Long Term Site Movements at the ESRF

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This paper will address ground motion observed at the European Synchrotron Radiation Facility (ESRF). We have observed both long term and annual vertical and horizontal motions of the ESRF site and accelerators. The identification of these movement signatures will be presented and discussed.

1. INTRODUCTION

The ESRF is built on the confluence of the Drac and Isère Rivers. The valley geology is composed of a glacial deposit to a depth of at least 200 m (possibly up to 500 m) topped with alluvial material. A dam is located approximately 4 km downriver of the site. This dam is used to generate electricity and control the river water level. In doing so, it opens its sluice gates periodically, lowering the water level in the adjacent rivers. The area is surrounded by mountains up to 1000 m above the site altitude of 200 m. The local water level is just 2.5 m below the accelerator and necessitates constant pumping to maintain this level. The ESRF site situation is shown in Figure 1.

After fifteen years of operation of the ESRF, the ALignment and GEodesy (ALGE) group has amassed a considerable amount of information concerning the evolution of ESRF site. Altimetric data over this fifteen year period includes: bi-monthly leveling survey data taken with the Wild (now Leica) N3 optical level up to 1999, and electronic leveling issued from the Zeiss (now Trimble) DiNi 12 since; and hourly Hydrostatic Leveling System (HLS) data. Planimetric data includes bi-monthly coordinates issued from Distinvar and Wire Offset data up to 1998 and from the Leica TDA5005 distance and angle measurements since.

Although the level data is easily comparable over the fifteen year period, the manner in which the planimetric measurements were made and calculated up until 1998 was fundamentally different to the way in which they are made today. Recently a considerable effort was made to re-calculate all of the Distinvar and Wire Offset data in the same manner as the TDA5005 data so as to homogenize the calculations over the fifteen year period. This effort has been rewarded because we have uncovered some interesting horizontal movement signatures.

2. NETWORK CALCULATIONS

It has always been the policy at the ESRF to separate the altimetric and planimetric calculations. This is because the machine is essentially flat (horizontal) with maximum height variations in the order of ±0.5 mm. Furthermore, all of the survey monuments are installed in the same plane. Therefore inclusion of zenithal angles and slope distances brings little additional information to the least squares calculation.

2.1. Storage Ring Altimetric Network Measurement and Calculation

From the start of the ESRF to 1998, the leveling campaigns were made with the Wild (now Leica) N3 precise level. This instrument has since been replaced by the Zeiss (now Trimble) DiNi 12 electronic level. The main reasons behind this modernization was to decrease the intervention time of a level survey and to eliminate well know problems.
associated with optical level surveys and in particular operator fatigue. Furthermore, precise optical levels like the N3 are no longer manufactured.

Nevertheless, a number of problems and in particular lighting diminished the announced precision of modern electronic levels under our conditions of use in accelerator tunnels. An in-house illuminated level staff development permitted the reliable use of one such electronic level - the Zeiss DiNi 12. This change of instrument has been accompanied by a change in the stationing of the level and post survey collimation corrections to the measures as a function of distance [1]. Table 1 gives an outline of the main parameters of the N3 and DiNi 12 leveling surveys. It is worth noting the net improvement in point uncertainty between the two leveling schemas (i.e. N3 0.16 mm and DiNi 12 0.08 mm).

Figure 1: In these photographs we see the ESRF site situation. The ESRF is situated at the confluence of the Drac and Isère rivers. It is nestled between the three ‘Massifs des Alpes’: the Vercors, the Belledonne and the Chartreuse mountain ranges. The valley geology is composed of a glacial deposit to a depth of at least 200 m (possibly up to 500 m) topped with alluvial material. A dam is located approximately 4 km downriver of the site (St Égrève Dam). This dam is used to generate electricity and control the river water level. The area is surrounded by mountains up to 1000 m above the site altitude of 200 m. The local water level is just 2.5 m below the accelerator.

