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Massive Metrology: Development and Implementation of a 3D Reference Frame for the Realignment of Fermilab's Tevatron

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The authors of this paper will discuss the project known as TeVnet. TeVnet is a combined horizontal and vertical survey network that was developed to provide spatial control for the three key machines of the Fermilab accelerator complex – Tevatron, Main Injector, and Anti-Proton source. This paper focuses on the survey network design, observation, and analysis, of an effort with the objective of increased performance and reliability of the accelerator complex by ensuring spatially correct placement of the beam-line components.

1. INTRODUCTION

After a series of upgrades, the performance and reliability of the Tevatron, a 6.3-km circumference, (***see Pictures 1 and Picture 2***) one trillion electron-volt proton and antiproton accelerator, was well below expectations. It had long been suspected that the Murphy Line system, the current alignment method, was not capable of ensuring a reliable orbit at increased energy levels. The solution was the use of modern metrology methods and instrumentation for the alignment of the Tevatron.

This paper introduces the concept of combining networks measured using different methods of surveying to develop the metrology for TeVnet, network design configuration alternatives, and observational procedures used to accomplish the network measurements, along with the simultaneous determination of the existing position of more than 1000 components of the Tevatron machine. The position of the Tevatron components was developed by best-fit transformation of the as-found data into the adjusted TeVnet reference frame.

2. PROJECT TeVnet: THE PROBLEM AND SOLUTION

In 2003, Tevatron Alignment Task Force (TATF) was formed by Accelerator Division to address this situation. TATF set a timetable for the improvement of various units of the facility. As project planning developed, it became apparent that modern dimensional metrology would be a great tool for this major upgrade of the *still most powerful accelerator in the world*.

Very important to the project was the development of a geodetic network design - TeVnet - that would be capable of providing 3D-coordinates of the control, with accuracy sufficient to meet the requirements of the relative position, in the horizontal and vertical directions, for all magnetic elements, with respect to the closed orbit of the machine. The TATF stipulated the diametrically opposite points of the machine would be accurate within 2.5mm, 1σ.

Picture 1. View of Fermilab with Tevatron area

2.1 Investigation of the Existing Tevatron Alignment System-Murphy Line

The Murphy Line System, which has served as the alignment reference artifact since the inception of the Tevatron, can be described as *a series of 200 unconnected tangent-offset lines, inscribed by the Tevatron magnet array*. Part of the TeVnet project was to investigate the appropriateness of the Murphy Line System as an alignment method. Since the performance of the Tevatron was below expectations, the question that needed to be answered was: is part of the problem attributable to the underlying concept embodied in the Murphy Line?

Picture 2. View of Tevatron tunnel

- **The problem with Murphy line principle:** Each line controls only five components; the orbit cannot be strongly defined. (see Fig 1. for typical Tevatron cell)

