INSTRUMENTATION AND SURVEY NETWORKS AT THE ESRF

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1. INTRODUCTION

The ESRF uses the Leica TDA5005 motorized theodolite with automatic target recognition (ATR) for all high precision survey work. 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). Over the past few years, the ESRF Survey and Alignment group has strived to improve upon the already impressive results given by this instrument. Today, 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. This paper will discuss the measurement of the ESRF first order survey networks and the different procedures implemented to achieve these results.

2. ESRF SURVEY NETWORKS

The philosophy of the ESRF Alignment and Geodesy group is to produce the best results in the shortest intervention time. At present this translates to a full Storage Ring survey in less than 8 hours. This is of primary importance for a service institute where presently, there are 44 beam lines operating 24 hours a day, 6 days a week in User Service Mode (USM). 3500 researchers come each year to the ESRF to carry out experiments.

The precision one can expect in a given survey network is dependent upon the accuracy of the instruments used and the configuration of the network itself. The configuration and instrumentation in turn will determine the time required to measure it. Typically these are mutually competing elements and some compromise must be made.

The Storage Ring (SR) is the main ESRF survey network. It is a regular lattice divided into 32 repeating cells. It is composed of 32 wall brackets mounted on the tunnel walls located in mid cell. There are also 64 survey monuments (CERN socket or alésages) mounted on the magnets at the entrance and exit of each cell of the machine. Each of these points is occupied and observed by the TDA5005. Each of the 320 points in the network is observed on average 4 to 5 times. Stations on the machine observe 13 points, while the wall bracket stations observe on average 25 other points. In total, slightly more than 1600 angle and distance observations are made.

Although the SR is the largest and most important, there are three other networks which are also measured regularly. They are the Booster, and two transfer lines networks TL1 and TL2. We will concentrate on the SR network in this discussion, but everything said concerning this network applies equally to the others as well.

When a network configuration has been fixed, the relationship between point determination, and in particular radial error (direction perpendicular to the travel of the particle beam), with respect to distance and angular precision can be studied. Simulating the survey network under different precision conditions does this. An incertitude surface [3] can be constructed. This surface can then be used to estimate radial error for different instrument precisions. The surface modelled for the ESRF shows that, statistically, for an amelioration in radial error standard deviation of 10 µm either the distance precision must be increased by 48 µm or the angle precision must increased by 0.08 arc seconds.

Comparative tests between the distinvar and ecartometer[1] instrument pair, the LTD500 laser tracker and the TDA5000 were made on the ESRF SR network in 1999. The results of these tests are summarized in annex 1 at the end of this paper. Briefly, neither the distinvar and ecartometer pair nor the laser tracker can compare with the precision of the TDA5005. In the case of the laser tracker, there is a clear explanation for this. Leica the manufacturer of the LTD500 laser tracker quotes its angle precision as 10 ppm or 10 µrad (2 arc seconds at 2σ). Leica quotes the TDA5005 precision as 0.5 arc seconds or 2.42 µrad at 1σ. Even the remarkable distance accuracy of the laser tracker (10 µm/m) is insufficient in the ESRF context to offset its comparatively poor angular accuracy.

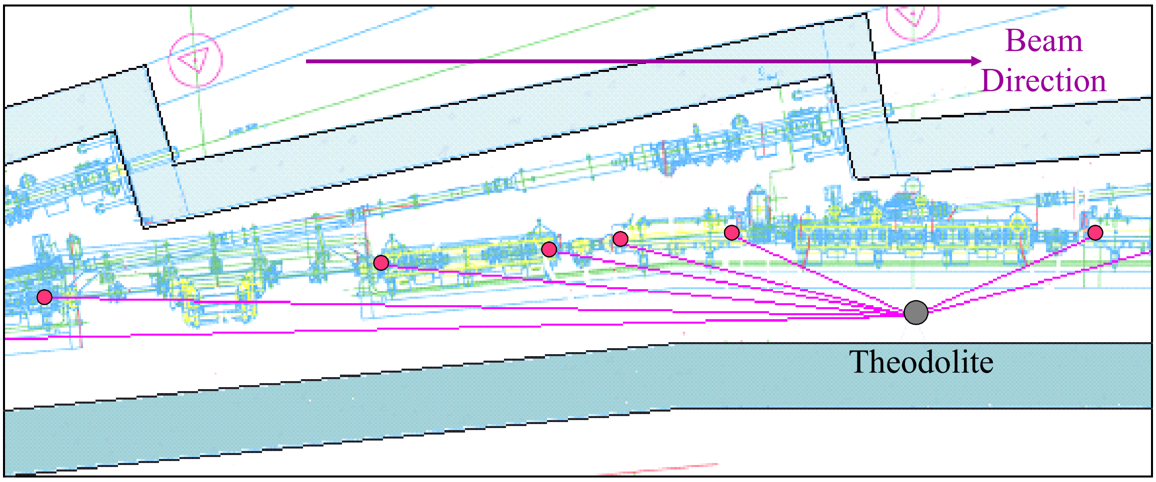

Figure 1 The majority of observations on the ESRF SR network are along the direction of the beam. The direction most sensitive to alignment errors is perpendicular to this. This is also the direction most sensitive to angle errors. Absolute error ellipse semi-major axes are aligned in the direction perpendicular to the beam travel as well.

