

First Application of the LGC2 Software to SuperKEKB Main-Ring Survey Data: A Section-to-Section Consistency Check

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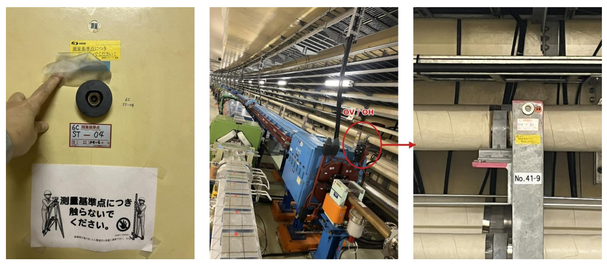
Motivation

- SuperKEKB is a 3016 m double-ring collider. Because of the nano-beam scheme, it is much more sensitive to magnet misalignment than KEKB.
- The 2015 laser-tracker survey was successful. The circumference predicted from the survey agreed with the beam within 1 mm (0.3 ppm) [1].
- However, the tunnel is still moving. It has subsided by more than 40 mm since 1998, and the floor level changes by more than 1 mm with the season [2]. The HLS [1,2], the gap sensors on the IR cryostats [4] and the GPS network [5] are processed separately from the survey.
- LGC2, developed at CERN, adjusts laser-tracker, levelling, inclination and wire observations together in 3D and gives the full statistics of the solution [3].

We checked what the raw tracker data can show by themselves and what LGC2 adds.

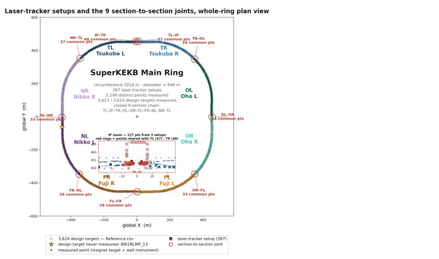
The 2015 Survey

The survey was carried out by three teams with Faro laser trackers (Ion and Vantage), about 30 m of tunnel per set-up [1]. The IT and IB monuments (inner top, inner bottom) are drilled into the inner wall. The OV and OH monuments (outer vertical, outer horizontal) are mounted on steel posts on the opposite wall, across the beam line.



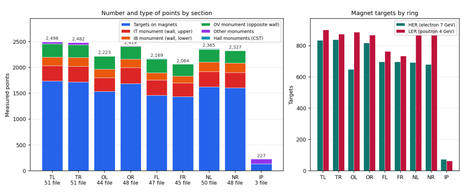
Left: a wall monument. Centre: the tunnel from the magnet side; the red ellipse marks an OV monument. Right: the same OV monument close up.

- The data consist of 387 files, one per set-up, in nine sections: 18 190 sightings to 4786 points (3614 magnet targets and 1091 wall monuments), from 27 July to 9 September 2015.
- Each file is given in its own local frame. All files contain a @LEVEL plane, so the local Z axis is the true vertical.

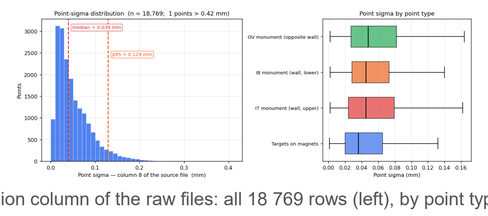


The survey on the ring: 387 set-ups (squares), measured points by section (dots), nine joints with the number of points seen from both sides (red circles). Inset: the interaction region.

What the Raw Data Alone Can Show



Measured points per section and type (left); magnet targets per ring (right).

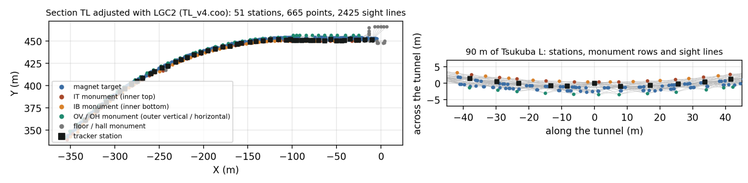


Per-point precision column of the raw files: all 18 769 rows (left), by point type (right).

The median is 0.039 mm, and the OV/OH monuments have the widest distribution (0.052 mm). The instrument performed well. However, this value is evaluated within one set-up, so it cannot show whether two set-ups agree with each other.

