Preliminary reception of IMCCE Ephemeris

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07 December, 2006

GAIA-CA-TR-OCA-FM-031-2

Objectives

- Test and validate the test delivery of IMCEE ephemeris
- Applicable document : GAIA-CA-SP-OCA-FM-028-2 :
  - Specifications for the solar system ephemeris delivery
- check of the file structure : format, header content
- check of the implementation, reading and computation of the Chebyshev coefficients
- check of the time boundaries
- The goal is not to check the accuracy, but the understanding of the delivery and to see whether there are unaccounted systematic differences.
  - 3 mas orientation difference means ~ 2 km and 0.5 mm/s.
    - but with a well defined signature.

Method and limitations

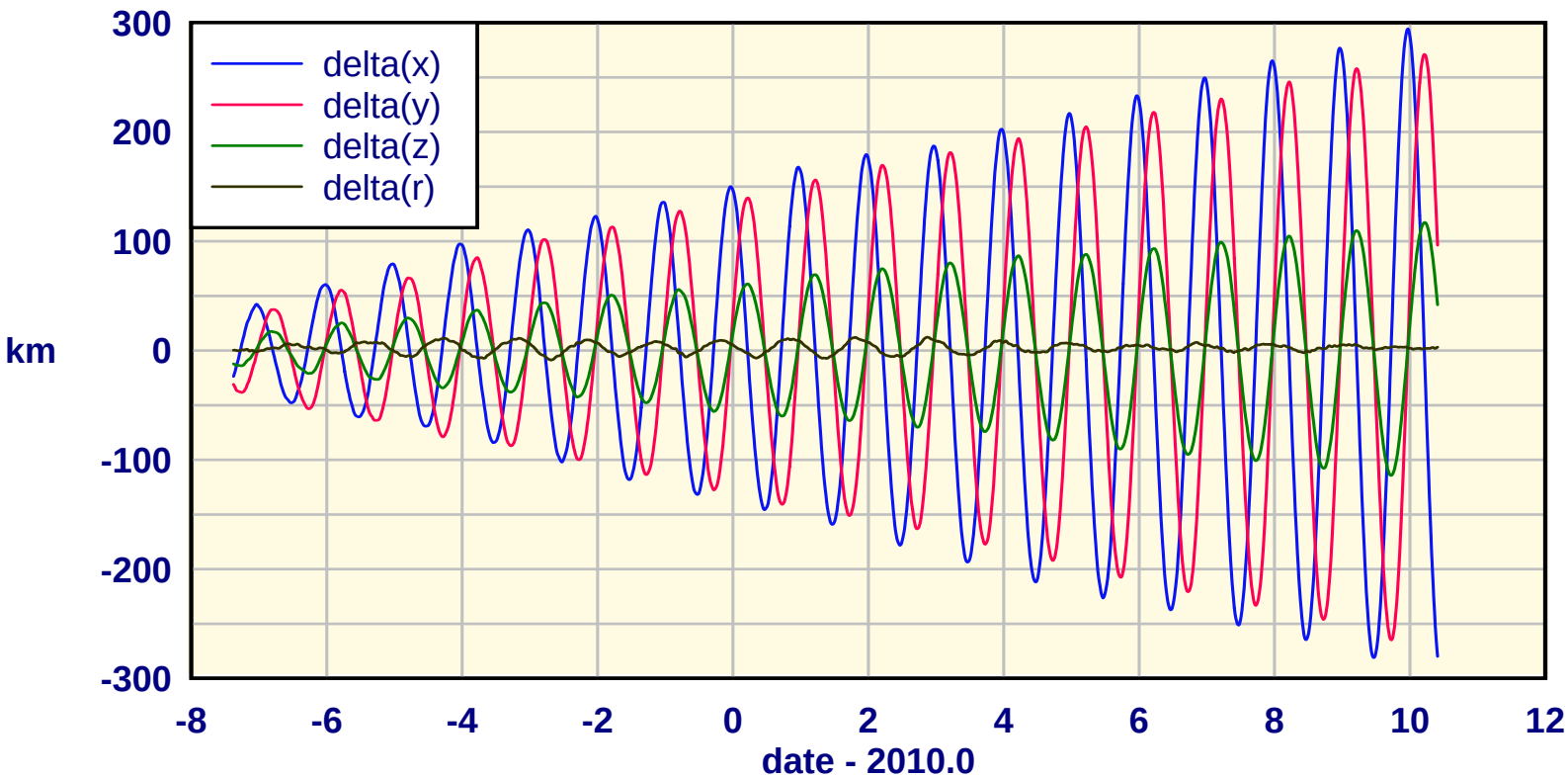
- Comparison of the position and velocity vectors to an independent source:
  - F. Mignard implementation of IPS2000 from :
    - Improvements of planetary theories over 6000 years. Chapront J.: 2000, Celes. Mech., 78, 75-82.
  - Computed in mean inertial ecliptic frame (DE405 equinox) and later referred to ICRS frame
    - ε = 23d 26'21".40909 ϕ = - 51.74 mas (Equinox DE405 to O405)
  - Timescale : TDB
  - Estimated external accuracy in the BCRS ~ 5 km and 1-2 mm/s
  - IMCCE external accuracy is far superior but:
    - This is not a problem to detect systematic differences even of smaller amplitudes
    - If one sees such systematic differences, it does not mean IMCEE is not correct, but just that we don't understand yet some assumptions.