Recall that for the ESRF at least, and for accelerators in general, the radial direction is the most sensitive to alignment errors. Because of the confines of the tunnel and the network configuration, this direction is the most sensitive to angle measurements. The direction along the travel of the beam is most sensitive to distances. This is demonstrated in Figure 1 where we see that the majority of observations on the ESRF SR network are along the direction of the beam. It is important to note that at the ESRF, the direction of the absolute error ellipse semi-major axes is also in the direction perpendicular to the travel of the beam.

[1] The distinvar and ecartometer are instruments developed at CERN. These two instruments are very precise but are time consuming and require special skills to use correctly.

3. STEPS TAKEN TO AMELIORATE THE ESRF NETWORK PRECISION

In 1997, the ESRF survey networks were measured using the distinvar and ecartometer. This had been the case since the inception of the ESRF in 1990. At that time there was considerable discussion as to what instrument the ESRF could use to evolve in its network measurement. The only viable alternative to the Distinvar and Ecartometer was the laser tracker. The laser tracker is a relatively cumbersome instrument to use in the ESRF SR tunnel. It is also a very expensive. Fortunately, about this same time, Leica introduced their new line of theodolites with Automatic Target Recognition (ATR). This instrument line appeared ideally suited as a replacement to the distinvar and ecartometer. The ESRF has since purchased four of these instruments and employed different methods to optimize their performance.

3.1. Electronic Distance Meter (EDM) Calibration

The TDA5000 and the TDA5005 have EDM manufacturers quoted incertitude of 1mm + 2 ppm. We have found uncorrected distances for the TDA5005 to be fully in line with the manufacturers quoted typical distance accuracy of ± 0.2 mm.

We know that the EDM error follows a well defined and highly repeatable characteristic curve which can be calibrated and corrected for [1], [2], [3], [4]. The ESRF, possessing a modern calibration bench has exploited this by employing the appropriate corrections and improving the EDM incertitude to between 0.08 and 0.1 mm.

3.2. Angle Calibration

The TDA5000 has manufacturers quoted angle accuracy of 0.6 arc seconds. The TDA5005, the latest in this line of instruments has angle incertitude of 0.5 arc seconds. At the ESRF an angle dependence on distance has been observed (see Figure 2). To date this dependence has been modelled but not integrated into the least squares network calculation. The reason it has not as yet been fully integrated into the calculation is because its effect is confounded with a problem of forced centring. Its incorporation will be the next and possibly last step in the effort to improve the incertitude in point determination [4].

3.3. Forced Centring Errors

We have identified a forced centring error in the instruments and supports used at the ESRF. In order to understand this error and its significance, one must understand the historical circumstances of how it was identified.

In 1999 when we first started measuring the ESRF SR network with motorized theodolites equipped with ATR, we used two instruments; a TDA5000 (instrument no. TDA5000-1) and a TDA5005 (instrument no. TDA5005-2). These two instruments gave consistent results. The standard deviations in the angle and distance residuals were 0.8 arc seconds and 0.16 mm respectively. Although these results are in line with the instrument specifications, the angle and distance residuals were not particularly well normally distributed (see Figure 3). We were somewhat perplexed by these results. However, we attributed them to; first the fact that we were not as yet correcting the distances for their calibration errors, and secondly and more importantly, we were measuring a considerable number of angles and distances (16%) below the manufacturers recommended minimum operating distance of 6 m.

