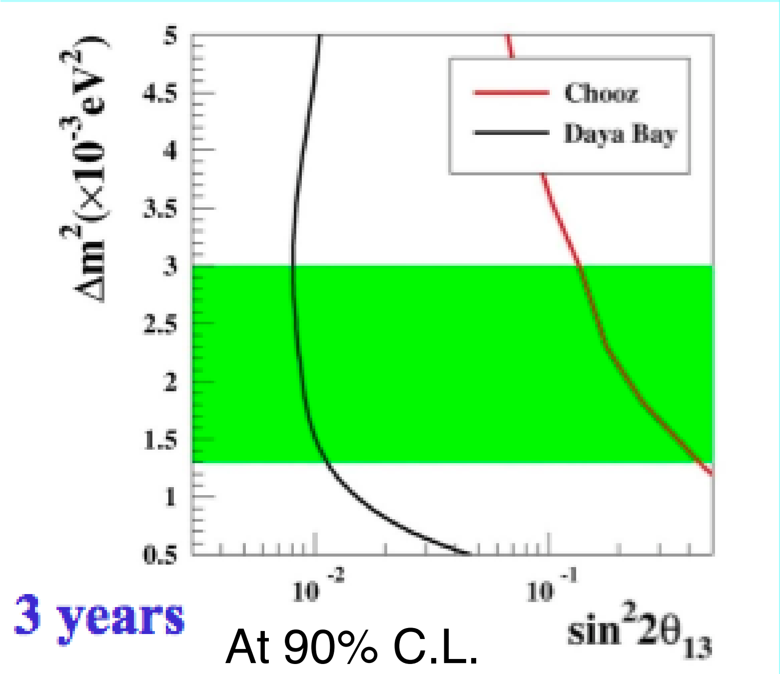
High Precision Measurement of the Target Mass of the Daya Bay Neutrino Detectors

Tom Wise on behalf of Daya Bay collaboration

Day Bay is a reactor based experiment dedicated to measurement of the last unknown neutrino mixing angle θ_{1-3}

Sensitivity to $\mathrm{Sin}^2 2\theta_{13}$



Target mass measurement enters here

	Uncertainty
Reactors	0.13% (6 cores)
Detector (per module)	0.38% (baseline) 0.18% (goal)
Backgrounds	0.32% (Daya Bay near) 0.22% (Ling Ao near) 0.22% (far)
Signal statistics	0.2%

Why do we need to know the target masses to high precision? What precision is needed?

The Day Bay experiment measures the amount of $\bar{\nu}_e$ disappearance between “near” and “far” detectors.

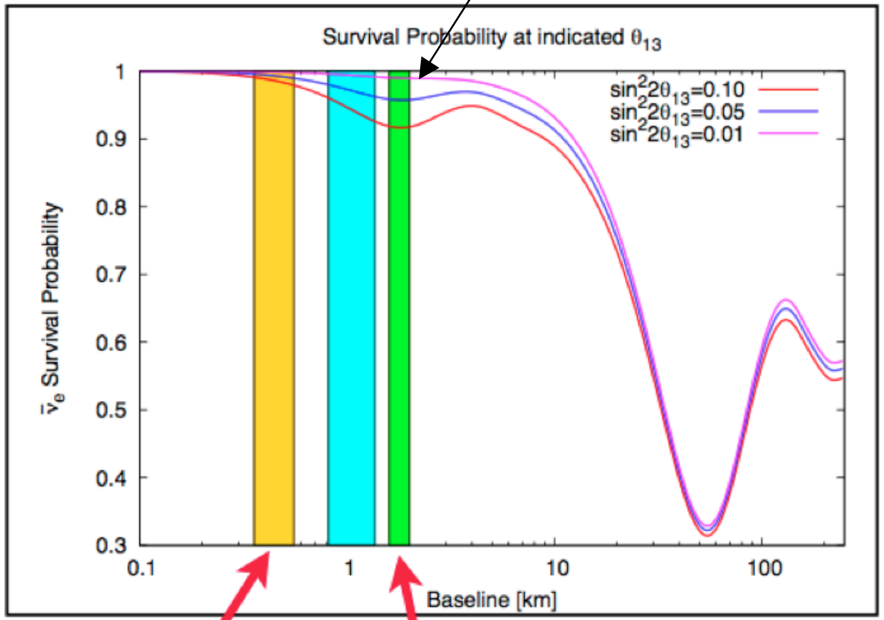
The $\bar{\nu}_e$ interact with proton rich liquid scintillator via the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$. They “disappear” if they oscillate into another flavor before reaching a detector.

