THE MEASUREMENT OF THE ESRF STORAGE RING

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Abstract

The European Synchrotron Radiation Facility (ESRF) was established in 1988 as the world's first 3rd generation light source. Alignment was critical to its success, with quadrupole and sextupole magnet alignment tolerances maintained within 100 µm in both the horizontal and vertical directions perpendicular to the beam (dR and dZ respectively) (Farvacque L, 1988).

The dZ tolerance was achieved through high precision levelling. However, in the late 1980's only very specialised instruments could measure with the precision required for 100 µm or more in the horizontal plane. Two such instruments capable of reaching these tolerances were the distinvar and ecartometer. Developed at CERN for specialised high-precision accelerator alignment applications, the distinvar measured distances, and the ecartometer measured offsets, both with an accuracy of 50 µm.

However, the distinvar and ecartometer were cumbersome and the ESRF Survey and Alignment group were looking for an alternative. In 1999, the group successfully replaced both instruments with the Leica TDA500x robotic total station (RTS) without loss of precision. However, it was the combination of the TDA500x and specialised software that piloted the instrument, resulting in significant improvements and savings in time.

Today, the ESRF Storage Ring survey is conducted using the AT40x laser tracker. A total of 9,600 observations are made to 354 points by four teams of two people, all within an 8-hour shift. This paper discusses the evolution in instrumentation and techniques from the distinvar ecartometer survey that took 71 working-days to complete in the 1990s, to the current AT40x survey that takes 8-working days and is four times more precise than the distinvar ecartometer survey.

INSTRUMENTS: SOME BACKGROUND

In the 1980s, the distinvar was the only instrument capable of measuring precise distances in the range of 1 to 50 m, with a precision of less than 1 mm. This instrument used stretched calibrated invar wires, which is why many older laboratories (CERN, SLAC, ESRF…) are equipped with calibration benches.

The ecartometer measures precise offset distances from a point to a wire stretched between two fixed points. Geometrically, this configuration forms a triangle, with the ecartometer providing highly accurate small angle measurements (Mayoud, 1987).

In the mid to late 1980s, KERN introduced the Mekometer ME5000, a distancemeter capable of measuring precise distances from roughly ~20 m up to several thousand meters. Programs were developed to try to decrease the minimum distance, but the process remained labour-intensive (Copeland-Davis, 1989). Other instruments on the market, such as the Com Rad geomensor 204 DME offered similar capabilities to the mekometer. Another similar instrument used at CERN for the LEP, (later the LHC) primary network was the terrameter, a two-coloured laser distancemeter. However, it was both expensive and complicated to operate.

Precise electronic theodolites, such as the Kern E2 were available but were not considered for use in the ESRF accelerators.

Nevertheless, electronic theodolites were used elsewhere, often for angle intersections with scale derived from invar bars or other distance measurements. Modern total station instruments, as we know them today had not yet been developed.

All of this occurred before the advent of precise easily available GNSS technology and laser trackers.

Meanwhile, in the mid to late 1980s there was a significant effort to develop a functional laser tracker. According to Wikipedia:

> *"The first laser tracker was invented in 1987 by Dr Kam Lau, CEO of API (Automated Precision, Inc.) while at NIST and made commercially available by API in 1988 with its first production unit being made available to Boeing under a 9-month lease agreement. Tennessee Technology University received an API 6-D laser tracker in 1989. Instruments were later produced by Kern in 1991 following a technology agreement with API. Currently, there are three well known manufacturers of Laser Trackers; FARO, API, and Leica."*

Other early laser tracker systems, such as SMX and Chesapeake were also developed. These systems were used in accelerators in the USA, including SLAC and APS in Chicago. However, they were very expensive and never considered for use at the ESRF in the early days.

While photogrammetry was extensively used in large detectors such as those at CERN, it was not commonly applied in accelerator alignment during that time.

THE INITIAL ESRF NETWORK AND THE DISTINVAR/ECARTOMETER YEARS

As with all accelerators at the time, the original ESRF network was a hierarchical system of reference points. At the ESRF these reference points were installed on pillars, wall brackets, metal tripods and the magnets within the accelerators.

The primary ESRF network comprised of 10 exterior concrete pillars strategically installed around the site (Figure 1). The positions of these pillars were accurately measured using a DI2000 distancemeter. Notably, the DI2000 was calibrated on the CERN calibration bench to remove the characteristic cyclic error associated with the instrument. These pillars were initially used to determine the precise positioning of the buildings that comprise the ESRF (Figure 2).

This primary network was mainly used to define and integrate all other networks; including the secondary networks. These secondary networks comprised 24 pillars and 24 articulated wall brackets installed in the Booster Synchrotron (SY), as well as 32 pillars and 32 wall brackets installed in the Storage Ring (SR) tunnel. Additionally, 128 removable aluminium tripod stations were used to form the original Experimental Hall (EXPH) network.

Links were established and maintained through an elaborate system of wall penetrations, extending to both the SR exterior and interior tunnel walls along the axes between the periphery pillars and the central pillar shown in Figure 1. Additionally, the port-end walls contained penetrations that could be opened for observations between the machine and the beamlines.

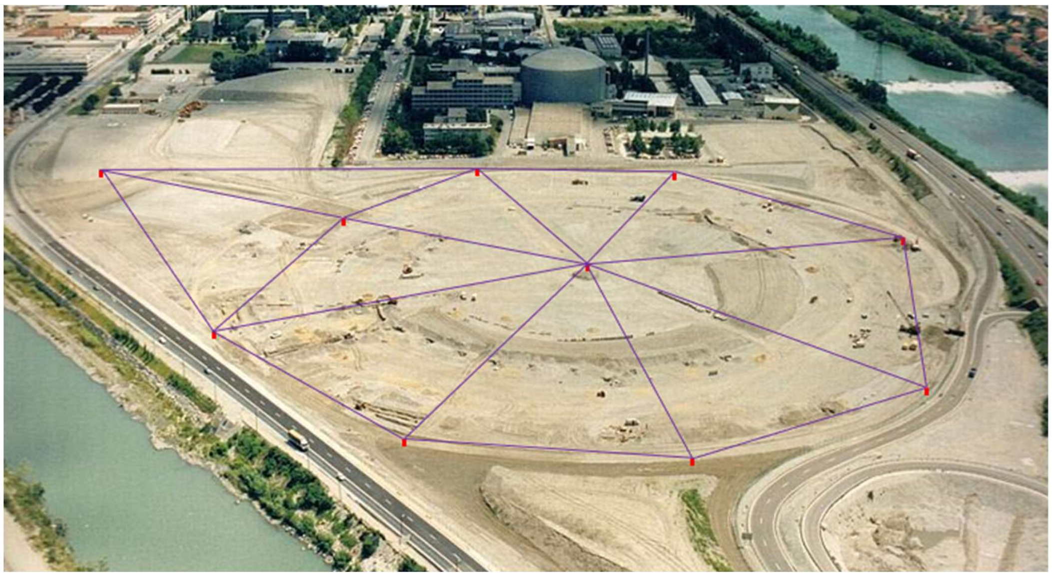

Figure 1 The original exterior pillar network showing some of the distance measurements that were made.

