T2K Beam Misalignment Monte Carlo Studies at the Near Detector

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Abstract

The T2K neutrino oscillation experiment is scheduled to begin commissioning in 2009. The experiment uses a simulation of the neutrino beam to produce predictions of the relationship between observed events in the near (control) detector and the far detector, Super-Kamiokande. This correction is affected by the alignment of the proton beam on the target. We report on the results of a simulation-based study of special studies with the near neutrino detectors which could be used to measure this alignment in situ.
1 Introduction

1.1 Overview
The Tokai to Kamioka (T2K) experiment is an International neutrino oscillation experiment stationed in Japan. T2K consists of neutrino beam created at the Japan Proton Accelerator Complex (J-PARC) in Tokai, which travels approximately 295km to a large water Cerenkov detector, Super-Kamiokande, in Kamioka [2]. Beam operation is scheduled to begin in late 2009. It is to be expected that experimental results will be sensitive to slight misalignments of the neutrino beam components [6]. Monte carlo studies have been conducted in the past to study the severity of various types of misalignments. This paper discusses the results of a study extending previous simulation-based misalignment studies. We focus mostly on developing a new systematic method for identifying various types of misalignments using the on-axis near detector, called INGRID.

1.2 Neutrino Oscillations
Neutrinos are minuscule neutral leptons that frequently travel throughout the Universe at close to the speed of light. Very rarely do neutrinos interact with matter as they pass through it, which makes them difficult to detect. It has been postulated that nearly 50 trillion solar neutrinos pass through the human body every second, yet essentially all of them go unnoticed [7]. Neutrinos can be created by solar activity, by nuclear reactors, and as the byproducts of cosmic ray showers [4]. In general, however, not a lot is known about extragalactic neutrino sources.

There are (at least) three flavors of neutrinos—electron neutrinos, muon neutrinos, and tau neutrinos—which correspond to the types of charged leptons produced when the neutrinos interact [4]. The standard model predicts that each neutrino flavor has zero mass. We know today that this is not the case, in part through our experimental observation of neutrino oscillations. In the 1970s, Ray Davis’ Homestake Experiment was the first to observe neutrinos oscillating between flavors. A neutrino that starts out of one flavor will sometimes spontaneously change flavor as it travels. This phenomenon, appropriately named neutrino oscillation, is somewhat analogous quark mixing, which was observed in quarks as early as the 1960s. Since the 1970s, neutrino oscillation has been verified by many experiments, including MINOS, K2K, KamLAND, and MiniBooNE. Though it may sound surprising, neutrino oscillation can be predicted using quantum mechanics. The key factor leading to neutrino oscillations is that each neutrino flavor eigenstate is not a mass eigenstate, but is instead a linear superposition of mass eigenstates. This is best shown by example.

Assume that a neutrino $\nu_l$ can have one of three flavors, $l = \{e, \mu, \tau\}$, and that there exist three mass eigenstates $\nu_m$, $m = \{1, 2, 3\}$\(^1\). As stated above, a given flavor eigenstate $\nu_l$ is a coherent superposition of mass eigenstates [4]:

$$\nu_l = \sum_{m=1}^{3} U_{lm} \nu_m,$$  \hspace{1cm} (1)

where $U$ is the neutrino mixing matrix, also known as the Maki-Nakagawa-Sakata (MNS) matrix. Assume for simplicity that the neutrino being considered is created at $t = 0$ with momentum $p_\nu$. Therefore, in units where $c = \hbar = 1$, the neutrino’s wave function is

$$\psi(x, t = 0) = \sum_{m=1}^{3} U_{lm} \nu_m e^{ip_\nu x},$$  \hspace{1cm} (2)

\(^1\)It is questionable whether or not there are only three neutrino flavors, but for the purpose of this example we will assume this to be true.
where $x$ represents the position of the neutrino. Furthermore, since $\nu_m$ are mass eigenstates, time dependency can be incorporated simply by multiplying each eigenstate by a factor $e^{-iE_m t}$, where $E_m$ is the energy of mass eigenstate $m$. The time dependent wave function becomes

$$\psi(x, t) = \sum_{m=1}^{3} U_{lm} \nu_m e^{ip_{\nu} x} e^{-iE_m t}. \quad (3)$$

Given what we know about neutrinos, we can begin to alter and reduce this wave function by making reasonable approximations. Since neutrinos have very small masses, we know that $M_m << p_{\nu}$, where $M$ is mass, and therefore

$$E_m = \sqrt{M_m^2 + p_{\nu}^2} \simeq p_{\nu} + \frac{M_m^2}{2p_{\nu}}. \quad (4)$$

In addition, since we know that neutrinos travel at close to the speed of light, as long as we define $x = 0$ as the position where the neutrino is born we can approximate $x \simeq t$ (keeping in mind that we are using units such that $c = 1$). The approximate time dependent wave function for our neutrino becomes

$$\psi(x, x) \simeq \sum_{m=1}^{3} U_{lm} \nu_m e^{-\frac{M_m^2}{2p_{\nu}} x}. \quad (5)$$

Using the inverse of eq. (1), $\nu_m = \sum_l U_{lm}^* \nu_l$, we can replace $\nu_m$ in eq. (5), which gives us the new wave function

$$\psi(x, x) \simeq \sum_{l'} \left[ \sum_m U_{lm}^* e^{-\frac{M_m^2}{2p_{\nu}} x} U_{l'm}^* \right] \nu_{l'}. \quad (6)$$