General comments

- No problem at all with the input file format
  - header complies with the specs
  - general layout and number format are fine
  - starting and end dates agree with the specs
- Computation of position and velocity
  - units (m, m/s) are as expected
  - the computations have been straightforward and no problems were met
- Comparison in equatorial frame, rectangular coordinate
  - position and velocity vectors

Straight comparison : position I

- Sampling every 2 days over the full time interval of 6500 days
  - Sense INPOP – IPS2000
  - x, y, z and $r = (x^2 + y^2 + z^2)^{1/2}$
- Comment: systematic difference due to the use of TCB = t and TDB= τ
  - the plots suggest $t - \tau = 0$ in J2000



Straight comparison : position II

- Frequency analysis of the differences
  - $\Delta(x)$ (km) ~ [145.1 +14.59(t-2010.0)] cos($2\pi\nu t + \psi$) with ν = 1cy/yr
  - $\Delta(y)$ (km) ~ [133.5 +13.34(t-2010.0)] cos($2\pi\nu t + \psi'$)
  - $\Delta(z)$ (km) ~ [57.7 +5.76(t-2010.0)] cos($2\pi\nu t + \psi''$)

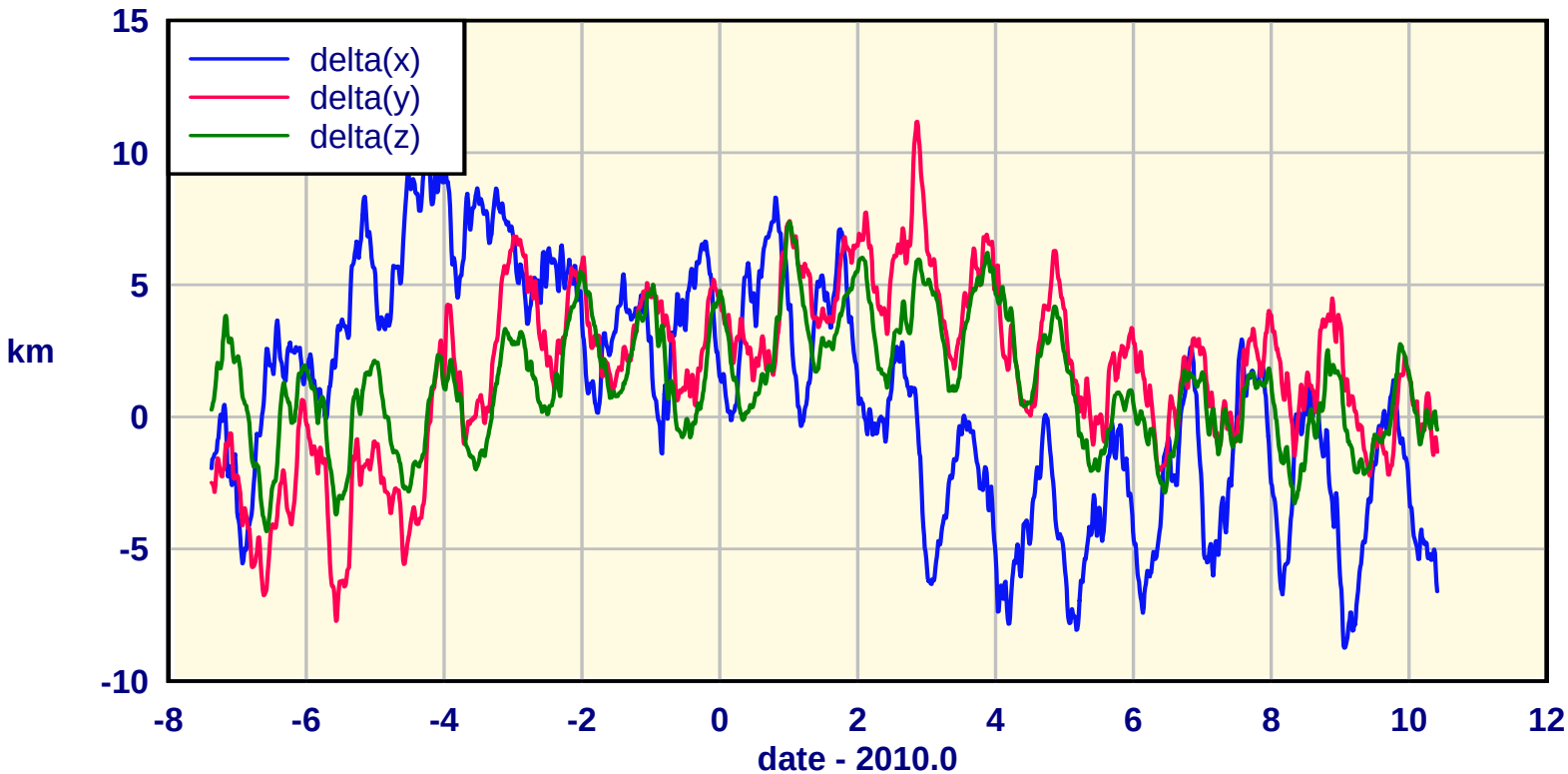
- This confirms that the amplitude is ~ 0 at t= J2000.

