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FACULTY OF CIVIL ENGINEERING

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DIPLOMA THESIS
HIGH-ACCURACY LOCAL POSITIONING NETWORK FOR THE ALIGNMENT OF THE MU2E EXPERIMENT

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Název diplomové práce anglicky: High.accuracy local positioning network for the alignment of the Mu2e experiment

Pokyny pro vypracování:
Návrh a optimalizace rozložení bodů prostorové referenční sítě na základě zadaných přesností. Tvorba statistického modelu z naměřených dat Laser Trackerem a ostatních velmi přesných metod měření. Vyrovnání sítě metodou nejmenších čtverců dvěma způsoby (s uvážením zakřivení Země a čistý kartesiánský prostor) a jejich porovnání. Analýza šíření chyb v referenční síti. Tato referenční síť bude dále užívána pro prostorové urovnání různých technologických celků experimentu Mu2e ve Fermi National Accelerator Laboratory (U.S. Department of Energy Science Office)

Seznam doporučené literatury:
L. Bartoszek et al., Mu2e Technical Design Report, Batavia 2014,
F.Q. Wei et al., Survey and Alignment For the Swiss Light Source, IWAA 1999.

Jméno vedoucího diplomové práce: Mgr. Ing. Jakub Šolc, Ph.D.

Datum zadání diplomové práce: 12.1.2017 Termín odevzdání diplomové práce: 21.5.2017

Údaj uveďte v souladu s datem v časovém plánu příslušného ak. roku

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12. 1. 2017
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Network geometric configuration design and optimization, required accuracy computation, stochastic model formulation. Implementation of the model using a measurements of the network with Laser Tracker and other high accuracy instrumentation techniques. Rigorous geodetic adjustments by least square methods, analysis and optimization of the error propagation will be applied and the results will be validated and interpreted. The adjustment calculations will use two approaches - a geodetic approach (taking into account the influence of the Earth's curvature), a pure 3D Cartesian (Laser Tracker Spatial Analyzer) approach and a comparison between these two methods will be conducted. The network will be used for the future alignment of the Mu2e experiment components in the Fermi National Accelerator Laboratory (U.S. Department of Energy Science Office).

List of recommended literature:
L. Bartoszek et al., Mu2e Technical Design Report, Batavia 2014,
F.Q. Wei et al., Survey and Alignment For the Swiss Light Source, IWAA 1999.

Name of Diploma Thesis Supervisor: Mgr. Ing. Jakub Šole, Ph.D.

DT assignment date: 12.1.2017 DT submission date: 21.5.2017

DT Supervisor's signature Head of Department's signature

III. ASSIGNMENT RECEIPT

I declare that I am obliged to write the Diploma Thesis on my own, without anyone's assistance, except for provided consultations. The list of references, other sources and consultants' names must be stated in the Diploma Thesis and in referencing I must abide by the CTU methodological manual "How to Write University Final Theses" and the CTU methodological instruction "On the Observation of Ethical Principles in the Preparation of University Final Theses".

12.1.2017

Assignment receipt date Student's name

ABSTRAKT

Tato diplomová práce popisuje proces implementace velmi přesné lokální referenční sítě a accelerator alignment (pozicování urychlovačů částic) pro fyzikální experiment Mu2e. Proces realizace nové referenční sítě se skládá z několika kroků. Prvním krokem je návrh sítě, a pak následuje analýza použitelnosti před instalací, instalace, zaměření a vyrovnání naměřených hodnot. Vyrovnání sítě je realizování dvěma postupy a to tradičním geodetickým se započtením vlivu zakřivení Země a více metrologickým přístupem s využitím čistě třídimenzionálního Kartézského prostoru.Tyto dva postupy jsou v této práci porovnány v sekci výsledků společně s očekávanými rozdíly. Rozdíl mezi těmito přístupy byl shledán signifikantním pro tento typ sítě a neměl by být zanedbáván. Síť byla zaměřena pomocí Absolutního Trackeru Leica AT401, nivelačního přístroje Leica DNA03 a gyroteodolitu DMT Gyromat 2000. Souřadnice bodů referenční sítě byly získány vyrovnáním zprostředkujících měření Metodou Nejmenších Čtverců a jejich přehled je uveden v přílohách.

KLÍČOVÁ SLOVA

Alignment, velmi přesná referenční síť, Mu2e, 3D Kartézský prostor, zakřivení Země

ABSTRACT

This Diploma thesis describes the establishment of a high-precision local positioning network and accelerator alignment for the Mu2e physics experiment. The process of establishing new network consists of few steps: design of the network, pre-analysis, installation works, measurements of the network and making adjustments. Adjustments were performed using two approaches. First is a geodetic approach of taking into account the Earth's curvature and the metrological approach of a pure 3D Cartesian system on the other side. The comparison of those two approaches is performed and evaluated in the results and compared with expected differences. The effect of the Earth's curvature was found to be significant for this kind of network and should not be neglected.

The measurements were obtained with Absolute Tracker AT401, leveling instrument Leica DNA03 and gyrotheodolite DMT Gyromat 2000. The coordinates of the points of the reference network were determined by the Least Square Method and the overall view is attached as Annexes.

KEYWORDS

Alignment, high-precision network, Mu2e, 3D Cartesian system, Earth's curvature

DECLARATION

I declare that Master's Thesis "High-accuracy local positioning network for the alignment of the Mu2e experiment" is all my own work and I have cited all sources I have used in the bibliography.

In Chicago ....

(Author's signature)

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I would like to give my thanks to the Fermilab at people who helped to make my dream come true by giving me the opportunity to work in one of the best research facilities in the world.

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Introduction

Accelerator alignment is a field on the borders of industrial (engineering) geodesy and metrology. It is a process during which the discreet components come from a warehouse to the right positions in the experimental building with a precision of few tenths of a millimeter. The main job of an alignment (metrology) team is to transfer components from the ideal drawings made in Cartesian a coordinate system to the reality of the Earth surface. Common challenges include long distance, tight tolerances, handling and positioning of unique scientific devices, and limited space and visibility. Accelerator Alignment builds a bridge between drawing and reality.

This Thesis is about one of the many steps in alignment process - establishing new reference network. The reference network is intended for the new physics particle experiment Mu2e. Mu2e is a experiment in which will help to find the answers about the physics beyond the Standard Model.

1 Mu2e experiment

All known laws of physics are expressed in a single model called the Standard Model (with an extension to include neutrino masses). It specifies twelve fundamental matter particles: six quarks, three electrically neutral leptons called neutrinos, and three electrically charged leptons. These are tabulated in 1.1.

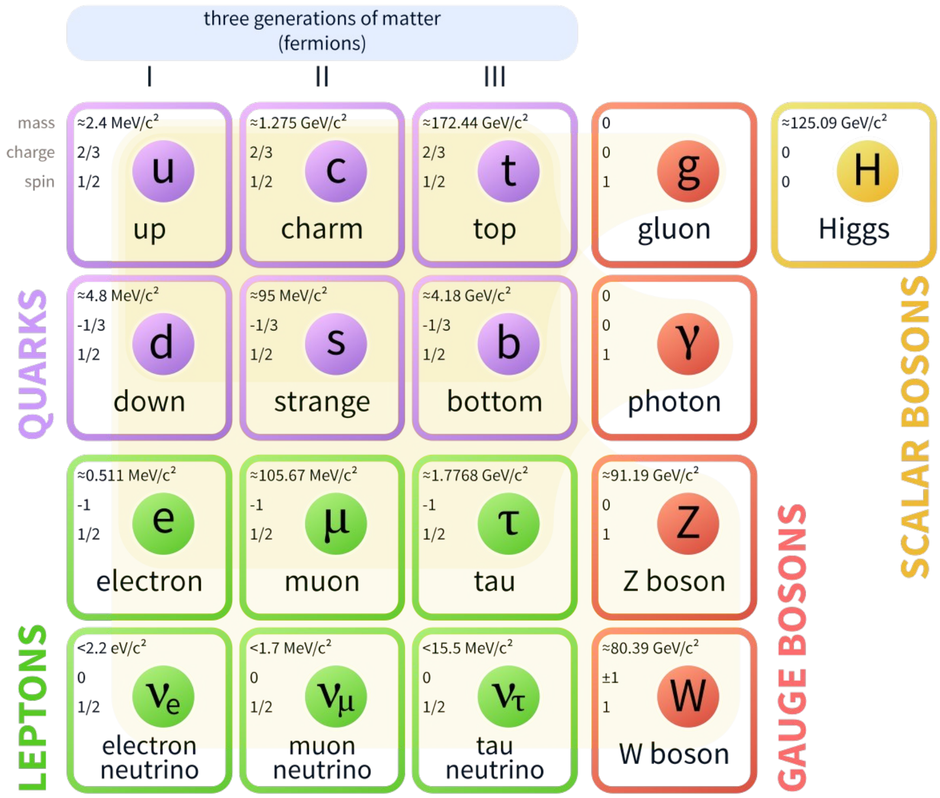


Figure 1.1: Standard Model of Elementary Particles

The “flavor” of leptons corresponds to the column in which they are tabulated in 1.1. There are three flavors of leptons: electron-flavor, muon-flavor, and tau-flavor. For each flavor there is a physics quantity called a lepton number. Before the discovery of neutrino oscillations, lepton numbers were thought to be conserved in all interactions. The observation of lepton number violation in neutrino oscillations indicates that lepton number conservation is not fundamental and invites the possibility of further lepton number violation among the charged leptons. Lepton number violation among the charged lepton is called CLFV for Charged Lepton Flavor Violation. Many possible extensions of known physical laws that are actively pursued

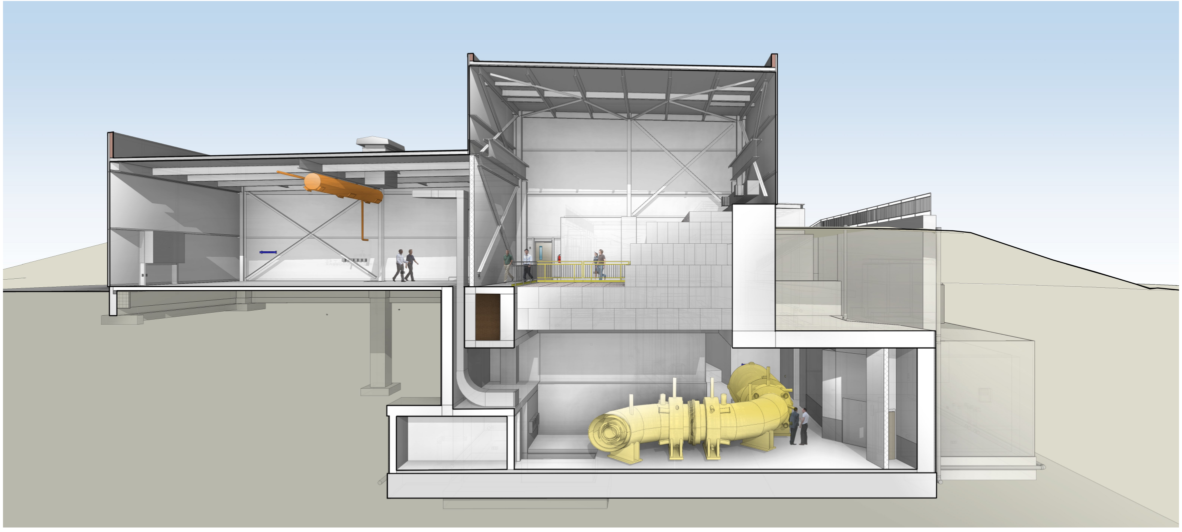


Figure 1.2: Transvers section of the Mu2e building

by the physics community can produce CLFV. CLFV within the experimental reach of the Mu2e experiment will be sensitive to a broad range of new physics at energies vastly beyond the reach of CERN's LHC, extending up to 10 000 TeV. This makes the Mu2e experiment a key step in humanity's understanding of the nature and structure of the universe.

1.1 Building

The Mu2e experiment site is a complex of buildings on the Muon Campus at Fermilab and consists mainly of the experimental building with grade and lower level detector hall, Extinction Monitor enclosure and a beamline transport enclosure tunnel.

The grade part of the experiment building contains primarily support system rooms (cryogenics, air conditioning, data acquisition, etc.), a control room and assembly halls. The underground part of the building (lower level) is divided into various areas of different purposes. There are the Remote Handling area, the Production Solenoid Assembly area, the Production, the Transport and the Detector Solenoid area and the Detector Staging area.

The Extinction monitor enclosure is on the north-west end. It has its own entrance due to radiation safety conserns. The Extinction Monitor area is connected

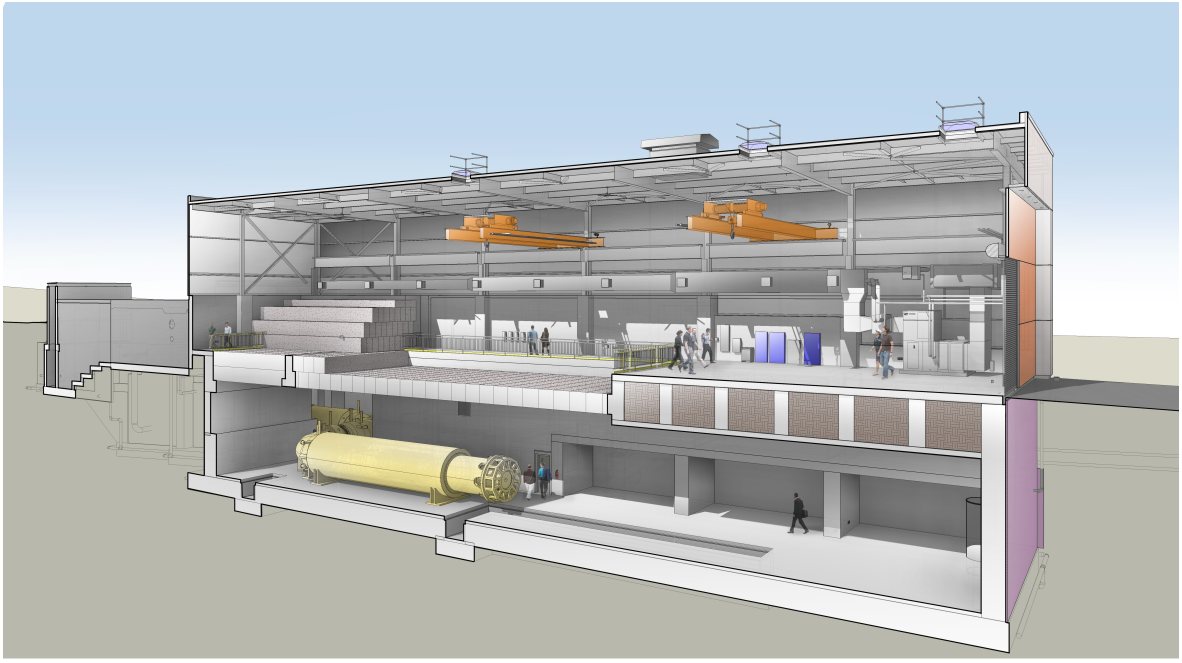


Figure 1.3: Longitudinal section of the Mu2e building

to the Detector area through the Primary Absorber area passage during the construction and installation phase. The passage will be filled with radiation shielding and sealed at the end of the installations.

The beamline tunnel connects the Experiment building with the Delivery Ring (Antiproton source - $\bar{P}$) located South-East.

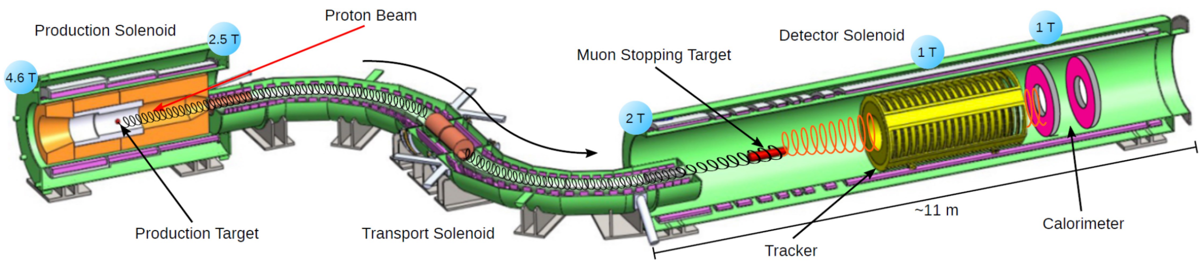


Figure 1.4: The Mu2e designed components

An overview of the Mu2e components is shown in Figure 1.4. Mu2e consists of four main segments: an initial proton beam to produce the muons are made, a muon production solenoid, a detector solenoid, and a transport solenoid that moves muons from the production section to the detector section.

Muon production:

Muons are produced by impinging an 8 GeV proton beam from the Fermilab accelerator complex onto a suspended tungsten rod called the “production target”. This produces a spray of pions and other nuclear debris. Charged pions quickly decay into muons. The production target is contained within a large magnet with a non-uniform magnetic field called the production solenoid. The production solenoid is specially constructed to efficiently collect low energy pions and muons, and channel them into the transport solenoid.

Muon transport:

To keep the detector environment clean fro spurious radiation from muon production must be kept out of the detector. A thick wall separates the detector from the site of muon production. This wall is traversed by the S-shaped transport solenoid so that no line-of-sight paths exist between the detector and site of muon production. The transport solenoid also filters out undesirable charged particles. The transport solenoid delivers muons to the aluminum muon-stopping target.

The detector:

Figure 1.5: Muon Campus

The detector and aluminum muon-stopping target are contained within a magnet called the detector solenoid. This solenoid directs electrons emitted from the stopping target towards the detector.

1.1.1 Experiment site

The experiment is located in the Fermi National Accelerator Laboratory (FNAL) - Fermilab is a world leading facility in high-energy particle physics. Fermilab is based near Chicago, on the border between Kane and DuPage county, in the state of Illinois, of the United States of America (USA). The facility occupies 27.5 km^2 of land. It is managed by the Fermi Research Alliance (FRA) under contract with the Unites States Department of Energy (DOE). The Fermi Research Alliance (FRA) is an alliance between the University of Chicago and the Universities Research Association, Inc. (URA), which is a nonprofit consortium of 89 research universities, placed primarily in USA and in Canada, Italy, Japan and the United Kingdom.

Figure 1.6: The Fermilab overview (Author: Fermilab)

1.2 Experiment

The Mu2e experiment will search for muons decaying directly into electrons without producing additional neutrinos. Such an interaction requires a third particle to recoil against the electron's momentum, which in this case is a near by aluminum nuclei. Muons will be manufactured and introduced into an aluminum target within a detector apparatus. The muons spontaneously bond to neutral aluminum atoms to form muonic atoms. The muons then decay while in orbit of stationary nuclei at a controlled location within a detector. Normal Michel decay of muons produces an electron and two neutrinos. The neutrinos cary away a significant fraction of the mass-energy of the muon, so electrons emerging from these decays have a broad spectrum of energies.

$$R_{\mu e} = \frac{\Gamma\left(\mu^- + N \rightarrow e^- + N\right)}{\Gamma\left(\mu^- + N \rightarrow \text{all muons captures}\right)} \tag{1.1}$$

In the case of CLFV muon decay, no neutrinos are produced and the electron emerges at a unique energy slightly less than the mass-energy of the muon, which is greater than the energy of muons from Michel decay. The experiment then searches for electrons emerging from the aluminum muon target with this exact energy.

The sensitivity of the experiment relies on both single-particle sensitivity to muons and the production of as many muons as possible. Both of which ultimately rely on careful alignment of the Mu2e experiment's components with each other and with the rest of the Fermilab accelerator complex.

The Fermilab accelerators allows a unique opportunity to produce large numbers of muons ($10^{10}\,\mathrm{s}^{-1}$), which will allow the Mu2e experiment to exceed the sensitivity of previous experiments by a factor of 10 000.

1.2.1 Experiment coordinate system

The official experiment coordinate system (Fig. 2.1) is called Mu2e Coordinate System (MCS) and it is mathematical right-handed system [13], defined as follows:

- the Origin is placed on the axis of the TS straight section (TS centerline) in equal distance from the PS and DS centerlines (solenoid axes of symmetry).

- the Z-axis is parallel to the PS and DS centerlines with positive direction towards the DS

- the Y-axis is congruent with the gravity vector in the origin. The negative direction of the Y-axis is in direction of the gravity.

- the X-axis complements the right-handed cartesian system. That means its positive direction runs towards the PS.

This coordinate system doesn't reflect the Earth's curvature and should be used just locally for design purposes. The experiment component coordinates must be transformed to the FSCS.

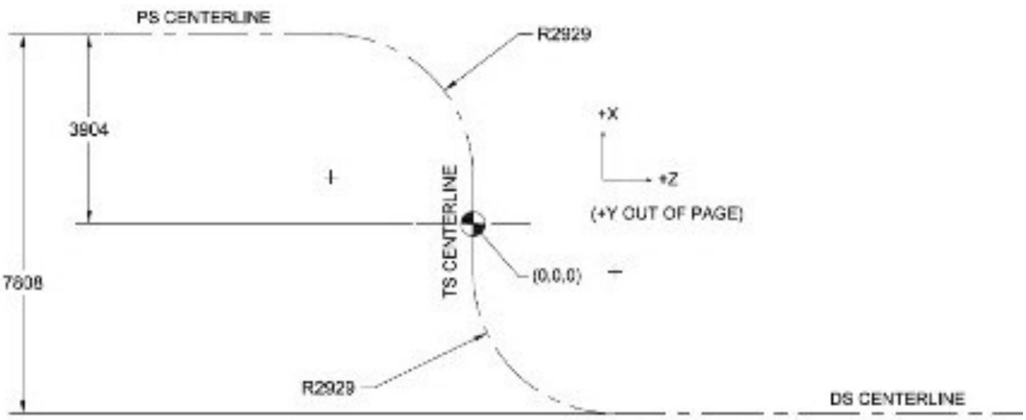


Figure 1.7: Mu2e Coordinate System [13]

The Local Coordinate System (LCS) used for pre-analysis of the network is also a right-handed Cartesian system which has the same origin as the MCS. The difference between the MCS and the local system lies in the nomenclature of the axes. The transformation between these two systems is given by:

$$\begin{pmatrix} X_{LCS} \\ Y_{LCS} \\ Z_{LCS} \end{pmatrix} = \begin{pmatrix} Z_{MCS} \\ X_{MCS} \\ Y_{MCS} \end{pmatrix} \tag{1.2}$$

The position of the Mu2e project will be determined by future measurements of the building features such as the DS trench, rails and walls. These measured parts will be the constraints of the position of the whole experiment.

2 Preparation Phase

Unfortunately no comprehensive alignment requirement table for the experiment components was officially published for design on the Mu2e project. For that reason the network was designed on the base of experience of the Alignment and Metrology Department. The position criterium ±0.3 mm on the 1σ confidence level was used for the network design.

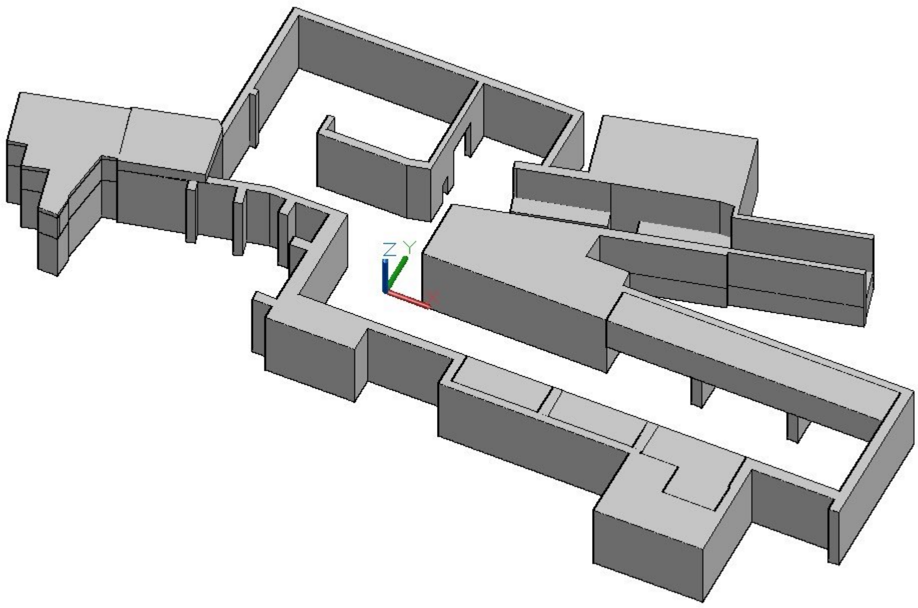


Figure 2.1: The origin in the Mu2e model

2.1 Software

Multiple different software packages were used for establishing the Positioning Network described in this work. Softwares as the Microsoft Office package, Matlab, Python, LaTeX, TextMate, BowPAD, AutoCAD are widely known applications and won't be described in document. This chapter is dedicated to introducing and describing software packages that were crucial for this thesis and which are not that widely known.

2.1.1 Spatial Analyzer

The Spatial Analyzer (SA) [10] by New River Kinematics, Inc. (NRK) is a multi-functional software for metrology applications. It runs on Windows platforms (Win7 or later) and is protected with a Hardware lock driver. This software was primarily developed as a reverse engineering tool for turbine repair works in nuclear power plants. Since the application's introduction in 1994 it has grown into a complex metrology software used in a wide variety of field of industry, including aerospace, shipbuilding, automotive, and also particle accelerators alignment. The biggest advantage of this software is that it can operate more than one hundred instruments from various manufacturers (Laser Trackers, Metrology Arms, Theodolites, Total Stations, Photogrammetric cameras, etc.)

Apart from reverse engineering, SA offers many other features such as transformations, fitting mathematically defined objects to measured points (and analysis of there fits), point cloud processing, etc. One of the key features for alignment is the ability to create Measurement Plan (MP)s. MP is a scripting tool inside SA for standardizing routine jobs. MP can be used when the same object (or objects of same type) is measured multiple times and the results should be consistent. It is also possible to use SA for handling the measured data, such as inserting error ellipses. Basically, it is a "To Do list" for recurrent jobs, which keeps operators from making mistakes and simplify repeating tasks. Measurement Plans, created within the AMD and also by NRK, were used during the preparation phase, network measurements, and data post-processing.

The usage of the SA parts is described later in more detail.

2.1.2 GeoPAN

Geodetic Plane Adjustment and Analysis (GeoPAN) is a software package for geodetic network adjustments. It was developed by the Department of Surveying Engineering at the University of New Brunswick in Fredericton, Canada in 1978. It can be used in two modes: network adjustment mode and pre-analysis mode.

2.2 Network Draft

The design and implementation of every high-accuracy position network is an iterative process of finding a compromise between price, labor time and optimal position and density of points. A network designer has to take into account many unknowns such as sufficient future spatial rigidity, point loss, already existing facilities, etc. The installed network is rarely ideal (or as designed). The process of network design is described in following text.

As a first step, the construction site was visited on the 20^{th} January, 2017. A network of this accuracy and range should not be designed just on the base of drawings (and/or models). A detailed photo-documentation was made during the visit. A large amount of Unitstruts were found on the site. Unitstruts are advantageous for placing monuments. For more details about Unitstruts monuments in 2.4.1.

