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Title: The SLC Vertical Survey Network

General

During 1984 and 1985 the SLC alignment group established and measured a system of elevation benchmarks (BM's) over the whole of the SLAC site, ranging from the injector area to the NGS horizontal control point (surface monument) AA on the hill to the east of the collider hall outside the radiation fence.

Precise elevations are needed in general for survey, alignment, placement, and monitoring of SLC tunnels and components. In particular, precise elevations of the survey instruments, mounted over penetrations to the tunnels and over the horizontal control points, are needed for the reductions of measured distances on the surface. Precise elevations were also needed at several other locations, like sector 1, 10, 19, and 30 along the LINAC (for the Global Positioning System measurements), outside of the IR 8 access to PEP (to connect the run from the SLC Master Benchmark R306 close to LINAC station 100+00 through the PEP SIT tunnel), and at the south-west adit to the SLC tunnel (to connect the BSY run). Permanent benchmarks were, therefore, installed close to these locations. To minimize errors and simplify re-leveling, turning points were also permanently installed. Figure 1 shows the locations of the elevation benchmarks east of LINAC sector 30 and the course of the permanently installed leveling runs.

Benchmarks and Turning Points

Most benchmarks consist of sections of threaded 5/8 inch rebar driven to refusal and topped with a stainless steel sphere. The top 2 feet of the rebar is enclosed by a 6 inch diameter plastic tube, set in concrete. An aluminum access cover is on top (fig.2), which in the field has the BM number stamped on top.

The SLC Master Benchmark, R306, is a stainless steel rivet epoxied into the LINAC floor close to LINAC station 100+00. Its elevation was measured by leveling directly off the LINAC waveguide structure on several locations in sector 30. The elevation of R306 thus determined was then defined to be the SLC reference elevation for BSY, Arcs and Final Focus. To do so keeps SLC alignment in accordance with LINAC alignment practice which always kept sector 30 as one of the two fixed points along the LINAC to which it was aligned.

The turning points are either railroad spikes driven in asphalt (and originally marked with blue ribbon) or 3 foot sections of rebar in natural ground. As a safety measure the latter were marked by 6 foot steel fence posts a few inches away. To reduce the effect of instrument error sources turning point spacing is such that maximum sight distance is about 20 meters and sights

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are balanced to 0.2 meters. The average number of setups between benchmarks is 12, and to double-run the entire net requires 700 set-ups.

Observations and Instruments

All observations were made with new WILD N3 split bubble levels and KERN 3m INVAR level rods with 5 mm graduations. The WILD level is not an automatic level. Automatic levels have fallen out of favor in the last two years, when it was discovered that they are very susceptible to magnetic fields. In an accelerator environment, where many magnets with remnant fields are around, we did not want to run this risk.

The KERN level rods were calibrated at the German National Bureau of Standards (Physikalisch-Technische Bundesanstalt) in Braunschweig, West-Germany, before delivery by KERN, and we believe they are good to 0.02 mm. The rods were equipped with digital temperature sensors attached to the invar to allow correction for different temperatures.

All observations were directly recorded on an EPSON HX-20, and when those turned out to be not rugged enough for field use, on an HP 110. Two separate rods are used for backsight and foresight. Each has two scales, shifted with respect to each other by an arbitrary, but known, amount. This allows reading and transfer errors to be discovered by a checking program before the rods and instruments are moved to a new location.

Error Treatment

Each leveling set-up, that is, the transfer from one benchmark to turning point, or from turning point to the adjacent one, has an assumed *a priori* standard deviation, σ_a *a priori*, of 0.1 mm. A level run from benchmark to benchmark is the summation of all individual set-ups. An estimate for the standard deviation of the level run is then given by $\sigma_l = 0.1 \sqrt{N}$, where N is the number of set-ups.

The *a priori* assigned total individual measurement error is somewhat arbitrary; 0.1 mm is a value found to be reasonable in precise leveling. For the error determination of the whole network with a least squares adjustment it acts like a scale factor on the weights and its precise value has no impact. This error treatment assumes that the *a priori* error includes contributions from temperature gradients, instrument calibration, micrometer reading, split bubble resolution, or any other source.

Figure 1 shows that many benchmarks are overdetermined when more than two level runs connect in a benchmark. Consequently an individual standard deviation is assigned to these benchmarks by the least squares fit. This also means that for benchmarks which are not overdetermined, like the ones along the LINAC, the error is $\sigma_l = 0.1 \sqrt{N}$. The least squares fit was done with GEONET ⁽¹⁾, a FORTRAN program system developed for SLAC, based on the theory of free networks (see, e.g. ref. 2)

Finally, the ratio of the standard deviation of the average weight *a priori* and *a posteriori* was computed, which is equivalent to performing a χ^2 per degree of freedom test. The ratio was close to one, showing that the *a priori* error was chosen sensibly, and that the measurements did not contain a gross blunder.