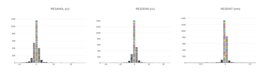
Nine Sections Adjusted with LGC2

One input file was prepared for each section. The error model (*INSTR/*POLAR) was estimated from the data, and a free network was used (*CONSI LIBR, TX TY TZ RZ). Each set-up has *TSTN and *V0 and one *PLR3D line per sighting. With IHFIX instead of ROT3D the levelling is used, and the vertical point sigma of TL decreased from 0.074 mm to 0.026 mm.

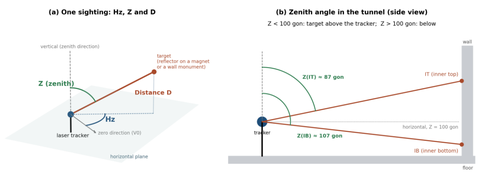


Section TL from the LGC2 output file: 51 stations, 665 points, 2425 sight lines; right, 90 m along the tunnel.

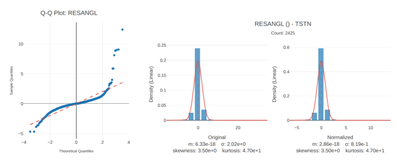
Reading the LGC2 Report: Section TL



TL residuals of 2425 sight lines: horizontal angle Hz, zenith angle Z, distance D.



(a) One sighting: Hz in the horizontal plane from the zero direction, Z from the vertical, D along the line. (b) Z < 100 gon for IT, > 100 gon for IB.



TL horizontal-angle residuals: Q–Q plot (left), histogram in cc and in RES/SIG (right).

How to read it

The residual ε is the observed value minus the value recomputed from the adjusted coordinates. An angle residual moves the sight line sideways (Hz) or up and down (Z) by e = d·ε, and a distance residual moves it along the line. The unit is 1 cc = 10^{-4} gon = 1.571 µrad, which is 0.016 mm at 10 m.

- RES/SIG is the residual divided by the declared sigma. If the error model is correct, it follows the standard normal distribution, with 99.7 % of the values inside ±3.
- The Q–Q plot compares the sorted RES/SIG with the values of a normal distribution (dashed line). For TL the middle part is flat and the right tail is steep.
- The standard deviation is 2.02 cc (3.2 µrad), or 0.82 in RES/SIG; since this is below 1, most sight lines are better than declared.
- The skewness (0 for a normal distribution) is 3.5, so the long tail is on the positive side. The excess kurtosis (also 0 for a normal distribution) is 47, which means a sharp peak with a few very large residuals.

The largest residual, 30.6 cc at 9.6 m, corresponds to a sideways offset of 0.46 mm. Every point in the tail can be found in the .res file:

Set-up	Target	Dist.	RESANGL	RES/SIG
TLX09	BLC1LP2D	9.6 m	30.6 cc	12.4
TLIT22	QF6P_2D	4.4 m	22.3 cc	9.0
TLIT27	SD5TLE_1D	10.8 m	22.2 cc	9.0
TLIT101	QLC2LPD	7.3 m	21.8 cc	8.8
TLIT24	SD5TLP_1D	11.3 m	20.0 cc	8.1

The five largest horizontal-angle residuals of section TL.

- 22 of the 23 angle residuals beyond 3σ belong to magnet targets. The wall monuments do not show such outliers.
- QF6P_2D is flagged from three set-ups, so the problem is probably in the target itself. BLC1, QLC and QKB are near the IP, where the magnets moved during the campaign.