The drawing in Autodesk's AutoCAD dwg format were obtained after the initial visit. The drawing contains the basic building structure and the experimental layout (without details) drawn as a plan and two cross-sections and it is situated in the Local Coordinate System described in 1.2.1. The first draft of the network was made on the base of this visit, partial construction documentation, and the previously mentioned drawing.

While making the first draft of the network point positions, focus was put on the logical symmetrical placement of the network points, following the current spatial arrangement scheme in the M4 beamline tunnel, and on using the Unitstruts for network advantage. The initial draft was made in Local Coordinate System.

Approximate locations of the network points were marked in the building during the second visit on the base of the initial draft. Locations were adapted to the site situation with alterations made due to visibility check and already existing facilities. Changes in point positions were recorded and taken into account for finalizing the documentation for the pre-analysis. The marking took place on the 3^{rd} February, 2017. The designed network is shown in Figure 2.2.

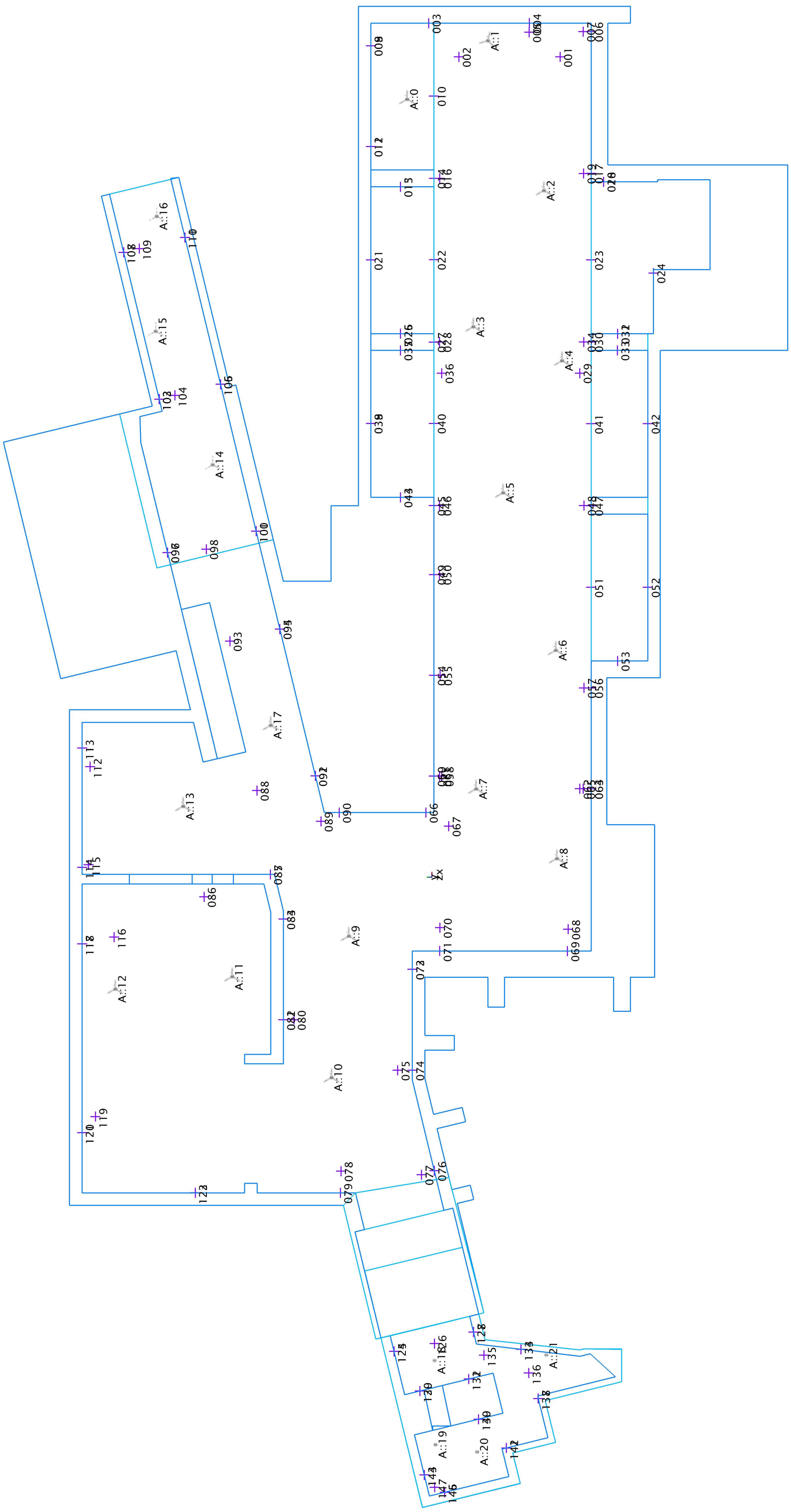


Figure 2.2: The designed network

2.3 Pre-analysis

The pre-analysis of a high precision reference network is a very important step in-between design and installation work. Pre-analysis is performed by Least Squares Method (LSM) see chapter: 5.1.1. The accuracy of measurements fed into the pre-analysis can originate from manufacturers or be empirical standard deviations of each type of measurement. The manufacturer-provided accuracy 0.15 mgon was used for angular measurements and an empiric value was used for distance measurements: 0.020 mm+2.5 ppm.

The 3D model of the building was made in AutoCAD on the base of the obtained drawings. It was imported into SA, where a visibility check was performed and possible measurements were simulated. The simulation of the measurements was done by a Measurement Plan developed by NRK[1]. The simulated measurements are shown in figure 2.3

The pre-analysis was performed in GeoPAN on the base of final design of the network. The results of the pre-analysis are in Annex A and fixed points are listed in table: 2.1.

Table 2.1: Fixed points

Point	Fixed in
40	XY
76	Z
109	Z
135	Z

[1]The Measure Plan is available from: `http://www.kinematics.com/`

Figure 2.3: Simulated measurements for pre-analysis

Table 2.2: Maximum standard deviations

Point	σ_X [mm]	σ_Y [mm]	σ_Z [mm] σ_{XYZ} [mm]	
35	0.059	0.048	0.038	0.085
111	0.048	0.087	0.015	0.100
108	0.052	0.086	0.016	0.102

Table 2.3: Pre-analysis summary

Number of observations	
Slope distance	614
Directions	614
Azimuths	1
Zenith Angles	614
Level heights	57
Total	1900
Number of unknowns	
Orientations	22
Coordinates	499
Total	521
Degrees of freedom	1379

2.4 Network Installation

The main part of the installation of the control points took place in the first half of February, 2017. The incoming beamline enclosure, grade (ground-level) floor, and extinction monitor enclosure control network were installed first. The ground-level (though well above the lowest floor) part of the network was installed after a decision to expand the network. The outside elevation points were installed as last. Points are labeled with site-wide unique six-digit identification number. The numbers are allocated in the primary database and assigned to the project.

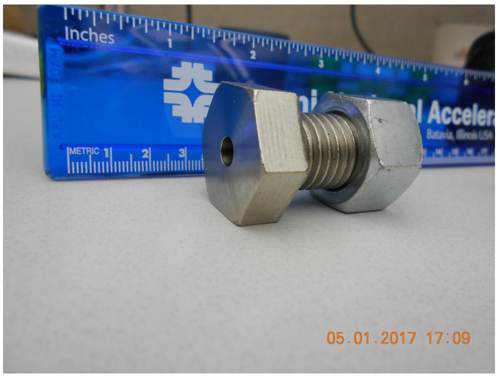
2.4.1 Control points realization

The chosen type of stabilization has to suit the needs of the reference network in terms of precision, location, service life, purpose, as well as economical aspects. Repeatability of the measurement of the point (SMR) influences on the overall accuracy of the network. Incorrectly chosen type of stabilization can lead to an unusable reference network. Points in high-accuracy reference networks are usually mechanically force centered, then the repeatability depends just on the manufacturing accuracy of individual components of the stabilizing unit. Optical centering cannot fulfill the required accuracy. Points in these networks are not physical; their coordinates are calculated to the centers of SMRs. That eliminates also the need of knowing exact dimension of each stabilization unit. Longterm resistance to mechanical wear is critical for the measurement equipment. Stainless steel is usually used for most of the parts. Fasteners, flat plate fittings and other accessories can be made from aluminum. The out-doors units are made from durable brass.

Fermilab AMD has developed its own types of stabilization units to fulfill all the requirements. Usually the alignment reference networks contains hundreds of points, so the economical aspect is highly relevant.

Floor points are stabilized with Dijak Bolts, named after its inventor - Edward Dijak [19]. They are modified bolts of variable length with a $1/4$ inch (6.35 mm) hole drilled for the shank holders. To improve the stability, bolts are fitted with a nut and then recessed into the drilled holes in the floor. The bolt is bonded to the floor by quick-setting cement. Centering is provided by the shank-hole relation. Vertical positioning is provided by the surface-surface contact between the SMR (shank) holder and the Dijak bolt. The SMR with holder is fixed by gravitational force.

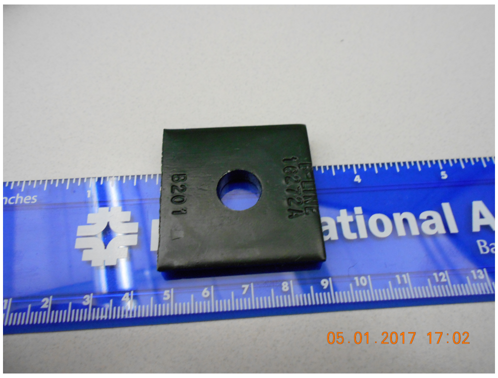
Bolts developed also by AMD are used for wall points. The wall bolts consist of a hex-socket head bolt and a ring magnet glued onto circumference of the bolt's head. There are two ways how to attach this bolt type to the wall. The first is for use in combination with Unitstrut system. The other possibility is attach the bolt to an expander in a drilled hole. The vertical and horizontal centering is guaranteed by the cone-sphere relation. The SMR is fixed in the place by the magnetic force of



(a) Dijak Bolt

(b) Magnet ring wall bolt

(c) Expander and Unistrut mounting



(d) Washer

(e) Point cover

(f) Tie rod

Figure 2.4: Monuments

Figure 2.5: Point 226099 installation

the ring magnet and so does not need a holder. The magnets are protected with a plastic cover.

There are several advantages of using the Unitstrut monuments. First of them is the simplicity of installation, another is the option to reuse or relocation of points which have to be removed. The grade-level part of the experiment building uses just ring magnets glued to the walls and steel columns. This way of fixing points is also possible, but is just for temporary points with no longterm use or with low future accuracy demands.

Outside leveling points are stabilized with standard brass bolts and tierods [19]. Tierods are devices installed in a wall which can hold a leveling scale in combination with a special holder or a carbon-fibre rod (see Sec: 3.4.2). The elevation of both leveling monuments is determined to the top of the unit.

2.4.2 Final network

The network design was described in section 2.2. Usually the design of the network changes during the installation phase because of aspects of the real building that cannot be determined from models and drawings. The network contains 196 primary reference points (for SMR) from which 146 are newly installed points and 50 points are pre-existing points (with coordinates) in M5 beamline tunnel. The pre-existing points were readjusted together with the new points and their coordinates were updated in the database. New points were also installed outside the building due to the need to connect the building's network to the existing Fermilab Site leveling network using elevation measurements.

2.4.3 Rough coordinates shooting

Rough measurement of the positions of the network points were made after installation of monuments. During network measurements the AT401 is operated through SA using an internally developed Measurement Plan (Author Charles C Wilson). For the best performance of the MP it is good to know the approximate coordinates of the network points and assign them names from labels.

3 Equipment

Traditional instruments in combination with special devices are used in the field of accelerator alignment (industrial geodesy and metrology in general). The significant hardware instrumentation used for this project will be introduced in following section.

3.1 Leica AT401

The main instrument used for network measurements is the Leica Absolute Tracker AT401 (Fig. 3.1). This instrument is not a traditional laser tracker but it is a combination of a very precise total station (which measures angles and distances) and a laser tracker. The reason why the AT401 should not be called laser tracker is that the instrument does not have the main feature of the tracker category: dynamic tracking measurements. It is the only tracker-like instrument which is gravity referenced. This was the reason for choosing it for the network measurements.

Angular measurements are provided by four encoder measurements of a rotating glass disk. The circumference of the glass disk is gradated by a bar code pattern so that each spot on the circle is marked by a unique line pattern. Each sensor of the quadruple reading angle system contains a LED light source for projecting the pattern from a glass circle onto a bar-code sensor. First, a rough reading of an angle is provided with an accuracy of about 0.3 gon and it is read from the bar-code lines. Then more precise readings are obtained. The result is the average of from the readings from all four sensors. The angular precision of this instrument is 0.15 mgon according to ISO 17123-3.

Most common Electronic Distance Meters (EDM, Electronic Distance Meter) in total stations are time-of-flight or phase based. These methods are precise enough (tenths of millimeters in the top series) for basic geodetic measurements. For the use in the field of industrial geodesy, the distance measurement device must be at least one order of magnitude more precise (hundredths of a millimeter) than common EDM measurements. Based on EDM technology from the Kern Mekometer (with a

Figure 3.1: Leica AT401, picture by Leica Geosystems

measurement range up to 8 km with accuracy 0.2 mm + 0.2 ppm), Leica developed a new system, called the Absolute Distance Meter (ADM) with a patented polarization modulation method. Repeatability of the distance measurement in the vicinity of 80 m is $\pm 5\,\mu$m. The precision of the ADM is $\pm 10\,\mu$m [2] over the whole range of 180 m.

Table 3.1: Leica AT401 Basic Specifications

	Manufacturer	Used for pre-analysis
Horizontal direction [1]:	0.15 mgon	0.15 mgon
Zenith angle [1]:	0.15 mgon	0.15 mgon
Slope distance [2]:	$\pm 10\,\mu$m	$100\,\mu$m

In contrast with traditional angular terrestrial geodetic measurement devices, the Leica AT401 does not have an electronic display. The instrument is operated through software on a near by computer. The data are delivered to the computer as they are collected, either wirelessly or via an ethernet cable. There are multiple options on the market for the operating software; the device is equipped with the Leica Tracker Pilot. For this project, the tracker was operated by SA.

3.2 Leica DNA03

Digital levels were developed in the 1980's [7] and changed the field of precise leveling. The major change was not in the precision but in the ease of execution of these measurements and in reducing the risks of possible human errors. Research and development was conducted in multiple institutions. Besides Leica (Wild) the research was done simultaneously by Carl Zeiss Jena (Germany) in collaboration with the Technical University Dresden and last but not least Neues Technicum Buchs (Switzerland). Also the leveling staff had to be changed to be computer readable.

The type of bar code used on the leveling staff varies for each manufacturer. Leica uses an aperiodic pseudo-stochastic binary code. The length of the complete code is 4050 mm and contains 2000 uniform elements (i.e. dimension of each element is exactly 2.025 mm). The staff for precise leveling are made from an aluminum case with an independently suspended Invar steel tape. The bar code is usually engraved by a CO_2 laser into two color layers (yellow at the top and black at the bottom) on the Invar steel tape [9]. The accuracy which can be achieved with this technology is $\pm 7\,\mu m$ per element.

Generally, the optical part of a digital level contains a focusing lens, a compensator, a beamsplitter and a CCD microchip. On top of the previously mentioned components, Leica instruments have a position sensor for the focusing lens. The reason for this is the need of getting rough distance information for the determination of the scale of the received bar-code image.

The processing of a signal begins with capturing the incoming visible-light image by the CCD sensor. The second step is the conversion of the digital image to an analog video signal with 256 values of intensity. The last part of the process is the comparison of the captured image with the pattern saved in the instrument.

The Leica DNA03 digital level (Fig. 3.2) is a well known leveling instrument. It is a second generation version of the first digital level in the World Wild NA2000 (1990), NA3000 (1991) [5]. With a precision of 0.3 mm (standard deviation height measurement per 1 km, double-run according to ISO 17123-2, using the Invar staff) it is among the most precise digital levels available. The Leica DNA03 is a compensator leveling instrument. The compensator is a magnet damped pendulum with an electronic range control used for leveling the instrument relative to the direction of gravity. It is possible to operate the instrument using external commands through a RS232 interface.

Figure 3.2: Leica DNA03, picture by Leica Geosystems

Table 3.2: Leica DNA03 Basic Specifications [6]

Double-run precision:	0.3 mm/km
Height measurement resolution:	0.01 mm
Electronic measurement range:	1.8 m to 110 m

3.3 DMT Gyromat 2000

The Gyrotheodolite Gyromat 2000 by the DMT (Deutsche Montan Technologie) company is the first automated gyroscopic azimuth measurement device. It was introduced in 1991 as the most precise gyrotheodolite. The measurement takes about 10 minutes in the high-precision mode, where the accuracy of the measurement is

0.93 mgon for Fermilab but the precision is latitude dependent. The Gyromat 2000 is permanently mounted to the Wild digital theodolite.

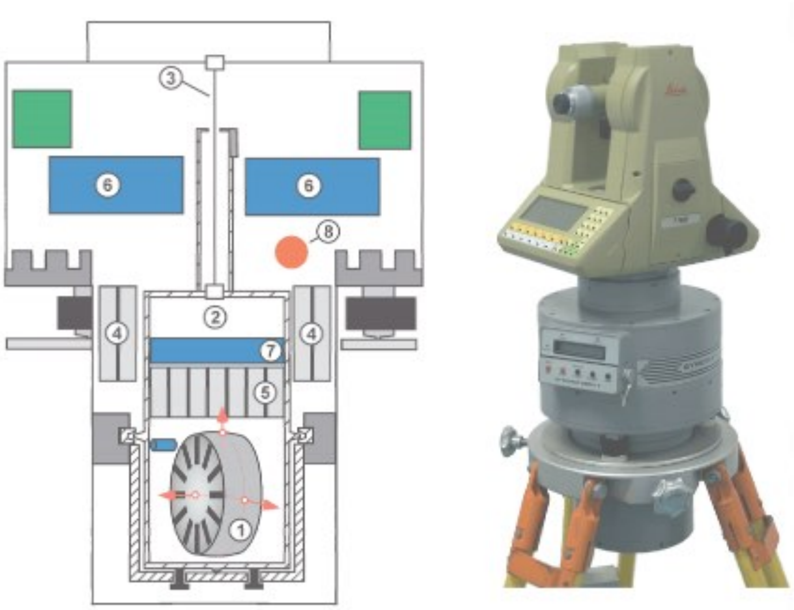


Figure 3.3: The components of the Gyromat 2000 [24]

The parts of the gyrotheodolite are visible on the figure 3.3 which contains of: the rotor (1) with a mass of 2 kg dismounted in a cage (2), which contains the interior battery (5), and the electronics (7). The cage (2) is attached to a steel suspension tape (3). The exterior battery (4) and the computing unit (6) are also identified in the figure 3.3. There is a sensor (8) for monitoring the internal temperature and the temperature gradient (this description is taken from [24])

3.4 Miscellaneous

Other significant equipment used for measurements is listed bellow.

3.4.1 Reflectors

Repeatable and precise centering are requisite features for measurement of targets in the field of alignment. Special Spherically Mounted Reflectors (SMR) were developed for the field of alignment. The standard centering error is within the interval 1 - 5 µm. SMR are made in three standard sizes 1.5", 0.75" and 0.5". For the Mu2e network more than 30 SMR were used for the measurements.

Table 3.3: Specification of the used SMRs

	Radius	Centering	Sphericity
Leica RRR	19.05 mm ±0.0025 mm 0.7500" ±0.00010"	< ±0.003 mm < ± 0.00012"	< ±0.0015 mm < ± 0.00006"
API SMR [12]	19.05 mm ±0.0025 mm 0.7500" ±0.00010"	< ±0.013 mm < ± 0.0005"	< ±0.0012 mm ±0.00005"
Hubbs BMR	19.05 mm 0.7500"		< ±0.0013 mm < ± 0.00005"

There were 32 SMR of different type used for network measurements. Most of them (19) are the Leica Red Ring Reflector (RRR) type (serial numbers: 6248, 6284, 6462, 6463, 6465, 6468, 6469, 6701, 6704, 6928, 7188, 8707, 8737, 8783, 9133, 9357, 10127, 10168 and 10172), 11 are API (serial numbers: 01011B, 01012B, 11833, 11842, 11897, 12084, 12085, 13559, 13570, 13575 and 13701), the last two were Hubbs Machine PLX (4839 and 4867). From the experience all the SMRs are exchangeable without effecting the precision of the measurements. There is no reason to keep documenting the use of the particular SMRs on a point.

3.4.2 Leveling tools

Standard leveling staves (2 m and 3 m) are used for outside measurements. Special leveling tools were developed for the need of AMD. The height of the tool for measurements of a Dijak Bolt stabilized point, is automatically offset to the "real point". The "real point" is a centre of the Spherically Mounted Reflector. Thus eliminating the need to later offset measurements by about 0.75". The tool consists of a carbon fibre rod with a 1.5" dummy ball on the end, an Invar leveling scale, and a scale holder placed between these two components. The scale is identical to the scales used for the leveling stuff just with different length. The scale is equipped with bubble level. Wall (magnetic ring) points are measured using a leveling scale hanging on a 1.5" dummy ball and heights are again calibrated to the centre of the sphere.

All the components of the leveling tools are calibrated. Scales are calibrated using a Leica DNA03 leveling instrument. Carbon fibre rods length corrections are determined using CMM machine. Calculated corrections and reductions for all used components are incorporated in the adjustment calculations.

The zero offset check of the used leveling staff was performed using the standard calibration procedure defined by norm ISO 17123-2. The Collimation check “Peg check” is performed daily before measurements.

3.4.3 Others

Drift stability of the measuring instrument is very important. The highly rigid heavy tripods respective stands are used for supporting the instrument during measurements. A light metal tripod with adjustable centre column is used for leveling runs in the building. The standard Leica 120-9 wooden tripod is used for outside leveling. The Leica AT401 is supported by one of two heavy steel stands which differ in height. Both stands have adjustable height which can be beneficially used for the network measurements. The possible range of height above the floor is 1.0 m to 5.0 m.

(a) Hight heavy metal stand (b) Heavy metal stand

Figure 3.4: Stands used for terrestrial measurements

The targets for optical measurements with the gyrotheodolite are called "eyeballs" and it is sphere of the same radius as the SMRs (1.5") very accurately manufactured. The eyeballs are sphere segments, nearly a hemisphere, with a milling cut creating a planar surface at the exact middle of the sphere. The plane is fitted with a target in the centre of the sphere which materialize the actual point which is measured without applying any reductions or corrections.

SMRs and optical targets are placed in a Dijak Bolt monuments by a shank holders. The centering is guaranteed by a shank-hole mechanical relation and vertical alignment is guaranteed a plane to plane mechanical relation.

4 Fermilab Coordinate Systems

Through time, Fermilab had various Coordinate Systems [14]. The reasons for changing or adding a new one were different (connecting local system to the global positioning system or taking into account Earth curvature, etc.). The first used CS was named DUSAF after the company, which provided the surveying work for the construction of the Tevatron. As was mentioned before, the Tevatron is a particle collider called synchrotron with a circular shape. The DUSAF coordinate system used this fact to minimize the corrections by creating a (XY) plane, which intersects with the Earth in the path of the Tevatron beamline (or very close to it).

The Fermilab Site Coordinate System (FSCS) was created for the tangential fixed target beamlines extracted from the Tevatron Main Ring and implemented in 1992. The FSCS has an identical origin as DUSAF and two subsystems FSCS:XYZ as a 3D Cartesian system and a FSCS:XYH as a mapping plane system with an orthometric height above the DUSAF Datum. The FSCS:XYH is the default working coordinate system at Fermilab.

Other local coordinate systems are used on the Fermilab site, such as the Local Tunnel Coordinate System (LTCS) used in the Main Injector Ring, local experiment CS, etc.

The Mu2e experiment will be held in the FSCS to ensure the continuity in relation to other experiments and existing beamlines in the surrounding area. All the coordinate systems needed and used for processing the Mu2e project will be described bellow.

4.1 DUSAF

The DUSAF coordinate system is a right-handed Cartesian CS. It was defined as follows:

- Origin at A0, the take off point in the accelerator ring for the fixed target experiments

- Y-axis - North axis, positive towards Neutrino Campus,

- X-axis - East axis, positive to the right,

- Z-axis positive in the opposite direction of gravity in A0 and perpendicular to X and Y axis.

False coordinates of the Origin were defined for easier calculations:

Table 4.1: False Coordinates of DUSAF Origin

X	100 000.000 ft	30 480.060 96 m
Y	100 000.000 ft	30 480.060 96 m
Z	720.000 ft	219.456 44 m

Unfortunately the documentation for the DUSAF system is not available and, thus, it was not possible to continue using this system. That was the reason to develop a new site system - The Fermilab Site Coordinate System.

4.2 General Reference Frames

Fermilab coordinate systems need to be connected to the outer World for various reasons. Among these reasons are the usage of GNSS measurements, astronomical measurements, experiments which start on the Fermilab site but have detectors far remote areas. The global systems in use are described in the text below.

4.2.1 Geodetic Coordinate System

The North American Datum 1983 is one of the geodetic coordinate systems used in the USA. NAD83 is defined over the reference ellipsoid GRS80 (Geodetic Reference System 1980) [20]. GRS80 is an equipotential (level) ellipsoid recognized by the International Association of Geodesy (IAG) and the International Union of Geodesy and Geophysics (IUGG). The GRS80 replaced the GRS67. It supposed to be a geocentric reference system, but further measurements showed that the origin of the ellipsoid is about 2 m eccentric from the Earth Centre of Mass (ECM). This finding has been neglected. The surface fulfills the following constraint to be an Equipotential surface:

$$U = U_0 = const, \tag{4.1}$$

where U is the normal potential.

The GRS80 bi-axial reference ellipsoid is defined by conventional constants:

- $a = 6\,378\,137.0\,\mathrm{m}$ ... equatorial radius of the Earth,
- $GM = 3\,986\,005 \times 10^{-8}\,\mathrm{m^3 s^{-2}}$ ... geocentric gravitational constant of the Earth,
- $J_2 = 108263 \times 10^{-8}$ ... dynamical form factor of the Earth, excluding the permanent tidal deformation (also known as a Stokes coefficient C_{20}),
- and $\omega = 7\,292\,115 \times 10^{-11}\,\mathrm{rad\ s^{-1}}$ ... angular velocity of the Earth.

These are the minimum constraints, many additional constraints and features apply. One of the specified features of the reference ellipsoid is that the minor axis (b) is parallel to the vector from ECM towards CTP (Conventional Terrestrial Pole) and has the same direction. This vector is called Conventional International Origin (CIO). Another feature of this ellipsoid is that the primary meridian is parallel to the mean meridian of Greenwich (defined as zero meridian by the Bureau International de l'Heure (BIH)). Other derived geometric constants:

- $b = 6\,356\,752.3141\,\mathrm{m}$ ... semi-minor axis,
- $e^2 = 0.00669438002290$ ... first eccentricity (e)
- $f = 0.00335281068118$ ... flattening,
- $f^{-1} = 298.257222101$ ... reciprocal flattening.

A location of a point P in the Geodetic Coordinate System (GCS) is defined as:

$$P = [\varphi_P, \lambda_P, h_P]\,,$$

where:

φ_P is a Geodetic Latitude,

λ_P is a Geodetic Longitude,

h_P is an Ellipsoidal Height (height above the ellipsoid normal to the ellipsoidal surface).

