The Adjustment of the Fermilab Main Injector Underground Geodetic Survey

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1. INTRODUCTION

This paper will discuss the survey and adjustment of the Fermilab Main Injector control line. The main concerns of this paper deal with the design of the control network, the methods of measurement and reduction used to meet the accuracy specifications needed to position the machine components and monitoring devices. The paper will analyze the accuracy of the results achieved through the combination of measuring with the Chesapeake Laser Tracker, the Kern ME5000, the Kern E2 and the Leica NA3000.

2. SPECIFICATIONS OF ACCURACY FOR THE FERMI MAIN INJECTOR

The survey and adjustment of Fermi Main Injector transport line control network was carried out by Fermilab Survey, Alignment and Geodesy Group in 1996 and 1997. Accuracy requirements for the network points was calculated a priori to meet the requirement of the conceptual design, a one-sigma error of 0.25 mm in both horizontal and vertical directions for all magnetic elements with respect to the closed orbit. This requires achieving a one-sigma control point accuracy of 0.15 mm over a one betatron wave length of 127.699 meters. Additionally, the circumference of the tunnel was to be established to +/- 10 mm, an implied radial accuracy across the ring of +/- 2 mm. The tunnel is ≅3 meters (≅10 feet) wide and ≅3319 meters (≅10900 feet) in circumference. Photo 1 shows a typical view of the tunnel.

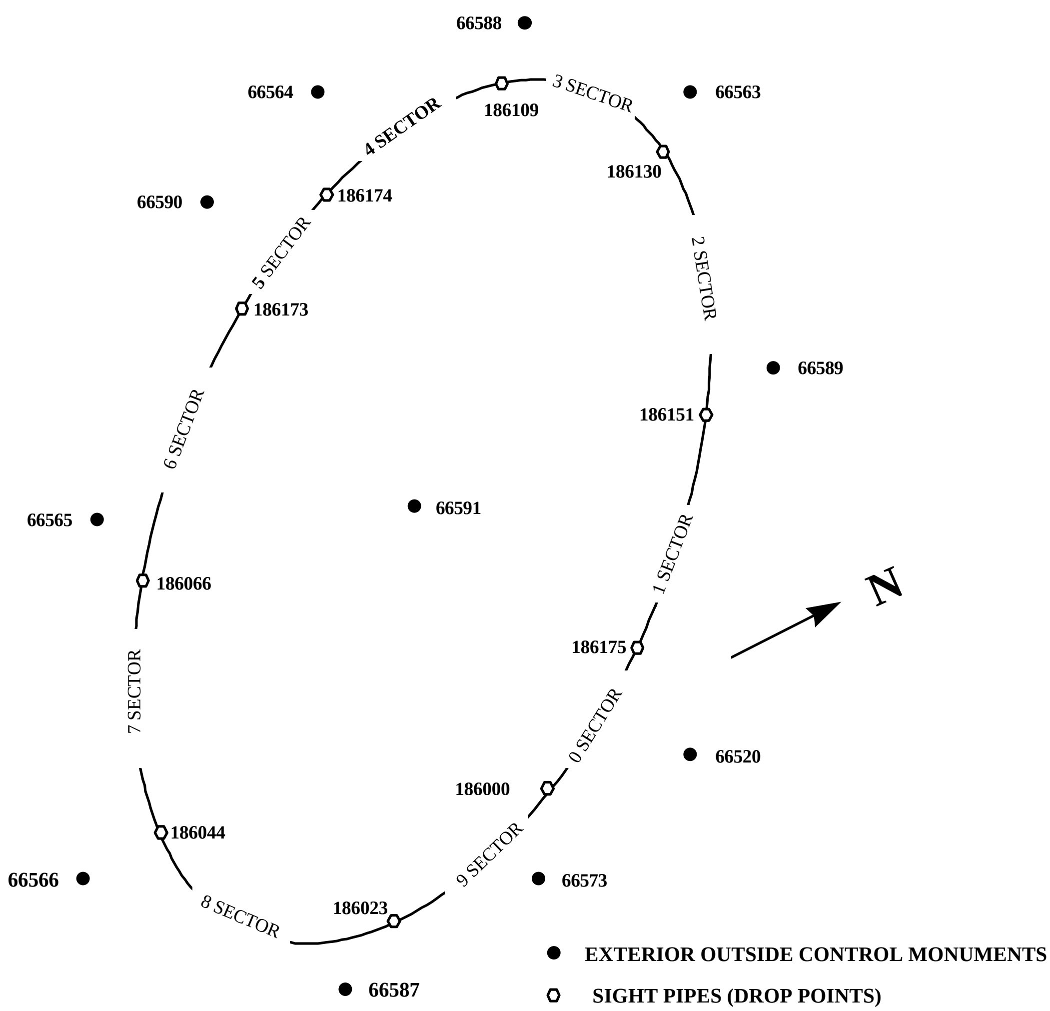
Photo 1

3. THE DESIGN AND MEASUREMENT OF THE UNDERGROUND NETWORK

The existing surface global control consists of ten exterior monuments distributed on the outside of the ring with an additional monument near the center, see figure 1. The tunnel network is anchored with drop points (sight pipes) at ten locations about the ring. Both horizontal and vertical control had been transferred into the tunnel at these locations from the outside control network.

