NuMI-L-765-Rev2

Proposal to Measure the Speed of Mu-type Neutrinos to Two Parts in 10^6

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September 21, 2004

Abstract

We propose to measure the propagation time of muon-type neutrinos from the NuMI source at Fermilab to the MINOS detector in northern Minnesota, a distance of 735.34 km. The proposed timing instrumentation will provide an accuracy of ±2 ns in the ν_μ propagation time. With an accuracy in the distance of ±0.7 m, we expect to show that the speed of a neutrino differs from the speed of light by no more than two parts in 10^6. The time-of-flight instrumentation will also enable a search for slow-moving weakly-interacting particles.

1 Introduction and Motivation

One of the neutrino beams constructed thirty years ago for the debut of Fermilab was the site of the first measurement of the speed of a neutrino [1]. The experiment showed for μ-type neutrinos that $|v_\nu/c-1| < 40\times 10^{-6}$ [2]. An idea from that era that partially motivated the measurement was that neutrinos moving with a speed different from c might help to explain CP violation in K-meson decay [3]. Information on the speed of e-type neutrinos comes exclusively from the observation of neutrinos from SN1987A. The supernova showed that $|v_\nu/c-1| < 2\times 10^{-9}$ [4].

We propose here to undertake a measurement of the ν_μ speed with precision considerably higher than achieved previously. The MINOS experiment, designed for the study of neutrino oscillations, offers an incomparable opportunity for this measurement. The 735 km distance between the production target and the Far Detector has been determined to an accuracy of ±0.7m. With additional instrumentation to measure the propagation time, we can determine the ν_μ speed to two parts in 10^6. Still better accuracy may eventually become possible.

The measurement that we propose, as good as it is, is not good enough to compete with conventional methods of constraining the ν_μ mass. From analysis of charged pion decay we know that the mass of ν_μ is less than 190 keV [5]. The upper limit obtained from our speed measurement will be no less than 5 MeV, larger by a factor of 25. Clearly we do not advocate this experiment as a competitive mass measurement. Rather we regard the speed as an independent observable, and we seek to check that neutrinos behave as expected vis-à-vis this observable.

If the neutrino mass will not be under the proverbial microscope, are there less orthodox theoretical ideas that might be tested by a speed measurement? Chodos, Hauser, and Kosteleckỳ [6] proposed that the neutrino might be a tachyon, a faster-than-light object whose speed is inversely related to its energy. Hughes and Stephenson [7] criticized this idea, but were inturn rebuffed by Chodos *et al.* [8]. More recently several papers have proposed a limiting speed for neutrinos that is less than c [9]. The time of flight measurement could also test for Lorentz invariance violation in neutrinos [10]. Tests of CPT violation [11] could also be made in the neutrino sector and compared to parameter limits from the photon sector. While we view these theoretical speculations as interesting, we do not regard them as essential to the motivation of the project. If neutrinos indeed adhere to some unorthodox theory, as likely as not it is a theory that no one has yet considered.

The Main Injector RF imposes a high-contrast microstructure on the NuMI beam, and this feature is essential to the speed measurement. We expect neutrinos to arrive at Soudan in phase with the RF buckets. As proposed by Shrock [12] the voids between buckets offer the complementary opportunity of a search for weakly-interacting particles that are massive, in our case ≥ 10 MeV. Gallas *et al.* conducted this kind of search within the confines of Fermilab [13]. They were sensitive to anomalous particles no lighter than 500 MeV.

One possible source of an anomalous weakly interacting particle, an "anomalon," is anomalous pion decay. The KARMEN experiment reported evidence for an anomalon from π decay [14] that turned out to be an artifact. KARMEN data now rule out a particle matching their artifact, but an anomalon with slightly diferent properties remains consistent with their data and other data. One can also imagine that an exotic K decay channel or an exotic Primakoff effect in the interactions of the primary protons on carbon produces the anomalon. The focusing of π's and K's by the NuMI horns enhances the flux of their decay products in MINOS. Clearly the focusing does not enhance anomalons produced at the carbon target.

In the balance of this document we discuss methodology in the context of the ν_μ speed measurement, but the identical technology and techniques enable the anomalous particle search. The two objectives will have equal claim on our interest and analysis effort.