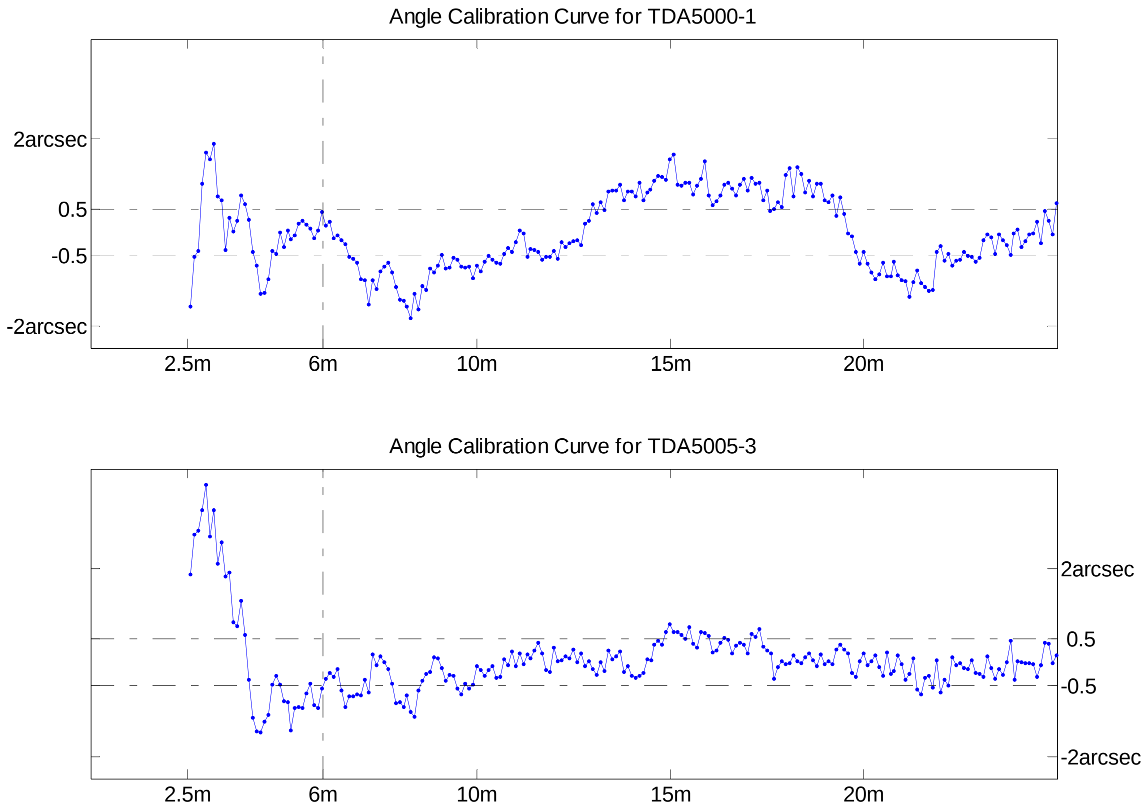

Figure 2 Angle calibration curves as a function of distance for two ESRF instruments.

At the beginning of 2001, we began using a third instrument, a TDA5005 (instrument no. TDA5005-3). The angle and distance residuals issued from the network calculation were identical to those measured prior to use of this instrument. However the radial positions of certain points on the machine were offset from what they had previously been. Comparing measurements with the other two instruments on a small test network, we mistakenly attributed this discrepancy to an error associated with the newest TDA5005 (TDA5005-3). Also, looking at the angle residuals, we remarked that there were large residuals associated with angles made to points at distances less than 6m from the theodolite station. Finally, measurements at the calibration bench also supported the possibility of angles issued from this instrument being erroneous (see Figure 2).

It must be remarked that we had on several occasions verified the instrument centring errors. At the ESRF, the instrument tribrach is fixed to, and very carefully centred on a forced centring tail which itself fits into a CERN type *alésage* or forced centring sphere socket. The centring verification was done by fixing a prism attachment to the tribrach/forced centring tail, blocking the movement of this attachment, and rotating tribrach/forced centring tail through 360 degrees in steps of 45 degrees, and measuring radial displacements of the tail with a micrometer dial gauge. The centring errors determined this way were 0.060, 0.023, and 0.053 mm for instruments TDA5000-1, TDA5005-2 and TDA5005-3 respectively. The differences we observed on the radial positions of certain points in the network were in the order of 0.1 to 0.15 mm with some even larger values! Thus, we did not consider centring errors to be the primary source of the observed differences before and after starting to use the newest instrument.