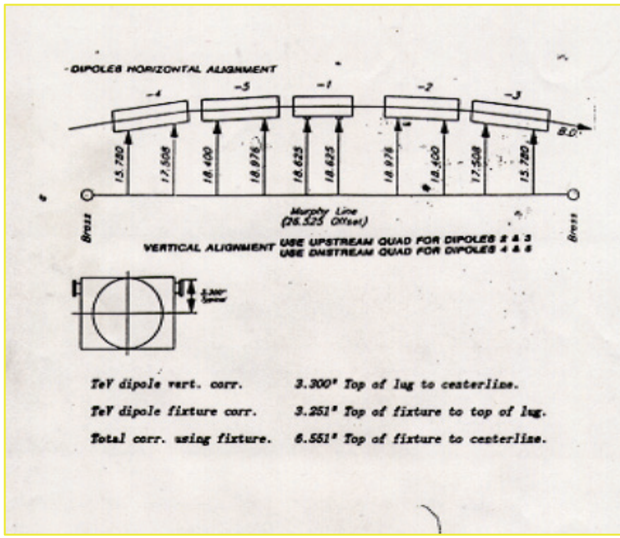
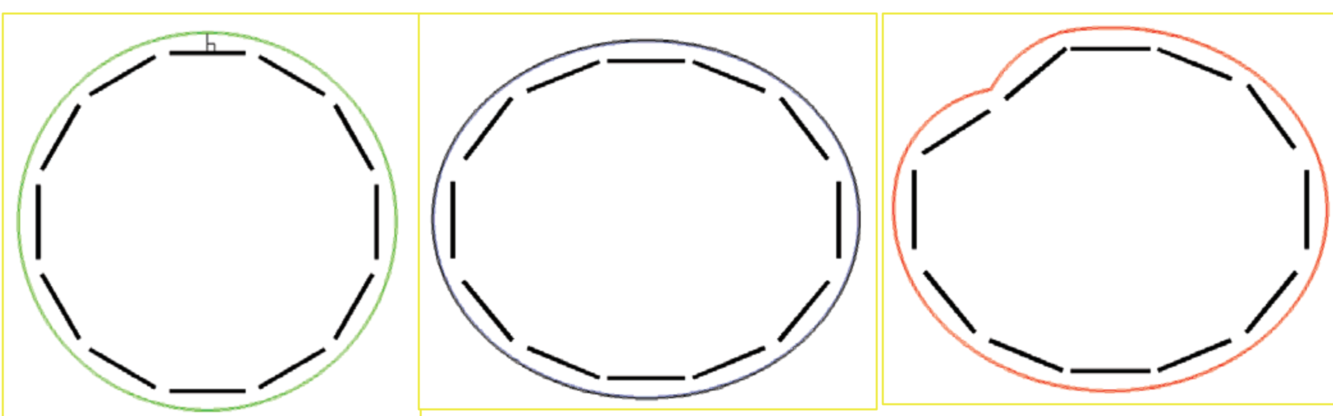


Figure 1 Typical Tevatron magnets configuration

- **The problem with the orbit when using Murphy lines:** Practically unknown orbit shape (***see Figure 2 for orbit expectation***).



1. 2. 3.

Figure 2. Ideal 1, possible 2, likely 3 Murphy line orbits

Method to investigate the suitability of the Murphy Line System: The TATF requested that the coordinates of the Murphy plugs be determined by traversing around the Ring, using the best available metrological techniques, tying each plug to the traverse, and holding the position of A0 fixed. Aside from the issue of not having a suitable azimuth, the preanalysis using this scenario produced 19mm semi-major axis error ellipses at D0, which is diametrically opposite the origin. This is very much below the desired accuracy (***Figure 3***.). An alternative scenario was to constrain the traverse by using the positions of the two available sight-risers. This did not significantly improve the results of the preanalysis.

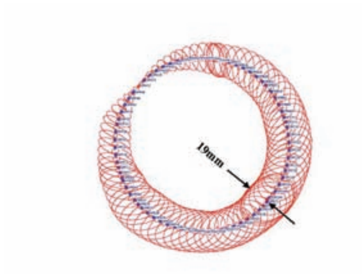
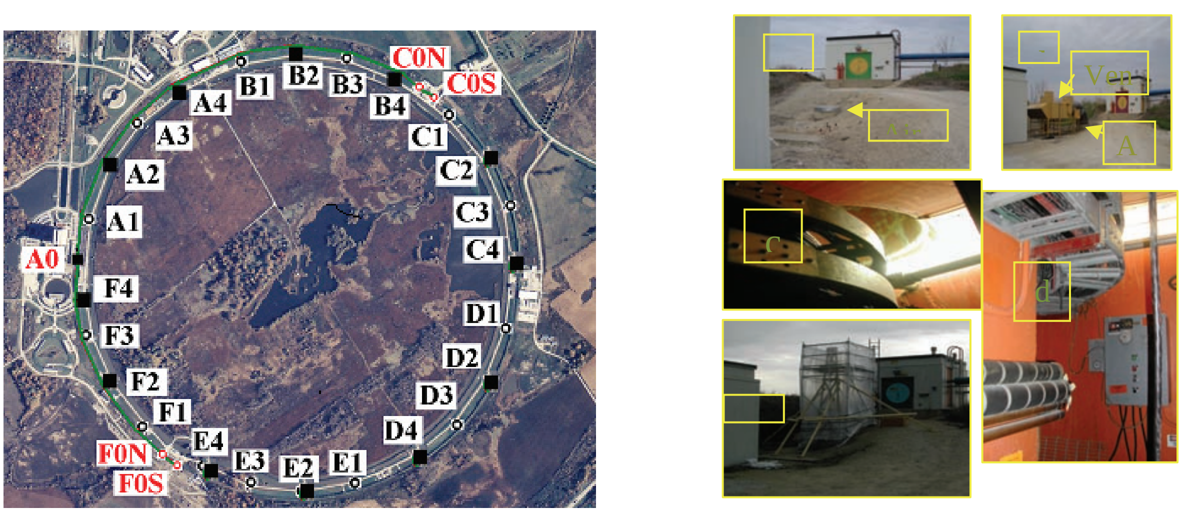