Heights used at Fermilab are based on Orthometric Heights of the North American Vertical Datum 1988 (NAVD88). An Orthometric Height is a distance along the plumb line from a measured point to the geoid and is, in the case of NAVD88, determined by:

$$H_{NAVD88} = h - N, \tag{4.2}$$

where:

h is the Ellipsoidal Height,

N is the Geoid-ellipsoid separation undulation.

The Geoid-ellipsoid separation values are interpolated from the Geoid Model GEOID93 (based on GRS80).

Because the CS used at Fermilab should be as close as possible to the obsolete DUSAF system, the heights above the DUSAF datum are defined as:

$$H_{NAVD88} = H_{DUSAF} + dH_{NAVD88}, \tag{4.3}$$

where: $dH_{NAVD88} = -0.173\,08\,\text{m}$.

The relation between all heights mentioned above is given by:

$$h = H_{DUSAF} + dH_{NAVD88} + N. \tag{4.4}$$

4.2.2 Geodetic Cartesian Coordinate System (GCCS)

This system is used for transformations between GCS and other systems used at Fermilab.

GCCS is a 3D Cartesian, right-handed coordinate system. Its axes are identical with the GRS80 ellipsoid. A point in GCCS is defined as:

$$P = [X_P, Y_P, Z_P]\,.$$

Tha transformation from the GCS to GCCS is exact and defined by:

$$\begin{pmatrix} X_P \\ Y_P \\ Z_P \end{pmatrix} = \begin{bmatrix} (N_P + h_P)\cos\varphi_P \cos\lambda_P \\ (N_P + h_P)\cos\varphi_P \sin\lambda_P \\ \left(N_P \frac{b^2}{a^2} + h_P\right)\sin\varphi_P \end{bmatrix}, \tag{4.5}$$

where:

$$N_P = \frac{a}{\sqrt{1 - e^2 \sin^2 \varphi_P}}. \tag{4.6}$$

The transformation from GCCS to GCS is partially iterative and defined by the following relations. The exact formulae for Geodetic Longitude are:

$$\lambda_P = \arctan \frac{Y_P}{X_P + P_P}, \tag{4.7}$$

where:

$$P_P = \sqrt{X_P^2 + Y_P^2}. \tag{4.8}$$

The iterative process for Geodetic Latitude and Ellipsoidal Height is:

$$h_P = \frac{P_P}{\cos\varphi_{P_{i-1}}} - \nu_{P_{i-1}}, \tag{4.9}$$

$$\varphi_P = \arctan\left[\frac{Z_P}{P_P\left(1 - \frac{e^2 v_{P_{i-1}}}{\nu_{P_{i-1}} + h_{P_i}}\right)}\right]. \tag{4.10}$$

Initial values:

$$\begin{aligned} h_{P_0} &= 0, \\ \varphi_{P_0} &= \arctan\left[\frac{Z_P}{P_P\,(1 - e^2)}\right]. \end{aligned} \tag{4.11}$$

Coordinates are considered final if the difference between two consecutive iterations does not exceed the stopping criteria:

$$\begin{aligned} \left|h_{P_i} - h_{P_{i-1}}\right| &< 10^{-9}, \\ \left|\varphi_{P_i} - \varphi_{P_{i-1}}\right| &< 10^{-14}. \end{aligned} \tag{4.12}$$

Once these criteria have to met, the standard Helmert transformation can be applied to transform coordinates to any 3D Cartesian coordinate system.

4.3 Fermilab Site Coordinate System

The FSCS was implemented to substitute the no longer sufficient DUSAF system. In order to preserve the coordinates of already existing and aligned components, the FSCS was designed as an assimilated DUSAF CS. The FSCS has the same origin as DUSAF (see Tab: 4.1).

4.3.1 Cartesian FSCS

As mentioned before, the FSCS was developed for the Main Ring tangential beamlines outgoing at the point A0. It is a right-handed Cartesian system called FSCS:XYZ and defined in the same way as DUSAF with fololwing definitions. The North (Y) axis is deviated from the Conventional Terrestrial Pole by the Geodetic Azimuth α. The Z-axis is identical to the normal of the ellipsoid with the direction upwards (from the ellipsoidal surface). The ellipsoidal height of the Origin A0 in GCS is:

$$h_0 = 186.498\,80\,\mathrm{m}. \tag{4.13}$$

The Geodetic Azimuth is:

$$\alpha = 38^\circ 16' 48.014\,29''. \tag{4.14}$$

Transformation from GCCS to FSCS:XYZ is basically just a rotation and a translation:

$$\boldsymbol{X}_{FZ} = \boldsymbol{R}_{Z(\alpha)} \boldsymbol{P}_{XY} \boldsymbol{X}_{GCCS} + \boldsymbol{X}_{AO}, \tag{4.15}$$

where:

$\boldsymbol{X}_{FZ}$ are coordinates in FSCS:XYZ,

$\boldsymbol{R}_{Z(\alpha)} = \begin{pmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}$ is a Rotation Matrix about the Z-axis,

$\boldsymbol{P}_{XY} = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$ is a Polarity Matrix,

$\boldsymbol{X}_{GCCS}$ are coordinates in GCCS,

$\boldsymbol{X}_{AO}$ are the False Origin coordinates (see Tab: 4.1).

Then the reverse transformation (FSCS:XYZ → GCS) is given by:

$$\boldsymbol{X}_{GCCS} = \boldsymbol{P}_{XY} \boldsymbol{R}^T_{Z(\alpha)} \left(\boldsymbol{X}_{FZ} - \boldsymbol{X}_{AO} \right). \tag{4.16}$$

4.3.2 Ellipsoidal heights FSCS

The FSCS:XYH is implemented for taking into account the Earth's curvature. It is a right-handed Cartesian CS where the coordinates X and Y are derived by Double Stereographic Projection from the reference ellipsoid to the mapping plane. The projection is double because the coordinates $[\varphi, \lambda]$ are first projected onto a sphere $[U, V]$ and then to the plane $[X, Y]$. The system is rotated about the Z-axis by the same Geodetic Azimuth α as the FSCS:XYZ. The Origin of this system is also A0 with the same False Coordinates (see Tab: 4.1) and coordinates in GCS are:

Table 4.2: Coordinates of A0 in GCS

φ_{A0}	$N41°50'14.312\,704''$
λ_{A0}	$W88°15'41.143\,123''$
h_0	$186.498\,80\,\mathrm{m}$

The separation of the Geoid and ellipsoid at the point A0 is:

$$N_{A0} = -32.784\,56\,\mathrm{m}. \tag{4.17}$$

The Orthometric Height at A0 is given by:

$$H_{720NAVD88} = h_0 - N_0 = 219.283\,36\,\mathrm{m}. \tag{4.18}$$

The Orthometric Heights of other points are given by:

$$H_{DUSAF} = H_{NAVD88} - dH_{NAVD88}. \tag{4.19}$$

The scale factor for A0 is determined as:

$$F_0 = 1.000029251309483. \tag{4.20}$$

A transformation from the GCS to the FSCS:XYH using Double Stereographic Projection is described below ([15], [17]). A first step is the transformation from the ellipsoid to the sphere, using Gauss Conformal Projection:

$$V = c_1 \cdot \lambda, \tag{4.21}$$

$$U = 2\left\{\arctan\left[c_2\left(\tan\left(\frac{\pi}{4}+\frac{\varphi}{2}\right)\left(\frac{1-e\sin\varphi}{1+e\sin\varphi}\right)^{\frac{e}{2}}\right)^{c_1}\right]-\frac{\pi}{4}\right\}, \tag{4.22}$$

$$k_P = c_1 k_0 \frac{R\cos U}{M\cos\varphi}, \tag{4.23}$$

where:

$\begin{pmatrix}\varphi_i\\ \lambda_i\\ h_i\end{pmatrix}$ are coordinates of point i in the GCS,

$\begin{pmatrix}U_i\\ V_i\end{pmatrix}$ are spherical coordinates of point i,

k_i is a scale factor on an point i,

$$c_1 = \left[1+\left(\frac{e^2}{1-e^2}\right)\cos^4\varphi_{A0}\right], \tag{4.24}$$

$$c_2 = \tan\left(\frac{\pi}{4}+\frac{U_0}{2}\right)\left[\tan\left(\frac{\pi}{4}+\frac{\varphi_{A0}}{2}\right)\left(\frac{1-e\sin\varphi_{A0}}{1+e\sin\varphi_{A0}}\right)^{\frac{e}{2}}\right]^{-c_1}, \tag{4.25}$$

$$U_0 = \arcsin\left(\frac{\sin\varphi_0}{c_1}\right), \tag{4.26}$$

$$V_0 = c_1\lambda_{A0}, \tag{4.27}$$

$$R = \sqrt{M_{A0}N_{A0}} \tag{4.28}$$

and

$$M = \frac{a\left(1-e^2\right)}{\left(1-e^2\sin^2\varphi\right)^{\frac{3}{2}}}, \tag{4.29}$$

$$N = \frac{a}{\left(1-e^2\sin^2\varphi\right)^{\frac{1}{2}}}. \tag{4.30}$$

The transformation from a sphere to the Mapping Plane as follows:

$$X_{DS} = 2k_0' k_0 R \left\{ \frac{\cos U \sin \Delta V}{1 + \sin U_0 \sin U + \cos U_0 \cos U \cos \Delta V} \right\}, \tag{4.31}$$

$$Y_{DS} = 2k_0' k_0 R \left\{ \frac{\cos U_0 \sin U - \sin U_0 \cos U \cos \Delta V}{1 + \sin U_0 \sin U + \cos U_0 \cos U \cos \Delta V} \right\}, \tag{4.32}$$

where:

$\boldsymbol{X_{DS}} = \begin{pmatrix} X_{DS} \\ Y_{DS} \end{pmatrix}$ are coordinates in the DSP system,

k_0' is scale factor at the Origin of the Projection (Sphere to Plane) and

$$\Delta V = V - V_0. \tag{4.33}$$

Then the 2D transformation into FSCS:XYH is defined as:

$$\boldsymbol{X_{FH_{2D}}} = F_0 \boldsymbol{R_{(\alpha)}} \boldsymbol{X_{DS}} + \boldsymbol{X_{A0}}, \tag{4.34}$$

where:

$\boldsymbol{X_{FH_{2D}}} = \begin{pmatrix} X_{FH} \\ Y_{FH} \end{pmatrix}$ are coordinates in FSCS:XYH on the mapping plane, and

$\boldsymbol{R}_{(\alpha)} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix}$ is the rotation matrix, with

α is Geodetic Azimuth,

F_0 as the Scale Factor at the Origin

and $\boldsymbol{X_{A0}}$ the False Coordinates at the Origin.

The height of a point is given by:

$$H_{FH} = H - dH, \tag{4.35}$$

with:

$$H = h + N, \tag{4.36}$$

H_{FH} is the Fermilab Orthometric Height above the DUSAF datum,

H is the Orthometric Height above the NAVD88 datum,

dH is the height correction from DUSAF to NAVD88,

h is the ellipsoidal height and

N is the Geoidal (GEOID83) Height of ellipsoid geoid separation.

Then, the coordinates of a point in FSCS:XYH can be written as:

$$\boldsymbol{X_{FH}} = \begin{pmatrix} X_{FH} \\ Y_{FH} \\ H_{FH} \end{pmatrix}.$$

The transformation from FSCS:XYH to GCS is a partially an iterative process. The transformation from FSCS:XYH to DS is done as follows:

$$\boldsymbol{X_{DS}} = F_0^{-1}\boldsymbol{R_\alpha}(\boldsymbol{X_{FH_{2D}}} - \boldsymbol{X_{A0}}). \tag{4.37}$$

The transformation from the Mapping Plane to the Spherical coordinates:

$$U = \arcsin\left(\sin U_0 \cos\delta + \cos U_0 \sin\delta \sin D\right), \tag{4.38}$$

$$V = V_0 + \arcsin\left(\frac{\cos D \sin\delta}{\cos U}\right), \tag{4.39}$$

where:

$$D = \arcsin\left(\frac{Y_{DS}}{\rho}\right), \tag{4.40}$$

$$\rho = \sqrt{X_{DS}^2 + Y_{DS}^2}, \tag{4.41}$$

$$\delta = 2\arctan\left(\frac{\rho}{2\ k_0'\ k_0\ R}\right). \tag{4.42}$$

Then the transformation from Sphere to Ellipsoid is:

$$\lambda = \frac{V}{c_1} \tag{4.43}$$

and the latitude of a point is calculated by an iterative Newton-Raphson solution:

$$\varphi_i = \varphi_{i-1} - \frac{f_{(\varphi_{i-1})}}{g_{(\varphi_{i-1})}}, \tag{4.44}$$

where:

$$f_{(\varphi_i)} = c_2\left[\tan\left(\frac{\pi}{4} - \frac{\varphi_i}{2}\right)\left(\frac{1 - e\sin\varphi_i}{1 + e\sin\varphi_i}\right)^{\frac{e}{2}}\right]^{c_1} - \tan\left(\frac{\pi}{4} - \frac{U}{2}\right), \tag{4.45}$$

$$g_{(\varphi_i)} = c_1 c_2\left[\tan\left(\frac{\pi}{4} + \frac{\varphi_i}{2}\right)\left(\frac{1 - \sin\varphi_i}{1 + e\sin\varphi_i}\right)^{\frac{e}{2}}\right]\left(\frac{1 - e\sin\varphi_i}{1 + e\sin\varphi_i}\right)^{\frac{e}{2}}$$
$$\cdot\left[\frac{1}{2}\sec^2\left(\frac{\pi}{4} + \frac{\varphi_i}{2}\right) - \left(\frac{e^2\cos\varphi_i}{1 - e^2\sin^2\varphi_i}\right)\tan\left(\frac{\pi}{4} + \frac{\varphi_i}{2}\right)\right]. \tag{4.46}$$

The initial value for latitude is $\varphi_0 = U$. The iteration stops when the difference of two successive is less than $\varepsilon = 10^{-14}$ rad.

The Ellipsoidal Height is given by:

$$h = H_{FH} + dH - N. \tag{4.47}$$

5 Network Measurements and Adjustment

5.1 Laser Tracker Measurements (local network)

The terrestrial measurements are obtained using a Leica AT401 and stored in the operating computer. Data are collected using the previously mentioned network MP (which used rough coordinates of the network points) in the software SA. The measurements are taken in the way to have at least three measurements on each point with good resection angle. There are few exceptions from that rule. After careful consideration of the ballence between the contribution of points to the future alignment on the one side and economical (time) point of view on the other side, it was decided that for some specific points this rule will be violated.

Points are measured in both faces immediately after each other and in one set. Every instrument station has its own file where measurements are stored. The name of the file is identical to the number of the closest point. All the instrument stations are done by a free-stationing method. The number of the visible points from one instrument station usually does not exceed 32 (the number of dedicated SMRs), but if does, it is recommended to measur the closest ones.

The initial plan called for the measurements to begin in the Detector Staging area and proceed to solenoids area, then continue to the beamline enclosure and beamline tunnel (MC4) and finally connect the Extinction Monitor enclosure. During preparation phase (network design), it was found that due to commissioning of the g-2 experiment, which shares part of the beamline, a shielding wall has to be built in the area of measurements. Based on that, a decision was made to change the initial plan to now start from the beam tunnel and proceed to the experimental building.

After finishing the initial measurements it was decided to expand the underground network by adding another points placed on the support structure of the main (ground) floor of the experiment building. And using this part of network to connect (loop) to the so-called sight-risers which were also measured during the underground measurement phase. Sight-risers are floor points in underground structure (in this case tunnel) with see-through pipe to the surface. Thanks to that feature is possible to measure the underground points, even from above ground. The centering was done using a Wild NL optical plummet. A closure was done to check the data measured underground.

5.1.1 Theory

In this section describes the mathematic apparatus which is generally used for adjustments of terrestrial measurements (angles and distances). The determination of out-layers is usually individual for each SW, robust methods and Monte-Carlo method was introduced recently. The standard out-layer determination is used for the purposes of the network in this thesis.

Least Square Method

The Least Squares Method (LSM) is a mathematical-statistical method to optimize overconstrained system of linear equations. The essence of the method is to minimize the sum of the squares of measurement correction corrections. LSM is used to determine the error estimate in the set of an input variables. This method was first used by C. F. Gauss for geodetic measurements. Assuming a linear problem:

$$\boldsymbol{A}\boldsymbol{x} \approx \boldsymbol{b}, \tag{5.1}$$

$$\boldsymbol{A}\boldsymbol{x} - \boldsymbol{b} \approx \boldsymbol{0}, \tag{5.2}$$

where:
$\boldsymbol{A}$ is a matrix of linear equations,
$\boldsymbol{b}$ is a vector of results,
and $\boldsymbol{x}$ is a vector of solution that is sought when the following apply:

$$min||\boldsymbol{A}x - \boldsymbol{b}||_2. \tag{5.3}$$

Assuming $\boldsymbol{A}$ has linearly independent columns:

$$\left(\boldsymbol{A}^T\boldsymbol{A}\right)^{-1}\boldsymbol{A}\boldsymbol{b} = \boldsymbol{0}. \tag{5.4}$$

If different weights of input valuables are used (matrix $\boldsymbol{P}$):

$$\left(\boldsymbol{A}^T\boldsymbol{P}\,\boldsymbol{A}\right)^{-1}\boldsymbol{A}\,\boldsymbol{P}\,\boldsymbol{b} = \boldsymbol{0}. \tag{5.5}$$

Use of LSM for geodetic measurements adjustment

The quantities for adjustment, when trigonometric measurements are performed, are in horizontal directions (φ), zenith angles (z) and slope distances (d). These quantities are the input valuables for the adjustment. The orientation unknown and XYZ coordinates of the measured points are the sought quantities in the local orthonormal three-dimensional space.

Process description

Relations between measured and sought unknowns are following [16]:

$$\varphi_{ij} = \arctan\left(\frac{Y_j - Y_i}{X_j - X_i}\right) - o_i, \tag{5.6}$$

$$z_{ij} = acos\left(\frac{Z_j - Z_i}{\sqrt{(X_j - X_i)^2 + (Y_j - Y_i)^2 + (Z_j - Z_i)^2}}\right), \tag{5.7}$$

$$d_{ij} = \sqrt{(X_j - X_i)^2 + (Y_j - Y_i)^2 + (Z_j - Z_i)^2}, \tag{5.8}$$

where:

φ_{ij}, z_{ij}, d_{ij} are the horizontal direction, the zenith angle, and the slope distance between instrument station i and target j respectively,

X_i, Y_i, Z_i are the coordinates of the instrument station,

X_j, Y_j, Z_j are the coordinates of the target,

a o_i is the orientation unknown on the instrument station i.

General equations for parametric adjustment:

$$\boldsymbol{l} + \boldsymbol{\varepsilon} = \boldsymbol{f}(\boldsymbol{x}), \tag{5.9}$$

$$\bar{\boldsymbol{l}} = \boldsymbol{l} + \boldsymbol{v} = \boldsymbol{f}(\bar{\boldsymbol{x}}), \tag{5.10}$$

where: $\boldsymbol{l}$ is a vector of measured quantities (random selection from the the base file with the normal distribution),

$\bar{\boldsymbol{l}}$ is the vector of estimated measured quantities,

$\bar{\boldsymbol{x}}$ is the vector of estimated unknowns $\boldsymbol{x}$,

$\boldsymbol{\varepsilon}$ is the vector of the vector of actual errors,

and $\boldsymbol{v}$ is vector of the measurement corrections for which apply:

$$\boldsymbol{v} = \boldsymbol{f}(\bar{\boldsymbol{x}}) - \boldsymbol{l}. \tag{5.11}$$

Solution of the adjustment

From the relation equations between measured and unknowns (equation (5.6), (5.7) a (5.8)) is evident, that relations between there quantities are not linear, except the orientation unknown. The LSM solves just sets of linear equations. The relation equations are then approximated by linearized equations. For the linear model applies:

$$\bar{\boldsymbol{x}} = \boldsymbol{x}_0 + \boldsymbol{dx}, \quad (5.12)$$

$$\boldsymbol{v} = \boldsymbol{f}(\boldsymbol{x}_0) + \left.\frac{\partial \boldsymbol{f}(\boldsymbol{x})}{\partial \boldsymbol{x}}\right|_{\boldsymbol{x}=\boldsymbol{x}_0} \cdot \boldsymbol{dx} - \boldsymbol{l}. \quad (5.13)$$

After rebranding:

$$\left.\frac{\partial \boldsymbol{f}(\boldsymbol{x})}{\partial \boldsymbol{x}}\right|_{\boldsymbol{x}=\boldsymbol{x}_0} = \boldsymbol{A}, \quad (5.14)$$

where:

$\boldsymbol{x}_0$ is the vector of approximate values of unknowns,

$\boldsymbol{dx}$ is the vector of the increments to the adjusted values,

$\boldsymbol{A}$ is a plan matrix, containing of partial derivations.

The process of matrix assembly is below. Approximation of the function relations is done by two term Taylor expansion. The chosen approximation is precise enough just for the vicinity of the $\boldsymbol{x}_0$. This doesn't apply for the linear relation functions and there will be no further effect to the first approximations.

For the vector of reduced measurements apply:

$$\bar{\boldsymbol{l}} = \boldsymbol{f}(\boldsymbol{x}_0) - \boldsymbol{l}. \quad (5.15)$$

After introduction of the vector of reduced measurement ($\bar{\boldsymbol{l}}$) and the plan matrix ($\boldsymbol{A}$) apply:

$$\boldsymbol{v} = \boldsymbol{A} \cdot \boldsymbol{dx} + \bar{\boldsymbol{l}}. \quad (5.16)$$

The weight matrix $\boldsymbol{P}$ changes the influence of individual measurements to the adjustment. The weight matrix is a way how to insert other information about the precision of the measured quantities to the adjustment process. The matrix is diagonal. The dimension of the matrix is identical with the number of measured quantities in the whole network and identical with number of rows of matrix $\boldsymbol{A}$.

$$\boldsymbol{P} = diag\,(p_1, \dots p_m) \quad (5.17)$$

p_i is usually chosen as:

$$p_i = \frac{\sigma_0^2}{\sigma_i^2} \tag{5.18}$$

where σ_0 is an apriori standard deviation and σ_i apriori sample standard deviation of the measured quantities.

The LSM with implemented weight matrix ($\boldsymbol{P}$) is given by:

$$\boldsymbol{v}^T \cdot \boldsymbol{P} \cdot \boldsymbol{v} = min. \tag{5.19}$$

The normal equation model is produced after substituting:

$$\left(\boldsymbol{A}^T \boldsymbol{P} \boldsymbol{A}\right) \cdot \boldsymbol{dx} + \boldsymbol{A}^T \boldsymbol{P} \bar{\boldsymbol{l}} = 0. \tag{5.20}$$

Assuming the regularity of the normal equations $\left(\boldsymbol{A}^T \boldsymbol{P} \boldsymbol{A}\right)$ results in solving the equations (or determining the increments to the apriori approximates):

$$\boldsymbol{dx} = -\left(\boldsymbol{A}^T \boldsymbol{P} \boldsymbol{A}\right)^{-1} \cdot \boldsymbol{A}^T \boldsymbol{P} \bar{\boldsymbol{l}}. \tag{5.21}$$

Determination of the adjusted unknowns:

$$\boldsymbol{x} = \boldsymbol{x}_0 + \boldsymbol{dx}. \tag{5.22}$$

Corrections calculation:

$$\boldsymbol{v} = \boldsymbol{A} \cdot \bar{\boldsymbol{l}} \tag{5.23}$$

and correction of the measured quantities from calculated correction is given by:

$$\bar{\boldsymbol{l}} = \boldsymbol{l} + \boldsymbol{v}. \tag{5.24}$$

Plan matrix for trigonometric measurements

The whole matrix $\boldsymbol{A}$ consists of submatrices for individual instrument stations:

$$\boldsymbol{A} = \begin{pmatrix} \boldsymbol{A}_1 \\ \vdots \\ \boldsymbol{A}_S \end{pmatrix}, \tag{5.25}$$

where $_S$ is the number of the instrument stations,

$$\boldsymbol{A}_i = \begin{pmatrix} \boldsymbol{G}_{11}^i & \boldsymbol{G}_{12}^i & \cdots & \boldsymbol{G}_{1n}^i & \boldsymbol{J}_j^i \\ \boldsymbol{G}_{21}^i & \boldsymbol{G}_{22}^i & \cdots & \boldsymbol{G}_{2n}^i & \boldsymbol{J}_j^i \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \boldsymbol{G}_{m1}^i & \boldsymbol{G}_{m2}^i & \cdots & \boldsymbol{G}_{mn}^i & \boldsymbol{J}_j^i \end{pmatrix}, \tag{5.26}$$

m is the number of measured quantities on the instrument station and n is number of points in the network,

$$\boldsymbol{G}_{kj}^{i} = \begin{pmatrix} \frac{\partial \varphi_{ij}}{\partial X_j} & \frac{\partial \varphi_{ij}}{\partial Y_j} & \frac{\partial \varphi_{ij}}{\partial Z_j} \\ \frac{\partial z_{ij}}{\partial X_j} & \frac{\partial z_{ij}}{\partial Y_j} & \frac{\partial z_{ij}}{\partial Z_j} \\ \frac{\partial d_{ij}}{\partial X_j} & \frac{\partial d_{ij}}{\partial Y_j} & \frac{\partial d_{ij}}{\partial Z_j} \end{pmatrix} \tag{5.27}$$

and

$$\boldsymbol{J}_{j}^{i} = \begin{pmatrix} \frac{\partial \varphi_{ij}}{\partial o_1} & \dots & \frac{\partial \varphi_{ij}}{\partial o_p} \\ \frac{\partial z_{ij}}{\partial o_1} & \dots & \frac{\partial z_{ij}}{\partial o_p} \\ \frac{\partial d_{ij}}{\partial o_1} & \dots & \frac{\partial d_{ij}}{\partial o_p} \end{pmatrix}. \tag{5.28}$$

The size of matrix $\boldsymbol{J}$ is $3 \times p$ (the number of sets of angles).
Partial derivative in matrices $\boldsymbol{G}_{kj}^{i}$ and $\boldsymbol{J}_{j}^{i}$ for horizontal directions are given by:

$$\frac{\partial \varphi_{ij}}{\partial X_i} = -\frac{\partial \varphi_{ij}}{\partial X_j} = \frac{(Y_j - Y_i)}{(X_j - X_i)^2 + (Y_j - Y_i)^2}, \tag{5.29}$$

$$\frac{\partial \varphi_{ij}}{\partial Y_i} = -\frac{\partial \varphi_{ij}}{\partial Y_j} = \frac{-(X_j - X_i)}{(X_j - X_i)^2 + (Y_j - Y_i)^2}, \tag{5.30}$$

$$\frac{\partial \varphi_{ij}}{\partial Z_i} = \frac{\partial \varphi_{ij}}{\partial Z_j} = 0, \tag{5.31}$$

$$\frac{\partial \varphi_{ij}}{\partial o_l} = -1, \tag{5.32}$$

for measured zenith angles:

$$\frac{\partial z_{ij}}{\partial X_i} = -\frac{\partial z_{ij}}{\partial X_j} = \frac{-(X_j - X_i) \cdot (Z_j - Z_i)}{\left((X_j - X_i)^2 + (Y_j - Y_i)^2 + (Z_j - Z_i)^2\right) \cdot \sqrt{(X_j - X_i)^2 + (Y_j - Y_i)^2}}, \tag{5.33}$$

$$\frac{\partial z_{ij}}{\partial Y_i} = -\frac{\partial z_{ij}}{\partial Y_j} = \frac{-(Y_j - Y_i) \cdot (Z_j - Z_i)}{\left((X_j - X_i)^2 + (Y_j - Y_i)^2 + (Z_j - Z_i)^2\right) \cdot \sqrt{(X_j - X_i)^2 + (Y_j - Y_i)^2}}, \tag{5.34}$$

$$\frac{\partial z_{ij}}{\partial Z_i} = -\frac{\partial z_{ij}}{\partial Y_j} = \frac{\sqrt{(X_j - X_i)^2 + (Y_j - Y_i)^2}}{(X_j - X_i)^2 + (Y_j - Y_i)^2 + (Z_j - Z_i)^2}, \tag{5.35}$$

$$\frac{\partial z_{ij}}{\partial o_l} = 0, \tag{5.36}$$

for measured slope distances:

$$\frac{\partial d_{ij}}{\partial X_i} = -\frac{\partial d_{ij}}{\partial X_j} = \frac{-(X_j - X_i)}{\sqrt{(X_j - X_i)^2 + (Y_j - Y_i)^2 + (Z_j - Z_i)^2}}, \tag{5.37}$$

$$\frac{\partial d_{ij}}{\partial Y_i} = -\frac{\partial d_{ij}}{\partial Y_j} = \frac{-(Y_j - Y_i)}{\sqrt{(X_j - X_i)^2 + (Y_j - Y_i)^2 + (Z_j - Z_i)^2}}, \tag{5.38}$$

$$\frac{\partial d_{ij}}{\partial Z_i} = -\frac{\partial d_{ij}}{\partial Y_j} = \frac{-(Z_j - Z_i)}{\sqrt{(X_j - X_i)^2 + (Y_j - Y_i)^2 + (Z_j - Z_i)^2}}, \tag{5.39}$$

$$\frac{\partial d_{ij}}{\partial o_l} = 0. \tag{5.40}$$

Standard deviations

Matrix of weight coeficients of adjusted point coordinates:

$$\boldsymbol{Q}_x = \left(\boldsymbol{A}^T \boldsymbol{P} \boldsymbol{A}\right)^{-1} \tag{5.41}$$

where $\boldsymbol{A}$ is the plan matrix and $\boldsymbol{P}$ is a weight matrix.