The measurement of neutrino speed raises substantially the outreach potential of the MINOS project. The phenomenon of neutrino oscillation, the principal focus of study of NuMI-MINOS, is essentially quantum mechanical and is conceptually inaccessible to a majority of citizens. By contrast, virtually everyone appreciates the notion of speed. The measurement proposed here creates an opportunity to present to interested nonprofessionals a NuMI-MINOS activity that they can fully understand.

Our present estimate of the capital cost of this project is about \$318,000. An important influence on the capital cost is the economics of communications satellite air time. We have designed around a source of air time that is not optimal for our application, and we are seeking a more compatible source. Success in this regard may reduce the capital cost to as little as \$282,000.

We intend that the speed measurement and search for anomalous particles should exist completely within the MINOS umbrella. Contributions to the measurement from all MINOS collaborators are welcome, and we especially encourage participation from institutions where outreach is a high priority. We should not allow this proposal to perturb our progress toward oscillation physics, but we should appreciate the enrichment of the NuMI physics potential that it promises.

2 Methodology

2.1 Overview

Conceptually a measurement of speed by time of flight is about as straightforward as a physical measurement can be. In a conventional time-of-flight measurement signals from separated sources are assembled at a single location where the delay is measured. We depict this approach schematically in Fig. 1 in which the signal source is the flashes of light produced in plastic scintillator by

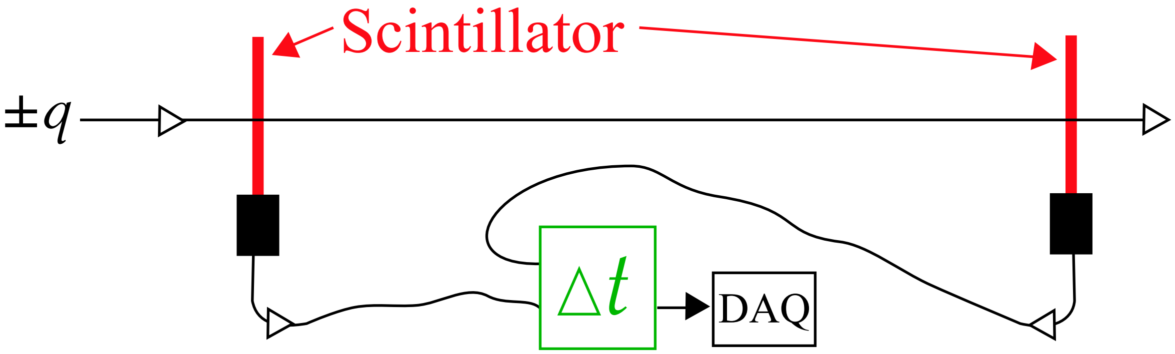

Figure 1: Schematic of a conventional time-of-flight measurement.

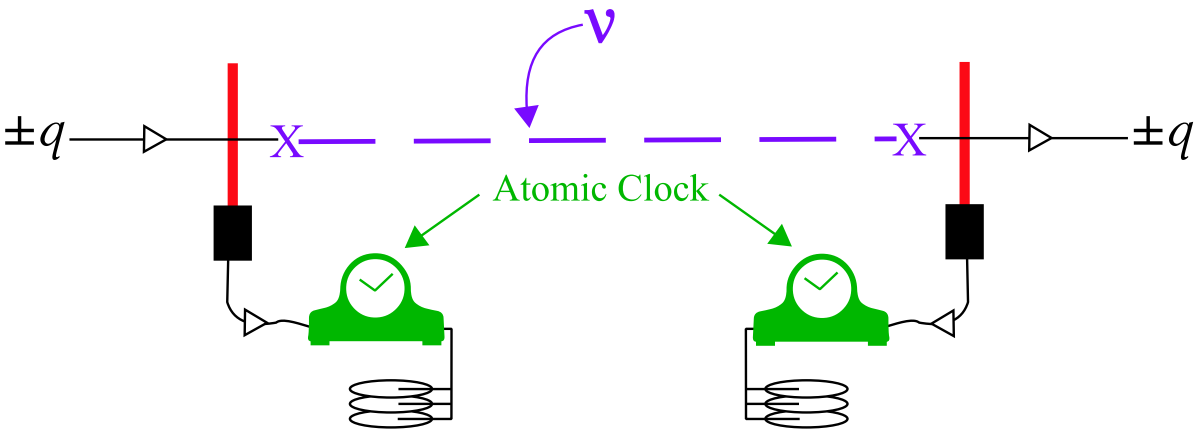

Figure 2: Method for measurement of time of flight using atomic clocks.

a passing charged particle.