Figure 3 - Murphy Line Traverse preanalysis error ellipses, fixed at A0

After further investigation, TATF requested 22 additional sight-risers (at 250m intervals) but a quick budget estimate indicated a cost of $10-15k each. A total cost of approximately $250k was deemed an unrealistic expenditure for a single part of the project. A search of old plans found a series of abandoned ventilator shafts that could be used as *faux* sight-risers. The use of the ventilation shafts was found acceptable, not only because of the elimination of the expense, but also the time that would be required to install normal sight-risers. (*Picture 3*.)



Picture 3. Sight risers ventilation shafts location and view.

The preanalysis now includes the tunnel traverse and the surface network, with sight-risers at the two available locations and 12 additional sight-risers created by repurposing decommissioned ventilation shafts.

This refinement produces an accuracy of 3.2mm which is a significant improvement, but does not meet the desired accuracy of < 2.5mm, and is insufficient to be considered as the basis for the TeVnet project. (*Figure 4)*

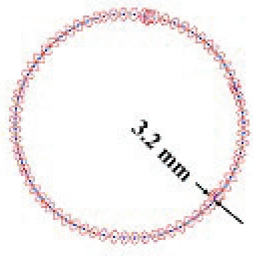


Figure 4. Error ellipses for the Murphy Line using 14 sight-risers

2.2 The Design and Monumentation of TeVnet

To achieve the requested accuracy, a geometrically stronger network can be developed by including a Laser Tracker survey**.** Points surveyed using the Laser Tracker are not measured in a gravity-based system. Measurements are introduced to the global adjustment dataset as follows:

- The Laser Tracker-head coordinates were converted to pseudo-observations as weighted slope distances. The slope distances were calculated from three or more stations with weights being calculated according to the factory specification of the Laser Tracker, which has been validated by experience in previous surveys, such as the Main Injector and P-bar networks.
- Pseudo-observations were evaluated to remove gross errors by comparing redundant distances from different Laser Tracker stations with a rejection criteria based on the standard deviation of the observations.

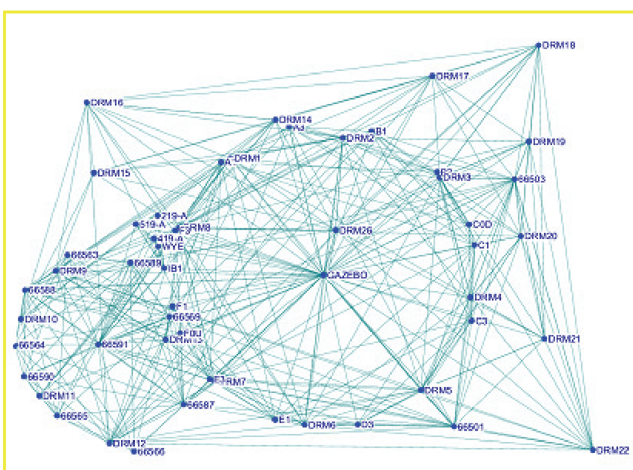


Figure 5. Surface network

A pre-analysis dataset was prepared to include the Laser Tracker pseudo-observations with tunnel traverse and surface network. To obtain the final Laser Tracker observation configuration of the underground network required performing several pre-analyses.