We are interested in finding the probability that a neutrino of a given flavor $l$ oscillates into a different flavor $l'$. Quantum mechanics tells us that this probability can be derived simply by taking the absolute square of the coefficient to $\nu_{l'}$ in eq. (6). If $P(l \rightarrow l', x)$ denotes the probability that the change of flavor has occurred when the neutrino is at a position $x$, then we reach the result [4]

$$P(l \rightarrow l', x) = \left| \sum_{m'} U_{lm'}^* \nu_{l'} e^{-\frac{M_m^2}{2p_{\nu}} x} U_{l'm}^* \right|^2 \sum_{m} U_{lm}^* e^{-\frac{M_m^2}{2p_{\nu}} x} U_{l'm}^*$$

$$= \sum_m |U_{lm}|^2 |U_{l'm}|^2$$

$$+ \sum_{m \neq m'} \text{Re} \left[ U_{lm} U_{lm'}^* U_{l'm'} U_{l'm}^* \cos \left( \frac{\Delta M_{mm'}^2 x}{2p_{\nu}} \right) \right]$$

$$+ \sum_{m \neq m'} \text{Im} \left[ U_{lm} U_{lm'}^* U_{l'm'} U_{l'm}^* \sin \left( \frac{\Delta M_{mm'}^2 x}{2p_{\nu}} \right) \right] \quad (7)$$

where $\Delta M_{mm'}^2 = M_m^2 - M_{m'}^2$.

Note two important points:

1. If we had started our derivation under the assumption that each neutrino flavor eigenstate is a mass eigenstate (rather then a superposition), we would not observe the possibility of neutrino oscillation as we do in eq. (7). In order for neutrinos to oscillate, eq. (1) must be true.

2. If $\Delta M_{mm'}^2$ is equal to zero, eq. (7) becomes constant with respect to $x$, and the probability of a neutrino changing flavor becomes independent of its position. As a result, the oscillatory phenomenon that has been observed by experiments would not be accurately
predicted by eq. (7). This is one of the leading arguments supporting massive neutrinos, which contradicts the theory of massless neutrinos predicted by the standard model. Since neutrinos must not have equal masses, their masses cannot all be equal to zero.

In qualitative terms, neutrino oscillations can be described in the following way. Due to differences in mass, the mass eigenstates $\nu_m$ for a neutrino that starts out of flavor $l$ propagate at different speeds. In particular, the heavier mass states of $\nu_l$ propagate slower than the light mass states. Over time, the components $\nu_m$ become out of phase, and no longer add up to $\nu_l$. As a result, the neutrino picks up components of other flavors, and the probability of the neutrino being observed as a different flavor becomes nonzero.

1.3 The Maki-Nakagawa-Sakata Matrix

The Maki-Nakagawa-Sakata (MNS) matrix describes the superposition of neutrino mass eigenstates that make up each flavor eigenstate, as in eq. (1). It is a 3 $\times$ 3 matrix when we consider the standard three neutrino theory. In some experimental cases, a neutrino flavor can be ignored and the MNS matrix takes on a simpler 2 $\times$ 2 form. On the other hand, if one or more sterile neutrinos are considered, it becomes larger. Assuming that neutrinos are not majorana particles, the 3 $\times$ 3 form of the MNS matrix is given by

$$ U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 1 & 0 & 1 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} $$

where

$$ \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}. $$(8)

In eq. (8) $s_{12}$ represents $\sin \theta_{12}$, $c_{23}$ represents $\cos \theta_{23}$, and so on. The parameters of $U$ ($\theta_{12}$, $\theta_{13}$, $\theta_{23}$, and the complex phase $\delta$) are measured by experiment. $\theta_{12}$ and $\theta_{23}$ have been measured reasonably well, and $\theta_{13}$ is known to be very close to if not equal to zero. In order for CP violation to exist for the case of neutrino oscillations, all elements of $U$ must be nonzero. Hence, an accurate measurement of $\theta_{13}$ is of utmost importance to the scientific community, and it is one of the primary objectives of T2K. A measurement of $\theta_{13}$ requires the observation of neutrino oscillations between electron and muon neutrinos, which has yet to be seen.

1.4 The Basic Idea of T2K

T2K is a second-generation experiment designed for observing neutrino oscillations between $\nu_\mu$ and $\nu_e$ [2]. The methodology for doing this is actually quite simple. A proton beam is smashed into a target, generating a beam of secondary particles (mostly pions) that decay to create neutrinos of muon flavor. A near detector that is located relatively close to the target, detects some of the muon neutrinos as they pass through it. Though not a whole lot is known about the studied oscillation, it can be shown that the probability of a neutrino changing flavor before reaching the near detector is infinitesimal. The neutrinos then travel approximately 295km across Japan to a far detector called Super-Kamiokande (SK). This large trek gives muon neutrinos the opportunity to oscillate into electron neutrinos. As they pass through SK, some neutrinos interact and create detectable charged leptons which correspond to their

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2A majorana neutrino is one that is its own anti-particle.
flavor. Based on what we see at the near detector, we can make approximations as to how many neutrinos of each flavor we should see at SK. Theoretically, if oscillations do not take place, we will only see muon neutrinos at both detectors. To search for evidence of neutrino oscillations, we use SK to simultaneously look for the appearance of electron neutrinos and the disappearance of muon neutrinos, and thus T2K is classified as both an appearance and a disappearance experiment.

Perhaps the most relevant plot that will be used to observe oscillations, called the far-near ratio, is a ratio of the $\nu_\mu$ (or $\nu_e$) flux at SK to the $\nu_\mu$ (or $\nu_e$) flux at the near detector plotted with respect to energy. Monte carlo has been used extensively to study what we should expect a far-near ratio to look like assuming that oscillations between $\nu_\mu$ and $\nu_e$ do not occur (fig. (1) shows an example of a far-near ratio generated by monte carlo). T2K will generate experimental versions of this plot that can be compared to the monte carlo. Without going into detail, deviations between experimental far-near ratios, and simulated far-near ratios (which assume oscillations do not occur) are evidence that oscillations between $\nu_\mu$ and $\nu_e$ are possible.