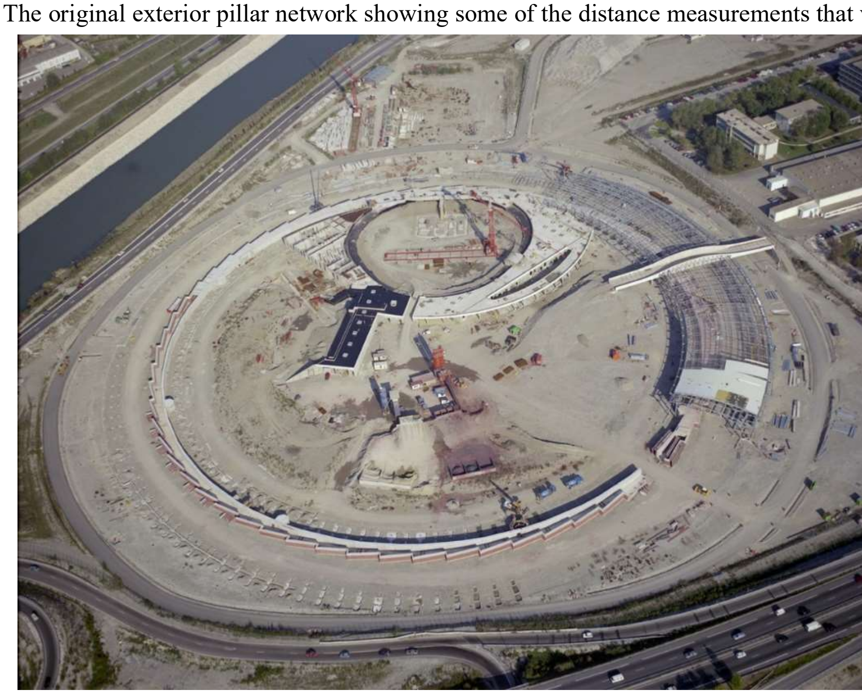

Figure 2 The construction of the ESRF in 1990.

Figure 3 View of the old SR tunnel showing the pillar wall bracket secondary network and the machine. Just to the left of the inscription ID26 is a (closed) window penetration between the SR and the ID26 beamline.

In the early 1990s, calculating the 64 points comprising the secondary network with 452 measurements plus 14 T3000 angle, and DI2000 distance measurements pushed the limits of the existing software and hardware. However, it was still possible; allowing us to calculate the secondary network in a homogeneous manner.

Measurements were taken from the fixed secondary pillar wall bracket network which was held fixed in the calculation to the magnets themselves. The network consisted of 320 points with 480 ecartometer and 760 distance measurements. The standard deviations for the distances and ecartometer offsets were approximately 100 µm and 50 µm respectively. The error ellipse semi-major axes were around 220 µm and aligned perpendicular to the beam travel. The semi-minor axes were roughly 120 µm aligned along the beam.

Distinvar ecartometer surveys were challenging and highly labour-intensive. Many measurements required teams of three; with up to five needed for the longer distances of 52 m.

We were keen to find an alternative to this labour-intensive method for measuring our networks.

THE TDA500X

Several key developments in the late 1990s provided an effective solution to our problem. One of the most notable was the release of Leica TDA5000 in autumn 1997. At the same time, significant developments in both hardware and software simplified instrument control and calculations.

The TDA5000 was introduced to the accelerator alignment community during the 1997 IWAA held at APS in Chicago (Gottwald R, 1997). The ESRF purchased the first of five TDA500x instruments in June 1998. The TDA5000 had the following specifications: 0.2 mgon (i.e. 3 µrad) in the horizontal and vertical angle measurements, and 1 mm + 2 ppm in the distance measurements.

At this time, the accelerator alignment community was more focused on laser trackers equipped with high-precision absolute distance meters (ADM) and interferometric distance meters (IFM), than on Robotic Total Stations (RTSs) like the TDA5000.

However, the TDA5000 had two significant benefits over laser trackers in the late 1990s.

The angle encoders in the TDA5000 offered two major advantages over the laser trackers available at the time. First, its angle encoders were 4 to 5 times more precise than those in most laser trackers, such as the LTD500, Faro Xi and API T3. Although the significance of this angle precision for accelerator alignment (discussed in the next section) was not fully understood at the time, it was a crucial factor. Second, and perhaps even more importantly, the TDA5000 was at least four times less expensive than the Leica, Faro or API laser trackers.

In the late 1990s, there was little or no market software available for accelerator alignment. We, at the ESRF as colleagues at other laboratories, had to rely on poorly adapted commercially available software or develop our own. Writing software in the 1990s, often using languages like C, C++, Visual Basic, Turbo Pascal -was resource intensive, laborious and required skills that most surveyors simply did not and still do not, possess.

At the ESRF, starting in 1997, we began using LabVIEW to interface with our various instruments. LabVIEW provided an intuitive program Graphical User Interface (GUI) and supported many commonly used communication protocols such as RS232, RS422, A/D conversion, UDP and TCP. This made it relatively easy to control devices like electronic theodolites, levels and importantly Robotic Total Stations (RTSs) like the TDA5000; as well as other devices such as HLS systems, Jacks, interferometers.

LabVIEW provided us with the tools to create relatively sophisticated applications; significantly simplifying and improving our network measurement processes.

Note, it wasn't until the mid-2000s that Spatial Analyzer (SA) started being used in accelerator laboratories, initially at DIAMOND and then later at most other accelerator laboratories. The ESRF didn't start using SA extensively until the early 2010s.

THE IMPORTANCE OF ANGLE MEASUREMENT IN ACCELERATOR ALIGNMENT

In the late 1990s, the accelerator community was highly interested in high-precision distance measurement alternative to the distinvar, which was universally disliked and avoided at the time. This led many laboratories to adopt instruments like the LTD500, the Faro Xi, or API Laser Tracker3. On paper, these instruments had similar specifications. When we tested these instruments at our calibration bench, we observed some differences in the ADM, but overall their IFM and angle performance were roughly the same (Figure 6). Typically, coordinate precision was quoted in parts per million - ppm. For example, the LTD500's coordinate precision for a static target was specified as 10 ppm at 2σ. Although the angle precision was unclear, the 10 ppm suggests that, at a distance of 1 m distance, the horizontal and vertical angle precisions would be approximately 10 µrad. The Faro Vantage laser tracker had a maximum permissible error (MPE) of ±20 µm + 5 µm/m. In comparison, the TDA5000's angle precision was specified as 3 µrad.

