Off-Axis-Note_SIM -13

On Siting the Offaxis Detector

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ABSTRACT

Physics considerations that contribute to the determination of the optimal site for the offaxis NuMI experiment Far Detector are examined. More specifically, 2 US and 2 Canadian locations are looked at. Of these four, the "Fort Frances" Canadian location at about 850m km distance appears optimal. The loss of sensitivity due to a choice of non optimal transverse location appears relatively minimal: a deviation of up to 2 km from optimum position results in few percent loss in figure of merit value. There is a similar loss in sensitivity if one chooses a transverse location that is optimized for a value of Δm^2_{13} up to +-0.5 x 10^{-3} eV^2 away from the true value.

Introduction.

An offaxis neutrino experiment allows a certain degree of flexibility in the choice of a site once one knows the approximate range of physics parameters to be investigated. The choice of optimum location is determined by two sets of considerations. The first set takes into account such considerations as access, availability of power, geology, etc. The second set considers how well the different candidate sites would satisfy the physics goals of the experiment. In this note we describe calculations performed to evaluate the physics criteria. Many of these conclusions are not new and have been obtained previously in other calculations. This note attempts to present the relevant results in a systematic manner.

We consider 4 different sites. They are the "LTV" site located apprximately at 715 km from the Fermilab source; the "Buyck" site at 775 km, the "Fort Frances" site at 850 km and "Kenora" site at 986 km. The choice is determined by the fact that they span the range of possible distances available and appear, on initial examination, to be able to offer an acceptable site. A site near route 502, around 870-890 km might also be acceptable even though this area appears to lack the required utilities

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Simulation Procedure.

Since we are interested mainly in a relative evaluation, certain approximations in the simulation code appear justified. This is especially true since our conclusions are principally determined by geometrical and kinematical consideration. The code used for the simulations was custom written for studies of this nature and allows processing of about 1 M events in 5 minutes on a laptop.

The secondary flux is generated according to the BMPT prescription [1]. Some account is taken of attenuation in the target and secondary production. The horn geometry follows the design but the magnetic field terminates sharply at surfaces. Coulomb scattering and absorption in the horns are taken into account. The boundaries of chase and decay pipe are considered as a sharp ending of the trajectories. There is no allowance for possible meson production in the absorber. Polarization of muons is taken account of in their decay. No neutral kaons are considered and electron energy spectrum in the charged K rest frame is taken to be linear.

The figure of merit (FOM) for each configuration is taken as the number of signal events divided by the square root of the number of background events. The backgrounds considered are ν_e's in the beam (due to both μ and charged K decays), neutral current (NC) events simulating signal, and charged current (CC) ν_μ interactions simulating signal. The number of background NC and CC events is taken to be proportional to the number of events with hadronic energy with a "measured" value in the energy band used to define accepted signal events. For the CC events an additional criterion was used that the muon has to have an energy less than 500 MeV. The distribution of the hadronic energy was taken to follow the parametrization given in [2] without any allowance for possible variation with neutrino energy. The proportionality factor for the NC and CC events was chosen so that typically the number of background NC events was between 50 and 100% of the beam ν_e contamination.

The cross section for neutrino interactions was taken to be linear in energy. The energy resolution for ν_e CC interactions was taken to be 0.2 divided by the square root of the neutrino energy. The resolution of the hadronic system in NC and ν_μ CC events was taken as 0.4 divided by the square root of the hadronic energy.

Physics Considerations.

From the perspective of physics arguments, we can evaluate each site based on three considerations:

a) relative probability of observing ν_μ->ν_e transition
b) sensitivity to mass hierarchy
c) relative insensitivity to changes in oscillation parameters

There is a certain level of ambiguity as to how one should evaluate quantitatively the first factor, since the transition probability depends not only on the values of θ_{13} and Δm^2_{13} but also on mass hierarchy and the value of CP phase δ. The dependence on other parameters of the MNS matrix and Δm^2_{12} is rather weak in the region of interest and thus can be ignored. In performing our calculations we assume a rather arbitrary *ansatz,* ie we set all terms proportional to both $\cos\delta$ and $\sin\delta$ equal to zero and assume normal mass hierarchy. The specific formula we use is the approximate version derived by Cervera et al. [3] which should hold very well in the parameter space being investigated.