Probability of a $\bar{\nu}_e$ disappearing on the path from reactor core to one of our detectors due to flavor oscillations is given by

$$P_{13} \approx \sin^2 2\theta_{13} \sin^2 \left[1.27 \Delta m^2_{31}(eV^2) \frac{L(km)}{E_\nu(GeV)}\right]$$

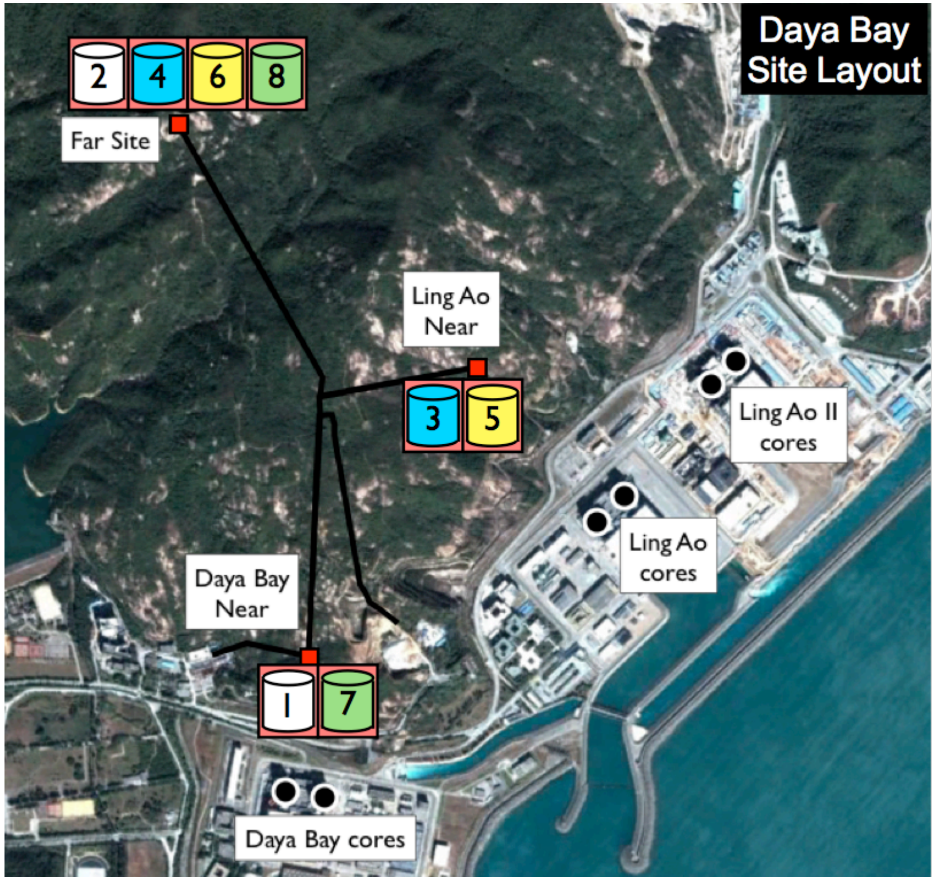
Eight “identical” detectors deployed in a (2,2,4) pattern, with 4 detectors at a FAR site and 4 detectors split between two NEAR sites.

