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Long term performance of the MINOS calibration procedure and stability of the MINOS detectors

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Abstract.

The MINOS detectors are steel-scintillator sampling tracking calorimeters and are calibrated using an in-situ light-injection system and cosmic ray muons. The MINOS Near and Far Detectors have been operating almost continuously since 2003 and 2005, providing opportunity to quantify the behavior of the various detector components, many of which are used in the next generation neutrino oscillation experiments, under long-term experimental operation. We report on the calibration procedure and its stability, as well as the time and temperature dependencies of the scintillator, wavelength-shifting fibers and photo-multiplier tubes.

The MINOS [1, 2] experiment is a two-detector long-baseline experiment. The 0.98 kT Near Detector (ND) is located approximately 1 km from the NuMI [3] target and is used to measure the neutrino energy spectrum and composition of the beam. The 5.4 kT Far Detector (FD) is located 734 km further down stream in the Soudan Underground mine. By comparing the neutrino energy spectrum observed at the Far Detector with that observed at the Near Detector neutrino oscillation parameters can be determined [4, 5, 6, 7]. A robust calibration technique has been developed [2, 8] and is employed to remove the spatial and temporal variations in the detector response which would otherwise degrade the calorimetric energy resolution and therefore the ability to measure the oscillation parameters.

The two MINOS detectors have been designed to be as similar as possible to minimize systematic errors due to uncertainties in the beam-flux and neutrino interaction cross-sections. Each detector is comprised of torroidally magnetized one-inch-thick steel layers interleaved with scintillator. The scintillator is made of Dow STYRON 664 polystyrene doped with 1% PPO by weight, plus 0.03% POPOP fluors [9]. Each scintillating layer is comprised of 4.1 cm wide, 1.0 cm thick strips of varying length. The strips in each alternate scintillator layer are rotated 90° to allow for three-dimensional track reconstruction. The scintillating strips are contained in a co-extruded TiO₂ cladding to maximize internal reflection. The scintillation light is read out by a 1.2 mm Kuraray “non-S” type wavelength shifting (WLS) fiber, containing the Y-11 fluor at 175 ppm, embedded in center of the wide face of each strip. The light is transmitted from the end of the scintillation module by clear acrylic fibers to Hamamatsu multi-anode photomultiplier tubes (PMTs) [10, 11, 12].

The Near Detector is required to read out several events per 10 μ s spill, and is therefore created for continuous readout. The Near detector readout [13] integrates PMT charge in intervals of 19 ns, continuously reading out the pulse-shape via a QIE chip for each PMT pixel. Successive samples come from four charge-holding capacitors that are read out with a

combination of an 8-bit ADC and a 4-bit range. The response function of this device is therefore very nonlinear, and is calibrated in hardware using a reference DAC to calibrate and linearize each channel. During normal data-taking, each sample is passed through a look-up table to determine the linear charge for that sample. The readout system is regularly re-calibrated, particularly when hardware is swapped, and therefore is known to be much more linear and stable than the PMTs. During beam spills, the detector reads out continually. Outside of beam spills (e.g., cosmic-ray events) the detector reads out a set of 8 samples from each PMT pixel when triggered by a dynode tap on that PMT.

In contrast, the Far Detector readout [14] is constructed to service many more channels of electronics at low rate. Each PMT is read out only when triggered by the PMT dynode tap. Charge from each pixel is stored on a capacitor and then each capacitor is read out sequentially through a common line shared among 3 PMTs. Pedestals are subtracted by the readout system, but the resulting charge is highly nonlinear due to a roll-off effect in the ADC at large charges. This nonlinearity is eventually calibrated out along with the PMT nonlinearity.

Because of the differences in detector conditions, the PMT readout electronics differ between the Near and Far Detectors. Because this is one of the few differences between Near and Far Detectors, it has been studied extensively in a test-beam environment [15].

1. Long Term Detector Trends

We have tracked the long term behavior of the detector response and the response of the PMT gains in both the Near and Far Detectors in the period from January 2005 to February 2011. During this time the detector and PMT response was frequently monitored and a uniform calibration scheme was applied. This data was used to measure the stability of the response of the MINOS detectors over time. We also quantified the effects of hall conditions such as temperature fluctuation. Since the detector response is a product of the PMT response and the amount of light incident on the PMT photo-cathodes, we can measure the changes in light level as a function of time by calculating the ratio of the detector response to the PMT gains.

