60 years of Earth Tide observations in Strasbourg (1954-2014)

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Abstract

There is a tradition in gravity recording of Earth tides at Strasbourg which was initiated by Prof. Robert Lecolazet in the 50s. Since then, the surface time gravity changes have been measured locally using different kinds of gravimeters (spring, absolute and superconducting) at two different stations; first in the Seismological Observatory of Strasbourg for almost 13 years (1954-1967) and later on since the 70s at the J9 Observatory, 10 km far away from Strasbourg city. Over these years many kinds of improvements have been achieved in terms of instrumentation, of tidal potential developments and more specifically in terms of data analysis techniques, which have allowed obtaining some fundamental results.

Keywords: earth tides, spring gravimeter, superconducting gravimeter, absolute gravimeter

1. Introduction

The first observations of the Earth tides in Strasbourg were carried out in 1954 using a North American spring gravimeter, which is the first permanent gravimeter installed by R.Lecolazet in the Seismological Observatory of Strasbourg. It was the first time that such a 'long series' (almost 6 months) was recorded. Since then, first in the Seismological Observatory of Strasbourg and later on in the 70s in the J9 Observatory, the surface time gravity changes have been measured locally at different consecutive periods; at the beginning using spring gravimeters, and since 1987 using superconducting gravimeters (SG) and also absolute gravimeters (AG) since 1997. The different improvements (instrumental, processing) over these years allowed obtaining some fundamental results that we recall hereafter.

We will first review all the instrumentation (Fig. 1) that has been used in both observatories to observe Earth tides during those 60 years, and we will highlight some of the major results obtained directly from these data series as for example the observation of long period waves (Mm, Mf, Mtm) in 1966, the observation of the Free Core Nutation resonance in diurnal waves in 1974 or the first observations of the quarter-diurnal tidal waves of a few pico-g amplitude in 1995.