The conventional approach becomes unattractive, if not infeasible, when the source separation grows to hundreds of kilometers. Timekeeping with atomic clocks offers a viable alternative. In this approach we place one atomic clock (AC) at Fermilab and another in the cavern at Soudan as we show schematically in Fig. 2. The time of an arbitrary "event" at Fermilab is established by reference to the local AC and recorded locally and similarly for an event at Soudan. The delay between related events at the two locations may be determined by comparing the recorded clock times "offline."

The bunching of the proton beam imposed by the accelerator RF is the essential feature of the experiment that allows events at the two locations to be correlated. If we assume that the pions produced in the proton target travel at precisely c and that the daughter neutrinos do likewise, then the neutrinos arriving at Soudan will faithfully preserve the microstructure of the primary protons. This structure consists of pulses of width 3 ns spaced by 19 ns. In Fig. 3 we represent the various metamorphoses of the beam on its trip from the Main Injector to Soudan and the preservation of the pulse structure from beginning to end. Although pions actually propagate down the decay pipe at a speed a bit less than c, the delay induced is typically only 300 ps for the neutrinos that we will catch in the Far Detector. We will measure the time of protons on target against the AC at Fermilab and the arrival time of a neutrino at Soudan against the AC in the cavern.

Although the periodic bunching of the proton beam is essential to the speed measurement, clearly it leaves some ambiguity unresolved. We can not know from which bunch a neutrino was

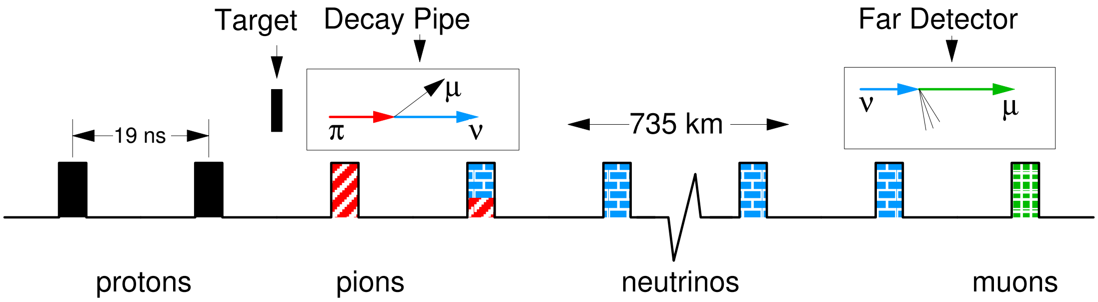

Figure 3: Between the Main Injector and Soudan the beam undergoes several metamorphoses but preserves the original microstructure.

produced, and therefore we can know the transit time to Soudan only modulo the 19 ns period of the beam microstructure. Because we will measure the arrival time with precision much better than 19 ns, this ambiguity is of no real consequence. If, as we tend to believe, neutrinos propagate only with speed c, then all will arrive "in phase" with the microstructure. The alternative is a spectrum of arrival times with mean slightly lagging (bradyon) or slightly leading (tachyon) the in-phase arrival time. The 19 ns phase ambiguity will not confound the null hypothesis with these alternatives.

A second factor that distinguishes this measurement from a typical time-of-flight measurement is the low interaction rate of neutrinos. Acquisition of an adequate number of events necessitates that substantially all of the massive and voluminous MINOS detector participate in the measurement.