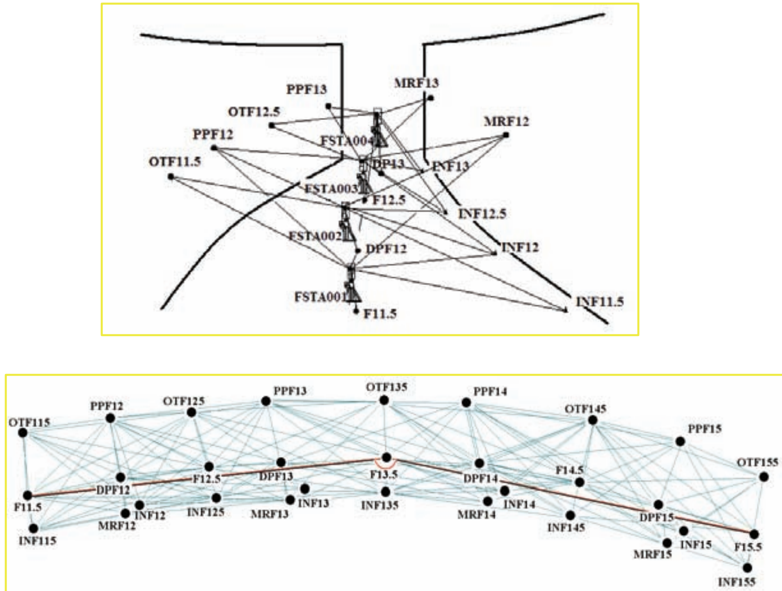


Figure 6. Schematic of tunnel control points and survey strategies for underground network

The final pre-analysis of TeVnet, which includes the Laser Tracker network and the surface-tunnel traverse network, produces error ellipses of 1.2mm, around the ring. This yields a relative accuracy across the ring of 1.7mm,well below that requested by TATF. All pre-analysis was conducted using 95% confidence limit.

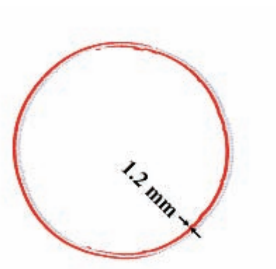


Figure 7. Final pre-analysis of TeVnet

The following survey instrumentation was selected for TeVnet: SMX Laser Tracker, Kern ME5000 Mekometer, Geodimeter 640 total station with Autolock, Leica DNA03 digital levels, Trimble 4000SSE and 5700 GPS receivers with Zephyr Geodetic antenna, and DMT Gyromat 2000 gyro-theodolite.   The surface network positions were transferred to the tunnel through the sight-risers using precision zenith-nadir plummets. Vertical control was transferred via the sight-risers and access stairways.

2.3 Field Measurement

The Fermilab's Alignment and Metrology Group (AMG), with additional personnel supplied by Argonne, Brookhaven, and SLAC national laboratories, and contract surveyors from James, Schaeffer & Schimming, Inc. and Measurement Sciences Inc., performed the survey and adjustment of TeVnet, and the alignment of components of the Tevatron in 2003 – 2005.

First part of the field survey project was to update surface and tunnel monuments. AMG installed 26 Deep Rod Monuments (DRM) at ground-surface. The DRM were deployed at strategic locations around the accelerator complex, including eight around Ring Road, the Tevatron interior service road, and six around the exterior service road of the Main Injector. In addition, twelve towers were built above the converted ventilator shafts to facilitate Mekometer laser distance measurements between adjacent ventilator shafts and to the nearby DRM. (*Pictures 3*) Seeking to derive the greatest benefit from the TeVnet effort, it was decided by AMG to tie the Main Injector and Anti-proton Source to the network. Fixtures were installed on the sight-risers of these portions of the accelerator complex to facilitate acquisition of GPS observations. The monument at the center point of the Tevatron ring, known as Gazebo, was adopted for the primary GPS station.