In order to reduce experimental error, the neutrino beam must be nearly monoenergetic. Parent pions that are generated at the target decay isotropically into neutrinos in the center of mass frame. Due to the Lorenz boost, however, at certain finite decay angles, the energy of a neutrino exhibits little dependence on the energy of its parent pion as illustrated in fig. (2) [3]. In order to take advantage of this effect, T2K is designed such that the neutrino beam is oriented at a 2.5$^\circ$ angle with the parent pion beam. As a result, the neutrino beam is quasi-monoenergetic regardless of the energy spread among the parent pions [2].

1.5 T2K Goals

Experiments in the past have measured oscillations between $\nu_\mu$ and $\nu_\tau$, and between $\nu_e$ and $\nu_\tau$, but oscillations between $\nu_\mu$ and $\nu_e$ have yet to be observed. It is believed that these oscillations can exist, but are rare due to the fact that $\theta_{13}$ is small. T2K hopes to be the first experiment to observe transitions from $\nu_\mu$ to $\nu_e$, and thereby obtain a measurement for $\theta_{13}$.

There are several other less direct experimental goals associated with T2K. The field of neutrinos is relatively young, and our understanding of neutrino mass and behavior is weak at best. Many unanswered questions remain. What is the neutrino mass hierarchy? How much mass in the universe is contributed by neutrinos? Do neutrinos exhibit CP symmetry, and if
Figure 2: Transverse neutrino momentum vs. longitudinal neutrino momentum: we see that at certain decay angles the energy of the neutrino produced becomes relatively independent of that of the parent pion.

not, can they be used to help explain the existence of the universe? Do sterile neutrinos exist, and are neutrinos majorana particles? In addition to measuring $\nu_\mu$ and $\nu_e$ oscillations, the T2K collaboration hopes to take steps towards answering some of these broader questions.
2 Components of T2K

T2K begins as a proton beam accelerated between 30GeV and 50GeV by J-PARC [6]. Many experimental components are responsible for making this beam useful for studying neutrino oscillations. In this section I give an overview of each major component of the experiment by explaining its purpose and basic functionality. Those who are familiar with T2K are advised to skip over this section.

2.1 Target

A carbon target is used to generate a pion beam from the proton beam created at J-PARC [6]. When protons are accelerated and smashed into the target, secondaries result from the interactions that take place within the copper core. The target for T2K is a 90cm long cylinder with a radius of 1.3cm. 90cm corresponds to roughly 1.9 interaction lengths, which means that about 85% of the protons that hit the target interact as they pass through it. The composition and size of the target are designed to maximize the production of pions, which decay into muon neutrinos through the following decays:

\[
\pi^+ \rightarrow \mu^+ + \nu_\mu \\
\pi^- \rightarrow \mu^- + \bar{\nu}_\mu .
\]  

The target also creates a small percentage of kaons, which are responsible in part for background particles. $\nu_e$, $\bar{\nu}_e$, and $\bar{\nu}_\mu$ backgrounds generated by secondary decays need to be minimized in order to prevent improper particle identification and false oscillation measurements. The two most relevant kaon decays are

\[
K^+ \rightarrow \mu^+ + \nu_\mu \\
K^+ \rightarrow \pi^0 + \mu^+ + \nu_e .
\]  

Muons, which are generated from pion and kaon decays are also responsible for background given the relevant decay

\[
\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu .
\]

Backgrounds can be minimized by clever engineering of the beamline.

2.2 Focusing Elements and Decay Volume

Secondaries that are created at the target often do not have trajectories that are perfectly aligned with the beam path. Instead, they exhibit a broad momentum spread that needs to be focused [3]. Magnetic horns are designed to focus the beam onto the correct path.

A focusing horn, pictured in fig. (3), consists of two axially symmetric conductors [3]. A toroidal magnetic field is produced between the conductors who’s magnitude $(qv \times B)$ creates a restoring force for particles of the correct sign ($\pi^+$, for example), and a defocusing force for particles of the opposite sign. Due to the (often parabolic) shape of the horn, the amount of time that particles spend within the magnetic field depends on how well focused they are. Secondaries traveling along the beam path pass through the horns unperturbed. Those that are less focused, however, spend a greater amount of time between the conducting sheets and thus get a stronger kick towards the beam path. Magnetic horns are by no means perfect, but we will see in the results of this paper that the effect of their absence is significant.

Horns can be placed consecutively with one another in order to provide a stronger (but more complicated) focusing effect. T2K utilizes a three-horn system to focus the beam before it enters the decay volume [2]. A decay volume of approximately 100m is used in which secondaries decay to produce muon neutrinos and backgrounds. The decay volume ends at a muon monitor and a beam dump designed to stop secondaries but not neutrinos, and prevent them from reaching the near detector.
2.3 Near Detector

There exist two near detectors located 280m downstream of the target. An off-axis near detector made from fine-grain scintillator tracker sits on the same axis as the far detector, and is used to determine the neutrino flux that is expected at SK [6]. It is designed to detect $\nu_\mu$ and $\nu_e$ indirectly through the following neutron interactions:

$$\nu_\mu + n \rightarrow \mu^- + p$$
$$\nu_e + n \rightarrow e^- + p,$$

where $\mu^-$ and $e^-$ are detectable and distinguishable by the scintillator tracker.

