4. NOνA Scientific Design Criteria

4.1 NOνA Goals

The primary goal of the NOνA experiment is to use the existing Fermilab NuMI muon neutrino (ν_μ) beam [1] to measure electron neutrino (ν_e) appearance due to $\nu_\mu \rightarrow \nu_e$ oscillations. A secondary goal is a greatly improved measurement of the ν_μ disappearance parameters.

4.1.1 Table of Scientific Design Criteria

The two main NOνA goals translate into the scientific performance requirements summarized in Table 4.1. The requirements are developed in this chapter in the sections indicated in the table and are identical to the performance requirements of the NOνA Conceptual Design Report [1] with two exceptions: 1. We have reduced the amount of overburden required over the Far Detector as a result of further simulation, and, 2. We now require Near Detector to be rotated in the tunnel such that the directions of the neutrinos pass through the Near Detector matches those at the Far Detector as a result of further simulations and optimization of investment in the Near and Far detectors

Design Parameter	Scientific Design Criterion	Section
Distance off-axis	11.5 to 12.0 km	4.2.1
Distance from Fermilab	As far from Fermilab as practically possible.	4.2.2
Experimental Sensitivity	Figure of merit greater than or equal to 30 *The Figure of Merit is defined as the number of ν_e signal events divided by the square root of the background for 32.5 x 10^{20} protons on the NuMI target at the oscillation values $\sin^2(2\theta_{13}) = 0.1$ and $\Delta m^2_{32} = 0.0025$ eV^2 without regard to matter and atmospheric-solar interference effects.*	4.3.1
Energy resolution for ν_e Charged Current events	Less than 8% at 2 GeV	4.4.1
Energy resolution for Quasi-Elastic ν_μ Charged Current events	Less than 4% at 2 GeV	4.4.1
Far Detector overburden	~10 radiation lengths	4.4.2
Near Detector	a) At least a 20 ton fiducial volume located about 1 kilometer from the NuMI target with sufficient transverse and longitudinal size for neutrino event containment.\ b) Segmentation and orientation identical to the far detector	4.5

Table 4.1: Summary of the scientific design criteria and the chapter sections in which they are established.

4.2 Siting Requirements

4.2.1 Transverse Siting

NOνA has multiple physics goals and each goal is optimized by a slightly different neutrino spectrum. The shape and central value of the neutrino energy spectrum is determined by the transverse location (i.e. the off-axis angle) of the Far Detector so the optimization of the neutrino spectrum is realized by choosing the optimum distance to place the detector off-axis. As shown in Figure 4.1, measurements of $\sin^2(2\theta_{13})$ and measurements of the mass hierarchy are optimized at slightly different off-axis locations. The measurement of $\sin^2(2\theta_{13})$ is optimized by maximizing the total neutrino rate, favoring a more on-axis location, while the hierarchy measurement is optimized by maximizing the ratio of *L/E*, favoring a location further from the beam axis.

Since the unique feature of NOνA is the ability to measure the mass hierarchy, we have optimized for a mass hierarchy measurement at a cost of having a slightly lower event rate for the $\sin^2(2\theta_{13})$ measurement. The requirement for transverse location is chosen to be between 11.5 and 12 km off-axis. This requirement can be stated independent of the baseline since the relevant physics parameter is the ratio of a neutrino's flight distance to its energy, *L/E*, and *E* approximately scales inversely with the off-axis distance for large distances.

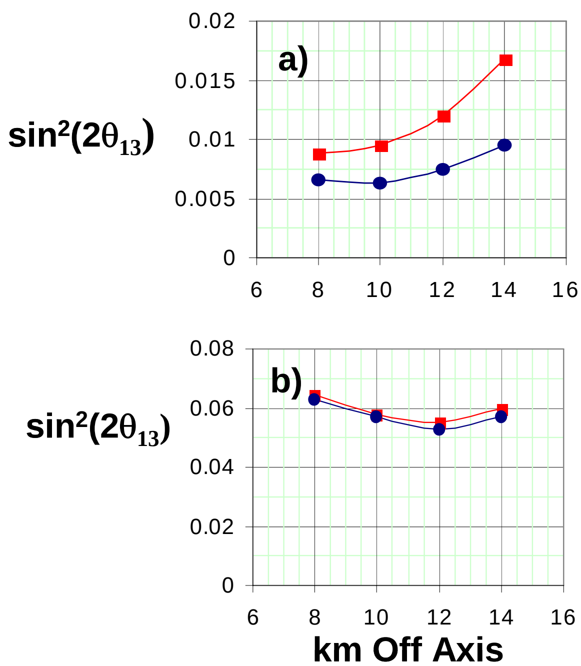

Fig. 4.1: a) Three standard deviation discovery limits for the observation of $\nu_\mu \rightarrow \nu_e$ oscillations versus the off-axis distance, and b) $\sin^2(2\theta_{13})$ versus the off-axis distance for the 95% confidence level resolution of the mass hierarchy. The upper red curve is for inverted mass hierarchy and the lower blue curve is for the normal mass hierarchy in both figures.