We are looking for small differences in count rates after applying corrections



Near Sites

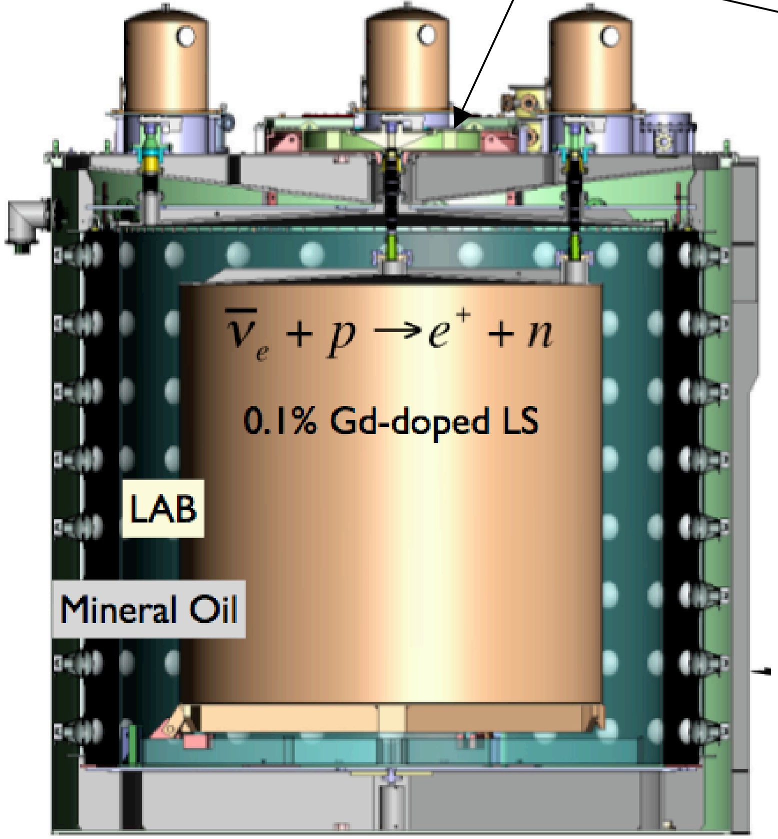
Far Site



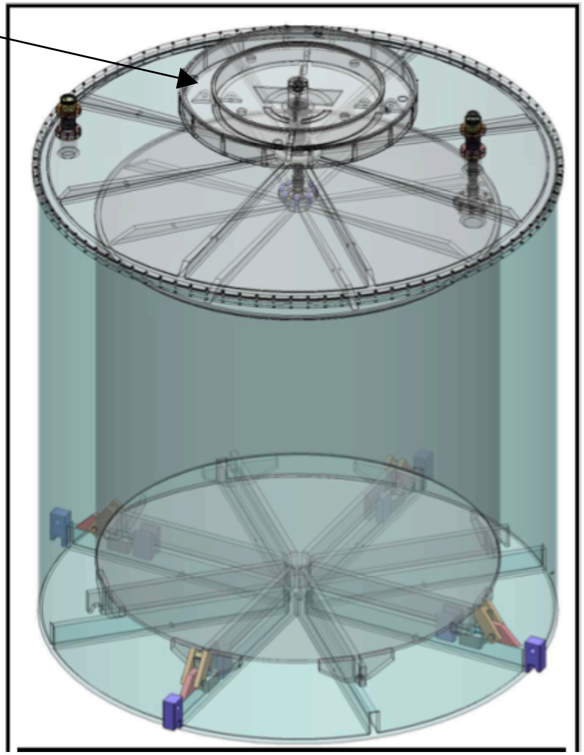
For Day Bay to measure $Sin^2 2\theta_{13}$ to a sensitivity <0.01 we need to keep uncertainties from detector to detector variations below 0.38%.

One of the most important corrections we need to make is to account for target mass differences. The target region has ~ 20 tons of 0.1% Gd-doped LS. The exact amount of GDLS depends on geometry details of the eight hand made 3.1m diameter inner acrylic vessels. Survey information on the vessels is not sufficient to determine target mass because they are too flexible. We need to directly measure fluid flow. We also need to know the mass of liquid in overflow tanks required for thermal expansion.

Section view of a complete detector module. Note overflow tanks required for thermal expansion.



Model of hand made 3.1m diameter acrylic vessel shown nested inside a hand made 4m diameter acrylic vessel



Measurement of mass flow at the 20 ton level to a precision of $\Delta m/m < 0.1\%$

There are a multitude of mass flow devices on the market but there are really only two methods with the accuracy we require:

- Precision Coriolis flow meter

Siemens SITRANS F C
MASS 2100 DI 6

- Precision load cells

Sartorius model PR 6221 in special accuracy class C6. Advertised accuracy is 0.008% per load cell

To reduce risk from instrumentation failure and add cross-checks we decided to use both methods.

Class C6 load cells:

- Simple-- M_{full}-M_{empty}
- Highest advertised accuracy
- Independent of flow history

x- Requires special Teflon lined tank

x- subject to time drift

Also requires correction for barometric pressure

Coriolis meter:

- Gives instantaneous flow rates
- excellent process monitoring
- sufficient accuracy
- High resolution--50 gm mass/pulse

x-very low flows not allowed

x- subject to zero drift

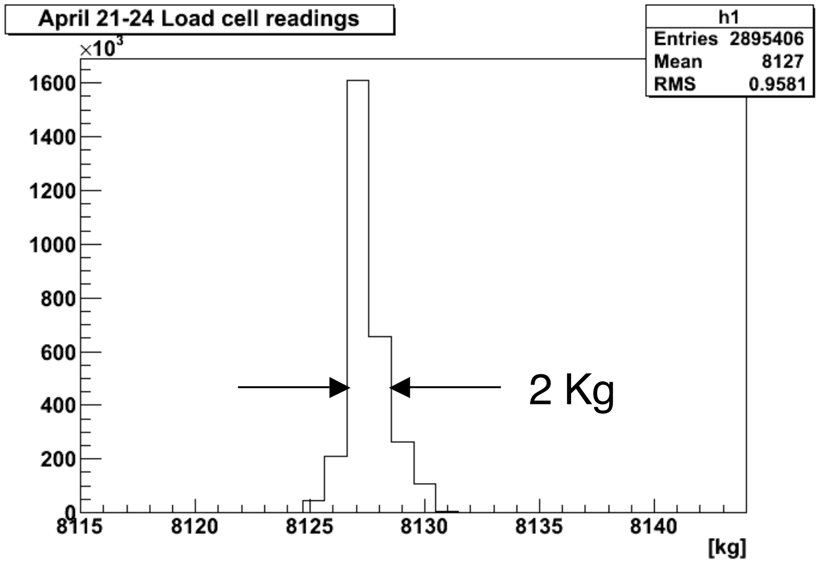
x- output sensitive to gas bubbles

x- integration of flow requires uninterrupted operation for entire filling campaign