Picture 4. Surface monuments

After investigating the current tunnel monument configuration, only the wall monuments could be carried over to TeVnet. New floor monuments, known as Dijak Plugs (DP), were set near to the existing Murphy Line brass in order to establish a precise representation of the Murphy Line System. The tunnel was monumented with approximately 1500 wall and floor monuments, designed to accommodate traditional surveying, optical tooling, and laser tracker technology.

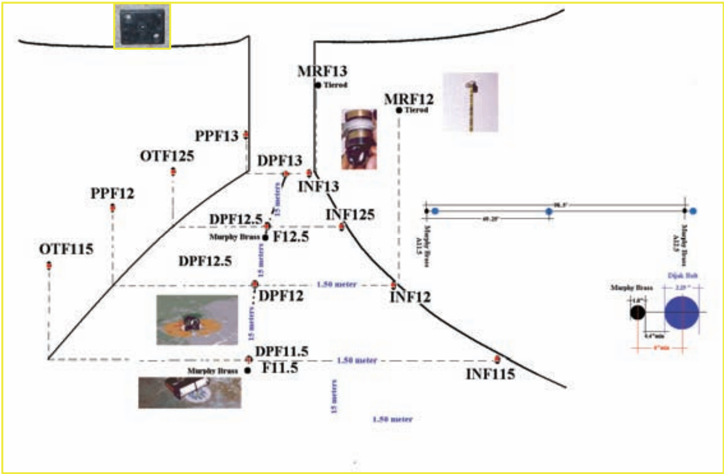


Figure 8. Tunnel monuments

Every Laser Tracker setup contained control points and the fiducials points of the magnetic components, which were measured simultaneously in the Laser Tracker-head coordinate system.

Picture 5. Survey fiducial points of the element

To obtain three-dimensional coordinates of the 1940 TeVnet control points, the following observation effort was required:

- 482 Tracker setups
- 69,658 Tracker observations
- 29,498 Tracker chords
- 623 GPS baselines
- 141 Mekometer observations
- 84 Autolock angles
- 14 vertical drops
- 1035 Tunnel elevations
- 86 Surface elevations