There are a number of parameters that can be varied to obtain the optimum FOM for each source-to-detector distance. We vary five: the transverse distance, the locations of the target and the second horn with respect to the first horn, the center of the energy band for the accepted signal, and the width of the energy band accepted. The last parameter has invariably turned out to be very close to +-30% for the optimum. We do not change any of the target dimension parameters, based on the desire to reduce the parameter search space and the belief that this variation would not affect significantly the relative comparison. We also do not vary the horn current but stay with the maximum practical one of 200 kA in each horn. For θ_{12} and Δm^2_{12} we take the values quoted recently by a compilation of Fogli et al. [4] who take into account the most recent SNO [5] and KamLAND [6] results. My guess is that the phase space has been explored sufficiently so that the optimum obtained is within less than 1 % of the true optimum, an uncertainty comparable to the statistical uncertainty.

In varying the transverse distance, one has to ensure that the distance chosen corresponds to a possible location on the surface of the earth. In practice this limitation is relevant only for the furthest distance where the on-axis beam is about 18.5 km above the surface. We take 19 km as the minimum transverse distance possible there.

FOM for Different Sites.

The values of the parameters which maximize FOM for each distance, together with the corresponding FOM value, are enumerated in Tables I, II and III. We present there

Site	Distance from Fermilab	Transverse distance	Horn position	Target position	Central energy value	Optim1zed FOM value
LTV	715 km	13 km	13.0 m	-0.7 m	1.75 GeV	0.803
Buyck	775 km	14 km	13.0 m	-0.65 m	1.75 GeV	0.852
Fort Frances	850 km	14 km	14,0 m	-0.75 m	1.9 GeV	0.894
Kenora	986 km	19km	13.0 m	-0.7 m	1.7 GeV	0.834

Table I. Parameters and the FOM value for Δm^2_{13} =2.0 x 10^{-3} eV^2.

Site	Distance from Fermilab	Transverse distance	Horn position	Target position	Central energy value	Optim1zed FOM value
LTV	715 km	11 km	15.0 m	-0.8 m	2.05 GeV	1.108
Buyck	775 km	11 km	16.0 m	-0.85 m	2.2 GeV	1.151
Fort Frances	850 km	12 km	17.0 m	-0.9 m	2.2 GeV	1.202
Kenora	986 km	19 km	14.0 m	-0.75 m	1.75 GeV	0.732

Table II. Parameters and the FOM value for Δm^2_{13} = 2.5 x 10^{-3} eV^2.

Site	Distance from Fermilab	Transverse distance	Horn position	Target position	Central energy value	Optim1zed FOM value
LTV	715 km	9.5 km	18.0 m	-0.95 m	2.3 GeV	1.407
Buyck	775 km	10 m	18.0 m	-0.95 m	2.4 GeV	1.459
Fort Frances	850 km	10m	18.0 m	-0.95 m	2.65 GeV	1.500
Kenora	986 km	19 km	15.0 m	-0.8 m	1.8 GeV	0.726

Table III. Parameters and the FOM value for $\Delta m^2_{13} = 3.0 \times 10^{-3}$ eV^2.

these calculations for three different values of Δm^2_{13}, 2.0, 2.5 and 3.0 x 10^{-3} eV^2, which span the currently suggested value of that parameter from the SuperKamiokande [7] and K2K [8] experiments. Finally, in Fig.1 we plot the optimum FOM values for the 4 different sites and the 3 values of Δm^2_{13} used.