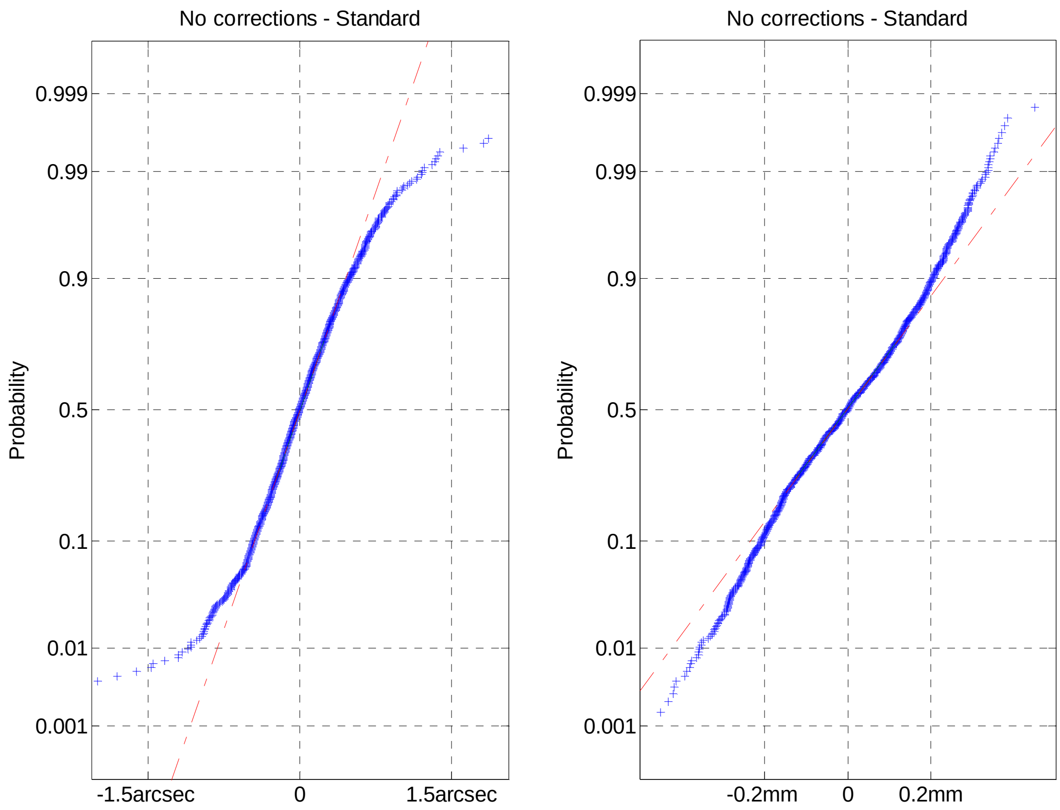

Figure 3 Normal probability plots for horizontal angles and distances measured ESRF SR survey campaign of July 1999. In a normal probability plot, the data are plotted against a theoretical normal distribution in such a way that the points should form an approximate straight line. Departures from this straight line indicate departures from normality [5].

We decided to investigate the angle dependence on distance at the calibration bench. Here we observed rather large angle errors at distances inferior to 6 m (See Figure 2).This led us to apply an empirical correction on angles as a function of distance to the angles observed by instrument number TDA5005-3. This brought the radial errors back in line with their previous positions. However there was an overall degradation in the angle residual magnitudes passing from 0.8 to 1 arc second. In parallel we had applied the calibration correction for the EDM which significantly improved the distance residuals from 0.16 to better than 0.1 mm. The net result was an overall improvement in point determination as evidenced by the amelioration in the absolute error ellipses. These results were reported at the International Workshop on Accelerator Alignment held at SPRING-8 in 2002 [3].

At that time we were not altogether comfortable with the angle results and decided to investigate further. In particular, we had not as yet achieved the manufacturers quoted angle accuracy of 0.5 arc seconds with the TDA5005. In fact, at a factor of two, we were still quite far from this desired goal.

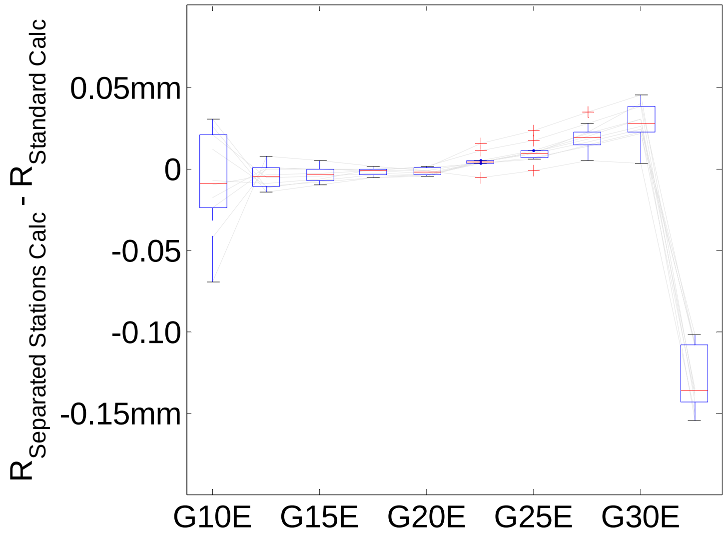

Figure 4 Boxplot of the difference in radial positions with respect to the standard calculation of the ten machine points issued from the separated stations calculation. This plot shows quit clearly that the last point in the cell (G30S) is offset by 0.14 mm. This offset configuration can be explained by the combined effect of the instrument and prism centring errors. Also, because we position the instrument in a highly systematic way (i.e. always the same for each instrument station type), errors are issued from the least squares calculation are reflected in the same highly systematic manner. The boxplot shows the median value for the point (horizontal red line), the upper and lower quartile ranges (the box limits), whiskers at ±1.5 (inter-quartile-range) approximately 2σ or 95% and outliers (shown by crosses)[5]. It is an appropriate way to show location and spread results for 320 points, 10 each in the 32 ESRF SR cells.