Figure 1

FMI OUTSIDE CONTROL, DROP POINTS (SIGHT PIPES) AND SECTOR DESIGNATIONS



The tunnel was monumented with 463 wall and floor monuments, designed to accommodate traditional surveying, optical tooling and laser tracker technology. The wall monuments are automotive tie rod ends and are used primarily as vertical monuments, while the floor monuments or Dijak plugs consist of a ¾" x 10 diameter stainless steel bolt, machined to accept a 0.250" pin for various fixtures and attachments. Connected to a ¾" x 10 diameter stainless nut, this assembly is grouted into the concrete floor of the FMI tunnel. Please refer to photos 2 & 3 showing a model of the Dijak plug with SMR in place and Photo 3, a tunnel shot of an SMR on a Dijak plug.

Photo 2

Photo 3

The tie rods are mounted about 2 meters above the floor on the radially inward wall of the tunnel and situated at ≅17 meter intervals throughout the tunnel with corresponding floor plugs half way between the tie rods, centered on the floor of the tunnel. Elevations have been established on these points with the Leica NA3000 using the 60cm bar code scales(see Photo 4) on the tie rods and the 2 meter bar code rods on a 1½" diameter ball and ¼" thick nest on the Dijak plug. The elevations are established either on the top or bottom of the tie rod while the elevation for the Dijak plug is established 1 ¾" above the surface of the plug, the sweet spot for the laser tracker spherical mounted reflector (SMR).

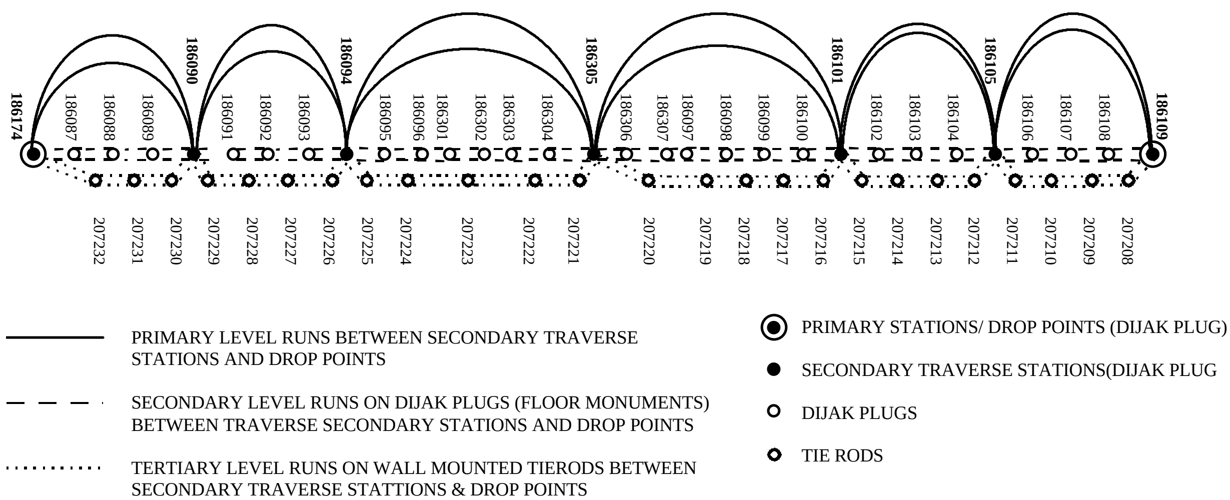
Photo 4

Elevations were transferred from the outside with the use of an unique invar rod manufactured by the Brunson Instrument Company. This invar rod consists of 6 interchangeable individually calibrated sections, ≅60 inches in length, which may be used in any combination. With nominal calibration values of +/- 0.0001", this rod was observed simultaneously above ground and in the tunnel to transfer the vertical control to the ten primary control points, Dijak plugs, directly under each site pipe. Inter-visible secondary control points, Dijak plugs, were identified through out the length of the tunnel for vertical and horizontal control.

Multiple level runs were made in each sector connecting the secondary control points to the primary stations first, with subsequent runs between secondary stations to connect both the tertiary Dijak plugs and tie rods to the network. See figure 2 for the network schematic in sector 4 of the tunnel. The 893 observations were adjusted simultaneously with least squares resulting with an aposteriori standard deviation of the unit weight to be 0.65 mm/ km through the 463 benchmarks.

Figure 2

SECTOR 4 LEVEL RUNS



The outside horizontal control was extended to the FMI tunnel with a trilateration network measured with the Kern ME5000 Mekometer. Wild NL nadir plummets were employed at the sight pipes for centering over the primary control stations. A total of 56 observations were made, with the resulting adjustment passing the 95% confidence level with a variance factor of 1.0005. A review of the ellipses of error in the table 1 clearly shows the initial criteria of 2.0 mm across the ring had been met.

TABLE 1: Units are in meters.