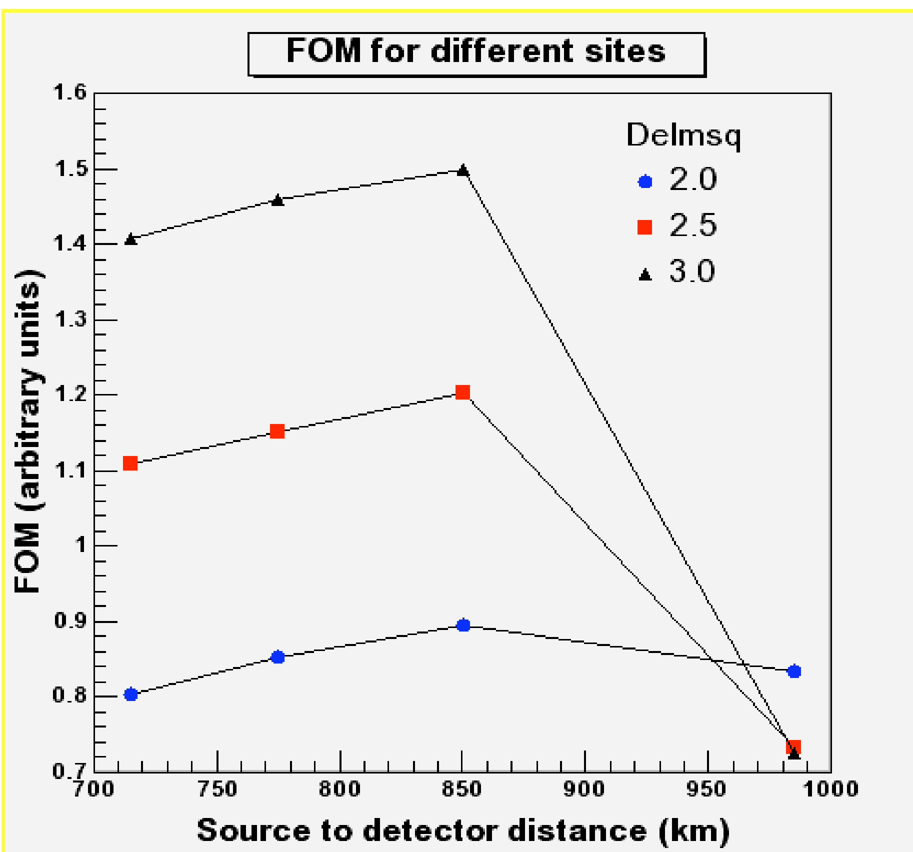

Fig. 1. Maximum FOM values for the possible sites.

We can make several relevant observations based on this study. The slight improvement in FOM as distance increases is due to the enhancement from matter effects and hence due to our assumption that mass hierarchy is the normal one. An opposite conclusion would be reached if mass hierarchy were inverted. This point is seen in a quantitative manner in Fig. 2, where we plot the absolute value of the contribution of the mass term as a function of distance from the detector. Without the matter effect the optimum FOM would be relatively independent of the distance. The flux falls off as $1/L^2$ giving an 1/L dependence to FOM which is canceled by the linear rise in the cross-section, since the mean energy in the acceptance band increases proportionately to the distance. The other factors, like energy dependence of the production spectra and acceptance of the optical system do not introduce a major variation with length in the off axis beam.