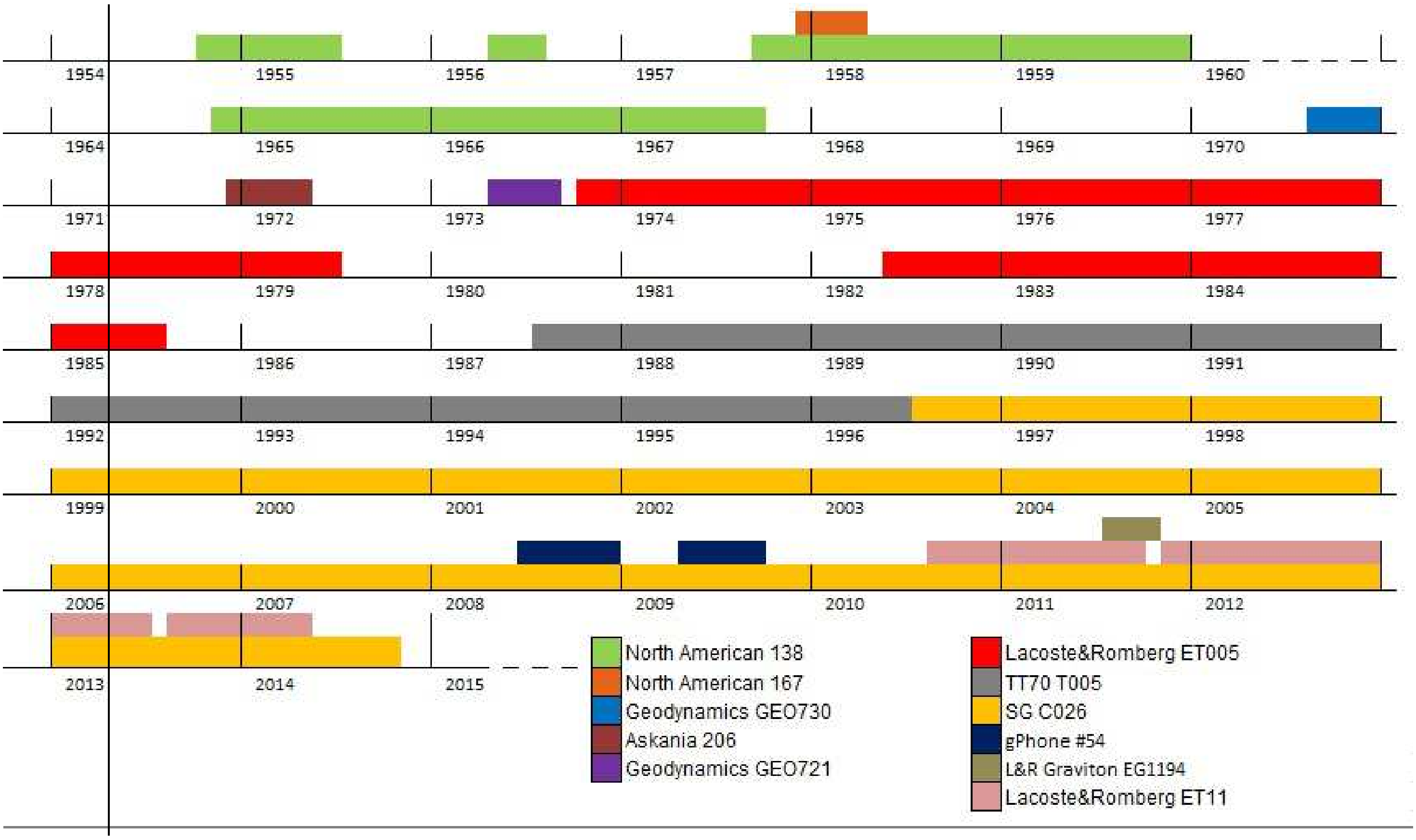

Fig 1: Summary of the time periods when the various gravimeters have been recording at the Seismological Observatory (1954-1967) in Strasbourg, and then at J9 Observatory (1970-today), close to Strasbourg.

2. Seismological Observatory of Strasbourg (1950-1970)

The first location that R. Lecolazet chose to install permanent gravimeters was inside the Seismological Observatory of Strasbourg, a building belonging to the University in the city center (48.583 ° N, 7.767 ° E, 138 m). The first observations there were carried out in 1954 using a spring gravimeter, the North American 138, which was equipped with a photographic recording device. Pr. Lecolazet and co-workers obtained more than 5 months of consecutive record, precisely 163 days from October 1954 to March 1955. This series was published as the longest series recorded at that time (Lecolazet, 1956, Melchior 1957). Since then, they continued to gradually improve their equipment obtaining longer and better data series. In November 1964 they installed the sensor in an isolated box thermostatically controlled. The gravimeter was equipped, among other improvements, with a permanent electrostatic calibration device. Moreover the photographic recording system was highly improved. As expected, the drift became much more regular and gradually decreased, making it possible to study long-period waves.

2.1 Observations of Long Period tidal waves

Since November 1964 this gravimeter was continuously recording for almost 3 years. Using the first 13 months of this series, they were able to observe for the first time the monthly, fortnightly and ter-monthly waves Mm, Mf and Mtm (Fig. 2 - Lecolazet and Steinmetz, 1966). These first results were still not very precise but were very encouraging. Such observations were possible not only because of the data quality, but also because of the use of new techniques of signal processing.

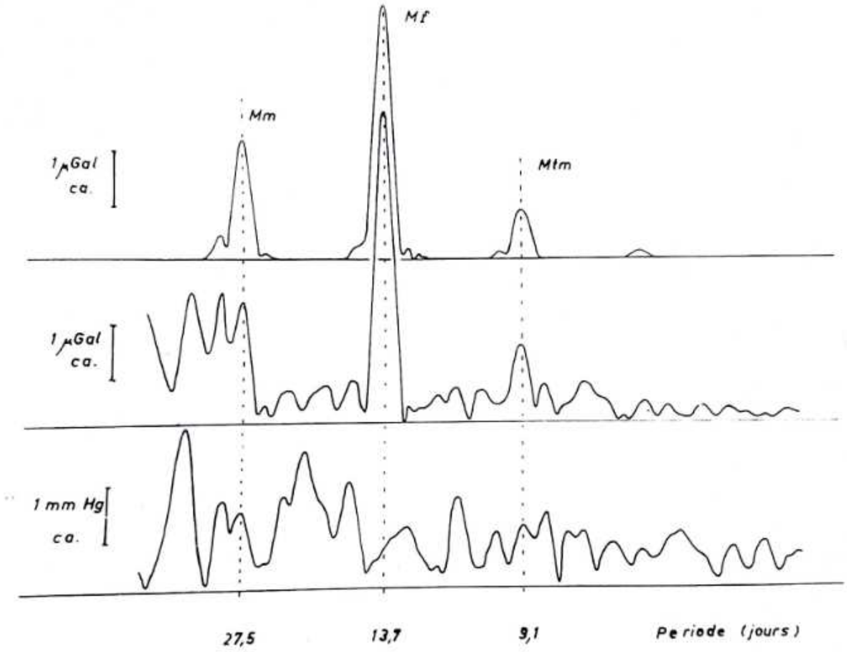

Fig.2: First observation of the monthly, fortnightly and ter-monthly waves Mm, Mf and Mtm, using the 3 year series recorded by the North American 138 gravimeter installed in Strasbourg from 1964 until 1967 (extracted from Lecolazet and Steinmetz, 1966). Upper plot; theoretical waves. Medium plot; observed waves. Lower plot; observed air pressure variation.