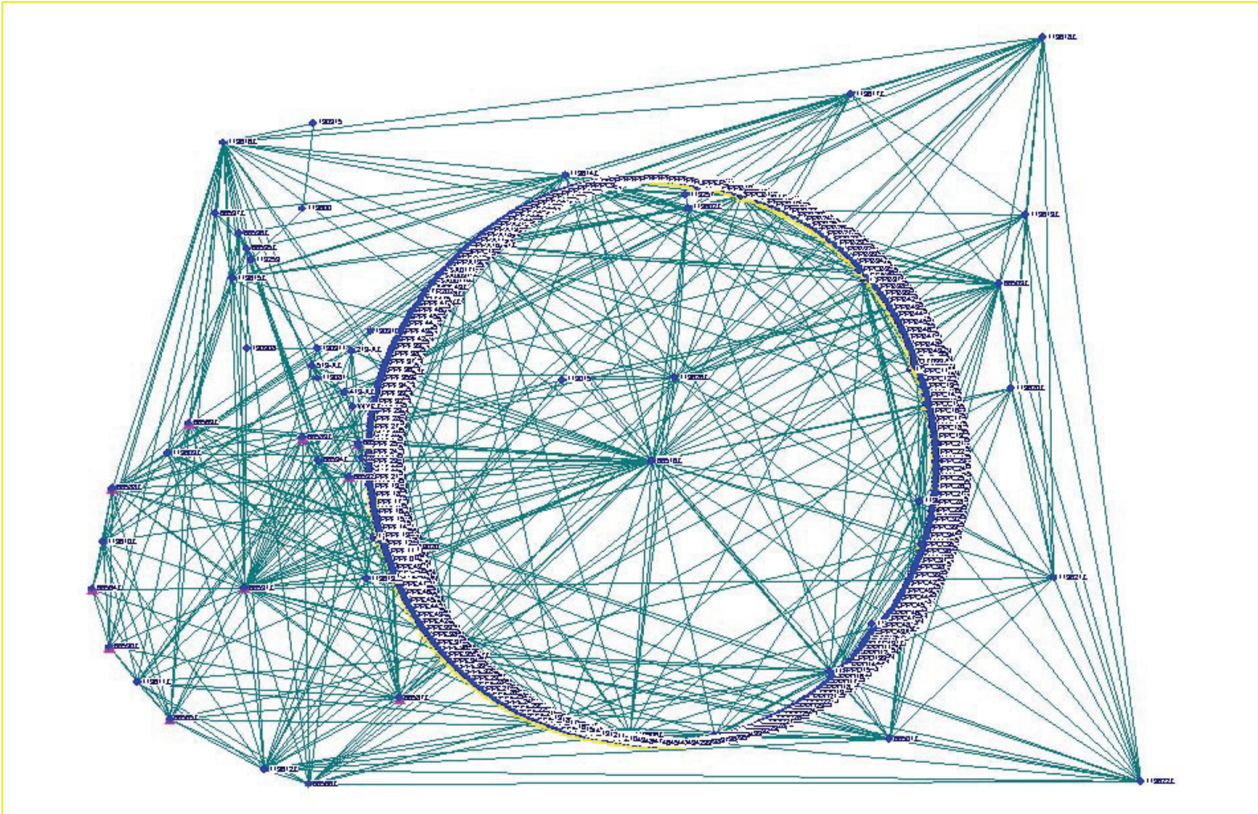


Figure 9. TeVnet Survey Network

2.4 Least Squares Adjustment of TeVnet Network and Calculation of Spatial Position of Magnetic Components of the Tevatron

Field observations included all control points of tunnel, Murphy brass, and magnet component fiducials. For the global adjustment, the Murphy brass and fiducial observations were removed because of less precise point-definition of the artifact when compared to DP-type monuments. The final adjustment of the combined surface and tunnel surveys, approximately 1940 coordinate points, was accomplished using COLUMBUS, a three-dimensional geodetic least squares adjustment program.

ADJUSTMENT STATISTICS

- Constrained on 10 primary site points (horizontal only) and local master benchmark (vertical only)
- Observations: 30,403
- Degree of Freedom: 23,308
- Outliers: 145
- Rejections: 11
- Global accuracy: $X_{2\sigma} = 0.65$mm, $Y_{2\sigma} = 0.63$mm, $Z_{2\sigma} = 0.63$mm

The result of the adjustment clearly demonstrates the survey has met the requirements of the TATF.

