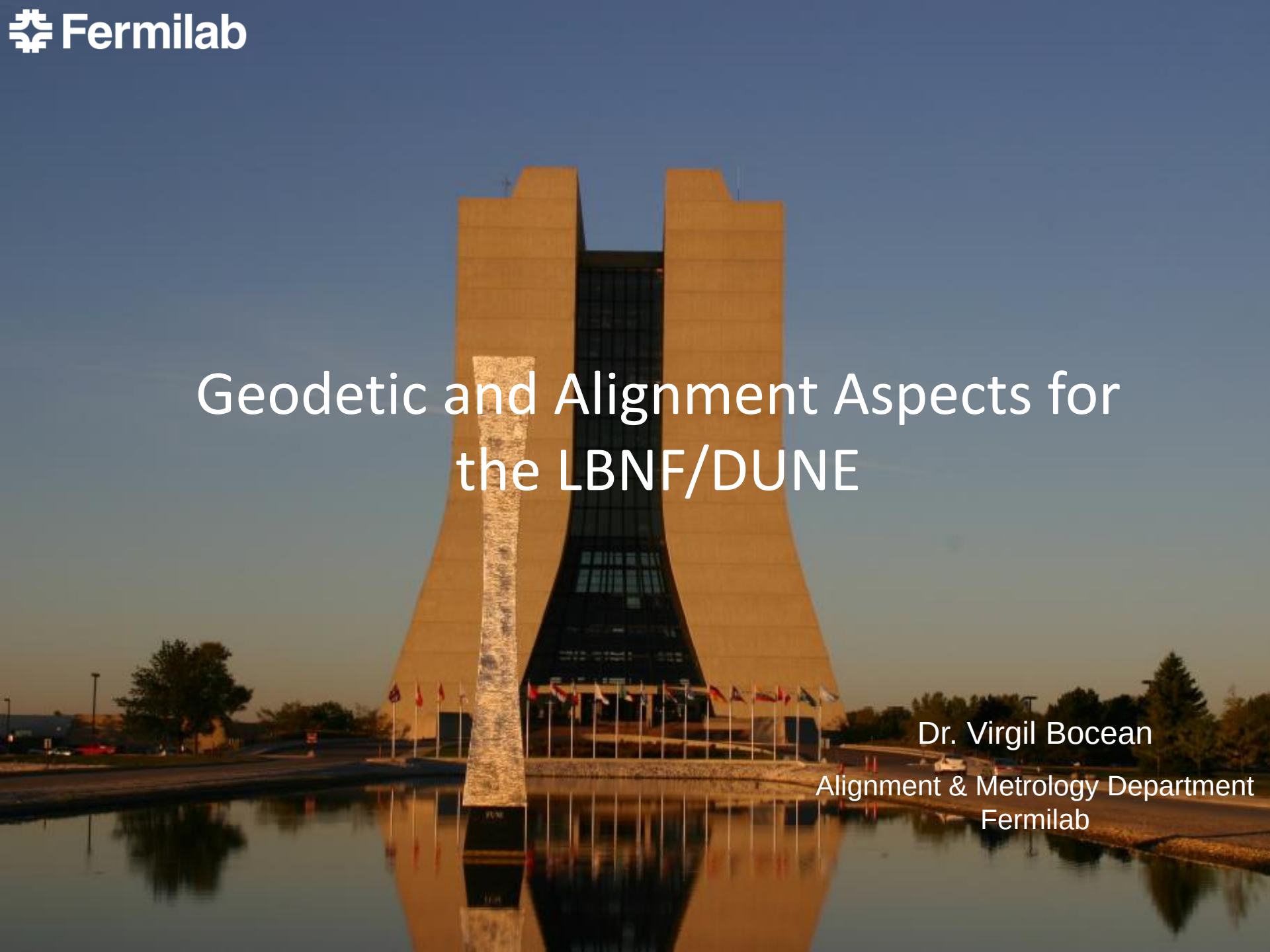

Geodetic and Alignment Aspects for the LBNF/DUNE

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Alignment & Metrology Department
Fermilab

The Deep Underground Neutrino Experiment (DUNE)

- The neutrino research program is part of the Intensity Frontier research priorities at Fermilab
- **DUNE** is a newly proposed leading-edge, international experiment for neutrino science and proton decay studies
- Physics Goals:
  - determine the mass hierarchy and look for CP violation
  - precision measurement of other oscillation parameters
  - test the validity of the three-neutrino mixing model
- Discovery possibilities: Origin of matter, Neutron Star and Black hole formation, Unification of forces

- **DUNE scope**:
- **Near site**: Fermilab, Batavia, IL
  - Build a highly capable Near Neutrino detector (=> reduce systematic errors of oscillation measurements + enable a broad program of short-baseline neutrino physics)
- **Far site**: Sanford Underground Research Facility, Lead, SD - located at 1300 km distance
  - Build four massive 10 kTon fiducial mass LAr TPC Far Detectors (each ~60m x 12m x 15m) placed underground at the 4850 ft (≈1500 m) level (=> enable proton decay + supernova neutrino physics)

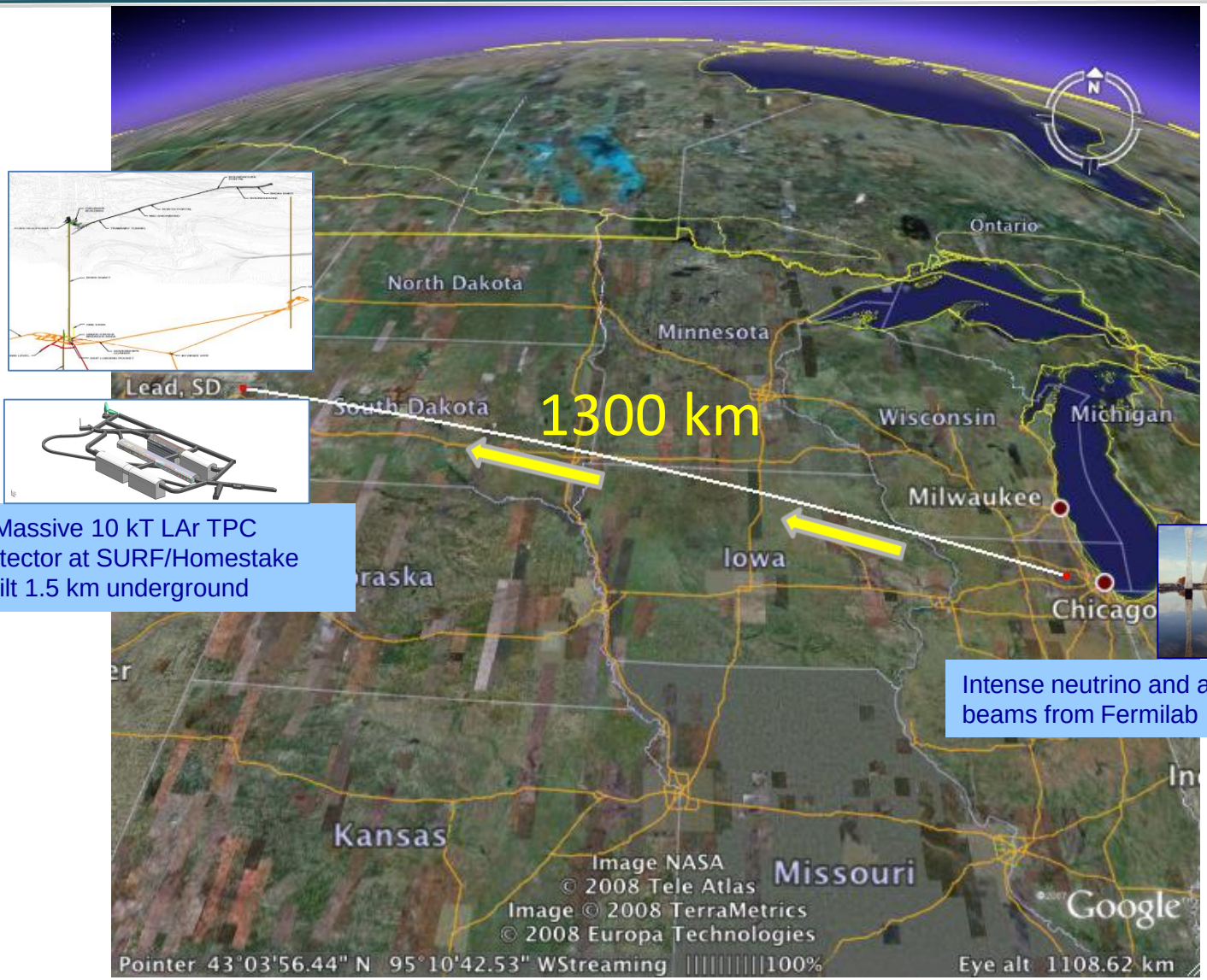
Long-Baseline Neutrino Facility (LBNF)

- The **LBNF** project provides the infrastructure for the DUNE experiment
- LBNF scope includes Technical Components and Conventional Facilities at the two locations:

- **Near site**
  - A high energy primary proton beam extracted from the Main Injector:
    - with the flexibility to operate at energy range from 60 to 120 GeV
    - beam power: start with a 1.2 MW beam upgradeable > 2.4 MW with PIP-III
  - The world's highest-intensity (muon) neutrino beam
  - Near Detector facility