The detector response, or drift, is monitored daily using cosmic ray muons. The response in both the MINOS Near and Far Detectors has decreased gradually over the life of the MINOS experiment. For the period between January 2005 and February 2011, the raw response of the detector has decreased by roughly 8%. This decrease is shown in Fig. 1. In this figure, the drift is shown as a percentage decrease from the first data for each detector. The start date for the Near and Far Detectors is slightly different, reflecting the fact that the Near Detector turned on after the Far was already running in a stable manner.

1.1. PMT Behavior

The MINOS Near Detector uses R5900-00-M64 multi-anode PMTs, while the Far uses R5900-00-M16 PMTs; the low occupancy of hits at the Far Detector allows an 8-fold multiplexing of non-neighborhood scintillating strips on each of the PMT pixels. In total the Near (Far) Detector has 192 (1452) PMTs. The characteristics of these PMTs have been extensively evaluated [11, 12]. To determine the gain each Near (Far) Detector strip-end is pulsed 1000 (300) times per hour [2] by the LI system at approximately 50 PE. The data are then summed over a three day interval and the gains evaluated using photon statistics [8]. The gain determined is therefore an average over a 3 day period, averaging out daily fluctuations.

Figure 2 plots the Near and Far Detector gains as a function of time. Since November 2004, the gains have increased by 19% and 16% at the ND and FD, respectively. The ND data indicates that the PMTs experience an initial rapid increase in gain in their first year of operation. After this initial increase, the rate of the increase slows with time.

The short term fluctuations in gain are well correlated with temperature and are more pronounced in the ND data as the temperature variations are larger. The temperature of the FD

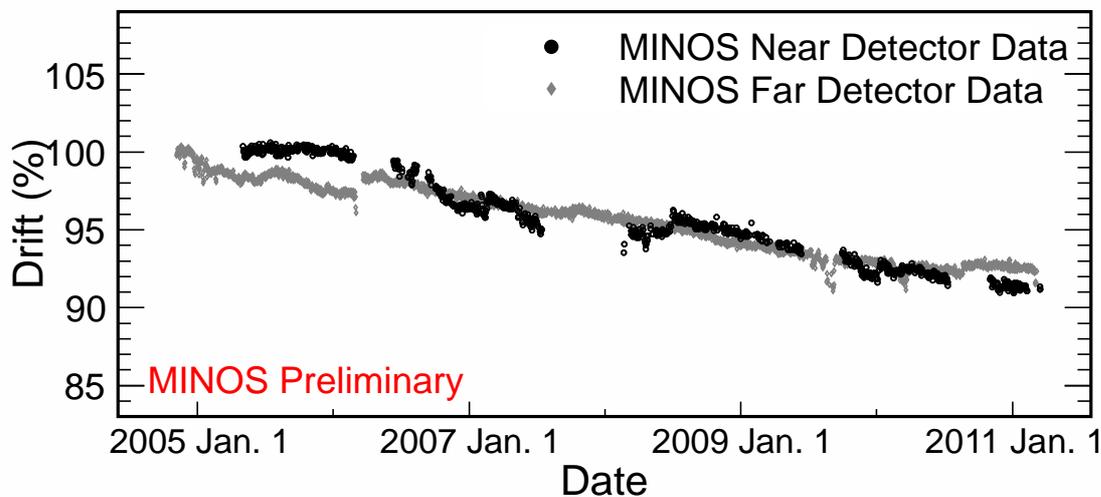


Figure 1. The daily change in detector response of the MINOS Near and Far Detectors.