STATION	SEMI-MAJOR AXIS	SEMI-MINOR AXIS	AZIMUTH SEMI-MAJOR AXIS	AREA OF ELLIPSE
66330	0.00088	0.00034	72 40 29	0.93822D-06
66567	0.00048	0.00036	292 17 52	0.53510D-06
66575	0.00116	0.00034	80 15 27	0.12500D-05
66589	0.0003	0.00022	342 58 22	0.20522D-06
66591	0.0003	0.00022	342 58 22	0.20522D-06
186000	0.00051	0.00036	342 10 59	0.57950D-06
186023	0.00067	0.00031	6 35 14	0.66357D-06
186044	0.00074	0.00038	34 31 50	0.88142D-06
186066	0.00072	0.00037	55 58 15	0.82786D-06
186109	0.00046	0.00028	338 26 35	0.40247D-06

186130	0.00045	0.00032	26 55 36	0.44946D-06
186151	0.00038	0.00031	87 26 9	0.37207D-06
186173	0.00065	0.00045	74 41 58	0.90775D-06
186174	0.00053	0.00032	289 1 19	0.52588D-06
186175	0.00045	0.00034	342 50 43	0.48109D-06

The Chesapeake 3000 Laser Tracker(CMS-3000), see photo 5**,** was selected to perform a three dimensional trilateration network in the FMI tunnel in conjunction with a ME5000 Mekometer and Kern E2 electronic theodolite traverse through the secondary control stations between the site pipes**.** The traverse was included to constrain the azimuth error between sight risers during the adjustment of the laser tracker network. The CMS-3000 is specified to measure to an accuracy of 1 micron /meter radially, 10 microns/meter transversely and with a repeatability of 1 and 2 microns/meter respectively.

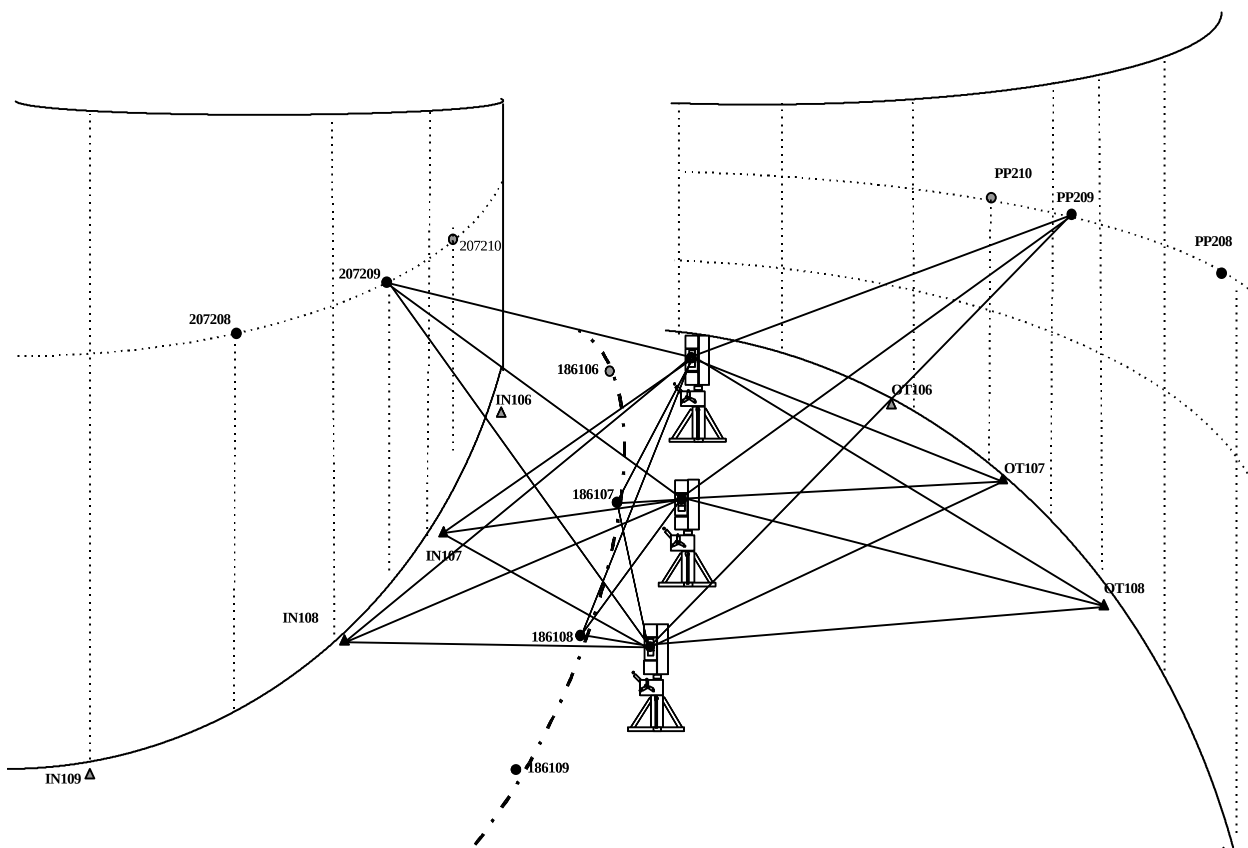
Photo 5

The observations made by the Laser Tracker are reported as coordinate values. A typical setup resulted with coordinates on 4 floor plugs, 3 tie rods, and 11 pass points. The pass points were temporary fixtures set at floor level, next to the walls, on both sides of the Dijak plugs and on the radially outward wall directly across from and at the same height of each tie rod.