The covariance matrix consists of accuracy characteristics of determination of the adjusted point coordinates. The covariance matrix can be calculated as:

$$\boldsymbol{M}_x = \sigma_0^2 \cdot \boldsymbol{Q}_x, \tag{5.42}$$

$$\boldsymbol{M}_x = s_0^2 \cdot \boldsymbol{Q}_x, \tag{5.43}$$

where:

σ_0 is the apriori sample standard deviation, usually chosen to be one,

s_0 is the aposteriory sample standard deviation determined in the adjustment process:

$$s_0 = \sqrt{\frac{\boldsymbol{v}^T \boldsymbol{P} \boldsymbol{v}}{n'}}, \tag{5.44}$$

where: n' is number of of degrees of freedom.

An important characteristic of adjusted unknowns is their standard deviation. For general adjusted unknown x_i apply:

$$\sigma_{x_i} = \sqrt{M_{x_{ii}}}, \tag{5.45}$$

where $M_{x_{ii}}$ is i-th diagonal element of covariance matrix of adjusted unknowns $\boldsymbol{M}_x$.

For the standard deviations apply the law of accumulation of standard deviations:

$$\boldsymbol{M}_{\bar{l}} = \boldsymbol{A} \boldsymbol{M}_x \boldsymbol{A}^T, \tag{5.46}$$

$$\sigma_{\bar{l}_i} = \sqrt{M_{\bar{l}_{ii}}}, \tag{5.47}$$

where $M_{\bar{l}_{ii}}$ is i-th diagonal element of the covariance matrix of adjusted measured quantities $\boldsymbol{M}_{\bar{l}}$ a $\sigma_{\bar{l}_i}$ is standard deviation of adjusted measured quantity $\bar{l}_i$.

Other characteristics of adjusted unknowns are normalized residuals which can be calculated as:

$$\hat{v}_{l_i} = \frac{v_{l_i}}{\sigma_{l_i}}, \tag{5.48}$$

where:

$\hat{v}_{l_i}$ is normalized value of residual v_{l_i} for measurement l_i,

5.1.2 Process

When taking measurements, data are collected directly in the computer in MP in an internal format particular to the software. Every instrument station has its own file. Those files have to be connected during the first post-processing of the measured quantities. Three MP in SA are used for this step. Files for all stations to be use in calculations are placed in one directory and automatically read by the first MP. The MP connects the stations together using USMN and user defined rough coordinates. In the beginning of the process is needed to choose criterium for detecting gross errors (misnaming, etc.). MP stops when the disagreement between the fitted coordinates of any point and the measurement exceed a chosen criterium and it is possible to correct the error or skip the point. At the end of this process, all the stations are in the same frame and ready to be exported to the *.xlsx files for further processing. The second two MPs export the data to those files.

The exported data are processed into a GeoPAN format using an AMD software package. The result is a formatted text file with rough coordinates and all measurements used for bundle adjustment. A user has just to add a header with adjustment informations and choices. The header used for Mu2e network adjustment is in following format:

```
Project name (units=meters+grad)
----+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
 0              3 0     1 0 0 1       0 1 1 1      9          0   1 1
CRITERIA
 0.00000            0.00000  0.00000  0.00000  0.00000  0.00000   1000.00   01.000
FACTORS
   1.000    1.000    1.000    1.000    1.000    1.000    1.000    1.000    1.000
```

Table 5.1: Criteria of adjustment

Column	Information
1 - 8	Convergence Criterion
10 - 17	Confidence Level
19 - 26	Centering Error for Distance Observations
28 - 35	Centering Error for Direction Observations
37 - 44	Centering Error for Angle Observations
46 - 53	Centering Error for Azimuth Observations
55 - 62	Centering Error for Offset Observations
64 - 72	Misclosure Criterion for Angle Observations
74 - 82	Misclosure Criterion for Distance Observations

Table 5.2: Factors of adjustment

Column	Information
1 - 8	Factor CONSTANT for st. dev. of Horizontal Distance Observations
10 - 17	Factor PPM for st. dev. of ALL Types of Distance Observations
19 - 26	Factor for st. dev. of Direction Observations
28 - 35	Factor for st. dev. of Angle Observations
37 - 44	Factor for st. dev. of Azimuth Observations
46 - 53	Factor for st. dev. of Offset Observations
55 - 62	Factor for st. dev. of Zenital Angle Observations
64 - 71	Factor CONSTANT for st. dev. of Slope Distance Observations
73 - 80	Factor for st. dev. of Delta Height Observations

The network is adjusted as a minimally constraint network and the results represent the accuracy of the network. Coordinates coming from this adjustment are in a quasi-geodetic system. The adjustment of the network is done by LSM, described above.

Table 5.3: Adjustment summary

Number of observations	
Slope distance	808
Directions	806
Zenith Angles	771
Total	2385
Number of unknowns	
Orientations	33
Coordinates	692
Total	725
Degrees of freedom	1660

Table 5.4: Apriori and aposteriori precisions

Quantity	Apriori	Aposteriori
Direction σ_φ	0.300 mgon (1″)	0.287 mgon (0.958″)
Zenith angle σ_z	0.300 mgon (1″)	0.607 mgon (2.024″)
Distance σ_d	2 ppm	2.36 ppm

5.2 Leveling

Terrestrial observations, even with lots of redundancy, are not sufficient enough to fulfill the requirements for the required accuracy of the reference network. There were used other types of measurements.

Two types of leveling were used during heights determination of the points of the reference network. Traditional geometrical double-run leveling for high-precision leveling was used for outside ties and for loops through floor points. Wall points used "bundle" leveling. Bundle leveling is basically grid leveling with high-precision leveling instrument. The instrument is placed approxomately in the center of the measured points and measures all the unknown points in one sitting from one station, along with at least two known points. The minimum requirement is to have at least three height difference measurements for each unknown point.

The basic rules for high-precision leveling were used during measurements. The minimum reading on the leveling staff was at least 0.234 m and maximum reading (on the 2 m) staff is at most 1.745 m. Maximum sight length is 25 m. Elevations were transferred from existing points of the Site Elevation network. Leveling data were adjusted by John C Kyle (AMD) in the modified version of a GeoPAN SW. The stability of the point 113075 was checked during the outside measurements using two neighborhood points (113009 and 113231) which are also included in the adjustment. The point 113075 was held for the adjustments, because this point is considered as very stable even for future deformation monitoring of the Mu2e building.

5.3 Gyrotheodolite measurements

Gyrotheodolite measurements were performed to check of the rotation of the reference network. Three baselines were chosen for that purpose. The gyrotheodolite was placed eccentrically on (adjacent to) each baseline. The first baseline was between points 226053 and 226014, second was from 226013 to 225980 and the third one was between points 225962 to 225993. The first two baselines were measured twice as foresight and backsight. The calibration of the instrument was checked on the outside monument baseline 66589 - 66563 before the measurements of the baselines. The measurement protocols are attached in the Electronic Annexes.

The azimuths were first corrected from the eccentricity and then reduced by Laplace correction. The Laplace corrections were calculated in software using the GEOID93 model from [23]. This software is no longer available on the NGS webpage due to upgrades of Geoid models. The 1993 Geoid model is obsolete, but the FSCS is based on this model, and for continuity with the existing Fermilab system, the azimuths and corrections are calculated using the model GEOID93.

The adjusted coordinates (chapter 5.1) were transformed to the GCS and then the azimuths were calculated using the "INVERSE" webform [23]. Calculations are tabulated in Annex C.

5.4 Final adjustment

Adjusted measurements (see Section 5.1) are calculated from the raw data, i.e no mathematical corrections are applied. The Leica AT401 instrument corrects the raw data are for physical effects (temperature, presure and humidity). One option how to reduce measurements to the Earth surface (from quasi curvilinear system as in Section 5.1) is applied by using the traditional series of reduction equations where the number of applied correction depends on the required resulting precision. The reduction equations are correction from the height above the sea level, Earth curvature, mark-mark reduction, etc. It is also possible to use heights obtained by adjusting the leveling measurements. Leveling measurements follows the Earth surface are much better than terrestrial angular and distance measurements which are taken at the local Cartesian system with origin in the centre of the instrument and with Z direction identical with the gravity vector and XY plane normal to this vector. The final coordinates produced by combining the terrestrial measurements with the leveling measurements and also the gyrotheodolite measurements. The leveled heights are introduced to the adjustments by fixing heights of the leveled points. This guarantee that the measured data are calculated on the Earth's surface. The gyrotheodolite azimuth measurements are used as base-line measurements and they are matter for adjustments as another measured quantities. The adjustment process is the same like in the Section 5.1.

The accuracy of the network is determined by the minimally constrained network and the final coordinates are produced by the constrained network.

Figure 5.1: The final network

6 Cartesian and Earth Curvature Approach

The metrology measurements are usually done in small scale thus the standard geodetic corrections are (and can be) neglected. That is not possible in the field of accelerator alignment. The precision demands and size of the reference network are too high to omit the Earth curvature.

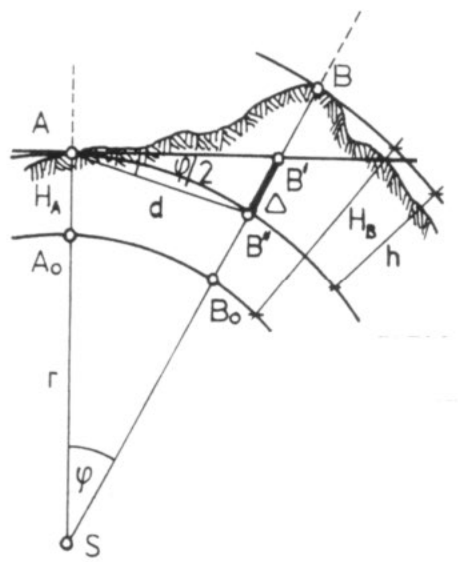


Figure 6.1: The Earth curvature effect

The theoretical corrections are clearly visible on the picture 6.1 and can be mathematically described as:

$$\Delta = d \cdot \sin\frac{\varphi}{2}, \tag{6.1}$$

assuming for small angles ($< 5°$) $\sin\alpha = \alpha$ rad:

$$\frac{\varphi}{2} = \frac{d}{2r}, \tag{6.2}$$

$$\Delta = \frac{d^2}{2r}, \tag{6.3}$$

where r is a radius of a reference sphere, calculated by:

$$r = \sqrt{M_{Mu2e}N_{Mu2e}}, \tag{6.4}$$

where M_{Mu2e} is a meridian radius of curvature in φ_{Mu2e} and N_{Mu2e} is a prime-vertical radius of curvature at φ_{Mu2e}:

$$M_{Mu2e} = M = \frac{a\left(1-e^2\right)}{\left(1-e^2\sin^2\varphi_{Mu2e}\right)^{\frac{3}{2}}}, \qquad (6.5)$$

where:

$$\varphi_{Mu2e} = \frac{\sum_{i=1}^{n}\varphi_i}{n}, \qquad (6.6)$$

is an average (centre of mass) of all network points of the Mu2e reference network in the Geodetic Coordinate System (see Annex I). The expected effect of the Earth curvature is in the table 6.1.

Table 6.1: The Earth curvature effect

d [m]	Δ [mm]
10	0.008
50	0.196
75	0.442
100	0.786
150	1.767
200	3.142

The substitution of the Earth for the estimated effect of the curvature could be done by using a spheroid approximation of the geoid model. The angle φ respective $\frac{\varphi}{2}$ can be derived from the Helmert or Clairaut spheroid with much higher accuracy if necessary.

6.1 USMN SA

The Unified Spatial Metrology Network [21] is a powerful tool in Spatial Analyzer. Software SA is a metrology application designated to primarily fulfill needs of mechanical engineers. SA is not a geodetic software and doesn't taking into account even the basic geodetic measurement corrections such as curvature of the Earth, corrections of height above sea level, etc. The LSM is used for adjustments of the metrology network. Thanks to this feature is possible to compare the pure Cartesian (3D) coordinate system and Earth curvature approach which is represented by results from final adjustments (5.4) which are taking into account the Earth curvature.

The USMN is basically a best-fit tool for combining multiple instruments. It can be multiple stations of one instrument or multiple instruments in real time. The adjustment of the geodetic network uses the first option by chaining the instruments together. As a best-fit method it uses 6-parameter transformation. The transformation with K instrument locations (stations) for I points for the k-th instrument is given by:

$$T_k = \begin{pmatrix} & & & B_x \\ & \boldsymbol{R}(\gamma, \beta, \alpha) & & B_y \\ & & & B_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{6.7}$$

where $\boldsymbol{R}(\gamma, \beta, \alpha)$ is a rotation matrix,
$\boldsymbol{B} = (B_x, B_y, B_z)$ is a translation vector representing the origin of the instrument in the global coordinate system.
The system consists of $6 \times K$ variables for the adjusted network. If nothing would be fixed, the system would have infinite number of possible solutions and the results could float around the whole coordinate system. That is possible to overcome with fixing one instrument station and then the system has just $(6-1) \times K$ variables.

The instrument station in the Transportation Solenoid area (014_BASE) was fixed to adjust the Mu2e reference network. That should decrease the error from Earth curvature. The rough coordinate determination was used as first approximation. The adjusted coordinates with uncertainties are in the Annex F.

7 Results

The geodetic and metrological approaches to the coordinate calculations were described in chapters 5.4 and 6.1 respectively. The results are in Annexes D and F. Comparison of those two approaches is in the Table E.1 below. The graphical representation of the results is in the figure 7.1. The confidence level for calculations is 95% (level of significancy $\alpha = 0.05$) except the USMN calculations which are calculated on the 1σ uncertainty level (68.27%).

Pt. number	H_{FCSC} [m]	Z_{USMN} [m]	Δ [mm]	Pt. number	H_{FCSC} [m]	Z_{USMN} [m]	Δ [mm]
186004	222.035760	222.036665	0.905	226008	221.997900	221.997393	-0.507
186005	222.078820	222.081123	2.303	226009	219.787640	219.787607	-0.033
225806	222.071570	222.072045	0.475	226010	222.008550	222.008356	-0.194
225816	223.690830	223.691091	0.261	226011	220.070960	220.070874	-0.086
225817	224.064520	224.064801	0.281	226012	221.643630	221.643884	0.254
225819	222.058070	222.058474	0.404	226013	219.780020	219.780653	0.633
225825	223.674670	223.674952	0.282	226014	219.787050	219.787674	0.624
225828	222.047110	222.047409	0.299	226015	220.201370	220.201501	0.131
225857	223.543300	223.543535	0.235	226016	222.002840	222.002101	-0.739
225858	223.938280	223.938532	0.252	226017	221.938310	221.938142	-0.168
225859	222.538340	222.538660	0.320	226018	220.169830	220.170457	0.627
225861	223.543710	223.543950	0.240	226019	225.429480	225.428923	-0.557
225862	223.967740	223.967982	0.242	226020	225.435120	225.435180	0.060
225863	222.524560	222.524798	0.238	226021	219.782910	219.783388	0.478
225864	222.063640	222.063986	0.346	226022	219.782130	219.782243	0.113
225874	223.540440	223.540711	0.271	226023	219.783280	219.783803	0.523
225875	223.914260	223.914431	0.171	226024	221.961850	221.961149	-0.701
225876	222.468300	222.468520	0.220	226025	221.985140	221.985060	-0.080
225877	222.038660	222.038574	-0.086	226026	221.948090	221.949371	1.281
225887	223.545900	223.546109	0.209	226027	221.965240	221.964313	-0.927
225888	223.882190	223.882432	0.242	226028	221.984580	221.985644	1.064
225889	222.560090	222.560239	0.149	226029	222.031350	222.030896	-0.454
225890	222.038660	222.038380	-0.280	226030	221.965210	221.965265	0.055
225900	223.524130	223.524363	0.233	226031	219.789700	219.790233	0.533
225901	223.984070	223.984172	0.102	226032	221.738600	221.738589	-0.011
225902	222.492420	222.492343	-0.077	226033	220.199010	220.199127	0.117
225903	222.041700	222.041330	-0.370	226034	219.784160	219.784581	0.421
225913	223.526990	223.527158	0.168	226035	220.178440	220.178400	-0.040
225914	224.032590	224.032665	0.075	226036	222.028800	222.027886	-0.914
225915	222.586600	222.586521	-0.079	226037	221.951890	221.951966	0.076
225916	222.044500	222.043577	-0.923	226038	219.785470	219.786164	0.694
225926	223.534560	223.534766	0.206	226039	221.949360	221.949449	0.089
225927	224.079110	224.079168	0.058	226040	219.788370	219.788819	0.449
225928	222.550770	222.550600	-0.170	226041	221.978750	221.978778	0.028
225929	222.060380	222.059585	-0.795	226042	220.212420	220.212562	0.142
225935	224.249930	224.250255	0.325	226043	222.013420	222.013811	0.391

225936	223.883270	223.883388	0.118	226044	220.192410	220.192451	0.041
225937	222.553130	222.552340	-0.790	226045	222.030260	222.029885	-0.375
225939	224.263000	224.263567	0.567	226046	219.789220	219.788655	-0.565
225940	224.038490	224.038431	-0.059	226047	219.779290	219.778940	-0.350
225941	222.511750	222.511711	-0.039	226048	220.283160	220.283192	0.032
225942	222.070680	222.069331	-1.349	226049	221.897810	221.898045	0.235
225948	224.207840	224.208334	0.494	226050	221.902830	221.903410	0.580
225949	223.883650	223.883089	-0.561	226051	220.161320	220.161429	0.109
225952	224.133690	224.134047	0.357	226052	221.923570	221.923665	0.095
225953	224.112270	224.111921	-0.349	226053	219.787730	219.787811	0.081
225954	222.489560	222.489546	-0.014	226054	221.964610	221.964951	0.341
225955	222.065930	222.065326	-0.604	226055	221.969580	221.969570	-0.010
225957	224.228610	224.228881	0.271	226056	220.248720	220.248643	-0.077
225958	224.087620	224.087696	0.076	226057	221.968750	221.969217	0.467
225959	222.558860	222.557174	-1.686	226058	220.162120	220.162137	0.017
225960	224.120660	224.121934	1.274	226059	221.960620	221.960508	-0.112
225961	224.198110	224.197370	-0.740	226060	219.787500	219.786977	-0.523
225962	222.064390	222.063851	-0.539	226061	219.778810	219.779380	0.570
225963	224.078390	224.078799	0.409	226062	219.785630	219.785772	0.142
225964	224.191870	224.190961	-0.909	226063	221.960910	221.961177	0.267
225965	222.057240	222.056834	-0.406	226064	221.944410	221.944691	0.281
225966	223.001600	223.001641	0.041	226065	221.969450	221.969488	0.038
225967	224.158840	224.159179	0.339	226066	220.902530	220.902665	0.135
225968	224.153640	224.153343	-0.297	226067	221.979330	221.975640	-3.690
225969	219.788220	219.787755	-0.465	226068	219.780690	219.780145	-0.545
225970	221.745360	221.745022	-0.338	226069	219.784220	219.782008	-2.212
225971	223.936710	223.936544	-0.166	226070	221.992830	221.998790	5.960
225972	219.777120	219.776549	-0.571	226071	225.184710	225.183183	-1.527
225973	221.895800	221.895716	-0.084	226072	220.322540	220.322546	0.006
225974	223.852580	223.852299	-0.281	226073	222.001560	222.000786	-0.774
225975	219.781880	219.781906	0.026	226074	221.965630	221.967534	1.904
225976	221.988710	221.988576	-0.134	226075	225.183710	225.181803	-1.907
225977	223.154390	223.155412	1.022	226076	224.960100	224.960563	0.463
225978	219.775260	219.775856	0.596	226077	224.908040	224.902474	-5.566
225979	221.971040	221.970027	-1.013	226078	224.995760	224.995336	-0.424
225980	219.786960	219.786551	-0.409	226079	225.312190	225.312017	-0.173
225981	219.776410	219.775926	-0.484	226080	225.371090	225.371291	0.201
225982	221.768330	221.769075	0.745	226081	224.881320	224.881360	0.040
225983	221.960180	221.960030	-0.150	226082	224.165810	224.165379	-0.431
225984	220.590570	220.589523	-1.047	226083	224.165050	224.163984	-1.066
225985	219.787470	219.787326	-0.144	226084	224.159630	224.160449	0.819
225986	221.649320	221.649455	0.135	226085	224.652700	224.652649	-0.051
225987	221.924630	221.924477	-0.153	226086	226.232240	226.231790	-0.450
225988	220.617570	220.617129	-0.441	226087	224.566540	224.566708	0.168
225989	219.795630	219.795382	-0.248	226088	226.267250	226.266711	-0.539

225990	221.972580	221.972394	-0.186	226089	224.834770	224.834695	-0.075
225991	220.409240	220.408493	-0.747	226090	226.324930	226.325221	0.291
225992	219.783540	219.783210	-0.330	226091	226.059940	226.059161	-0.779
225993	221.663110	221.662915	-0.195	226092	224.161540	224.162301	0.761
225994	219.788340	219.788601	0.261	226093	224.524970	224.525011	0.041
225995	221.973560	221.974296	0.736	226094	226.253740	226.257464	3.724
225996	221.699350	221.699441	0.091	226095	229.639180	229.639951	0.771
225997	219.785660	219.786261	0.601	226096	229.431990	229.432940	0.950
225998	220.225990	220.226067	0.077	226097	229.443340	229.444255	0.915
225999	221.967390	221.967071	-0.319	226098	229.695180	229.695542	0.362
226000	221.982740	221.982708	-0.032	226099	227.537770	227.536888	-0.882
226001	220.329190	220.329504	0.314	226100	229.653340	229.652621	-0.719
226002	219.787240	219.787833	0.593	226101	229.652790	229.652306	-0.484
226003	221.751810	221.751670	-0.140	226102	229.790900	229.789955	-0.945
226004	220.167430	220.167871	0.441	226103	229.716940	229.715901	-1.039
226005	221.996530	221.996160	-0.370	226104	229.728190	229.727427	-0.763
226006	219.787440	219.787522	0.082	226105	229.594120	229.594561	0.441
226007	221.968090	221.967129	-0.961	226106	229.735910	229.739708	3.798

The maximum difference between ellipsoidal height and USMN Z coordinate is $\Delta = 5.566\,\mathrm{mm}$ and the expected simplified maximum difference was determined as $\Delta_m = 3.000\,\mathrm{mm}$ (see the Table 6.1). The effect of the Earth's curvature is distance dependent, but for easier comparison the measured deviations from the pure cartesian height are compared with the maximum expected vertical deviation over the length of the network.

Figure 7.1 shows a rotation between compared systems. This rotation is most probably due the USMN calculation method. Unified Spatial Metrology Network uses for referencing the measurements together the six-parameters transformation (three rotation angles and three translations) with these parameters determined by Least Squares Method. The measurements are determined on the base of one "fixed" instrument station and the rest is transformed on the previous ones. This approach means that every uncertainty is amplified as it propagates through network.