Results

The following tables show the elevations of the leveling benchmarks as of May 1985. These elevations, and their future updates, should be used for all SLC related work. However, it must

be stressed that elevations for other SLAC systems are not consistent with the SLC coordinates, in other words, for historical reasons SLAC does not have a unified coordinate system.

Any elevation measured in the SLC system must use the adjusted geodetic elevation $H_g(fit) - 2000$ for the bench mark referenced.

Table 1 shows the actual observations, the elevation differences between the benchmarks with their *a priori* standard deviation. From the adjusted elevation differences (not shown) we get the adjusted elevation of every benchmark and their *a posteriori* (fitted) standard deviation (Table 2).

Finally TRANSPORT heights (Y_T) have to be computed, taking into account the difference between the TRANSPORT plane and the geoid which is the reference for leveling. Approximating the geoid by a sphere, which touches the TRANSPORT plane in station 100+00, geodetic elevations are transformed into TRANSPORT vertical coordinates. These results, together with approximate x,z coordinates which will facilitate location of the benchmarks in the field, and were needed for reduction of the data, are given in Table 3. For details we refer to section 8.2 of the SLC Design Handbook.

Closures from the SLC master benchmark, R306, to old LINAC and BSY benchmarks showed a 47 mil a contradiction between the existing LINAC coordinate system and the SLC coordinate system used in TRANSPORT and other computer simulation programs. Therefore, as of March 22, 1985 the canonical value for the elevation of the SLC coordinate system at station 100+00 was redefined and is now set to 254.7365 feet above mean sea level. All numbers given here reflect this change.

The elevation value given in the preceding paragraph has an immediate physical meaning: the elevation of the physical center of the copper accelerator structure at station 100+00 has to be set to the nominal value (within tolerances).

The tables describe the status of the level net as of May 1985. It connects the LINAC elevations to the surface net by runs through the BSY, the PEP south injection tunnel, the PEP tunnel, and the IR 8 PEP gate. To make each coordinate positive and unique an identifying number has been added. These false origins are for the geodetic height (H_g) = 2000, the TRANSPORT vertical coordinate (which is not a height) (Y_T) = 3000, the transverse coordinate (X) = 70,000, and the longitudinal coordinate (Z) = 90,000, numbers which have to be subtracted before any actual calculations can be done.

Generally we have carried digits to the 0.01 mm level. This last digit in the fitted or defined elevations is not physically significant in the sense that we could measure to such an accuracy. Rather we give this digit to prevent round-off errors in further calculations.

Fixed point: R306, the master benchmark for SLC, which is a rivet in the LINAC tunnel floor next to station 100+00.

References:

1. Ingolf Burstedde, "Ausgleichung Geodätischer Netze bei SLAC" (Adjustment of Geodetic Networks at SLAC), Program Manual, September 1983. Update: "GEONET, a FORTRAN Program System for the Adjustment of Geodetic Networks", August 1985.
2. H.R. Koch, "Parameterschätzung und Hypothesentests in linearen Modellen" (Parameter Estimation and Hypothesis Tests in Linear Models), Dümmler, Bonn, 1980.

Table 1: Observations (as measured differences in meter between benchmarks).

BM_{low}	BM_{high}	difference [m]	$(\sigma_l)_{a priori}$ [mm]
40	N1	01.20419	0.20
N2	N1	02.14477	0.28
20	32	01.79042	0.32
SA	20	10.29620	0.32
N3	32	06.37802	0.24
SA	36	14.66802	0.32
S8	36	03.49009	0.20
N5	33	10.16172	0.28
S3	20	20.93378	0.42
38	SA	12.82807	0.32
38	S3	02.19176	0.24
S3	S2	15.47462	0.32
N8	AA	17.95692	0.47
SA	N8	02.39304	0.60
AD	40	09.68306	0.28
S8	AA	09.17167	0.28
AD	S2	12.46138	0.35
S6A	S7	13.75742	0.32
N4	N2	15.60507	0.47
N2	N3	04.58988	0.37
34	N7	08.87813	0.28
N5	34	11.27244	0.37
N4	33	04.80285	0.20
N7	35	07.40102	0.24
N8	35	05.31538	0.24
S7	36	12.24801	0.28
S6	S6A	17.26925	0.40
39	AD	03.48532	0.40
39	S3	00.47149	0.42
S4	S3	13.18029	0.32
S6	S4	04.78900	0.60
S6	38	15.77891	0.60
38	S3	02.19176	0.24
GA	SIT	11.45755	0.40
SIT	AD	02.88978	0.35
GA	AD	14.31754	0.35
GA	S3	11.30358	0.40
SIT	R306	00.25722	0.20
40	SE19	03.78248	0.60
SE1	SE10	04.41569	0.60
SE1	SE9	00.62254	0.60
SE9	SE0	04.64994	0.60

Table 2: Least squares fit results for the complete network.