Moving from setup to setup, every Dijak plug, tie rod and pass point was measured from three different stations. At the start of a setup, seven of the previously measured points were remeasured and a 7 parameter best fit solution obtained for those observations based on the coordinate values generated for those points during the previous setup.. Once the best fit solution was obtained the additional points were measured. Figure 4 shows the stations common to three adjacent laser tracker stations.

Figure 4

CONTROL STATIONS COMMON TO THREE LASER TRACKER SETUPS IN THE FMI TUNNEL



4. THE LOCAL STATION ADJUSTMENT.

It would have been possible to perform all of the laser tracker measurements within the tunnel without ever doing a 7 parameter best fit of the data. Introducing the best fit provided an opportunity to check the observations in the field by reviewing the residuals of the coordinates that were developed in the process. Table 3 shows a comparison between the laser tracker coordinates for Dijak plugs 186107 and 186108 for 3 different setups.

Table 3

BEST FIT	DIFF COORDINATES	FILE1 4STA001	FILE2 4STA002
NAME	DELTAX(M)	DELTAY(M)	DELTAZ(M)
186107	-0.00003	0.00005	-0.00026
186108	0.00001	-0.00006	0.00001
		4STA001	4STA003
186107	0.00004	0.00002	-0.00012
186108	-0.00001	-0.00002	0.00006
		4STA002	4STA003
186106	-0.00006	0.00004	-0.00022
186107	0.00007	-0.00003	0.00014

This comparison was critical for the verification of the integrity of the field data; but introduced a bias resulting from the scale factors generated with the 7 parameter transformation created with each tracker setup. Actual site coordinate values had been entered for the starting points and were carried through out the survey. Since these coordinates have values at or about 30,000 meters in both X and Y, the scale factors determined in the course of the measurements had a rather significant impact on the coordinate values reported by the system. The coordinates developed for stations 107 and 108 from three different laser tracker stations along with the respective scale factors are shown in table 4.

TABLE 4
Units are in meters.

4STA001	SCALE	EAST COORD	NORTH COORD	ELEV
186107	0.99999810	30139.74290	29131.13866	217.26874
186108	0.99999810	30134.37159	29147.54442	217.24913
4STA002	SCALE	EAST COORD	NORTH COORD	ELEV
186107	1.00000041	30139.74287	29131.13871	217.26848
186108	1.00000041	30134.37160	29147.54436	217.24914
4STA003	SCALE	EAST COORD	NORTH COORD	ELEV
186107	1.00000057	30139.74294	29131.13868	217.26862
186108	1.00000057	30134.37158	29147.54440	217.24919

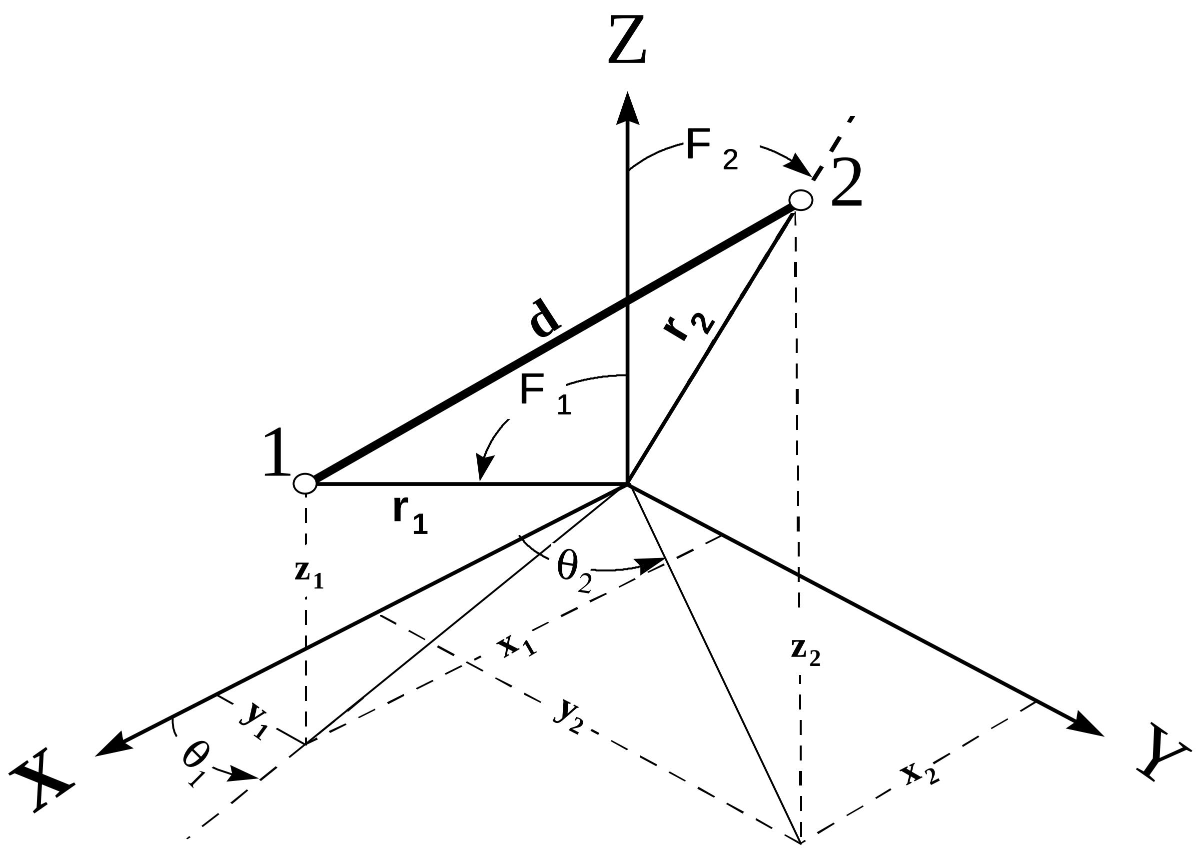
Since these coordinates reflected the scale correction introduced through the transformation, the bias at 30,000 meters between 4STA001 and 4SAT003 amounted to more than 7 centimeters. The coordinates determined in each of the setups were corrected for scale as shown in table 5 which only lists the corrected coordinates for 186107 and 186108.