The North American AG 138 recorded at the same site until 1967. Another North American gravimeter (AG 167) was also recording in parallel during 82 days at the end of 1957 beginning of 1958. The aim was to study and compare the sensitivity and accuracy of both instruments (Lecolazet 1958). Using the last period of data recorded by the North American 138 (1012 days between November 1964 and August 1967) they were able to observe the Free Core Nutation resonance.

2.2 First observation of Free Core Nutation resonance with gravimetric data

The fluid core resonance phenomenon affects the amplitude of the tidal waves close to the Free Core Nutation (FCN) period in the diurnal frequency band. Although this has been studied for a long time, the accuracy in the determination of most relevant resonance parameters (resonance frequency and quality factor) has improved rather slowly.

As the rest of the gravity community, Lecolazet became interested in searching for the FCN in gravity records after the theoretical works of Jeffreys (1949, 1950, 1957), Vicente (1964, 1971) and Molodensky (1961, 1971) in the middle of last century, concentrating much effort to try to detect it in the data series recorded in Strasbourg.

In a first step, the study of the existence of the Earth's FCN focused on the computation of gravimetric delta factors δ of the main diurnal tides. Lecolazet initiated the search for a clear evidence of the FCN by its associated resonance effects on the diurnal tides using the 5-month data recorded with the North American AG 138 from October 1954 until March 1955. Unfortunately, the first results he published were in disagreement with the theoretical models (Lecolazet 1957, Melchior 1957). Two years later, using the series from 1957 to 1958, he published the first clear observation of $\delta(O1) > \delta(K1)$ in agreement with Jeffreys' theory

(Lecolazet, 1959). Then Lecolazet (1960) obtained even better results using the complete series of 860 days of the NA 138 registered between August 1957 and December 1960.

After these first results, correct values were found at other stations all around the world, a few years later. We can cite Pariiskii (1963) who confirmed Lecolazet's results using an Askania GS 11, and also Popov's results (Popov, 1963). Later Melchior (1966) compiled the results obtained at different worldwide stations even though some of them did not achieve the expected results.

In a second step, once the existence of this resonance was confirmed, efforts were focused on the search for its frequency. After some failed attempts (Lecolazet and Steinmetz, 1973) where they were not able to locate correctly the frequency, Lecolazet and Steinmetz published in 1974 the first results of the discovery of the resonance of the core (Lecolazet and Steinmetz, 1974) determining that the eigenfrequency should be located either between K1 and PSI1, or between K1 and PHI1 frequencies.

These results were then much improved by using a longer series recorded between 1973 and 1975 with a LaCoste-Romberg Earth-Tide (LR-ET005) gravimeter equipped with a feedback system installed at the J9 Gravimetric Observatory of Strasbourg, definitively confirming that the FCN frequency lies between K1 and PSI1 frequencies (Abours and Lecolazet, 1978, Lecolazet and Melchior, 1977).

Since then, developments in both theory and observations have allowed substantial improvements in the estimation of the FCN resonance parameters, especially with the development of the superconducting gravimeters (SGs) during the 80s.

Finally, we have to mention that a Geodynamics model, the GEO730 owned by J.T. Kuo, recorded during 79 days in Strasbourg between September and December 1970. Within the international context of the station, these data were included in different international profiles and networks (Melchior et al., 1976, Melchior et al., 1981).

3. Gravimetric Observatory of Strasbourg J9 (1970s – today)

At the beginning of the 70s, R.Lecolazet and co-workers decided to move the gravimetric observatory to a quieter place situated outside the city. The chosen place is located about 10 km from Strasbourg in a bunker named J9 built by the Germans after the 1870 war on the top of a sedimentary hill (48.622 ° N, 7.684 ° E, 180 m).

