ESTIMATION OF DIURNAL POLAR MOTION TERMS USING RING LASER DATA

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1. INTRODUCTION

Today, Earth rotation parameters are routinely obtained using the geodetic space techniques VLBI (Very Long Baseline Interferometry), SLR (Satellite Laser Ranging), GPS (Global Positioning System) und DORIS (Doppler Orbitography by Radiopositioning Integrated on Satellite). Technical progress over the last decades resulted in a precision of recently 0.01 milliseconds in length of day and 0.1 milliarcseconds in pole coordinates. The common principle is the relative measurement of rotation by observing reference points, stars or satellites, outside the rotating Earth. All these techniques require global networks and structures for the observation and data handling, which are coordinated by the international services IVS, ILRS, IGS and IDS.

The absolute measurement of rotation using inertial rotation sensors is a completely different approach. Mechanical gyroscopes measuring the coriolis force are by far not sensitive enough to detect Earth rotation variations. Instruments measuring the centrifugal acceleration as a part of the total gravity vector, gravimeters and tiltmeters, are basically sensitive to Earth rotation variations, but even the excellent resolution of superconducting gravimeters of 10^{-11} g is not sufficient to resolve short-period Earth rotation variations. In contrast, laser gyroscopes use the Sagnac effect, where the small wavelength of the laser light allows an extreme high resolution. An adequate sensitive laser gyroscope attached to the Earth gives us instantaneous access to the spin of the Earth and the orientation component of its axis in the observed direction. For the determination of the complete rotation vector, three linear independent laser gyroscopes are required.

The basic goals of laser gyroscopes for Earth rotation monitoring are:

- Detection of short-term spin fluctuations with a resolution of 10^{-9}
- Detection of short-term polar motions with a resolution of 0.2 mas or 6 mm
- Near real time acquisition with a temporal resolution of 1 hour or less

It is not expected that laser gyroscopes will ever reach the excellent long-term stability of the geodetic space techniques. However, the increasing interesting short-time range is poorly covered by these techniques. Furthermore ring laser measurements are quasi continuous, while VLBI and SLR usually have a resolution of one day, with gaps of some days.

2. THE WETTZELL RING LASER "G"

Ring lasers are inertial rotation sensors using the Sagnac effect, which is the frequency splitting of two counter-rotating laser beams due to rotation (Sagnac 1913). Four mirrors form a closed light path in a ring resonator. The resonator cavity is filled with the laser medium, a helium/neon gas mixture. The plasma is excited at one location by an alternating electrical field generating two counter-propagating laser beams. When this assembly is rotating, the (also rotating) observer sees a frequency difference between the co-rotating and the counter-rotating beam being proportional to the rotation rate. This beat frequency or Sagnac frequency Δf is described by the Sagnac formula for active resonators:

$$\Delta f = \frac{4A}{\lambda P}\vec{n} \cdot \vec{\Omega}$$

A	enclosed area
P	perimeter (beam path length)
λ	optical wavelength
$\vec{n}$	normal vector to A
$\vec{\Omega}$	rotation vector

The task is to measure the frequency of the optical interference pattern, approximately 12 magnitudes below the optical frequency, with a relative precision of 10^{-9}.

The large ring laser "G" has been developed on behalf of the Research Group Satellite Geodesy (FGS) by the Bundesamt für Kartographie und Geodäsie (BKG) and the Forschungseinrichtung Satellitengeodäsie of the Technical University Munich (FESG) in close cooperation with the University of Canterbury in Christchurch, New Zealand. "G" is in operation since 2001. The unique resolution and stability was reached by its size of 4 m x 4 m, its extreme mechanical and thermal stability resulting from the use of the glass ceramic Zerodur as base material, and the use of dielectric mirrors with minimum losses. The instrument operates under stable thermal conditions (annual variation less than 0.6 deg C in an underground laboratory at the Fundamentalstation Wettzell, Bavaria. A detailed description of the "G" ring laser is given in Klügel et al. (2005) or at http://www.wettzell.ifag.de/LKREISEL/G/LaserGyros.html. Table 1 shows the basic properties of three large ring lasers. Due to its construction, the "G" ring laser is the most stable instrument which is an important condition for monitoring Earth rotation variations.

Ring	Location	Area $[m^2]$	Δf $[Hz]$	Resolution $[rad/(s\sqrt{Hz})]$	Stability $[\Delta f/f]$
C-II	Christchurch	1	79.4	$4.8 \cdot 10^{-10}$	$1.0 \cdot 10^{-6}$
G	Wettzell	16	348.6	$9.1 \cdot 10^{-11}$	$1.0 \cdot 10^{-8}$
UG1	Christchurch	366	1512.8	$7.3 \cdot 10^{-12}$	$1.0 \cdot 10^{-7}$

Table 1: Properties of the 3 most sensitive ring lasers.