The first thing that we did was to recalculate our networks by separating the occupied and observed stations[2] in the least squares calculation. In principle, this will eliminate the instrument centring errors at the cost of introducing a considerable number of additional unknowns into the calculation (17%). This improved the angle residual standard deviation from 0.8 to 0.65 arc seconds. However, the radial positions of certain points in the network were once again offset in a systematic and non-negligible amount with respect to their previously calculated positions (see Figure 4). In particular we remarked that certain exit points of the standard ESRF cell were moved towards the interior of the machine by approximately 0.14 mm with respect to their previous positions. The points concerned by this had been measured with the instrument TDA5000-1. Additionally, these results were corroborated in certain zones with independent T3000 and ecartometer observations.

[2]Using forced centring, the instrument is nominally positioned in the same place as the prism is when the station is observed from another point. With what is referred to in this paper as the standard calculation these points are considered the same in the least squares calculation. A separated occupied and observed station calculation, or simply separated calculation refers to physically and nominally separating the station into an occupied point when the instrument is positioned on it and an observed point when the prism is positioned on it. This *free stationing* approach has the net effect of increasing the number of unknowns in the least squares calculation.

Troubled by these results we began to suspect a problem with centring. We made two tests at our calibration bench where we have a full size model of one cell of the ESRF SR network and can test measurements of a typical cell.

The first test consisted of positioning the instrument on the wall bracket in the centre of the cell and observing 6 points in the cell. The measurements were then repeated seven more times each time turning the instrument and its support through 45 degrees. The results of this test show the full effects of instrument centring errors. Each instrument was measured twice on two different occasions (see Table 1). The instrument resection coordinate changes describe, as one would expect, a circle. The radius of this circle is the centring error. Nevertheless, these centring errors, as before, do not fully account for what was observed by separating the occupied and observed stations in the least squares calculation.

Table 1 Full instrument centring errors determined by rotating the instrument and its forced centring mount through 360º ins steps of 45º.

	TDA-5000-1 (mm)	TDA5005-2 (mm)	TDA5005-3 (mm)	TDA5005-4 (mm)
Instrument Centring Test 1	0.105	0.040	0.040	
Instrument Centring Test 2	0.108	0.072	0.078	0.081
Mean	0.107	0.056	0.059	0.081

The second test was designed to elucidate the centring errors attributable to the prisms. This was done by measuring angles to each of the four prisms used with the ESRF TDA5000/5005 instruments as well as to a so called reference prism whose centring was considered to be very good. Each prism was placed in turn on the measurement point and an angle measurement taken. The process was then repeated at several distances. At each distance, the angles were reduced to offset distances with respect to the reference prism. The mean of these offsets at 16 distances between 2.5 an 20 m was calculated for each prism. The test was repeated with two different instruments (TDA5000-1 and TDA5005-4). The results are consistent and show that the prism paired with TDA5000-1 has a significant offset error[3]. The results of these tests are shown in Table 2.

Table 2 Prism centring error tests showing offsets with respect to the so-called reference prism position.

	TDA5000-1 Prism (mm)	TDA5005-2 Prism (mm)	TDA5005-3 Prism (mm)	TDA5005-4 Prism (mm)
PrismTestTDA5000-1	-0.140	-0.008	-0.063	0.016
PrismTestTDA5005-4	-0.134	-0.018	-0.057	0.025
Mean ± Standard Deviation	-0.137 ± 0.018	-0.013 ± 0.012	-0.060 ± 0.015	0.021 ± 0.018

[3] We use the LEICA CCR 1.5 inches prism for all measurements. This prism is delivered with a calibration certificate guaranteeing its centring to within 0.01 mm. However, due to our particular configuration, we are required to use an interface between the prism and the forced centring socket. Presumably, the prism used with instrument TDA5000-1 had been either removed from its support at one point in time and poorly centred when it was reinstalled or physically shocked and displaced in its mount.

Armed with this information, we made two more calculations on our network integrating the prism corrections into the standard and the separated occupied and observed stations. One observes statistically significant improvement in the angle residuals when using either the separated stations or the prism correction. We also remark a further statistically significant improvement using combined corrections. These results are shown in Table 3.

Table 3 Angle and distance residuals (1σ) for different types of least squares calculations for the December 2002 network determination using instruments TDA5000-1, TDA5005-2 and TDA5005-3.

Least Squares Calculation Type	Angle Residual (arc sec)	Angle Residual (mm)	Residual Distance (mm)
Standard	0.76	0.084	0.097
Separated Occupied and Observed Stations	0.67	0.082	0.092
Standard with Prism Correction	0.68	0.082	0.090
Separated Occupied and Observed Stations with Prism Correction	0.62	0.078	0.086

The error ellipses issued from these different calculations are shown in Figure 5. We remark that with the separated stations, there is slight degradation in the longitudinal incertitude as evidenced by the larger semi-minor error ellipse axis on the first and last points in the cell. There is also a corresponding small amelioration in the error ellipse semi-major axis. Recall this is in the direction (i.e. perpendicular to beam travel) in which the beam is sensitive to alignment errors.

Table 4 Angle and distance residuals for different types of least squares calculations using instruments TDA5005-2, TDA5005-3 and TDA5005-4 for the August 2004 network determination.