The curves in a) are for six years of neutrino running, while the curves in b) are for 3.6 years each of neutrino and antineutrino running. Both figures assume $\Delta m^2_{32} = 0.0025\ eV^2$ and a 25 kiloton detector at 810 km.

The curves in a) assume a typical CP phase δ, while the curves in b) are for δ such that 25% of δ values give a lower $\sin^2(2\theta_{13})$ limit and 75% give a higher limit since in this case the typical δ gives a limit above the existing experimental limit. See reference [2] for additional details.

4.2.2 Longitudinal Siting

Equation 3.4 in Chapter 3 indicates how the matter effect modifies the oscillation probability observed in the experiment. The difference between the normal mass hierarchy (blue curves) and inverted mass hierarchy (red curves) in Figure 3.3 depends on the size of the matter effect. This is displayed in a slightly different form in Figure 4.2 which plots the neutrino oscillation probability versus the antineutrino oscillation probability for experiments operating at the oscillation maximum at different baselines *L*. A measurement of the mass hierarchy depends on the separation of the red and blue curves in Figure 4.2, and this is accomplished by inserting as much matter as possible in the path between the neutrino source and the NOνA detector.

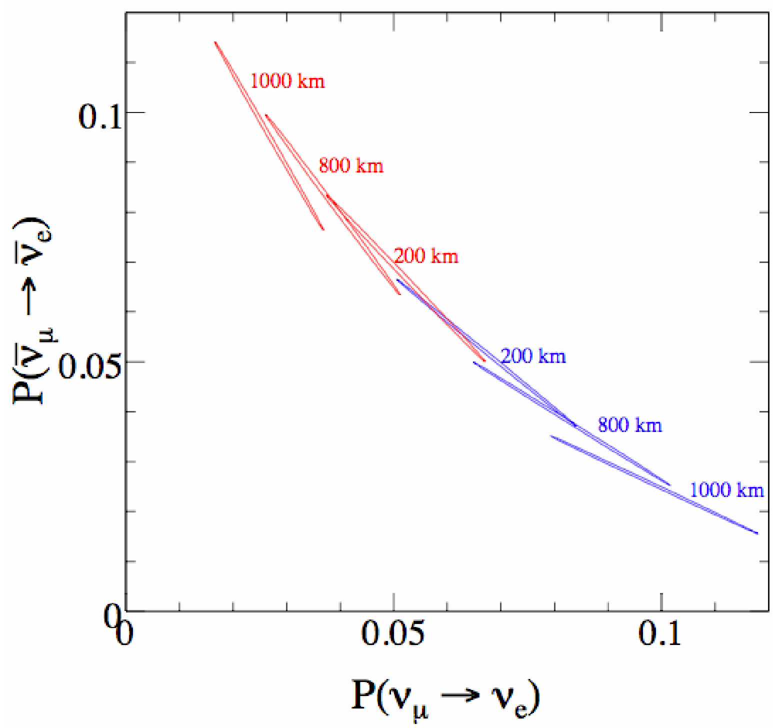

Fig. 4.2: The bi-probability curves for $\nu_\mu \rightarrow \nu_e$ oscillation for anti-neutrinos versus neutrinos, assuming a constant matter density of $\rho = 2.8$ g. cm^{-3}. Curves are calculated assuming a normal mass hierarchy (blue) and an inverted mass hierarchy (red). The curves are computed using $\Delta m^2_{12} = 8\text{x}10^{-5}$ eV2, $|\Delta m^2_{13}|=2.5\text{x}10^{-3}$ eV^2, $\theta_{12} = 35^o$, $\theta_{23}=45^o$ and $\theta_{13}=10^o$; the choice of the CP phase δ phase varies from 0 to 2π around each ellipse. The curves are computed for an experiment operating at the first oscillation maximum ($E = 2.54\ \Delta m^2_{13}$ [eV^2] L [km] / π) several choices of baseline locations as indicated

Since the sensitivity of the determination of the mass ordering depends on the distance the neutrinos travel through the earth, the NOνA Far Detector should be sited as far away from Fermilab as is practically possible. For a given detector mass, this longitudinal siting requirement is modified somewhat by the solid angle of the detector as seen from Fermilab and by the inherent divergence of the off-axis beam. Modifications also occur because longer baselines with the same off-axis transverse distance have a higher energy neutrino beam and the interaction cross section for neutrinos is proportional to the beam energy. As an example, we have calculated the 95% confidence level for determining the mass ordering for detectors at 810 km and 775 km from Fermilab. In order to have the same sensitivity to the mass ordering, a detector at 775 km would have to have 40% more mass than a detector at 810 km. It is difficult to make up for a shorter baseline with greater statistics.