- With $\Delta(x)$ one also finds d(TCB - TDB)/dt ~ L_B = 1.5505..10^{-8}
  - the TCB vs. TDB as a source is strengthened

- In the following I have used $t - \tau = L_B$ (t-J2000)
  - IPS2000 called in TCB

Comparison with common timescale : position

- Sampling every 2 days over the full time interval of 6500 days
- $\tau = t - L_B (t\text{-}J2000)$ in the call of IPS2000
  - x, y, z
- Comment: much smaller residuals
  - the plots suggest a one year effect due to frame orientation



Search for a systematic rotation : position

- From the residuals one searches three angles (α, β, γ) for infinitesimal rotations about (x, y, z) axes.
- Least squares fit with the equations

$$\begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix} = \begin{bmatrix} 0 & \gamma & -\beta \\ -\gamma & 0 & \alpha \\ \beta & -\alpha & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

- solution for (α, β, γ) in mas.

$$\alpha \quad -1.4 \pm 0.16$$
$$\beta = \quad 0.7 \pm 0.16$$
$$\gamma \quad -0.6 \pm 0.13$$

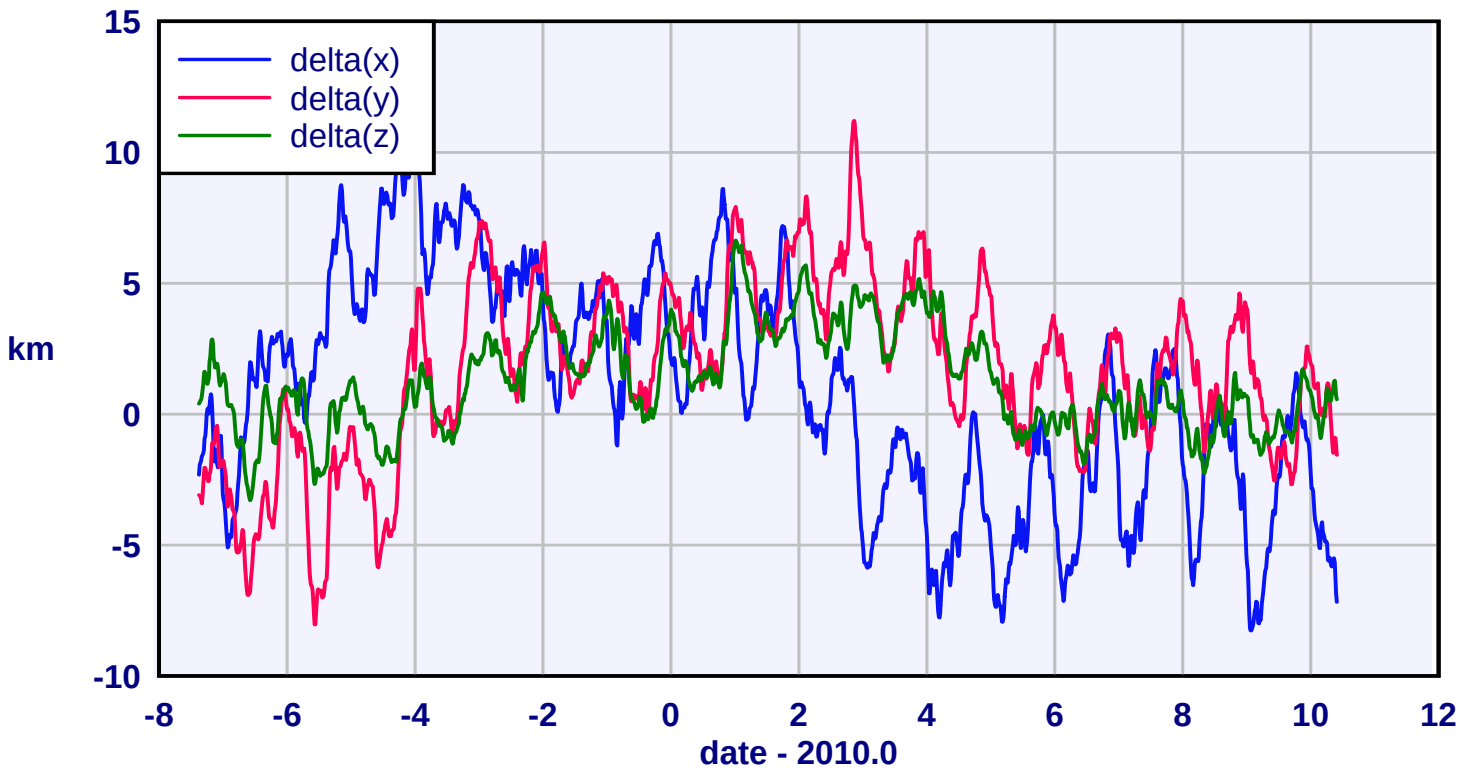
RMS residual : 3.5 km

Effect of the rotation ~ 1 km

Nothing serious and to be solved by comparing the constants used, like ε.