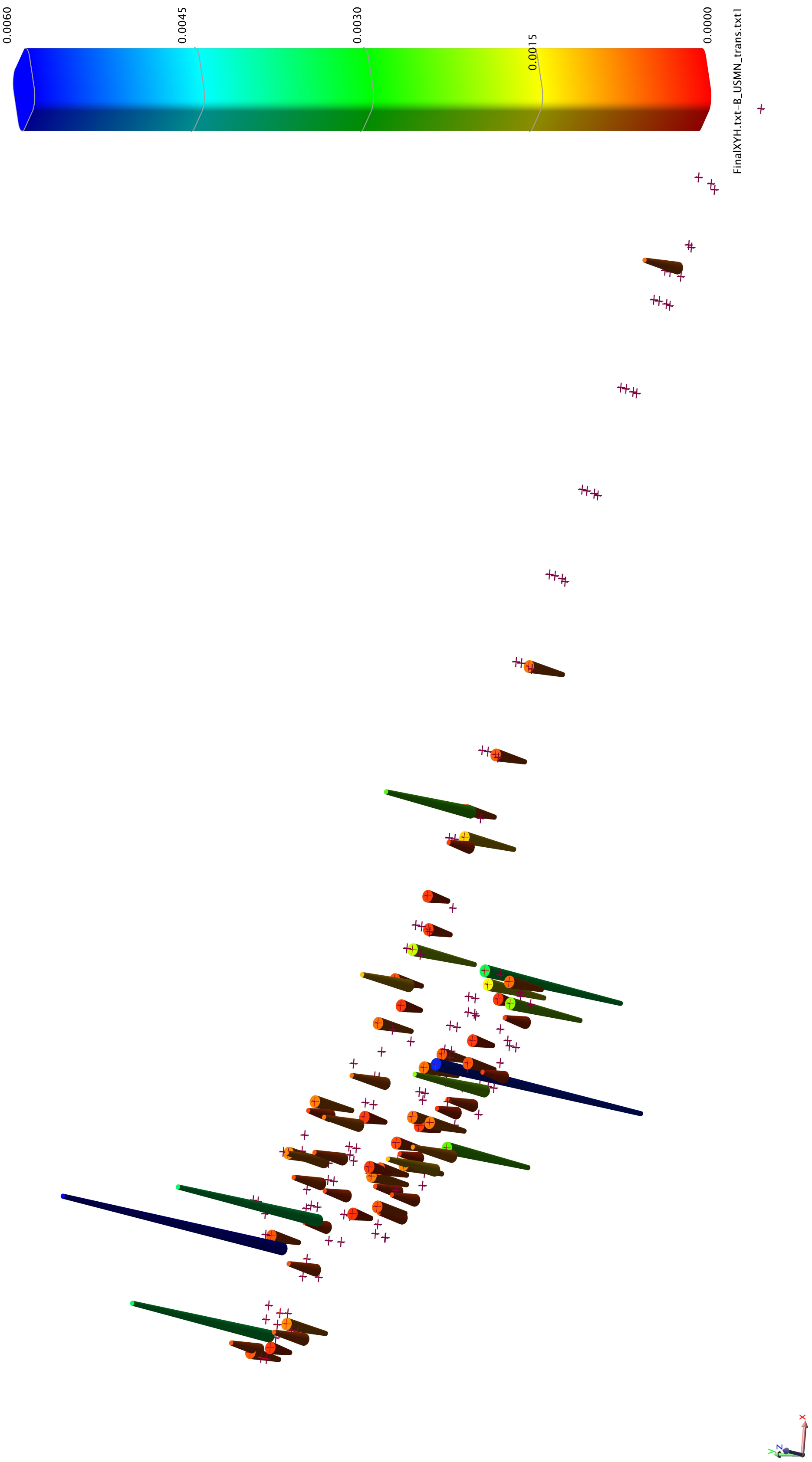


Figure 7.1: The graphical representation of the height differences between FSCS:XYH and USMN

Conclusion

The process of establishing new local high-precision reference network was described in this Thesis. Design of the network was done as a foundation for the installation works. Pre-analysis of a geometry and resulting precision was modeled and calculated before the installation of the monuments with a successful results fulfilling the requirements imposed on the network. Measurements of the network took place after the installation works. The expected standard deviations of points were modeled on the base of measured quantities and theoretical (given by manufacturer and expirience) accuracies of the measured values. The network was measured with a Absolute Tracker Leica AT401 as a terrestrial angular and distance measurement instrument. The fixed heights of chosen points were determined by adjusting the leveling measurements provided by Leica DNA03. The network was also referenced to the true North (CIO) using gyrotheodolite measurements performed by DMT Gyromat 2000.

All the measured data are used for calculations. The heights from the level measurements are used for fixing the network to the Earth surface. Terrestrial measurements together with measured gyroscopic azimuths are used to determine the best possible results. The coordinates were calculated by Least Squares Method using SW GeoPAN. Accuracies are in the expected range and fulfill the demands and needs of different areas.

The adjustments were done by two different approaches: metrological approach of a pure 3D Cartesian system on one side and a traditional geodetic with taking into account the Earth's curvature on the other side. The comparison was performed and evaluated in previous chapter. The differences between these two approaches are significant which leads to a conclusion that Earth's curvature effect shouldn't be neglected during network adjustments. Using of a pure 3D Cartesian system for larger reference networks is not recommended.

7.1 Suggestion of the further research

Perform the gyro measurements above ground on the sight-risers because of a the observed systematic deviation of the gyro azimuths in comparison to the calculated coordinates.

Investigate the possibility and advantage of centering the eccentric measurements in the network and use the triangles for higher rigidity of the reference network.

Test the use of the terrestrial angular and distance measurements for determining the height differences and include those measurements to the adjustment of the leveled height differences. Included measurements should be close to the point. The terrestrial measurements should be used with corresponding accuracies.

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List of Abbreviations

USA	United States of America
CTU	Czech Technical University in Prague
FRA	Fermi Research Alliance
URA	Universities Research Association, Inc.
FNAL	Fermi National Accelerator Laboratory
DOE	Unites States Department of Energy
EDM	Electronic Distance Meter
ADM	Absolute Distance Meter
SA	Spatial Analyzer
SMR	Spherically Mounted Reflector
Mu2e	Muon to Electron
MCS	Mu2e Coordinate System
LCS	Local Coordinate System
RRR	Red Ring Reflector
FSCS	Fermi Site Coordinate System
API	Automated Precision Inc.
GeoPAN	Geodetic Plane Adjustment and Analysis
MP	Measurement Plan
USMN	Unified Spatial Metrology Network
NRK	New River Kinematics, Inc.
LSM	Least Squares Method

AMD	Alignment and Metrology Department
DS	Detector Solenoid
TS	Transportation Solenoid
PS	Production Solenoid
CS	Coordinate System
FSCS	Fermilab Site Coordinate System
LTCS	Local Tunnel Coordinate System
GCS	Geodetic Coordinate System
GCCS	Geodetic Cartesian Coordinate System
NAD83	North American Datum 1983
NAVD88	North American Vertical Datum 1988
GRS80	Geodetic Reference System 1980
IAG	International Association of Geodesy
ECM	Earth Centre of Mass
IUGG	International Union of Geodesy and Geophysics
CTP	Conventional Terrestrial Pole
CIO	Conventional International Origin
BIH	Bureau International de l'Heure
DSP	Double Stereographic Projection
MI	Main Injector
MR	Main Ring
DMT	Deutsche Montan Technologie

NGS National Geodetic Survey

CLFV Charged Lepton Flavor Violation

DESY Deutsches Elektronen-Synchrotron

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A The design network pre-analysis results

Point number	X [m]	Y [m]	Z [m]	σ_X [mm]	σ_Y [mm]	σ_Z [mm]
1	39.71747	-6.21336	3.17393	0.043	0.030	0.027
2	39.71745	-1.30568	3.17392	0.042	0.028	0.031
3	41.35120	0.15329	-0.21250	0.043	0.017	0.020
4	41.35121	-4.72550	-0.21246	0.042	0.030	0.020
5	40.90923	-4.71434	-2.31244	0.042	0.029	0.022
6	40.93946	-7.71327	-0.21247	0.045	0.034	0.024
7	40.93944	-7.32785	-2.31244	0.044	0.033	0.024
8	40.25182	2.95398	-0.21252	0.046	0.029	0.022
9	40.25184	2.95399	-1.01249	0.047	0.029	0.022
10	37.81553	-0.09296	-2.31248	0.042	0.025	0.021
11	35.37325	2.95399	-0.21249	0.047	0.029	0.022
12	35.37326	2.95400	-2.01256	0.047	0.029	0.023
13	33.42642	1.52443	-0.21249	0.049	0.039	0.029
14	33.83688	-0.09399	-0.21246	0.045	0.030	0.023
15	33.42638	1.52451	-2.01249	0.048	0.036	0.027
16	33.83684	-0.37492	-2.31242	0.044	0.026	0.021
17	34.08209	-7.71398	-0.21239	0.042	0.029	0.020
18	33.66767	-8.31846	-0.21258	0.042	0.034	0.021
19	34.07257	-7.35280	-2.31253	0.042	0.028	0.021
20	33.66765	-8.31860	-2.01249	0.042	0.034	0.022
21	29.88887	2.95400	-0.21254	0.047	0.038	0.026
22	29.89737	-0.09298	-2.31254	0.044	0.029	0.021
23	29.88770	-7.71294	-2.31252	0.043	0.028	0.020
24	29.24951	-10.73619	-0.21237	0.044	0.033	0.023
25	26.31442	1.52449	-0.21246	0.044	0.039	0.023
26	26.31435	1.52456	-2.01251	0.044	0.039	0.024
27	25.90792	-0.09404	-0.21246	0.041	0.032	0.019
28	25.91204	-0.36360	-2.31255	0.041	0.030	0.020
29	24.40089	-7.16845	3.65003	0.040	0.029	0.025
30	25.91201	-7.71701	-0.21248	0.041	0.031	0.018
31	26.31450	-8.99620	-0.21238	0.047	0.038	0.027
32	26.31434	-8.99606	-2.01250	0.047	0.038	0.027
33	25.50161	-8.99183	-0.21261	0.041	0.038	0.020
34	25.91201	-7.36288	-2.31252	0.040	0.029	0.020
35	25.50168	1.52393	-0.21240	0.059	0.048	0.038
36	24.40086	-0.47898	3.64997	0.042	0.030	0.025
37	25.50161	1.52391	-2.01260	0.048	0.042	0.029
38	21.96451	2.95400	-0.21248	0.046	0.039	0.025
39	21.96451	2.95400	-2.01248	0.046	0.039	0.025
40	21.96451	-0.09298	-2.31248	Fixed		
41	21.96181	-7.71316	-2.31248	0.043	0.032	0.020
42	21.96180	-10.45713	-0.21246	0.045	0.040	0.025

43	18.38960	1.52450	-0.21248	0.045	0.046	0.025
44	18.38960	1.52450	-2.01248	0.045	0.046	0.026
45	17.98725	-0.09400	-0.21248	0.041	0.038	0.020
46	17.98725	-0.36897	-2.31248	0.041	0.037	0.020
47	17.98320	-7.71400	-0.21248	0.041	0.036	0.020
48	17.98725	-7.36666	-2.31248	0.041	0.035	0.020
49	14.64795	-0.09400	-0.21248	0.043	0.037	0.022
50	14.64869	-0.37015	-2.31248	0.043	0.037	0.021
51	14.03909	-7.71298	-2.31248	0.042	0.035	0.020
52	14.03772	-10.45720	-0.21248	0.044	0.041	0.024
53	10.46480	-8.99280	-0.21248	0.040	0.045	0.021
54	9.77084	-0.09400	-0.21248	0.042	0.038	0.021
55	9.77189	-0.40185	-2.31248	0.042	0.038	0.021
56	9.16087	-7.71400	-0.21248	0.040	0.037	0.018
57	9.16229	-7.36460	-2.31248	0.040	0.035	0.020
58	4.89711	-0.47905	3.64999	0.037	0.038	0.029
59	4.89566	-0.09400	-0.21248	0.038	0.041	0.018
60	4.89566	-0.09400	-2.01248	0.038	0.040	0.020
61	4.89711	-0.36924	-2.31248	0.037	0.039	0.021
62	4.28178	-7.16841	3.64999	0.039	0.037	0.025
63	4.28178	-7.71400	-0.21248	0.040	0.038	0.019
64	4.28178	-7.71400	-2.01248	0.040	0.037	0.019
65	4.28178	-7.32617	-2.31248	0.040	0.037	0.019
66	3.12420	0.28745	-0.21248	0.042	0.044	0.025
67	2.46395	-0.81765	-2.31248	0.037	0.036	0.018
68	-2.52177	-6.60018	-2.31248	0.042	0.038	0.021
69	-3.58140	-6.56405	-0.21248	0.042	0.039	0.021
70	-2.44977	-0.38542	-2.31248	0.038	0.039	0.019
71	-3.58140	-0.37340	-0.21248	0.038	0.040	0.019
72	-4.46228	0.94740	-0.21248	0.037	0.038	0.019
73	-4.46228	0.94740	-2.01248	0.037	0.038	0.020
74	-9.35534	0.94740	-0.21248	0.037	0.040	0.021
75	-9.35534	1.66267	-2.31248	0.036	0.038	0.021
76	-14.21998	-0.11585	-0.21248	0.050	0.040	-
77	-14.41357	0.50501	-2.31248	0.044	0.042	0.026
78	-14.23660	4.40391	-2.31248	0.046	0.037	0.023
79	-15.29080	4.43410	-0.21248	0.048	0.039	0.026
80	-6.90481	6.68576	-2.31248	0.040	0.034	0.019
81	-6.90481	7.19580	-2.01248	0.041	0.035	0.020
82	-6.90367	7.19580	-0.21248	0.041	0.035	0.019
83	-2.02798	7.19580	-2.01248	0.040	0.040	0.020
84	-2.02798	7.19580	-0.21248	0.040	0.040	0.019
85	0.12700	7.82300	-0.21248	0.045	0.041	0.023
86	-0.95099	11.03425	-2.31248	0.051	0.043	0.026
87	0.12700	7.82300	3.64999	0.045	0.041	0.028

88	4.18998	8.47394	-2.31248	0.041	0.041	0.017
89	2.69980	5.37654	-2.31248	0.040	0.039	0.018
90	3.12420	4.48777	-0.21248	0.046	0.042	0.025
91	4.90440	5.64574	-0.21248	0.040	0.042	0.017
92	4.90440	5.64574	3.64999	0.040	0.042	0.024
93	11.42796	9.78458	-2.31248	0.052	0.054	0.024
94	12.01088	7.36814	3.64999	0.045	0.052	0.025
95	12.01088	7.36814	-0.21248	0.047	0.053	0.020
96	15.71166	12.81265	1.88999	0.054	0.061	0.023
97	15.71166	12.81265	0.08999	0.054	0.061	0.024
98	15.87523	10.93085	-0.21248	0.053	0.060	0.022
100	16.75270	8.51741	1.88999	0.048	0.062	0.020
101	16.75270	8.51741	0.08999	0.048	0.062	0.020
102	23.14217	13.21166	1.88999	0.051	0.072	0.016
103	23.14244	13.21052	0.08999	0.051	0.072	0.017
104	23.32671	12.45495	-0.21248	0.050	0.072	0.017
105	23.86431	10.23471	0.08999	0.047	0.073	0.017
106	23.86403	10.23585	1.88999	0.047	0.073	0.017
107	30.25170	14.93542	1.88999	0.052	0.086	0.016
108	30.25170	14.93542	0.08999	0.052	0.086	0.016
109	30.43528	14.17776	-0.21248	0.051	0.086	-
110	30.97219	11.96380	0.08999	0.048	0.087	0.017
111	30.97219	11.96380	1.88999	0.048	0.087	0.015
112	5.34663	16.56405	-2.31248	0.055	0.053	0.025
113	6.25042	16.94736	0.21246	0.058	0.057	0.030
114	0.47228	16.94940	-0.21248	0.058	0.054	0.031
115	0.59341	16.63442	-2.31248	0.057	0.053	0.029
116	-2.90143	15.39594	-2.31248	0.051	0.038	0.022
117	-3.23699	16.94736	-2.01248	0.055	0.041	0.025
118	-3.23699	16.94736	-0.21248	0.055	0.041	0.023
119	-11.59677	16.30441	-2.31248	0.056	0.042	0.026
120	-12.38099	16.94736	-2.01248	0.058	0.043	0.029
121	-12.38099	16.94940	-0.21248	0.058	0.043	0.029
122	-15.28876	11.46350	-0.21248	0.052	0.045	0.029
123	-15.28876	11.46350	-2.01248	0.052	0.045	0.030
124	-22.96367	1.83667	3.18477	0.041	0.055	0.014
125	-22.96367	1.83667	2.38477	0.041	0.055	0.014
126	-22.58930	-0.12601	2.08477	0.042	0.046	0.015
127	-22.02894	-2.01377	2.38477	0.045	0.052	0.015
128	-22.02894	-2.01377	3.18477	0.043	0.049	0.015
129	-24.88694	0.58640	3.53477	0.043	0.050	0.015
130	-24.88694	0.58640	2.93477	0.045	0.050	0.012
131	-24.30700	-1.78727	3.08477	0.041	0.051	0.012
132	-24.30698	-1.78726	3.48477	0.040	0.050	0.014
133	-22.86682	-4.31577	4.18477	0.041	0.050	0.016

134	-22.86682	-4.31577	2.38477	0.041	0.050	0.017
135	-23.14871	-2.51699	2.08477	0.042	0.050	-
136	-24.01275	-4.68806	2.08477	0.042	0.050	0.017
137	-25.25125	-5.15283	2.38477	0.049	0.058	0.022
138	-25.25125	-5.15283	4.18477	0.049	0.058	0.022
139	-26.25075	-2.26055	2.38477	0.045	0.054	0.018
140	-26.25075	-2.26055	4.18477	0.045	0.054	0.017
141	-27.64535	-3.61015	2.38477	0.044	0.057	0.017
142	-27.64535	-3.61015	4.18477	0.044	0.056	0.017
143	-28.94603	0.37156	2.38477	0.048	0.068	0.023
144	-28.94603	0.37156	4.18477	0.048	0.068	0.024
145	-29.79121	-0.61851	4.08477	0.044	0.058	0.016
146	-29.79121	-0.61851	3.68477	0.044	0.058	0.016
147	-29.54588	-0.13252	2.08477	0.045	0.058	0.019

B Azimuths calculations [23]

```
 Ellipsoid : GRS80 / WGS84  (NAD83)
  Equatorial axis,    a   =    6378137.0000
  Polar axis,         b   =    6356752.3141
  Inverse flattening, 1/f =  298.25722210088
  First  Station : 226013
    LAT =  41 50 11.29769 North
    LON =  88 15 57.51458 West
  Second Station : 225980
    LAT =  41 50 11.54870 North
    LON =  88 15 56.53608 West
  Forward azimuth        FAZ =  71  4  0.3159 From North
  Back azimuth           BAZ = 251  4  0.9685 From North
  Ellipsoidal distance     S =        23.8681 m
----------------------------------------------------------

  Ellipsoid : GRS80 / WGS84  (NAD83)
  Equatorial axis,    a   =    6378137.0000
  Polar axis,         b   =    6356752.3141
  Inverse flattening, 1/f =  298.25722210088
  First  Station : 225962
    LAT =  41 50 10.68833 North
    LON =  88 15 56.32880 West
  Second Station : 225993
    LAT =  41 50 11.91441 North
    LON =  88 15 57.39045 West
  Forward azimuth        FAZ = 327  4 30.4678 From North
  Back azimuth           BAZ = 147  4 29.7596 From North
  Ellipsoidal distance     S =        45.0663 m
----------------------------------------------------------

  Ellipsoid : GRS80 / WGS84  (NAD83)
  Equatorial axis,    a   =    6378137.0000
  Polar axis,         b   =    6356752.3141
  Inverse flattening, 1/f =  298.25722210088
  First  Station : 226053
    LAT =  41 50 10.30282 North
    LON =  88 15 56.91573 West
  Second Station : 226014
    LAT =  41 50 11.24659 North
    LON =  88 15 57.33914 West
  Forward azimuth        FAZ = 341 27  9.5168 From North
  Back azimuth           BAZ = 161 27  9.2344 From North
  Ellipsoidal distance     S =        30.7131 m
```

C Gyrotheodolite calculations

Table C.1: Gyrotheodolite check on Baseline 66598 - 66663

$277°4'56.0''$	Measured azimuths
$277°5'2.0''$	
$277°5'0.0''$	
$277°4'59.0''$	
$277°4'59.0''$	
$277°4'59.2''$	Azimuth measured
$-1.2''$	Laplace correction
$277°4'58.0''$	Geodetic Azimuth
$277°4'56.1''$	Azimuth from Coordinates
$-1.9''$	Difference

Table C.2: Baseline 226013 - 225980

$67°31'65.0''$	Measured azimuths
$67°31'59.0''$	
$67°31'61.0''$	
$67°31'62.0''$	
$67°31'61.0''$	
$67°31'61.6''$	Average Gyro eccentric
$3°31'59.4''$	Eccentric correction
$70°64'1.0''$	Azimuth measured
$-1.2''$	Laplace correction
$71°3'59.8''$	Geodetic Azimuth
$71°3'60.3''$	Azimuth from Coordinates
$0.5''$	Difference

Table C.3: Baseline 226980 - 225013

253°29′26.0″	Measured azimuths
253°29′24.0″	
253°29′25.0″	
253°29′25.0″	
253°29′27.0″	
253°29′25.4″	Average Gyro eccentric
−2°25′36.3″	Eccentric correction
251°3′49.1″	Azimuth measured
−1.2″	Laplace correction
251°3′47.8″	Geodetic Azimuth
251°4′1.0″	Azimuth from Coordinates
13.1″	Difference

Table C.4: Baseline 225962 - 225993

327°4′16.0″	Measured azimuths
327°4′23.0″	
327°4′23.0″	
327°4′20.0″	
327°4′19.0″	
327°4′20.2″	Average Gyro eccentric
−2.4″	Eccentric correction
327°4′17.8″	Azimuth measured
−1.2″	Laplace correction
327°4′16.6″	Geodetic Azimuth
327°4′30.5″	Azimuth from Coordinates
13.9″	Difference

Table C.5: Baseline 226053 - 226014

341°26′53.0″	Measured azimuths
341°26′58.0″	
341°26′53.0″	
341°26′54.0″	
341°26′59.0″	
341°26′55.4″	Average Gyro eccentric
2.3″	Eccentric correction
341°26′57.7″	Azimuth measured
−1.2″	Laplace correction
341°26′56.5″	Geodetic Azimuth
341°27′9.5″	Azimuth from Coordinates
13.0″	Difference

Table C.6: Baseline 226014 - 226053

161°26′58.0″	Measured azimuths
161°26′58.0″	
161°26′58.0″	
161°26′58.0″	
161°26′58.0″	
161°26′58.0″	Average Gyro eccentric
−0.5″	Eccentric correction
161°26′57.5″	Azimuth measured
−1.2″	Laplace correction
161°26′56.2″	Geodetic Azimuth
161°27′9.2″	Azimuth from Coordinates
13.0″	Difference

D Coordinates and St. Dev. of the network points

Point	Adjusted						Expected		
number	X [m]	Y [m]	Z [m]	σ_X [mm]	σ_Y [mm]	σ_Z [mm]	σ_X [mm]	σ_Y [mm]	σ_Z [mm]
186004	30390.56777	30134.62785	222.03576	Fixed			Fixed		
186005	30304.75106	30165.05734	222.07882	Fixed			0.107	0.046	0.071
225806	30415.73562	30121.37374	222.07157	0.201	0.285	0.586	0.194	0.294	0.291
225816	30402.73065	30127.73641	223.69083	0.245	0.194	0.319	0.215	0.187	0.160
225817	30404.59491	30130.72896	224.06452	0.278	0.187	0.329	0.239	0.187	0.165
225819	30403.88367	30129.67119	222.05807	0.158	0.168	0.323	0.142	0.172	0.162
225825	30393.61190	30131.21607	223.67467	0.119	0.100	0.149	0.109	0.092	0.078
225828	30394.23194	30132.93153	222.04711	0.104	0.079	0.140	0.094	0.078	0.075
225857	30389.05010	30132.83037	223.54330	0.076	0.095	0.087	0.074	0.084	0.051
225858	30389.89745	30135.66227	223.93828	0.08	0.044	0.073	0.074	0.044	0.046
225859	30389.89090	30135.66707	222.53834	0.114	0.045	0.084	0.102	0.044	0.057
225861	30384.45137	30134.45898	223.54371	0.092	0.064	0.097	0.084	0.064	0.055
225862	30385.29459	30137.30307	223.96774	0.091	0.061	0.088	0.084	0.059	0.051
225863	30385.29437	30137.30276	222.52456	0.091	0.061	0.097	0.084	0.059	0.052
225864	30384.91251	30136.18814	222.06364	0.106	0.056	0.096	0.096	0.057	0.060
225874	30370.63555	30139.34673	223.54044	0.133	0.117	0.171	0.122	0.120	0.086
225875	30371.47826	30142.19793	223.91426	0.138	0.111	0.175	0.126	0.116	0.087
225876	30371.46944	30142.20037	222.46830	0.138	0.111	0.172	0.126	0.116	0.087
225877	30371.05189	30141.10612	222.03866	0.101	0.110	0.172	0.100	0.115	0.087
225887	30354.53518	30145.05795	223.54590	0.141	0.140	0.184	0.131	0.145	0.092
225888	30355.39518	30147.90071	223.88219	0.135	0.148	0.188	0.128	0.149	0.094
225889	30355.36814	30147.90485	222.56009	0.135	0.148	0.189	0.128	0.149	0.095
225890	30355.00739	30146.83553	222.03866	0.095	0.138	0.186	0.096	0.143	0.094
225900	30340.93797	30149.87446	223.52413	0.122	0.142	0.191	0.127	0.146	0.092
225901	30341.99638	30152.65308	223.98407	0.128	0.137	0.190	0.129	0.144	0.092
225902	30341.98768	30152.65732	222.49242	0.128	0.137	0.190	0.129	0.144	0.092
225903	30341.58880	30151.56576	222.04170	0.106	0.136	0.190	0.114	0.142	0.092
225913	30327.16568	30154.76023	223.52699	0.126	0.117	0.184	0.129	0.125	0.088
225914	30328.20038	30157.53806	224.03259	0.118	0.122	0.182	0.124	0.127	0.085
225915	30328.19440	30157.53917	222.58660	0.120	0.123	0.182	0.125	0.128	0.087
225916	30327.75666	30156.44793	222.04450	0.087	0.115	0.180	0.099	0.122	0.086
225926	30313.20886	30159.71921	223.53456	0.101	0.081	0.161	0.117	0.086	0.072
225927	30314.23033	30162.50678	224.07911	0.104	0.078	0.165	0.118	0.086	0.075
225928	30314.25797	30162.49530	222.55077	0.108	0.078	0.168	0.120	0.086	0.076
225929	30313.81957	30161.31649	222.06038	0.102	0.075	0.164	0.115	0.082	0.075
225935	30303.51821	30161.54067	224.24993	0.098	0.068	0.164	0.115	0.076	0.074
225936	30305.04287	30165.76617	223.88327	0.080	0.070	0.161	0.105	0.076	0.072
225937	30305.01358	30165.78185	222.55313	0.089	0.077	0.164	0.112	0.082	0.074