Why is this important?

Physically, all particle accelerators, whether linear, circular or racetrack shaped, can be reduced to the notion of a long narrow tunnel with magnet components extending in both directions.

See Figure 3 for what this really looks like.

In general, the sensitive alignment directions for all accelerators are the two directions perpendicular to the beam's travel. At the ESRF, we refer to these directions as dR (R is for radial) for the horizontal direction perpendicular to the beam's travel, and dZ for the vertical direction perpendicular to the beam. At the ESRF the direction along the beam is designated as L for longitudinal.

Given the long, narrow tunnel and our measurement method, what factors are most important?

Figure 4 illustrates the relationship between angle and distance measurements in particle accelerator alignment. Clearly, angle measurements are more important in the directions perpendicular to the beam travel, as these directions are most sensitive to alignment. In contrast, interferometric distance measurements in the direction along the beam have limited impact on alignment in these sensitive directions, and alignment along the beam itself is not as important as in the directions perpendicular to beam travel. What is essential in this configuration is achieving very precise angles. as demonstrated by numerous network simulations.

This has also been proven by measurement, which, is how we uncovered the principle at the ESRF.

In the late 1990s during our efforts to replace the distinvar/ecartometer network surveys, we tested the LTD500 and a TDA5000 against the distinvar and ecartometer network surveys (Martin D, 1999). Figure 5 shows a comparison between the LTD500 laser tracker, the distinvar/ecartometer and the TDA5000 determinations of the ESRF SR network.

What stands out immediately in Figure 5 is that the LTD500 laser tracker network determination is less accurate than both the distinvar/ecartometer and, particularly, the TDA5000 network determination. This discrepancy is due to the relative angular imprecision of the LTD500 compared to the ecartometer and the TDA5000. This is further confirmed when we combine the LTD500 distance measurements with the TDA5000 angles, which produces the best results, though not significantly better than those from the TDA5000 network surveys.

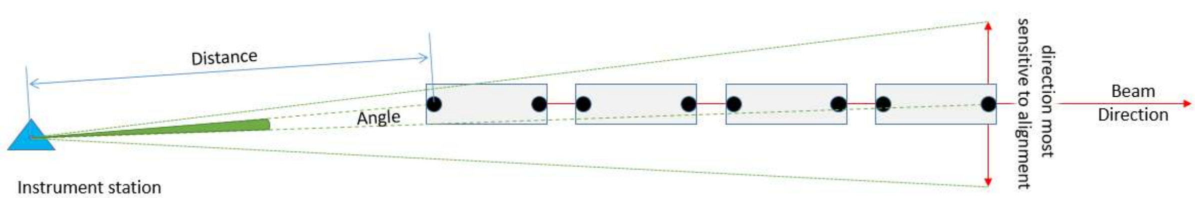

Figure 4 Interplay between distance and angle in particle accelerator alignment.

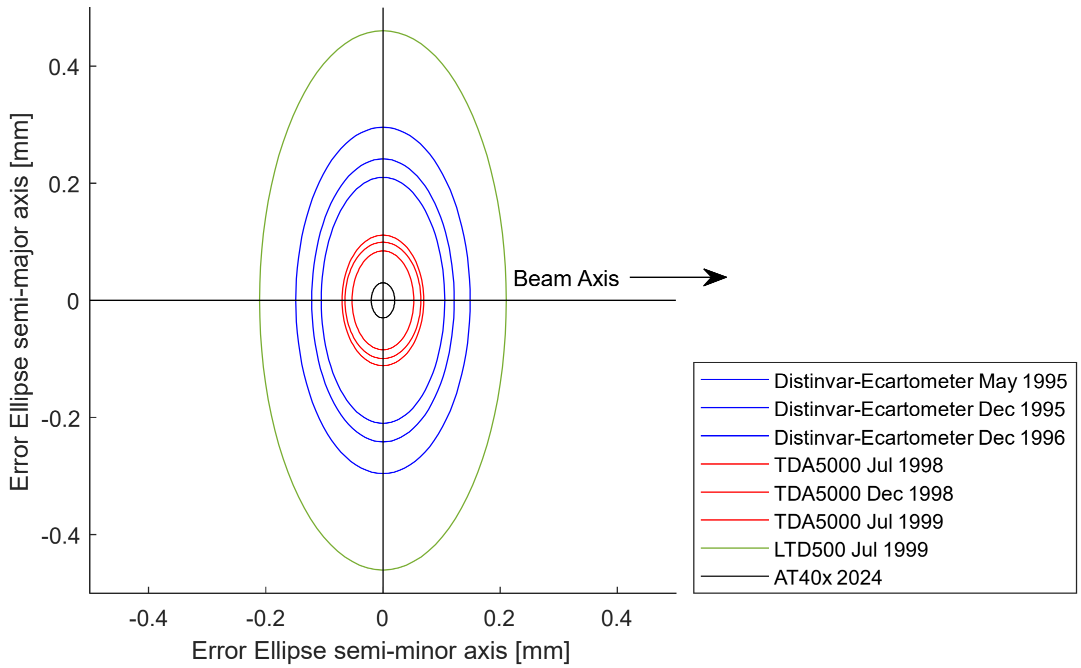

Figure 5 Comparison of the measurement precision of the ESRF SR network determined by a LTD500 laser tracker, the distinvar/ecartometer and a TDA5000.