Table 5
Units are in meters.

STATION	E COORD	N COORD	ELEV
4STA001			
186107	30139.68563	29131.08331	217.26833
186108	30134.31433	29147.48904	217.24872
4STA002			
186107	30139.75523	29131.15065	217.26857
186108	30134.38396	29147.55631	217.24923
4STA003			
186107	30139.76012	29131.15528	217.26874
186108	30134.38876	29147.56101	217.24931

Although each laser tracker observation is comprised of a radial distance, **r**, a horizontal angle, θ, and a vertical angle ϕ, the results are reported as coordinates. Considering the volumes being observed, the laser tracker was measuring the distances to an accuracy of 40 microns while the angles were being measured to an accuracy of 1 arc second. So a strategy had to be developed to weight the inverses from the coordinates shown in table 5. Figure 10 is used in the following derivation.

Figure 10



$\mathbf{d} = ((X_2-X_1)^2 + (Y_2-Y_1)^2 + (Z_2-Z_1)^2)^{1/2}$

where :

$X_1 = r_1 \cos \theta_1 \sin \phi_1$
$Y_1 = r_1 \sin \theta_1 \sin \phi_1$
$Z_1 = r_1 \cos \phi_1$

$X_2 = r_2 \cos \theta_2 \sin \phi_2$
$Y_2 = r_2 \sin \theta_2 \sin \phi_2$
$Z_2 = r_2 \cos \phi_2$

In polar coordinates, the equation for line **d** will take the following form:

$\mathbf{d} = (r_1^2 + r_2^2 - 2r_1r_2 [\sin \phi_2 \sin \phi_1 \cos (\theta_2-\theta_1) + \cos \phi_2 \cos \phi_1]^{1/2}$

Defining the priori standard errors as follows:

δ_{r1} = a priori standard error for radial distance 1
δ_{r2} = a priori standard error for radial distance 2
$\delta_{\theta 1}$ = a priori standard error for horizontal angle 1
$\delta_{\theta 2}$ = a priori standard error for horizontal angle 2
$\delta_{\phi 1}$ = a priori standard error for vertical angle 1
$\delta_{\phi 2}$ = a priori standard error for vertical angle 2

The corresponding standard error is given by

$\delta_d = [(\partial d/\partial r_1)^2\delta^2_{r1} + (\partial d/\partial r_2)^2\delta^2_{r2} + (\partial d/\partial\theta_1)^2\delta^2_{\theta 1} + (\partial d/\partial\theta_2)^2\delta^2_{\theta 2} + (\partial d/\partial\phi_1)^2\delta^2_{\phi 1} + (\partial\delta/\partial\phi_2)^2\delta^2_{\phi 2}]^{1/2}$

with a corresponding weight given by

$W = 1/(\delta_d)^2$

where

$\partial d/\partial r_1 = [r_1 - r_2 (\sin \phi_2 \sin\phi_1 \cos(\theta_2-\theta_1) + \cos\phi_2 \cos\phi_1)]/d$

$\partial d/\partial r_2 = [r_2 - r_1 (\sin\phi_2 \sin\phi_1 \cos(\theta_2-\theta_1) + \cos\phi 2 \cos\phi_1)]/d$

$\partial d/\partial\theta_1 = [-r_1 * r_2 \sin \phi_2 \sin\phi_1 \sin(\theta_2-\theta_1)]/d$

$\partial d/\partial \theta_2 = [\ r_{1*}\ r_2 \sin \phi_2 \sin\phi_1 \sin(\theta_2-\theta_1)]/d$