225939	30298.92338	30163.17329	224.26300	0.090	0.077	0.164	0.111	0.087	0.070
225940	30300.43747	30167.39221	224.03849	0.094	0.071	0.159	0.115	0.080	0.070
225941	30300.45507	30167.38694	222.51175	0.095	0.072	0.162	0.115	0.081	0.072
225942	30300.78409	30165.90036	222.07068	0.080	0.069	0.158	0.103	0.077	0.070
225948	30289.39230	30165.42245	224.20784	0.113	0.125	0.176	0.125	0.133	0.079
225949	30291.26845	30170.65778	223.88365	0.090	0.112	0.154	0.115	0.118	0.066
225952	30285.64984	30169.50819	224.13369	0.105	0.146	0.159	0.123	0.153	0.068
225953	30286.67599	30172.28276	224.11227	0.095	0.134	0.149	0.119	0.142	0.062
225954	30286.68234	30172.27501	222.48956	0.114	0.138	0.156	0.130	0.146	0.066
225955	30286.27881	30171.25951	222.06593	0.103	0.139	0.149	0.122	0.146	0.063
225957	30282.00910	30170.78698	224.22861	0.095	0.173	0.137	0.118	0.178	0.056
225958	30283.01167	30173.58609	224.08762	0.099	0.157	0.133	0.124	0.165	0.052
225959	30283.02415	30173.57349	222.55886	0.108	0.157	0.136	0.129	0.165	0.057
225960	30277.10272	30172.51822	224.12066	0.100	0.200	0.131	0.123	0.209	0.051
225961	30278.07862	30175.33327	224.19811	0.108	0.197	0.132	0.132	0.205	0.052
225962	30274.27903	30175.21772	222.06439	0.124	0.224	0.144	0.141	0.233	0.060
225963	30270.21218	30174.96612	224.07839	0.125	0.255	0.148	0.142	0.266	0.060
225964	30271.17910	30177.77228	224.19187	0.136	0.249	0.148	0.154	0.259	0.060
225965	30267.00189	30178.16236	222.05724	0.138	0.279	0.134	0.155	0.290	0.053
225966	30262.83012	30177.57588	223.00160	0.127	0.312	0.123	0.148	0.324	0.045
225967	30262.82861	30177.57466	224.15884	0.127	0.313	0.123	0.148	0.325	0.045
225968	30264.83043	30181.80425	224.15364	0.156	0.302	0.132	0.176	0.313	0.049
225969	30262.83434	30179.86448	219.78822	0.170	0.319	0.181	0.179	0.332	0.079
225970	30258.71282	30179.05218	221.74536	0.145	0.346	0.129	0.162	0.359	0.045
225971	30258.70990	30179.05234	223.93671	0.204	0.388	0.411	0.207	0.403	0.199
225972	30256.99941	30181.99950	219.77712	0.160	0.359	0.128	0.178	0.373	0.048
225973	30251.81104	30181.48867	221.89580	0.155	0.402	0.117	0.174	0.417	0.035
225974	30251.81265	30181.49527	223.85258	0.193	0.410	0.197	0.200	0.425	0.087
225975	30251.02720	30184.10529	219.78188	0.171	0.408	0.117	0.190	0.424	0.037
225976	30249.43350	30186.45741	221.98871	0.188	0.423	0.118	0.208	0.439	0.036
225977	30249.42747	30186.45931	223.15439	0.201	0.434	0.205	0.218	0.447	0.093
225978	30257.15422	30188.53372	219.77526	0.211	0.361	0.139	0.228	0.375	0.052
225979	30259.07902	30190.13282	221.97104	0.228	0.348	0.152	0.244	0.361	0.059
225980	30254.08046	30193.09384	219.78696	0.250	0.395	0.178	0.269	0.406	0.077
225981	30251.56013	30193.34899	219.77641	0.244	0.408	0.132	0.264	0.421	0.049
225982	30246.16707	30187.73323	221.76833	0.206	0.453	0.151	0.225	0.469	0.056
225983	30251.13027	30195.32462	221.96018	0.262	0.410	0.133	0.282	0.425	0.045
225984	30251.12961	30195.32140	220.59057	0.262	0.411	0.134	0.281	0.426	0.046
225985	30245.53120	30191.75651	219.78747	0.234	0.456	0.132	0.253	0.473	0.042
225986	30242.31676	30190.24308	221.64932	0.222	0.488	0.145	0.242	0.505	0.052
225987	30243.48190	30200.32261	221.92463	0.305	0.475	0.139	0.326	0.492	0.047
225988	30243.48635	30200.31859	220.61757	0.305	0.475	0.139	0.326	0.492	0.047
225989	30241.65300	30199.29498	219.79563	0.296	0.491	0.134	0.316	0.508	0.044
225990	30238.08907	30197.32862	221.97258	0.278	0.520	0.129	Fixed		
225991	30238.09582	30197.32805	220.40924	0.278	0.520	0.125	0.298	0.539	0.040

225992	30234.63156	30190.60951	219.78354	0.224	0.549	0.129	0.243	0.569	0.042
225993	30231.61526	30189.73994	221.66311	0.230	0.576	0.170	0.245	0.597	0.070
225994	30231.77758	30188.02287	219.78834	0.199	0.574	0.146	0.219	0.595	0.054
225995	30232.57425	30187.14460	221.97356	0.199	0.568	0.146	0.217	0.589	0.053
225996	30237.27420	30185.36164	221.69935	0.183	0.526	0.129	0.202	0.545	0.041
225997	30239.57912	30187.35587	219.78566	0.195	0.506	0.121	0.215	0.524	0.037
225998	30242.73873	30189.14865	220.22599	0.210	0.480	0.126	0.229	0.497	0.042
225999	30242.73345	30189.14702	221.96739	0.209	0.481	0.126	0.229	0.498	0.042
226000	30241.37853	30182.66731	221.98274	0.161	0.491	0.119	0.181	0.508	0.036
226001	30241.38109	30182.66713	220.32919	0.161	0.491	0.120	0.181	0.509	0.038
226002	30244.55793	30184.07609	219.78724	0.171	0.463	0.116	0.190	0.480	0.035
226003	30246.82270	30186.47668	221.75181	0.188	0.444	0.117	0.208	0.461	0.035
226004	30246.82852	30186.48313	220.16743	0.188	0.444	0.119	0.208	0.461	0.038
226005	30249.80193	30181.73168	221.99653	0.156	0.419	0.116	0.176	0.435	0.035
226006	30248.18835	30180.09547	219.78744	0.143	0.433	0.117	0.164	0.449	0.037
226007	30247.42573	30178.08206	221.96809	0.134	0.439	0.114	0.155	0.455	0.035
226008	30241.47699	30181.06477	221.99790	0.153	0.490	0.121	0.173	0.508	0.040
226009	30240.16318	30177.64509	219.78764	0.133	0.505	0.123	0.153	0.522	0.047
226010	30238.38788	30176.35647	222.00855	0.129	0.518	0.115	0.148	0.536	0.039
226011	30238.05632	30175.84089	220.07096	0.128	0.520	0.115	0.147	0.539	0.040
226012	30237.84194	30174.62389	221.64363	0.133	0.522	0.113	0.149	0.541	0.036
226013	30241.15412	30173.02823	219.78002	0.116	0.493	0.117	0.136	0.511	0.040
226014	30245.30842	30174.29810	219.78705	0.123	0.458	0.125	0.142	0.474	0.044
226015	30248.63310	30176.59855	220.20137	0.137	0.430	0.120	0.153	0.446	0.045
226016	30248.62979	30176.60370	222.00284	0.134	0.430	0.120	0.152	0.445	0.041
226017	30243.93370	30170.65370	221.93831	0.117	0.470	0.123	0.136	0.487	0.043
226018	30243.93781	30170.65603	220.16983	0.117	0.470	0.124	0.136	0.487	0.043
226019	30248.39242	30176.18075	225.42948	0.131	0.432	0.122	0.148	0.447	0.046
226020	30244.78632	30170.68197	225.43512	0.119	0.463	0.125	0.137	0.479	0.047
226021	30246.31020	30169.75330	219.78291	0.122	0.450	0.127	0.139	0.466	0.047
226022	30250.47052	30174.93114	219.78213	0.125	0.416	0.125	0.144	0.430	0.047
226023	30250.58606	30170.88922	219.78328	0.126	0.416	0.144	0.142	0.431	0.056
226024	30252.70745	30173.93044	221.96185	0.122	0.398	0.123	0.141	0.413	0.044
226025	30248.02993	30167.98473	221.98514	0.123	0.435	0.121	0.140	0.451	0.043
226026	30248.44989	30166.06019	221.94809	0.136	0.435	0.137	0.150	0.450	0.054
226027	30256.79119	30171.26964	221.96524	0.121	0.366	0.125	0.139	0.379	0.045
226028	30250.63066	30163.01000	221.98458	0.150	0.380	0.118	0.163	0.431	0.056
226029	30259.46498	30169.52790	222.03135	0.125	0.351	0.143	0.143	0.362	0.057
226030	30255.58575	30163.05284	221.96521	0.146	0.373	0.112	0.158	0.387	0.038
226031	30257.74416	30164.45522	219.78970	0.130	0.358	0.116	0.146	0.371	0.046
226032	30260.78820	30170.49987	221.73860	0.123	0.341	0.139	0.142	0.352	0.054
226033	30260.79496	30170.49637	220.19901	0.123	0.340	0.140	0.141	0.351	0.056
226034	30262.68682	30166.93721	219.78416	0.123	0.322	0.115	0.140	0.334	0.040
226035	30264.56877	30169.83375	220.17844	0.123	0.316	0.138	0.141	0.325	0.057
226036	30264.57182	30169.83864	222.02880	0.139	0.319	0.178	0.153	0.329	0.077

226037	30257.27639	30158.67214	221.95189	0.171	0.366	0.133	0.183	0.378	0.051
226038	30258.96202	30161.42623	219.78547	0.057	0.436	0.250	0.162	0.361	0.037
226039	30261.87645	30158.94531	221.94936	0.167	0.328	0.117	0.179	0.340	0.039
226040	30264.88172	30163.11627	219.78837	0.144	0.307	0.117	0.156	0.318	0.043
226041	30266.21215	30165.11378	221.97875	0.129	0.298	0.109	0.145	0.309	0.033
226042	30267.44894	30166.18137	220.21242	0.129	0.296	0.124	0.144	0.305	0.044
226043	30267.45274	30166.18205	222.01342	0.129	0.299	0.124	0.145	0.307	0.044
226044	30271.21299	30165.50424	220.19241	0.140	0.274	0.136	0.152	0.283	0.051
226045	30271.21407	30165.51960	222.03026	0.139	0.273	0.136	0.152	0.282	0.051
226046	30269.19160	30162.65146	219.78922	0.144	0.281	0.113	0.158	0.291	0.037
226047	30265.71818	30156.96419	219.77929	0.182	0.302	0.116	0.193	0.312	0.037
226048	30261.69827	30157.37179	220.28316	0.187	0.332	0.140	0.197	0.344	0.053
226049	30261.70367	30157.36991	221.89781	0.186	0.332	0.140	0.196	0.344	0.053
226050	30263.17762	30154.48895	221.90283	0.204	0.321	0.131	0.215	0.332	0.048
226051	30268.13123	30153.92302	220.16132	0.204	0.291	0.117	0.215	0.300	0.038
226052	30268.12920	30153.92389	221.92357	0.204	0.294	0.118	0.215	0.302	0.040
226053	30271.01598	30157.49120	219.78773	0.179	0.271	0.117	0.190	0.280	0.035
226054	30268.94287	30154.34314	221.96461	0.201	0.286	0.116	0.212	0.295	0.037
226055	30272.80316	30160.82070	221.96958	0.160	0.266	0.135	0.172	0.274	0.047
226056	30273.33948	30162.33880	220.24872	0.163	0.270	0.166	0.174	0.277	0.069
226057	30273.33482	30162.34312	221.96875	0.165	0.271	0.166	0.175	0.279	0.069
226058	30275.79644	30162.51084	220.16212	0.149	0.253	0.124	0.162	0.260	0.037
226059	30275.81041	30162.51629	221.96062	0.149	0.254	0.124	0.162	0.261	0.037
226060	30275.73242	30158.39959	219.78750	0.171	0.251	0.121	0.183	0.259	0.033
226061	30272.06530	30152.75037	219.77881	0.218	0.268	0.127	0.228	0.277	0.041
226062	30276.21493	30154.15118	219.78563	0.205	0.250	0.123	0.215	0.258	0.040
226063	30274.67452	30150.58447	221.96091	0.237	0.259	0.134	0.247	0.267	0.044
226064	30276.56641	30152.78022	221.94441	0.216	0.252	0.122	Fixed		
226065	30279.22987	30156.85256	221.96945	0.183	0.242	0.120	0.194	0.249	0.032
226066	30279.88652	30159.84151	220.90253	0.163	0.241	0.122	0.175	0.248	0.034
226067	30279.88983	30159.84570	221.97933	0.165	0.241	0.123	0.177	0.248	0.035
226068	30255.71060	30171.38705	219.78069	0.128	0.377	0.142	0.144	0.390	0.056
226069	30252.25742	30165.74596	219.78422	0.133	0.401	0.126	0.147	0.415	0.049
226070	30235.85545	30193.87917	221.99283	0.250	0.538	0.123	0.269	0.558	0.036
226071	30277.29978	30156.71635	225.18471	0.193	0.249	0.157	0.200	0.257	0.067
226072	30266.69690	30166.66766	220.32254	0.135	0.299	0.130	0.147	0.308	0.055
226073	30266.70010	30166.66205	222.00156	0.137	0.300	0.125	0.149	0.310	0.048
226074	30260.95796	30157.86184	221.96563	0.177	0.339	0.135	0.190	0.351	0.052
226075	30274.32750	30152.15516	225.18371	0.223	0.259	0.152	0.233	0.267	0.064
226076	30261.12058	30160.01752	224.96010	0.160	0.333	0.119	0.172	0.345	0.045
226077	30264.71535	30165.51825	224.90804	0.126	0.308	0.113	0.142	0.319	0.041
226078	30226.57480	30193.38859	224.99576	0.247	0.622	0.179	0.265	0.644	0.047
226079	30224.32997	30193.43132	225.31219	0.240	0.641	0.179	0.266	0.664	0.046
226080	30223.51916	30191.13279	225.37109	0.228	0.649	0.178	0.246	0.672	0.046
226081	30225.36234	30189.69277	224.88132	0.216	0.633	0.180	0.234	0.655	0.048

226082	30225.49064	30191.70180	224.16581	0.233	0.631	0.179	0.250	0.653	0.048
226083	30223.77363	30190.26695	224.16505	0.222	0.647	0.178	0.239	0.670	0.048
226084	30221.38056	30186.65107	224.15963	0.210	0.834	0.260	0.213	0.693	0.052
226085	30222.53153	30187.68499	224.65270	0.201	0.659	0.179	0.219	0.682	0.049
226086	30222.54609	30187.69929	226.23224	0.202	0.658	0.179	0.219	0.681	0.050
226087	30219.70678	30191.40538	224.56654	0.231	0.684	0.178	0.248	0.708	0.050
226088	30219.72107	30191.45688	226.26725	0.231	0.684	0.179	0.249	0.708	0.051
226089	30218.17029	30193.02268	224.83477	0.254	0.698	0.179	0.263	0.723	0.050
226090	30218.16486	30193.02648	226.32493	0.246	0.698	0.180	0.263	0.723	0.052
226091	30218.97618	30195.32630	226.05994	0.264	0.691	0.179	0.282	0.715	0.051
226092	30219.70506	30195.06948	224.16154	0.263	0.685	0.181	0.281	0.709	0.055
226093	30221.54816	30191.82266	224.52497	0.234	0.667	0.179	0.252	0.691	0.051
226094	30221.55786	30191.83125	226.25374	0.234	0.667	0.179	0.252	0.691	0.051
226095	30249.02994	30178.31072	229.63918	0.173	0.438	0.240	0.187	0.452	0.110
226096	30254.36232	30175.93953	229.43199	0.151	0.391	0.186	0.167	0.404	0.086
226097	30260.99979	30171.59977	229.44334	0.127	0.340	0.125	0.143	0.351	0.054
226098	30267.62218	30167.27349	229.69518	0.136	0.299	0.136	0.149	0.307	0.060
226099	30277.42844	30151.00681	227.53777	0.254	0.285	0.176	0.260	0.286	0.079
226100	30264.30055	30156.02603	229.65334	0.208	0.327	0.205	0.217	0.335	0.090
226101	30258.22426	30159.26012	229.65279	0.172	0.359	0.124	0.183	0.371	0.051
226102	30254.86625	30162.23787	229.79090	0.150	0.380	0.118	0.162	0.394	0.047
226103	30248.24596	30166.54286	229.71694	0.132	0.436	0.141	0.146	0.451	0.065
226104	30241.59454	30170.89346	229.72819	0.143	0.494	0.175	0.150	0.512	0.083
226105	30236.02474	30177.31913	229.59412	0.262	0.570	0.317	0.250	0.586	0.153
226106	30239.33204	30182.00094	229.73591	0.197	0.525	0.334	0.211	0.542	0.153

E Points details

Point number	Fixed	Location	Monument type
186004	XYZ	MC4 Tunnel	Dijak Bolt
186005	XY	MC4 Tunnel	Dijak Bolt
225806	-	MC4 Tunnel	Dijak Bolt
225816	-	MC4 Tunnel	Magnet Ring
225817	-	MC4 Tunnel	Magnet Ring
225819	-	MC4 Tunnel	Dijak Bolt
225825	-	MC4 Tunnel	Magnet Ring
225828	-	MC4 Tunnel	Dijak Bolt
225857	-	MC4 Tunnel	Magnet Ring
225858	-	MC4 Tunnel	Magnet Ring
225859	-	MC4 Tunnel	Magnet Ring
225861	-	MC4 Tunnel	Magnet Ring
225862	-	MC4 Tunnel	Magnet Ring
225863	-	MC4 Tunnel	Magnet Ring
225864	Z	MC4 Tunnel	Dijak Bolt
225874	-	MC4 Tunnel	Magnet Ring
225875	-	MC4 Tunnel	Magnet Ring
225876	-	MC4 Tunnel	Magnet Ring
225877	Z	MC4 Tunnel	Dijak Bolt
225887	-	MC4 Tunnel	Magnet Ring
225888	-	MC4 Tunnel	Magnet Ring
225889	-	MC4 Tunnel	Magnet Ring
225890	-	MC4 Tunnel	Dijak Bolt
225900	Z	MC4 Tunnel	Magnet Ring
225901	Z	MC4 Tunnel	Magnet Ring
225902	-	MC4 Tunnel	Magnet Ring
225903	Z	MC4 Tunnel	Dijak Bolt
225913	Z	MC4 Tunnel	Magnet Ring
225914	Z	MC4 Tunnel	Magnet Ring
225915	-	MC4 Tunnel	Magnet Ring
225916	Z	MC4 Tunnel	Dijak Bolt
225926	Z	MC4 Tunnel	Magnet Ring
225927	Z	MC4 Tunnel	Magnet Ring
225928	-	MC4 Tunnel	Magnet Ring
225929	Z	MC4 Tunnel	Dijak Bolt
225935	Z	MC4 Tunnel	Magnet Ring
225936	Z	MC4 Tunnel	Magnet Ring
225937	-	MC4 Tunnel	Magnet Ring
225939	Z	MC4 Tunnel	Magnet Ring
225940	Z	MC4 Tunnel	Magnet Ring
225941	-	MC4 Tunnel	Magnet Ring
225942	Z	MC4 Tunnel	Dijak Bolt

225948	-	MC4 Tunnel	Magnet Ring
225949	-	MC4 Tunnel	Magnet Ring
225952	Z	MC4 Tunnel	Magnet Ring
225953	Z	MC4 Tunnel	Magnet Ring
225954	-	MC4 Tunnel	Magnet Ring
225955	Z	MC4 Tunnel	Dijak Bolt
225957	-	MC4 Tunnel	Magnet Ring
225958	-	MC4 Tunnel	Magnet Ring
225959	-	MC4 Tunnel	Magnet Ring
225960	Z	MC4 Tunnel	Magnet Ring
225961	Z	MC4 Tunnel	Magnet Ring
225962	Z	MC4 Tunnel	Dijak Bolt
225963	-	MC4 Tunnel	Magnet Ring
225964	Z	MC4 Tunnel	Magnet Ring
225965	Z	MC4 Tunnel	Dijak Bolt
225966	-	MC4 Tunnel	Magnet Ring
225967	Z	MC4 Tunnel	Magnet Ring
225968	-	MC4 Tunnel	Magnet Ring
225969	Z	MC4 Tunnel	Dijak Bolt
225970	Z	MC4 Tunnel	Dijak Bolt
225971	-	MC4 Tunnel	Magnet Ring
225972	Z	MC4 Tunnel	Dijak Bolt
225973	Z	Mu2e Lower level	Magnet Ring
225974	-	Mu2e Lower level	Magnet Ring
225975	Z	Mu2e Lower level	Dijak Bolt
225976	Z	Mu2e Lower level	Magnet Ring
225977	-	Mu2e Lower level	Magnet Ring
225978	Z	Mu2e Lower level	Dijak Bolt
225979	Z	Mu2e Lower level	Magnet Ring
225980	Z	Mu2e Lower level	Dijak Bolt
225981	Z	Mu2e Lower level	Dijak Bolt
225982	Z	Mu2e Lower level	Magnet Ring
225983	Z	Mu2e Lower level	Magnet Ring
225984	-	Mu2e Lower level	Magnet Ring
225985	Z	Mu2e Lower level	Dijak Bolt
225986	Z	Mu2e Lower level	Magnet Ring
225987	Z	Mu2e Lower level	Magnet Ring
225988	-	Mu2e Lower level	Magnet Ring
225989	Z	Mu2e Lower level	Dijak Bolt
225990	Z	Mu2e Lower level	Magnet Ring
225991	-	Mu2e Lower level	Magnet Ring
225992	Z	Mu2e Lower level	Dijak Bolt
225993	-	Mu2e Lower level	Magnet Ring
225994	Z	Mu2e Lower level	Dijak Bolt
225995	-	Mu2e Lower level	Magnet Ring

225996	Z	Mu2e Lower level	Magnet Ring
225997	Z	Mu2e Lower level	Dijak Bolt
225998	-	Mu2e Lower level	Magnet Ring
225999	Z	Mu2e Lower level	Magnet Ring
226000	-	Mu2e Lower level	Magnet Ring
226001	-	Mu2e Lower level	Magnet Ring
226002	Z	Mu2e Lower level	Dijak Bolt
226003	Z	Mu2e Lower level	Magnet Ring
226004	-	Mu2e Lower level	Magnet Ring
226005	-	Mu2e Lower level	Magnet Ring
226006	Z	Mu2e Lower level	Dijak Bolt
226007	Z	Mu2e Lower level	Magnet Ring
226008	Z	Mu2e Lower level	Magnet Ring
226009	Z	Mu2e Lower level	Dijak Bolt
226010	Z	Mu2e Lower level	Magnet Ring
226011	-	Mu2e Lower level	Magnet Ring
226012	-	Mu2e Lower level	Magnet Ring
226013	Z	Mu2e Lower level	Dijak Bolt
226014	Z	Mu2e Lower level	Dijak Bolt
226015	-	Mu2e Lower level	Magnet Ring
226016	Z	Mu2e Lower level	Magnet Ring
226017	Z	Mu2e Lower level	Magnet Ring
226018	-	Mu2e Lower level	Magnet Ring
226019	-	Mu2e Lower level	Magnet Ring
226020	-	Mu2e Lower level	Magnet Ring
226021	Z	Mu2e Lower level	Dijak Bolt
226022	Z	Mu2e Lower level	Dijak Bolt
226023	Z	Mu2e Lower level	Dijak Bolt
226024	Z	Mu2e Lower level	Magnet Ring
226025	Z	Mu2e Lower level	Magnet Ring
226026	-	Mu2e Lower level	Magnet Ring
226027	Z	Mu2e Lower level	Magnet Ring
226028	Z	Mu2e Lower level	Magnet Ring
226029	-	Mu2e Lower level	Magnet Ring
226030	-	Mu2e Lower level	Magnet Ring
226031	Z	Mu2e Lower level	Dijak Bolt
226032	-	Mu2e Lower level	Magnet Ring
226033	-	Mu2e Lower level	Magnet Ring
226034	Z	Mu2e Lower level	Dijak Bolt
226035	-	Mu2e Lower level	Magnet Ring
226036	-	Mu2e Lower level	Magnet Ring
226037	-	Mu2e Lower level	Magnet Ring
226038	Z	Mu2e Lower level	Dijak Bolt
226039	Z	Mu2e Lower level	Magnet Ring
226040	Z	Mu2e Lower level	Dijak Bolt

226041	Z	Mu2e Lower level	Magnet Ring
226042	-	Mu2e Lower level	Magnet Ring
226043	Z	Mu2e Lower level	Magnet Ring
226044	-	Mu2e Lower level	Magnet Ring
226045	Z	Mu2e Lower level	Magnet Ring
226046	Z	Mu2e Lower level	Dijak Bolt
226047	Z	Mu2e Lower level	Dijak Bolt
226048	-	Mu2e Lower level	Magnet Ring
226049	Z	Mu2e Lower level	Magnet Ring
226050	Z	Mu2e Lower level	Magnet Ring
226051	-	Mu2e Lower level	Magnet Ring
226052	Z	Mu2e Lower level	Magnet Ring
226053	Z	Mu2e Lower level	Dijak Bolt
226054	Z	Mu2e Lower level	Magnet Ring
226055	Z	Mu2e Lower level	Magnet Ring
226056	-	Mu2e Lower level	Magnet Ring
226057	Z	Mu2e Lower level	Magnet Ring
226058	-	Mu2e Lower level	Magnet Ring
226059	Z	Mu2e Lower level	Magnet Ring
226060	Z	Mu2e Lower level	Dijak Bolt
226061	Z	Mu2e Lower level	Dijak Bolt
226062	Z	Mu2e Lower level	Dijak Bolt
226063	Z	Mu2e Lower level	Magnet Ring
226064	Z	Mu2e Lower level	Magnet Ring
226065	Z	Mu2e Lower level	Magnet Ring
226066	-	Mu2e Lower level	Magnet Ring
226067	Z	Mu2e Lower level	Magnet Ring
226068	Z	Mu2e Lower level	Dijak Bolt
226069	Z	Mu2e Lower level	Dijak Bolt
226070	Z	Mu2e Lower level	Magnet Ring
226071	-	Mu2e Lower level	Magnet Ring
226072	-	Mu2e Lower level	Magnet Ring
226073	-	Mu2e Lower level	Magnet Ring
226074	-	Mu2e Lower level	Magnet Ring
226075	-	Mu2e Lower level	Magnet Ring
226076	-	Mu2e Lower level	Magnet Ring
226077	-	Mu2e Lower level	Magnet Ring
226078	Z	Extinct. M. Encl.	Magnet Ring
226079	-	Extinct. M. Encl.	Magnet Ring
226080	-	Extinct. M. Encl.	Magnet Ring
226081	-	Extinct. M. Encl.	Magnet Ring
226082	-	Extinct. M. Encl.	Dijak Bolt
226083	Z	Extinct. M. Encl.	Dijak Bolt
226084	Z	Extinct. M. Encl.	Dijak Bolt
226085	-	Extinct. M. Encl.	Magnet Ring

226086	-	Extinct. M. Encl.	Magnet Ring
226087	-	Extinct. M. Encl.	Magnet Ring
226088	Z	Extinct. M. Encl.	Magnet Ring
226089	-	Extinct. M. Encl.	Magnet Ring
226090	-	Extinct. M. Encl.	Magnet Ring
226091	Z	Extinct. M. Encl.	Magnet Ring
226092	Z	Extinct. M. Encl.	Dijak Bolt
226093	-	Extinct. M. Encl.	Magnet Ring
226094	-	Extinct. M. Encl.	Magnet Ring
226095	-	Mu2e High Bay	Magnet Ring
226096	-	Mu2e High Bay	Magnet Ring
226097	-	Mu2e High Bay	Magnet Ring
226098	-	Mu2e High Bay	Magnet Ring
226099	Z	Mu2e High Bay	Magnet Ring
226100	-	Mu2e High Bay	Magnet Ring
226101	-	Mu2e High Bay	Magnet Ring
226102	-	Mu2e High Bay	Magnet Ring
226103	-	Mu2e High Bay	Magnet Ring
226104	-	Mu2e High Bay	Magnet Ring
226105	-	Mu2e High Bay	Magnet Ring
226106	-	Mu2e High Bay	Magnet Ring