- **Far site**
  - Far Detectors facility, cryostats, cryogenic systems

LBNF Beamline
From Fermilab to SURF, South Dakota

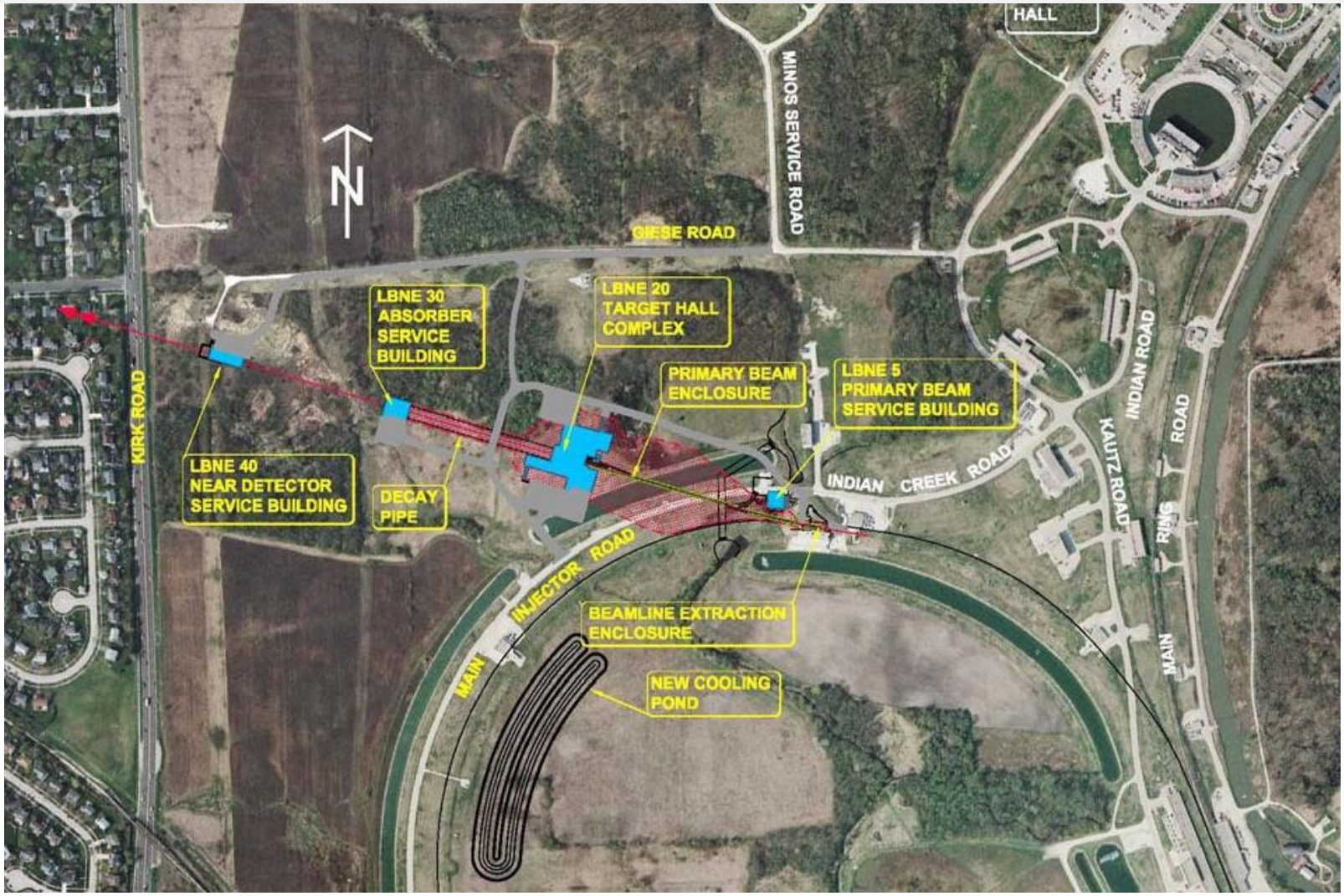


4 Massive 10 kT LAr TPC detector at SURF/Homestake built 1.5 km underground

Intense neutrino and anti-neutrino beams from Fermilab

The LBNF Beam Facility at Fermilab

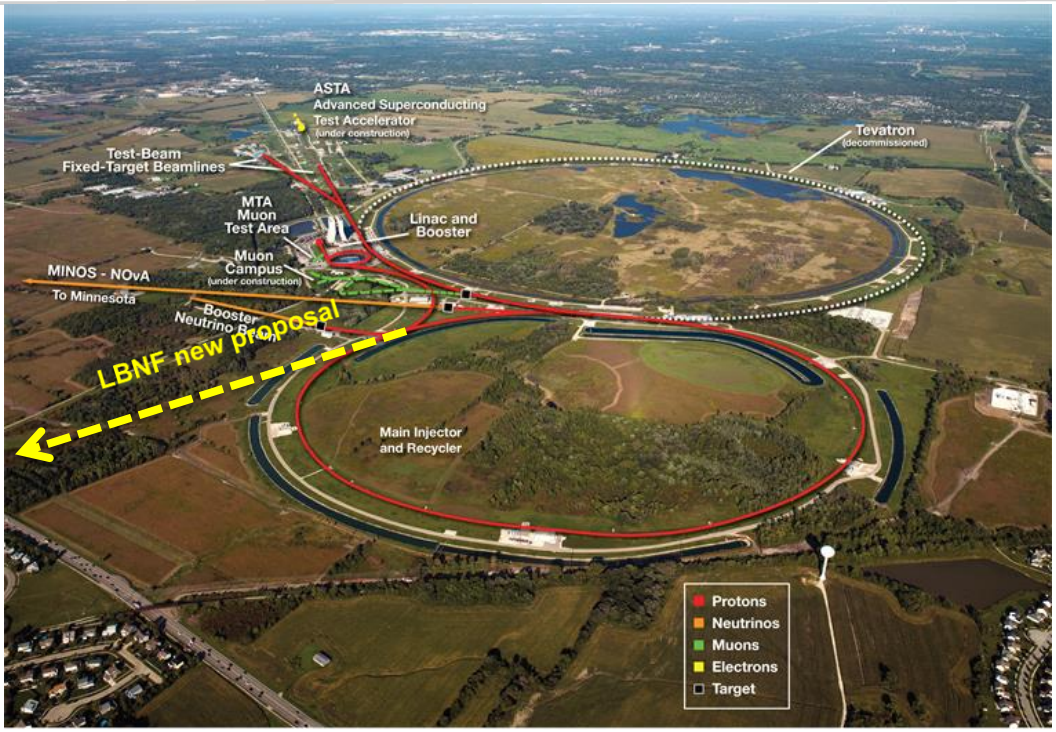
- Primary beam extracted from the Main Injector – MI-10

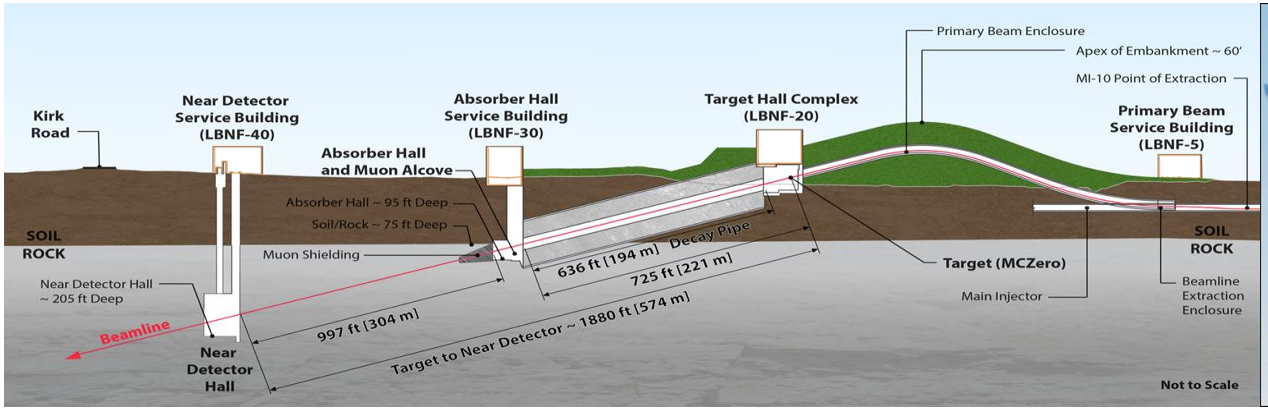


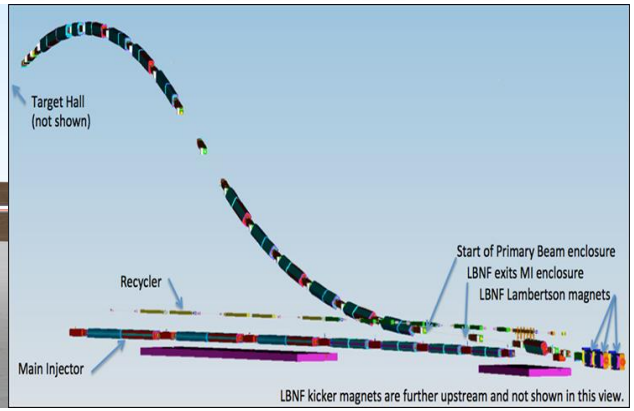
The LBNF Beam Facility at Fermilab

Tunnels and Halls

- "Shallow" beam extracted at MI-10:
  - Avoids beam crossings
  - Allows for a simpler extraction enclosure
  - Enables a cost-effective facility design of the entire extraction region
  - Interferes minimally with existing beam systems in this region
  - Provides some shielding separation from accelerator tunnel



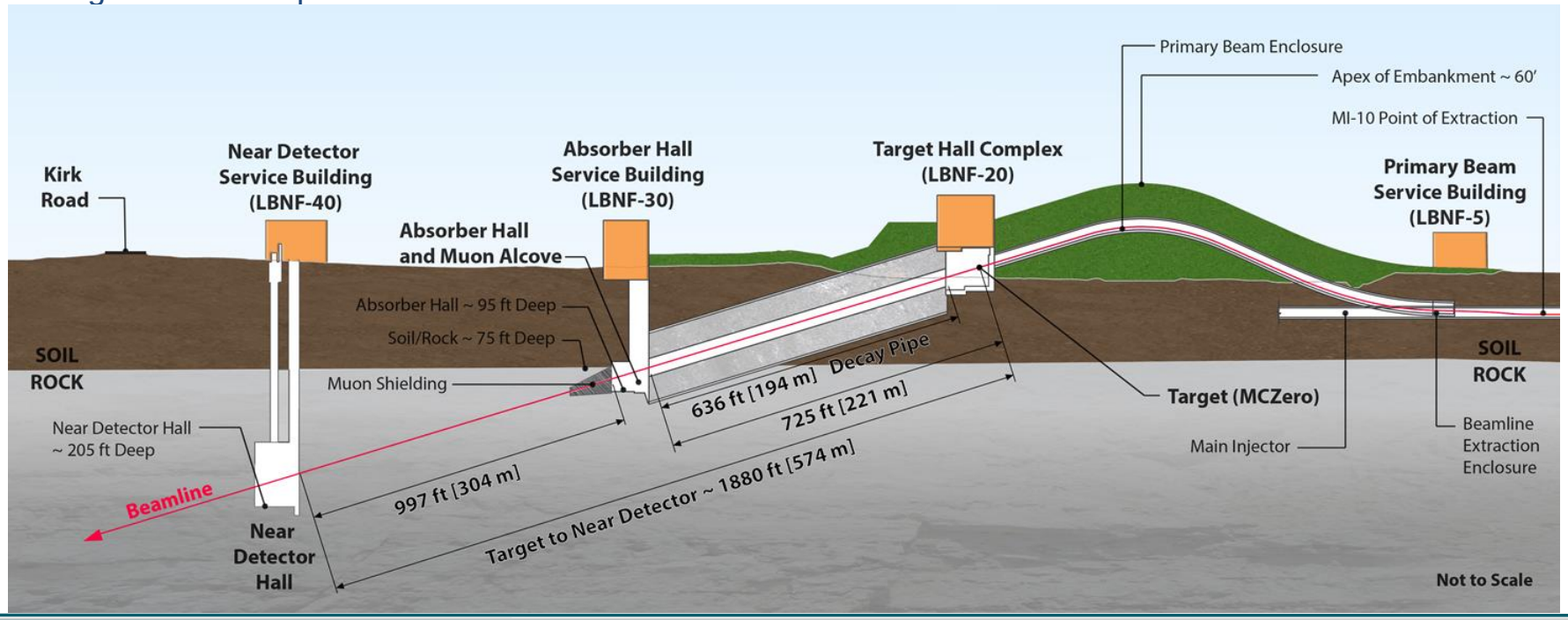




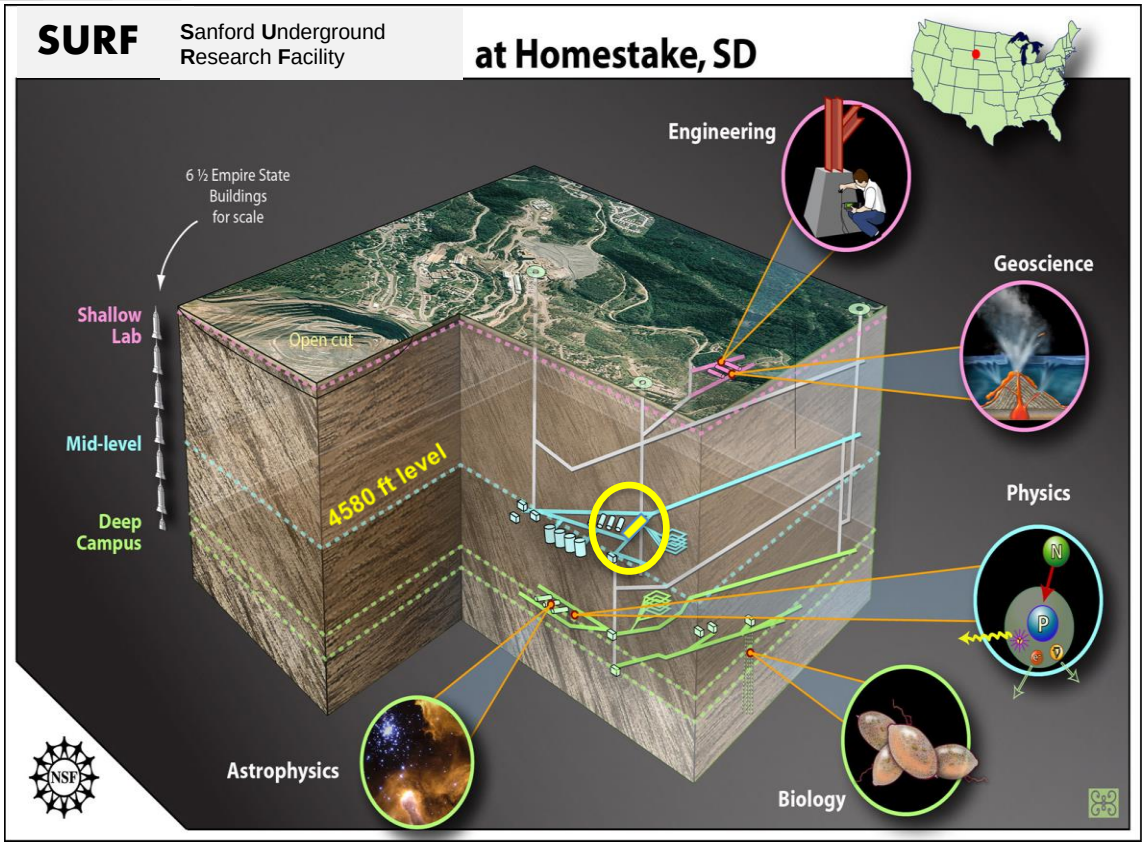
The LBNF Beam Facility at Fermilab

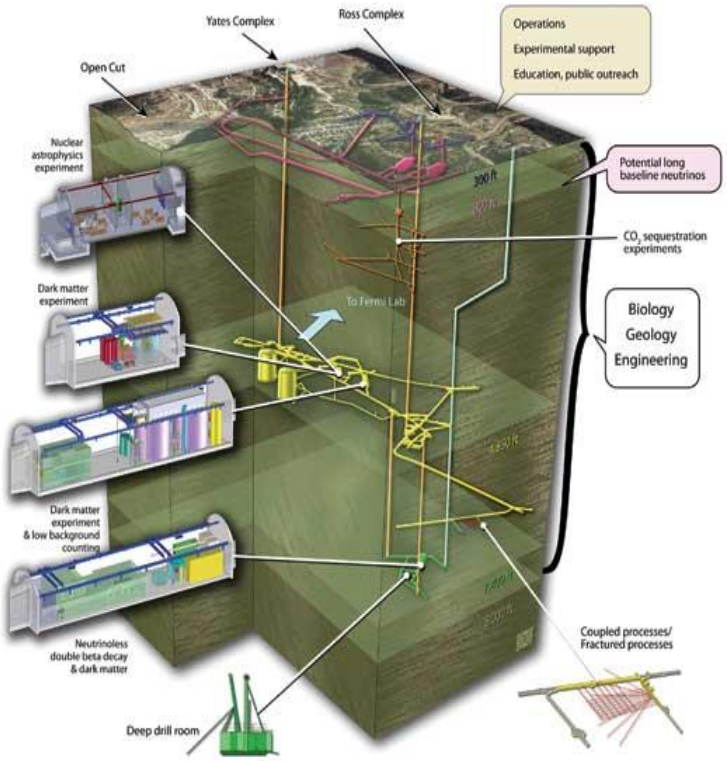
Tunnels and Halls – elevation view

- Showing the concept of elevating the beamline through construction of an earthen embankment (hill):
  - minimizes expensive underground construction
  - enhances significantly capability for ground-water radiological protection
- The primary beam enclosure and Target Hall will be founded on columns to bedrock
- The embankment will need to be approximately 280 m long and 18 m high above grade at its peak
- The primary beam will be above grade for about 168 m
- The downward pitch angle is 5.79^0 (101 mrad)
- The green shaded part indicates fill used to elevate the beam.