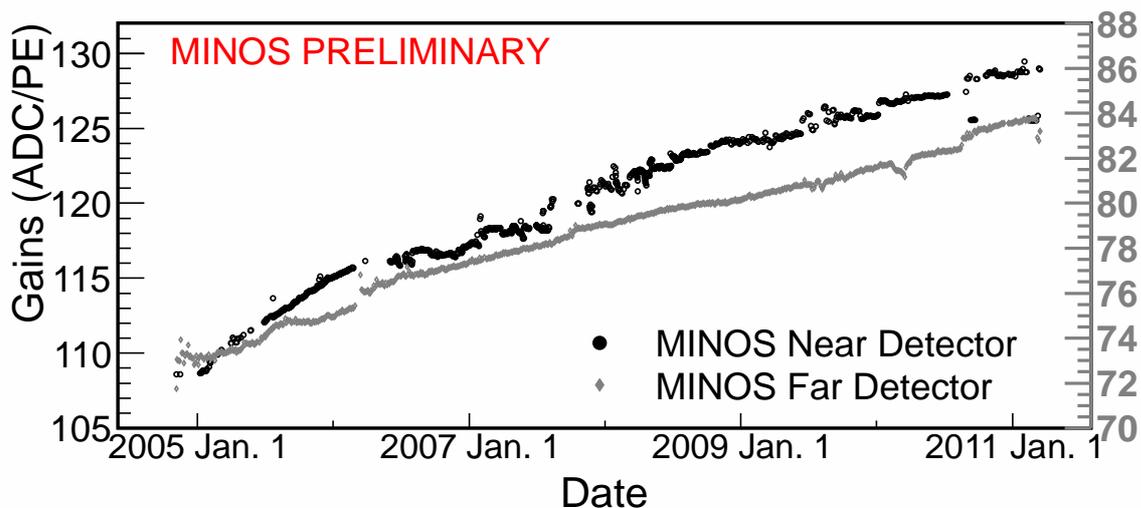


Figure 2. The measured Near and Far Detector gains as a function of time. The short-term fluctuations away from a smooth curve correlate well with temperature. The small discontinuity in the FD gains in 2006 is due to a re-tuning of the PMT high voltages.

PMTs closely tracks the cavern temperature. To identify the effect that variation in temperature has on the gain, short periods of time with large variations in temperature ($\sim 2^\circ\text{C}$) have been identified. In these instances it was observed that the PMT gain changes with temperature at a rate of $(-0.58 \pm 0.05)\%/^\circ\text{C}$ for the FD and $(-0.232 \pm 0.019)\%/^\circ\text{C}$ for the ND.

The gain curves fit well to an exponential of the form $1 - Ae^{-t/\tau}$ with a time constant of 10.57 ± 0.05 years at the ND and 20.2 ± 1.8 years at the FD. The Near Detector has two distinct exponential periods, and we report the result for the latter and longer one, which covers June 1, 2006 through March 19, 2011. Moreover, individual PMTs and PMT pixels are aging at different rates increasing the spread in the gains by 4.6 % in the ND and 8.9 % in the FD.

1.2. Detector Light Yield

The amount of light incident on the PMTs can be defined by dividing the observed detector response by the average gain. This measurement is affected by the scintillator light yield, the attenuation in the WLS and clear fibers and the optical transparency of the readout chain. Figure 3 plots the light level for both detectors from November 2004 to February 2011. In this period of time, the overall light level in both detectors has dropped approximately 20% with an average rate of 3.5% per year in the ND and 3.0% per year in the FD.