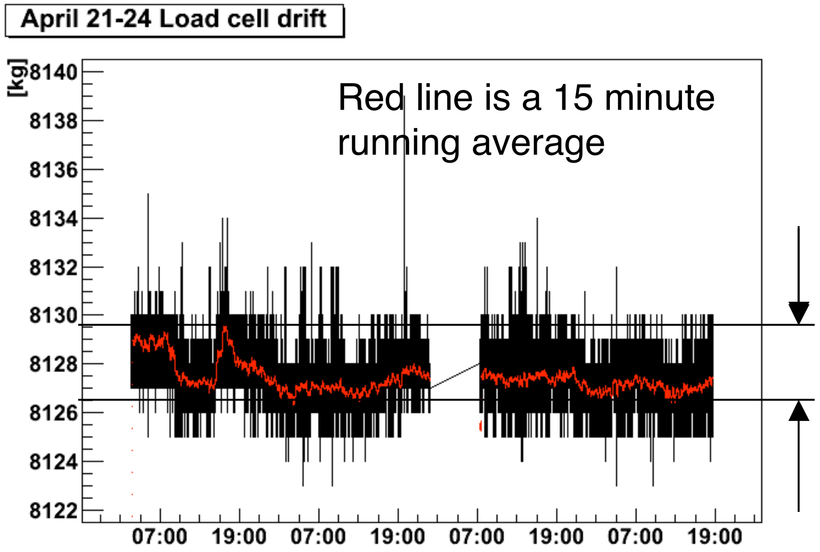
Some typical load cell data

Based on this data and other drift runs we determine M_{full} and M_{empty} with 15 minute averages.

Four day drift study



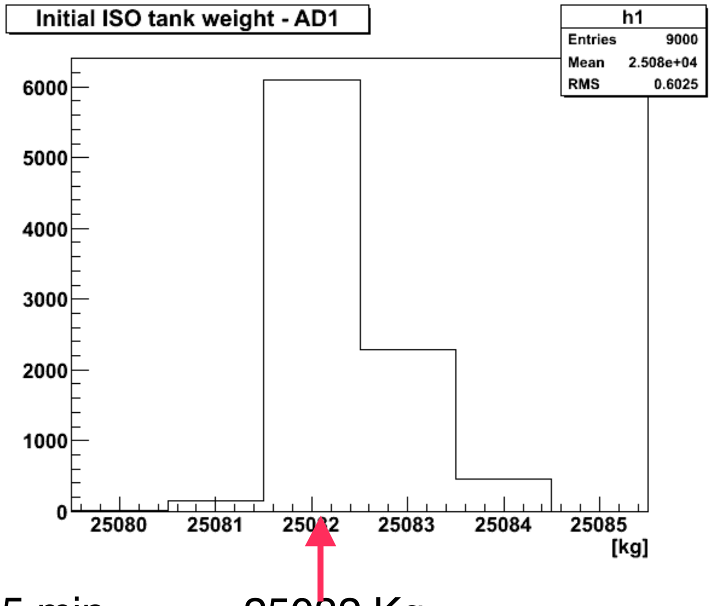
2 Kg



Red line is a 15 minute running average

Load cell 15 min running average drifts inside a 3Kg band over 4 days

Histogram of 15 minutes of load cell output with a full ISO tank.