2.2 Distance from Fermilab to Soudan Site

The separation of benchmarks on the surface at Fermilab and at the Soudan site has already been determined to ±1 cm [15]. The translation of the Soudan surface benchmark to the MINOS cavern incurs a larger error [16]. The error underground is currently estimated at ±70 cm. We consider this error to be acceptable for the purpose of this proposal. Perhaps we will eventually arrive at a point where this error dominates the error budget of the speed determination. In that case additional attention to the problem might significantly reduce the surface-to-depth translation error .

2.3 Timekeeping and Time Transfer

A valid measurement of time of flight requires that we establish synchronization of the two clocks and maintain it while the neutrinos are in transit, an interval of about 2.5 ms. Even inexpensive AC's routinely maintain synchronization to better than 1.0 ns over intervals of 5000 s. The neutrino transit time is therefore easily accommodated.

The challenge then is to resynchronize the AC's on a schedule that holds the drift to less than 1.0 ns. For this purpose we have considered and rejected GPS. Based on the literature [17] and discussions with experts we believe that even after heroic efforts GPS would achieve synchronization no better than 5.0 ns, which is marginal at best for our purposes. The synchronization technology we prefer is two-way satellite time transfer (TWSTT). In this technique a pulse generated at one clock propagates to the other via a geostationary satellite link as we show in Fig. 4. The readings

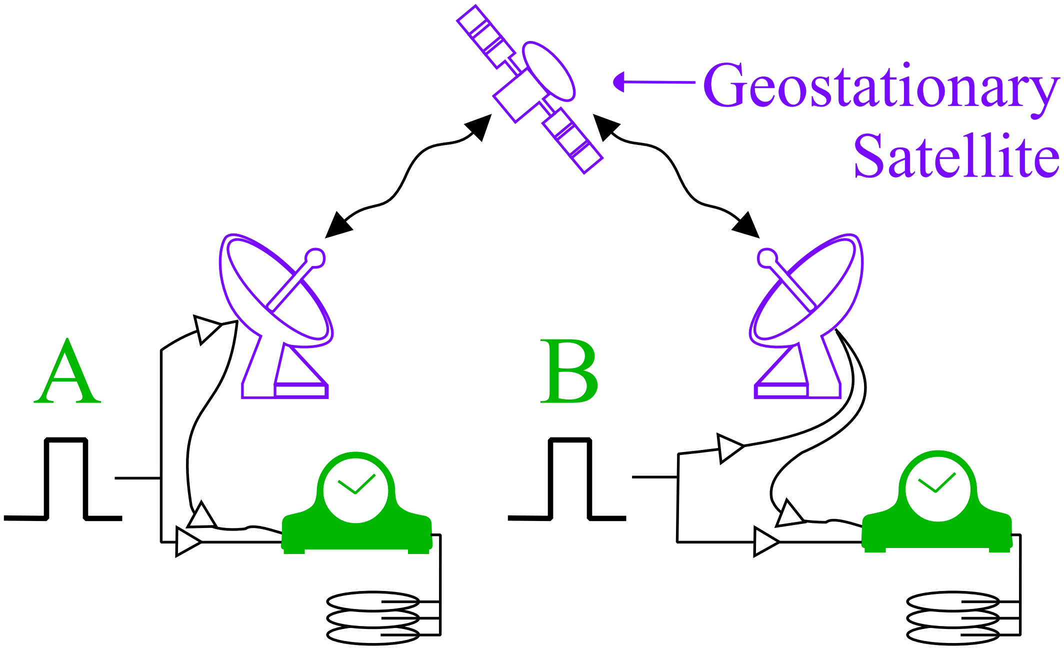

Figure 4: Synchronization of atomic clocks by two-way satellite time transfer (TWSTT).

of the clocks at the pulse time are recorded and exchanged either through the satellite link or the Internet. The clock comparison is repeated with the pulse generated first at one end of the link, then at the other end. Provided that the propagation delay of the link is independent of direction (to a part in 10^8), the ΔT between the clocks can be determined. In practice the procedure is somewhat more elaborate. Most of the equipment, however, is available as a turn-key system [18].

2.4 Temporal Calibration of the Far Detector

In this section we assume that synchronization of the AC's is a solved problem. It remains to determine the time of events at Fermilab and at Soudan relative to these clocks. The necessary calibration is a multistep process.