As it turns out, the alignments of components along the beamline are much easier to determine by looking at on-axis neutrino decays rather than decays that occur $2.5^\circ$ off-axis. A second near detector called the Interactive Neutrino GRID (INGRID) is located on-axis with the parent pion beam, and is used to monitor beam direction, stability, and mean energy [6]. Ideally, it will be possible to detect any significant experimental misalignments at INGRID, and it is therefore the primary focus of this paper.

INGRID consists of 14 detector modules in the shape of a plus sign as illustrated in fig. (4). Each module covers approximately one square meter of beam area [6]. Modules are composed of iron plates and scintillator trackers sandwiched together. A single module contains 11 scintillator trackers at $1 \times 1 \times 0.03 m^3$, each consisting of vertical and horizontal layers. Sandwiched between the trackers are 10 iron plates of $1 \times 1 \times 0.1 m^3$. This means that each module contains roughly 7.8 tons of iron for neutrinos to interact with. The scintillator panels of INGRID detect the products of the neutron decays shown above in eq. (13) that occur within the iron. Each module is also surrounded by scintillator veto panels.

For an interaction to be identified as an event, it must hit multiple layers of scintillator. Three relevant event selection cuts are considered [6]:

1. **Tracker Cut**: Selected events must hit at least three successive tracker planes in-time (both vertical and horizontal layers).

2. **Veto Cut**: Events are rejected if the veto scintillator upstream of the tracker plane is hit in-time. Events that hit the veto scintillator have a high probability of being background
3. Optional $\theta$ Cut: It is possible to require selected events to have a track angle less than a given value from the neutrino beam. It is still uncertain of whether or not this cut will be implemented during data collection. For simplicity, it was ignored in the monte carlo studies discussed in this paper.

Contamination by neutrinos interacting outside of INGRID are expected to account for less than 1% of the event rate.

Much effort has gone into understanding INGRID’s sensitivity to beam direction. By looking at the event rate of seven consecutive modules, we get an understanding of the beam alignment with respect to the axis of the modules. Previous monte carlo studies have shown that the beam profile center can be measured at INGRID with 2.3cm precision given $2.4 \times 10^{18}$ protons on target (POT).

2.4 Far Detector

The Super-Kamiokande detector (SK) located in Kamioka Japan is a water Cerenkov detector used as the far detector for T2K experiment [2]. Its cylindrical cavity is 42m high and has a radius of 19.5m. Inside the detector, 11,146 photo-multiplying tubes (PMT) surround 50,000 tons of pure water. During standard beam operation, roughly one neutrino will interact with a water molecule within the detector per day. Events at SK are synchronized with spills at the target to ensure that they are not caused by backgrounds. Synchronization accuracy has been demonstrated to be less than 200ns.

When a neutrino interacts in SK, it generates either a muon or an electron depending on its flavor, which then produces Cerenkov light rings that can be seen by the photo-multiplying tubes. Since electrons generate fuzzier rings then muons the two particles are distinguishable, and thus so are different neutrino flavors. The PMT trigger threshold has been shown to be as low as 4.3MeV.
3 Monte Carlo Studies

3.1 Overview

Since T2K is made of large hardware components spread over vast distances, misalignments within the experiment are a serious concern. It is expected that experimental results will be sensitive to the angle and position of the incident proton beam, and to the positions of the focusing horns [6]. As illustrated in fig. (6), misalignments on the millimeter scale can effectively alter the measured far-near ratio.

This poses a problem, since differences between the experimental and theoretical far-near ratios will ideally be used as evidence of neutrino oscillations. In order to be sure that deviations are not associated with sources of error it is important to minimize misalignments in the experiment. It was predicted in the 2006 PAC report, for example, that for T2K to obtain reasonable results, the beam direction must be monitored with precision better than 1 mrad.

3.2 JNUBEAM

Nearly all interactions can be modeled by probability distributions. Thus, computer simulations can use weighted random number generators (called monte carlo) to generate preliminary results for particle physics experiments. Extensive monte carlo has been implemented by the T2K collaboration to develop our understanding of the experimental setup [2].

The predecessor of T2K was modeled using GEANT3, a particle physics simulation program. This outdated simulation has since been updated for T2K. The current simulation, called JNUBEAM, models proton interactions within the target and the behavior of particles moving along the beamline with reasonable accuracy. JNUBEAM has been used in the past for preliminary data generation and the determination of the basic experimental setup of T2K. Since JNUBEAM is a fairly accurate model of T2K, it is a great utility for studying experimental misalignments. In this study, we use JNUBEAM to simulate misalignments and thereby understand how they effect the quality of the neutrino beam, and how they can be observed at INGRID.
3.3 Calculating Alignments

The focusing effect caused by the three magnetic horns along the beamline is complicated and difficult to predict and study. As a result, a single measurement of the neutrino flux at INGRID does not provide enough information to expose all potential misalignments. A shift of the beam center at INGRID could be the result of a proton beam positional shift, a misalignment of the first focusing horn, a misalignment of the second focusing horn, etc. In order to refine our understanding of proton beam and horn alignments, it is important to generate monte carlo beam data for a variety of configurations.

For this project, we attempted a unique study that involved measuring the beam center at INGRID while turning different horns on and off systematically. The motivation for this idea was straightforward. We figured that measurements of the beam center at INGRID for different horn on/off configurations could be compared to generate a thorough understanding of misalignments of the proton beam and focusing horns. Setting up this analysis, however, turned out to be more difficult than we had originally hoped, due in part to our discovery of some interesting characteristics of the unfocused beam. An equation for generating misalignments that utilized the INGRID beam center for multiple different horn configurations never emerged. Instead, we used a templated fitting technique to calculate the alignment of the proton beam for different horn configurations separately. The results of this method, among other things, are discussed in the following sections.
4 Positional Misalignments

4.1 Misalignments Tested

A realistic misalignment of the position of the proton beam relative to the target is 1mm. In order to thoroughly understand the effect of this type of misalignment, however, it is important to look at a wider range of positional offsets. Horizontal (x) and vertical (y) misalignments were simulated independently. For each axis, the beam was shifted between -8mm to 8mm in 2mm increments, where the origin is considered to be the center of the front face of the target. In this section, we only discuss data related to the cases where all horns were turned on and all horns were turned off.