F Pure 3D Cartesian

Point number	X [m]	Y [m]	Z [m]	σ_X [mm]	σ_Y [mm]	σ_Z [mm]
186004	30390.5683	30134.6281	222.0367	0.218	0.596	0.591
186005	30304.7511	30165.0572	222.0811	0.048	0.153	0.248
225806	30415.7361	30121.3741	222.0720	0.333	0.822	0.758
225816	30402.7311	30127.7367	223.6911	0.268	0.700	0.722
225817	30404.5953	30130.7293	224.0648	0.275	0.760	0.651
225819	30403.8841	30129.6715	222.0585	0.262	0.706	0.684
225825	30393.6123	30131.2163	223.6750	0.245	0.602	0.645
225828	30394.2324	30132.9318	222.0474	0.218	0.630	0.611
225857	30389.0505	30132.8306	223.5435	0.234	0.572	0.602
225858	30389.8978	30135.6625	223.9385	0.202	0.587	0.577
225859	30389.8913	30135.6673	222.5387	0.210	0.589	0.584
225861	30384.4518	30134.4592	223.5439	0.210	0.544	0.583
225862	30385.2950	30137.3033	223.9680	0.206	0.546	0.561
225863	30385.2948	30137.3030	222.5248	0.194	0.540	0.565
225864	30384.9129	30136.1884	222.0640	0.208	0.531	0.583
225874	30370.6359	30139.3469	223.5407	0.184	0.439	0.515
225875	30371.4786	30142.1981	223.9144	0.163	0.443	0.489
225876	30371.4698	30142.2006	222.4685	0.152	0.447	0.509
225877	30371.0522	30141.1063	222.0386	0.153	0.421	0.495
225887	30354.5355	30145.0581	223.5461	0.128	0.326	0.484
225888	30355.3955	30147.9008	223.8824	0.119	0.363	0.451
225889	30355.3684	30147.9050	222.5602	0.134	0.351	0.488
225890	30355.0077	30146.8356	222.0384	0.135	0.363	0.463
225900	30340.9382	30149.8745	223.5244	0.120	0.273	0.412
225901	30341.9967	30152.6532	223.9842	0.078	0.268	0.434
225902	30341.9879	30152.6574	222.4923	0.081	0.272	0.413
225903	30341.5889	30151.5658	222.0413	0.077	0.267	0.403
225913	30327.1659	30154.7602	223.5272	0.076	0.204	0.350
225914	30328.2006	30157.5381	224.0327	0.067	0.212	0.339
225915	30328.1945	30157.5391	222.5865	0.072	0.220	0.346
225916	30327.7568	30156.4479	222.0436	0.073	0.204	0.349
225926	30313.2091	30159.7192	223.5348	0.060	0.169	0.279
225927	30314.2306	30162.5067	224.0792	0.058	0.188	0.293
225928	30314.2581	30162.4952	222.5506	0.036	0.181	0.293
225929	30313.8195	30161.3164	222.0596	0.049	0.180	0.272
225935	30303.5185	30161.5406	224.2503	0.050	0.147	0.237
225936	30305.0431	30165.7661	223.8834	0.028	0.152	0.261
225937	30305.0136	30165.7817	222.5523	0.047	0.155	0.257
225939	30298.9237	30163.1732	224.2636	0.043	0.147	0.229
225940	30300.4377	30167.3921	224.0384	0.027	0.144	0.229
225941	30300.4551	30167.3867	222.5117	0.038	0.151	0.234
225942	30300.7841	30165.9001	222.0693	0.042	0.146	0.224

225948	30289.3926	30165.4223	224.2083	0.048	0.132	0.177
225949	30291.2686	30170.6576	223.8831	0.034	0.125	0.193
225952	30285.6501	30169.5080	224.1340	0.039	0.118	0.176
225953	30286.6762	30172.2826	224.1119	0.024	0.100	0.177
225954	30286.6823	30172.2748	222.4895	0.024	0.113	0.173
225955	30286.2787	30171.2592	222.0653	0.034	0.102	0.164
225957	30282.0094	30170.7867	224.2289	0.028	0.099	0.166
225958	30283.0119	30173.5859	224.0877	0.029	0.096	0.161
225959	30283.0242	30173.5732	222.5572	0.027	0.104	0.164
225960	30277.1007	30172.5173	224.1219	0.026	0.078	0.152
225961	30278.0789	30175.3329	224.1974	0.018	0.087	0.141
225962	30274.2789	30175.2175	222.0639	0.029	0.082	0.139
225963	30270.2124	30174.9659	224.0788	0.024	0.063	0.150
225964	30271.1793	30177.7721	224.1910	0.025	0.074	0.123
225965	30267.0017	30178.1622	222.0568	0.013	0.064	0.113
225966	30262.8302	30177.5757	223.0016	0.015	0.043	0.107
225967	30262.8289	30177.5746	224.1592	0.018	0.056	0.106
225968	30264.8306	30181.8040	224.1533	0.025	0.047	0.088
225969	30262.8339	30179.8643	219.7878	0.037	0.055	0.105
225970	30258.7127	30179.0521	221.7450	0.023	0.039	0.076
225971	30258.7101	30179.0525	223.9365	0.092	0.118	0.120
225972	30256.9989	30181.9994	219.7765	0.030	0.039	0.065
225973	30251.8109	30181.4887	221.8957	0.012	0.022	0.027
225974	30251.8129	30181.4953	223.8523	0.036	0.035	0.053
225975	30251.0268	30184.1053	219.7819	0.021	0.021	0.032
225976	30249.4335	30186.4574	221.9886	0.025	0.019	0.026
225977	30249.4277	30186.4594	223.1554	0.041	0.038	0.042
225978	30257.1539	30188.5337	219.7759	0.036	0.051	0.076
225979	30259.0790	30190.1328	221.9700	0.037	0.039	0.079
225980	30254.0802	30193.0938	219.7866	0.040	0.030	0.066
225981	30251.5599	30193.3489	219.7759	0.041	0.028	0.051
225982	30246.1670	30187.7333	221.7691	0.017	0.032	0.027
225983	30251.1304	30195.3246	221.9600	0.044	0.024	0.045
225984	30251.1295	30195.3214	220.5895	0.047	0.022	0.051
225985	30245.5309	30191.7566	219.7873	0.045	0.029	0.047
225986	30242.3168	30190.2433	221.6495	0.038	0.021	0.038
225987	30243.4821	30200.3227	221.9245	0.057	0.027	0.056
225988	30243.4863	30200.3187	220.6171	0.061	0.021	0.056
225989	30241.6529	30199.2950	219.7954	0.061	0.034	0.064
225990	30238.0892	30197.3288	221.9724	0.050	0.027	0.048
225991	30238.0957	30197.3282	220.4085	0.058	0.024	0.048
225992	30234.6314	30190.6098	219.7832	0.026	0.029	0.053
225993	30231.6153	30189.7402	221.6629	0.033	0.045	0.073
225994	30231.7773	30188.0231	219.7886	0.023	0.048	0.072
225995	30232.5742	30187.1448	221.9743	0.028	0.026	0.066

225996	30237.2741	30185.3618	221.6994	0.018	0.022	0.049
225997	30239.5788	30187.3560	219.7863	0.027	0.022	0.037
225998	30242.7385	30189.1488	220.2261	0.031	0.020	0.035
225999	30242.7335	30189.1471	221.9671	0.022	0.010	0.025
226000	30241.3785	30182.6674	221.9827	0.018	0.015	0.024
226001	30241.3808	30182.6673	220.3295	0.023	0.018	0.028
226002	30244.5576	30184.0762	219.7878	0.022	0.011	0.017
226003	30246.8227	30186.4767	221.7517	0.024	0.023	0.022
226004	30246.8283	30186.4832	220.1679	0.025	0.017	0.024
226005	30249.8019	30181.7317	221.9962	0.008	0.018	0.024
226006	30248.1879	30180.0955	219.7875	0.047	0.043	0.044
226007	30247.4256	30178.0821	221.9671	0.017	0.025	0.031
226008	30241.4769	30181.0649	221.9974	0.020	0.009	0.016
226009	30240.1627	30177.6451	219.7876	0.016	0.024	0.032
226010	30238.3878	30176.3566	222.0084	0.013	0.024	0.030
226011	30238.0559	30175.8411	220.0709	0.015	0.028	0.022
226012	30237.8417	30174.6241	221.6439	0.011	0.018	0.039
226013	30241.1535	30173.0285	219.7807	0.023	0.013	0.039
226014	30245.3079	30174.2982	219.7877	0.023	0.021	0.023
226015	30248.6327	30176.5986	220.2015	0.014	0.013	0.024
226016	30248.6296	30176.6038	222.0021	0.011	0.018	0.016
226017	30243.9335	30170.6538	221.9381	0.036	0.010	0.036
226018	30243.9373	30170.6562	220.1705	0.038	0.012	0.033
226019	30248.3928	30176.1808	225.4289	0.018	0.022	0.015
226020	30244.7866	30170.6821	225.4352	0.024	0.022	0.034
226021	30246.3096	30169.7534	219.7834	0.028	0.016	0.027
226022	30250.4701	30174.9312	219.7822	0.025	0.032	0.045
226023	30250.5855	30170.8892	219.7838	0.024	0.023	0.032
226024	30252.7073	30173.9305	221.9611	0.019	0.034	0.041
226025	30248.0297	30167.9848	221.9851	0.037	0.016	0.057
226026	30248.4496	30166.0603	221.9494	0.034	0.025	0.058
226027	30256.7910	30171.2696	221.9643	0.023	0.031	0.056
226028	30250.6303	30163.0100	221.9856	0.041	0.022	0.056
226029	30259.4648	30169.5278	222.0309	0.025	0.041	0.066
226030	30255.5855	30163.0528	221.9653	0.038	0.021	0.051
226031	30257.7436	30164.4551	219.7902	0.031	0.028	0.043
226032	30260.7880	30170.4998	221.7386	0.027	0.047	0.052
226033	30260.7945	30170.4963	220.1991	0.034	0.054	0.051
226034	30262.6863	30166.9370	219.7846	0.034	0.050	0.047
226035	30264.5683	30169.8336	220.1784	0.038	0.053	0.076
226036	30264.5716	30169.8385	222.0279	0.040	0.047	0.061
226037	30257.2760	30158.6721	221.9520	0.059	0.034	0.060
226038	30258.9614	30161.4262	219.7862	0.036	0.028	0.049
226039	30261.8761	30158.9452	221.9494	0.041	0.050	0.062
226040	30264.8812	30163.1161	219.7888	0.038	0.045	0.061

226041	30266.2119	30165.1136	221.9788	0.037	0.048	0.061
226042	30267.4484	30166.1812	220.2126	0.035	0.055	0.087
226043	30267.4525	30166.1818	222.0138	0.035	0.053	0.077
226044	30271.2125	30165.5040	220.1925	0.031	0.065	0.091
226045	30271.2138	30165.5193	222.0299	0.036	0.068	0.088
226046	30269.1909	30162.6513	219.7887	0.045	0.054	0.063
226047	30265.7176	30156.9640	219.7789	0.048	0.050	0.063
226048	30261.6976	30157.3717	220.2832	0.057	0.054	0.066
226049	30261.7033	30157.3698	221.8980	0.057	0.041	0.079
226050	30263.1772	30154.4888	221.9034	0.074	0.043	0.070
226051	30268.1305	30153.9228	220.1614	0.053	0.053	0.076
226052	30268.1288	30153.9238	221.9237	0.059	0.062	0.076
226053	30271.0152	30157.4909	219.7878	0.046	0.067	0.077
226054	30268.9424	30154.3431	221.9650	0.065	0.061	0.071
226055	30272.8028	30160.8204	221.9696	0.055	0.085	0.096
226056	30273.3389	30162.3385	220.2486	0.041	0.073	0.080
226057	30273.3345	30162.3428	221.9692	0.053	0.051	0.089
226058	30275.7959	30162.5105	220.1621	0.046	0.082	0.100
226059	30275.8101	30162.5159	221.9605	0.043	0.082	0.096
226060	30275.7317	30158.3993	219.7870	0.053	0.079	0.091
226061	30272.0645	30152.7502	219.7794	0.057	0.074	0.090
226062	30276.2142	30154.1510	219.7858	0.062	0.082	0.092
226063	30274.6739	30150.5842	221.9612	0.086	0.089	0.095
226064	30276.5659	30152.7799	221.9447	0.071	0.090	0.096
226065	30279.2294	30156.8521	221.9695	0.054	0.097	0.109
226066	30279.8860	30159.8410	220.9027	0.044	0.096	0.124
226067	30279.8894	30159.8452	221.9756	0.046	0.105	0.124
226068	30255.7101	30171.3870	219.7801	0.046	0.061	0.089
226069	30252.2568	30165.7460	219.7820	0.041	0.035	0.044
226070	30235.8556	30193.8793	221.9988	0.036	0.023	0.049
226071	30277.2998	30156.7160	225.1832	0.068	0.080	0.094
226072	30266.6964	30166.6675	220.3225	0.030	0.049	0.063
226073	30266.6998	30166.6618	222.0008	0.033	0.060	0.071
226074	30260.9576	30157.8617	221.9675	0.059	0.055	0.065
226075	30274.3275	30152.1548	225.1818	0.070	0.067	0.099
226076	30261.1206	30160.0174	224.9606	0.045	0.039	0.051
226077	30264.7155	30165.5181	224.9025	0.030	0.046	0.059
226078	30226.5753	30193.3890	224.9953	0.051	0.049	0.097
226079	30224.3305	30193.4317	225.3120	0.046	0.056	0.116
226080	30223.5197	30191.1332	225.3713	0.043	0.059	0.119
226081	30225.3628	30189.6931	224.8814	0.038	0.052	0.114
226082	30225.4909	30191.7021	224.1654	0.129	0.115	0.151
226083	30223.7740	30190.2673	224.1640	0.043	0.056	0.119
226084	30221.3815	30186.6526	224.1604	0.038	0.060	0.150
226085	30222.5319	30187.6854	224.6526	0.039	0.060	0.142

226086	30222.5467	30187.6997	226.2318	0.046	0.073	0.131
226087	30219.7073	30191.4058	224.5667	0.057	0.078	0.161
226088	30219.7219	30191.4574	226.2667	0.060	0.091	0.164
226089	30218.1708	30193.0231	224.8347	0.070	0.081	0.176
226090	30218.1656	30193.0269	226.3252	0.072	0.103	0.181
226091	30218.9769	30195.3266	226.0592	0.075	0.086	0.170
226092	30219.7058	30195.0693	224.1623	0.079	0.079	0.175
226093	30221.5486	30191.8231	224.5250	0.062	0.082	0.153
226094	30221.5585	30191.8317	226.2575	0.070	0.081	0.161
226095	30249.0308	30178.3107	229.6400	0.034	0.043	0.060
226096	30254.3631	30175.9395	229.4329	0.054	0.048	0.069
226097	30261.0006	30171.5996	229.4443	0.033	0.066	0.083
226098	30267.6230	30167.2733	229.6955	0.042	0.087	0.087
226099	30277.4289	30151.0064	227.5369	0.092	0.116	0.092
226100	30264.3012	30156.0257	229.6526	0.073	0.073	0.073
226101	30258.2249	30159.2600	229.6523	0.064	0.056	0.054
226102	30254.8670	30162.2378	229.7900	0.047	0.047	0.041
226103	30248.2468	30166.5429	229.7159	0.039	0.059	0.042
226104	30241.5954	30170.8936	229.7274	0.044	0.053	0.068
226105	30236.0257	30177.3194	229.5946	0.069	0.073	0.084
226106	30239.3329	30182.0010	229.7397	0.053	0.076	0.073

G USMN Graphs

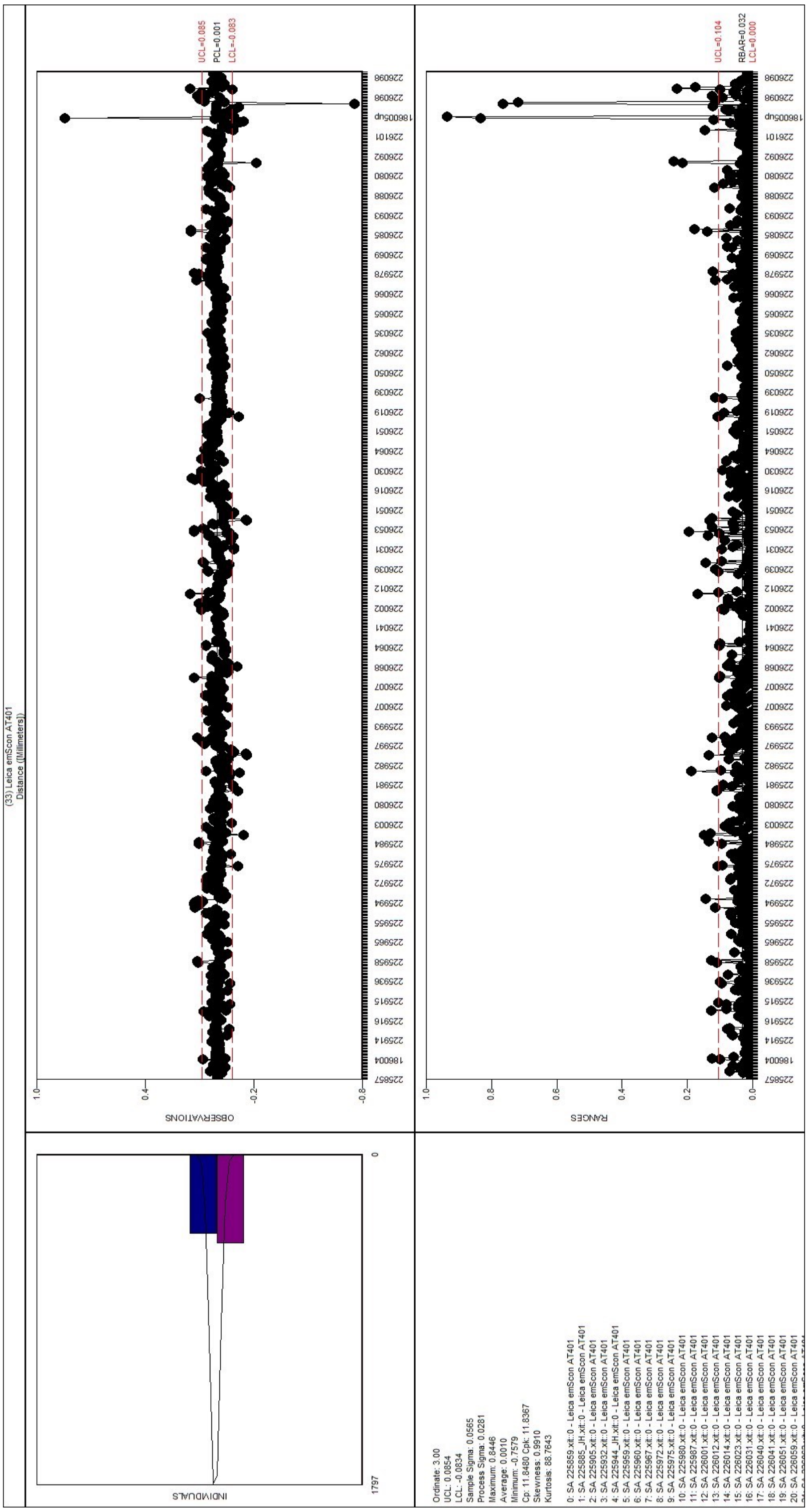

Figure G.1: USMN Best fit distance outliers

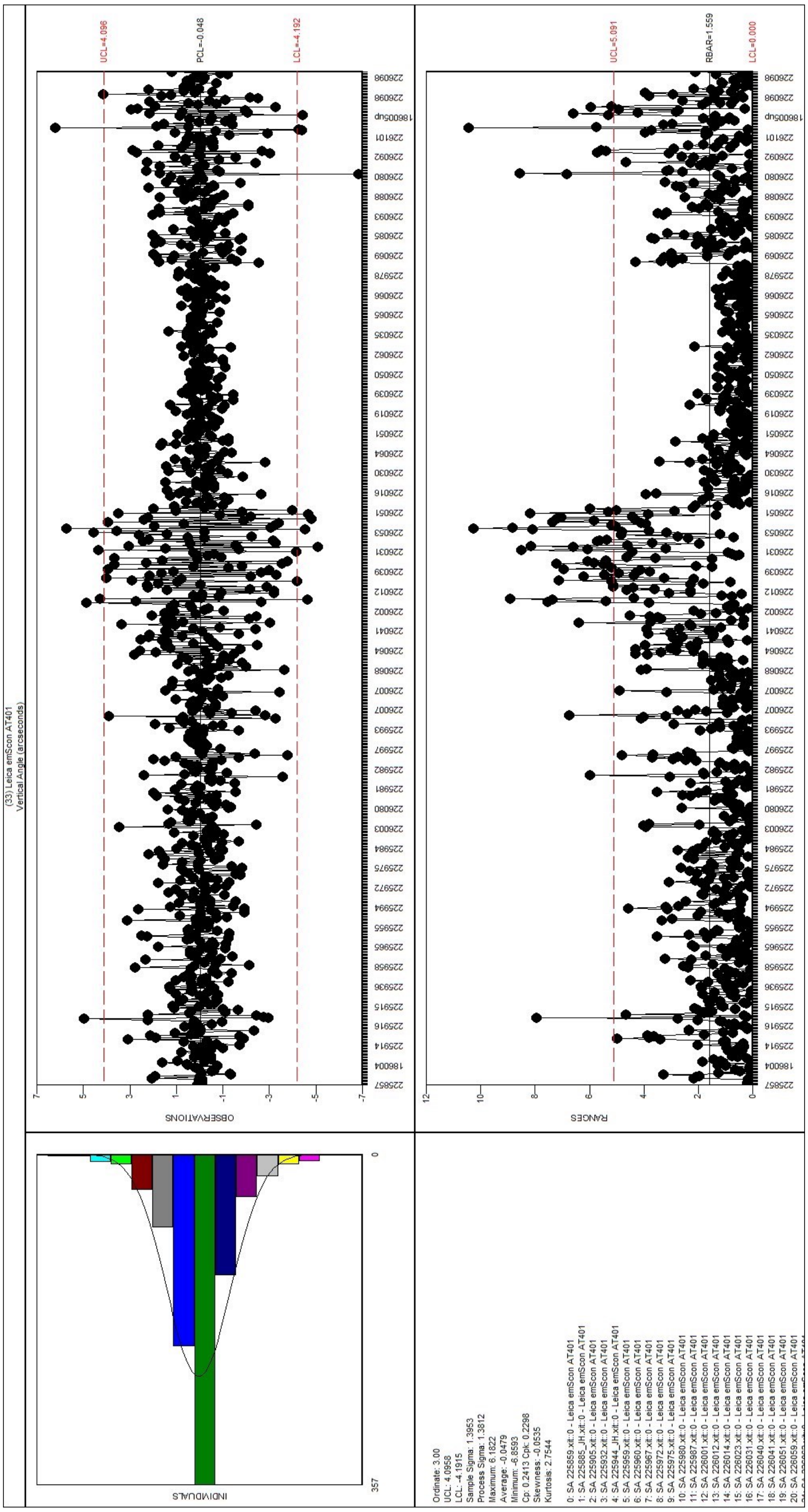

Figure G.2: USMN Best fit zenith angles outliers

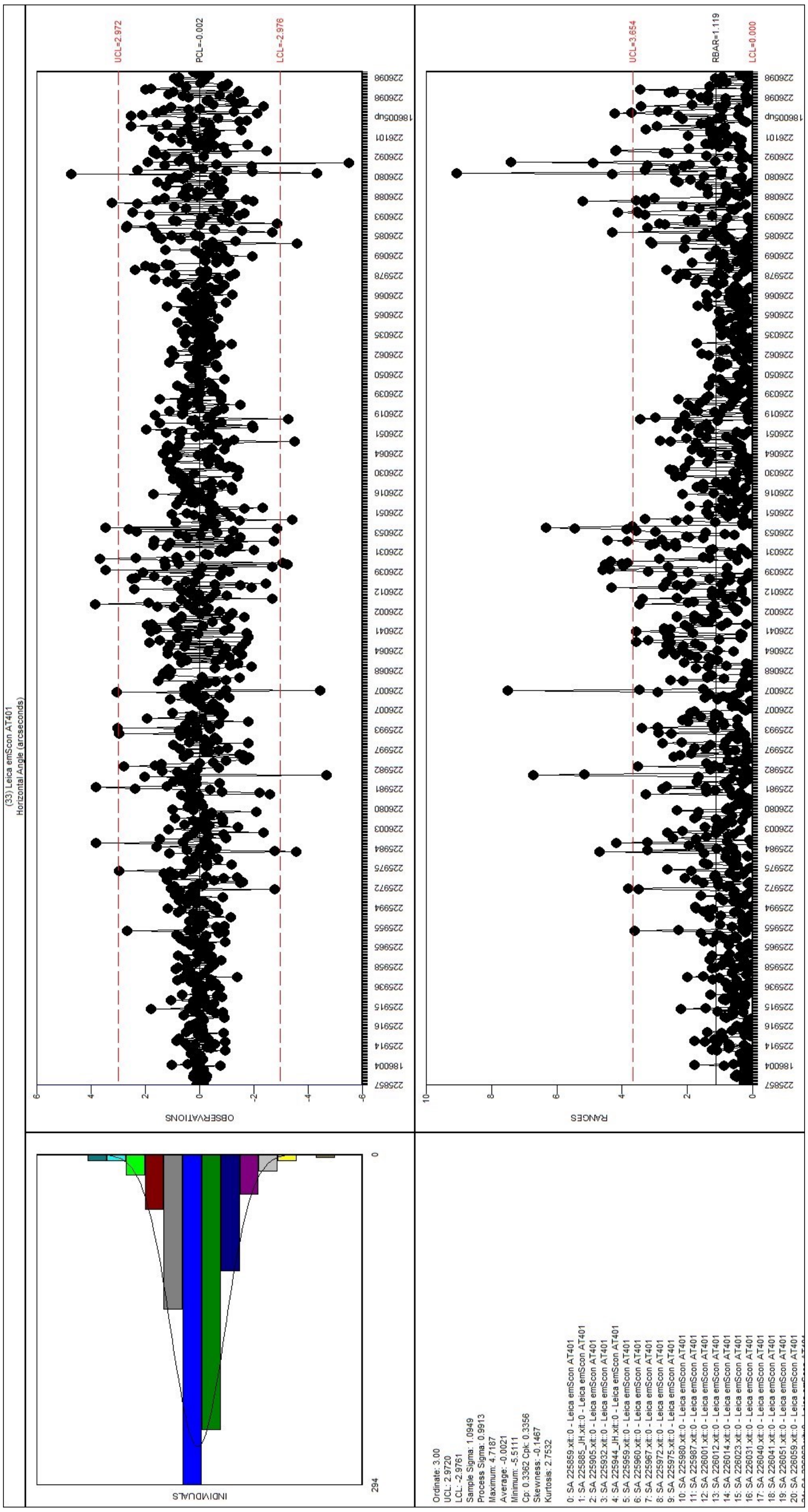

Figure G.3: USMN Best fit direction outliers

H USMN and FSCS:XYH comparison

Point number	Δ_X [mm]	Δ_Y [mm]	Δ_Z [mm]	Point number	Δ_X [mm]	Δ_Y [mm]	Δ_Z [mm]
186004	-0.767	-2.255	-2.585	226008	-0.221	1.167	-0.471
186005	-0.540	-0.641	2.213	226009	-0.703	1.057	0.011
225806	-1.075	-2.696	0.184	226010	-0.326	1.207	-0.144
225816	-0.975	-2.443	-0.008	226011	-0.716	1.292	-0.035
225817	-0.925	-2.482	0.003	226012	-0.508	1.296	0.307
225819	-0.914	-2.472	0.129	226013	-0.944	1.257	0.681
225825	-0.906	-2.279	0.029	226014	-0.836	1.053	0.660
225828	-0.861	-2.287	0.043	226015	-0.656	0.925	0.156
225857	-0.883	-2.183	-0.009	226016	-0.433	0.936	-0.714
225858	-0.828	-2.201	0.002	226017	-0.634	1.102	-0.124
225859	-0.826	-2.206	0.070	226018	-0.883	1.098	0.671
225861	-0.859	-2.102	0.004	226019	0.084	0.922	-0.531
225862	-0.804	-2.111	0.001	226020	-0.114	1.060	0.102
225863	-0.801	-2.110	-0.003	226021	-0.988	1.032	0.518
225864	-0.820	-2.110	0.107	226022	-0.778	0.829	0.136
225874	-0.770	-1.818	0.061	226023	-0.929	0.833	0.551
225875	-0.716	-1.835	-0.045	226024	-0.507	0.784	-0.682
225876	-0.734	-1.843	0.004	226025	-0.743	0.941	-0.042
225877	-0.793	-1.837	-0.299	226026	-0.816	0.928	1.321
225887	-0.679	-1.510	0.029	226027	-0.589	0.604	-0.914
225888	-0.607	-1.515	0.056	226028	-0.920	0.859	1.103
225889	-0.663	-1.539	-0.037	226029	-0.650	0.510	-0.445
225890	-0.666	-1.553	-0.463	226030	-0.838	0.661	0.082
225900	-0.632	-1.224	0.079	226031	-1.145	0.484	0.553
225901	-0.551	-1.217	-0.059	226032	-0.644	0.469	-0.006
225902	-0.653	-1.289	-0.238	226033	-0.848	0.457	0.122
225903	-0.707	-1.302	-0.528	226034	-1.042	0.324	0.426
225913	-0.554	-0.975	0.039	226035	-0.882	0.333	-0.043
225914	-0.459	-0.967	-0.060	226036	-0.635	0.316	-0.917
225915	-0.581	-1.034	-0.214	226037	-1.043	0.583	0.105
225916	-0.577	-1.077	-1.055	226038	-1.276	0.597	0.715
225926	-0.461	-0.712	0.103	226039	-1.048	0.427	0.107
225927	-0.353	-0.710	-0.051	226040	-1.083	0.327	0.454
225928	-0.496	-0.792	-0.279	226041	-0.798	0.241	0.028
225929	-0.674	-0.803	-0.901	226042	-1.013	0.240	0.137
225935	-0.310	-0.517	0.242	226043	-0.793	0.152	0.386
225936	-0.311	-0.563	0.026	226044	-1.038	0.106	0.028
225937	-0.455	-0.639	-0.882	226045	-0.784	0.077	-0.388
225939	-0.282	-0.443	0.493	226046	-1.258	0.168	-0.569
225940	-0.252	-0.484	-0.142	226047	-1.344	0.274	-0.338
225941	-0.431	-0.556	-0.122	226048	-1.347	0.455	0.052
225942	-0.514	-0.577	-1.431	226049	-1.130	0.428	0.255

