Gravitational effects from a series of IVS R&D VLBI-sessions with observations close to the Sun

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1. MOTIVATION

In 2011 + 2012 the IVS observed twelve VLBI research and development (R&D) sessions that include successful observations as angularly close as 3.9° from the heliocenter. The purpose of these IVS-R&D sessions was to demonstrate improvement of the determination of the PPN parameter γ (among other parameters). Besides, when analyzing this specific set of IVS sessions, it was for the first time possible to measure the dispersive effect of the Solar corona (Soja et al., 2014).
In our work we assess the formal error of the γ-parameter and investigate the size of the gravitational delays caused by:

- Solar monopole field at rest and with approx. linear translation
- Rotating solar monopole field
- Solar gravitational field dipole expansion
- Solar higher order term

2. APPROACH

1) We investigate and compare the gravitational delay models of

- „Conv“: IERS Conventions (2010), the *Consensus model* (Eubanks, 1991) with small changes
- „VieVS“: VieVS software (Böhm et al., 2012)
- „Klio“: Klioner (1991), Klioner & Kopejkin (1992)

2) We estimate the γ-parameter with and without the inclusion of observations with Solar elongation < 15° and compare the formal errors.

- Software: VieVS with adaptations (GFZ internal version)
- Twelve IVS-R&D sessions (Tab. 1)

Session	Date	Minimum elongation	No. of observations within 15°	Total no. of observations
RD1106	29 Nov 2011	3.9°	33	3,695
RD1107	06 Dec 2011	4.0°	59	4,242
RD1201	24 Jan 2012	4.8°	31	3,482
RD1202	03 Apr 2012	5.8°	39	2,776
RD1203	30 May 2012	10.5°	52	2,099
RD1204	19 Jun 2012	4.4°	32	828
RD1205	10 Jul 2012	6.1°	186	2,953
RD1206	28 Aug 2012	3.9°	193	1,558
RD1207	25 Sep 2012	6.1°	120	1,727
RD1208	02 Oct 2012	3.9°	103	1,918
RD1209	27 Nov 2012	4.2°	57	2,731
RD1210	11 Dec 2012	4.7°	80	3,540

The IVS R&D sessions in 2011 and 2012, which include observations close to the Sun starting at either 17:30 or 18:00 UT on the day given in the second column and lasting 24 h. For each VLBI session, the minimum Sun elongation and the number of successful observations in total as well as closer than 15° are shown.

Table 1. VLBI sessions used in this study (see Soja et al., 2014)

3. GRAVITATIONAL DELAY MODELS

Modell 1: „Conv“:
the current conventional gravitational delay model

$$\tau_{grav} = \tau_{pN} + \tau_{ppN}$$

$$\tau_{pN} = \sum_A 2\frac{GM_A}{c^3}\cdot ln\left(\frac{|\overrightarrow{R_{1A}}| + \vec{K}\cdot\overrightarrow{R_{1A}}}{|\overrightarrow{R_{2A}}| + \vec{K}\cdot\overrightarrow{R_{2A}}}\right) \qquad t_{\min A} = \min\left[t_1, t_1 - \frac{\vec{K}\cdot\left(\overrightarrow{R_A}(t_1) - \overrightarrow{R_1}(t_1)\right)}{c}\right]$$

$$\tau_{ppN} = 4\frac{(GM_A)^2}{c^5}\frac{\vec{b}\cdot(\hat{R}_{1A} + \vec{K})}{\left(|\vec{R}|_{1A} + \vec{R}_{1A}\cdot\vec{K}\right)^2}$$

- It is not specified, how the position of the gravitating body is to be evaluated
- The higher order term (τ_{ppN}) is to be applied in case of an “angle very close to the Sun” → what angle is it exactly?