4.3 Experimental Sensitivity Requirements

The primary goal of the NOνA experiment is to measure $\nu_\mu \rightarrow \nu_e$ oscillations at the "atmospheric" oscillation length with a three standard deviation sensitivity to a $\sin^2(2\theta_{13})$ value of ~ 0.01. This goal is approximately an order of magnitude greater sensitivity than can be achieved by the existing MINOS experiment [3] now operating in the NuMI beamline. This goal is also approximately the same sensitivity expected in the T2K experiment in Japan [4] that would be running in the same time frame as NOνA. Relative to T2K, NOνA has the unique advantage of a long baseline and is thus complementary to T2K.

4.3.1 Figure of Merit

There are five multiplicative factors that determine the sensitivity of the NOνA experiment to ν_e appearance: The beam power (or number of protons per year delivered to the NuMI target), the integrated data taking time (years) for the experiment, the mass of the NOνA detector, the detector's efficiency for identifying ν_e events, and the detector's ability to discriminate $\nu_\mu \rightarrow \nu_e$ oscillations from various backgrounds. The last two of these factors depend both on the detector design, such as its segmentation and light levels, and on the algorithms used to discriminate the signal from background.

The product of these factors can be expressed as a figure of merit (FoM), and its value is the basic scientific requirement for experimental sensitivity. The FoM is defined as the number of $\nu_\mu \rightarrow \nu_e$ signal events divided by the square root of the background for a six-year neutrino run with an 18 kt detector and 6 x 10^{20} protons on target per year for $\sin^2(2\theta_{13}) = 0.1$ and $\Delta m_{32}^2 = 0.0025$ eV^2, without regard to matter and atmospheric-solar interference effects.

A FoM of 30 corresponds to a three standard deviation sensitivity at the NOνA goal with $\sin^2(2\theta_{13}) = 0.01$. Matter effects (which depend on the mass hierarchy) and value of the CP violating phase δ modify the $\nu_\mu \rightarrow \nu_e$ oscillation probability and hence the sensitivity. Figure 3.4 in Chapter 3 shows the 3-sigma sensitivity of an 18 kt detector placed 12 km off axis at a baseline distance of 810 km from Fermilab as a function of δ and $\sin^2(2\theta_{13})$ for both mass hierarchies.

4.4 Far Detector Requirements

4.4.1 Neutrino Event Energy Resolutions

As discussed in Chapter 2, Section 2.2, one of the advantages of the off-axis site is that the narrow-band beam can be used to eliminate backgrounds. The rms width of the off-axis beam is about 25%, as can be seen in Fig. 2.4. With the limited statistics expected for the $\nu_\mu \rightarrow \nu_e$ oscillation signal, dividing this narrow energy range further does not increase the sensitivity appreciably. Therefore, the main use of good energy resolution is to prevent a widening of the visible energy spectrum, which would increase the background. An energy resolution of one-third the beam width, or 8% is sufficient for this purpose.

Chapter 3, Section 3.4 discussed the need for excellent energy resolution for quasi-elastic ν_μ charged current events for the precise measurement of the dominant mode oscillation parameters, $\sin^2(2\theta_{23})$ and Δm^2_{32}. The required rms resolution is 4%.

4.4.2 Far Detector Hall Overburden Requirement

The physics requirement for the detector hall comes from the need to reduce cosmic ray backgrounds to a negligible level. The very low duty cycle of the NuMI beam aids greatly in cosmic ray rejection. We assume (see reference [2], Chapter 11) that the NuMI beam will run 1.2 x10^7 cycles per year and that the spill will be 10 μs per cycle, yielding a live time of only 120 seconds per year.

To fake a $\nu_\mu \rightarrow \nu_e$ signal event, a cosmic ray would need to appear to be a horizontal event from Fermilab within a 45° cone, appear to have an electron-like track, and not leave any significant energy within 20 cm of the edges of the detector. Charged cosmic rays all fail the last requirement and thus are not a problem. Our simulation of the charged cosmic neutrino flux indicates that there would be less than one event simulating a signal event in a five-year run with no overburden over the detector.

Simulations of neutrons in cosmic rays also indicate NOνA should see only a fraction of an event from this source in a six-year run [2].

The major concern is the photon component of cosmic rays. These cosmic rays are strongly peaked towards the vertical as shown in Figure 4.3(a). Our acceptance for these events as ν_e interactions is limited to a 45° cone around the horizontal in the direction of Fermilab, see Figure 4.3(b). The convolution of the two in our simulation of the photon flux with no overburden over the detector yields 1900 events in a six-year run with a 18 kt detector as shown in Figure 4.3(c).