4.2 Flux and Far-Near Ratio

The accuracy of the results produced by T2K depend upon how well we understand the off-axis energy distribution of the neutrino beam, in addition to how well we can predict the far-near ratio. In this section, we try to understand the potential consequences associated with positional misalignments of the proton beam by focusing on these beam properties in particular. Since the beam that is used for generating oscillation data will always be fully focused, we will only consider the case where all three of the focusing horns are turned on in this section. Horns off data will be saved for our INGRID analysis in the following section.

The off-axis energy (or flux) of the neutrino beam can be measured either by the near off-axis detector 280 meters downstream of the target (OA280), or by SK. An example plot of the beam flux for a perfectly aligned default neutrino beam is illustrated in fig. (7), measured by both the off-axis detector and SK. As can be seen, the beam flux contains a single peak, the position of which remains relatively constant assuming the beam should be left unaltered (standard deviation \( \approx 2.5 \times 10^{-4} \text{GeV} \), based on simulation data). Changing the positional alignment of the proton beam, however, does have an effect on the shape and position of this peak. An example of the change in the flux caused by a misalignment of the proton beam can be seen in fig. (8).

For a quantitative analysis of how proton beam alignment affects the flux, we will look at how the peak flux position shifts for different x and y misalignments. In order to determine the energy of the peak flux, a certain region of the peak was approximated by a Gaussian function. The position of the peak could thus be determined by the center of the Gaussian fit. The near off-axis flux was fit between 0 and 0.75 GeV, while the flux at SK was fit between 0.45 and 0.8 GeV. These energy regions were selected because they appeared to offer the closest fit possible.

Using this technique, the flux peak energy was identified for each positional misalignment that was simulated. The relevant plot for this study, shown in fig. (9), shows the shift in...
flux peak position for each positional misalignment of the proton beam. What can be seen in this plot is that the flux peak position is more sensitive to y misalignments then it is to x misalignments. At the off-axis near detector, the peak energy shifts about -0.3MeV/mm for x offsets of the proton beam, and about 1MeV/mm for y offsets. At SK, the peak shifts about 1MeV/mm for x offsets, and about 3MeV/mm for y offsets. The increased sensitivity to y offsets is most likely the result of the geometry of the detectors. This agrees with previous results produced by Eric Zimmerman and Josh Spitz in 2006 [5].

Another key property of the neutrino beam, as mentioned above, is the far-near ratio. In order to understand the affect that the positional alignment of the proton beam has on the far-near ratio, we focused on the tail. At energies greater then 1GeV, the far-near ratio tends to follow a linear path. This can be seen in fig. (1). The tails of far-near ratios for differently aligned beams are plotted in fig. (10). Again, we see greater sensitivity to y misalignments. In the right-hand plot, Each linear best-fit is for the most part stacked in order by the magnitude of the misalignment. For example, the value of the far-near ratio at 1.5GeV shifts about 1.5% per millimeter offset. This correlation is not as evident for x misalignments of the proton beam, probably due to decreased sensitivity in the x direction.

4.3 Observing Positional Alignment at INGRID

One of the primary functions of the INGRID detector is to detect misalignments within the experimental setup. Monte Carlo can be used to predict the appearance of the beam at INGRID for specific misalignments. In this section, we try to understand how the beam center at INGRID changes with the positional alignment of the proton beam.

INGRID is shaped like a plus sign with vertical and horizontal extensions. Thus, when shifting the x (or y) position of the proton beam, we will look at the neutrino rates specifically on the x (or y) axis of INGRID. In other words, we make the assumption that shifting the x position of the proton beam has little effect on the beam center with respect to the y axis.

An example plot of neutrino rates at INGRID for default and misaligned beams is shown in fig. (11). As you can see, the shape of this curve can be fit reasonably well by a gaussian function. Thus, we can determine the center of the the beam at INGRID using the average of a gaussian fit. Fig. (12) shows the beam center measured in this way for each positional
Figure 9: Illustration of how the flux peak position shifts for different misalignments. The flux is measured by both off-axis near detector and by SK.

Figure 10: **Left:** Far-near ratio tails for proton beam offsets in the $x$ direction; **Right:** Far-near ratio tails for proton beam offsets in the $y$ direction
misalignment, with all of the horns turned on and off.

We see again that the beam center shifts more dramatically for y misalignments than it does for x misalignments, as predicted by earlier results. Furthermore, the shift at INGRID changes direction when the horns are turned off. A beam that is focused on the positive domain of x INGRID can be focused on the negative domain simply by removing any focusing. This effect is most likely the result of the complex three horn system. A misaligned proton beam may get over-bent by the first focusing horn, causing the misalignment to move in the opposite direction.

One of our goals is to understand how accurately we can predict a positional misalignment of the proton beam using our knowledge of the beam center at INGRID. To address this question, we developed a pseudo-experiment analysis utilizing a templated fitting technique. For each positional misalignment, 1,000 pseudo-experiments were generated with 10,000 neutrino events at INGRID in each. The details of this model are included in Appendix B.