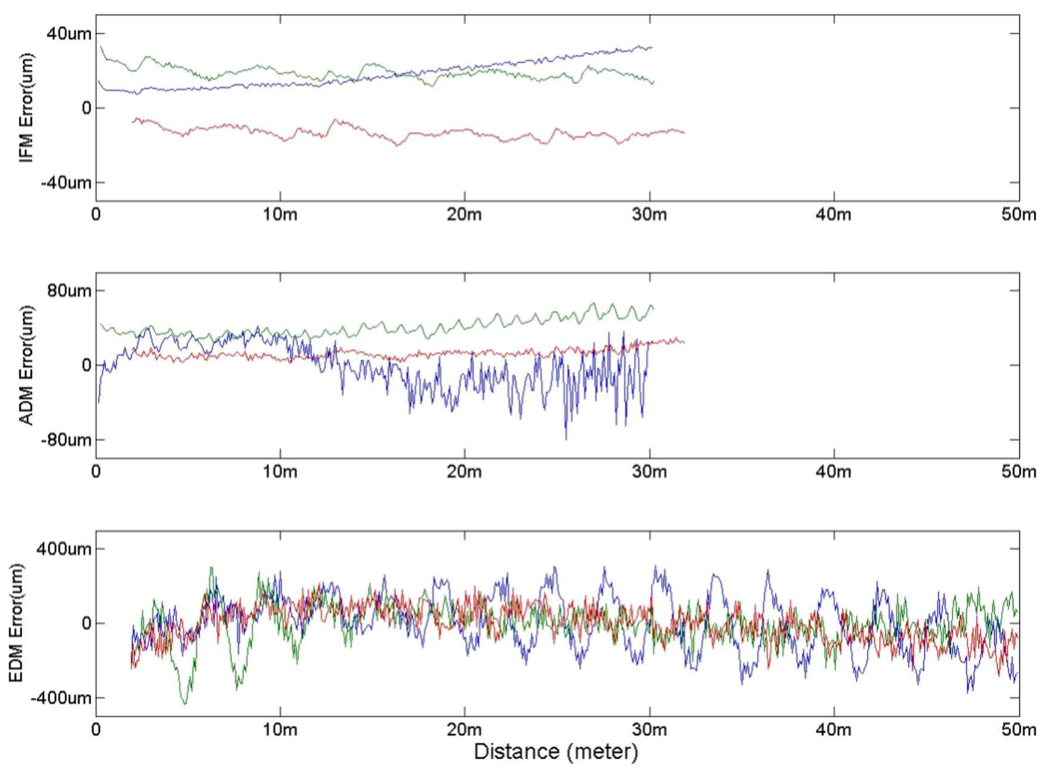

Figure 6 The top graph shows the calibration curves four three laser tracker IFMs. The middle graph shows calibration curves for three laser tracker ADMs. The bottom graphs show calibration curves for the TDA500x distancemeters.

Considering the cost difference between the laser trackers and the TDA5000 in the late 1990s, along with the improvement in overall precision, choosing the TDA5000 was an easy decision.

However, we significantly improved the performance of the TDA5000 by calibrating its distancemeters. Recall that the precision of the TDA5000 distancemeter was specified as 1 mm + 2 ppm. A key component of this uncertainty being the distancemeter's cyclic error.

From 2001 to 2012 the ESRF held COFRAC ISO 17025 accreditation for distancemeter calibrations (COFRAC Accreditation Number 2-1508). A key motivation for pursuing the accreditation was the drive to reduce the uncertainty of the TDA5000 distancemeter. Figure 6 shows calibration curves for three different laser tracker IFMs (top graphs), ADMs (middle graphs) and three ESRF TDA5000 distancemeters (bottom graphs). The expanded uncertainty (k=2) for the IFM and ADM calibrations is 0.050 mm, while for the TDA500x distancemeter calibrations the expanded uncertainty (k=2) is 0.170 mm.

Calibrating the TDA5000 distancemeters considerably improved the uncertainty in the network determinations.

BETTER SOFTWARE AND INSTRUMENTATION = FASTER MORE PRECISE NETWORK DETERMINATION

Improved instrumentation and improved application software provided the necessary groundwork for faster and more precise network determination. However, this process was gradual and did not happen overnight.

In 1998 the aim of the ESRF Survey and Alignment group was to:

a) Discontinue the distinvar/ecartometer survey method;
b) Achieve the capability to measuring the absolute positions of the entry and exit points of SR girders with a precision better than 0.2 mm in the directions most alignment-sensitive directions, to errors dR and dZ;
c) Complete a full SR survey of all 320 points in the network within a single eight-hour shift.

To accomplish these tasks, we required an instrument with the necessary capabilities along with a methodology and application software designed to realise these goals.

The Instruments

By October 1999 (i.e. the IWAA) we demonstrated convincingly that the TDA5000 was the instrument best suited to these goals. Indeed, it possessed several favourable attributes that made it an ideal choice:

- It offered the precision required for accurate point determination, particularly the precise angles required for better point determination that the distinvar/ecartometer pair, and the distancemeter performance could be improved considerably through calibration.
- It was highly portable, easily transported between stations quickly set up. Weighing less than 15 kg, it stood in clear contrast to the bulky laser trackers of the time, which along with their controllers weighed over 50 kg.
- It was highly user-friendly and easy to operate with a portable computer, allowing it to be integrated into very powerful programs.
- The Automatic Target Recognition (ATR) feature enabled fully automatic operation without the need for manual target sighting. This completely eliminated operator errors that often-affected theodolites. This was a key factor in their limited use of accelerator alignment at the time.
- It was rugged and reliable.
- The TDA5000 was highly cost-effective compared to laser trackers at the time. In fact, the combined cost of four out of the five TDA500xs, the ESRF eventually purchased was still less expensive than that of one single laser tracker.

In the early 2010s a new instrument appeared on the market that had all of the positive characteristics of the TDA5000, while offering even greater performance and precision. Due to the compatibility with our software and methodology, integrating the Leica AT40x series of compact laser trackers into the survey process was straightforward

The Methodology

The current methodology is closely based on the initial TDA5000 survey introduced in late 1999, which later evolved into the AT40x survey in 2012, with a final 2019 version implemented for the new ESRF EBS machine. With each successive change, the focus has been aimed on improving either precision or speed.

So, what do we do now?

The SR consists of 32 cells each containing four girders: G1, G2, G3 and G4. In the straight section of injection of Cell 4 there is a special G0 girder. There is also a combined function dipole/quadrupole DQ2 magnet installed between the G2 and G3 girders. This magnet assembly is fixed to the G2 girder exit, and freely supported on the G3 girder entrance.

In every version of the SR survey from 1999 to 2024, we have measured two points on each girder, one at its entrance and one at its exit. Generally, these points correspond to the entrance of the first magnet and the exit of the last magnet mounted on the girder. We assume, with a high degree of confidence, that the other magnets attached to the girders do not move independently of the girder*. For the EBS, we also measure three points on the DQ2 magnets which are positioned between the G2 and G3 girders.

There are a number of physical and temporal constraints we must respect in the survey.

The first and most critical requirement is the temporal constraint. The full survey of the SR must be completed within a single 8-hour shift, which must take place, on the first day of the shutdown. Typically, this shift is scheduled for the afternoon, from 13:00 to 21:00, though adjustments can be made for logistical reasons. This specific time window is the only period which we can guarantee that no other groups will interfere with our measurements. I.e. no roof openings, no bakeouts, or personnel working in the corridor where we install our instruments.

A second physical constraint involves the height of the DQ2 reference points, which are 200 mm lower than the reference points for the other magnets (see Figure 8a). This is just one of numerous visibility or line-of-sight constraints that must be managed during the survey. The challenge essentially lies in optimising the number and position of the instrument stations to ensure adequate redundancy in observations while completing the survey within the 8-hour shift. The network design initially included some test stations, followed by many simulations using different configurations – such as instrument station positions, number of observations and redundancy -. before deciding on one of several possible optimal configurations.