The Sanford Underground Research Facility
at Homestake, SD

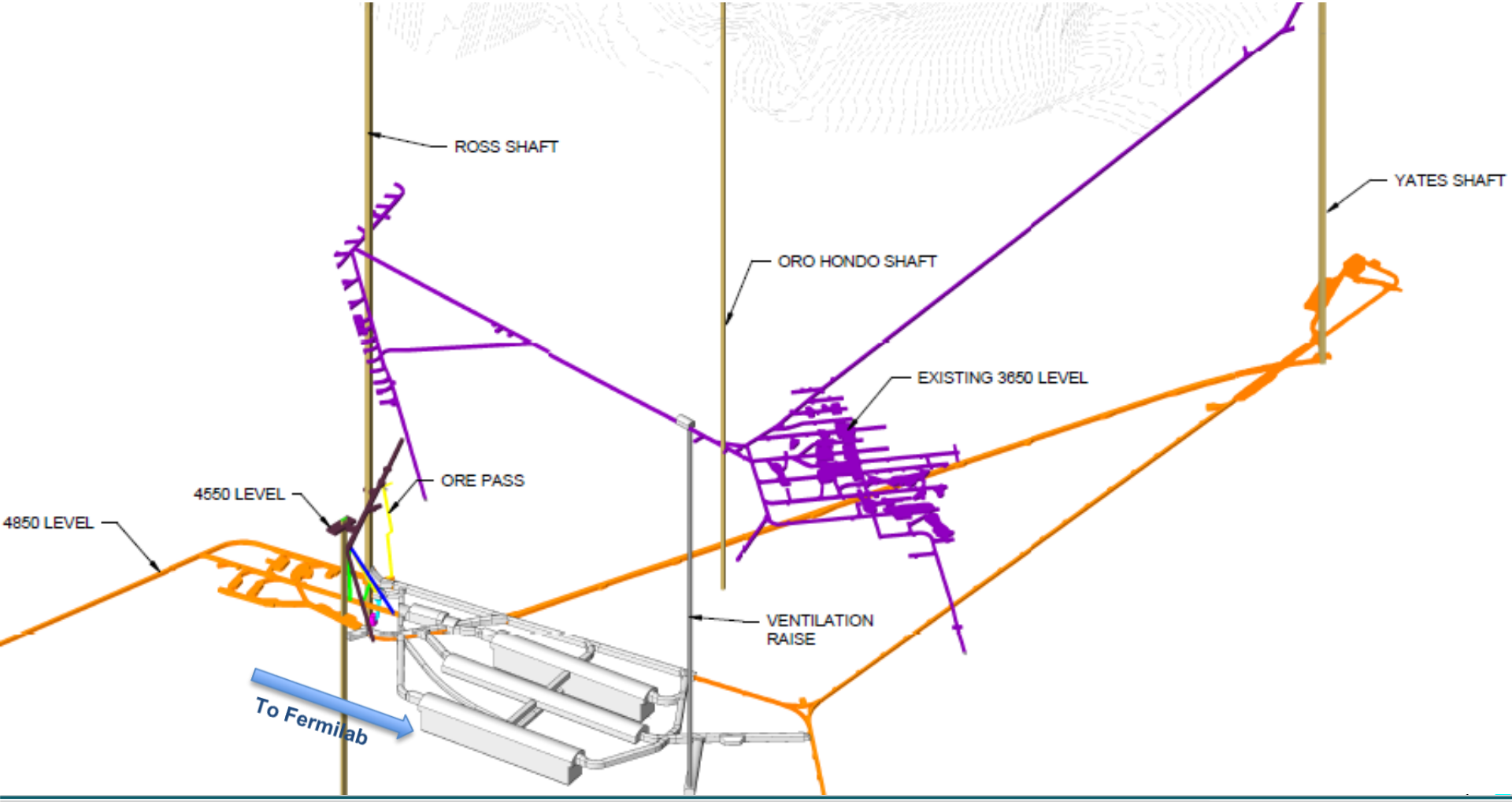




- Homestake is the deepest mine in North America with rooms at 8000 ft (2438 m)
- Major scientific fields solicited experiments: particle and nuclear physics, geology, hydrology, geo-engineering, biology, and biochemistry.
- Proposed physics experiments in five research categories: supernovae, dark matter, proton decay, neutrino mass hierarchy and neutrinoless double beta decay.
- Proposed LBNF far detector at 4850 ft (approximate depth 1500 m)

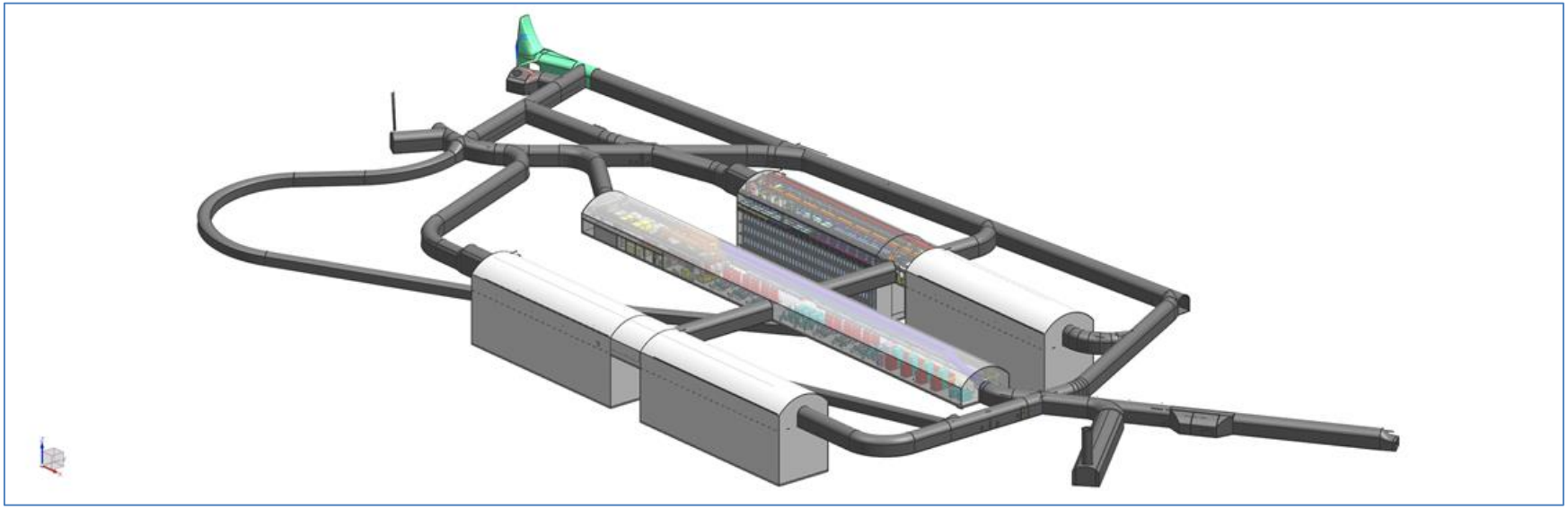
DUNE Far Detectors
Conceptual layout

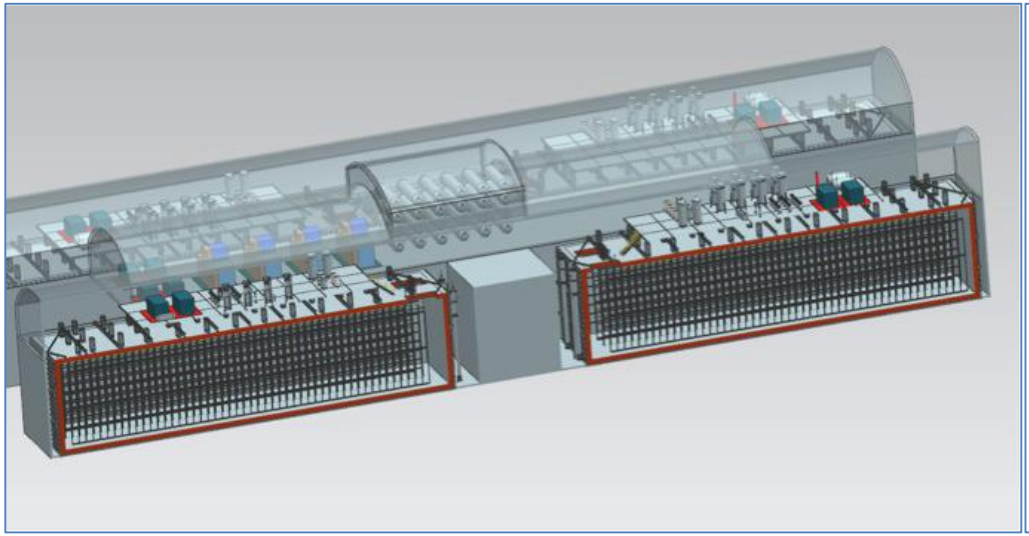
- At the proposed SURF laboratory in Lead, South Dakota, the caverns for the Homestake Neutrino Detector would be located 1500 m underground

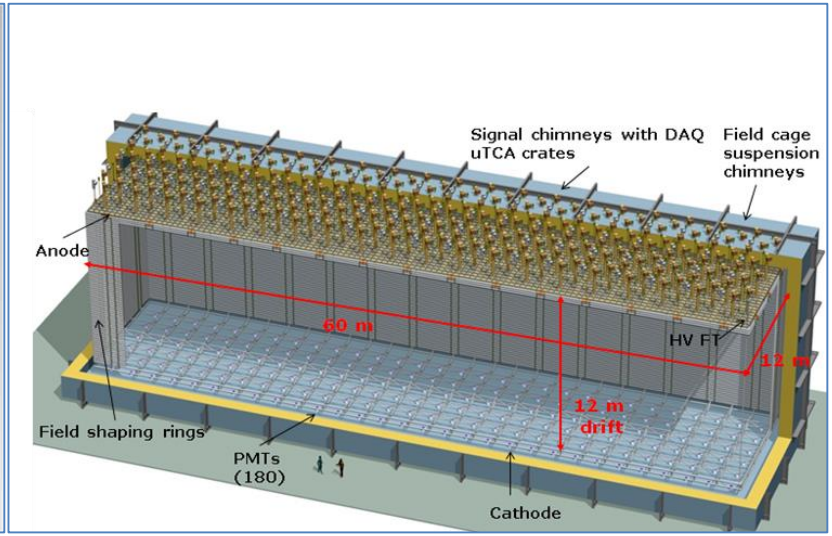


DUNE Far Detectors
Conceptual layout

- Designing four 10 kTon fiducial mass LAr TPC Far Detectors (each ~60m x 12m x 15m)

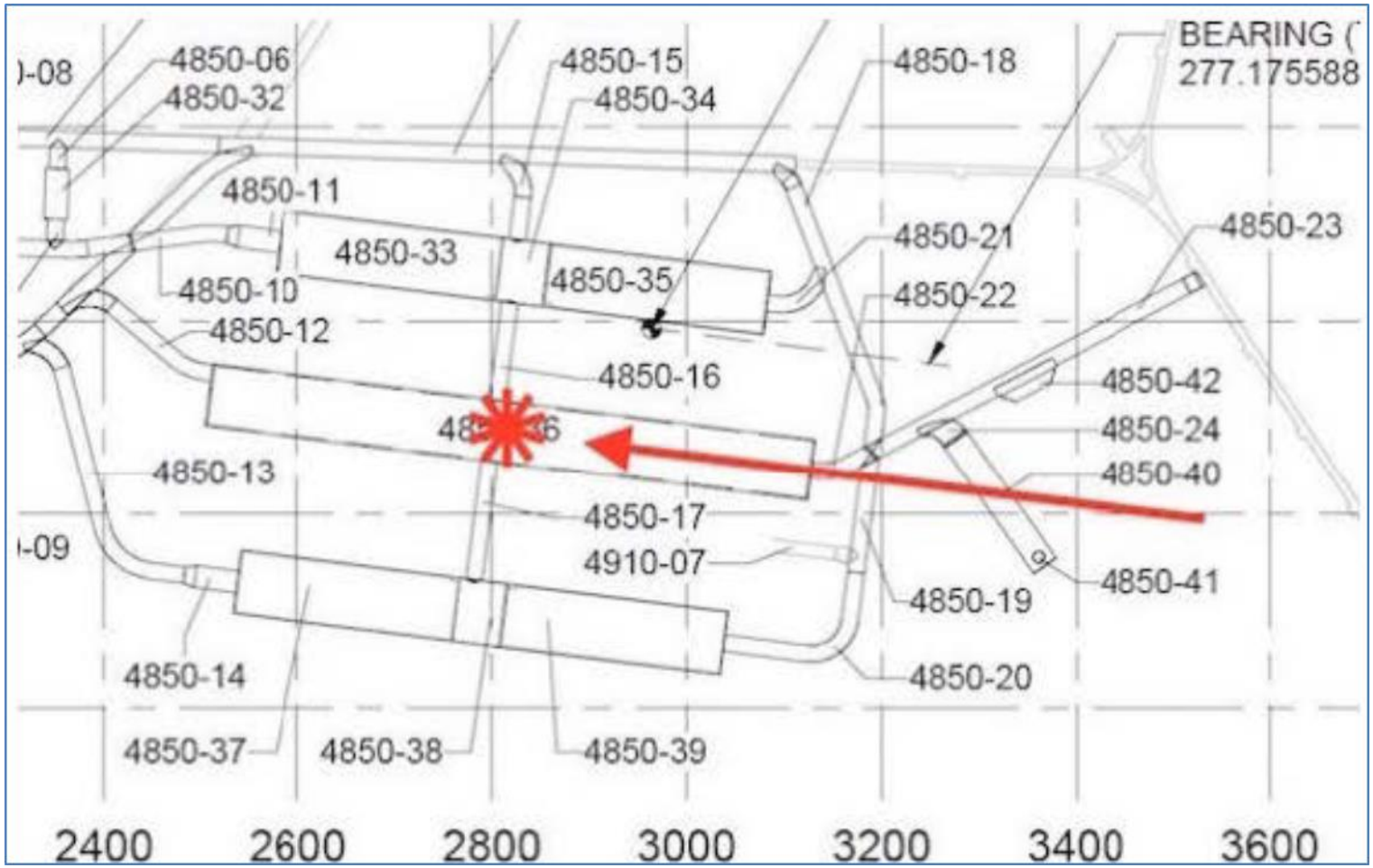






DUNE Far Detectors
Conceptual layout

- The red star shows the center of the Far Detector complex (center of the Utility Cavern) where the beam will be aimed
- The x-y coordinates at the 4850 Level in the Homestade Mine Control system (HMC)