Least Squares Calculation Type	Angle Residual (arc sec)	Angle Residual (mm)	Residual Distance (mm)
Standard	0.61	0.065	0.100
Separated Occupied and Observed Stations	0.45	0.055	0.088
Standard with Prism Correction	0.61	0.065	0.109
Separated Occupied and Observed Stations with Prism Correction	0.49	0.060	0.096

More recently, a forth TDA5005 was purchased and TDA5000-1 is no longer used to measure the network. In employing the instrument combination TDA5005-2, TDA5005-3, TDA5005-4, there is an improvement in the angle residuals and we now meet the manufacturer's specified angle accuracy for the TDA5005 of 0.5 arc seconds when using the stations calculation (refer to Table 4). There is also an improvement in the point determination. Absolute error ellipse semi-major axes pass from 0.156 mm in December 2002 to 0.113 mm in August 2004.

Once again, the first and last point in the cell has a slightly increased longitudinal incertitude with the separated stations calculation. It appears that the prism correction does not improve the results (see Figure 6) for the August 2004 calculation.

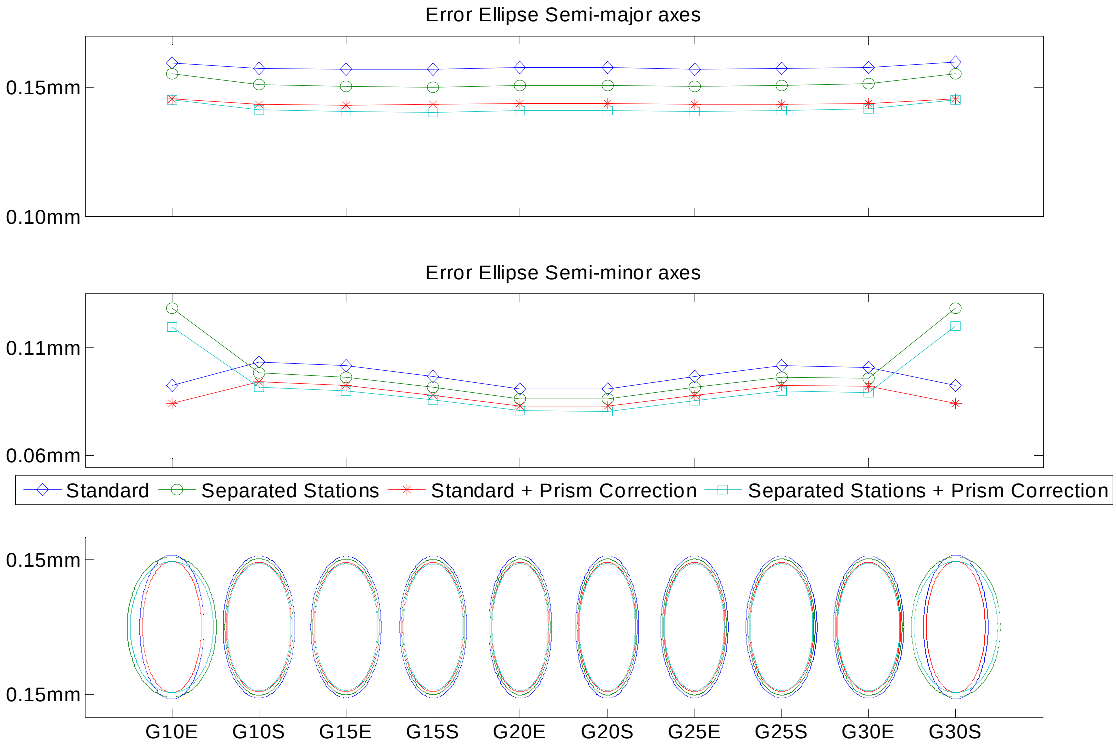

Figure 5 Mean absolute error ellipses of 320 points, 10 in each of the 32 cells, issued from the December 2002 ESRF SR network calculations showing the effect of separating stations and employing a prism correction. In particular, we remark a slight amelioration in both the semi-major and semi-minor axes. The notable exception to this is the increase in the semi-minor axes of the first and last points in the cell. These points correspond to the stations occupied by the instrument and as such are the separated stations.

4. WHERE TO NOW?

With the separated stations calculation and the prism correction, we have removed a main source of error-namely the instrument and prism centring error. Looking at the angle residual distribution, we remark that there remains a significant non-normal component in the distribution (see Figure 7). It is probable that this is due to two factors.

First we do not completely master the prism offset correction. This is demonstrated by the lack of improvement in the angle residuals when we incorporate our best estimate of it into the least squares calculation for August 2004. We hope to improve upon this in the future.