The final result of this study consists of three instrument stations per cell, with each station being independently occupied twice. The survey operation involves four teams, each offset by ¼ of the machine's length or eight cells apart. Each team measures ½ of the SR machine, covering. 16 cells in total. For example, Team 1 starts at Cell 01 and measures through to Cell 16, while Team 2 begins at Cell 08 and continues to Cell 24. As a result, both Team 1 and Team 2 will measure all points in Cells 08 through to Cell 16 using two different instruments. This means there are:

$$32 \text{ cells } \times 3\,\frac{\text{positions}}{\text{cell}} \times 2\,\frac{\text{instruments}}{\text{position}} = 192 \text{ instrument stations}$$

There are three additional special stations for a total of 195 instrument stations in the survey.

We also wanted each of the three instrument stations to follow the same observation pattern in all 32 cells. This is a challenging issue because although the machine is generally consistent, there are some notable exceptions particularly in the RF and collimator zones. Additionally, each straight section of the machine is different meaning that while a line of sight may work in one cell, it may not work in another. To address this, we chose the most restrictive option that still allowed the maximum number of common observations from all three instrument stations across all 32 cells. The general network schema is shown in Figure 7.

A total of 3,200 distance, horizontal and vertical angle measurements are made, for a total of 9,600 observations. There are between 8 and 12 measurements per point with the exception of the points on the DQ2 magnets which are measured four times each. Due to time constraints we do not use two-face measurements. However, we calibrate the four instruments before each survey, and the high level of redundancy and the number of independent measurements compensate for the lack of two-face observations. Indeed, with properly calibrated and functioning instruments, we believe two-face measurements are unnecessary. Finally, every point is measured by at least two different instruments.

There are additional logistical constraints to consider. For safety reasons, fences have been installed in the SR, but the grills on these fences obstruct the lines of sight. To address this and in agreement with the Safety Group, small holes have been cut in the fences (Figure 9). However, using these holes requires the instruments to be positioned very precisely. In fact, precise instrument positioning is generally required. To ensure this, all instrument stations have been clearly marked on the floor (Figure 8b).

The initial survey using the AT40x instruments was conducted with heavy Leica aluminium tripods, but the results were disappointing. We believe the instruments, and/or tripods moved during the measurement process, so we replaced the aluminium tripods with Brunson stands, which significantly improved the results and aligned with our expectations. However, the Brunson stands were very heavy, unwieldy, and difficult to manoeuvre on the uneven surface of the ESRF SR floor. Furthermore, the freeway where we position the instruments in the new EBS was considerably narrower than in the old machine, where the Brunson stands had been used. This made them impractical, so we had to find another solution.

We decided to use the heavy Leica stands equipped with a custom spacer to ensure the instrument was at the optimal height. The setup is shown in Figure 10.

* We have measured the magnet positions on the girders on several occasions both in the old and the new machine. The most recent measurement showed the difference between magnet positions measured on the on the girders between their assembly in 2018 and the measurement campaign in 2022 was $U(R) = 15$ µm and $U(z) = 13$ µm. Recall R and Z are the directions perpendicular to the beam in the horizontal and vertical directions respectively.

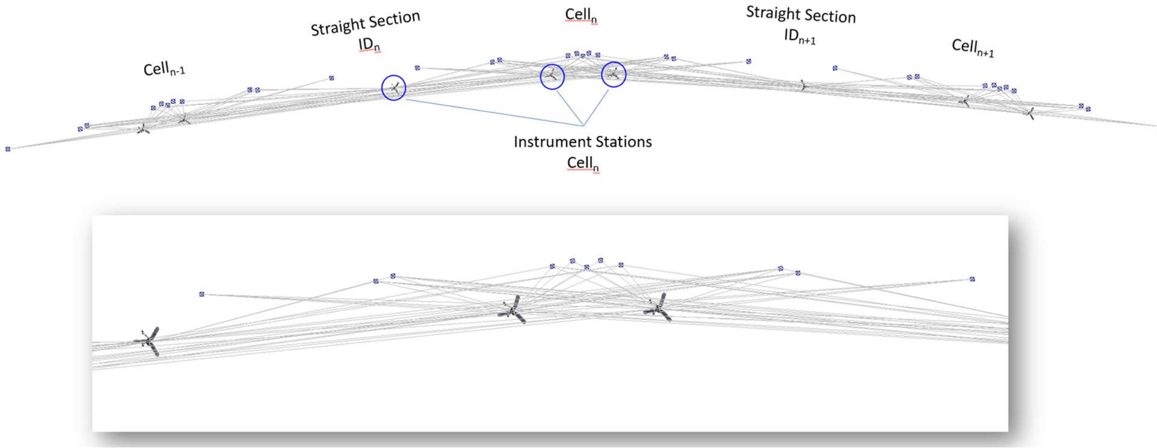

Figure 7 Instrument stations and measurements for three SR cells. The lower part of the figure zooms in on the instrument stations and observations in Cell n

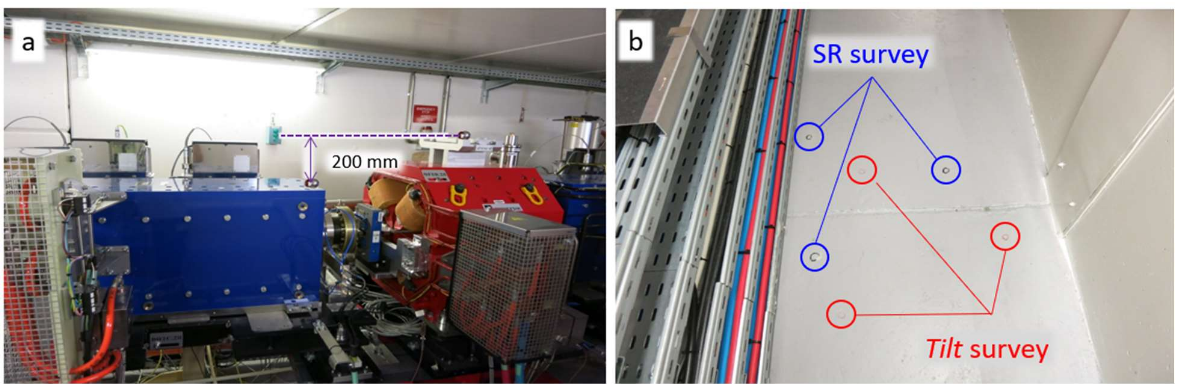

Figure 8 a) 200 mm height difference between the DQ2 magnet straddling the G2 and G3 girders, and the adjacent QF8 magnet. b) on the right-hand side - points marked on the floor to materialise the positions of the instrument stations.