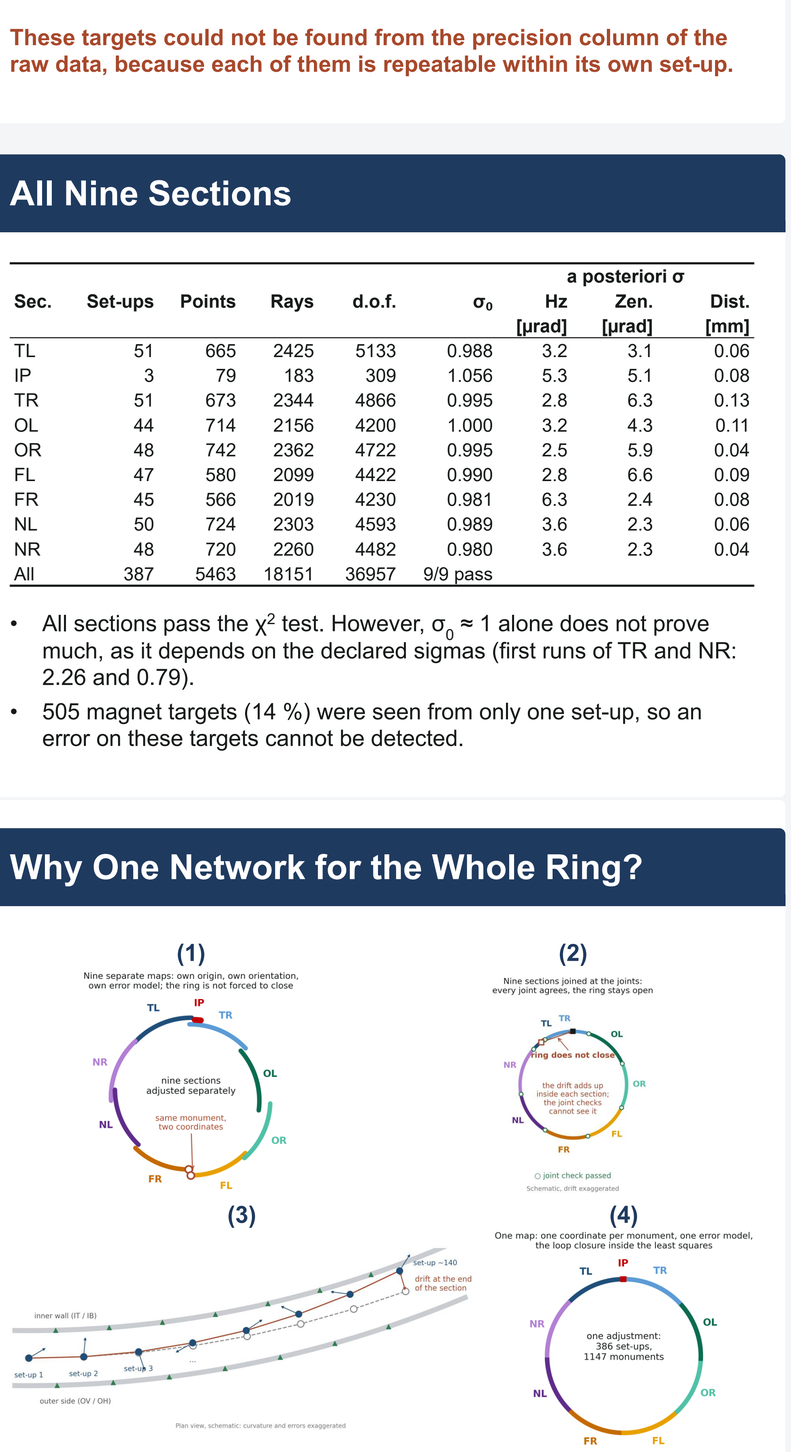
These targets could not be found from the precision column of the raw data, because each of them is repeatable within its own set-up.

All Nine Sections

Sec.	Set-ups	Points	Rays	d.o.f.	σ_0	a posteriori σ Hz [µrad]	Zen. [µrad]	Dist. [mm]
TL	51	665	2425	5133	0.988	3.2	3.1	0.06
IP	3	79	183	309	1.056	5.3	5.1	0.08
TR	51	673	2344	4866	0.995	2.8	6.3	0.13
OL	44	714	2156	4200	1.000	3.2	4.3	0.11
OR	48	742	2362	4722	0.995	2.5	5.9	0.04
FL	47	580	2099	4422	0.990	2.8	6.6	0.09
FR	45	566	2019	4230	0.981	6.3	2.4	0.08
NL	50	724	2303	4593	0.989	3.6	2.3	0.06
NR	48	720	2260	4482	0.980	3.6	2.3	0.04
All	387	5463	18151	36957	9/9 pass			

- All sections pass the χ^2 test. However, $\sigma_0 \approx 1$ alone does not prove much, as it depends on the declared sigmas (first runs of TR and NR: 2.26 and 0.79).
- 505 magnet targets (14 %) were seen from only one set-up, so an error on these targets cannot be detected.

Why One Network for the Whole Ring?

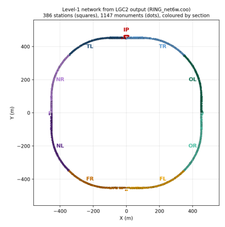


(1) Nine separate adjustments give nine maps. (2) Joined at the joints, each joint agrees but the ring is not closed. (3) Each set-up is oriented through the monuments (▲) shared with the previous one, and small errors add up over ~140 set-ups. (4) One adjustment: one coordinate per monument, with the loop closure.