Alignment Requirements

- Absolute and relative alignment tolerances for LBNF were assimilated from NuMI (absolute tolerances calculated proportionally to SURF, South Dakota)
- Absolute tolerances - at global level:
  - Primary proton beam centered ± 21 m at the far detector (± 0.016 mrad)
  - Neutrino beam centered ± 133 m at the far detector ± 0.102 mrad)
- Relative tolerances - between components:

Beam position at target	**± 0.45 mm**
Beam angle at target	**± 0.7 mrad**
Target position - each end	**± 0.5 mm**
Horn 1 position - each end	**± 0.5 mm**
Horn 2 and 3 position - each end	**± 0.5 mm**
Decay pipe position	**± 20 mm**
Downstream Hadron monior	**± 25 mm**
Muon Monitors	**± 25 mm**
Near Detector	**± 21 mm**
Far Detector	**± 133 m**

- LBNF is mainly sensitive to final primary beam trajectory : primary beamline components, Target and Horns alignment => relative positions ±0.35 mm (1σ)

Geodetic determination of global positions

- The correct aiming of the beam is of great importance for the experiment
- Requires a rather exact knowledge of the geodetic orientation parameters of the beam => absolute & relative positions of the target (Fermilab) and the Far Detector (SURF) at the global level
- In 2016, a comprehensive surveying campaign took place to refine the global positions of FNAL and the 4850 Level of the Sanford Lab by **Professional Mapping and Surveying LLC**, Spearfish SD and **Fermilab surveyors**
- Establish a rigorous underground control network at the 4850 Level of the mine to support the design and construction of Far Detector facility

Geodetic determination of global positions

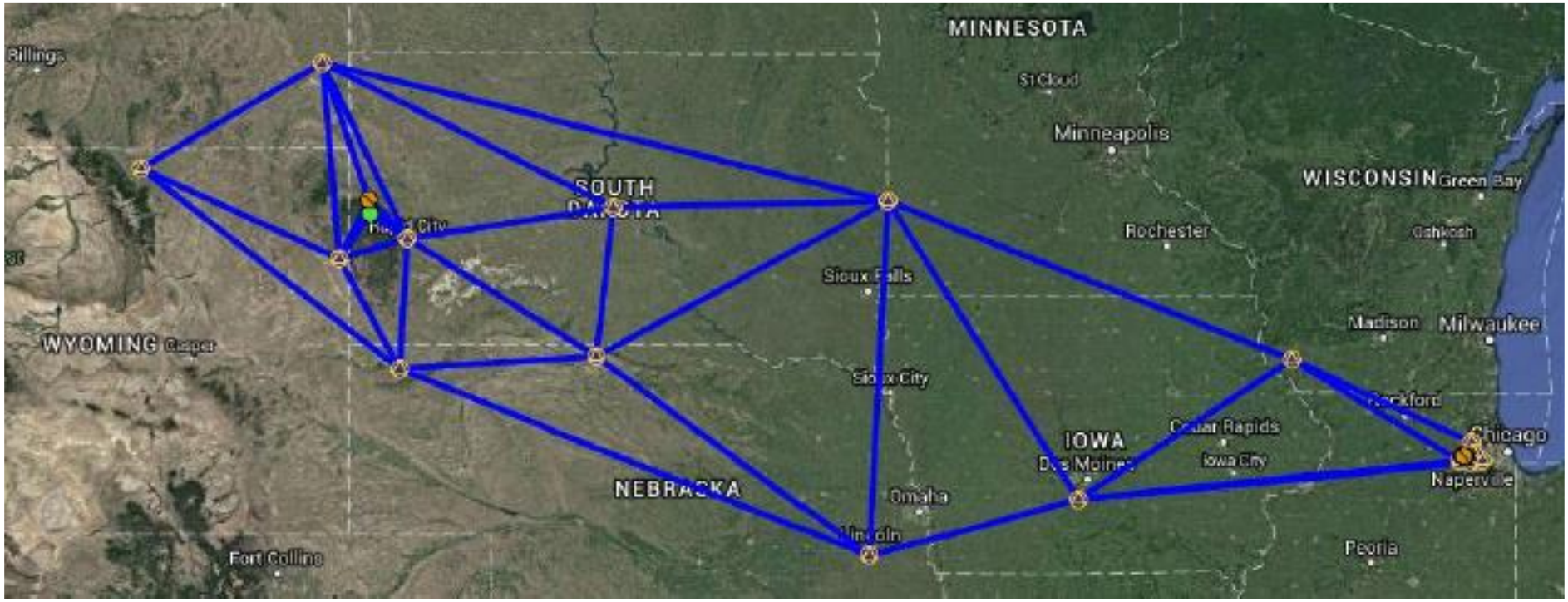
- Surveying procedure phases/steps:
  1. Precise GPS determination of the FNAL\SURF Primary Surface control between the two sites
  2. Transfer of surface global coordinates underground to the 4850 Level
  3. Underground network at the 4850 Level between the Ross and Yates shafts
  4. Additional network ties between the Ross and Yates shafts at 1700 and 4100 Levels
  5. Precision azimuth determination of the Homestake Mine Control (HMC) grid with respect to true North (important for the design of Far Detector orientation)
  6. Establish/refine the transformation parameters (formula) between the HMC Coordinates to Global Coordinates

Precise GPS determination of the FNAL/SURF Primary Surface control

- FNAL/SURF long GPS/GNSS baseline measurements tie the Primary Surface control to the National Geodetic Survey (NGS) Continuously Operating Reference Station (**CORS**) high accuracy national GPS geodetic network
  - network processed using NGS Online Positioning User Service (OPUS) Projects
  - GPS observations:
    - FNAL site: 4 days 8 hours sessions on 7 pillar monuments (4 of them part of IL High Accuracy Reference Network (HARN)) – only 4 used in OPUS adjustment
    - SURF site: 4 days 8 hours sessions on 4 control points
  - OPUS network built of 24 control points: constrained on 16 CORS stations + 8 free stations
  - 59 baselines included in the adjustment:
    - vector lengths vary from 1 km to 650 km – known on average to better than 15 mm rms
  - solution in North American Datum of 1983 (NAD 83(2011)) and North American Vertical Datum of 1988 (NAVD 88) Geoid 12A systems
  - Primary Surface control network accuracy results are within ±10 mm
  - an independent "Very Long Baseline Network" adjustment was performed to check of the OPUS Projects Primary Network solution - results showing excellent agreement within 10 mm

Precise GPS determination of the FNAL/SURF Primary Surface control

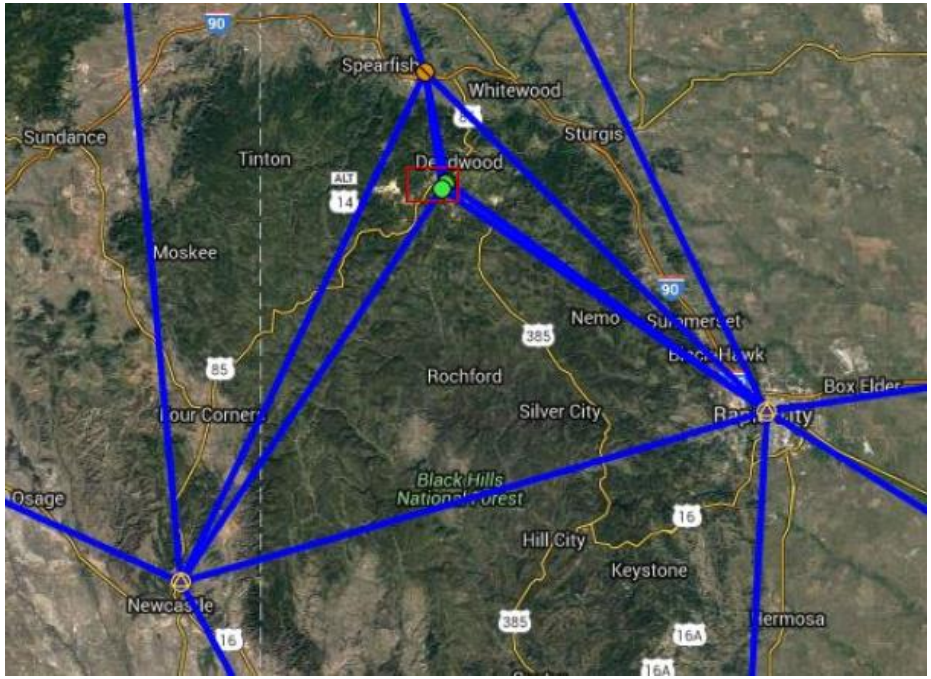
- Overview Map of the OPUS Projects Primary GPS Network



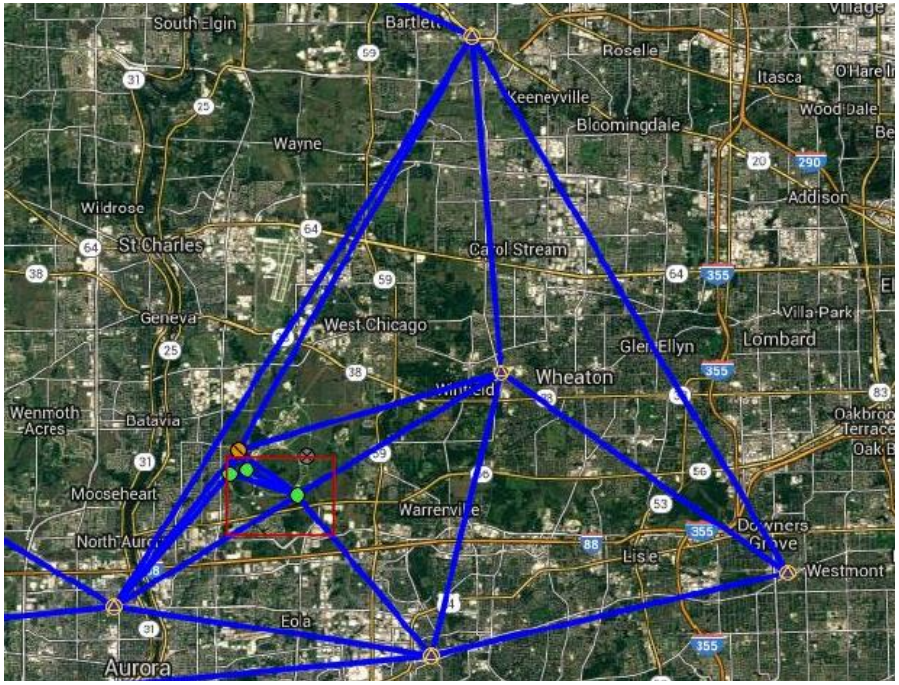
Courtesy Randy Deibert

Precise GPS determination of the FNAL/SURF Primary Surface control

- Sanford Lab Site Overview



- Fermilab Site Overview



Courtesy Randy Deibert

Precise GPS determination of the FNAL/SURF Primary Surface control - Accuracy results

Table 1: OPUS Project Network Solutions Displayed in Latitude, Longitude and Cartesian Coordinates.

		OPUS PROJECT NETWORK SOLUTIONS						
REF FRAME:	NAD_83(2011)						GEOID12A HGT	
Point Number	LATITUDE N (DMS)	estimated errors Meters	LONGITUDE W (DMS)	estimated errors Meters	Elipsoid Height	estimated errors Meters	Orthometric Height	estimated errors Meters
1601	44 21 08.73984	0.000	103 44 59.76086	0.000	1605.99	0.002	1619.781	0.032
2186 (700)	44 20 43.57742	0.000	103 45 27.44270	0.000	1619.698	0.002	1633.422	0.032
spfc	44 28 55.29859	0.004	103 47 02.68530	0.002	1170.001	0.03	1184.613	0.044
Yate (Yates)	44 21 04.89521	0.000	103 45 04.66381	0.000	1609.91	0.003	1623.69	0.032
6589 (66589)	41 49 56.56667	0.000	88 16 01.45860	0.000	197.356	0.002	230.474	0.029
6650 (66501)	41 49 22.05092	0.000	88 14 31.63473	0.000	201.198	0.001	234.322	0.029
6658 (66588)	41 49 50.75401	0.000	88 16 30.65726	0.000	198.717	0.002	231.829	0.029
6659 (66597)	41 50 22.16566	0.000	88 16 14.81923	0.000	195.858	0.001	228.981	0.029

	Cartesian Coordinates (ECEF)					
Point Number	X METERS	estimated errors Meters	Y METERS	estimated errors Meters	Z METERS	estimated errors Meters
1601	-1086061.384	0.001	-4438388.833	0.002	4437299.995	0.001
2186 (700)	-1086788.507	0.000	-4438780.032	0.001	4436754.041	0.001
spfc	-1086230.075	0.005	-4427647.440	0.021	4447283.305	0.021
Yate (Yates)	-1086187.276	0.001	-4438446.339	0.002	4437217.858	0.002
6589 (66589)	143933.096	0.000	-4757406.734	0.001	4231881.485	0.001
6650 (66501)	146026.704	0.000	-4758056.329	0.001	4231090.502	0.001
6658 (66588)	143263.271	0.000	-4757547.632	0.001	4231748.763	0.001
6659 (66597)	143609.008	0.000	-4756888.358	0.001	4232468.951	0.001

Table 5: Very Long Baseline Adjustment Cartesian Coordinates.