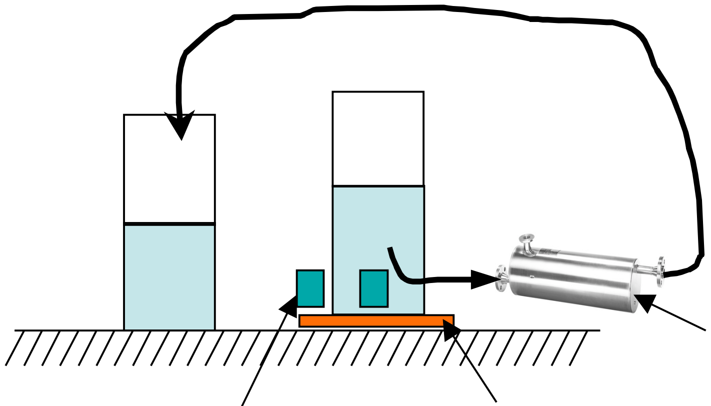


25082 Kg

Raw difference is accurate to ±3 Kg

Coriolis meter calibration

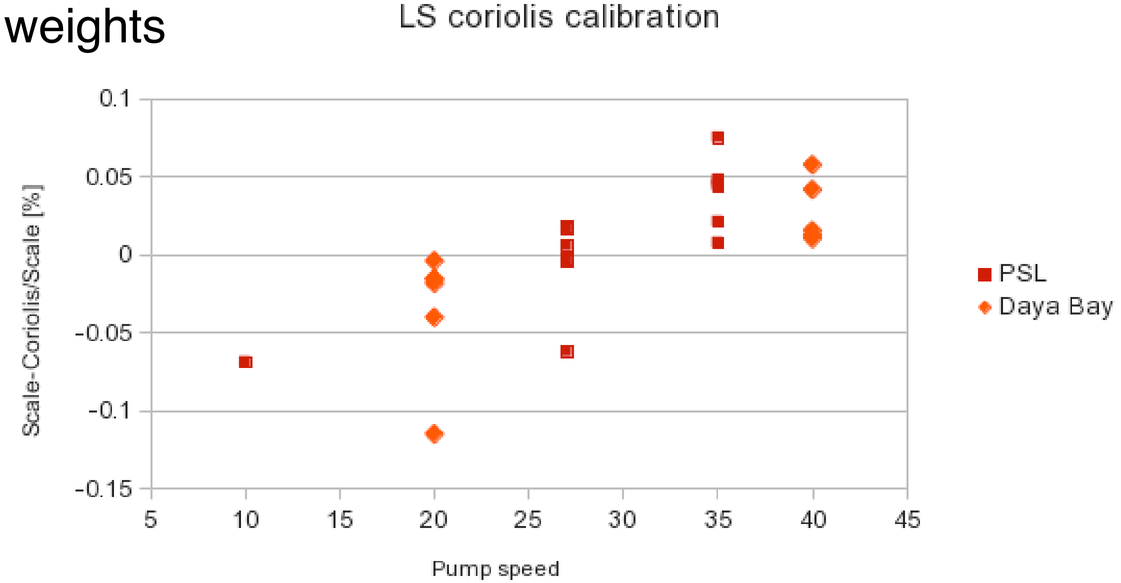
Calibrate tank scale with traceable weights. Then compare coriolis meter output with tank scale.



Coriolis meter

Precision digital floor scale (tank scale)

Traceable 25 Kg calibration weights



Based on these calibrations we can rely on coriolis meters to have ±0.1% accuracy. Less accurate than load cells but sufficient as a backup.

Absolute vs relative target mass and load cell calibration

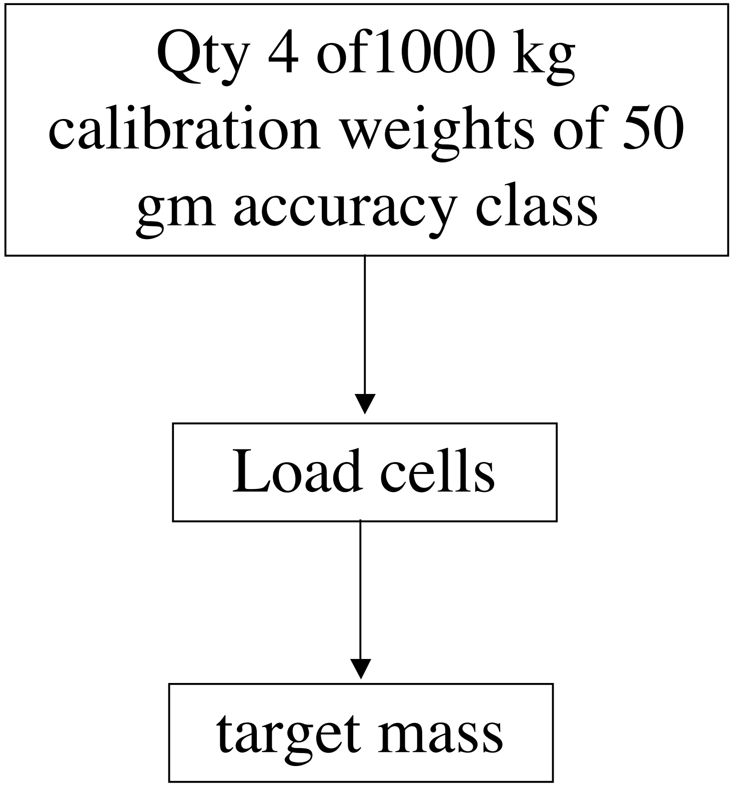
Day Bay primarily uses a near-far comparison so that absolute event rate and therefore absolute target mass cancels to first order. However there are some effects such as background events and detector efficiency that depend slightly on the absolute target mass.

We purchased four 1 ton certified calibration weights to verify the absolute accuracy of the load cells and to eliminate drift over time scale of years.