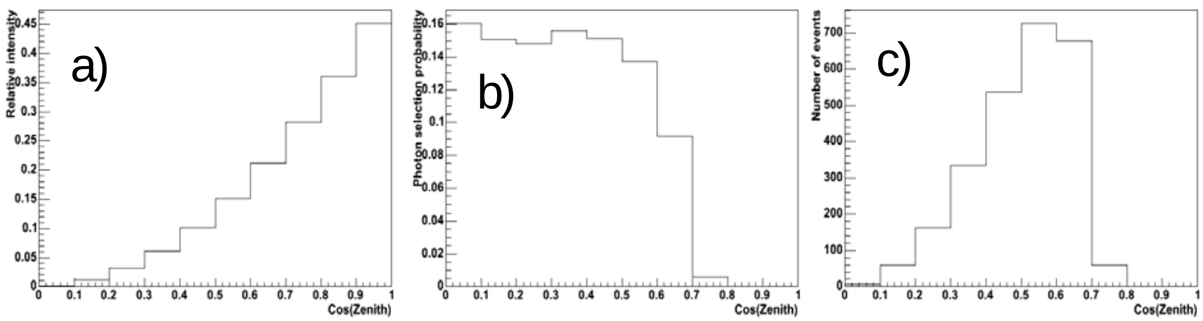

Fig 4.3: The photon component of cosmic rays. The incident cosmic rays are shown in (a) as a function of cos(Zenith). The NOνA selection probability for these events is shown in (b), and the convolution of production and selection yield the event distribution in (c).

To reduce these 1900 events to less than one event requires at least log(1900) = 7.5 radiation lengths of material in the path of cosmic-ray photons directed at the detector surface. Additional radiation lengths beyond 8 are desirable to contain the resulting shower. Previously, we planned to use 20 radiation lengths to completely contain the electromagnetic showers started by cosmic ray photons. Simulations of the residual shower component that punch through indicate that 12 radiation lengths are adequate to attenuate the energies of the shower components such that they fall outside the signal window for electron neutrino appearance.

4.5 Near Detector Requirements

The NuMI beam is not a pure ν_μ beam and has a small inherent ν_e beam admixture which can simulate the $\nu_\mu \rightarrow \nu_e$ oscillation signal. In addition neutral current ν_μ events (events where there is no outgoing muon) can simulate the $\nu_\mu \rightarrow \nu_e$ oscillation signal. In order to measure these backgrounds to the oscillation signals, NOνA requires a Near Detector to measure neutrino interactions before they have had a chance to oscillate.

The primary Near Detector design requirement is that it should be as similar as possible to the Far Detector in material, segmentation, and orientation. This requirement ensures that the efficiencies for signal and background events are identical to the NOνA Far Detector. Other requirements are that the fiducial volume be large enough to have well-defined boundaries and that the Near Detector be large enough to fully contain events from the fiducial volume. A transverse cross section of 4 m^2 is sufficient to meet the first requirement. Simulations have shown that a 70 cm wide border around the fiducial volume in the transverse dimensions and 4 m in the longitudinal dimension provides sufficient of containment of ν_e charged current events.

The NOνA Near Detector will be placed approximately 1 km from the NuMI target and will be approximately 800 m from the typical pion decay vertex. Since the neutrino flux falls roughly as the inverse of the distance squared, the flux per unit mass in the Near Detector will be approximately one million times higher than in the Far Detector. Thus, the fiducial volume of the Near Detector can be quite small. A twenty-ton fiducial volume in the Near Detector would produce about 800 times more events there than in the fiducial volume of the Far Detector. The requirement on the fiducial volume of the Near Detector is that the number of background events to the $\nu_\mu \rightarrow \nu_e$ oscillation signal be large enough to perform systematic studies over a period of about a year. A twenty-ton fiducial volume would produce approximately 1000 beam ν_e events in each of two detector locations (as discussed above) in one year, and this would be an adequate number for systematic studies.

Chapter 4 References

[1] NOνA Conceptual Design Report, March 31, 2006.

[2] The NOνA Collaboration, "Proposal to Build a 30 Kiloton Off-Axis Detector to Study $\nu_\mu \rightarrow \nu_e$ Oscillations in the NuMI Beamline," http://www-nova.fnal.gov/NOvA_Proposal/-Revised_NOvA_Proposal.html., Chapter 13.

[3] "Proposal for a Five Year Run Plan for MINOS, May 2003, NuMI Note 530.

[4] T2K Letter of Intent, January, 2003. http://neutrino.kek.jp/jhfnu/.