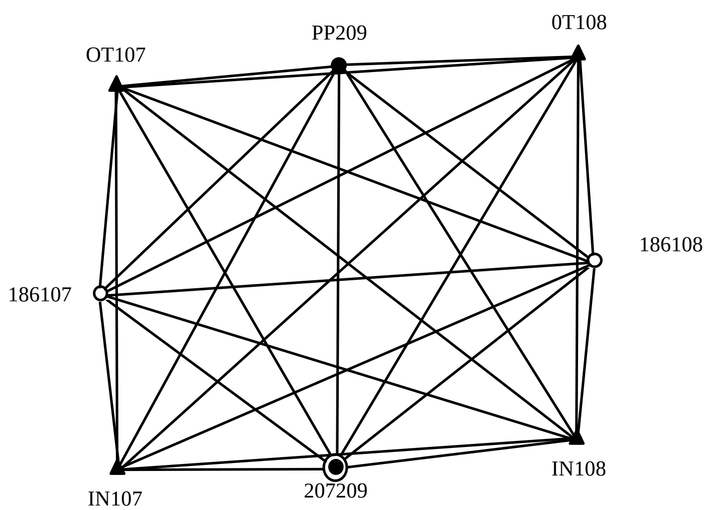
$\partial d/\partial \phi_1 = [\ -r_1 r_2\ (\sin \phi_2 \cos\phi_1 \cos(\theta_2-\theta_1)-\cos\phi_2 \sin\phi_1]/d$

$\partial d/\partial \phi_2 = [\ -r_1 r_2\ (\cos \phi_2 \sin\phi_1 \cos(\theta_2-\theta_1)-\sin\phi_2 \cos\phi_1]/d$

Using the previously stated accuracy's for the laser tracker, 40 microns and 1 arc second a computer program generated standard errors between all of the combinations of coordinates i.e. pseudo slope distances, see figure 5.

Figure 5

RESOLVED POINTS AFTER 3 SET UPS



The least squares adjustment program currently in use at Fermilab requires the input of the standard error of the observations for applying weights to the adjustment; so the standard error is shown rather than the weight. Table 6 shows the values determined for the observations computed for the coordinate at control point 186107 for three setups.

Table 6

LT STA	FROM	TO	STD ERR	DIST
4STA001	186107	186108	0.00004	17.26265
4STA001	186107	207209	0.00005	8.85466
4STA001	186107	IN107	0.00019	1.65691
4STA001	186107	IN108	0.00005	17.26580
4STA001	186107	OT107	0.00019	1.42721
4STA001	186107	OT108	0.00005	17.08661
4STA001	186107	PP209	0.00006	8.35687
4STA002	186107	186108	0.00004	17.26258
4STA002	186107	207209	0.00003	8.85481
4STA002	186107	IN107	0.00007	1.65700
4STA002	186107	IN108	0.00004	17.26572
4STA002	186107	OT107	0.00007	1.42733
4STA002	186107	OT108	0.00004	17.08661
4STA002	186107	PP209	0.00004	8.35695
4STA003	186107	186108	0.00004	17.26267
4STA003	186107	207209	0.00005	8.85474
4STA003	186107	IN107	0.00005	1.65701
4STA003	186107	IN108	0.00004	17.26581
4STA003	186107	OT107	0.00005	1.42737
4STA003	186107	OT108	0.00004	17.08664

In the same program, the pseudo slope distances are compared to each other with a rejection criteria based on the standard deviation of the observations. Table 7 shows a typical file, generated from this comparison, listing the rejected distances. If any of the distances are rejected, it is necessary to repeat the observations with the laser tracker.

Table 7

FROM	TO	STD ERR	DISTANCE	
186107	186108	0.00004	17.26225	
186107	186108	0.00004	17.26258	
DIFF DIS=-0.00033		REJECT.VALUE= 0.00017		
186107	207209	0.00005	8.85406	
186107	207209	0.00003	8.85481	
DIFF DIS=-0.00075		REJECT.VALUE= 0.00017		
186107	IN107	0.00019	1.65781	
186107	IN107	0.00007	1.65700	
DIFF DIS= 0.00081		REJECT.VALUE= 0.00061		

With three stations completed, a local tunnel adjustment can be made to further evaluate the integrity of the data. An examination of the configuration of a typical three station adjustment shows 28 unique lines, each measured three times. The weighted mean of these observations is computed from the pseudo slope distances and the standard errors. Table 8 reflects the weighted mean and standard deviation for the pseudo distances from station 186107.

Table 8

FROM	TO	STD ERR	DISTANCE
186107	OT107	0.00004	1.42733
186107	IN107	0.00004	1.65699
186107	PP209	0.00003	8.35691
186107	207209	0.00002	8.85475
186107	OT108	0.00002	17.08662
186107	186108	0.00002	17.26263