2.4.1 Integration of the Atomic Clock

Atomic clocks generate a digital pulse at precisely 1.0 Hz. (Some clocks produce only a 10 MHz sinusoid and require auxiliary electronics to produce 1.0 Hz.) We need to determine the time of scintillations in the MINOS Far Detector (FD) with respect to the “ticks” of the AC. The FD electronics, however, can not assimilate an asynchronous 1 Hz signal, and independent clock electronics can not assimilate the 23,000 channels of the FD. To bridge the gap we will introduce an intermediate reference pulse (IRP) at roughly 4.0 μs, i.e. half way, into the beam spill. We will insert the IRP into the FD electronics, which will treat it like a pulse from a PMT, and into electronics acquired from Timing Solutions Corp. (TSC), which will measure with 100 ps precision the delay between the IRP and neighboring ticks of the AC.

2.4.2 Timing Model for the Far Detector

Using only the FD electronics then, we will determine the delay between the reference pulse and all of the PMT signals that arrive during the beam spill. The FD electronics imposes a time quantization of 1.5 ns, which corresponds to a sigma of only 0.5 ns. Fluctuations in the integral and the shape of the PMT signals will produce jitter much more problematic than the quantization error. Jitter, however, is a statistical problem, and for each muon observed we will acquire arrival time measurements from at least 40 detector planes. Even with 10 ns jitter in the arrival of an individual PMT signal we can still achieve 1.5 ns error in the arrival time of the muon. These statistical errors are less important than the systematic error, which depends on the accuracy of the timing model (TM). By "timing model" we mean a compendium of the delays of all the scintillator strips, parametrized by track coordinates and relative to some common but arbitrary reference, for example the instant that a neutrino impinges on the upstream end of the detector. We assume that we can generate a sufficiently accurate TM from the same cosmic ray data that we will collect for the purpose of scintillator strip calibration [19].

In the system we have described so far there remain two uncalibrated delays. We do not know precisely the relationship between the instant at which the FD electronics registers the IRP and the instant at which the AC electronics registers the IRP. We also do not know one global delay in the TM. As we will see shortly, these two delays fold into one, and to fix this delay we require a set of auxiliary calibration detectors.

2.4.3 Auxiliary Calibration Detectors

These detectors consist of a thick scintillator viewed by high-speed PMT's and an adjacent hodoscope. We expect these detectors to achieve 300 ps resolution over a 1 m x 1 m area. A minimal system would require two of these detectors. We will deploy the "alpha" auxiliary in the MINOS near detector hall. It will detect neutrino-induced muons and will thus establish the phase of the neutrino bunches. Initially we will deploy the "beta" auxiliary at Fermilab also, along with all of the AC and TWSTT paraphernalia. It will sit one to three meters from the alpha detector so that a substantial flux of muons traverses both detectors. We will insert the signals from the alpha and beta detectors into independent chassis of TSC clock electronics and thus measure the time of flight of muons between the nearby detectors. This exercise will determine the relevant electronic delay in this system.

Next we will transfer the beta detector and its associated AC, clock electronics, and TWSTT system to the MINOS cavern. If every neutrino event would generate a pulse in the beta detector, the calibration task would already be complete. We are not so fortunate, and we must relatively time the beta detector and the FD. Muons that traverse both detectors will provide the requisite data, and cosmic rays are suited for this role just as they are suited for the construction of the FD timing model.

In Fig. 5 we show a timing diagram that may help to clarify these ideas. To simplify the discussion we assume that we have placed the beta detector at the reference plane of the FD timing model and that only one scintillator strip in the FD responds to a cosmic ray. We give the definitions of events in the timing diagram and of several time intervals in the following table.