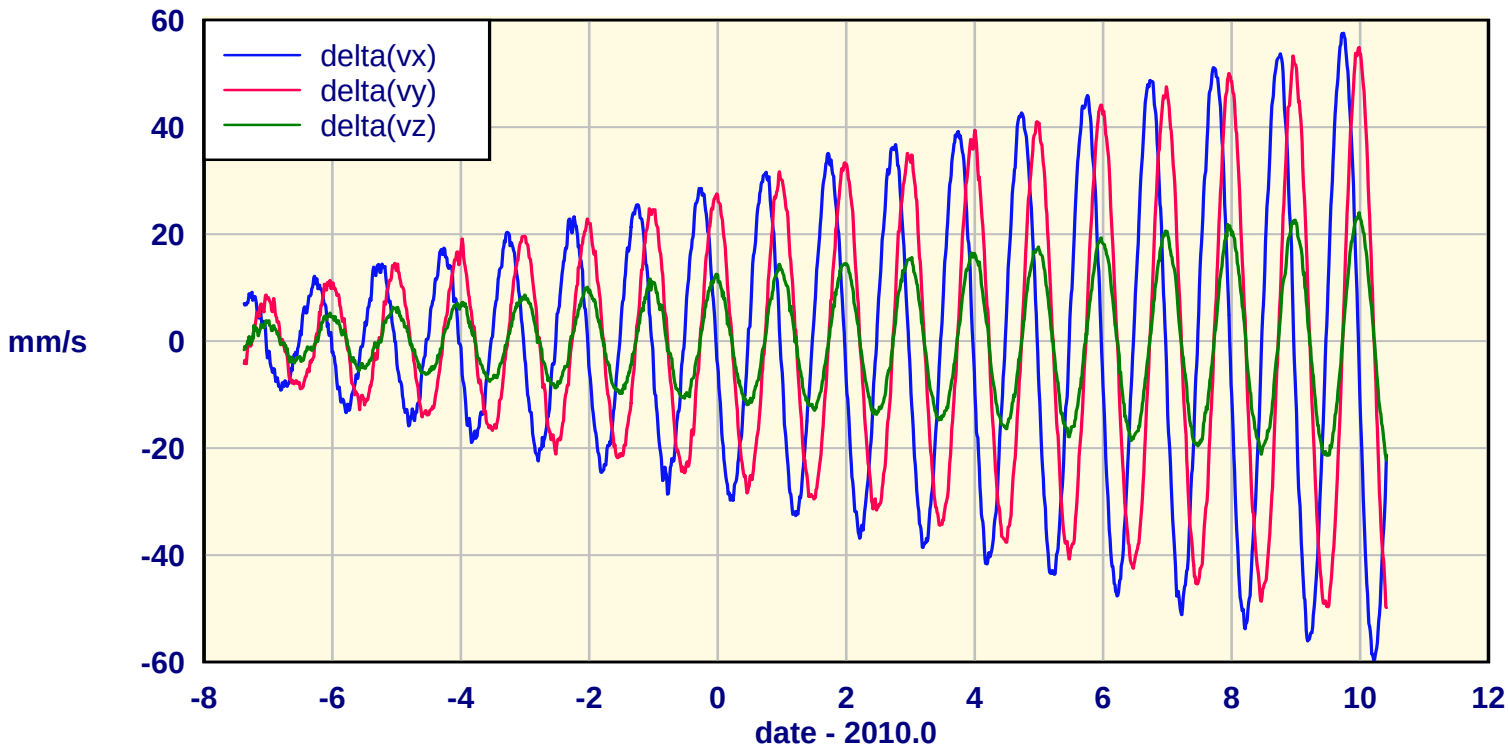
Residuals

- The rotation impact is much smaller than the signal (1 km vs. 10)
  - What remains is the difference between IPS2000 and INPOP
    - the difference is hardly visible with the plot p.7
  - it should be the improvement of INPOP compared to IPS2000
- No further useful test can be performed



Straight comparison : velocity I

- Sampling every 2 days over the full time interval of 6500 days
  - Sense INPOP – IPS2000
  - v_x, v_y, v_z
  - Comment: systematic difference due to the use of TCB = t and TDB= t
  - the plots suggest t - τ = 0 in J2000