3. ORIENTATION CHANGES

A horizontally installed ring laser being rigidly attached to the Earth measures the projection of the Earth rotation vector onto the laser plane normal vector. Considering the orientation the inner product between the rotation and the normal vector can be expressed as:

$$\vec{n} \cdot \vec{\Omega} = |\Omega| \cdot \sin(\phi + \delta_N) \cdot \cos \delta_E$$

where ϕ is the geographic latitude and δ_N and δ_E are small angular variations towards North and East, respectively. Consequently, both local tilts of the instrument and motions of the Earth rotation axis affect the ring laser signal. As an example, an angular variation of 1 μrad (200 mas) towards North results in a Sagnac frequency variation of $1 \cdot 10^{-6}$, whereas the same variation towards East alters the Sagnac frequency by only $5 \cdot 10^{-13}$, which ist negligible.

As local tilts due to ground deformations cannot be avoided, the orientation of the ring laser has to be monitored. For this purpose a set of six specially designed platform tiltmeters are employed on the ring laser body measuring in different directions. The high resolution of these vertical pendulums and the excellent environmental conditions allow the detection of tilts at the nanorad level. In the case of tidal effects, the ring laser feels only the geometric part of tidal deformation, while tiltmeters are additionally sensitive to tidal attraction. However, not only the direct attraction of the tidal bodies, but also the change of the potential due the shifted masses of the tidally deformed Earth has to be taken into account. This is expressed by the Love number k, that gives the fraction of the additional deformation potential V_d relative to the tidal potential of the attracting bodies V_t:

$$V_{at} = V_t + V_d = (1 + k)V_t$$

The total attraction potential V_{at} is subtracted from the tiltmeter timeseries before being transformed into variations of the Sagnac frequency.

4. DIURNAL POLAR MOTION

The torques of Sun and Moon on the ellipsoidal and tilted Earth cause a circular motion of the instantaneous rotation pole in an Earth-fixed frame. The same physical cause generates precession and nutation of the Earth's axis in space. In an Earth-fixed frame these motions have diurnal periods, because the observer rotates with the Earth. In a space-fixed frame the periods are identical to the nutation periods (14 d, 28 d, 0.5 y, 1 y, 18.6 y, ...) and also known as Oppolzer terms. Earth rotation parameter estimations using space geodetic techniques yield the complete rotation matrix of the Earth and are basically not able to distinguish between space-related (nutation terms) and Earth-related (Oppolzer terms) components. The Oppolzer terms have to be introduced in the analysis.

Ring lasers on the other hand are only sensitive to Earth-related motions of the rotation axis and provide the only technique to directly measure diurnal polar motion. Fourier spectra of ring laser timeseries clearly show the presence of this signal (fig. 2). The diurnal polar motion is superimposed on the Chandler/annual wobble. A comparison of the expected timeseries with the measured Sagnac frequency shows that it is recently not possible to identify the Chandler/annual wobble in the data due to instrumental drifts (fig. 1).

A detailed theoretical investigation of diurnal polar motion for an elastically deformable Earth has been carried out by McClure (1973). The model extension for an anelastic Earth with liquid core (Wahr 1981, Brzezinski 1986, Frede & Dehant 1999) did not result in a major difference

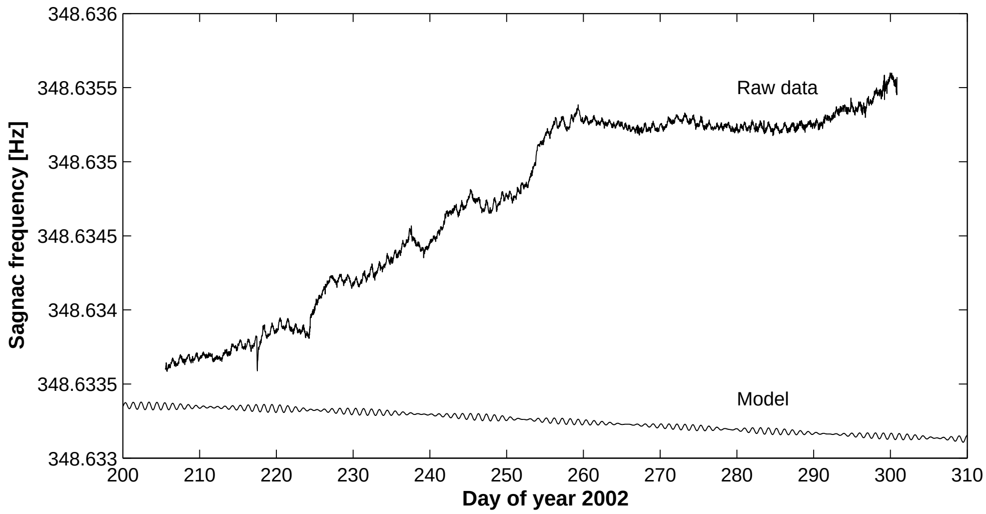

Figure 1: "G" ring laser raw timeseries (top) and predicted timeseries (bottom) from diurnal polar motion model plus Chandler/annual wobble.