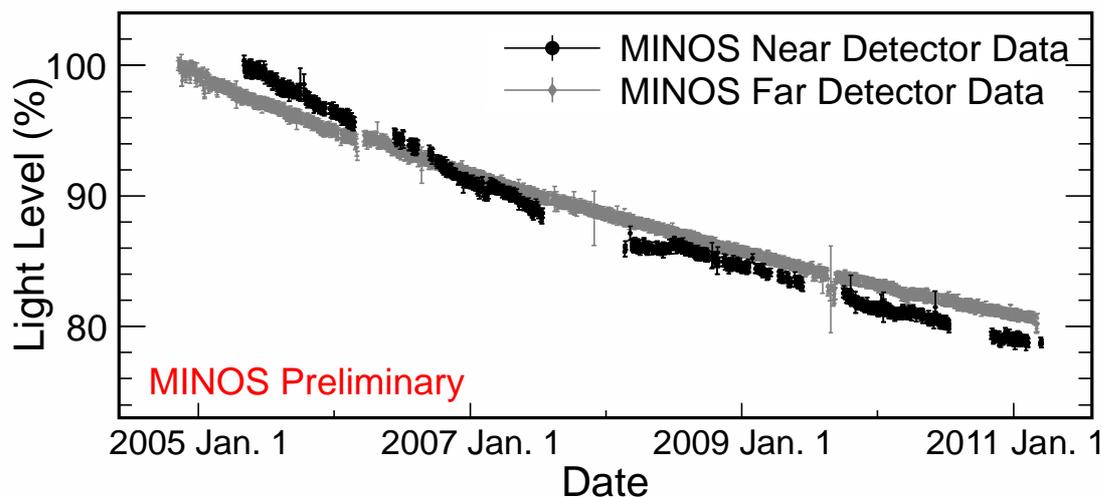


Figure 3. The relative light level of the MINOS Near and Far Detectors over time. The light level is a smoother curve than drift as it removes the large variations due to PMT gain.

As with the gain measurement, the rate at which the light level is dropping decreases with time. The data was fit to an exponential function of the form $(100 - A)e^{-t-t_0}/\tau + A$. The time constant is found to be $\tau=8.2$ years for the Far Detector and $\tau=5.4$ years for the Near Detector, and the parameter A is found to be $A=68\%$ for the Far Detector and $A=64\%$ for the Near Detector. This suggests that, ignoring the influence of more catastrophic types of aging such as large temperature changes, the scintillator in the MINOS detectors is aging much more slowly in 2011 than in 2004 and the light level will not decrease below 60% of its original value.

In addition to the long-term decrease in light level, short-term variations in the light level are observed. These short-term variations are due to a variety of sources including detector and hardware instabilities and temperature variations. For both detectors, the scintillator temperature tracks that of the detector hall. We identified several regions where the Near and Far hall temperature exhibits large, smooth changes in short regions of time, and fit these periods to determine the decrease in light level as a function of temperature. We find that the light level decreases by $0.2\pm 0.06\%$ per $^{\circ}C$ in the ND and $0.4\pm 0.07\%$ per $^{\circ}C$ in the FD.

1.3. Calibration Stability

The raw and calibrated detector response as a function of position is shown in Fig. 4. The 30% variation in response that is observed across the face of the detector is effectively removed by the calibration chain. Figure 5 plots the calibrated response of the Far Detector as a function of time; the response is stable over the complete run period. The response of the Near Detector is more stable than that of the Far Detector.