The second factor is likely due to the large number of angles (16%) observed below the manufacturers recommended minimum operating distance of 6 m. In fact when we examine the residuals in the zones deemed to be non-normal, this is to say for distance residuals outside of the range -0.18 to +0.18 mm and for angle residuals outside on the range -0.71 arc seconds to +0.71 arc seconds we note some curious effects. First, there are no angle residuals in the non-normal zones for measurements taken below the 6 m mark. At the same time the 45% of distance residuals falling in the non-normal zones are from observations taken below the 6 m mark. A possible explanation for this is that there are systematic angle errors which due to their strong assigned weight in the least squares calculation are deforming the distances. We have observed in the past a strong dependence of angle on distance for observations made below the 6 m mark (Figure 2). Now having addressed problems associated with centring errors, we will endeavour to incorporate a calibration correction for this error into the least squares calculation.

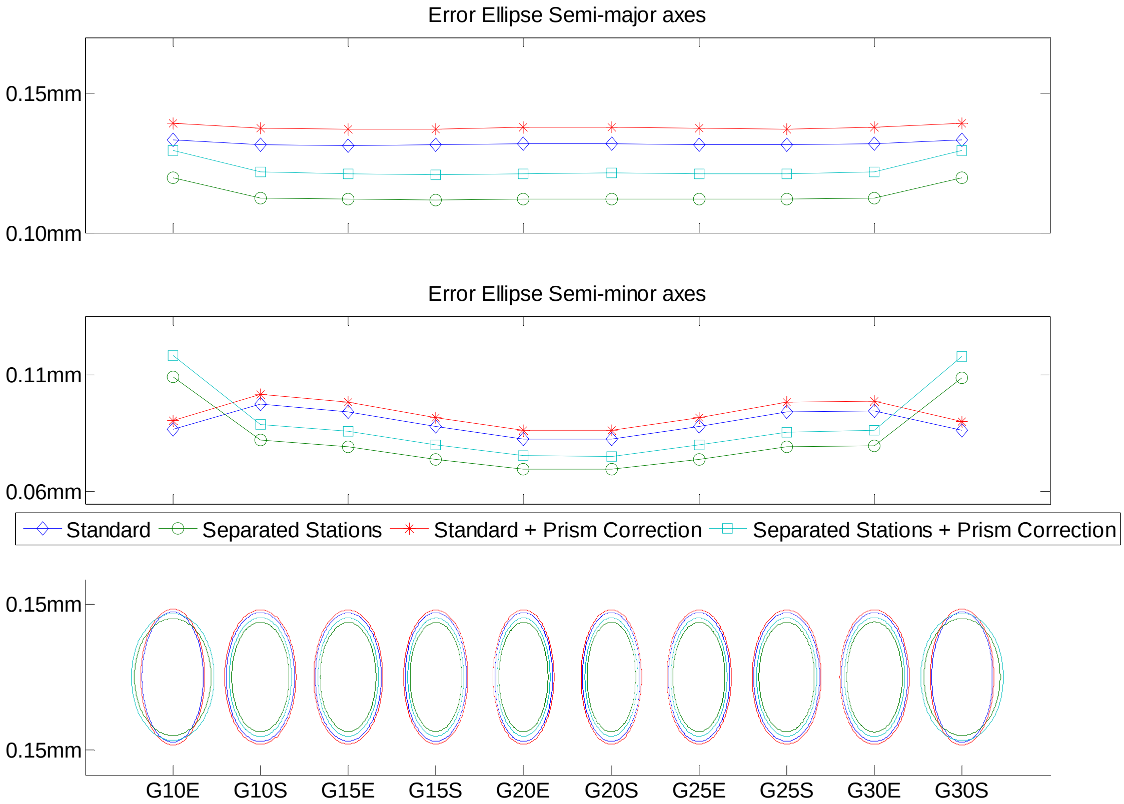

Figure 6 Mean absolute error ellipses of 320 points, 10 in each of the 32 cells, issued from the August 2004 ESRF SR network calculations showing the effect of separating stations and employing a prism correction. We see that the prism correction no longer improves the results. As with the December 2002 calculation, there is an increase in the semi-minor axes of the first and last points in the cell. These points correspond to the stations occupied by the instrument and as such are the separated stations.