Modell 2: „VieVS“:
the gravitational delay model used in VieVS

$$\tau_{grav} = \tau_{pN}$$

$$\tau_{pN} = \sum_A 2\frac{GM_A}{c^3}\cdot ln\left(\frac{|\overrightarrow{R_{1A}}| + \vec{K}\cdot\overrightarrow{R_{1A}}}{|\overrightarrow{R_{2A}}| + \vec{K}\cdot\overrightarrow{R_{2A}}}\right) \qquad t_{\min A} = t_1 - \frac{|\overrightarrow{R_A} - \overrightarrow{R_1}|}{c}$$

- The calculation of the time of closest approach is wrong:
  - the signal propagates in the direction of the radio source, not from the center of the gravitating body to the receiver
  - The case that the gravitating body is situated „behind the baseline“ is not considered ($t_{\min A} = t_1$)
- No higher order term is applied

Modell 3: „Klio“:
the gravitational delay model of Klioner

$$\tau_{grav} = \tau_{pN} + \tau_M + \tau_Q + \tau_R + \tau_{ppN}$$

$$\tau_{pN} = \sum_A 2\frac{GM_A}{c^3}\cdot ln\left(\frac{|\overrightarrow{R_{1A}}| + \vec{K}\cdot\overrightarrow{R_{1A}}}{|\overrightarrow{R_{2A}}| + \vec{K}\cdot\overrightarrow{R_{2A}}}\right) \qquad t_{\min A} = \min\left[t_1, t_1 - \frac{\vec{K}\cdot\left(\overrightarrow{R_A}(t_1) - \overrightarrow{R_1}(t_1)\right)}{c} - \frac{2\vec{K}\cdot\left(\overrightarrow{R_A}(t_1) - \overrightarrow{R_1}(t_1)\right)\left(\vec{K}\cdot\overrightarrow{v_A}\right) - \overrightarrow{v_A}\cdot\left(\overrightarrow{R_A}(t_1) - \overrightarrow{R_1}(t_1)\right)}{c^2}\right]$$

$$\tau_M = \sum_A 2\frac{GM_A}{c^3}\cdot ln\left(\frac{|\overrightarrow{R_{1A}}| + \vec{K}\cdot\overrightarrow{R_{1A}}}{|\overrightarrow{R_{2A}}| + \vec{K}\cdot\overrightarrow{R_{2A}}}\right)\left(\frac{1}{c}\vec{K}\cdot\overrightarrow{v_a}(t_{\min A})\right)$$

$$\tau_Q = \sum_A 2\frac{GM_A}{c^3}J_2^A\left(1 - P_A^2(P_A + b)^{-2}\right)$$

$$\tau_R = \sum_A 2\frac{G}{c^4}\vec{K}\times\overrightarrow{S_A}\cdot\left(\frac{\hat{R}_{2A}}{|\overrightarrow{R_{2A}}| + \vec{K}\cdot\overrightarrow{R_{2A}}} - \frac{\hat{R}_{1A}}{|\overrightarrow{R_{1A}}| + \vec{K}\cdot\overrightarrow{R_{1A}}}\right)$$

$$\tau_{ppN} = \sum_A 4\frac{(GM_A)^2}{c^5}\left\{-\frac{1}{|\overrightarrow{R_{2A}}| + \vec{K}\cdot\overrightarrow{R_{2A}}} + \frac{1}{|\overrightarrow{R_{1A}}| + \vec{K}\cdot\overrightarrow{R_{1A}}} + \frac{\vec{K}\cdot\hat{R}_{2A}}{16|\overrightarrow{R_{2A}}|} - \frac{\vec{K}\cdot\hat{R}_{1A}}{16|\overrightarrow{R_{1A}}|} + \right.$$
$$\left. + \frac{15}{16|\vec{K}\times\overrightarrow{R_{2A}}|}\arccos\vec{K}\cdot\hat{R}_{2A} - \frac{15}{16|\vec{K}\times\overrightarrow{R_{1A}}|}\arccos\vec{K}\cdot\hat{R}_{1A}\right\}$$