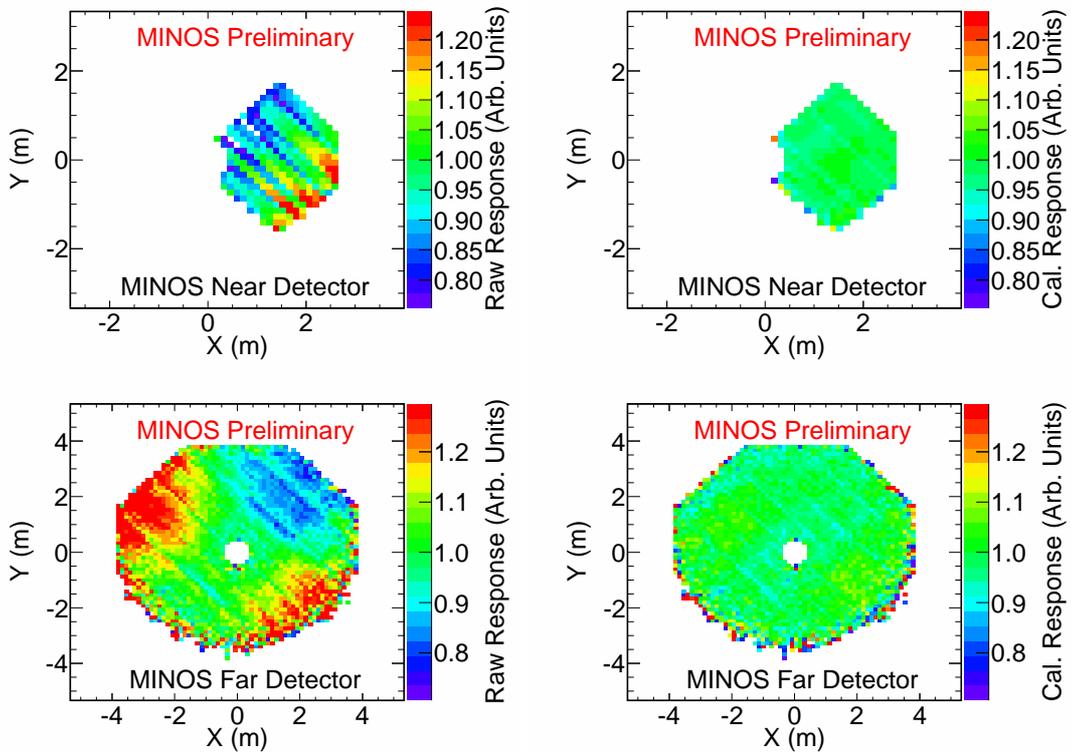


Figure 4. (left) The raw response of the detector as a function of XY coordinate. (right) The response of the detector after all the calibrations have been applied. The top row is the Near Detector response and the bottom row is the Far Detector response.

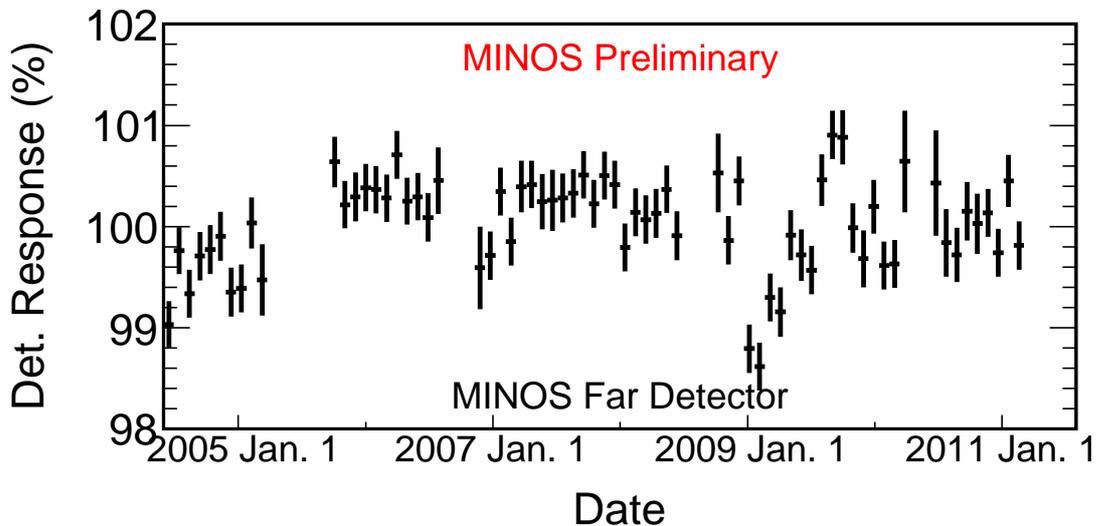


Figure 5. The calibrated response of the Far Detector as a function of time.

2. Absolute Energy Calibration

The MINOS Calibration Detector (CalDet) [8] was a scaled down, functionally identical version of the Near and Far Detectors. It was exposed to various test beams at CERN between 2001 and

2003 to determine the detector response to GeV energy protons, pions, electrons, and muons; the latter being important as stopping muons are used to determine equivalence of all three detectors. Using CalDet, it was found that the uncertainty on the absolute energy scale is 5.6%. Extrapolating this to the Near and Far Detectors, it becomes 5.7%. Taking into account differences between Near Detector data and Monte Carlo simulations, the error on the absolute energy scale of the Near Detector is 6.0% and the Near-to-Far relative energy scale is 2.1%.

3. Summary

During their operation, the responses of the Near and Far Detector have decreased by approximately 20%, which is better than the design specifications. We have demonstrated that the MINOS detector calibration method has been demonstrated to yield a uniform response as a function of position within the detector and in time. We measure the absolute energy scale to 5.7% and relative energy scales to be 1.9% and 0.9% at the Near and Far Detectors, respectively.

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