One calibration weight on each ISO tank corner

Traceability of our mass measurements

Load Cell

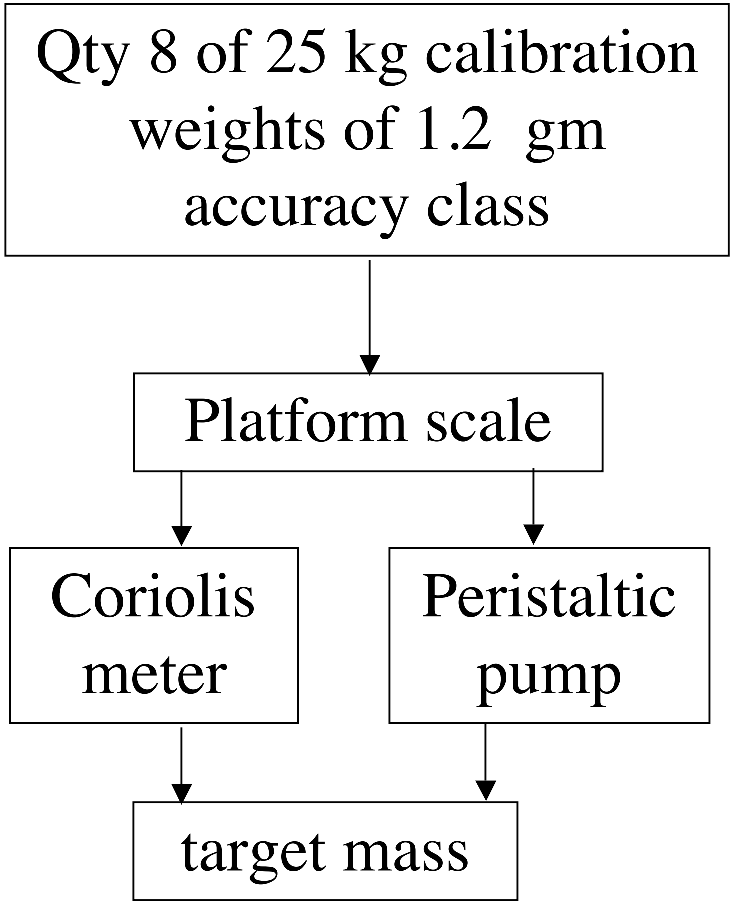


Qty 4 of1000 kg calibration weights of 50 gm accuracy class

Load cells

target mass

Coriolis meter



Qty 8 of 25 kg calibration weights of 1.2 gm accuracy class

Platform scale

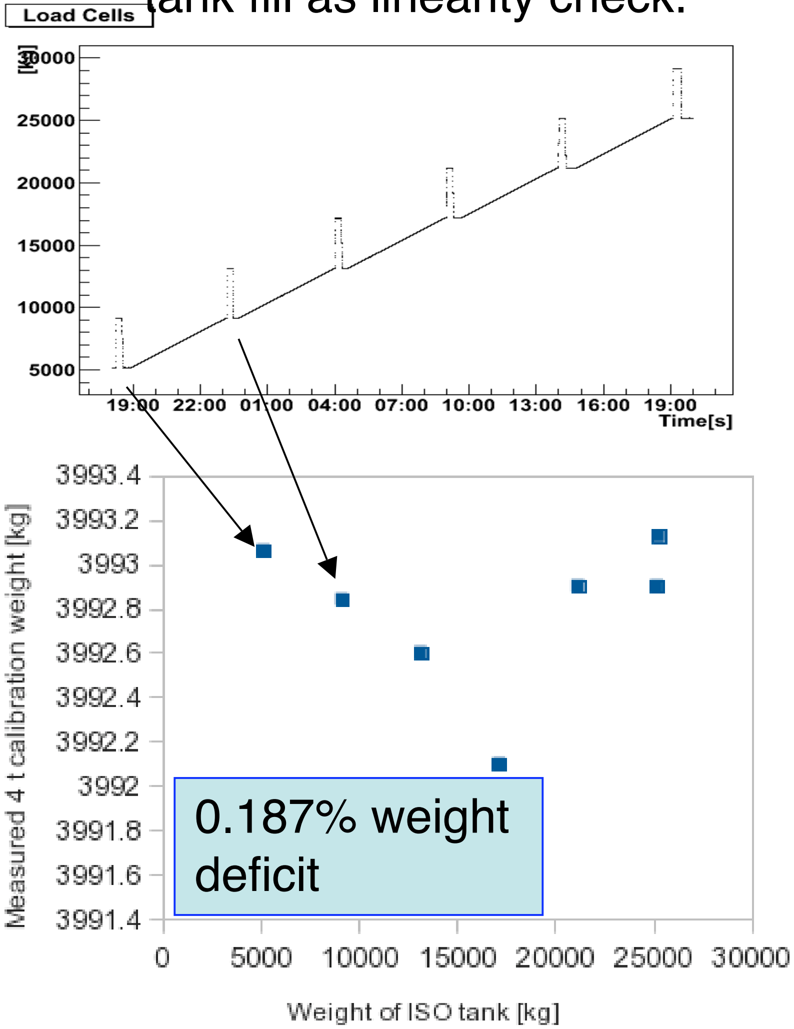
Coriolis meter

Peristaltic pump

target mass