4. GRAVITATIONAL DELAYS AND DIFFERENCES FROM IVS-R&D SESSIONS

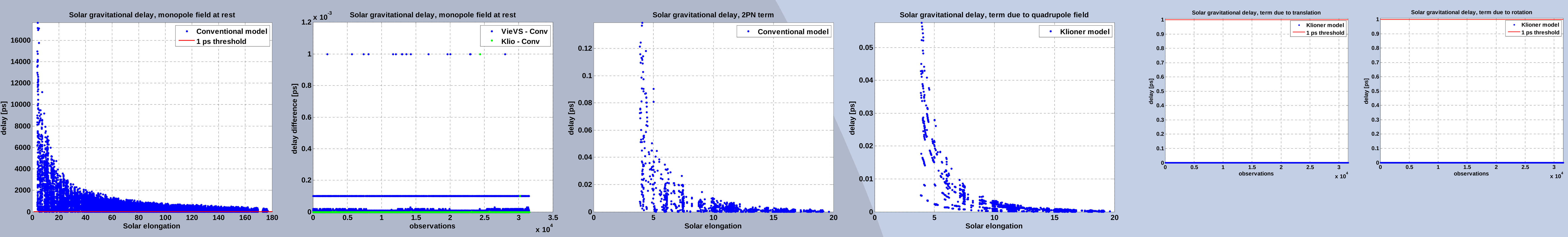

Figure 1 (left to right): Gravitational delay due to the Solar monopole field at rest, difference between the tested models, higher order term, term due to quadrupole expansion, translational and rotational terms

- If 1 ps precision is required for the gravitational delay model it is sufficient to consider the mass monopole field at rest with one of the three discussed models for the analysis of the twelve IVS-R&D sessions

5. ESTIMATION OF SOLAR PARAMETERS

We have developed capability in VieVS to estimate:

- Solar second zonal harmonic coefficient $J_2^{\odot}$
- Solar angular momentum $S_{\odot}$

However, with the currently available small number of observations angularly close to Sun it was not possible to estimate those parameters without large error bars. In our global VLBI solution we found in addition significant correlations among different groups of global parameters, e.g. station positions and Solar parameters. The minimal Solar elongation angle in the twelve IVS-R&D sessions analyzed here is about 3.9°. The observations scheduled closer to Sun could not be successfully correlated. It would be very beneficial to have even closer observations but with the current system this seems to be not feasible. It is likely that the correlations decrease when more sessions are included in the analysis.

6. FORMAL ERROR OF THE γ-PARAMETER

We have estimated the PPN parameter γ from the twelve IVS-R&D sessions following two approaches:

- Including the observations < 15° Solar elongation
- Excluding the observations < 15° Solar elongation

The number of observations with a Solar elongation angle < 15° is rather small (see Tab. 1), but the effect on the formal error of the γ-parameter is very significant (Tab. 2).

Correlations between the global station positions and the parameter γ are significant as well, see Tab. 2. It is likely that there are correlations with other global parameters as well.

formal error incl. obs. close to Sun	formal error excl. obs. close to Sun
0.000756	0.001338
0.001360*	0.002390*

*Table 2. The formal errors of the PPN parameter γ are about half the size when including a few observations close to Sun. The formal errors with the * denote the case when global station positions are fixed on the catalogue values*

7. ESTIMATION OF THE γ-PARAMETER

γ total partial derivative

	Component 1: Solar gravitation	Component 2: Lorentz transformation	Component 3: Earth gravitation	Component 4: Lunar + Planetary gravitation	Component 5: Additional Solar terms
Mean size of the component relative to Component 1 (Solar gravitational contribution)	1	0.3	0.01	0.0005	0.00001

8. CONCLUSIONS

- ➢ VLBI has the potential to determine certain Solar parameters only if substantially more observations close to Sun are observed or successful observations can be carried out even closer than 3.9° to the heliocenter.
- ➢ The formal error of the γ-parameter is significantly smaller if observations close to Sun are included.
- ➢ For the estimation of the γ-parameter apart from the contribution due to the Solar gravitation, the contribution from the Lorentz transformation should be considered as well.

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