Though our model is not perfect, it does predict positional offsets with reasonable accuracy. Fig. (13) shows the offsets predicted by this templated fitting technique versus the actual offsets of the proton beam. For each misalignment, the predicted offset fell within one standard deviation of the actual offset. Predicted offsets and actual offsets differed on average by 6%.

In order to interpret results produced by this templated fitting technique, we must assume that all aspects of the experimental setup are aligned except for the position of the proton beam with respect to the target. If we make this assumption, given 10,000 events at INGRID, we can predict the x position of the proton beam with a precision of 0.76mm, and the y position of the proton beam with a precision of 0.72mm. 10,000 events at INGRID corresponds to $4 \times 10^{17}$ protons on target, or approximately 75 minutes of beam at full intensity.

When the horns are turned off, however, these numbers look slightly different. Since the beam is no longer focused, generating 10,000 events at INGRID requires more beam time (when the beam is unfocused, there is a smaller probability that a neutrino generated via a pion decay will be on path to pass through INGRID). Namely, when the horns are off, 10,000 events corresponds to $2 \times 10^{18}$ POT, or approximately 370 minutes of beam at full intensity. In this case, 10,000 events at INGRID allows us to predict the x position of the proton beam...
4.4 Why are INGRID Offsets so Large?

Referring back to fig. (12), it is interesting to see that shifts in the beam center are large even when the horns are all turned off. With no horns on, the beam experiences no focusing effects, so one might expect it to travel in a relatively straight line. If this were true, a proton beam offset of several millimeters would cause the beam center at INGRID to shift by approximately the same amount. Instead, we see that a positional offset on the millimeter scale leads to an offset at INGRID on the centimeter scale. This implies that moving the position of the proton beam somehow causes the beam to be steered off path.

This effect is somewhat surprising, and its cause is still not thoroughly understood. A reasonable guess as to why this happens is that interactions within the target exacerbate positional misalignments. When the proton beam is not centered within the target, decay products that move away from the target center have a greater chance of escaping the target before further decaying, because they have less target material to pass through. As a result, on average, more particles escape through the thin side of the target than through the thick side, and the average beam path becomes angled away from the target center.

Since this is only a guess as to the actual cause of this effect, we will leave it to the interpretation of the reader. The following plots are included to help give a more thorough understanding of the effect. These plots are intended to be helpful even if they do not offer a complete picture of what is going on. Fig. (14) shows the average decay position within the target for default and misaligned beams where the decays produce parents that in turn generate neutrinos that pass through INGRID. Fig. (15) is similar, but instead shows the average position at which parents decay within the target. For both of these plots, all of the
Figure 13: Accuracy of templated fitting technique for positional offsets of the proton beam in the x and y directions.

Horns were turned off. Finally, fig. (16) shows the shape of the beam at x INGRID for different energy domains.
Figure 14: Average position of parent particle generation within the target. The target occupies the entire plot space. Misalignments are in x and parents are required to generate neutrinos that reach the x axis of INGRID.
Figure 15: Average position of parent particle decays within the target. The target occupies the entire plot space. Misalignments are in $x$ and parents are required to generate neutrinos that reach the $x$ axis of INGRID.
Figure 16: Rates at INGRID for different energy domains
5 Angular Misalignments

5.1 Misalignments Tested

A realistic angular misalignment of the proton beam’s collision with the target is on the order of 0.001 rad. For this study we focused on angular misalignments between 0.01 rad and 0.001 rad. For each angle, two types of misalignments were considered. First, we considered the case where the angle of the proton beam was skewed, but the beam was still focused on the center of the front face of the target (with respect to the \(x-y\) plane). In the second case, the beam was given a positional offset to compensate for its angular offset, such that a straight trajectory of the initial beam path would pass through the center of the target. Horizontal and vertical misalignments were studied independently. A complete list of the angular misalignments simulated is below:

- \( dx \cdot dz = \pm 0.01 \), beam enters target at origin
- \( dx \cdot dz = \pm 0.005 \), beam enters target at origin
- \( dx \cdot dz = \pm 0.001 \), beam enters target at origin
- \( dx \cdot dz = \pm 0.01 \), beam enters target at \( x = \mp 0.45\,cm \) (exits at \( x = \pm 0.45\,cm \))
- \( dx \cdot dz = \pm 0.005 \), beam enters target at \( x = \mp 0.225\,cm \) (exits at \( x = \pm 0.225\,cm \))
- \( dx \cdot dz = \pm 0.001 \), beam enters target at \( x = \mp 0.045\,cm \) (exits at \( x = \pm 0.045\,cm \))
- \( dy \cdot dz = \pm 0.01 \), beam enters target at origin
- \( dy \cdot dz = \pm 0.005 \), beam enters target at origin
- \( dy \cdot dz = \pm 0.001 \), beam enters target at origin
- \( dy \cdot dz = \pm 0.01 \), beam enters target at \( y = \mp 0.45\,cm \) (exits at \( y = \pm 0.45\,cm \))
- \( dy \cdot dz = \pm 0.005 \), beam enters target at \( x = \mp 0.225\,cm \) (exits at \( x = \pm 0.225\,cm \))
- \( dy \cdot dz = \pm 0.001 \), beam enters target at \( y = \mp 0.045\,cm \) (exits at \( y = \pm 0.045\,cm \))

Horns on and horns off cases were both considered.

5.2 Beam Flux

To understand the consequences of angular misalignments on the off-axis neutrino energy, we will use the same analysis as we did for positional misalignments in sec. (4.2). Namely, we will look at how angular misalignments alter the peak flux of the beam, where the flux is measured by either the off-axis near detector or by SK. Fig. (17) shows the shifts of the peak flux position for each angular beam alignment.