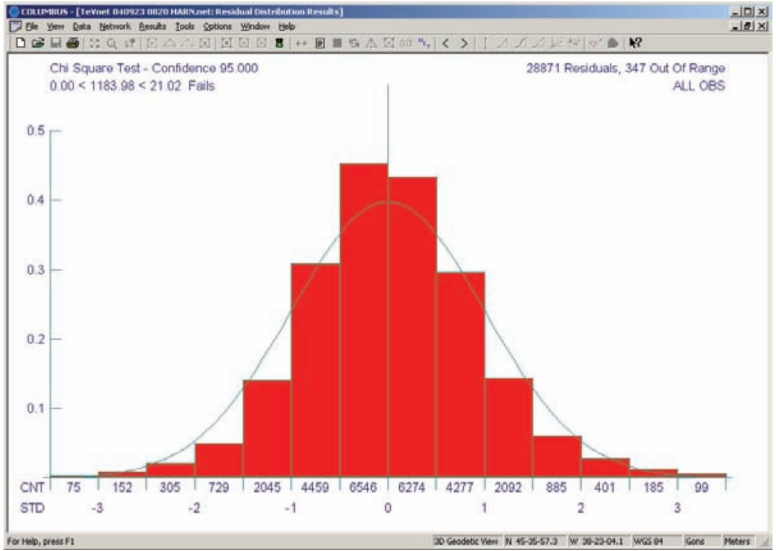


Figure 10. Distribution of TeVnet residuals with fit to Gaussian curve

As a by-product of TeVnet, all as-found positions of the major components of the Tevatron were determined. The observations previously removed from the global adjustment are necessary for calculation of the as-found positions of magnetic components. Coordinates of these points were obtained by using Helmert transformation, which transformed the Laser Tracker-head coordinates to the adjusted TeVnet system. In addition, transformed coordinates of the Murphy brass allowed estimation of the previously unknown orbit shape.

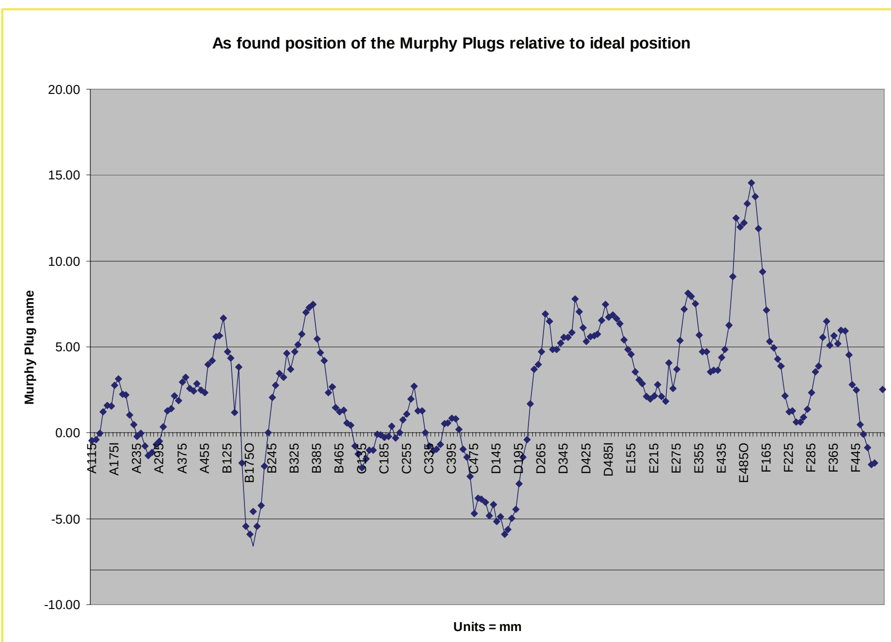


Figure 11. As found position of Murphy brass

Finally, incorporating magnet roll data from other sources, every measured magnet can be computed in six degrees of freedom in a TeVnet coordinates system.

Figure shows transformed coordinates of components - **Murphy line A125-A135**.

A125	30483.366138	30557.916426	220.296978
A135	30485.934577	30587.531035	220.293645
A12D4A	30483.104150	30559.433860	220.561880
A12D4E	30483.356280	30562.821010	220.561630
A12D4U	30483.086780	30559.331840	220.493300
A12D4D	30483.354360	30562.928680	220.492320
A12D4S	30482.816970	30558.167250	220.501730
A12D5A	30483.592620	30565.818340	220.560990
A12D5E	30483.872390	30569.207880	220.561080
A12D5U	30483.573770	30565.720040	220.497210
A12D5D	30483.870080	30569.314610	220.491240
A12D5S	30483.693180	30564.521720	220.513110
A13Q1A	30484.081470	30571.531620	220.561160
A13Q1E	30484.162720	30572.456870	220.561710
A13Q1U	30484.063830	30571.434780	220.486480
A13Q1D	30484.161470	30572.560320	220.491670
A13Q1S	30483.906040	30571.216690	220.658630
A13D2A	30484.490420	30576.327030	220.561770
A13D2E	30484.795680	30579.710950	220.560430
A13D2U	30484.471430	30576.222590	220.495800
A13D2D	30484.795590	30579.814760	220.490570
A13D2S	30484.338290	30575.048760	220.493210
A13D3A	30485.078580	30582.694780	220.560130
A13D3E	30485.413940	30586.078770	220.560520
A13D3U	30485.058300	30582.589360	220.495660
A13D3D	30485.414050	30586.178530	220.489850

Specially developed software for this project is used to compute and propagate magnet data.