This typical local system of 28 observations has 11 degrees of freedom. The resulting least squares adjustment develops residuals of 0.0001 meters or less. The following print out shows typical error ellipses resulting from the adjustment.

```
************************************************************************
*   LOCAL SYSTEM ADJUSTMENT (QC)                                       *
************************************************************************
1STATISTICS SUMMARY
 ---------------------------------------------------------------------------------------------------
 NUMBER OF ITERATIONS REQUIRED FOR CONVERGENCE -->    1
 MAXIMUM NUMBER OF ITERATIONS ALLOWED ----------->    9

 NUMBER OF OBSERVATIONS                 | NUMBER OF UNKNOWNS
 -------------------------------------------       |-----------------------------------------
                                        |
 HOR DIST              0                |
 SLOPE DIST           28                | ZERO ERRORS         0
 DIRECTIONS            0                | ORIENTATION         0
 ANGLES                0                |
 AZIMUTHS              0                |
 HOR OFF               0                |
 SLOPE OFF             0                |
 ZENITH ANG            0                | ZENITH OFFSETS      0
 LEVEL HTS             0                |
 COORDINATES           0                | COORDINATES                17
                   -----                                   -----
 TOTALS               28                                           17

    THE NUMBER OF DEGREES OF FREEDOM IS     11
    ESTIMATED VARIANCE FACTOR FOR DISTANCE    =     0.371993461
    COMBINED ESTIMATED VARIANCE FACTOR        =     0.946892445

 CHI-SQUARE TEST ON THE VARIANCE FACTOR
 ---------------------------------------------------------------------------------------------------
                (VARIANCE FACTOR KNOWN)
   0.474968      <  1.000000  <       2.730575     ?
 TEST ON VARIANCE FACTOR AT THE  95.000 % CONFIDENCE LEVEL PASSES
 (   0 RESIDUALS WERE FLAGGED FOR REJECTION   )
1STATION 95.000 % CONFIDENCE ELLIPSOIDS (METRES)
```

TOTAL VOLUME OF STATION ELLIPSOIDS = 0.48070D-11

1XY PLANE STATION 95.000 % CONFIDENCE ELLIPSES (METRES)

FACTOR USED FOR OBTAINING THESE ELLIPSES FROM STANDARD ELLIPSES: (VARIANCE FACTOR KNOWN) = 2.4484
(COVARIANCE MATRIX OF PARAMETERS WAS NOT MULTIPLIED BY THE ESTIMATED VARIANCE FACTOR (0.946892)).

STATION	SEMI-MAJOR AXIS	SEMI-MINOR AXIS	AZIMUTH OF SEMI-MAJOR AXIS	AREA OF ELLIPSE
207209	0.00010	0.00002	72 5 3	0.57273D-08
IN107	0.00004	0.00002	68 14 30	0.24258D-08
IN108	0.00005	0.00002	75 42 54	0.25901D-08
OT107	0.00009	0.00001	73 30 25	0.41770D-08
OT108	0.00010	0.00001	69 40 30	0.45084D-08
PP209	0.00018	0.00001	71 28 42	0.85647D-08

This local station adjustment confirms the integrity of the data obtained and provides the confidence to continue the measurement process . The local station adjustments continue throughout the sector, dropping the data from one station and adding the data from the next until the sector is completed.

5. THE PRELIMINARY SECTION ADJUSTMENT.

With the completion of a sector, it was possible to do a preliminary global adjustment of the sector. The preliminary global adjustment fixed the primary coordinates on the Dijak plugs at the sight pipes, held the elevations established with the level campaign, and constrained on the weighted secondary control stations established with the ME5000 Mekometer and Kern E2 Theodolite. The following printout shows a representative sample of the error ellipses resulting from this preliminary global adjustment of sector 4.

```
*****************************************************************************
*                                        *
*   FMI (LTCS SQ CONFIG) APR/MAY 1997 (4STA001 to 4STA026) B AND C FILES      *
*                                        *
******************************************************************************
1STATISTICS SUMMARY
------------------------------------------------------------------------------------------------------------------
 NUMBER OF ITERATIONS REQUIRED FOR CONVERGENCE -->          3
 MAXIMUM NUMBER OF ITERATIONS ALLOWED ----------->          9

 NUMBER OF OBSERVATIONS  | NUMBER OF UNKNOWNS
```

```
------------------------------------------           |------------------------------------
                                                      |
HOR DIST              6        |
SLOPE DIST         2158        | ZERO ERRORS          0
DIRECTIONS           10        | ORIENTATION          5
ANGLES                0        |
AZIMUTHS              0        |
HOR OFF               0        |
SLOPE OFF             0        |
ZENITH ANG            0        | ZENITH OFFSETS       0
LEVEL HTS             0        |
COORDINATES           0        | COORDINATES        381
                  ---------                       -------
TOTALS             2174                             386

    THE NUMBER OF DEGREES OF FREEDOM IS   1788
    ESTIMATED VARIANCE FACTOR FOR DISTANCE  =          0.814288587
    ESTIMATED VARIANCE FACTOR FOR ANGLE     =          0.198895833
    COMBINED ESTIMATED VARIANCE FACTOR      =          0.986638401

CHI-SQUARE TEST ON THE VARIANCE FACTOR
----------------------------------------------------------------------------------------------------------------
              (VARIANCE FACTOR KNOWN)
   0.925028      <  1.000000  <       1.054648     ?
TEST ON VARIANCE FACTOR AT THE  95.000 % CONFIDENCE LEVEL PASSES
(   0 RESIDUALS WERE FLAGGED FOR REJECTION   )
1STATION 95.000 % CONFIDENCE ELLIPSOIDS (METRES)
--------------------------------------
1XY PLANE STATION 95.000 % CONFIDENCE ELLIPSES (METRES)
--------------------------------------------
FACTOR USED FOR OBTAINING THESE ELLIPSES FROM STANDARD ELLIPSES: (VARIANCE
FACTOR KNOWN)   =   2.4484  (COVARIANCE MATRIX OF PARAMETERS WAS NOT
MULTIPLIED BY THE ESTIMATED VARIANCE FACTOR (    0.986638 )).
```