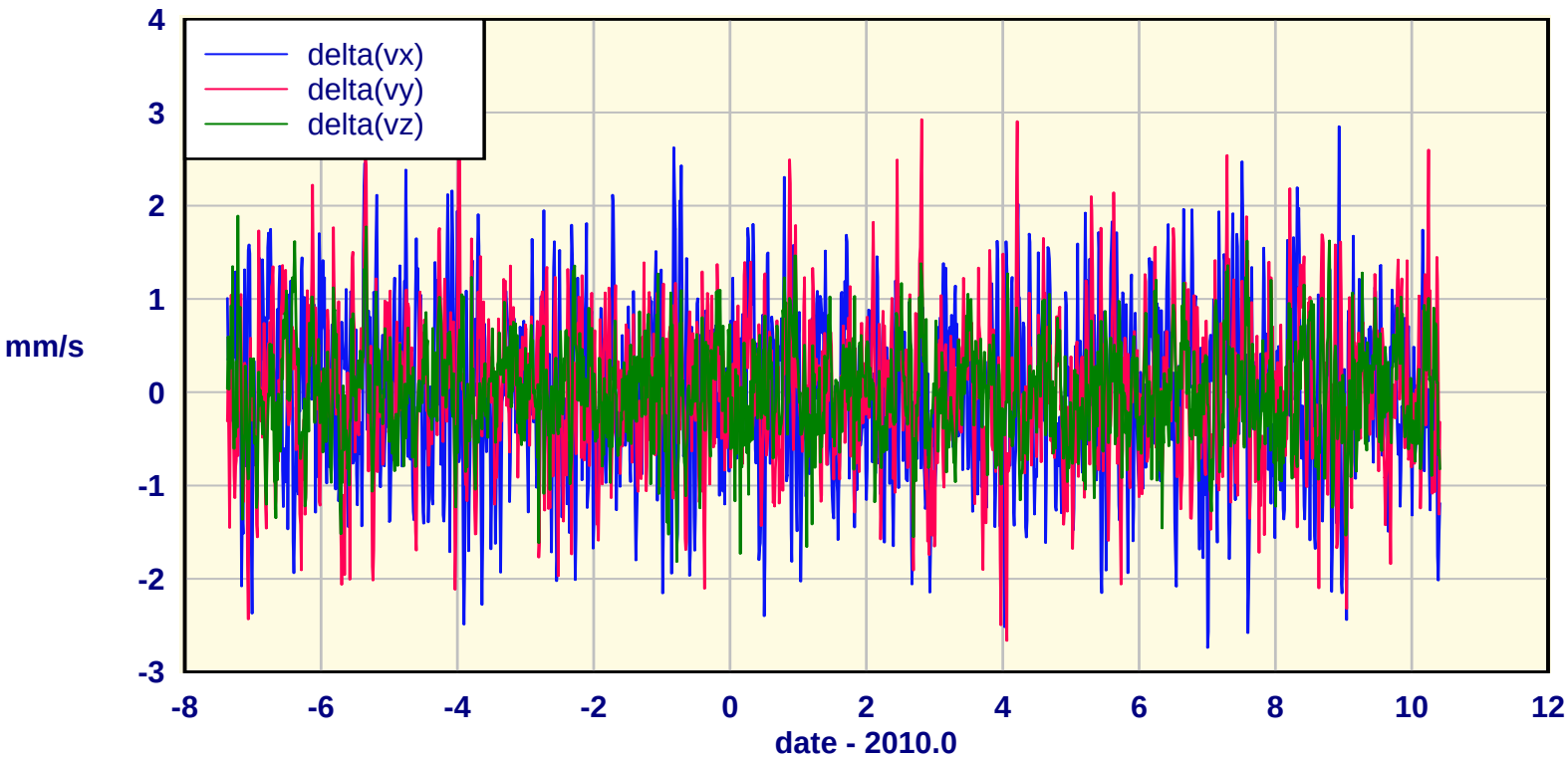
Straight comparison : velocity II

- Frequency analyis of the differences
  - $\Delta(v_x)$ (mm/s) ~ [28.91 +2.899(t-2010.0)] cos($2\pi\nu t + \psi$) with ν = 1cy/yr
  - $\Delta(v_y)$ (mm/s) ~ [26.57 +2.654(t-2010.0)] cos($2\pi\nu t + \psi'$)
  - $\Delta(v_z)$ (mm/s) ~ [11.48 +1.144(t-2010.0)] cos($2\pi\nu t + \psi''$)

- This confirms again that the amplitude is ~ 0 at t= J2000.

Comparison with common timescale : velocity

- Sampling every 2 days over the full time interval of 6500 days
- $\tau = t - L_B (t\text{-}J2000)$ in the call of IPS2000
  - v_x, v_y, v_z
- Comment: much smaller residuals ~ 1-2 mm/s
  - the plots suggest that most is noise or high-frequency terms



Search for a systematic rotation : velocity

- From the residuals one searches three angles (α, β, γ) for infinitesimal rotations about (x, y, z) axes.
- Least squares fit with the equations

$$\begin{bmatrix} \delta v_x \\ \delta v_y \\ \delta v_z \end{bmatrix} = \begin{bmatrix} 0 & \gamma & -\beta \\ -\gamma & 0 & \alpha \\ \beta & -\alpha & 0 \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix}$$

- solution for (α, β, γ) in mas.

$$\alpha \quad -1.35 \pm 0.16$$
$$\beta = \quad 0.55 \pm 0.16$$
$$\gamma \quad -0.45 \pm 0.13$$