225948	-0.248	-0.283	0.439	226050	-1.227	0.371	0.601
225949	-0.208	-0.319	-0.627	226051	-1.498	0.200	0.119
225952	-0.152	-0.220	0.305	226052	-1.247	0.331	0.105
225953	-0.153	-0.218	-0.407	226053	-1.477	0.057	0.080
225954	-0.398	-0.273	-0.072	226054	-1.306	0.360	0.349
225955	-0.469	-0.289	-0.659	226055	-0.984	-0.013	-0.020
225957	-0.118	-0.169	0.226	226056	-1.160	-0.019	-0.090
225958	-0.107	-0.158	0.025	226057	-0.929	-0.039	0.454
225959	-0.295	-0.207	-1.737	226058	-1.150	-0.139	-0.002
225960	-2.418	-0.753	1.238	226059	-0.913	-0.137	-0.131
225961	0.007	-0.237	-0.782	226060	-1.381	-0.107	-0.537
225962	-0.428	0.038	-0.572	226061	-1.646	0.089	0.572
225963	-0.111	0.161	0.386	226062	-1.515	0.003	0.133
225964	-0.005	0.125	-0.938	226063	-1.469	-0.057	0.266
225965	-0.419	0.222	-0.426	226064	-1.372	-0.096	0.273
225966	-0.197	0.372	0.032	226065	-1.196	-0.317	0.018
225967	0.018	0.433	0.330	226066	-1.186	-0.340	0.110
225968	0.078	0.259	-0.316	226067	-1.098	-0.335	-3.715
225969	-0.616	0.376	-0.477	226068	-0.867	0.643	-0.529
225970	-0.375	0.521	-0.339	226069	-1.095	0.771	-2.181
225971	-0.037	0.751	-0.167	226070	0.299	1.316	5.992
225972	-0.610	0.561	-0.572	226071	-0.675	-0.193	-1.542
225973	-0.249	0.795	-0.073	226072	-1.002	0.224	0.002
225974	0.067	0.776	-0.270	226073	-0.754	0.227	-0.778
225975	-0.469	0.816	0.036	226074	-1.096	0.451	1.926
225976	-0.025	0.881	-0.124	226075	-0.850	-0.097	-1.909
225977	0.157	0.910	1.032	226076	-0.594	0.442	0.481
225978	-0.347	0.625	0.586	226077	-0.386	0.306	-5.563
225979	0.045	0.557	-1.030	226078	0.668	1.764	-0.369
225980	-0.123	0.691	-0.418	226079	0.716	1.815	-0.113
225981	-0.090	0.675	-0.488	226080	0.604	1.839	0.266
225982	-0.041	0.992	0.761	226081	0.478	1.788	0.102
225983	0.273	0.830	-0.155	226082	0.363	1.719	-0.372
225984	0.058	0.787	-1.052	226083	0.384	1.805	-1.001
225985	-0.206	1.018	-0.132	226084	0.896	2.992	0.895
225986	0.052	1.188	0.157	226085	0.362	1.897	0.021
225987	0.474	1.037	-0.147	226086	0.601	1.909	-0.379
225988	0.266	1.048	-0.435	226087	0.604	1.940	0.241
225989	0.155	1.078	-0.236	226088	0.945	2.090	-0.466
225990	0.366	1.259	-0.164	226089	0.669	1.963	0.000
225991	0.106	1.274	-0.725	226090	0.895	1.967	0.366
225992	-0.128	1.481	-0.291	226091	0.914	1.861	-0.709
225993	0.035	1.517	-0.147	226092	0.959	1.387	0.829
225994	-0.253	1.532	0.311	226093	0.529	1.916	0.109
225995	-0.024	1.471	0.785	226094	0.776	1.935	3.792

225996	-0.128	1.304	0.131	226095	0.670	0.845	0.793
225997	-0.338	1.207	0.633	226096	0.553	0.672	0.963
225998	-0.182	1.107	0.099	226097	0.444	0.427	0.918
225999	0.063	1.092	-0.297	226098	0.323	0.190	0.355
226000	-0.179	1.141	0.002	226099	-0.349	-0.204	-0.890
226001	-0.430	1.155	0.348	226100	-0.111	0.175	-0.703
226002	-0.453	1.040	0.618	226101	0.025	0.541	-0.458
226003	-0.071	0.967	-0.124	226102	0.198	0.631	-0.915
226004	-0.300	0.964	0.457	226103	0.338	0.870	-0.999
226005	-0.211	0.864	-0.354	226104	0.497	1.178	-0.714
226006	-0.608	0.939	0.104	226105	0.729	1.417	0.495
226007	-0.385	0.948	-0.935	226106	0.785	1.114	3.838

I Ellipsoidal Coordinates in GCS

Point ID	φ (N)	λ (W)	h [m]	N [m]	H [m]
186004	41°50′7.320 785″	88°15′53.462 142″	189.081770	-32.780909	221.86268
186005	41°50′9.818 013″	88°15′55.564 848″	189.124490	-32.781249	221.90574
225806	41°50′6.478 243″	88°15′52.961 727″	189.117726	-32.780763	221.89849
225816	41°50′6.901 241″	88°15′53.233 357″	190.736916	-32.780833	223.51775
225817	41°50′6.939 951″	88°15′53.089 590″	191.110574	-32.780865	223.89144
225819	41°50′6.927 318″	88°15′53.142 185″	189.104138	-32.780851	221.88499
225825	41°50′7.172 859″	88°15′53.450 172″	190.720718	-32.780871	223.50159
225828	41°50′7.204 057″	88°15′53.383 022″	189.093139	-32.780890	221.87403
225857	41°50′7.305 523″	88°15′53.562 033″	190.589328	-32.780891	223.37022
225858	41°50′7.360 563″	88°15′53.457 176″	190.984279	-32.780920	223.76520
225859	41°50′7.360 816″	88°15′53.457 270″	189.584339	-32.780920	222.36526
225861	41°50′7.439 292″	88°15′53.674 766″	190.589722	-32.780907	223.37063
225862	41°50′7.494 725″	88°15′53.569 722″	191.013723	-32.780936	223.79466
225863	41°50′7.494 722″	88°15′53.569 738″	189.570543	-32.780936	222.35148
225864	41°50′7.474 029″	88°15′53.612 654″	189.109636	-32.780923	221.89056
225874	41°50′7.841 043″	88°15′54.013 583″	190.586398	-32.780961	223.36736
225875	41°50′7.896 667″	88°15′53.908 365″	190.960186	-32.780994	223.74118
225876	41°50′7.896 906″	88°15′53.908 600″	189.514225	-32.780994	222.29522
225877	41°50′7.877 448″	88°15′53.952 183″	189.084598	-32.780981	221.86558
225887	41°50′8.309 614″	88°15′54.408 017″	190.591795	-32.781024	223.37282
225888	41°50′8.364 676″	88°15′54.302 438″	190.928052	-32.781057	223.70911
225889	41°50′8.365 324″	88°15′54.303 247″	189.605952	-32.781057	222.38701
225890	41°50′8.345 360″	88°15′54.344 228″	189.084535	-32.781044	221.86558
225900	41°50′8.705 162″	88°15′54.741 311″	190.569970	-32.781080	223.35105
225901	41°50′8.754 609″	88°15′54.630 703″	191.029878	-32.781111	223.81099
225902	41°50′8.754 891″	88°15′54.630 886″	189.538228	-32.781111	222.31934
225903	41°50′8.735 127″	88°15′54.673 762″	189.087521	-32.781098	221.86862
225913	41°50′9.105 988″	88°15′55.078 703″	190.572772	-32.781137	223.35391
225914	41°50′9.155 890″	88°15′54.968 924″	191.078345	-32.781164	223.85951
225915	41°50′9.156 039″	88°15′54.969 097″	189.632355	-32.781164	222.41352
225916	41°50′9.137 063″	88°15′55.013 287″	189.090267	-32.781152	221.87142
225926	41°50′9.512 380″	88°15′55.420 410″	190.580287	-32.781192	223.36148
225927	41°50′9.562 797″	88°15′55.310 818″	191.124810	-32.781219	223.90603
225928	41°50′9.561 950″	88°15′55.310 186″	189.596470	-32.781219	222.37769
225929	41°50′9.540 759″	88°15′55.356 749″	189.106093	-32.781206	221.88730
225935	41°50′9.753 289″	88°15′55.701 206″	191.295635	-32.781214	224.07685
225936	41°50′9.830 189″	88°15′55.535 890″	190.928933	-32.781256	223.71019
225937	41°50′9.831 176″	88°15′55.536 466″	189.598793	-32.781256	222.38005
225939	41°50′9.887 082″	88°15′55.813 701″	191.308688	-32.781231	224.08992
225940	41°50′9.964 026″	88°15′55.648 922″	191.084133	-32.781276	223.86541
225941	41°50′9.963 539″	88°15′55.648 464″	189.557393	-32.781276	222.33867
225942	41°50′9.919 109″	88°15′55.677 181″	189.116342	-32.781257	221.89760

225948	41°50′10.135 669″	88°15′56.077 587″	191.253504	-32.781255	224.03476
225949	41°50′10.231 205″	88°15′55.873 201″	190.929256	-32.781313	223.71057
225952	41°50′10.314 763″	88°15′56.095 223″	191.179307	-32.781302	223.96061
225953	41°50′10.364 755″	88°15′55.985 821″	191.157860	-32.781330	223.93919
225954	41°50′10.364 431″	88°15′55.985 813″	189.535150	-32.781329	222.31648
225955	41°50′10.346 695″	88°15′56.026 806″	189.111531	-32.781318	221.89285
225957	41°50′10.420 397″	88°15′56.184 758″	191.274215	-32.781315	224.05553
225958	41°50′10.471 487″	88°15′56.075 499″	191.133196	-32.781343	223.91454
225959	41°50′10.470 916″	88°15′56.075 413″	189.604437	-32.781343	222.38578
225960	41°50′10.562 954″	88°15′56.305 206″	191.166245	-32.781334	223.94758
225961	41°50′10.614 985″	88°15′56.196 426″	191.243663	-32.781366	224.02503
225962	41°50′10.688 331″	88°15′56.328 800″	189.109946	-32.781363	221.89131
225963	41°50′10.763 582″	88°15′56.473 919″	191.123945	-32.781364	223.90531
225964	41°50′10.815 567″	88°15′56.365 684″	191.237397	-32.781392	224.01879
225965	41°50′10.909 360″	88°15′56.497 331″	189.102761	-32.781399	221.88416
225966	41°50′10.978 197″	88°15′56.655 010″	190.047128	-32.781391	222.82852
225967	41°50′10.978 196″	88°15′56.655 094″	191.204368	-32.781391	223.98576
225968	41°50′11.045 619″	88°15′56.473 434″	191.199121	-32.781438	223.98056
225969	41°50′11.036 342″	88°15′56.593 424″	186.833722	-32.781417	219.61514
225970	41°50′11.098 424″	88°15′56.755 457″	188.790871	-32.781408	221.57228
225971	41°50′11.098 487″	88°15′56.755 552″	190.982221	-32.781408	223.76363
225972	41°50′11.207 815″	88°15′56.734 624″	186.822599	-32.781440	219.60404
225973	41°50′11.298 987″	88°15′56.924 860″	188.941285	-32.781434	221.72272
225974	41°50′11.299 123″	88°15′56.924 628″	190.898065	-32.781434	223.67950
225975	41°50′11.381 300″	88°15′56.881 279″	186.827336	-32.781464	219.60880
225976	41°50′11.473 144″	88°15′56.872 352″	189.034138	-32.781491	221.81563
225977	41°50′11.473 313″	88°15′56.872 507″	190.199818	-32.781491	222.98131
225978	41°50′11.370 959″	88°15′56.553 930″	186.820671	-32.781508	219.60218
225979	41°50′11.373 001″	88°15′56.445 511″	189.016432	-32.781527	221.79796
225980	41°50′11.548 698″	88°15′56.536 080″	186.832321	-32.781558	219.61388
225981	41°50′11.605 792″	88°15′56.614 978″	186.821767	-32.781562	219.60333
225982	41°50′11.571 187″	88°15′56.949 233″	188.813747	-32.781502	221.59525
225983	41°50′11.664 689″	88°15′56.576 562″	189.005518	-32.781581	221.78710
225984	41°50′11.664 620″	88°15′56.576 671″	187.635908	-32.781581	220.41749
225985	41°50′11.686 319″	88°15′56.862 852″	186.832843	-32.781547	219.61439
225986	41°50′11.712 350″	88°15′57.012 847″	188.694708	-32.781531	221.47624
225987	41°50′11.945 415″	88°15′56.702 597″	188.969913	-32.781636	221.75155
225988	41°50′11.945 224″	88°15′56.702 553″	187.662853	-32.781636	220.44449
225989	41°50′11.955 988″	88°15′56.792 410″	186.840922	-32.781627	219.62255
225990	41°50′11.977 512″	88°15′56.966 457″	189.017891	-32.781608	221.79950
225991	41°50′11.977 362″	88°15′56.966 242″	187.454551	-32.781608	220.23616
225992	41°50′11.875 973″	88°15′57.264 481″	186.828921	-32.781538	219.61046
225993	41°50′11.914 408″	88°15′57.390 449″	188.708499	-32.781530	221.49003
225994	41°50′11.867 461″	88°15′57.431 026″	186.833749	-32.781510	219.61526
225995	41°50′11.829 119″	88°15′57.427 500″	189.018979	-32.781500	221.80048

225996	41°50′11.689 392″	88°15′57.315 463″	188.744788	-32.781481	221.52627
225997	41°50′11.693 855″	88°15′57.183 503″	186.831078	-32.781501	219.61258
225998	41°50′11.676 032″	88°15′57.027 873″	187.271391	-32.781519	220.05291
225999	41°50′11.676 097″	88°15′57.028 097″	189.012791	-32.781519	221.79431
226000	41°50′11.538 434″	88°15′57.248 158″	189.028210	-32.781449	221.80966
226001	41°50′11.538 378″	88°15′57.248 076″	187.374660	-32.781449	220.15611
226002	41°50′11.510 444″	88°15′57.102 164″	186.832695	-32.781464	219.61416
226003	41°50′11.526 052″	88°15′56.960 661″	188.797239	-32.781490	221.57873
226004	41°50′11.526 100″	88°15′56.960 290″	187.212859	-32.781490	219.99435
226005	41°50′11.345 508″	88°15′56.986 691″	189.042010	-32.781439	221.82345
226006	41°50′11.336 274″	88°15′57.085 517″	186.832936	-32.781423	219.61436
226007	41°50′11.300 357″	88°15′57.165 518″	189.013607	-32.781402	221.79501
226008	41°50′11.495 683″	88°15′57.287 832″	189.043384	-32.781435	221.82482
226009	41°50′11.435 053″	88°15′57.424 341″	186.833161	-32.781398	219.61456
226010	41°50′11.437 909″	88°15′57.519 337″	189.054082	-32.781387	221.83547
226011	41°50′11.431 448″	88°15′57.544 460″	187.116497	-32.781382	219.89788
226012	41°50′11.404 787″	88°15′57.584 426″	188.689182	-32.781367	221.47055
226013	41°50′11.297 688″	88°15′57.514 576″	186.825588	-32.781351	219.60694
226014	41°50′11.246 590″	88°15′57.339 144″	186.832607	-32.781363	219.61397
226015	41°50′11.238 370″	88°15′57.164 268″	187.246903	-32.781386	220.02829
226016	41°50′11.238 568″	88°15′57.164 243″	189.048373	-32.781386	221.82976
226017	41°50′11.181 465″	88°15′57.483 757″	188.983905	-32.781324	221.76523
226018	41°50′11.181 442″	88°15′57.483 555″	187.215425	-32.781324	219.99675
226019	41°50′11.232 572″	88°15′57.183 674″	192.475018	-32.781381	225.25640
226020	41°50′11.165 066″	88°15′57.453 990″	192.480716	-32.781324	225.26204
226021	41°50′11.110 842″	88°15′57.427 076″	186.828516	-32.781313	219.60983
226022	41°50′11.159 055″	88°15′57.146 520″	186.827680	-32.781369	219.60905
226023	41°50′11.053 895″	88°15′57.251 104″	186.828876	-32.781323	219.61020
226024	41°50′11.088 682″	88°15′57.097 280″	189.007412	-32.781358	221.78877
226025	41°50′11.031 315″	88°15′57.416 047″	189.030763	-32.781296	221.81206
226026	41°50′10.973 917″	88°15′57.453 428″	188.993735	-32.781274	221.77501
226027	41°50′10.938 991″	88°15′57.029 776″	189.010833	-32.781326	221.79216
226028	41°50′10.852 525″	88°15′57.461 122″	189.030258	-32.781242	221.81150
226029	41°50′10.840 992″	88°15′56.985 568″	189.076961	-32.781308	221.85827
226030	41°50′10.754 129″	88°15′57.291 387″	189.010888	-32.781242	221.79213
226031	41°50′10.746 475″	88°15′57.180 302″	186.835365	-32.781254	219.61662
226032	41°50′10.839 155″	88°15′56.914 454″	188.784201	-32.781318	221.56552
226033	41°50′10.838 931″	88°15′56.914 317″	187.244611	-32.781318	220.02593
226034	41°50′10.710 390″	88°15′56.945 505″	186.829798	-32.781281	219.61108
226035	41°50′10.746 303″	88°15′56.803 712″	187.224050	-32.781309	220.00536
226036	41°50′10.746 366″	88°15′56.803 477″	189.074410	-32.781309	221.85572
226037	41°50′10.608 725″	88°15′57.351 476″	188.997616	-32.781193	221.77881
226038	41°50′10.644 956″	88°15′57.220 187″	186.831165	-32.781224	219.61239
226039	41°50′10.523 318″	88°15′57.187 637″	188.995083	-32.781196	221.77628
226040	41°50′10.569 104″	88°15′56.973 411″	186.834051	-32.781238	219.61529

226041	41°50′10.593 215″	88°15′56.874 519″	189.024411	-32.781258	221.80567
226042	41°50′10.595 547″	88°15′56.803 778″	187.258069	-32.781270	220.03934
226043	41°50′10.595 488″	88°15′56.803 631″	189.059069	-32.781270	221.84034
226044	41°50′10.502 746″	88°15′56.693 895″	187.238065	-32.781264	220.01933
226045	41°50′10.503 115″	88°15′56.693 446″	189.075915	-32.781264	221.85718
226046	41°50′10.470 746″	88°15′56.839 257″	186.834906	-32.781233	219.61614
226047	41°50′10.395 780″	88°15′57.110 119″	186.825035	-32.781174	219.60621
226048	41°50′10.486 860″	88°15′57.235 944″	187.328899	-32.781180	220.11008
226049	41°50′10.486 704″	88°15′57.235 810″	188.943549	-32.781180	221.72473
226050	41°50′10.383 809″	88°15′57.263 009″	188.948600	-32.781149	221.72975
226051	41°50′10.269 954″	88°15′57.109 668″	187.207098	-32.781141	219.98824
226052	41°50′10.270 017″	88°15′57.109 714″	188.969348	-32.781141	221.75049
226053	41°50′10.302 822″	88°15′56.915 726″	186.833471	-32.781179	219.61465
226054	41°50′10.264 347″	88°15′57.070 775″	189.010382	-32.781147	221.79153
226055	41°50′10.351 654″	88°15′56.765 534″	189.015286	-32.781213	221.79650
226056	41°50′10.379 511″	88°15′56.706 530″	187.294411	-32.781228	220.07564
226057	41°50′10.379 715″	88°15′56.706 573″	189.014441	-32.781228	221.79567
226058	41°50′10.334 559″	88°15′56.618 320″	187.207809	-32.781231	219.98904
226059	41°50′10.334 417″	88°15′56.617 698″	189.006309	-32.781230	221.78754
226060	41°50′10.231 240″	88°15′56.730 873″	186.833234	-32.781185	219.61442
226061	41°50′10.161 131″	88°15′57.007 304″	186.824602	-32.781127	219.60573
226062	41°50′10.113 459″	88°15′56.828 515″	186.831409	-32.781140	219.61255
226063	41°50′10.053 637″	88°15′56.976 680″	189.006726	-32.781103	221.78783
226064	41°50′10.071 520″	88°15′56.853 364″	188.990203	-32.781126	221.77133
226065	41°50′10.121 658″	88°15′56.653 415″	189.015201	-32.781168	221.79637
226066	41°50′10.184 524″	88°15′56.550 829″	187.948250	-32.781199	220.72945
226067	41°50′10.184 564″	88°15′56.550 604″	189.025050	-32.781199	221.80625
226068	41°50′10.963 674″	88°15′57.063 388″	186.826280	-32.781329	219.60761
226069	41°50′10.889 476″	88°15′57.332 322″	186.829869	-32.781270	219.61114
226070	41°50′11.934 592″	88°15′57.135 059″	189.038178	-32.781571	221.81975
226071	41°50′10.156 944″	88°15′56.722 738″	192.230459	-32.781170	225.01163
226072	41°50′10.623 019″	88°15′56.816 309″	187.368182	-32.781277	220.14946
226073	41°50′10.622 812″	88°15′56.816 351″	189.047202	-32.781277	221.82848
226074	41°50′10.514 192″	88°15′57.247 974″	189.011367	-32.781183	221.79255
226075	41°50′10.100 568″	88°15′56.946 318″	192.229507	-32.781122	225.01063
226076	41°50′10.565 775″	88°15′57.184 568″	192.005812	-32.781207	224.78702
226077	41°50′10.633 559″	88°15′56.914 585″	191.953694	-32.781265	224.73496
226078	41°50′12.108 442″	88°15′57.463 983″	192.041110	-32.781569	224.82268
226079	41°50′12.154 599″	88°15′57.539 211″	192.357539	-32.781570	225.13911
226080	41°50′12.112 396″	88°15′57.628 507″	192.416464	-32.781545	225.19801
226081	41°50′12.038 750″	88°15′57.604 457″	191.926710	-32.781529	224.70824
226082	41°50′12.087 291″	88°15′57.546 155″	191.211176	-32.781553	223.99273
226083	41°50′12.085 257″	88°15′57.643 095″	191.210431	-32.781538	223.99197
226084	41°50′12.041 303″	88°15′57.821 590″	191.205048	-32.781501	223.98655
226085	41°50′12.044 501″	88°15′57.754 673″	191.698110	-32.781509	224.47962

226086	41°50′12.044 572″	88°15′57.753 794″	193.277650	-32.781509	226.05916
226087	41°50′12.195 874″	88°15′57.750 896″	191.611911	-32.781549	224.39346
226088	41°50′12.196 898″	88°15′57.749 028″	193.312620	-32.781549	226.09417
226089	41°50′12.267 873″	88°15′57.759 752″	191.880122	-32.781567	224.66169
226090	41°50′12.268 078″	88°15′57.759 835″	193.370282	-32.781567	226.15185
226091	41°50′12.310 305″	88°15′57.670 487″	193.105266	-32.781593	225.88686
226092	41°50′12.289 136″	88°15′57.652 583″	191.206872	-32.781587	223.98846
226093	41°50′12.169 521″	88°15′57.677 045″	191.570337	-32.781552	224.35189
226094	41°50′12.169 545″	88°15′57.676 484″	193.299107	-32.781552	226.08066
226095	41°50′11.273 966″	88°15′57.104 800″	196.684696	-32.781403	229.46610
226096	41°50′11.106 574″	88°15′56.987 038″	196.477532	-32.781377	229.25891
226097	41°50′10.862 892″	88°15′56.877 725″	196.488931	-32.781328	229.27026
226098	41°50′10.619 856″	88°15′56.768 564″	196.740816	-32.781283	229.52210
226099	41°50′10.009 091″	88°15′56.871 646″	194.583579	-32.781110	227.36469
226100	41°50′10.400 372″	88°15′57.183 537″	196.699095	-32.781164	229.48026
226101	41°50′10.604 655″	88°15′57.303 442″	196.698510	-32.781200	229.47971
226102	41°50′10.747 839″	88°15′57.337 745″	196.836586	-32.781233	229.61782
226103	41°50′10.990 292″	88°15′57.447 408″	196.762581	-32.781278	229.54386
226104	41°50′11.234 530″	88°15′57.556 905″	196.773782	-32.781327	229.55511
226105	41°50′11.509 848″	88°15′57.573 893″	196.639644	-32.781395	229.42104
226106	41°50′11.562 568″	88°15′57.335 675″	196.781384	-32.781445	229.56283