The new gravimetric observatory is settled at J9 since 1970. Thereafter gravity variations have been observed and recorded at J9 with various spring and superconducting gravimeters (Figure 3). Besides, since 1997, absolute gravity measurements are also performed regularly. During this long period, the relative gravimeters (sensors and electronics) and the acquisition systems were drastically improved. These improvements allowed increasing the measurement accuracy by more than 10 times (Calvo et al. 2014a).

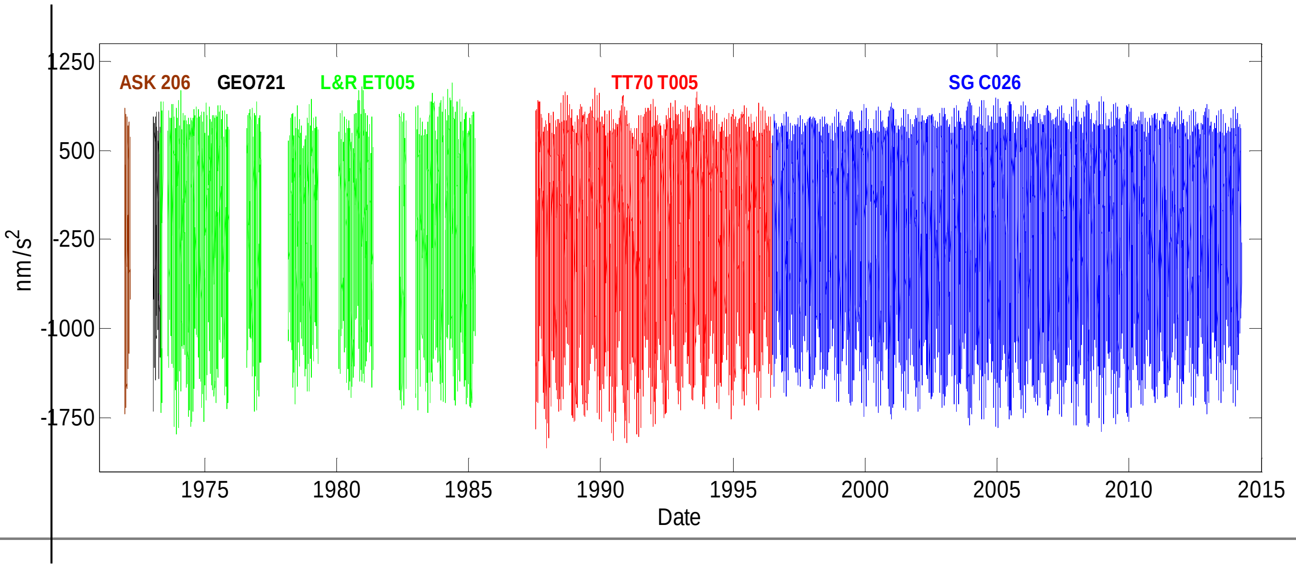

Fig 3: Time-varying gravity measured at the Gravimetric Observatory J9, located near Strasbourg, from 1970 to 2014. The first 3 series were recorded by spring gravimeters; Askania model in brown, Geodynamic model in black and Lacoste and Romberg model in green. The last 2 series were obtained by superconducting gravimeters; TT70-T005 model in red and SG-C026 model in blue.

3.1 Spring gravimeters

The first 10 years of observations were carried out by different models of spring meters: the first one was an Askania gravimeter belonging to M. Bonatz, ASK206, which was recording for 77 days at the end of 1971 beginning of 1972. After that, a Geodynamic gravimeter GEO721, was installed by B. Ducarme during 82 days in 1973. Later a Lacoste&Romberg ET005 modified in order to record earth tides by R. Lecolazet and J. Gostoli in 1970 with an electrostatic feedback system and a digital recording, was recording with a sampling rate of 1 hour (J. Gostoli, 1970). This later gravimeter was operational during two periods of 2100 and 1120 days respectively from August 1973 until middle 1981. This series was used in several studies, including the observation of the FCN resonance as seen before in section 2.2.

The spring meters are too sensitive to the changes of temperature, so to avoid such perturbations the L&R ET005 was installed in an isolated box thermostatically controlled. The box was located in a room itself thermally stable of the underground fort; the sealed box protected also the sensor against the direct influence of barometric pressure variations. This gravimeter was calibrated by a direct comparison with an Askania gravimeter GS15 in 1972 (Abours, 1977).