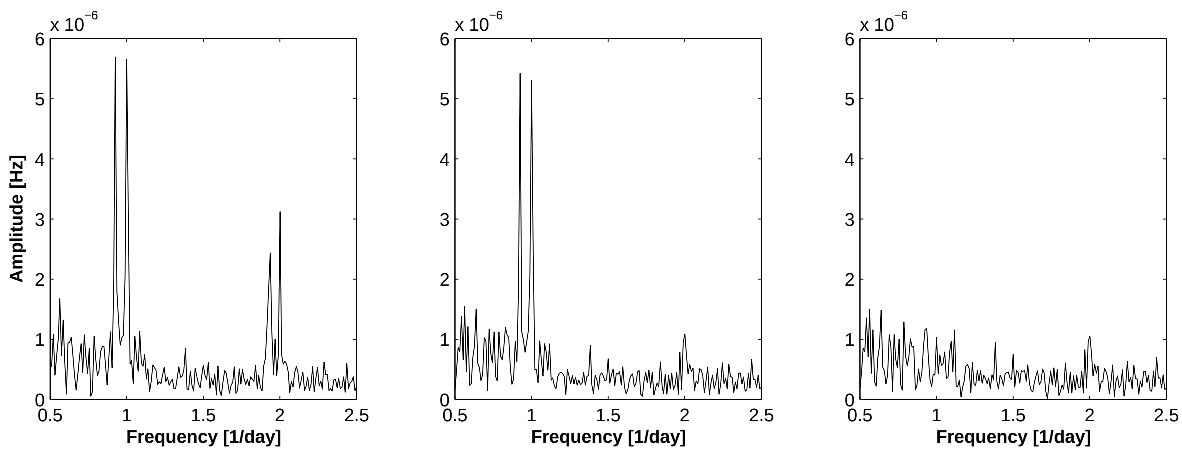

Figure 2: Fourier spectra of "G" ring laser data. Left: raw timeseries, middle: after removal of tidal tilt effects, right: after removal of diurnal polar motion model.

for the motion of the rotation axis. The diurnal polar motion terms are expressed in terms of fundamental arguments corresponding to particular orbital parameters. The procedure for the generation of the model timeseries is given in Scheiber et al. (2004).

For the estimation of the amplitudes of the diurnal polar motion components, the Bernese GPS software 5.0 has been modified for processing ring laser data in order to use the ERP estimation routines. Six continuous timeseries between 35 and 96 days long and a concatenated set of these data with a total contents of 401 days were analyzed. The data was resampled to 30-min averages and corrected for local and tidal tilts using attraction-corrected tiltmeter data. Only the amplitudes of the 8 strongest components were estimated. The formal errors of the individual solutions (table 2) are less than 1.2 mas for the group of shorter and less than 0.4 for the group of longer timeseries. The solution of the total data set shows formal errors of less than 0.2 mas. The estimated amplitudes (table 3) show in some cases good agreement with the expected model value, in other cases the amplitudes deviate from the model by more than 3 sigma. The total data set, however, yields amplitudes matching well the model.

Astron. arguments						wave	2002a	2002b	2003a	2003b	2004a	2004b	Total
l	l'	F	D	Ω	Θ		35 d	96 d	76 d	53 d	91 d	50 d	401 d
0	0	0	0	0	-1	K1	1.16	0.27	0.22	0.53	0.37	0.42	0.14
0	0	2	0	2	-1	O1	0.39	0.21	0.22	0.47	0.30	0.37	0.13
0	0	2	-2	2	-1	P1	1.16	0.25	0.23	0.53	0.27	0.42	0.12
1	0	2	0	2	-1	Q1	0.40	0.20	0.20	0.46	0.21	0.37	0.12
0	0	2	0	1	-1			0.21	0.22		0.30		0.13
0	0	0	0	1	-1			0.22	0.25		0.37		0.14
1	0	0	0	0	-1	M1		0.20	0.20		0.21		0.11
-1	0	0	0	0	-1	J1		0.20	0.20		0.21		0.11

Table 2: Formal errors in milliarcseconds.