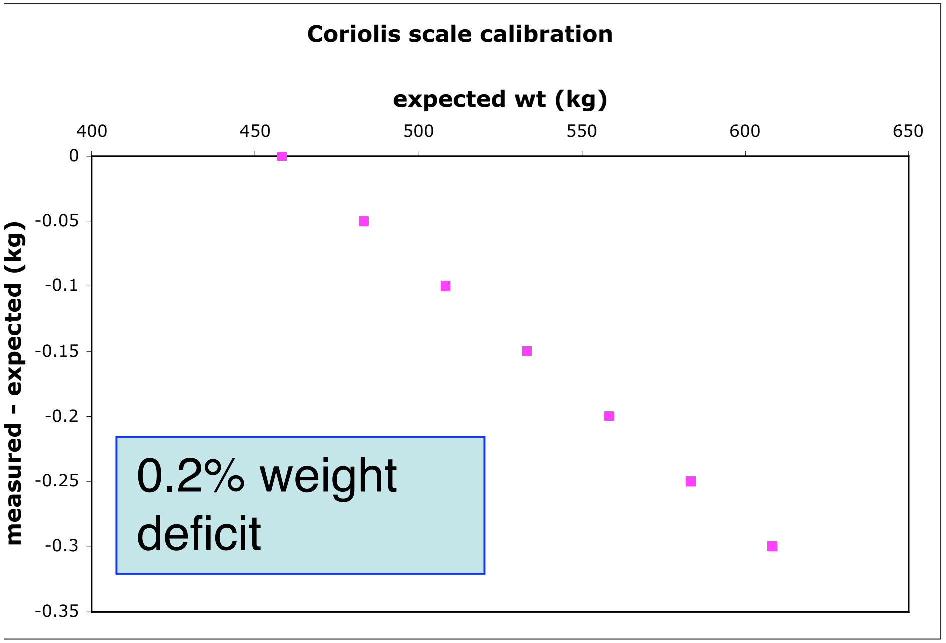
Both the ISO tank and Coriolis calibration weights read low.

Added/removed 4000 kg calibration weights during ISO tank fill as linearity check.



0.187% weight deficit

Added 25 kg calibration weights to tank scale



0.2% weight deficit

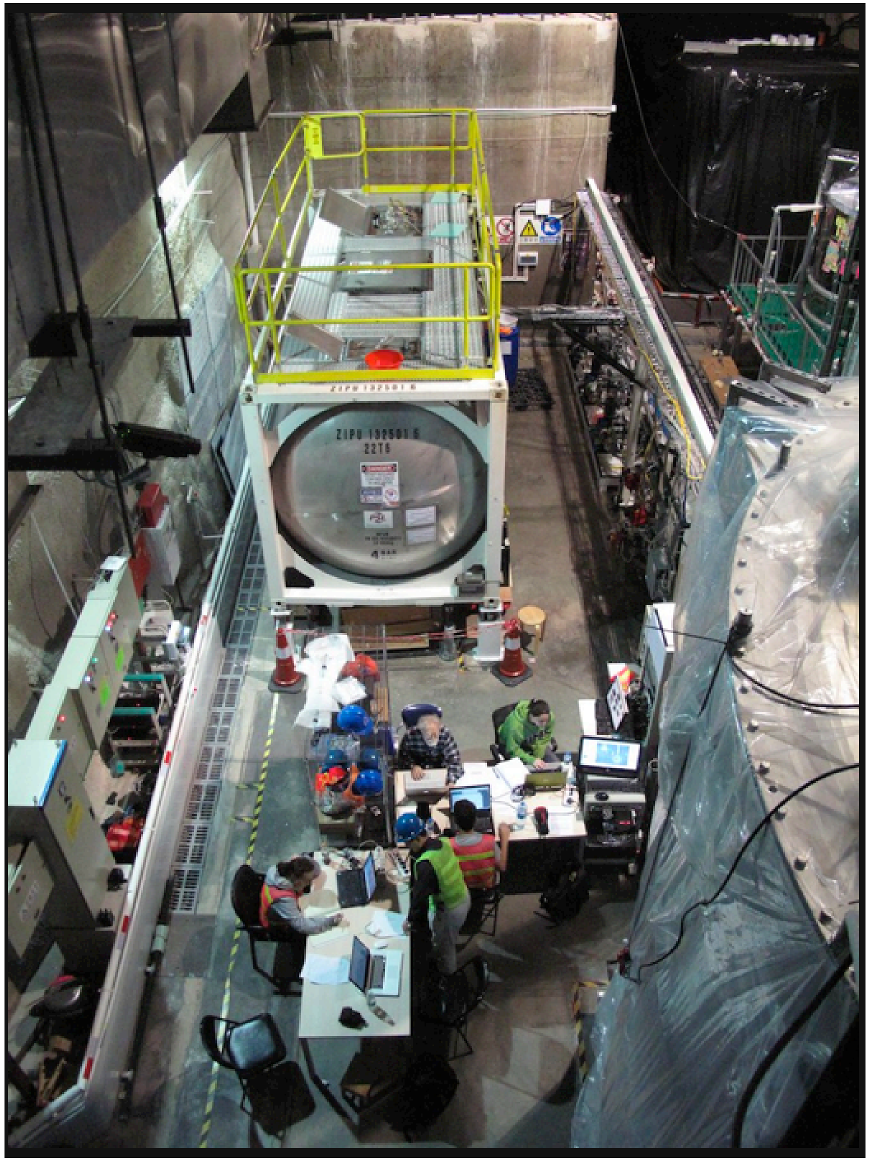
$$g_\phi = \left(9.780327 + 0.0516323\sin^2(\phi) + 0.0002269\sin^4(\phi)\right)\ \frac{\mathrm{m}}{\mathrm{s}^2}$$