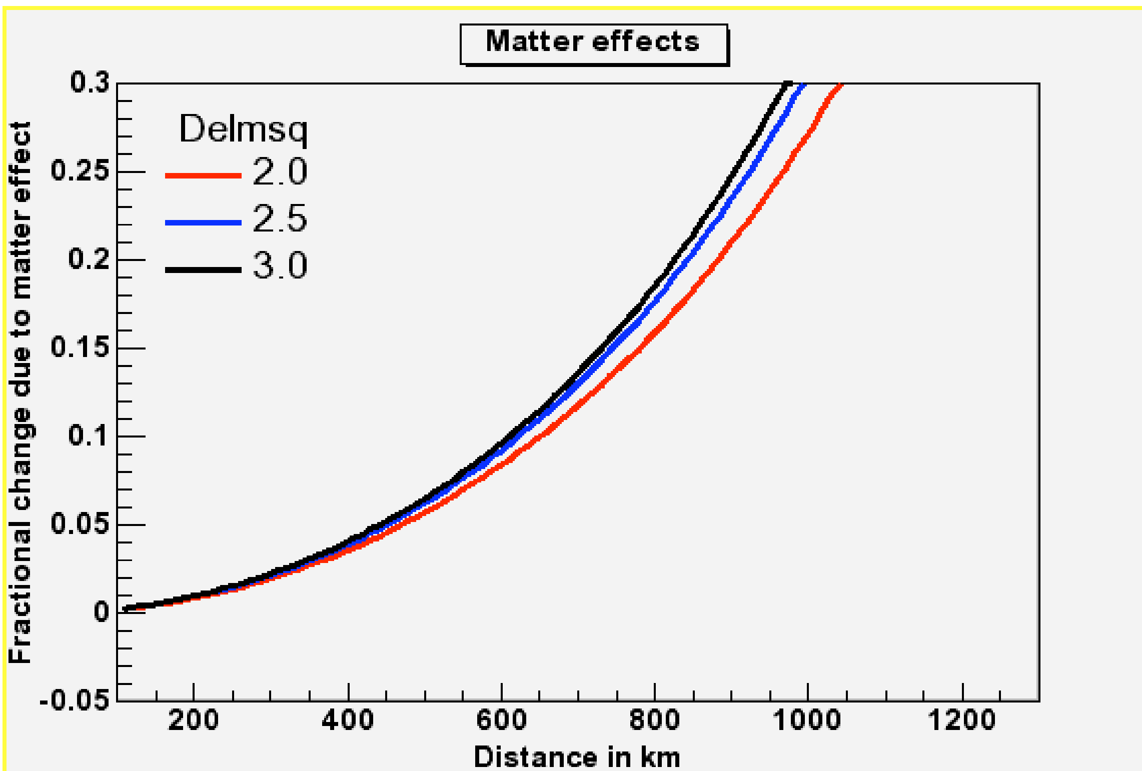

Fig.2. Fractional change in oscillation probability due to matter effects

The rapid FOM falloff at the furthest distance is just the effect that due to the earth's curvature and predetermined beam direction the optimum lower transverse distances are not possible at that site. Thus the allowed transverse distances are not optimum. Thus this site fails very badly our criterion 3, ie is not very forgiving in case of small changes to Δm^2_{13}.

Finally, we see that optimum FOM decreases as Δm^2_{13} decreases. The decrease, however, is very closely equal to the decrease in sensitivity of the CHOOZ result [9] as a function of that parameter. Thus the relative improvement of the NuMI offaxis experiment over CHOOZ is to a very good approximation independent of the precise value of Δm^2_{13}.

Sensitivity to Transverse Distance Changes.

An important question in choosing a site is knowing how sharp is the maximum in FOM as a function of the transverse distance. This is relevant in deciding how much one can compromise on the physics maximum if such a compromise results in a considerably better site from the point of view of geographical considerations. In Fig.3 we plot, for 850 km and Δm^2_{13}=2.5 x 10^{-3} eV^2 the percentage decrease in FOM as a function of transverse distance. We show these differences both for optics (ie second horn and target positios) identical to those for optimum location and for optics reoptimized for a given location.

As we can see there is at least a 3 km interval where the FOM value does not deteriorate by more than 2%. Furthermore, the degradation is much less as one moves towards the onaxis beam direction. This can be understood by noting that the increase in beam intensity at smaller angles tends to compensate partially for the worse match to the oscillation maximum.

Sensitivity to Δm^2_{13} changes.

A related question is how much FOM deteriorates if Δm^2_{13} turns out to be somewhat different than the one assumed in optimization. The answer can be deduced from Fig.2 and Tables I – III but for clarity we show it explicitly for 850 km distance and Δm^2_{13}=2.5 x 10^{-3} eV^2 in Fig.4.

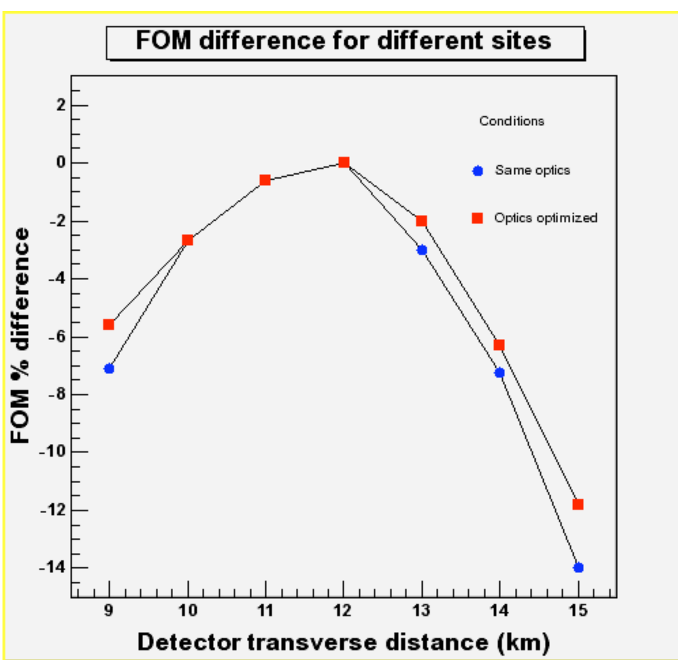

Fig. 3. Sensitivity of FOM to transverse distance for Δm^2_{13}=2.5 x 10^{-3} eV^2.