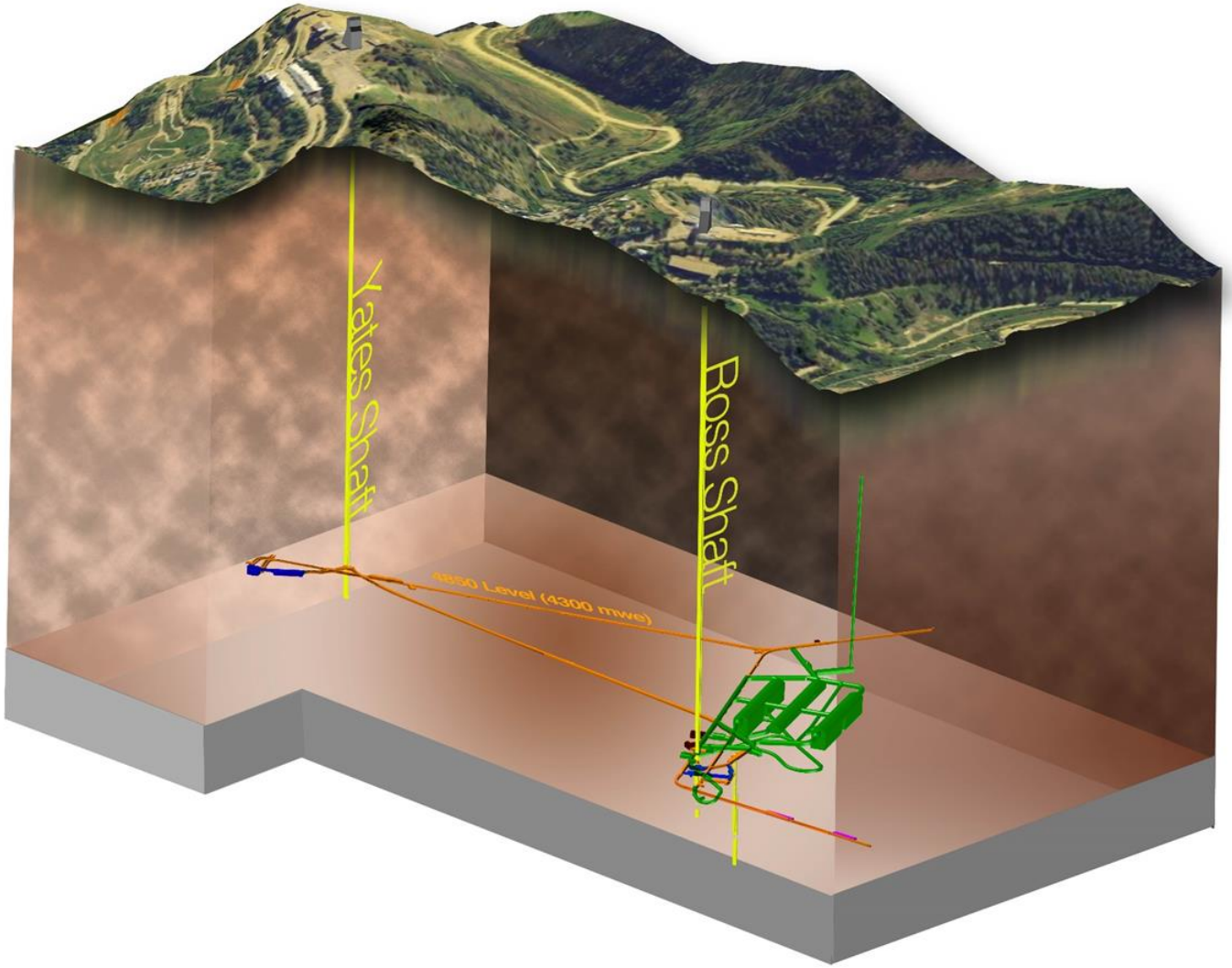
Adjusted ECEF Coordinates

Point ID	X (Meter)	X Error (Meter)	Y (Meter)	Y Error (Meter)	Z (Meter)	Z Error (Meter)	3D Error (Meter)	Constraint
1601	-1086061.372	0.006	-4438388.832	0.008	4437299.987	0.007	0.012	
66501	146026.703	0.005	-4758056.311	0.005	4231090.479	0.005	0.009	
66503	146381.726	0.005	-4756971.074	0.005	4232287.775	0.005	0.009	
66527	145905.924	0.005	-4756291.452	0.006	4233062.664	0.005	0.009	
66565	143484.854	0.005	-4758082.049	0.005	4231139.670	0.005	0.008	
66588	143263.269	?	-4757547.617	?	4231748.745	?	?	LLh
66589	143933.095	0.005	-4757406.720	0.005	4231881.467	0.005	0.008	
66597	143609.006	0.005	-4756888.349	0.005	4232468.935	0.005	0.009	
700	-1086788.505	0.006	-4438780.042	0.008	4436754.041	0.007	0.012	
SDRC	-1050082.629	?	-4468052.202	?	4415386.613	?	?	LLh
spap	-1086230.241	0.006	-4427647.385	0.008	4447283.128	0.007	0.012	
yates	-1086187.265	0.006	-4438446.333	0.007	4437217.847	0.007	0.012	

- GPS network accuracy is within ±10 mm

Courtesy Randy Deibert

Transfer of surface global coordinates underground to the 4850 Level



Transfer of surface global coordinates underground to the 4850 Level

- Used 1 mile long plumb lines at Yates and Ross shafts to determine the Northing and Easting:
  - the longest plumb line in the world down the 4850-foot (1.5-kilometer) mineshafts
  - lower three plumb lines down the shafts from pulleys at the collar at three corners of the cage compartment
  - total weight of each plumb line: 80 lb (steel cable) + 140 lb (weight) = 200 lb
  - the weight is immersed in a barrel of oil to dampen the movement
  - survey control was established outside the cage compartment and shaft at surface, 4850 and intermediate levels.
  - reflector-less total station and data was collected at each plumb line simultaneously at the surface, 1700, 4100 and 4850 levels
  - intermediate levels data compared to the surface and 4850 level indicates the attitude of the plumb lines.

- Elevation from surface was transferred at each level, through each shaft, using a total station distance measurements of multi-prisms reflectors

Transfer of surface global coordinates underground to the 4850 Level

- Plumb lines: steel cable, weight with fins and oil barrel

Transfer of surface global coordinates underground to the 4850 Level

- Plumb lines and reflectors: view of the shaft at 4850 Level

Transfer of surface global coordinates underground to the 4850 Level

- Plumbs line and reflectors: video of the shaft at 4850 Level

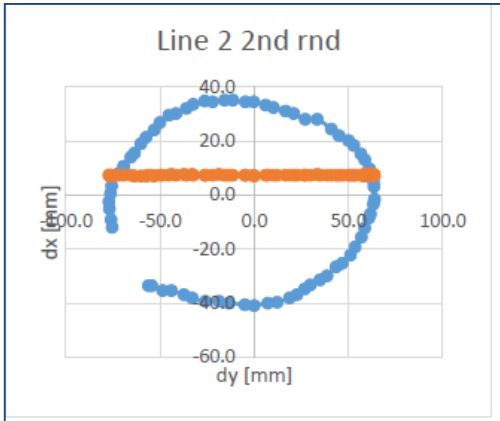
Transfer of surface global coordinates underground to the 4850 Level

- Two approaches were taken for plumb lines observations:
  - 1st approach - required the lines to come as close to a resting position as possible
  - 2nd approach - required a deliberate swing of each of the wires to be observed by a robotic total station in 3 second intervals over a 5 minute observation time.

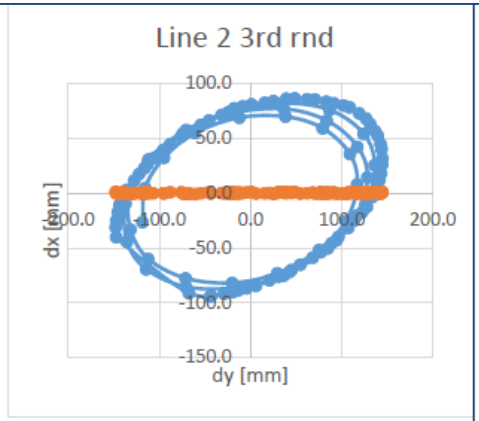
- All lines where observed multiple times at the 4850 level while simultaneous measurements were performed at other drift levels

Transfer of surface global coordinates underground to the 4850 Level - 1st approach

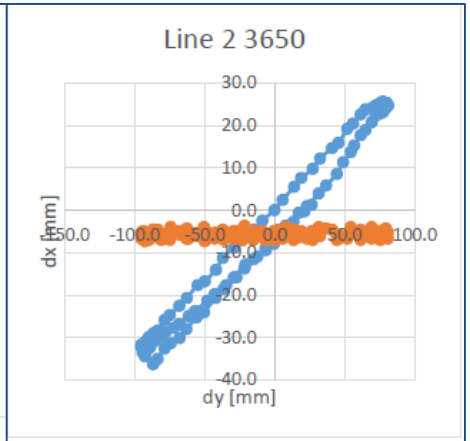
- Quasi static measurements of plumb line 2 – Ross Shaft 4850 Level



First measurement round

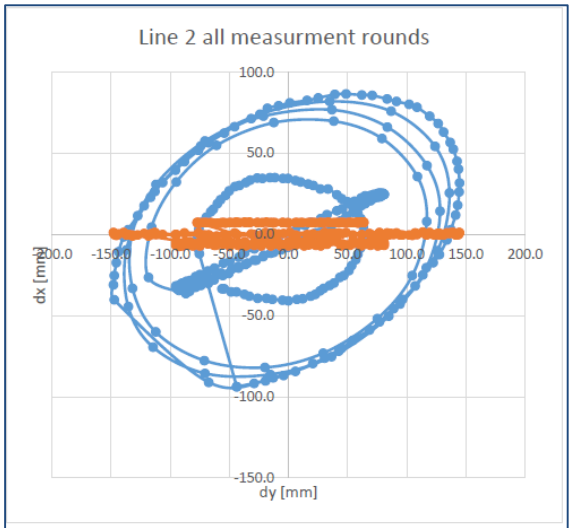


Second measurement round

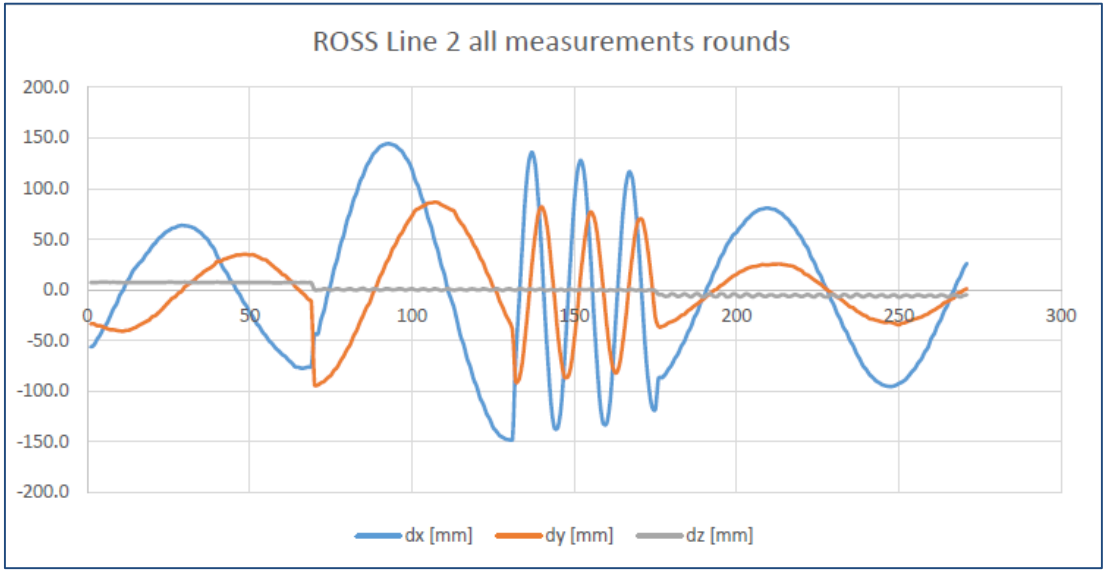


Third measurement round

Horst Friedsam

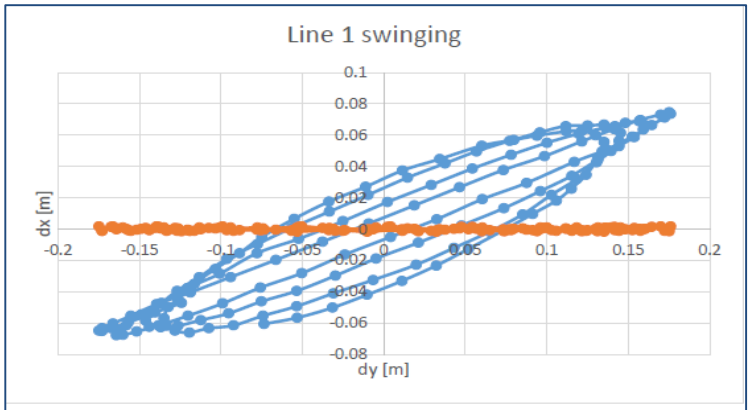


All measurement rounds combined

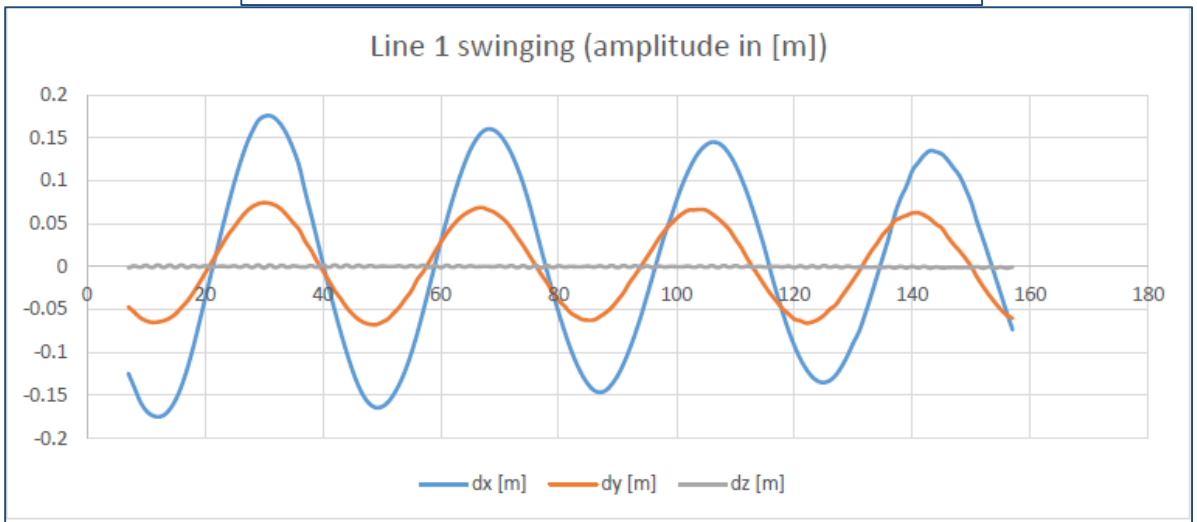


Transfer of surface global coordinates underground to the 4850 Level - 2nd approach