More recently, there have been also different spring gravimeters temporarily installed in J9, such as the Microg-LaCoste gPhone 054 owned by IGN-Spain and which was recording for almost 1 year between 2008 and 2009 (Riccardi et al., 2011). A LaCoste & Romberg Graviton-EG1194 from Instituto de Geociencias of Spain was operating there for 3 months during 2011, aiming to check its instrumental response, both in amplitude and phase as well as its time stability (Arnoso et al., 2014). Currently a Lacoste-Romberg ET11, belonging to BFO was installed by W. Zürn and is recording since 2012 (Rosat et al. 2015).

3.2 Superconducting gravimeters

Since 1987 two different superconducting gravimeters have been recording in two consecutive periods at J9. The first superconducting gravimeter was a TT70 model from GWR Instruments installed in 1987. This meter was recording for almost 10 years. Using the first 8 years of this series, Florsch et al. (1995) were able to observe for the first time 3 of the quarter-diurnal tides waves M4, N4, K4 (degree and order 4) with extremely small amplitude. Later on, Boy et al. (2004) definitively confirmed these observations by comparing observed gravity changes with loading estimates using different models of non-linear tides over the North-Western European shelf.

The loading contribution of non-linear oceanic tides has already been clearly observed using measurements from spring gravimeters (Baker, 1980). In 1990, Wenzel and Zürn identified tidal terms of 4th order in the 1 to 3 cycle/day frequency bands using the data from the Lacoste-Romberg ET19 installed in the Black Forest Observatory (Wenzel and Zürn, 1990) but thanks to the high precision of SG data, Florsch et al. (1995) could also identified the degree-four lunar tidal waves in the quarter-diurnal frequency band (fig. 4).

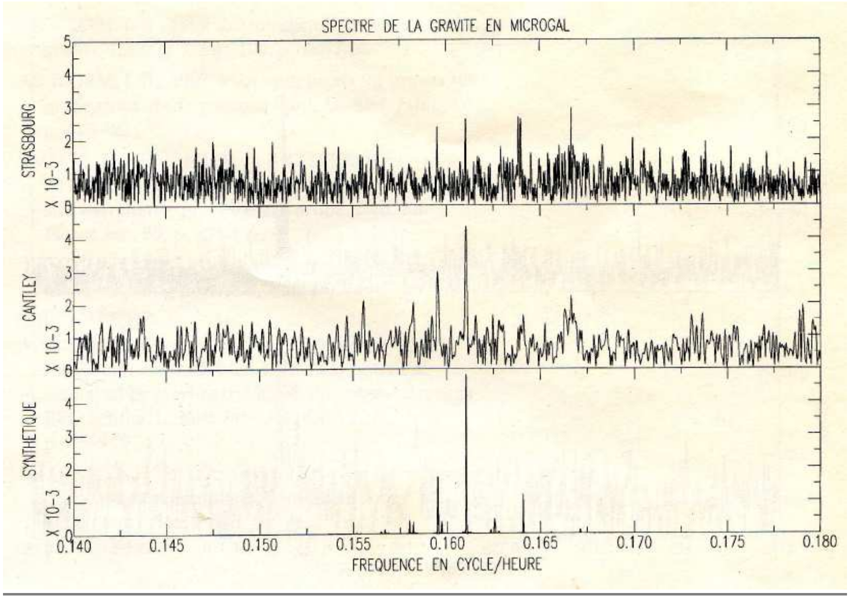

Fig 4: Gravity spectra recorded by the T005 SG at Strasbourg (France) and T012 at Cantley (Quebec) and comparison with spectra of the theoretically predicted tide calculated at Strasbourg, highlighting 3 of the quart-diurnal tides waves M4, N4, K4. Extracted from Florsch et al., 1995.

In 1996 this gravimeter was replaced by a more compact model, the C026, which is still recording (Fig 5.). These data are collected within the global GGP (Global Geodynamics Project) network (Crossley et al., 1999). This project began in 1997, as a long term initiative in order to establish a worldwide network of SG stations. The high accuracy and time stability of these gravimeters are useful to study of a wide range of geophysical applications (Hinderer et al., 2007).

Fig. 5: Superconducting gravimeters installed at the J9 Observatory. Left: TT70 model (T005). Right: OSG model (C026).

The SGs are using magnetic levitation against gravity on the contrary to the mechanical meters which use a spring. The SG long term stability is hence much better than in the case of spring meters mainly because of the unavoidable creep of any spring whatever its constitutive material (Torge 1989). The high sensitivity of the SGs is achieved by an efficient adjustment of a vertical magnetic gradient, so compared to the spring instruments, the superconducting gravimeters are characterized both by a higher accuracy and a significantly lower instrumental drift.