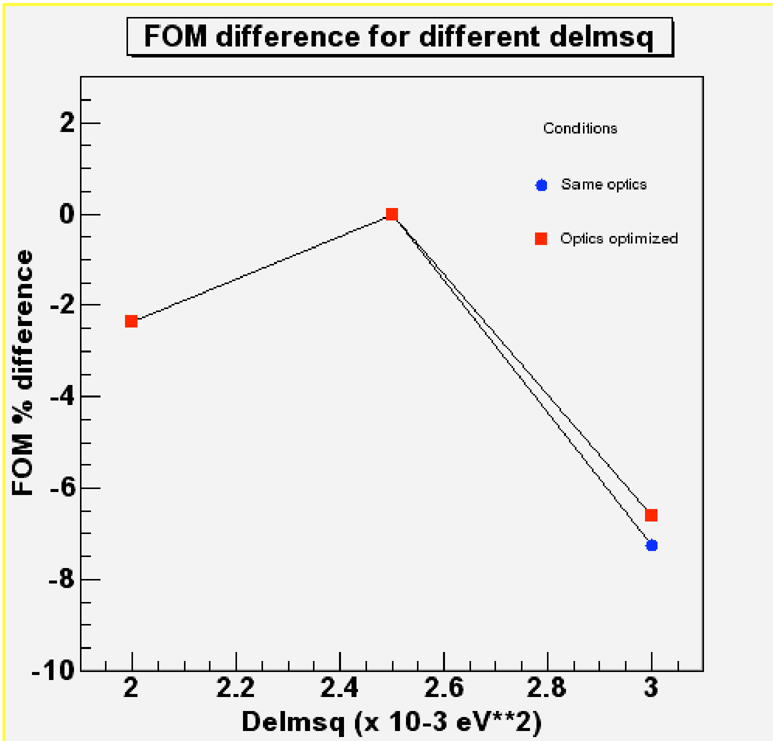

Fig. 4. Sensitivity of FOM to Δm^2_{13} changes when optimization is done for Δm^2_{13}=2.5 x 10^{-3} eV^2 and 850 km.

Possible 2nd Maximum Experiment.

To resolve some of the potential parameter ambiguities one may need to run at the 2nd maximum where the CP violation effects are enhanced and the matter effects relatively suppressed. We have investigated this possibility, albeit in a very perfunctory manner. More detailed and precise studies are needed to reach firm conclusions.

The FOM maxima were determined for three possible distances, 850 km, 986 km and 1100 km. The latter corresponds to the furthest potentially feasible location in Canada close to the NuMI beam line and is near Red Lake. The relevant parameters are shown in Table IV. The relative normalization of the FOM values is the same as used in the preceding calculations for the first maximum optimization.

As can be seen from the Table, larger distances provide better sensitivity. Furthermore, the optimum FOM values drop by pretty close to a factor of 10 compared to the value at 1st maximum location. For relatively large values of θ_{13}, however, a more meaningful number would be the ratio of signal events since the background suppression is still quite adequate. The ratio of the signals is about 1 : 40, implying the need to increase the product of mass x no of protons x time of exposure by roughly a factor of 40 to obtain equal signals. We can make a very rough estimate of what this implies in terms of feasibility of the experiment.

Distance from Source	Transverse Distance	Mean Energy	Optimized FOM value
850 km	44 km	0.65 GeV	0.099
986 km	44 km	0.75 GeV	0.115
1100 km	44 km	0.8 GeV	0.124

Table IV. Beam parameters at the second maximum and the optimum FOM values achievable for 3 potential source to detector distances

We can expect about 250 ν_μ->ν_e oscillation events at the first maximum for the value of θ_{13} near the current CHOOZ limit. For maximum CP violation the potential increase in rate there is about 30 %. Since the increase in the signal rate at the second maximum due to CP violation is roughly a factor of 3 larger than at the first, we would expect about 500 / 40 = 12.5 events at the second maximum for the same running conditions and assuming maximum possible effect due to CP violation. One could realistically expect a gain of 5-10 in the product of detector mass times the number of protons for the second phase of the experiment. One could be trying to resolve two hypotheses predicting signal size different by as much as a factor of two. Thus the 2^{nd} maximum experiment possibility does not appear to be excluded. More detailed study, including investigation of signal efficiency and background discrimination at these lower energies, is required before a firm conclusion can be reached.

Conclusion.

The physics potential of several different sites for a possible NuMI offaxis experiment has been investigated. The site around 850 km appears to be optimum from the point of view of maximizing the probability of seeing the oscillation signal, maximizing sensitivity to matter effects, and maintaining relative immunity to potential Δm^2_{13} changes after the site selection. The furthest (Kenora) site would only make sense for values of Δm^2_{13} below 2.0 x 10^{-3} eV^2 and the physics sensitivity there would be considerably degraded for higher values. An experiment at the second oscillation maximum might be feasible with increased proton intensity or detector mass but further, more detailed studies are needed to verify such a conclusion.

References.

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