- Swinging pendulum measurements of plumb line 1 – Ross Shaft 4850 Level



Graph of Line 1 swinging (vertical z-value in orange)



Graph showing decaying amplitude over time

Courtesy Horst Friedsam

Transfer of surface global coordinates underground to the 4850 Level - Analysis Results

- Comprehensive analysis done independently by Fermilab and PMS contractor
- Ross Shaft plumb lines analysis
  - the average X, Y plumb lines position is known within:
    - Line 1 = ±3 cm
    - Line 2 = ±8 cm
    - Line 1 = ±5 cm
  - the results from both approaches are within 10 mm

I. Results from the swinging pendulum

NAME	AVG [X]	AVG [Y]	AVG [Z]	STDev [X]	STDev [Y]	STDev [Z]
Line1	1409.352	651.830	115.455	0.110	0.048	0.001
Line2	1408.546	648.929	115.090	0.044	0.017	0.001
Line3	1409.210	649.328	116.221	0.029	0.015	0.000

II. Results from the quasi static pendulum

NAME	AVG [X]	AVG [Y]	AVG [Z]	STDev [X]	STDev [Y]	STDev [Z]
Line1	1409.349	651.830	115.461	0.026	0.027	0.004
Line2	1408.538	648.936	115.102	0.075	0.042	0.005
Line3	1409.209	649.328	116.220	0.045	0.044	0.145

III. Differences between these two approaches

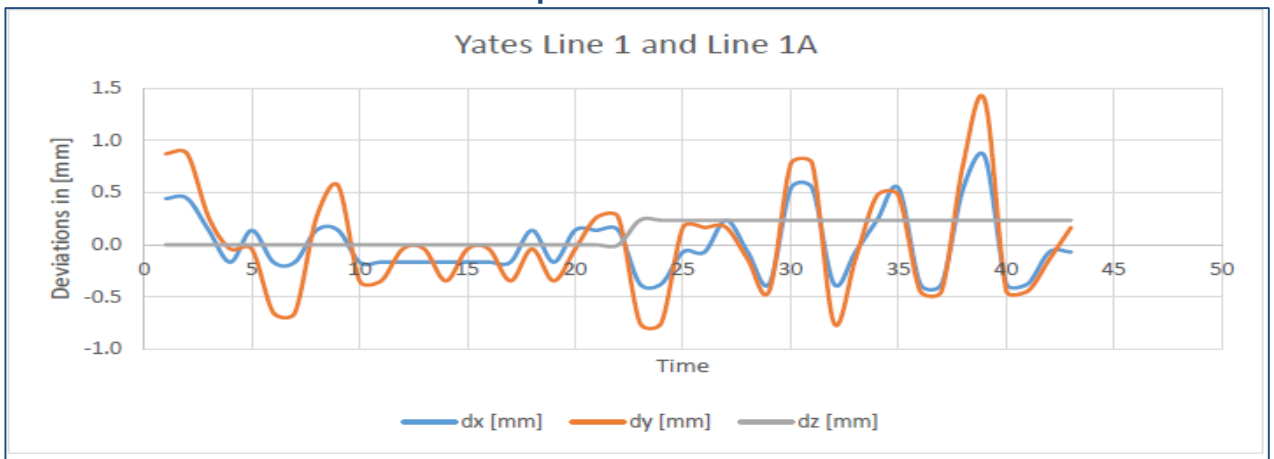
NAME	dx [mm]	dy [mm]	dz [mm]
Line1	-3.5	0.1	-6.6
Line2	-7.4	-6.6	-12.0
Line3	-0.2	0.6	0.7

- Yates Shaft plumb lines analysis
  - during the observation process, the stretch of the cables lowered the weights to resting on the bottom of the barrels => the cables were no longer plumb => **results discarded**
    - amplitudes dx, dy are suspiciously small (within 1 mm)
    - vertical dz component shows no up and down motion as expected in a freely swinging plumb line
    - similar conclusion drawn when projecting all level measurements to 4850 Level

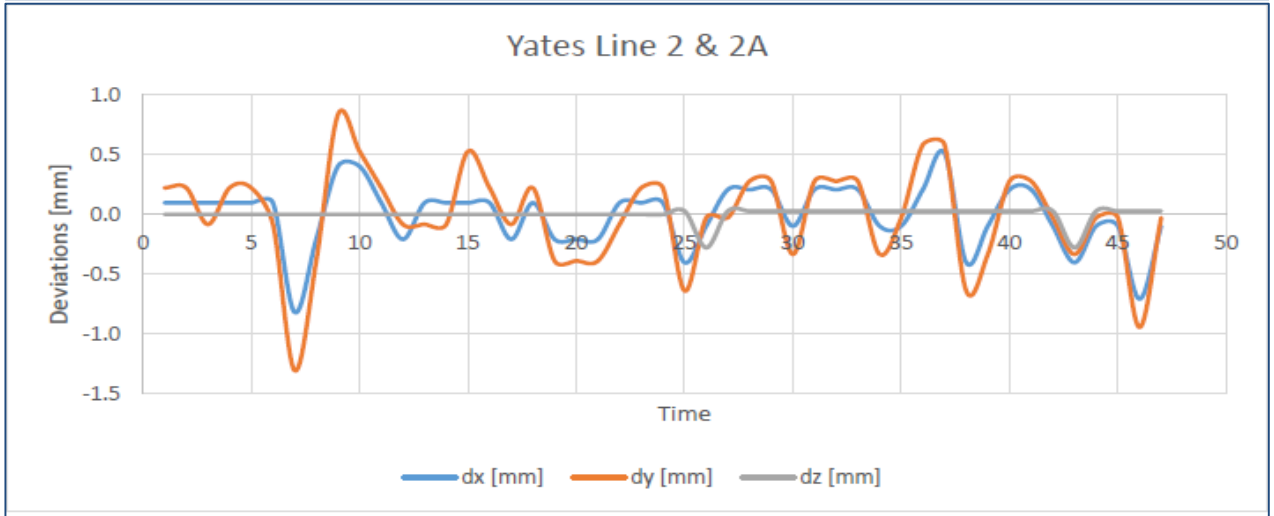
Courtesy Horst Friedsam

Transfer of surface global coordinates underground to the 4850 Level - 1st approach

- Quasi static measurements of plumb lines 1 and 2 – Yates Shaft 4850 Level



Yates Line 1



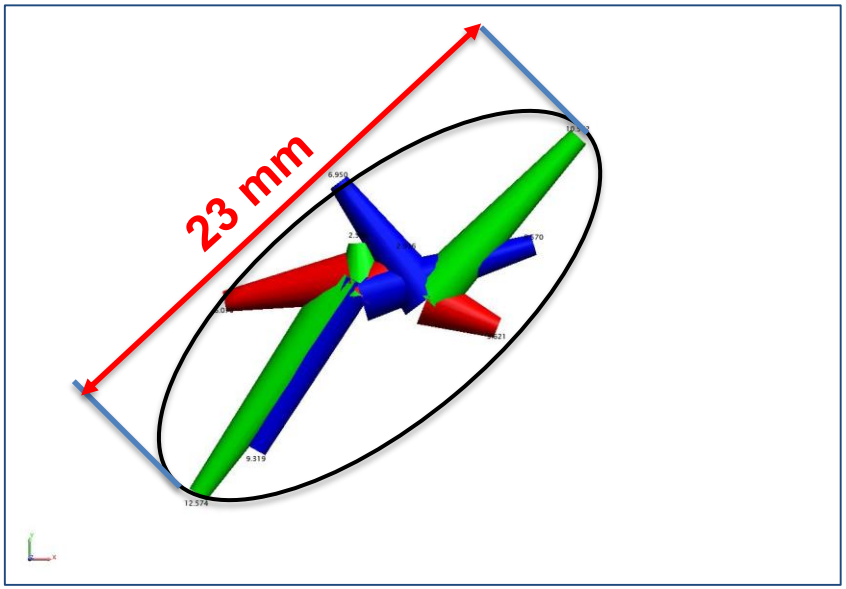
Yates Line 2

Courtesy Horst Friedsam

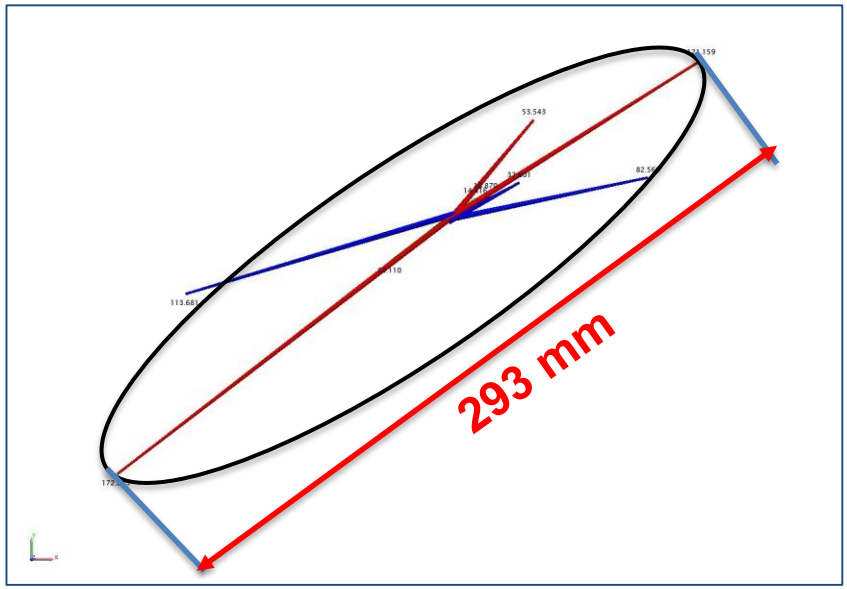
Transfer of surface global coordinates underground to the 4850 Level - 1st approach

- Quasi static measurements – surface, 1700, 4100 levels projected at 4850 Level

Ross Shaft



Yates Shaft

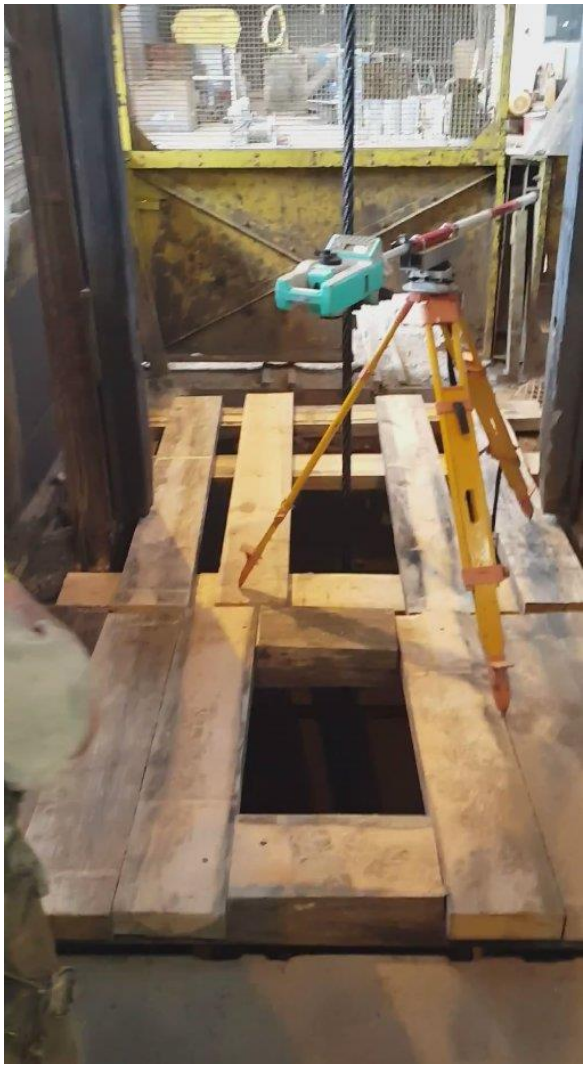


Transfer of surface global coordinates underground to the 4850 Level

- Elevation from surface was transferred at each level, through each shaft, using a total station distance measurements of multi-prisms reflectors
  - the total station was set in a horizontal position over the shaft and leveled
  - additional station on a control point at the shaft collar level monitors the position of the perpendicular total station during measurements

- The accuracy of measuring the depth distance is based on the influence of the ambient atmospheric conditions through the shafts and estimated ±5 cm
  - because of the water and wet conditions at Yates shaft, only the Ross shaft measurements were published