The model C026 was also improved with respect to the previous T005 version in terms of noise levels (Rosat et al., 2002) and drift rates (Amalvict et al., 2001) because of upgrades of the instrument itself and also of the data acquisition system. The high quality of this gravimeter records has allowed to carry out extensive researches on different topics of global geodynamics such as the study of global Earth deformation (tides, surface loading, etc.), non-linear ocean tides (Boy et al. 2004), hydrology (Longuevergne et al., 2009, Rosat et al., 2009) and metrological aspects such as calibration (Amalvict et al.,2002), long-term drift (Amalvict et al.,2001; Boy et al., 2000), noise levels estimates (Rosat et al., 2004) and comparison with other temporary instrumentation like the gPhone previously mentioned (Riccardi et al. 2011) or a broad-band seismometer (Rosat et al. 2015).

Considering only the J9 Observatory, we have almost 40 years of time-varying gravity record, more than 27 years of which have been registered with superconducting gravimeters, leading to the longest available series ever recorded by SGs at the same site. The SG C026, will be replaced in a near future by a more compact observatory model (iOSG), ensuring continuity of this long series.

We can benefit from this unprecedented length in different ways; both in achieving high spectral resolution in the tidal bands and also in obtaining higher precision in the tidal determination, allowing to separate small amplitude waves in the major tidal groups and also to attempt the detection of very long period tides that have never been observed in gravity data of shorter duration. Several examples (e.g. tides generated by the third-degree potential) are shown elsewhere (Calvo et al., 2014b).

3.3 Absolute gravimeters

Since 1997, there is also a portable absolute gravimeter FG5 # 206 manufactured by Micro-g Solutions which is regularly measuring at the J9 Observatory in parallel with the SG, but also at different sites in France and abroad. The main purposes of these AG measurements performed at J9 are the drift control and the calibration of the superconducting gravimeters.

For the T005, the absolute measurements were carried out by J. Makinen with the absolute gravimeter JILAg-5 belonging to FGI (Finnish Geodetic Institute). We only dispose of 6 measurements for all the period. For the C026, there have been numerous absolute measurements since its installation with instruments of the new generation of ballistic gravimeters, mainly the FG5#206. There was also one measurement realized in parallel with both instruments (JILAg-5 and FG5#206) in 1996 for comparison.

We have also used the AG measurements to determine the SG amplitude scale factor. Several scale factor experiments of different durations (from several hours up to 9 days) were regularly performed since 1996. These results allow us to discuss the time stability of the calibration of the SG. (Hinderer et al., 1991; Amalvict et al., 1999, 2001, 2002; Calvo et al., 2014a).

Furthermore, these absolute measurements have been combined with GPS data or hydrological data in different studies to investigate the long term evolution of gravity that was observed at J9 (Amalvict et al., 2004; Rosat et al., 2009).

In addition to all the gravimetric instrumentation, many other auxiliary sensors are installed at the observatory, such as a weather station, GPS permanent antenna, and different hydrological sensors (piezometers, soil moisture sensors).

4. Conclusion

The beginning of the Strasbourg tradition to record gravity Earth tides is due to Robert Lecolazet who decided to investigate this field in Strasbourg in the 50s. The first permanent gravimeter was installed in 1954 (a North American 138 spring meter) in the Seismological Observatory of Strasbourg. Since then, different models of gravimeters (spring, superconducting and absolute gravimeters) have been recording at different consecutive periods. In the 70s, the observatory was moved to a bunker, 10km from Strasbourg, the J9 Observatory. We have reviewed all the instrumentation that has been used in both observatories and we have pointed out some of the major results obtained using the recorded data.

Several major scientific achievements have been derived from the use of these data series, such as the observation of long period waves (Mm, Mf, Mtm) in 1966, the observation of the Free Core Nutation resonance in diurnal waves in 1974 or the first observations of the quarter-diurnal tidal waves of a few pico-g amplitude in 1995. Today, considering the J9 Observatory only, we have almost 40 years of record, more than 27 continuous years of which have been registered with superconducting gravimeters, leading to the longest SG record available. This exceptional duration helped us to separate tidal contributions of near frequencies, to detect some very weak amplitude signals and to exhibit signals of very low frequency. In a near future, the SG C026 will be replaced by a more compact SG observatory model (iOSG). This new gravimeter will ensure the continuity of this long series in Strasbourg, for further improvement in the study of time-varying gravity.

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