At the ESRF a high quality HLS was conceived and installed on the principal accelerator –the Storage Ring (SR)– at the inception of the facility. This system is composed of 288 devices (HLS pots and captors) installed on 96 magnet supports evenly distributed around the ring. It has a precision in the order of the micron (over the period of several hours). It is used in the short term monitoring of real time events and the control of the SR realignment with precision jacks. It has been reported on extensively.[2-9]

A second HLS was installed on the tunnel roof and has been operational since September 2001. This system has proved to be reliable with an estimated uncertainty better than 40 µm [2]. It is used to follow vertical ground motion of the ESRF site in real time.
Table 1: Summary of ESRF levelling

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<tr>
<td></td>
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<tr>
<td>845 m complete run of storage ring tunnel</td>
<td></td>
</tr>
<tr>
<td>32 cells in storage ring tunnel</td>
<td></td>
</tr>
<tr>
<td>2 points per cell are measured from only one station</td>
<td></td>
</tr>
<tr>
<td>3 level stations per cell</td>
<td>2 level stations per cell</td>
</tr>
<tr>
<td>Station 1 : 6 observations</td>
<td>Station 1 : 12 observations</td>
</tr>
<tr>
<td>Station 2 : 8 observations</td>
<td>Station 2 : 10 observations</td>
</tr>
<tr>
<td>Station 3 : 8 observations</td>
<td>No station 3</td>
</tr>
<tr>
<td>Total : 22 observations</td>
<td>Total : 22 observations</td>
</tr>
<tr>
<td>9 meters : longest observation distance</td>
<td>13 meters : longest observation distance</td>
</tr>
<tr>
<td>96 double height stations for a complete run</td>
<td>64 double height stations for a complete run</td>
</tr>
<tr>
<td>704 observations in a level run</td>
<td>704 observations in a level run</td>
</tr>
<tr>
<td>Estimated point uncertainty at $2\sigma$ 0.156 mm</td>
<td>Estimated point uncertainty $2\sigma$ 0.079 mm</td>
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2.2. Storage Ring Planimetric Network and Calculation

At the start of the ESRF, it was decided the only instruments capable of measuring the survey networks to the required precision were the Disinvar and Wire Offset instrument (commonly referred to as the Ecartometer) pair. These instruments were developed and extensively used at CERN. They were employed at the ESRF between 1990 and 1997 after which it was decided to modernize the instrumentation. To complement the distinvar and ecartometer measurements and help to hold the figure together, electronic distancemeter (EDM) and angle measurements were made from a concrete pillar located at the centre of the ESRF site to certain first order pillar – wall bracket stations in the machine network.

Since 1998 the Leica TDA5005 motorized theodolite (robotic total station RTS) with automatic target recognition (ATR) is used for all high precision survey work at the ESRF. This instrument provides an extremely high measurement rate accompanied by very good precision. Typically, the full storage ring survey is made by three teams of two people in one 8 hour shift (1600 angle and distance measurements). Typical distance and angle residual standard deviations are in the order of 0.1 mm and 0.5 arc second respectively. Absolute error ellipse semi-major axes are systematically better than 0.15 mm at the 95% confidence level [10, 11]. Table 2 gives an outline of the main parameters of the distinvar - ecartometer and TDA5005 surveys.

Over the past 15 years there have been huge advances in computing power and resources. However, one must remember that before 1995, there were severe limitations on the number of points that could be simultaneously calculated using the least squares software employed at the ESRF. For this reason the least squares calculation of the Storage Ring (SR) machine was typically divided into three parts. First, the first order pillar – wall bracket network
consisting of 64 points was calculated. In this calculation, one point was considered fixed in \(x\) and \(y\), and another point was fixed in orientation. The points issued from this calculation were then used as fixed points in two calculations each of half of the machine consisting of 166 points. There were several overlapping points between the two halves of the machine. Because the machine was measured more often than the first order pillar – wall bracket network calculations often used fixed point coordinates which could pre-date the actual survey by several months.

Table 2 Summary of ESRF planimetric surveys.

<table>
<thead>
<tr>
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<th>Distinvar Ecartometer Survey (1990 to 1998)</th>
<th>TDA5005 Survey (1998 to present)</th>
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<tbody>
<tr>
<td>No. distinvar distance obs.</td>
<td>864</td>
<td></td>
</tr>
<tr>
<td>No. ecartometre distance obs.</td>
<td>1033</td>
<td></td>
</tr>
<tr>
<td>No. EDM distance obs.</td>
<td>7</td>
<td>1728</td>
</tr>
<tr>
<td>No. angle obs.</td>
<td></td>
<td>1728</td>
</tr>
<tr>
<td>Total no. measures</td>
<td>1904</td>
<td>3456</td>
</tr>
<tr>
<td>No. Parameters</td>
<td>778</td>
<td>992</td>
</tr>
<tr>
<td>Redundancy</td>
<td>1126</td>
<td>2464</td>
</tr>
<tr>
<td>Semi-major; semi minor axes</td>
<td>0.285 mm</td>
<td>0.143 mm</td>
</tr>
<tr>
<td>d(R) envelope peak to peak; (2\sigma)</td>
<td>1.66 mm</td>
<td>0.53 mm</td>
</tr>
</tbody>
</table>

Today there are essentially no limitations on the number of points that can be simultaneously calculated. Additionally, all survey network calculations are made using a so-called free network adjustment scheme (e.g. [12]). This past year, all of these old surveys were recalculated in the manner used today [13]. This was done to provide a coherent link between the distinvar and ecartometer data and the more recent TDA5005 data.