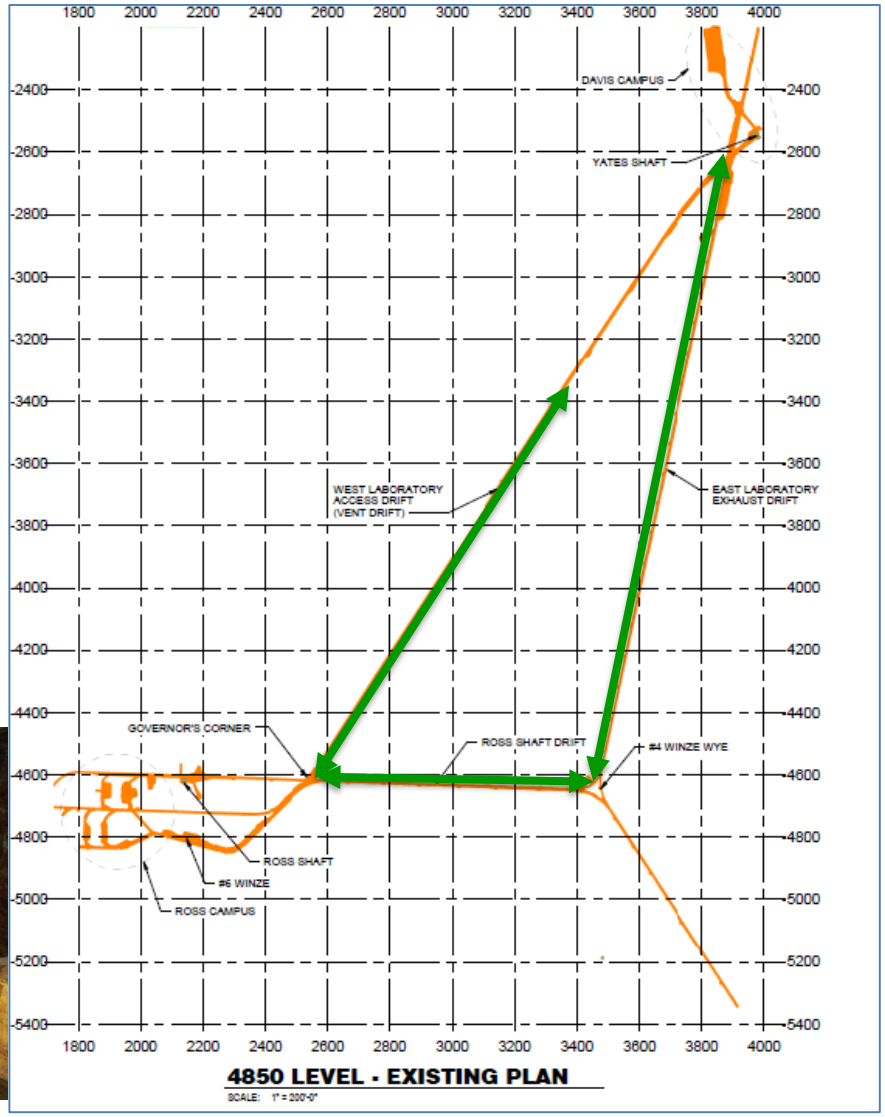
- In summary, the transfer of surface global coordinates underground to the 4850 Level was done in all x,y and H axes within ±10 cm envelope



Precision azimuth determination of the Homestake Mine Control (HMC) grid

- Precision gyro measurements with the DMT gyrothedolite Gyromat 2000 (accuracy ±3 arcseconds) were performed over long legs of the Ross to Yates 4850 level drifts tunnel.

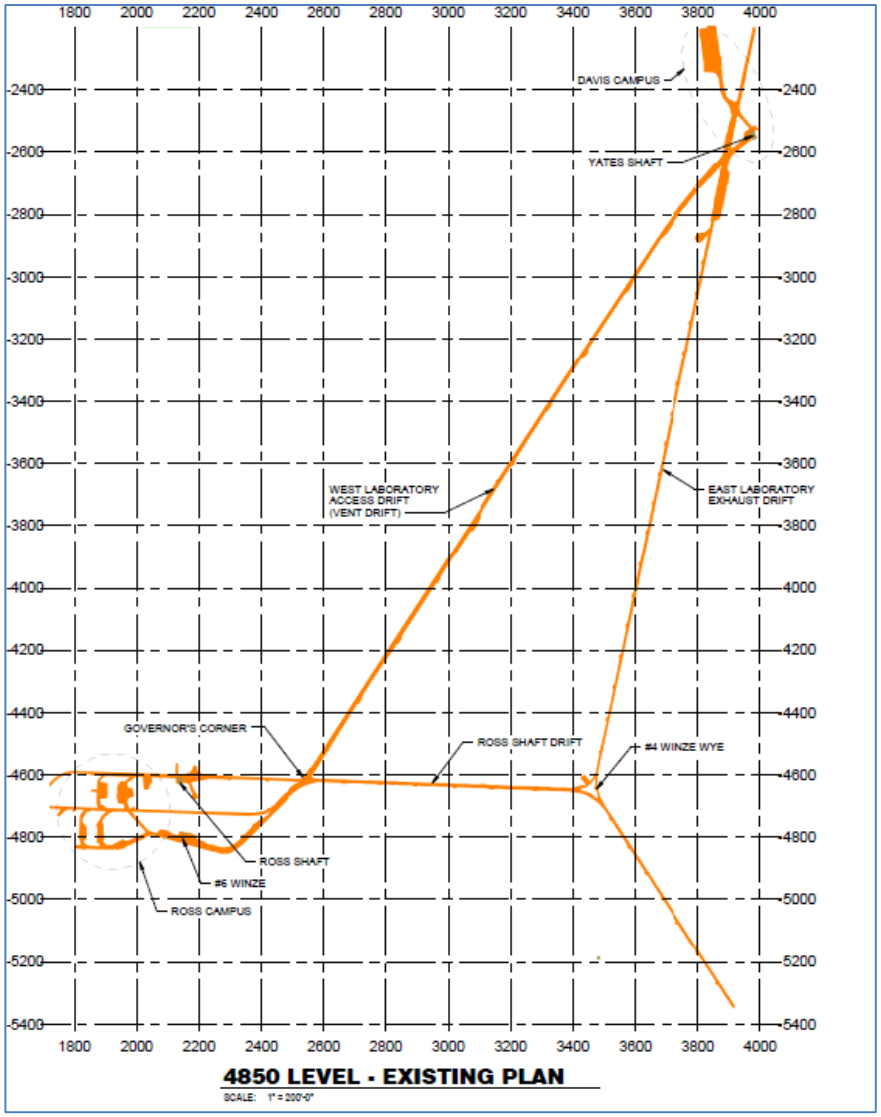
- Gyro results showed that the current HMC4850 grid is parallel with truth north within the 0º00'03" gyro accuracy and the construction facility designer doesn't need to apply any rotation correction when designing the caverns orientation



Underground network at the 4850 and Local HMC4850 to Global coordinates transformation

- A rigorous underground control network was established at the 4850 Level of the mine, along the triangle drifts tunnel between Ross and Yates shafts, with error ellipses and $\sigma x, \sigma y$ accuracy < 15 mm at 95 % confidence level

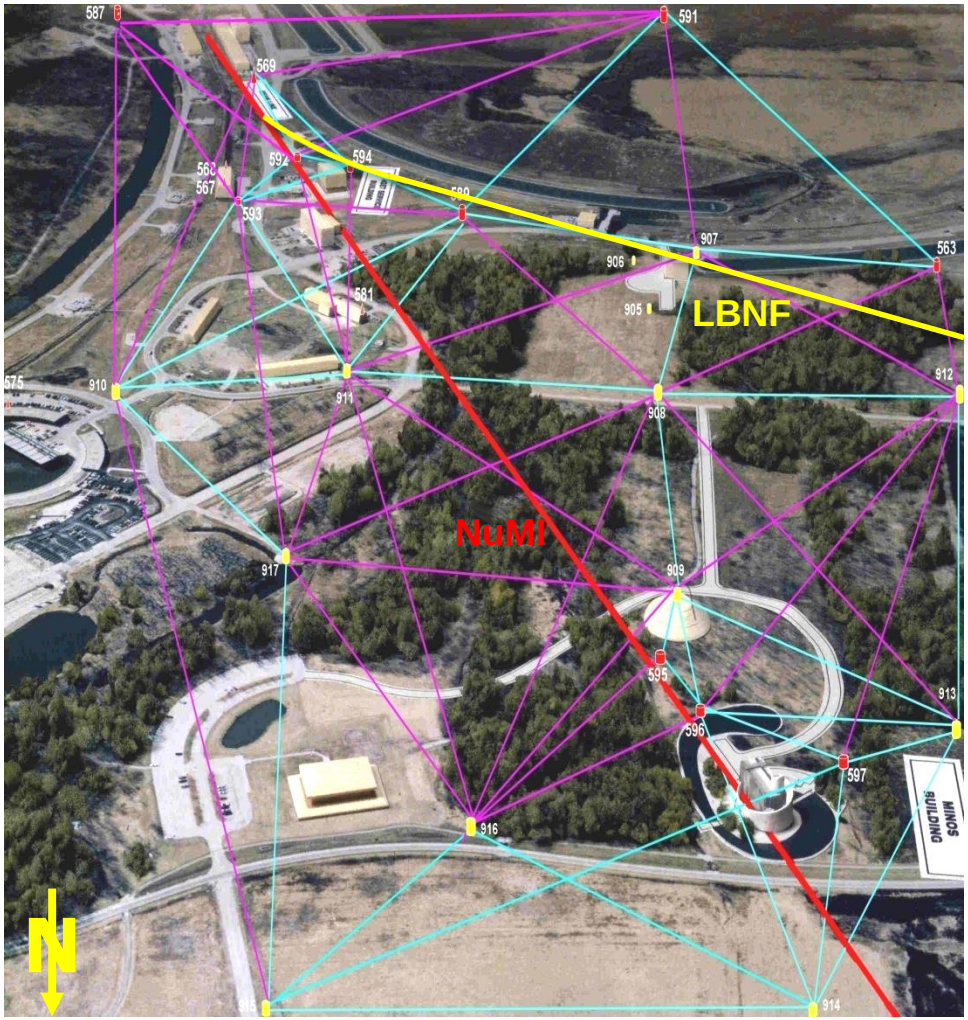
- New (2D) transformation parameters (affine function formulas) were developed between the HMC4850 Coordinates to UTM Zone 13 Global Coordinates then transformed to NAD83(2011)OPUS



Beam aiming trajectory refinement

- When calculating the neutrino beam trajectory to the center of the Far Detector as designed, the special relativity (Earth rotation) Sagnac correction should also be taken in consideration
- The correction, based on the neutrino Time of Flight and Earth's rotational velocity shows that, at the 1300 km distance and the spatial position of the Far Detector, the beam should be aimed 1.4 m ahead (Eastward) of the designed center of the detector

Primary LBNF surface geodetic network



- Provides the basis for construction surveys and for the precision underground control networks
- existing Fermilab control network (accuracy < 2 mm @ 95% confidence level)
  - horizontal geodetic datum = North American Datum of 1983 (NAD 83) based on the reference ellipsoid Geodetic Reference System 1980 (GRS-80)
  - vertical datum = North American Vertical Datum of 1988 (NAVD 88)
  - geoid model = NGS model Geoid93
- includes 3 monuments tied through CORS to SURF
- add 6 new geodetic monuments (densification around access shafts)
- ~400 GPS, terrestrial and astronomic observations
- expected error ellipses in millimeter range (@ 95% confidence level)

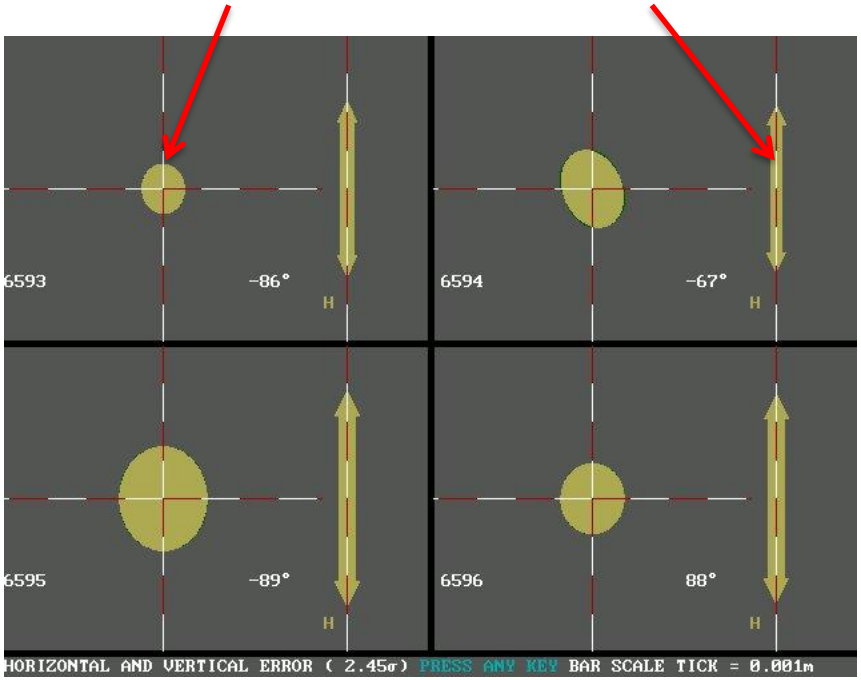
- NuMI surface geodetic network is shown
- LBNF surface network will have similar density and configuration