SERIAL		X	Y	H	ROLL	PITCH	YAW	STA.	LENGTH
A11Q1	UP	30480.778395	30512.806335	220.490869					
H9007	CT	30480.802077	30513.904632	220.491015	0.3800	0.1321	0.0092	34.113	2.20
	DN	30480.825758	30515.002929	220.491160					
A11D2	UP	30480.849453	30516.708273	220.491308					
TB0689	CT	30480.919674	30519.691959	220.491167	0.5600	-0.0471	3.9388	39.902	5.97
	DN	30481.001575	30522.675347	220.491027					

3. CONCLUSION

The survey and adjustment of TeVnet was accomplished through a combination of several metrological techniques. A Laser Tracker network was established around the Tevatron ring, which included the surface drop-points, tunnel controls points, and pass points. A final adjustment of the combined surface and tunnel surveys, approximately 1940 coordinate points, was accomplished using COLUMBUS, a three-dimensional geodetic least squares adjustment program. The result of the adjustment clearly demonstrates the survey has met the requirements of the TATF. While not the sole source of the improvement realized during this period, TeVnet made a significant contribution toward more than quadrupling the peak luminosity and integrated luminosity.

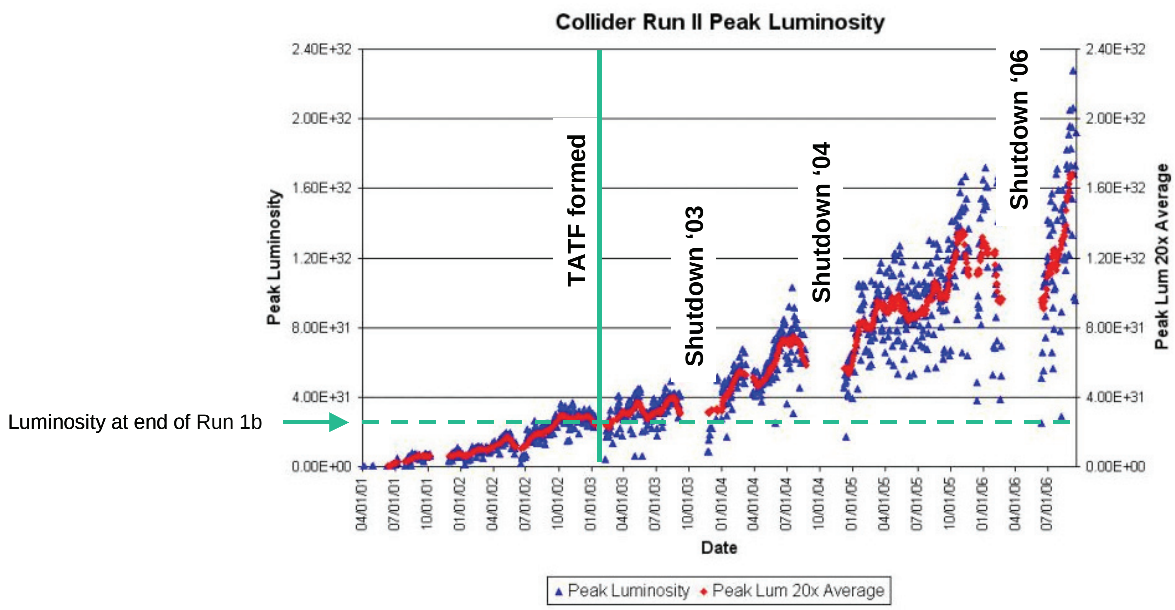


Figure 12. Collider Run II peak luminosity

The Tevatron now produces as much data in 6 weeks as it did in all of Run I, from 1992 through 1996.

Acknowledgements

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