STATION	SEMI-MAJOR AXIS	SEMI-MINOR AXIS	AZIMUTH SEMI-MAJOR AXIS	AREA OF ELLIPSE
IN107	0.00020	0.00002	72 9 40	0.15470D-07
IN108	0.00019	0.00003	72 54 0	0.15155D-07
OT107	0.00019	0.00002	72 8 25	0.13704D-07
OT108	0.00018	0.00002	73 6 1	0.13805D-07
PP209	0.00021	0.00002	73 11 36	0.16170D-07

6. THE FINAL ADJUSTMENT.

Once the tunnel was completely measured, the final weighted global adjustment was completed by constraining on the ten primary stations. The following print out shows a representative sample of the error ellipses resulting from this preliminary global adjustment.

```
*****************************************************************************
*                                        *
```

*   FMI (XYZ)   1997 (1 SECTOR TO 0 SECTOR)   *
*   *
****
STATISTICS SUMMARY

NUMBER OF ITERATIONS REQUIRED FOR CONVERGENCE -->   1
MAXIMUM NUMBER OF ITERATIONS ALLOWED ----------->   9

NUMBER OF OBSERVATIONS		NUMBER OF UNKNOWNS		
HOR DIST	53			
SLOPE DIST	14498	ZERO ERRORS	0	
DIRECTIONS	100	ORIENTATION	50	
ANGLES	0			
AZIMUTHS	0			
HOR OFF	0			
SLOPE OFF	0			
ZENITH ANG	0			
ZENITH OFFSETS	0			
LEVEL HTS	0			
COORDINATES	20	COORDINATES	277	0
	-------		-------	
TOTALS	14671		2820	

THE NUMBER OF DEGREES OF FREEDOM IS 11851

ESTIMATED VARIANCE FACTOR FOR DISTANCE =   0.798922781
ESTIMATED VARIANCE FACTOR FOR ANGLE   =   0.420646921
ESTIMATED VARIANCE FACTOR FOR WT COORD =   0.237542832

COMBINED ESTIMATED VARIANCE FACTOR   =   0.984890806

CHI-SQUARE TEST ON THE VARIANCE FACTOR

(VARIANCE FACTOR KNOWN)

0.960287   < 1.000000 <   1.010457   ?

TEST ON VARIANCE FACTOR AT THE 95.000 % CONFIDENCE LEVEL PASSES
1XY PLANE STATION 95.000 % CONFIDENCE ELLIPSES (METERS)

FACTOR USED FOR OBTAINING THESE ELLIPSES FROM STANDARD ELLIPSES: (VARIANCE FACTOR KNOWN)   =   2.4484
(COVARIANCE MATRIX OF PARAMETERS WAS NOT MULTIPLIED BY THE ESTIMATED VARIANCE FACTOR (0.984891)).

STATION	SEMI-MAJOR AXIS	SEMI-MINOR AXIS	AZIMUTH SEMI-MAJOR AXIS	AREA OF ELLIPSE

207209	0.00038	0.00026	61 11 25	0.30921D-06
IN107	0.00041	0.00026	61 0 34	
0.33253D-06				
OT107	0.00035	0.00025	55 50 4	0.28278D-06
IN108	0.00039	0.00026	64 51 35	0.32580D-06
OT108	0.00034	0.00026	60 48 21	0.27888D-06
PP209	0.00036	0.00026	60 51 48	0.29629D-06

7. CONCLUSION

The survey and adjustment of the Fermilab Main Injector control network was accomplished through a combination of measuring procedures utilizing the Chesapeake Laser tracker, the Kern ME5000, the Kern E2 and the Leica NA3000. The outside control network was transferred to the interior of the tunnel at ten drop points established around the main injector tunnel, extensive levels were run with the NA3000 along with a traditional traverse utilizing the ME5000 and the Kern E2. A laser tracker network was established around the ring, through the ten drop points with each tierod, Dijak plug and pass point being measured a minimum of three times. The laser tracker network generated preliminary global coordinates during the course of the survey, biased with the introduction of a scale factor through a seven parameter transformation.

The coordinates were corrected for scale and then typically three sets of pseudo slope distances were computed for every three sets of overlapping setups. A free floating local adjustment was made to verify the integrity of the data set. With the completion of a sector, a global adjustment was made, using the data generated with the laser tracker with the added constraint on the azimuth with the data generated from the classical traverse.

A final adjustment was made at the completion of the entire tunnel survey by constraining on the weighted coordinates of the ten primary stations. This adjustment clearly demonstrates the survey has met the requirements of the conceptual design.

8. REFERENCES

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