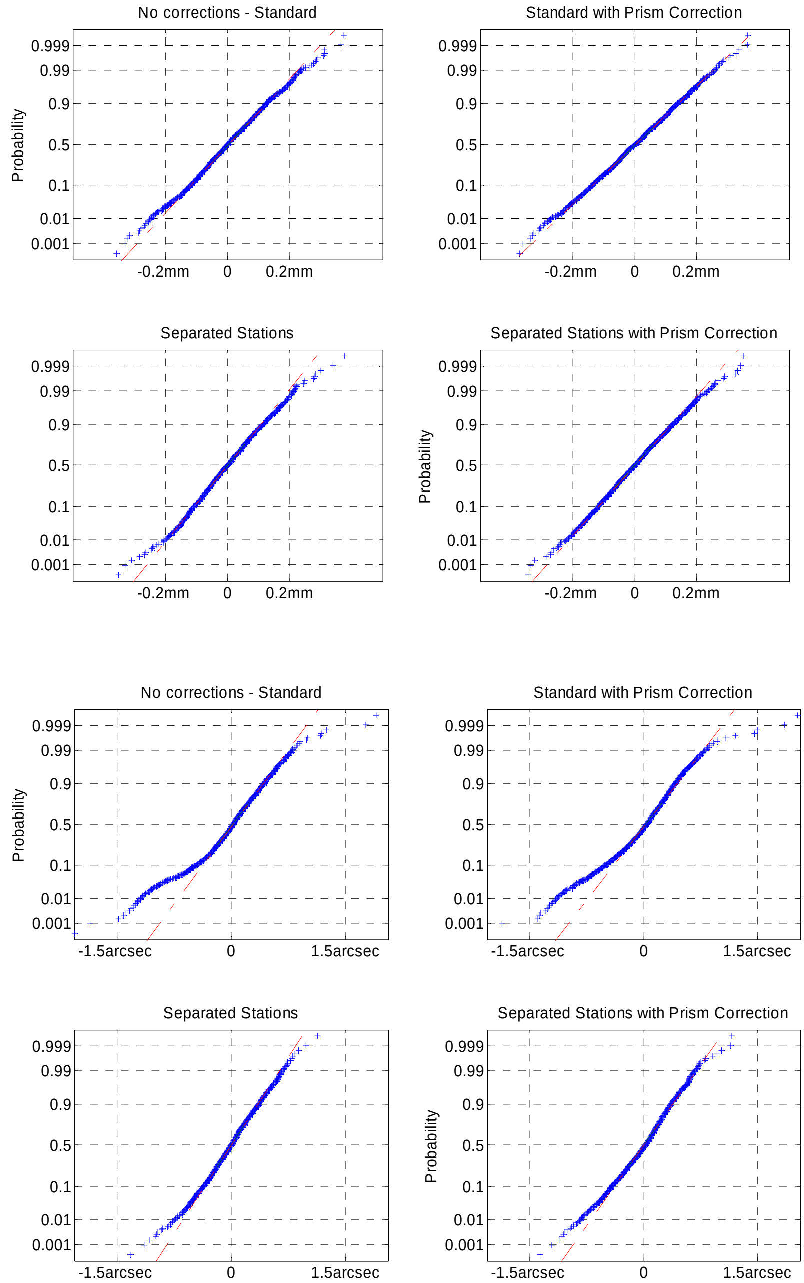

Figure 7 Normal Probability plots for the angle and distance residuals issued from the four calculations for the ESRF SR network measured in August 2004. These plots show first the near normal distribution of the distance residuals and the heavy tailed distribution of the angle residuals. It is postulated that the non-normal angle distributions may be due to a angle error as a function of distance. This is supported by measurements made at the ESRF calibration bench (see Figure 2).

5. CONCLUSION

The ESRF has been using the Leica TDA5005 motorized theodolite with automatic target recognition (ATR) for all high precision survey work since 1999. 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). Through the use of a distance calibration correction, the elimination of instrument centring errors and the employment of a prism centring error corrections, there has been a steady improvement in point determination accuracy as evidenced by the systematic decrease in the magnitude of the error ellipse semi-major axes.

	Error Ellipse Semi-Major axes at 95 % significance (mm) *Direction perpendicular to the electron beam travel*	**Error Ellipse Semi-Minor axes at 95 % significance (mm)** *Direction along the electron beam travel*
July 1999	0.212 ± 0.003	0.132 ± 0.006
December 2002	0.158 ± 0.002	0.096 ± 0.005
August 2004	0.113 ± 0.003	0.082 ± 0.013
Note that all values are the mean ellipse axes magnitude for the 320 observed machine points ± 1 standard deviation		

Two actions will now be followed to improve point determination. The first will be to reduce errors associated with prism centring to a minimum. The second will be to start to investigate and employ angle as a function of distance corrections for observations below the manufacturers recommended minimum measurement distance of 6 m. We will then be in a position to possibly investigate a final error source – namely refraction.

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ANNEX 1 SUMMARY OF 1999 COMPARATIVE ESRF SURVEYS

		Distances		Angles		Ecartometer Offsets			Precision	
	Number of Surveys	Number of Measures	Standard Deviation (mm)	Number of Measures	Standard Deviation (arc sec)	Number of Measures	Standard Deviation (mm)	Time (man days)	Error Ellipse Semi-major axes at 95% significance (mm) *Direction perpendicular to the electron beam travel*	Error Ellipse Semi-major axes at 95% significance (mm) *Direction along the electron beam travel*
Distinvar / Ecartometer	3	1054	0.137			1004	0.073	50	**0.609**	**0.307**
TDA5000	3	1629	0.165	1616	1.041			8	**0.241**	**0.153**
LTD500 Laser Tracker	1	1015	0.018	1015	4.309			12	**1.127**	**0.515**