Primary surface geodetic network at Fermilab

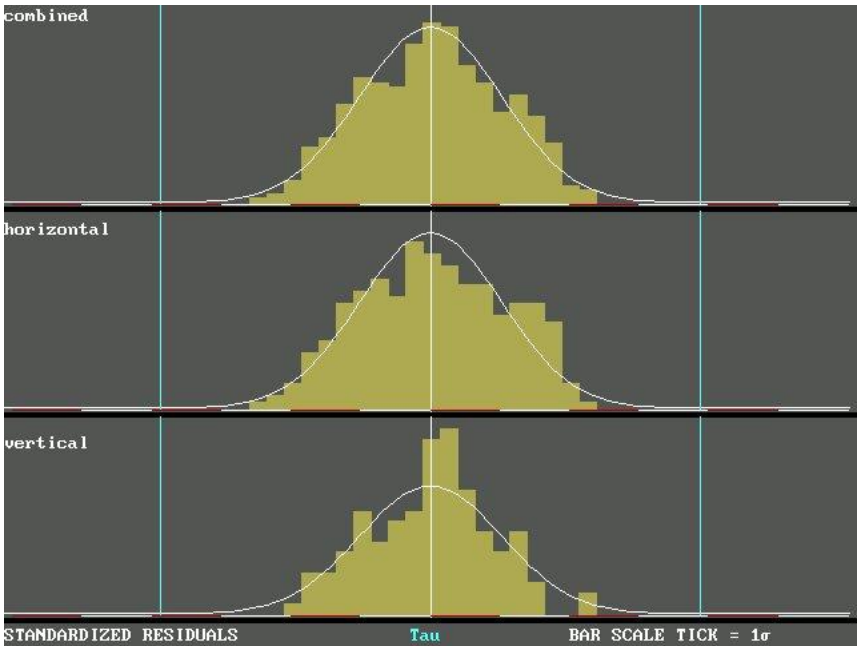
Expected accuracy results

Ellipses of Error in x, y plane

Errors in Height



Ellipses of Error @ 95% confidence level
(bar scale tick = 1 mm)

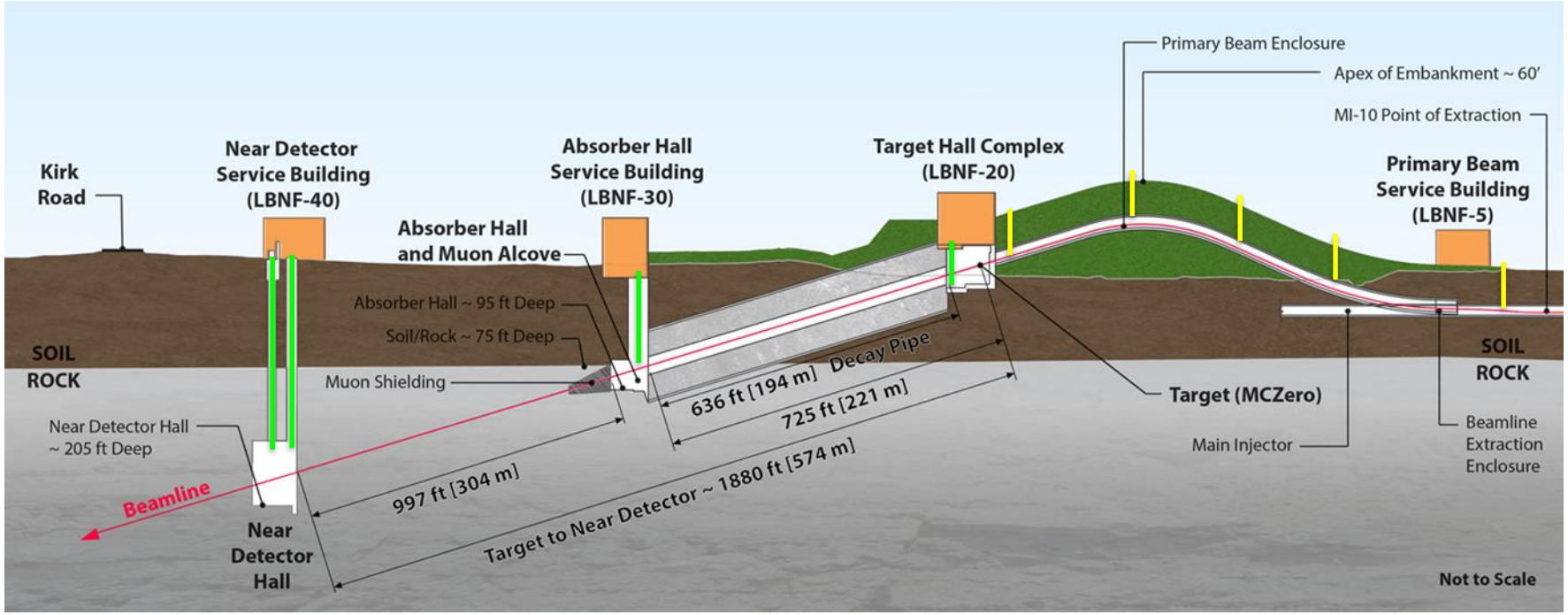


Histogram of standardized residuals
(bar scale tick = 1 s)

- NuMI surface geodetic network accuracy is shown
- LBNF results are expected to be similar

Precision underground control networks

- Provided vertical sight risers for transferring coordinates from the surface to the underground (better and more efficient for controlling error propagation in a weak geometry tunnel network)
- Network simulations => 9 locations for transferring coordinates from the surface (5 primary beamline tunnel vertical sight risers, 4 buildings Access Shafts)
- Due to the increased depth of the tunnel, designed adequate procedure for precision transfer of surface coordinates underground



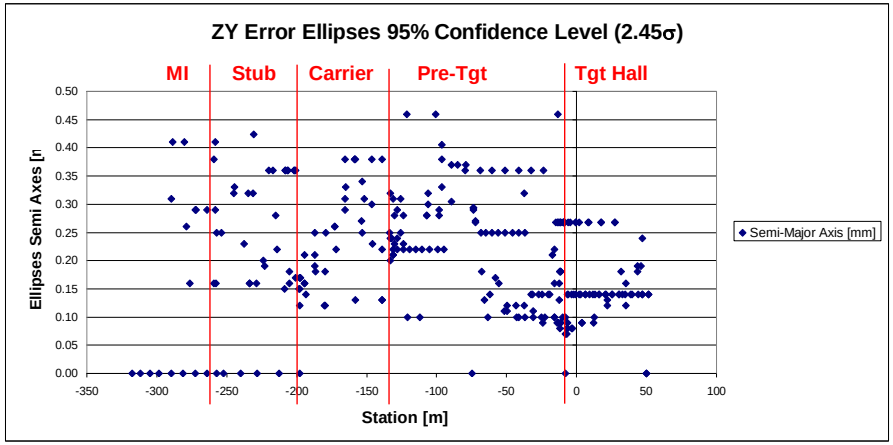
Precision underground control network
For the Primary Beam

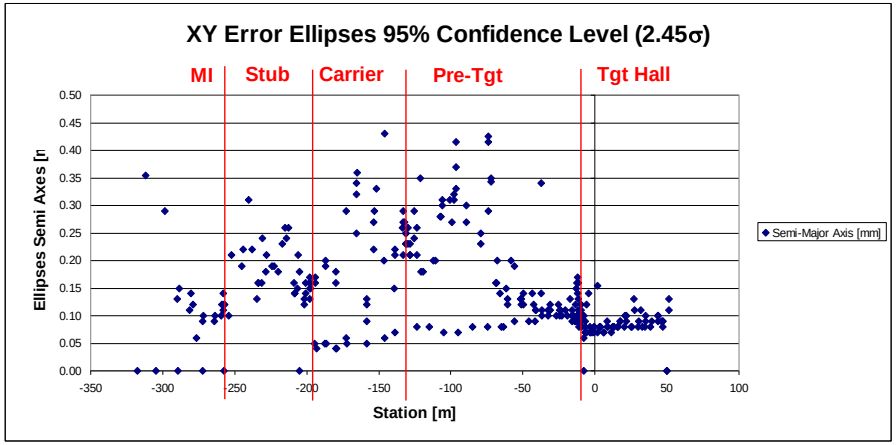
- Built to support the alignment of Primary Beam components and the Target and focusing Horns
- Components alignment scope are very similar to NuMI:
  - Primary beam magnets and instrumentation aligned to ±0.25 mm
  - Target station components aligned to ±0.5 mm
- Error budget network requirements ±0.50 mm at 95% confidence level
- Network: from MI-10 to the downstream end of the Target Hall
- Constraints at underground transfer points: MI-10, sight risers and access shafts
- Network type: Laser Tracker processed as trilateration
- Additional measurements to study and control network behaviour
- Azimuth confirmed by first order Astronomical Azimuth between final primary beam trajectory surface transfer points (for NuMI we had excellent agreement at 0.004 mrad with s=±0.001 mrad)

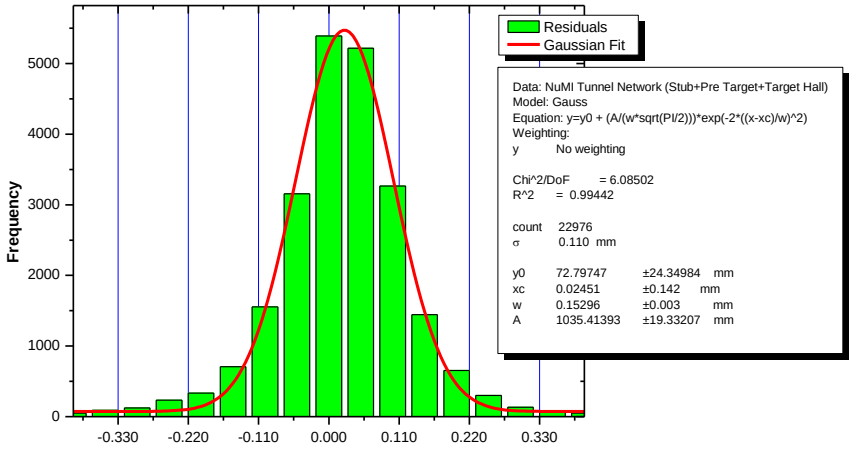
Precision underground control network

Expected accuracy results

- Errors Ellipses ±0.45 mm and histogram of residuals σ=±0.110 mm at 95% confidence level







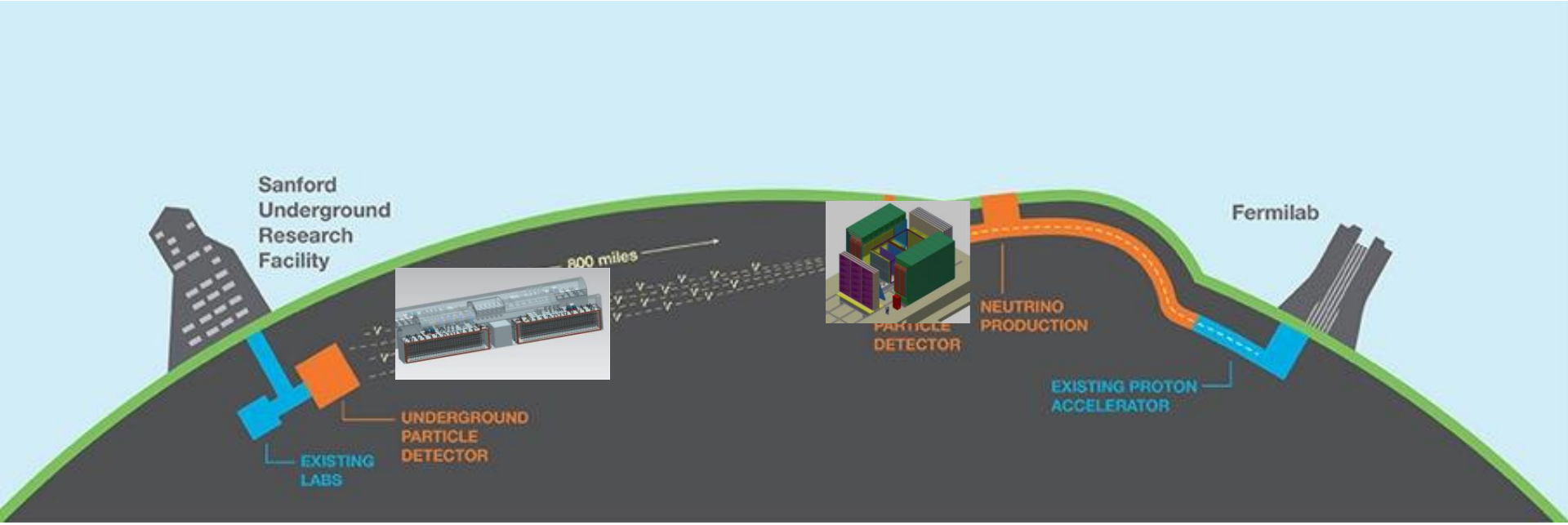
(bar scale tick = 1 σ)

- NuMI underground network accuracy is shown
- LBNF results are expected to be similar

Summary

- From the Alignment perspective, the LBNF/DUNE project is very similar with NuMI
- The distance to and the depth of the Far Detector have doubled from NuMI
- Presents a challenge with respect to the detail and complexity of the geodetic aspects
- Current status: successful 2016 comprehensive surveying campaign:
  - determined the geodetic global positions of the two sites FNAL and SURF
  - established global coordinates at the 4850 Level of the Sanford Lab to support the design and construction of Far Detector facility
  - confirmed the orientation of Homestake Mine Control (HMC) grid with respect to true North (important for the Far Detector design and construction)
  - refined the transformation parameters between the HMC Coordinates to Global Coordinates
- Past experience from NuMI:
  - The absolute global tolerances have been achieved successfully
  - The relative alignment tolerances of beamline components have been also achieved successfully
- Similar geodetic and alignment concepts are proposed for LBNF

Thank you


Sanford
Underground
Research
Facility
800 miles
Fermilab
NEUTRINO
PRODUCTION
DETECTOR
EXISTING PROTON
ACCELERATOR
UNDERGROUND
PARTICLE
DETECTOR
EXISTING
LABS