3. ESRF SITE MOVEMENTS

Several site movement signatures have been identified over the years at the ESRF [8]. Among these movements are:

- Peak to peak movements of nearly 6 mm caused by excavation, construction and landscaping on the ESRF site over an approximate 2½ year period ending in January 1993 causing. These one off movements remain the largest movements observed to date (Figure 2).
- Periodic purging of the St Égrève dam located 4 km downriver of the ESRF site to remove accumulated silt in the river bottom causes movements of approximately ±0.3 mm (Figure 2 and Figure 8).
- Cyclical movements on the support girders located next to the slab construction joints.
- Movements associated with the cooling of the tunnels and magnets.
- Long term horizontal and vertical deformation of the site.

At the ESRF we are specifically interested in the uncertainty and movements in the directions perpendicular to the electron beam travel. We refer to these directions as: \(R\), the horizontal direction perpendicular to the beam travel; and \(Z\), the vertical direction perpendicular to the beam travel. For the most part and unless otherwise stated, all data referred to below will be with respect to these directions.
Generally graphs in this paper present values of Z and R with respect to the mean value of a given survey. Furthermore they are given with respect to an origin which is typically the first of a series of values.

Figure 2: The top graph shows movements due to the construction and landscaping on the ESRF Site. In the bottom graph we see the effects of deformation due to silt accumulation and removal in the adjacent Drac and Isère rivers. ESRF Machine and Site Horizontal Movements

3.1. ESRF Machine and Site Vertical Movements

Figure 3: It has been observed for some time that the centre of the ESRF site is sinking. It has sunk nearly 1 cm over since the commissioning of the ESRF in 1992. The left hand graph shows successive level surveys between 1992 and 2006. Levelling is made over the route shown in red in the top right hand corner photo. The right hand graph shows the downward motion of one of the Pre-Injector (PINJ) points over this period.
It has been known for some time that the center of the site is sinking with respect to the Storage Ring (SR) and Experimental hall (EXPH). The injector (PINJ) has actually sunk nearly 1 cm with respect to the SR in the 14 years since the machine was commissioned in 1992 (Figure 3). This past year shims were inserted under the Booster girders to increase the alignment stroke and permit continued alignment in the future. There appears to be two periods of movement: 80% appears to have occurred over the first 8 years; since 2001 the downward motion has slowed considerably.

Considerable long term vertical motion has also been observed on the pillars located in the SR tunnel around the circumference of the SR (Figure 4). There has been a long term upward motion as shown by d) and b) in Figure 4. This motion is along the north-south axis of the ESRF site. Similarly there is a net downward motion in the zones marked by c) and particularly a). The point a) is at the start of the zone shown in Figure 3. This movement, which has attained nearly 4 mm, occurred after the construction period (Figure 2). It is more or less constant and systematic.

Figure 4: Considerable long term vertical motion has also been observed around the circumferences of the SR (Figure 4). The left hand graph shows: the development over time 1994 to 2006 coming out of the page; and over the SR circumference across the page. The right hand graph shows this movement geographically.

It is clear there is a long term systematic evolution of the site. Naturally one wonders if there is a systematic annual component to this movement. To estimate an annual component one must first remove the underlying long term trend. This can be done by passing a smooth function through the data as shown in Figure 5. Any annual systematic component in the data will be present in the residuals of the long term data with respect to this smooth trend curve.

Several different methods were used to analyze these residuals. Both one dimensional and two dimensional spectral analyses were not successful in identifying any underlying trend. Another approach is to classify the data by month. Generally several level surveys are made in a given year. However there is no consistent periodicity to these surveys.