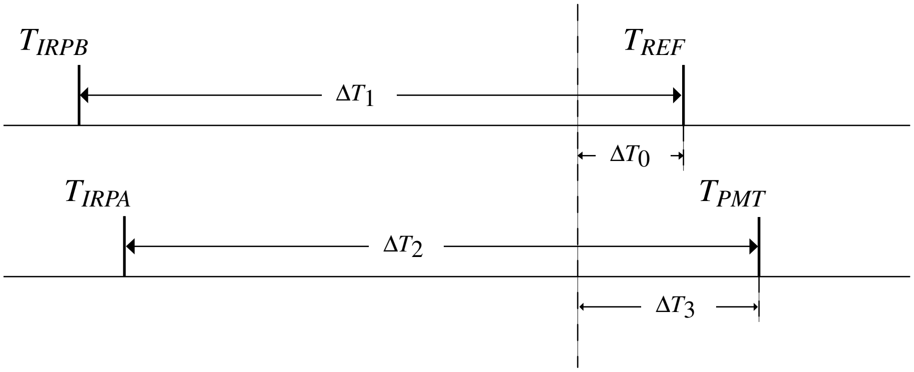

Figure 5: Timing diagram showing how signals from the Far Detector are referenced to the atomic clock.

Descriptor	Significance in calibration	Significance in data collection
T_{REF}	Time at which the cosmic crosses the TM reference plane. Measured using beta detector with TSC electronics.	Time at which the neutrino crosses the TM reference plane. Unobserved.
T_{PMT}	Time at which the FD electronics detects the PMT pulse from the cosmic ray.	Time at which the FD electronics detects the PMT pulse from the neutrino-induced muon.
T_{IRPA}	Time at which the FD electronics detects the IRP.	
T_{IRPB}	Time at which the TSC electronics detects the IRP.	
ΔT_0	Undetermined global offset of the TM. It is the same for all FD channels.	
ΔT_1	$T_{REF} - T_{IRPB}$, measured by TSC electronics, calibrated when beta auxiliary detector is at Fermilab	
ΔT_2	$T_{PMT} - T_{IRPA}$, measured by FD electronics.	
ΔT_3	$T_{PMT} - T_{REF} + \Delta T_0$, determined by the TM.	
ΔT_4	$T_{IRPA} - T_{IRPB} + \Delta T_0 = \Delta T_1 - \Delta T_2 + \Delta T_3$	

For data collection the origin of time (modulo 19 ns) is set by the alpha counter at Fermilab. For calibration the origin of time is arbitrary. The quantity ΔT_4 is the same for all calibration and neutrino-induced events, and each calibration event provides a measure of its value. For a neutrino event we can then reconstruct the unobserved T_{REF} as

$$T_{REF} = T_{IRPB} + \Delta T_2 - \Delta T_3 + \Delta T_4.$$

In a practical system we plan to deploy one or more auxiliary detectors at three stations in the MINOS cavern — upstream and downstream of the FD and in the gap between the supermodules. With this deployment we will measure a ΔT_4 at each of the three stations, and for any scintillator strip we will compute T_{REF} using the ΔT_4 of the nearest station. We will thus minimize the depth of detector over which we must depend on the TM.

2.5 Rubidium versus Cesium

The Agilent 5071A is a commercially available AC that would unquestionably serve the objectives of this project [20]. With the high-performance beam tube option the drift of this clock does not exceed 1.3 ns in 6 hr. Thus TWSTT twice per day would be adequate. The cost of this system, however is substantial — \$80,000 for two clocks and \$20,000/yr for commercial satellite time. The satellite time is available as intervals of 15 min for \$30. The TWSTT consumes only 1.5 min. The balance of a 15 min interval would be wasted.

Rubidium based clocks are as accurate as cesium for periods up to about an hour, and they generally cost less than \$5,000. With TWSTT on a two-hour schedule, however, the cost of satellite time as quoted above would quickly overshadow the cost of cesium based clocks. We are searching for a source of satellite time that would enable the cost savings of rubidium technology. In the meantime our budget for this project includes three Agilent 5071A's.

2.6 Clock Trips

An independent assessment of the systematics of the TWSTT procedure would be highly desirable. The only robust method that has come to our attention is a clock trip (CT). This technique utilizes a pair of Agilent 5071A's, one stationary at Fermilab, the other transported from Fermilab to Soudan and back. If the TWSTT system is utilizing Agilent 5071A's, then the AC normally at Fermilab would also serve as the stationary clock for a CT. The synchronization error for a CT grows like $\sqrt{R}$ where R is the round-trip time. In order to minimize R we plan to transport the itinerant clock in a small aircraft chartered for the purpose. We expect to hold R to less than 12 hr, which would yield a single-trip error of about 1.3 ns. Environmental effects might degrade this error to 2.0 ns. To check TWSTT at the 1.0 ns level will require a set of five to ten CT's. An annual repetition of the CT exercise should produce adequate confidence in the TWSTT method. The principal cost of a set of CT's will then be the aircraft rental, and we estimate this expense at \$1200 per trip.

