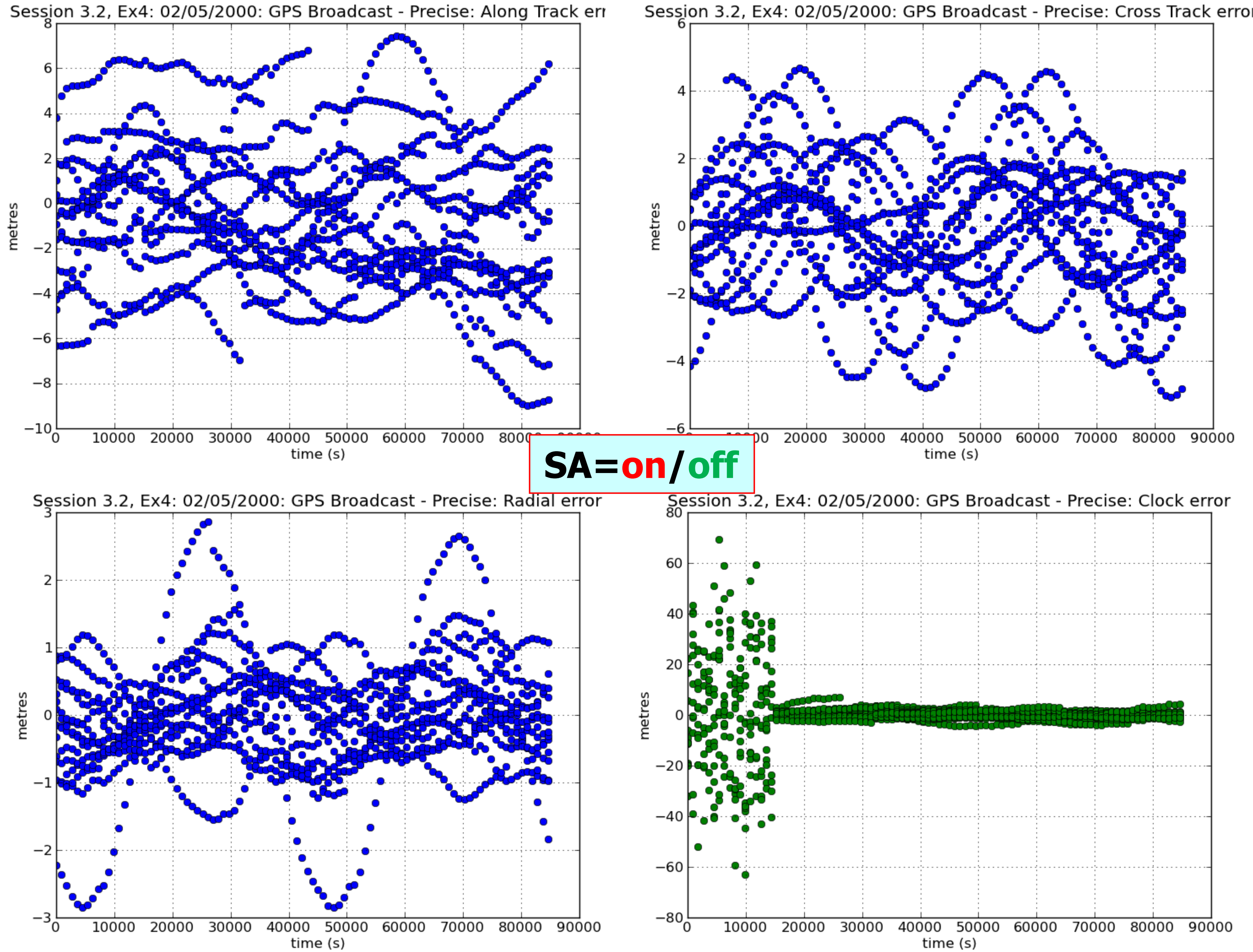
Contents

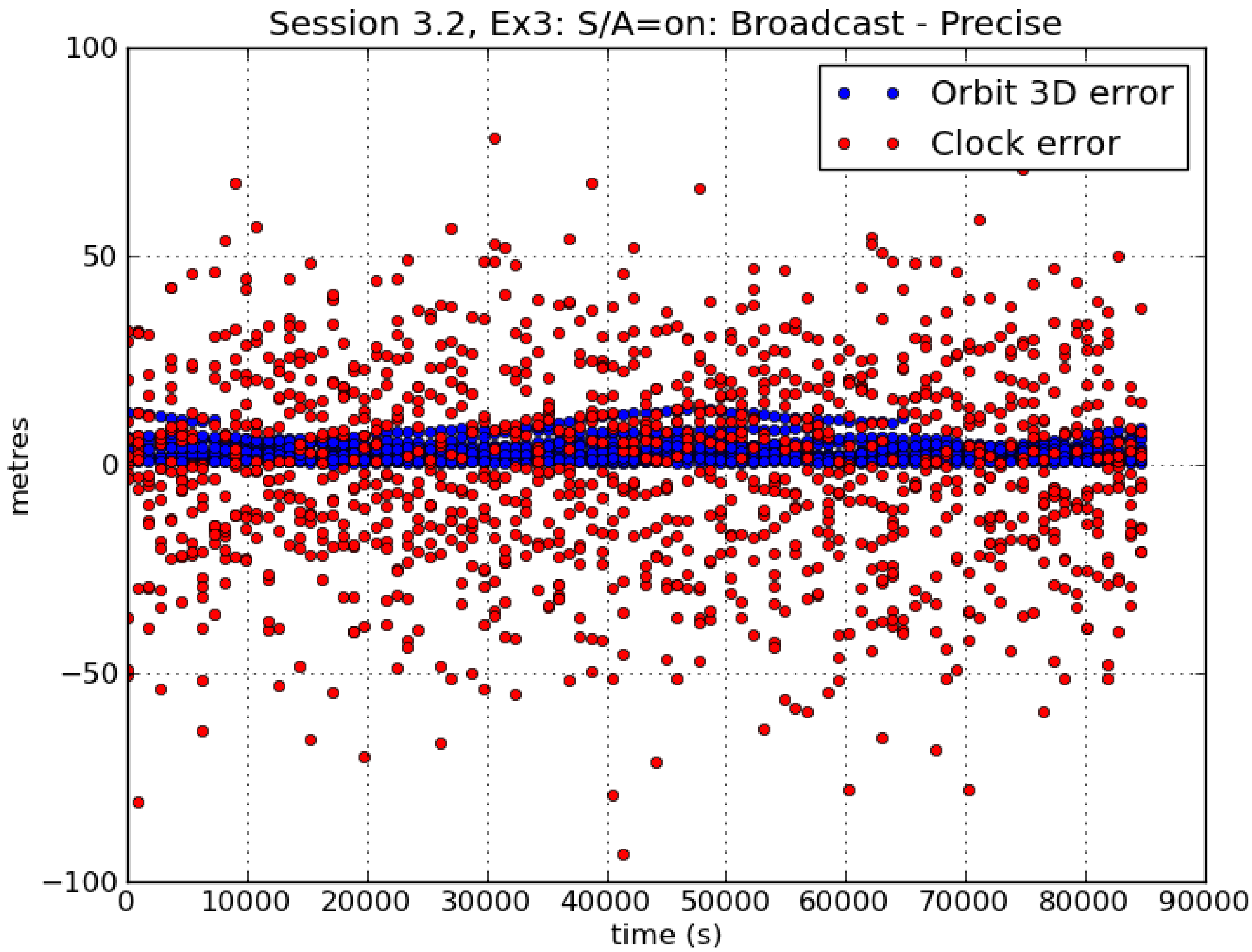
Selective Availability (S/A): Intentional degradation of satellite clocks and broadcast ephemeris from 25/03/1990 to 02/05/2000.