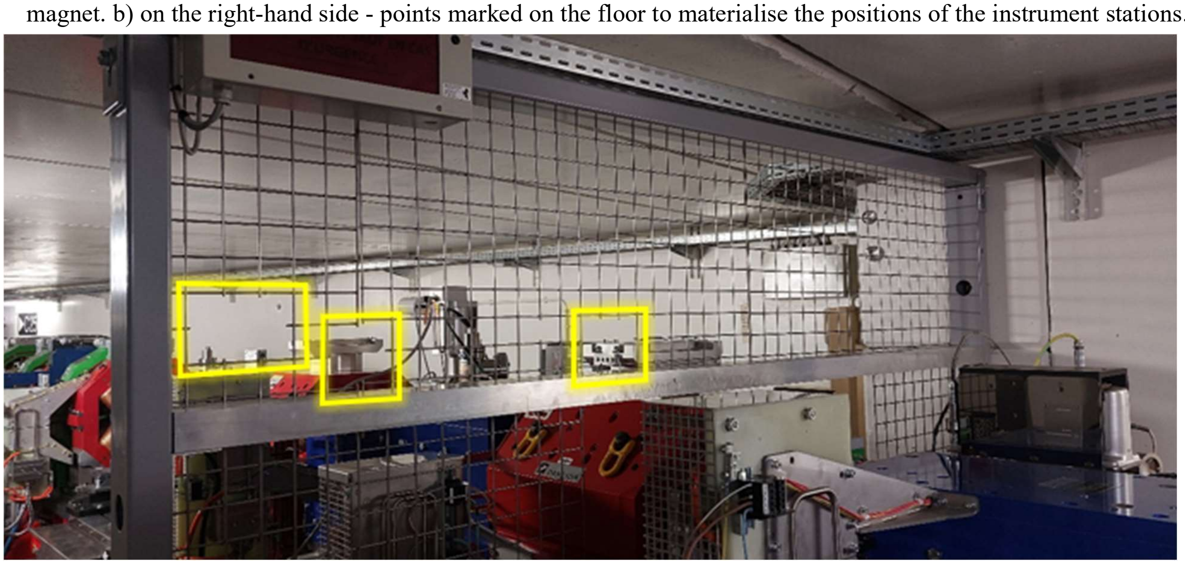
Figure 9 Holes in the safety fence for lines of sight.

Figure 10 A typical instrument station in the EBS SR. We can see the heavy Leica stand with the custom shiny aluminium spacer to ensure the instrument was at the optimal height. In the foreground we see the laptop on a cart that follows the instrument in the tunnel. This picture also shows the issues we have with lines of sight through the straight sections.

The application software

Instrument acquisition and application software has always been used at the ESRF. In the early 1990s, relatively simple software was used to pilot the distinvar and ecartometer measurements and recuperate observations. The operator could select the two or three points being measured, and the calibrated wire. This software had the huge advantage that data was transferred automatically from the instrument to a formatted text file. Instrument serial numbers, station names and calibrated distances and offsets were managed by the software thereby reducing common operator transcription errors to a minimum. The programs were written in Turbo Pascal running on Windows DOS.

At that time, levelling was performed using the Wild N3 precision level. However, there was no accompanying software so all data had to be recorded manually on paper. This introduced a high risk of error, s. Completing an 8-hour shift of N3 measurements to a Taylor-Hobson sphere was quite a challenge. There were more potential errors when the results were transcribed from paper to the text file used for calculations. Later, paper was replaced by Excel, but transcription issues remained, as there was still a risk of mistakes when relaying data from the person reading the level to the person entering the data.

Today, of course we can communicate directly with all the instruments we use. We also have quite sophisticated software that enables a nearly fully automated survey process, greatly reducing the potential for human error and improving efficiency.

Our survey application software is currently based on LabVIEW with a direct link to the instrument (Leica AT40x laser tracker) using the Leica Software Development Kit (SDK). With the SDK we can directly control the tracker, allowing access to key functions such as the instrument's initialisation, measurement, movement and locking.

The entire process is guided by an autopilot file representing the survey to be completed. The file essentially consists of a sequence of stations and points to be observed. It works in tandem with a database file containing approximate coordinates for all stations and measured points.

The measurement sequence starts by choosing the instrument, whether it has a wireless or cabled connection to the computer, the results file name and whether it is a new or existing file, and the autopilot file for the survey. The survey is started by selecting the instrument station and the first measurement.

Today, the survey is conducted exclusively with the AT403, which means we only need to initialize the instrument at the first station. This approach saves approximately one minute at each subsequent station. Although this may seem small, with around 50 stations per team, the total time saved amounts to 50 minutes which is significant.

With knowledge of the instrument and the approximate coordinates of the observed points, we only have to aim at the first point and initiate the automated process for the current station. The instrument then locks onto the reflector, takes the measurement and automatically targets the next station. It waits for the operator to position the reflector, measures the point and repeats the process for all observed points at that station.

There are several controls in place to prevent errors, such as:

- The possibility to stop a measurement if something goes wrong, such as an unexpected obstruction or interference in the measurement path.
- The main issue is the operator's speed in moving the reflector to the next station. In the narrow tunnel, if the operator is not quick enough, the tracker may inadvertently lock onto and measure the previous point instead of the new one. To address this, we continuously monitor the reflector's position to verify it has moved before initiating the actual measurement.
- We calculate a best-fit of the observed points against the approximate coordinates at each observation to check for any issues, such as measuring the wrong point or a potential movement of the point's position. If the fit is unsatisfactory, a pop-up window will alert us to the problem, offering the option to either retake the measurement or keep it but excluding it from future subsequent fits. This can happen if the point has indeed moved from the approximate position.

Figure 11 shows the main window of the application, where we can see the option to interrupt the process, if required, by pressing the *Interrupt Measure* button.

At the end of a measurement sequence for a station, additional measurements can be taken if required. While this is uncommon in the highly structured SR survey, it may occur in other surveys. For instance, just as lines of sight can be blocked by the installation of a new experimental hutch or cabin, new lines of sight may become available when equipment is removed (Figure 12).

After each measurement, all observation information is recorded in a text file and saved to disk. This file can then be imported into an Excel file which can then be used for least squares calculations. (Figure 13).

Typically, a team takes six hours to complete 900 measurements. On average, considering factors such as moving between stations, set-up, instrument installation, and the measurements themselves; this amounts to approximately 2.5 observations per minute.

Although the current setup works well, if we replace the AT40x with a new generation of trackers, for example the Leica AT500, we will need to rewrite the instrument interface to accommodate a different SDK, for example, the Leica Metrology Foundation (LMF) SDK. There is also the possibility of migrating the LabVIEW application to MATLAB or Python in the future. Finally, changing the instrument, will require modifications to both the stand and the interface with the instrument.