Note two important aspects of this plot. First, once again we see that the off-axis beam energy has greater sensitivity to \( y \) misalignments. Second, it is clear that the two different types of angular misalignments studied have a slightly different effect of the beam flux. When the proton beam is focused on the center of the target, we find that shifts in beam flux tend to be relatively small. When the proton beam is focused on the front face of the target, however, the shifts in beam flux are larger. This is summarized more precisely in tab. (1).
Figure 17: Shift in flux peak position for different angular misalignments, flux measured by both off-axis near detector and SK: Top: Proton beam centered on the front face of the target; Bottom: Proton beam focused on target center
5.3 Observing Angular Alignment at INGRID

Again, we will use the same analysis here as we did for positional misalignments in sec. (4.3). Fig. (18) shows the position of the beam center at INGRID for each angular offset, as measured by a Gaussian best-fit function.

Once again we see greater sensitivity to $y$ misalignments which is consistent with previous results. In addition, we see that small angular offsets of the proton beam lead to relatively large shifts of the beam center at INGRID. Since INGRID is located 280 meters downstream of the target, we could expect this result simply by extrapolating the initial beam path. Even small angles lead to large shifts after the beam travels 280 meters. Finally, INGRID shifts were larger for the case where the proton beam was centered on the front face of the target then they were for the case when the proton beam was aligned with the target center.

<table>
<thead>
<tr>
<th>Type of angular misalignment</th>
<th>Direction of angle</th>
<th>Flux measured by off-axis near detector</th>
<th>Flux measured by SK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton beam centered on target front face</td>
<td>x</td>
<td>peak shifts $0.4\text{MeV/rad}$</td>
<td>peak shifts $0.6\text{MeV/rad}$</td>
</tr>
<tr>
<td></td>
<td>y</td>
<td>peak shifts $-0.7\text{MeV/rad}$</td>
<td>peak shifts $-1.6\text{MeV/rad}$</td>
</tr>
<tr>
<td>Proton beam centered on target center</td>
<td>x</td>
<td>peak shifts $0.2\text{MeV/rad}$</td>
<td>peak shifts $0.2\text{MeV/rad}$</td>
</tr>
<tr>
<td></td>
<td>y</td>
<td>peak shifts $-0.4\text{MeV/rad}$</td>
<td>peak shifts $-0.4\text{MeV/rad}$</td>
</tr>
</tbody>
</table>

Table 1: Flux peak shifts for angular misalignments of the proton beam
Figure 18: Beam centers measured at INGRID for simulated misalignments in proton beam angle (d/dz) for two cases: **Top:** Proton beam centered on the front face of the target; **Bottom:** Proton beam focused on target center
6 Target Misalignments

6.1 Misalignments Tested

One of the more interesting results found in this study (described above in sec. (4.3)) is that small positional misalignments of the proton beam lead to relatively large offsets at INGRID even when all of the horns are turned off. We chose to conduct a brief study of target misalignments, primarily to search for the cause of this unexpected effect. While studies of target misalignments did not provide such fruit, they did lead to some noteworthy results, which are summarized in this section.

The target used in T2K rests inside the first of the three focusing horns. The two components are mechanically attached to one another. Thus, rather then adjusting the alignment of just the target, we decided to shift the target and the first horn together as a single unit. Furthermore, when shifting the target/first horn around, the proton beam was always kept aligned with the center of the target’s front face, and parallel to the beam path. In other words, the positions of the target, first horn, and proton beam were all kept the same relative to one another.

For this study, the configuration was moved independently along the x and y axes between 0mm and 8mm in 4mm increments (where the origin represents the default beam center).

6.2 General Results

First we will look at how the peak off-axis energy shifts for different target misalignments as we did for positional and angular misalignments of the proton beam. Fig. (19) shows an example plot of beam flux for default and offset beams. In general, we found that the peak energy shifts roughly 2MeV/mm movement of the target.

We also can look at how the beam center at INGRID shifts for target offsets. Fig (20) shows an example of the shift at INGRID associated with a target offset of 8mm in the x direction. Beam shifts at INGRID were found to be small in comparison to those associated with angular and positional offsets of the proton beam. For target misalignments in the x and y directions, the beam center at INGRID shifted roughly 2.5cm/mm shift in target position.
7 Conclusion

The results of this study bring up three significant conclusions, which are listed below.

1. The off-axis beam energy and the position of the beam center are both more sensitive to proton beam misalignments in y then they are to misalignments in x. This is true for both angular and positional misalignments of the proton beam. This effect is most likely a consequence of detector geometry. This is not necessarily a surprising conclusion because it agrees with previous results produced by Eric Zimmerman and Josh Spitz in 2006 [5].

2. When comparing angular misalignments of the proton beam to positional misalignments, we find that angular misalignments that lead to the same positional offsets at INGRID have a much smaller effect on the off-axis beam energy. In other words, an angular misalignment of the proton beam that is very apparent at INGRID may not have a drastic effect on the beam flux, or on the far-near ratio. Furthermore, when the angle of the proton beam is offset but the beam is still focused on the target center, the effects on the flux and the beam center at INGRID are small relative to angular beam offsets in which the beam is centered on the front face of the target.

3. Positional misalignments of the proton beam lead to relatively large offsets of the beam center at INGRID even when all of the horns are turned off. Namely, the unfocused INGRID beam center shifted about 9cm/mm x misalignment, and about 11cm/mm y misalignment. This effect is surprising and not fully understood; how does an unfocused beam get steered off of its beam path? Initial results suggest that this may be a result of interactions within the target, but further studies are critical for supporting this conclusion.
APPENDIX

A  Weighting Methods and Using PAW

The proper weighting of data was an important consideration for this study. In this section, I summarize the different weighting techniques that were used for plotting data and generating results. This section is intended for readers who are interested in following up on this study, or who are curious about the specific methods used to generate the above plots.