For each of the 64 level surveys made over the 13 year period, we can take the height ($dZ$) of each pillar (i.e. the residual calculated above). Then for each survey and for each pillar we can classify this $dZ$ value for the appropriate month of the year. We can then take the mean of each month for each pillar. One can then estimate a model by passing a two dimension smoothing spline surface through these mean monthly data. This represents a 32 pillar by 12 month array where each value of the array is the mean $dZ$ over the 13 year period for that pillar and that month. This is the procedure used to establish the model shown in Figure 6.
August for the years 2005 and 2006. Clearly one senses similarity, nevertheless, there is considerable variability
This is shown in Figure 8. These two graphs show movements as measured by the roof HLS between March and
20% to 25 % of the vertical motion compensated for regularly by the SR jacks system. However this motion is very small with a peak to peak range of approximately 100um. This corresponds to roughly
This model shows a type of rocking motion as illustrated in Figure 7. In the winter and summer the SR is flat (in relative terms). However in the spring there is upward motion to the south of the ESRF. There is accompanied with a corresponding downward motion to the north of the ESRF. The situation is reversed in the autumn. What is particularly interesting is that this motion is along the same axis of maximum systematic movement seen earlier in Figure 4. However this motion is very small with a peak to peak range of approximately 100um. This corresponds to roughly 20% to 25 % of the vertical motion compensated for regularly by the SR jacks system.
The rest of the vertical motion is less predictable. To get an idea of this variability we can look at the roof HLS data. This is shown in Figure 8. These two graphs show movements as measured by the roof HLS between March and August for the years 2005 and 2006. Clearly one senses similarity, nevertheless, there is considerable variability
between these two graphs. Figure 8 also shows a particularity of the ESRF. Periodically, generally in the spring or autumn after there has been a lot of rain or snow melt; the dam down river of the ESRF opens its sluice gates to purge accumulated sediments built up in the river bed. This was done from April 4 to 8 of this year (2006) and is shown in the right hand graph of Figure 8 where we see the classical signature of this purging.

Figure 7: In these graphs we see the dynamic of the surface established in Figure 6. It represents a type of rocking motion. In the winter and summer the SR is flat as shown in the blue and red lines in these graphs. However in the spring there is upward motion to the south of the ESRF. There is a corresponding downward motion to the north of the ESRF. The situation is reversed in the autumn. What is particularly interesting is that this motion is along the same axis of maximum systematic movement seen earlier.

Figure 8: These two graphs show movements as measured by the roof HLS between March and August for the years 2005 and 2006. In the right hand graph we see a particularity of the ESRF. The dam down river of the ESRF periodically opens its sluice gates to purge sedimentary build up in the river bottom. Here we see the classical signature of this purging.
3.2. ESRF Machine and Site Horizontal Movements

Recently one of us (Geoffroy Emain) recalculated all of the old Distinvar- Ecartometer surveys [13]. This titanic effort was made so that data from this epoch could be compared with the more recent TDA5005 data. However it was not made in vain. Analysis of the radial (dR) component of these planimetric surveys has revealed surprisingly large horizontal movement signatures (Figure 9). The axis of this movement is clearly aligned along the *presque ile* towards the confluence of the rivers.

![Figure 9](image)

Figure 9: As with the long term vertical SR motion (Figure 4) there is a surprisingly large and systematic horizontal movement. It is actually only slightly smaller that the vertical motion with a range of 3 mm over 11 years. The axis of this movement is clearly aligned along the *presque ile* towards the confluence of the rivers.

Using the same techniques discussed above with the vertical annual motions, we can identify a surprisingly large horizontal annual motion (Figure 10). Peak to peak motion is in the order of ±0.2 mm. Its form is considerably more complicated than the vertical annual motion and cannot be explained at present. In the winter the horizontal position appears as a three period sinusoid form similar to a *tricorn* hat with its three maximums oriented towards the two rivers and roughly along the river axis to the south. It then evolves smoothly over the course of the year rotating counter clockwise to an elliptical form roughly aligned along the east-west axis of the machine in autumn and back to the original shape the following winter.
4. CONCLUSION

It has been shown that we are able to reliably measure precise vertical and horizontal movement signatures of the ESRF site. For the most part these movements are smooth. The long term movement components observed after the one off movements due to construction and landscaping are systematic in nature. The horizontal and vertical motions are roughly equivalent in magnitude but are along different axes. We have identified vertical and horizontal annual movement signatures. The vertical annual motion is small and manifests itself as a rocking motion along the long term vertical movement axis. The horizontal annual movement is both larger in magnitude and more complex than the vertical motion.

References