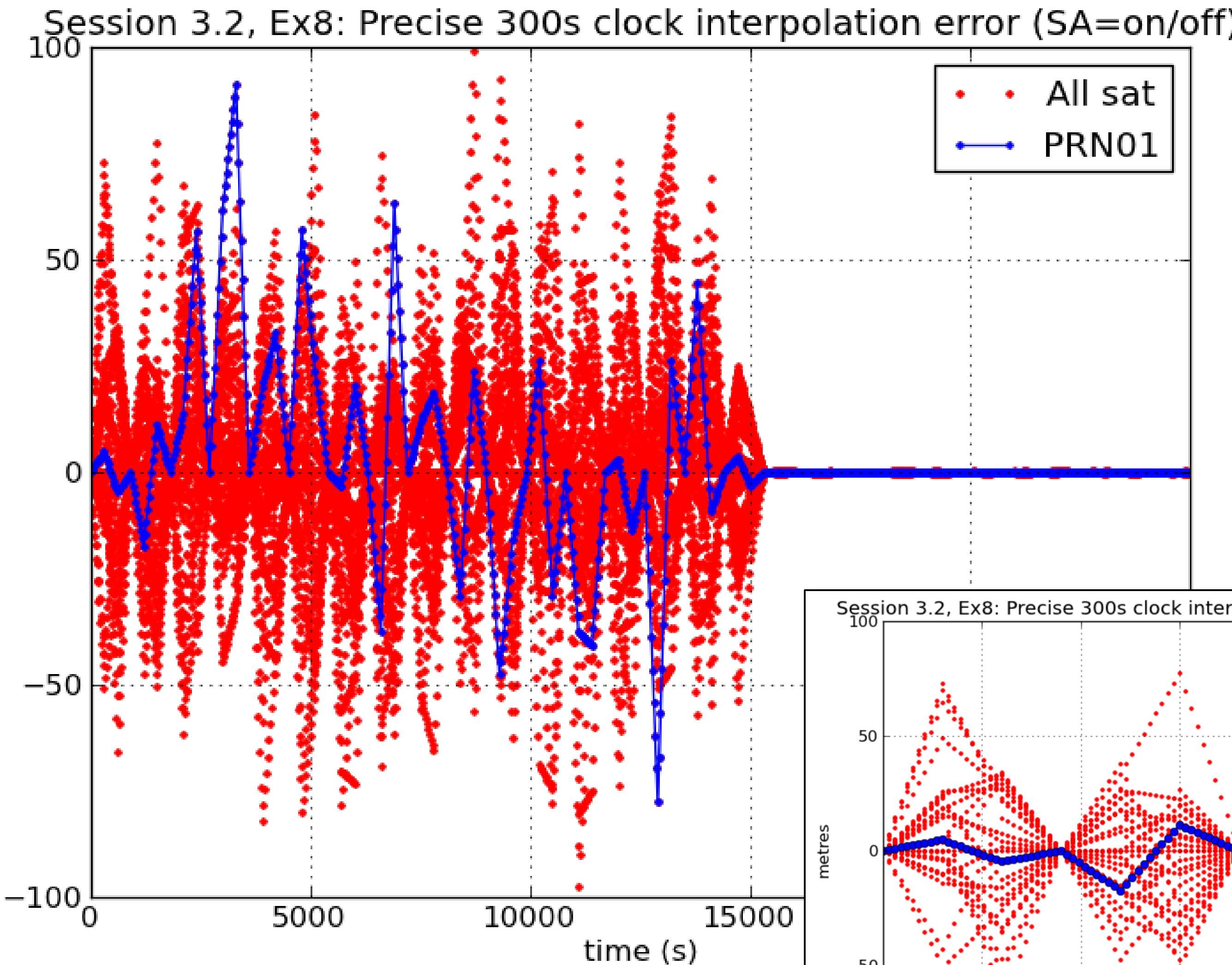
GPS Before and After S/A was switched off