RMS residual : 0.7 mm/s

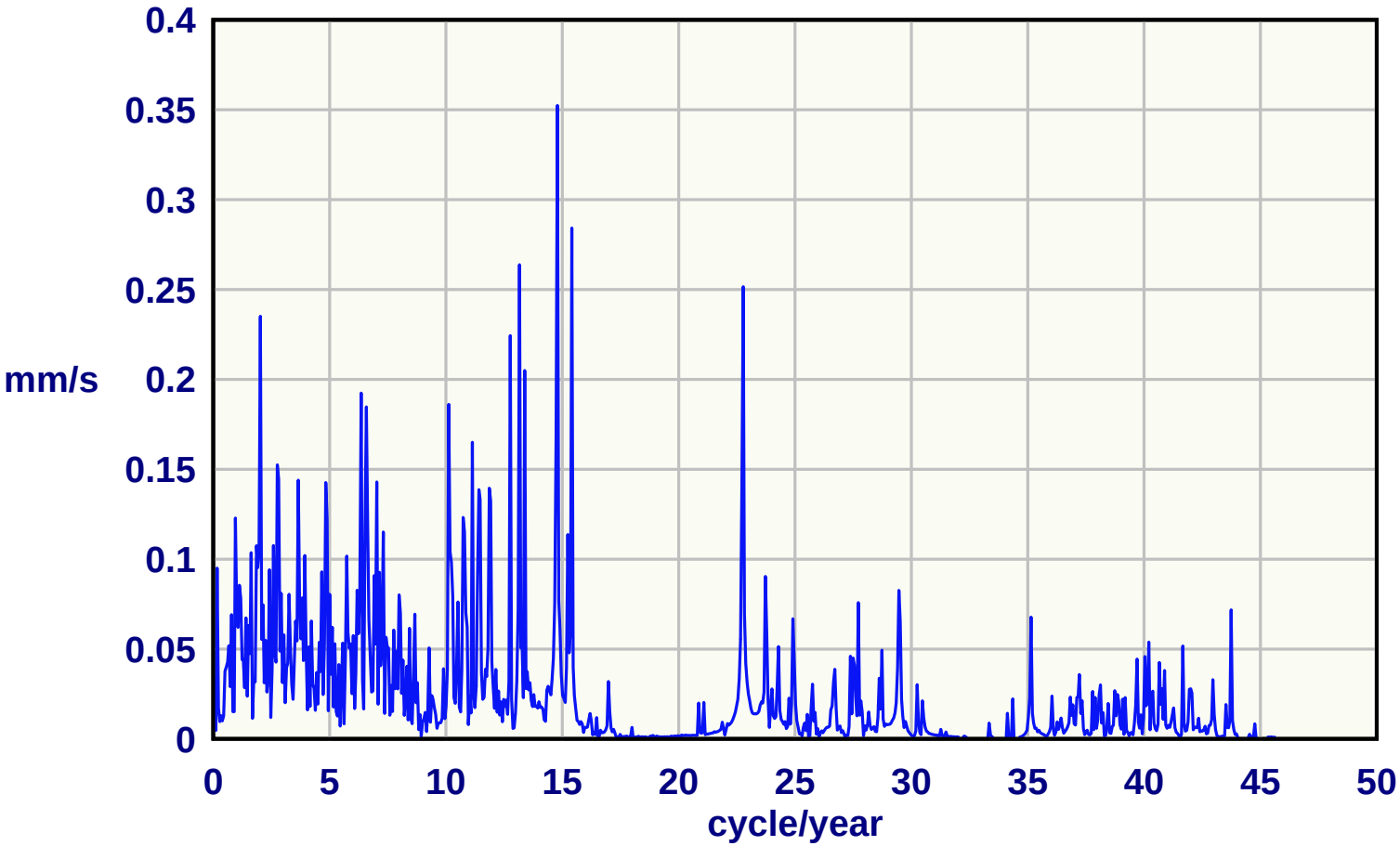
effect of the rotation ~ 0.2 mm/s

Excellent agreement with position➔ reference frame orientation.

Additional comments

- Positional differences between the two sources consists of low frequency terms (p. 7)
- Velocity differences contain many high-frequency lines (p. 12)
  - this is a good point for the validation of INPOP since :
    - IPS2000 is a positional analytical ephemeris derived from VSOP87
    - periodic terms are truncated in amplitude to give the final accuracy of ~ 3-5 km
    - velocity is obtained by analytical derivation of these terms. However small amplitude terms (then neglected) with small periods would contribute significantly to the velocity, because of the product by the frequency.
- this is visible in the Fourier transform (next page) of the plot on p.12
  - this feature is expected and goes in the right direction regarding the accuracy of INPOP
  - the largest lines are probably related to the Moon or to Mercury
    - e.g. : $4\lambda_1 - 2\lambda_3$, $5\lambda_1 + 2\lambda_3$

FFT of the residuals in velocity



Conclusion

- The comparison between IMCCE (INPOP) test delivery and an external source (IPS2000) is very satisfactory
- The external accuracy cannot be tested with the less accurate reference source
- The only large systematic effect is totally accounted for by the choice of the timescales
- The remaining reference frame rotation should be investigated by looking carefully at the constants used for the link between dynamical ecliptic and ICRS
  - in any case the problem is relatively minor
- The production for all the planets can be started
  - optimization of degree vs. base interval must be discussed with CU3