2.7 Error Considerations

The length of the proton pulse affects the sensitivity to non-light-like neutrinos. The NuMI beam design [21] currently accommodates some tradeoff between the bunch length and the momentum spread. The bunch length will be 3-8 ns according to the beam parameters document, but the document omits a careful interpretation of "bunch length." We guess that the sigma of the pulse will be no more than 2.0 ns. Whereas the distance between Fermilab and Soudan is purely a systematic issue, the impact of the bunch length is reduced by the square root of the number of neutrino arrival times we measure. Even in the case that the beam is tuned for maximum bunch length, arrival times for as few as 1000 neutrinos would suppress the error from bunch length to a level well below the systematic error.

We expect eventually to log arrival times for 10^4 ν_μ charged current events. The methods we are considering clearly produce single-event errors no more than 5 ns. When we average over our final sample, the statistical component of the error will shrink to less than 50 ps, and the systematic error will dominate. The sources of systematic error that we have identified are

1. the time of protons on target at Fermilab,

2. the Fermilab-Soudan distance,
3. clock synchronization error,
4. Far Detector Timing Model,
5. ΔT_4,
6. the distance traveled by the parent π^+.

A signal from the Main Injector RF will provide the time of protons on target, and the auxiliary detector at Fermilab will provide the calibration for this signal. We expect this systematic error to be well under 1 ns. The error of the Fermilab-Soudan distance is currently 0.7 m, corresponding to 2 ns. Very likely this error can be reduced a factor of ten or more by using a superior inertial measurement unit to translate the surface benchmark to the MINOS cavern. We expect a major portion of the clock synchronization error to be statistical, and we expect the single-event error to be less than 2 ns. The systematic part will surely be less than 1 ns. The purpose of clock trips is to constrain this error. To constrain the systematic error from the combination of the Timing Model and ΔT_4 we will divide the Far Detector into four zones and difference the arrival times obtained for single events that traverse multiple zones. We will take the means of these distributions as an estimate of this error. We do not foresee any reason that this error should exceed 1 ns. A portion of the distance from the proton target at Fermilab to the Far Detector is travelled not by the neutrino but by the parent π^+. Our rough calculation of the average delay incurred by the π^+ gives 300 ps. By simulation we will greatly refine this estimate, and only the residual error in the computation will remain as a systematic error. It will surely be much less than 300 ps. In summary, we anticipate that none of the sources of systematic error will exceed 1 ns with the possible exception of the distance, and we will have methods for controlling all of these uncertainties.

3 Budget and Milestones

In the following tables we list the salient project costs.

Capital costs:

Item	Quantity	Cost
Agilent 5071A clock	3	$120k
Rubidium clock	2	$10k
TSC clock electronics	2	50k
KU band modem	2	36k
VSAT ground station	2	30k
Radome	2	32k
Auxiliary detector	4	40k
TOTAL		$318k

Annual operating expense:

Item	Quantity	Cost
Air time	300 days	$18k
Clock trips	10	12k
TOTAL		$30k

If we succeed with procuring satellite air time on a favorable basis, we will be able to substitute rubidium atomic clocks for the Agilent 5071A's resulting in a cost savings of about $40k.

In the table below we list salient project milestones in order of expected completion together with the expenditures required to attain the respective milestone.

Milestone	Integrated cost
Measure cosmic ray TOF using Rb clock and TSC electronics	$30k
Measure drift of Rb clocks	35k
Synch Rb clocks using TWSTT	126k
Two auxiliary detectors operational	146k
Measure TOF at Fermilab	178k
First attempt at MINOS Timing Model	178k
Commission 2 Agilent 5071A clocks	258k
Four auxiliary detectors operational	278k
Relocate one clock ensemble and aux detectors to Soudan	278k
First clock trips	318k

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