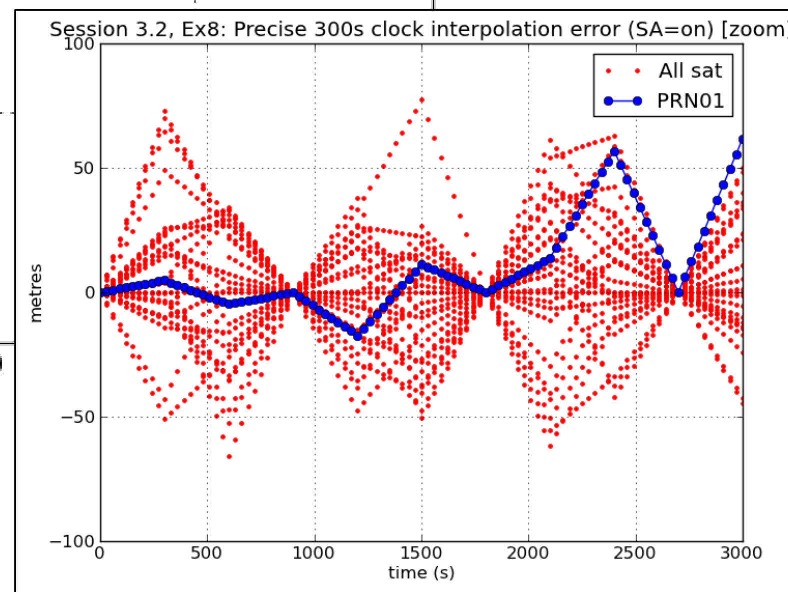


S/A was switched off at 2nd May 2000 and **permanently removed in 2008**


Session 3.2, Ex4: 02/05/2000: GPS Broadcast - Precise: Along Track err
Session 3.2, Ex4: 02/05/2000: GPS Broadcast - Precise: Cross Track error
Session 3.2, Ex4: 02/05/2000: GPS Broadcast - Precise: Radial error
Session 3.2, Ex4: 02/05/2000: GPS Broadcast - Precise: Clock error
metres
time (s)
SA=on/off


Session 3.2, Ex3: S/A=on: Broadcast - Precise
Orbit 3D error
Clock error
metres
time (s)
100
50
0
−50
−100
0
10000
20000
30000
40000
50000
60000
70000
80000
90000


Session 3.2, Ex8: Precise 300s clock interpolation error (SA=on/off)
All sat
PRN01
metres
time (s)
100
50
0
−50
−100
0
5000
10000
15000


Session 3.2, Ex8: Precise 300s clock interpolation error (SA=on) [zoom]
All sat
PRN01
metres
time (s)
100
50
0
−50
−100
0
500
1000
1500
2000
2500
3000

References

[RD-1] J. Sanz Subirana, J.M. Juan Zornoza, M. Hernández-Pajares, GNSS Data processing. Volume 1: Fundamentals and Algorithms. ESA TM-23/1. ESA Communications, 2013.

[RD-2] J. Sanz Subirana, J.M. Juan Zornoza, M. Hernández-Pajares, GNSS Data processing. Volume 2: Laboratory Exercises. ESA TM-23/2. ESA Communications, 2013.

[RD-3] Pratap Misra, Per Enge. Global Positioning System. Signals, Measurements, and Performance. Ganga –Jamuna Press, 2004.

[RD-4] B. Hofmann-Wellenhof et al. GPS, Theory and Practice. Springer-Verlag. Wien, New York, 1994.