Astron. arguments						wave	2002a	2002b	2003a	2003b	2004a	2004b	Total	Model
l	l'	F	D	Ω	Θ		35 d	96 d	76 d	53 d	91 d	50 d	401 d	
0	0	0	0	0	-1	K1	-7.70	-8.92	-5.67	-5.81	-8.75	-8.13	-7.44	-8.71
0	0	2	0	2	-1	O1	6.25	6.96	5.70	7.25	7.65	10.91	6.96	6.87
0	0	2	-2	2	-1	P1	0.89	2.99	1.89	2.87	3.90	1.72	2.40	3.00
1	0	2	0	2	-1	Q1	1.32	1.89	0.74	-0.38	1.55	3.47	1.56	1.36
0	0	2	0	1	-1			1.36	-0.03		1.13		1.39	1.30
0	0	0	0	1	-1			-2.35	-1.33		-0.25		-1.15	-1.18
1	0	0	0	0	-1	M1		-1.44	-0.03		0.25		-0.44	-0.52
-1	0	0	0	0	-1	J1		0.20	-0.10		-1.30		-0.40	-0.50

Table 3: Estimated amplitudes in milliarcseconds. Model amplitudes from Brzezinski (1986).

5. SUMMARY AND OUTLOOK

Among the inertial rotation sensors, only large ring lasers are recently able to monitor the rotation of the Earth continuously and with a resolution high enough for geodetic and geophysical applications. The world's most precise rotation sensor, the Wettzell "G" ring laser, resolves 10^{-8} of the Earth rotation rate, which is equivalent to 1 ms length of day or 2 mas polar motion. The minimum in the Allan deviation plot (fig. 3), which is adequate to describe resolution and stability, is reached after an integration time of 3 hours. Longer integration times suffer from instrumental drifts. The operation requires stable thermal and mechanical conditions and orientation monitoring in order to eliminate signals coming from local tilting.

Unlike for the geodetic space techniques, polar motion can directly be measured by ring lasers. From 6 timeseries covering 401 days of observations, the 8 largest diurnal polar motion terms were estimated with a formal error of less than 0.2 mas. A technical upgrade to improve resolution (shifts left branch of Allan deviation plot downwards) and stability (shifts minimum towards right) is in progress. This means that smaller signals like the effect of ocean tides or the atmosphere on Earth rotation may be detectable in future.

However by using one ring laser alone, one can not distinguish between variations of the Earth rotation rate and polar motions. Three linear independent instruments would eventually be required for the determination of the complete Earth rotation vector.

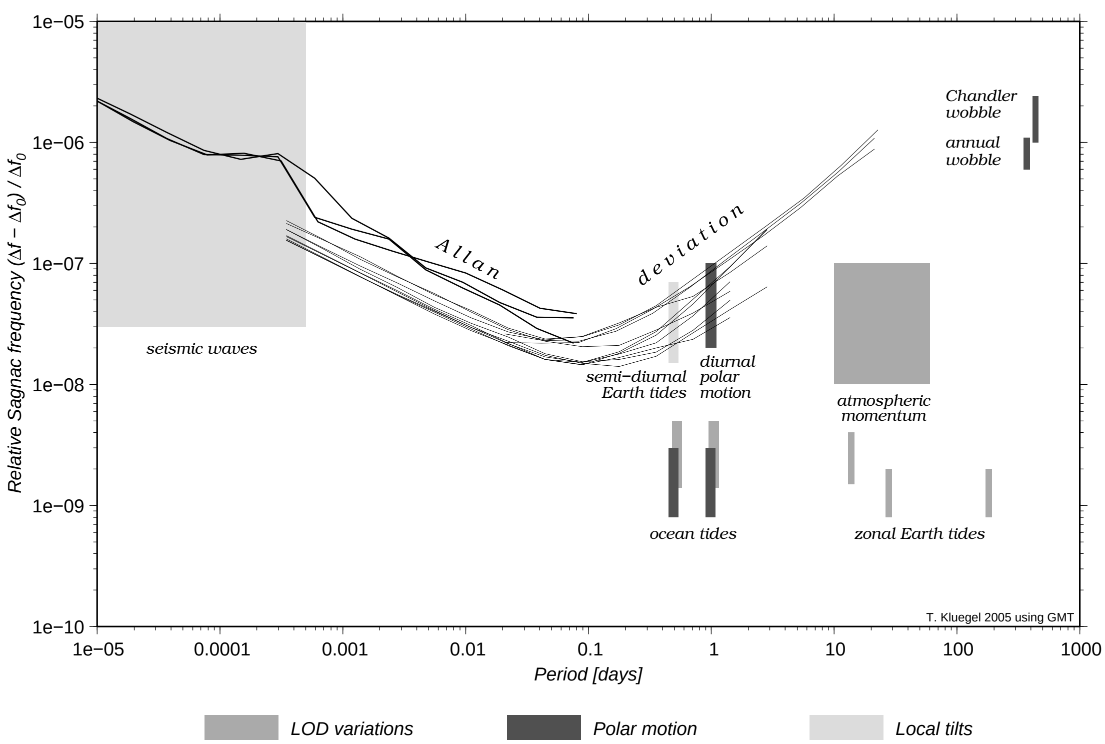

Figure 3: Resolution and stability of the "G" ring laser with respect to Earth rotation signals.

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