BM [m]	$H_g(est.)$ [m]	Δ_{fit} [m]	$H_g(fit)$ [m]	$(\sigma_{BM})_{a\ posteriori}$ [mm]
N3	2092.01	+0.00132	2092.01132	0.51
N1	2089.57	-0.00365	2089.56635	0.44
N2	2087.42	+0.00160	2087.42160	0.47
N4	2071.82	-0.00318	2071.81682	0.59
N5	2066.46	-0.00189	2066.45811	0.61
N7	2086.61	-0.00104	2086.60896	0.60
N8	2088.70	-0.00525	2088.69475	0.57
S2	2091.14	+0.00025	2091.14025	0.42
S3	2075.67	-0.00456	2075.66544	0.40
S4	2062.49	-0.00500	2062.48500	0.49
S6	2057.70	-0.00455	2057.69545	0.54
S6A	2074.97	-0.00530	2074.96470	0.57
S7	2088.72	+0.00213	2088.72213	0.55
S8	2097.48	+0.00004	2097.48004	0.54
32	2098.39	-0.00073	2098.38927	0.50
33	2076.62	-0.00028	2076.61972	0.60
34	2077.73	+0.00073	2077.73073	0.62
35	2094.01	+0.00006	2094.01006	0.59
36	2100.97	+0.00014	2100.97014	0.52
38	2073.48	-0.00620	2073.47380	0.43
39	2075.20	-0.00614	2075.19386	0.44
40	2088.37	-0.00784	2088.36216	0.42
20	2096.60	-0.00126	2096.59874	0.47
AA	2106.65	+0.00170	2106.65170	0.57
AD	2078.68	-0.00092	2078.67908	0.34
SA	2086.30	+0.00214	2086.30214	0.46
SI	2075.82	-0.00072	2075.81928	0.19
GA	2064.36	+0.00170	2064.36170	0.35
R306	2076.0765		2076.07650	fixed
SE19	2092.15	-0.00536	2092.14464	0.71
SE10	2096.56	+0.00033	2096.56033	0.92
SE9	2097.19	-0.00713	2097.18287	1.08
SE0	2101.84	-0.00719	2101.83281	1.23

Table 3: Approximate x,z-coordinates, and fitted Y_T -coordinates in the TRANS-PORT coordinate system. The last digit in Y_T is not physically significant.

BM	X(transverse) [m]	Z(longitudinal) [m]	$Y_T(fit)$ [m]
N1	70041.8	90153.7	3089.56436
N2	70144.9	90257.4	3087.41475
N3	70278.2	90347.3	3091.99578
N4	70417.4	90448.1	3071.78740
N5	70502.1	90540.2	3066.41543
N7	70262.9	90904.5	3086.53935
N8	70185.9	90931.7	3088.62393
S2	69861.7	90340.0	3091.12968
S3	69749.6	90406.6	3075.64755
S4	69620.3	90490.5	3062.45481
S6	69666.7	90847.0	3057.63045
S6A	69811.8	90953.9	3074.89053
S7	69886.8	90924.3	3088.65409
S8	69989.4	90900.0	3097.41648
32	70254.5	90422.3	3098.37020
33	70487.5	90418.7	3076.58732
34	70389.2	90832.2	3077.66450
35	70256.1	90999.7	3093.92649
36	69904.9	90842.8	3100.91370
38	69703.3	90550.3	3073.44314
39	69629.9	90144.9	3075.18146
40	70053.9	90027.6	3088.36187
20	70032.2	90540.9	3096.57570
AA	70017.7	91061.7	3106.56324
AD	69859.9	90126.8	3078.67628
SA	69930.7	90719.8	3086.26111
SI	69998.0	90030.0	3075.81921
GA	69864.0	90104.0	3064.35940
R306	69998.0	89976.0	3076.07645
SE19	69995.0	88863.6	3092.04331
SE10	69991.0	87968.0	3096.23635
SE9	69991.8	87859.0	3096.82320
SE0	69995.1	86953.8	3101.10473

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Figure 2