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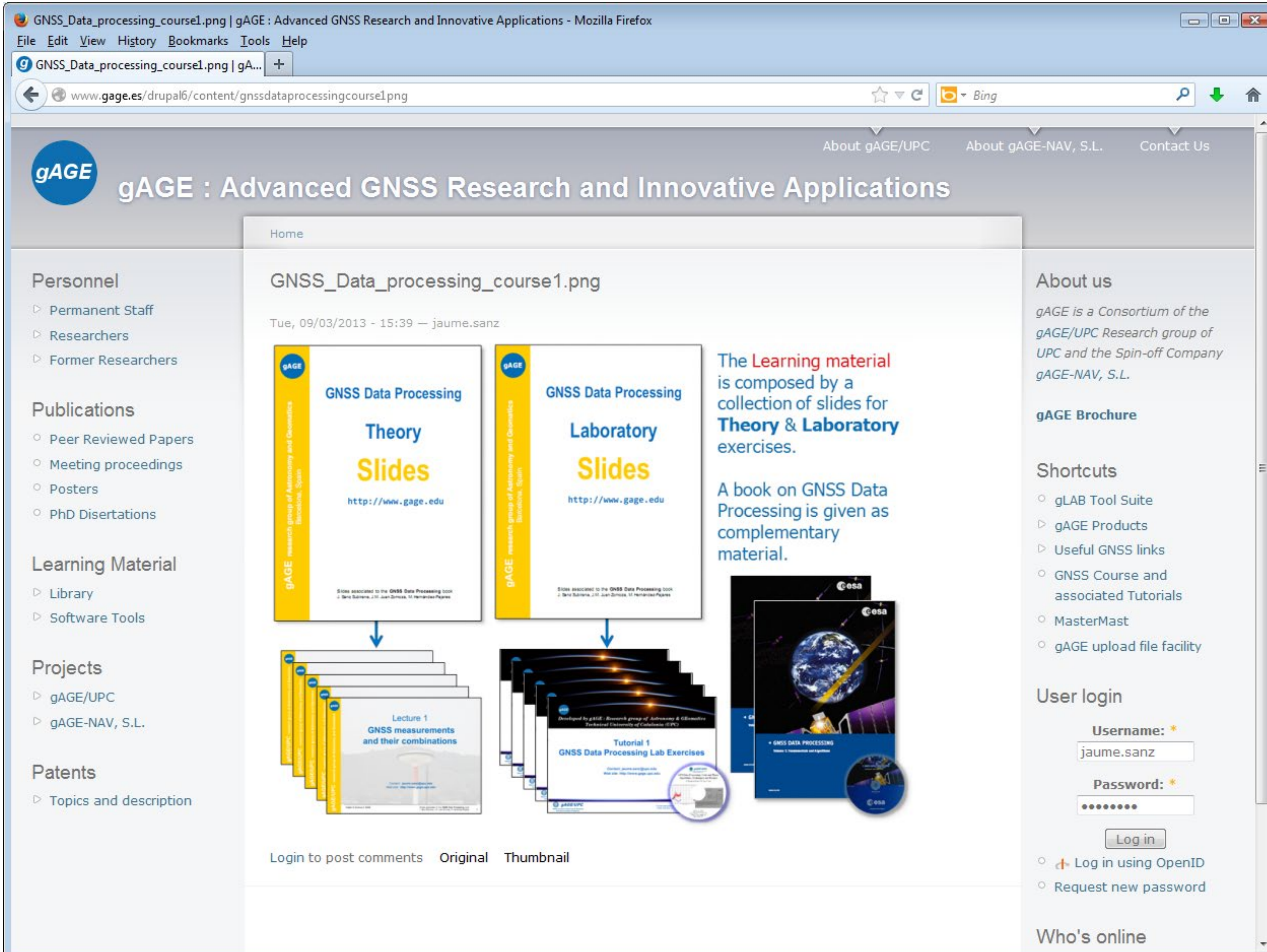
Thank you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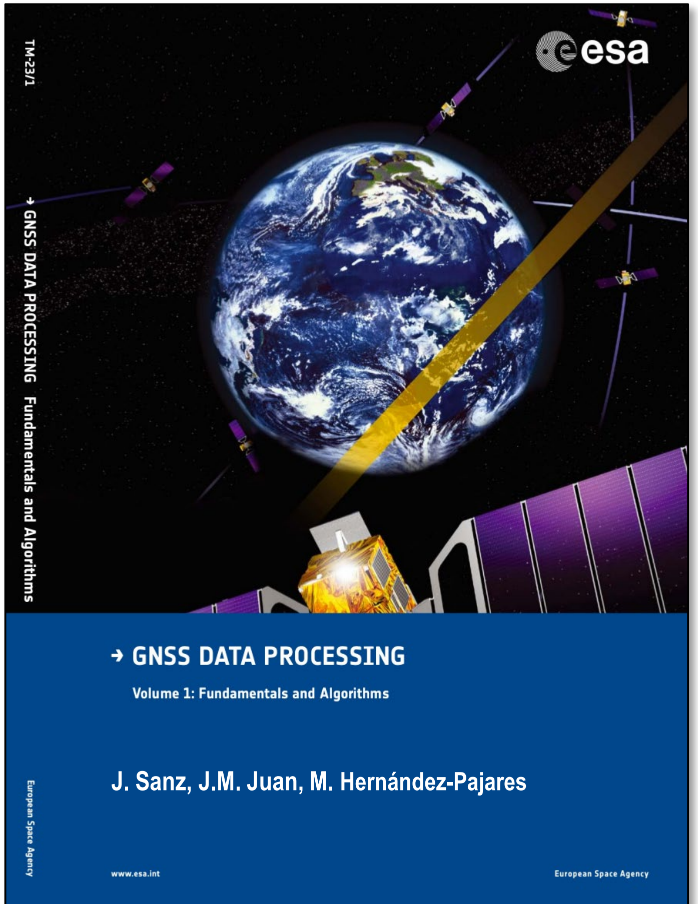

GNSS Data Processing, Vol. 1: Fundamentals and Algorithms.
GNSS Data Processing, Vol. 2: Laboratory exercises.