The default output of the JNUBEAM simulation is an hbook file that includes ntuples for the near (INGRID, OA280) and far (SK) detectors. Whenever a simulated particle passes through a detector plane, information about the particle including its energy, momentum, flavor, and decay position is stored in the appropriate ntuple. Once generated, ntuples can be analyzed easily using PAW. In this study, we looked at three plots of ntuple data: (1) the flux of the beam at SK, (2) the flux of the beam at OA280, and (3) the neutrino rates on a single axis of INGRID. Each of these plots required a slightly different weighting scheme. Examples of each scheme are shown below.

Flux at SK

The ntuple containing SK data is labeled 2000. Within the ntuple 2000, the variable mode denotes the neutrino flavor and parent flavor. Values of mode between 10 and 13 denote neutrinos of muon flavor. When plotting flux, we are interested only in muon neutrinos, so we make the necessary cut on mode. Plots of flux at SK were also weighted by the particle energy $E_{\nu}$ and the built in normalization factor norm. An example line in PAW designed to generated a plot of flux at SK is shown below:

\[
\text{ntuple/plot 2000.Enu norm } \ast \ Enu \ast (\text{mode.ge.10.and.mode.le.13})
\]

Flux at OA280

The ntuple containing near detector data is labeled 3001. Since most of the variables in the 3001 ntuple overlap with those in the 2000 ntuple, plotting the flux at OA280, was similar to plotting the flux at SK. However, the 3001 ntuple contains data on several different detectors located 280m downstream of the target. In order to be sure that we were only looking at data from the off-axis detector, we had to make the relevant cut. The variable idfd denotes detector id, and OA280 has an id equal to 5. Thus an example line in PAW designed to generate a plot of the flux at OA280 looks as follows:

\[
\text{ntuple/plot 3001.Enu norm } \ast \ Enu \ast (\text{mode.ge.10.and.mode.le.13.and.idfd.eq.5})
\]

INGRID Neutrino Rates

The ntuple that contains the INGRID detector is the same one that contains data on OA280–3001. Plotting neutrino rates at INGRID required the most complicated weighting scheme. In addition to weighting by norm and the particle energy $E_{\nu}$, we utilized an INGRID acceptance model based on particle energy that was generated by Magali Besnier in 2006. Magali Besnier’s acceptance model (which does not take an angle cut into account) was roughly parametrized using the function $0.625E_{\nu} e^{-0.441E_{\nu}}$. In addition, rather then only looking at neutrino rates from muon neutrinos, we looked at the rates produced by muon neutrinos plus half of the rates produced by electron neutrinos. Furthermore, the x axis of INGRID has an id equal to 3 while the y axis has an id equal to 4. An example line in PAW designed to plot the neutrino rates at x INGRID is shown below:

\[
\text{ntuple/plot 3001.xnu norm } \ast \ Enu \ast (0.625E_{\nu} e^{-0.441E_{\nu}}) \ast (1 \ast (\text{mode.ge.10.and.mode.le.13}) + 0.5 \ast (\text{mode.ge.20.and.mode.le.23})) \ast (idfd.eq.3)
\]
B Pseudo-Experiment Setup

In order to understand how precisely misalignments can be calculated based on the beam position at INGRID, a templated fitting technique was utilized, as mentioned in sec. (4.3). The details of the technique are described in this section.

Assume, for example that we would like to measure the positional alignment of the proton beam with respect to the x axis. The x extension of INGRID contains seven modules. Let the modules be numbered 1 through 7. Based on simulation data, we know the neutrino rates for the default beam for any given module $i$ to be $N^0_i$. We also know that for a given beam misalignment (assume it to be 1mm for simplicity), the neutrino rates for any module $i$ are equal to $N^+_i$. Now say a pseudo-experiment consisting of a relatively small number of events is conducted for an unknown misalignment. We record number of events for our unknown run to be $N^{\text{obs}}_i$ for each module $i$.

Finally, for each INGRID module $i$, we define a new variable $N^{\text{pred}}_i$ based on the following equation:

$$N^{\text{pred}}_i = (1 - x)N^0_i + xN^+_i. \quad (14)$$

Thus, if $N^{\text{pred}}_i$ were to represent neutrino rates for a proton beam misalignment of $m$ millimeters, given enough data, we would find that $x$ equals $m$ when solving the above equation for $x$. In other words, the variable $x$ would represent the misalignment of the proton beam. Now we define a variable $\chi$ such that

$$\chi^2 = \sum_i \left[ \frac{N^{\text{obs}}_i - N^{\text{pred}}_i}{\sigma^{\text{obs}}_i} \right]^2 = \sum_i \left[ \frac{N^{\text{obs}}_i - (1-x)N^0_i - xN^+_i}{\sigma^{\text{obs}}_i} \right]^2. \quad (15)$$

We minimize $\chi^2$ with respect to $x$ in order to solve for $x$, and hence, the misalignment of the proton beam. We can do this by differentiating $\chi^2$ with respect to $x$, and setting $\chi^2$ equal to zero. We get

$$x = \frac{\sum_i \left[ (N^{\text{obs}}_i - N^0_i)(N^0_i - N^+_i) \right]}{\sum_i \left[ (N^0_i - N^+_i)^2 \right]} \quad (16)$$

The above equation can be used to solve for the misalignment of the proton beam for a given pseudo-experiment. By solving for $x$ repeatedly for many different pseudo-experiments we get an idea of the precision of our measurement of the unknown misalignment.
References