The joints check only the local overlap; the whole ring is checked only when the loop is closed.

One Network for the Whole Ring

- Only the tunnel monuments were used: 1147 points from 386 set-ups. Magnet targets were not included, because the magnets are what we want to measure, not the reference. They are attached to this frame in a second step (not shown here).
- The input uses *CONSI LIBR TX TY TZ RZ, IHFIX for all stations and one sigma group per section. It has 5288 sight lines, 15 864 observations and 4989 unknowns.



The whole-ring network (386 set-ups, 1147 monuments) drawn from the LGC2 output file.

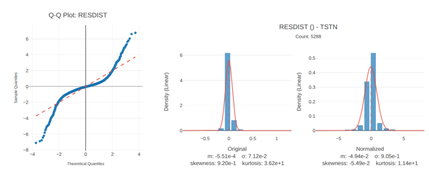
- The adjustment gave σ_0 = 0.991 with a redundancy of 10 879. Since σ_0 alone does not prove much, we compared the residuals:

	9 sections, separately	Whole ring, at once
Datum	9 (own origin, orientation)	1
Joint monuments	two coordinates each	one coordinate
Error model	9	1
Loop closure	not used	inside the least squares
Hz residual s.d., monuments	2.2–5.0 µrad	1.9 µrad

Both columns use the same monument sight lines. The zenith angle (4.4 µrad) and the distance (0.07 mm) are within the range of the sections.

Where the Survey Is Weak

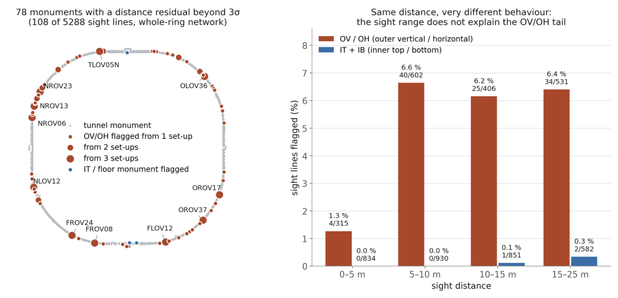
Beyond 3σ there are 0.42 % of the horizontal angles and 0.49 % of the zenith angles (0.27 % for a normal distribution), but 2.04 % of the distances, which LGC2 flags as non-normal.



Whole ring, distance residuals of 5288 sight lines: Q–Q plot and density.

Monument row	Flagged / total	Rate
IB (inner bottom)	0 / 1291	0 %
IT (inner top)	3 / 1918	0.2 %
OV / OH (outer vertical / horizontal)	**103 / 1871**	**5.5 %**
Floor and hall	2 / 208	1.0 %

Sight lines with normalised distance residual above 3.



Left: the 78 monuments carrying the 108 flagged sight lines, spread all around the ring; 11 OV monuments are flagged from three set-ups. Right: flagged rate against sight distance.

- At every sight distance, the OV/OH monuments are flagged at least 20 times more often than IT/IB. So the longer sight across the beam line is not the reason.
- Positive and negative residuals are balanced (56 and 52). This is not a constant offset; the OV position seems not to be stable between set-ups, which suggests a problem with the steel-post mounting.
- To be checked before the next campaign: OROV17, OROV37, OLOV36, NROV06, NROV13, NROV23, NLOV12, FROV08, FROV24, FLOV12, TLOV05N.

Conclusion

- The raw data show that the instrument performed well (0.04 mm), but not whether the set-ups agree. LGC2 can evaluate this.
- All nine sections passed the test, with 2.5 to 6.3 µrad for angles and 0.04 to 0.13 mm for distances.
- In the whole-ring network of 1147 monuments, the horizontal-angle residual is 1.9 µrad, smaller than in any section for the same monuments, and the vertical coordinate σ is 0.07 mm.
- The weak points are the magnet targets for the angles (TL) and the OV/OH monuments for the distances (11 to be inspected). 505 targets were seen from only one set-up.
- As the next step, we plan to add the HLS data near the IP, and later FSI, to the same adjustment.

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References. [1] M. Masuzawa et al., Proc. IWAA'16, Grenoble, 2016. [2] M. Masuzawa et al., Proc. IPAC'25, doi:10.18429/JACoW-IPAC2025-MOPM044. [3] LGC2, CERN, lgc2.docs.cern.ch [4] M. Masuzawa, eeFACT'25, Tsukuba, 2025. [5] Y. Ohsawa et al., Proc. PASJ9, 2012, p. 821.