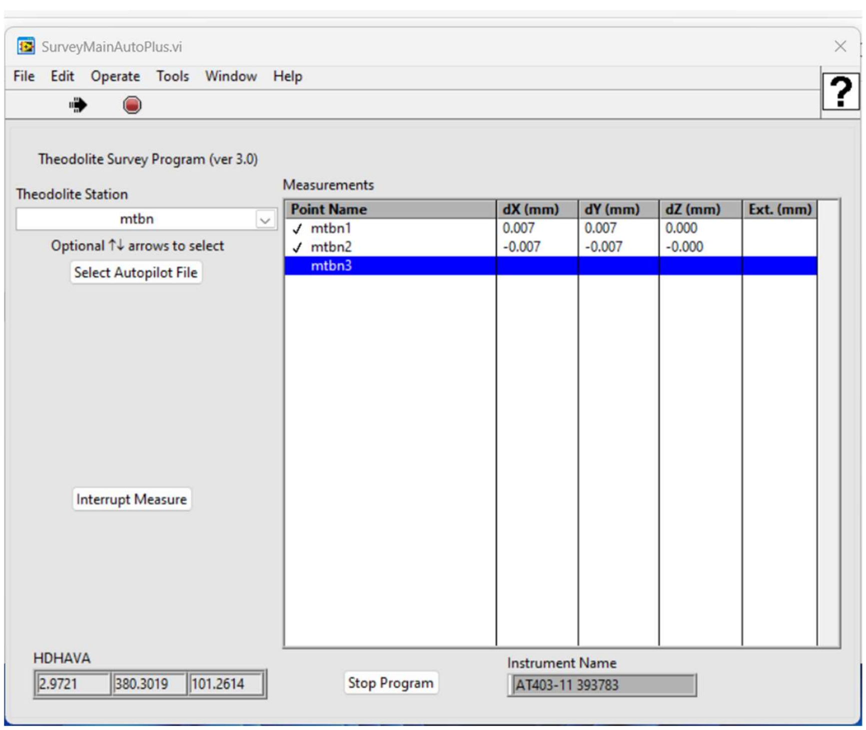

Figure 11 The main survey application.

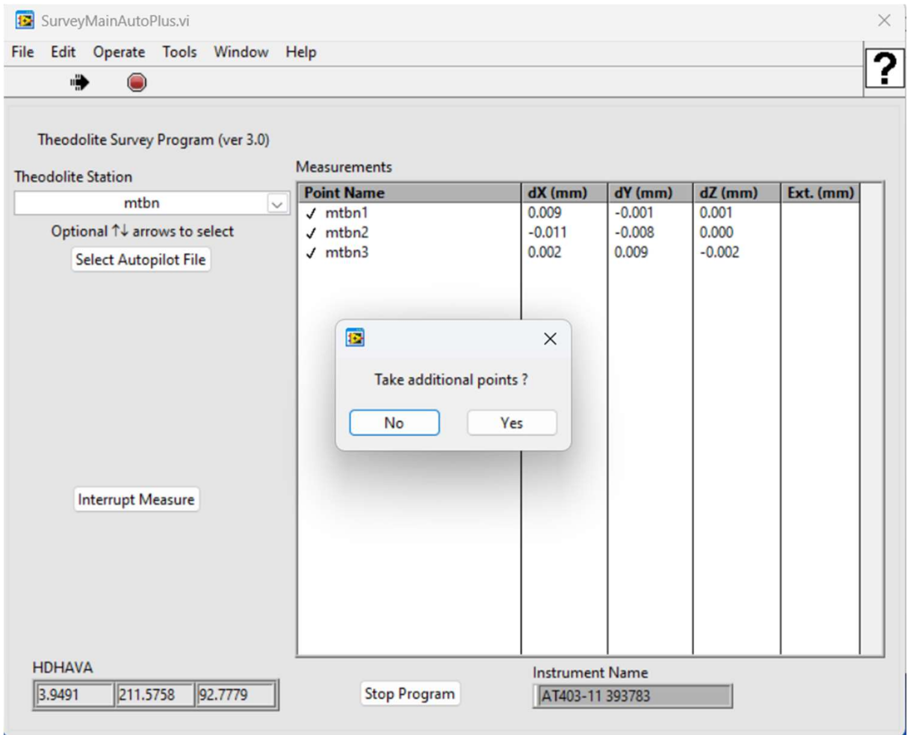

Figure 12 At the end of a measurement sequence we can take addition observations if appropriate.

Station	Measured Point	Horiz. Dist. (m)	Weight HD (mm)	Hz Angle (gon)	Weight Hz Angle (dmgon)	Vert. Dist. (m)	Weight VD (mm)
STAT_EXPH/A-FW/ID01	EXPH/A-PIL/004E	29.928940	0.015	184.4518	1.50	0.324833	0.03
STAT_EXPH/A-FW/ID01	EXPH/A-PIL/003E	37.545354	0.015	182.2869	1.50	0.418198	0.03
STAT_EXPH/A-FW/ID01	EXPH/A-PIL/002E	45.133869	0.015	180.3121	1.50	0.415194	0.03

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Date	Time	Tracker	Slope Dist. (m)	T (°C)	P (hPa)	H (%)	Horiz. Dist. (m)	Calib. Corr. (TDA only) (m)	Extension (m)	Vert. Angle (gon)	Sphericity Corr. (m)
Tue 30 Jul 2024	15:28:00	AT403-12 393781	29.930702	23.50	992.8	62.5	29.928940	0.000000	0.000000	99.3092	0.000070
Tue 30 Jul 2024	15:28:00	AT403-12 393781	37.547681	23.50	992.8	69.9	37.545354	0.000000	0.000000	99.2911	0.000110
Tue 30 Jul 2024	15:29:00	AT403-12 393781	45.135777	23.50	992.7	63.9	45.133869	0.000000	0.000000	99.4146	0.000159

Figure 13 After each measurement observations are written to a text file and saved to disk

IMPROVEMENT OVER TIME

We will now focus on the significant improvements made since the ESRF was built in the early 1990s. It is important to note that, there have been three main measurement epochs:

- 1992 to 1998 – the distinvar and ecartometer for planimetry and N3 for altimetry.
- 1999 to 2012 – TDA500x robotic total stations for planimetry and the DiNi for altimetry.
- 2013 to 2024 – AT40x laser trackers for both planimetry and altimetry.

1992-1998 period distinvar, ecartometer, N3 Level

As we have previously seen, in the early 1990s the ESRF had a hierarchy of survey networks. At the top of this hierarchy was the *primary* exterior pillar network, which provided the overall structure and connected all the other networks at the ESRF. This primary network served as a skeleton for the *secondary* networks which provided the reference for the accelerators themselves. At the ESRF there were several interlinked *secondary* networks consisting of pillar, wall bracket and metal tripod networks: the Pre-Injector/Transfer Line 1 (PINJ – TL1), the Booster Synchrotron/Transfer Line 2 (SY – TL2), the Storage Ring (SR), and the Experimental Hall (EXPH). These secondary networks provided the reference frame for the machine and beamline networks which were used to align and maintain all components of the accelerator such as magnets and beamline components.

The primary exterior pillar network was measured using the T3000 theodolite and the DI2000 distancemeter. However, in this paper we are mainly concerned with the alignment of the SR. As for the secondary pillar/wall bracket network which consists of 32 pillars and 32 brackets we conducted measurements using the distinvar and ecartometer. Specifically, the time and resources for the survey were:

- Team(s) of 2 people 4 hours for 60 measurements with a 2.5 m wire;
- Team(s) of 3 people 34 hours for 300 measurements with 13 m and 26 m wires;
- Team(s) of 5 people 8 hours for 60 measurements with a 52 m wire.
- Team(s) of 3 people 6 hours for 32 ecartometer measurements.

To summarize, the distinvar part of the survey took roughly 19-working days for 420 measurements, and the ecartometer part of the survey took roughly two working days for 32 measurements. In addition, a team of two people took roughly one day to measure distances and angles from the centre of the site to the machine and vice versa to connect the SR secondary to the primary exterior pillar network with the T3000 theodolite and the DI2000 distancemeter.

The second part of the survey connected the secondary reference network to the 320 points on the SR machine itself. This involved:

- Team(s) of 2 people 44 hours for 560 measurements with wires less than 6m;
- Team(s) of 3 people 16 hours for 200 measurements with wires greater than 6 m;
- Team(s) of 3 people 29 hours for the 480 ecartometer measurements.

To summarize, the distinvar part of the survey took approximately 17 working days to complete 760 measurements, while the ecartometer required about 11 working days to complete 480 measurements.

Finally, a team of three people took about two days before the survey and another two days after to calibrate all the wires used.

The height measurement of both pillar/wall bracket and machine network were conducted simultaneously. There were 64 pillars and wall brackets, plus 320 machine points for a total of 384 points in the two networks. Four teams of two people took eight hours to take the 1,000 measurements for a grand total eight working days to do the SR levelling.

In total, the complete survey required 63 working days for planimetry, a complete survey covering approximately 1,700 measurements, and eight working days for altimetry, for the period 1992-1998 covering 1,000 measurements.

In the early 1990s the network calculations were performed on a VAX computer Although it was considered one of the most advanced and high-performing computers available at the time., it was unable to perform the least squares calculation for both the combined ESRF pillar wall bracket and the machine networks simultaneously. The SR survey calculation instead was divided into two parts and required three separate calculations. The first part consisted of the pillar wall bracket network which included 64 points. The second part comprised the machine itself with 320 points. However, this calculation was divided into the two halves of the machine, with each half comprising about 170 points. The pillar wall bracket remained fixed for the two machine calculations.

1999-2012 period TDA500x and DiNi electronic level

The measurement of both pillar wall bracket networks and machine comprising 64 pillars and wall brackets and 320 machine points for a total of 384 points and 3,200 measurements, took three teams of two people one eight-hour shift, for a total of six working days to complete.

The height measurement of both the pillar/wall brackets and machine networks comprised 384 points and 680 observations. Note, each level station was measured twice. After the first series of measurements, the instrument height was changed and all of the points were re-measured a second time. If the two series of measurements matched, the average of the two height differences was calculated. If they did not match, a new series of measurements was taken at a different instrument height. This process was repeated, usually no more than twice, until the two series of height differences agreed within a specified tolerance. Therefore, the 680 observations were the average of two independent stations, or 1,360 observations. The survey took three teams of two people on one five-hour shift or about four working days to complete.

The total for a complete survey for the period 1999-2012 was therefore six working days for planimetry and four working days for altimetry.

By this time there were no longer any constraints on computing power and the pillar/wall bracket and machine networks could also be calculated together. During this period, we also recalculated all of the previous distinvar/ecartometer pillar/wall bracket networks in one global calculation. This allows us to compare all of the surveys from the difference epochs in the same way.

Finally, by this time we no longer relied on the exterior pillar network for the survey. There were enough angle and distance observations to maintain the machine's geometry.

2013-now AT40x

Since 2013 we have been using the AT40x laser tracker – initially with the old SR from 2013 to 2018 and with EBS starting in 2019

We will cover the EBS machine, but the AT40x laser tracker survey process was essentially the same for the old machine.

The measurement of the EBS machine comprising 354 points and 9,600 observations requires four teams of two people working an, eight-hour shift, for a total of eight-working days. Therefore, a complete survey of the EBS machine including both planimetry and altimetry takes eight working days.

DISCUSSION

The following tables provide a summary of the time required, the number of observations and the evolution for the ESRF SR survey since 1992. It is easy to see the enormous improvements made over the past 32 years.

Table 1 Summary of manpower required to survey the ESRF SR

	1992-1998	1999-2012	Since 2013
Planimetry	63	6	8
Altimetry	8	4	
Combined	**71**	**10**	**8**

Table 2 Summary of the number of measurements in the different survey epochs of the ESRF SR since 1992

	1992-1998	1999-2012	Since 2013
Planimetry	1700	3200	6400
Altimetry	1000	680	3200 (2000 used)
Combined	**2700**	**3880**	**9600**

Table 3 Summary of the number of measurements made per person in the different survey epochs of the ESRF SR since 1992.

	1992-1998	1999-2012	Since 2013
Planimetry	27	535	1200
Altimetry	125	170	

Table 4 Summary of the error ellipse semi major axes in the horizontal dR and vertical dZ the different survey epochs of the ESRF SR since 1992.

	1992-1998	1999-2012	Since 2013
dR semi-major error ellipse axis	~ 220 µm	~ 100 µm	~ 50 µm
dZ uncertainty	~ 50 µm	~ 35 µm	~ 20 µm

SUMMARY

Back in the late 1990s the ESRF Survey and Alignment group decided to change the way we measured our survey networks. It turns out this was an opportune moment for this change, coinciding with the emergence of instruments and software tools that enabled us to significantly improve the previous arduous distinvar/ecartometer measurement process.

Over time, we developed and refined highly streamlined software and techniques, ultimately being able to measure the main EBS SR machine network comprising 354 points measured from 195 instrument stations with 3,200 distance, and vertical and horizontal angle observations (i.e. a total of 9,600 observations) in one eight-hour shift with four teams, i.e. eight-working days to complete the task.

This flexible and efficient methodology originally developed for the Leica TDA500x robotic total stations in 1999 and employed at the ESRF for the past 25 years easily accommodated the evolution to the AT40x series of laser tracker, and even the new EBS accelerator.

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