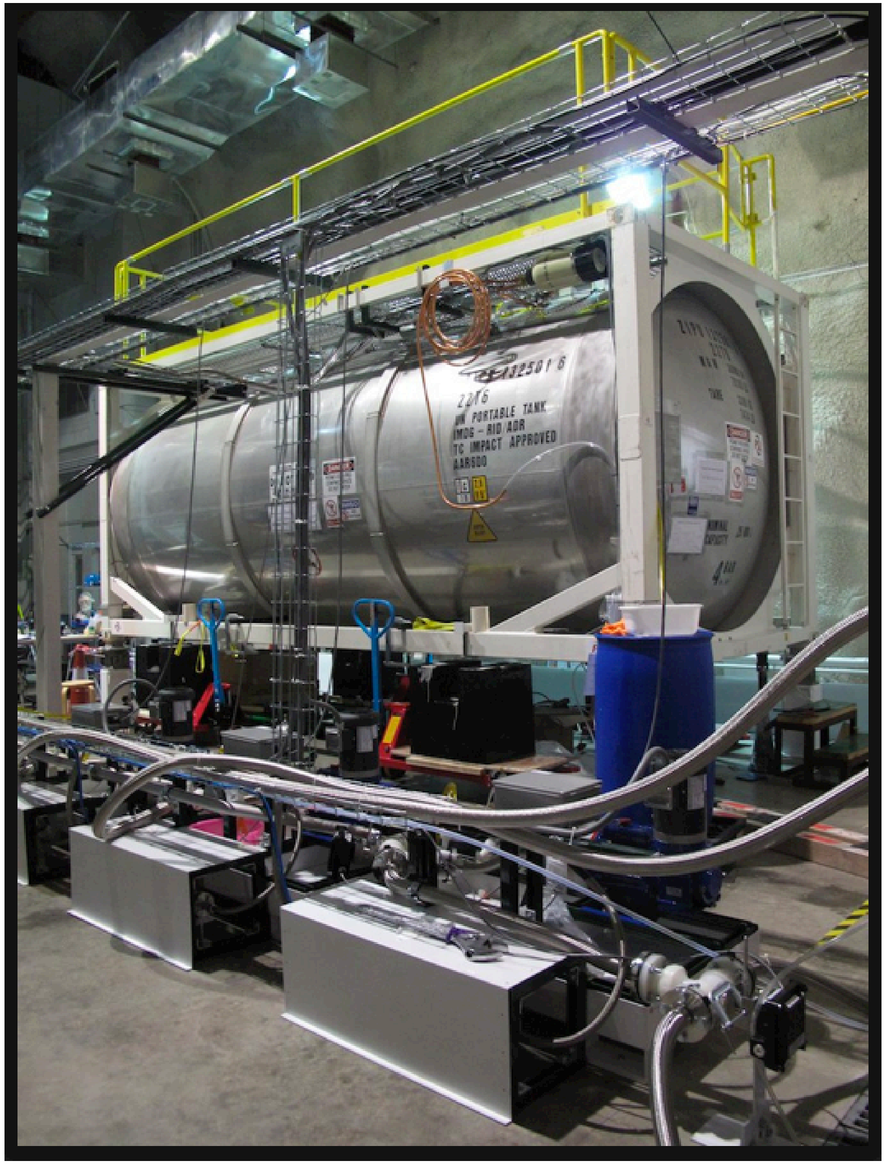
Helmert’s equation for *g* vs latitude gives 0.16% weaker gravity at Day Bay compared to Chicago.

Another correction required to obtain absolute target mass with load cells is the buoyancy of air. We monitor barometric pressure, temperature and humidity. The correction is on the order of +29 kg.

Hardware

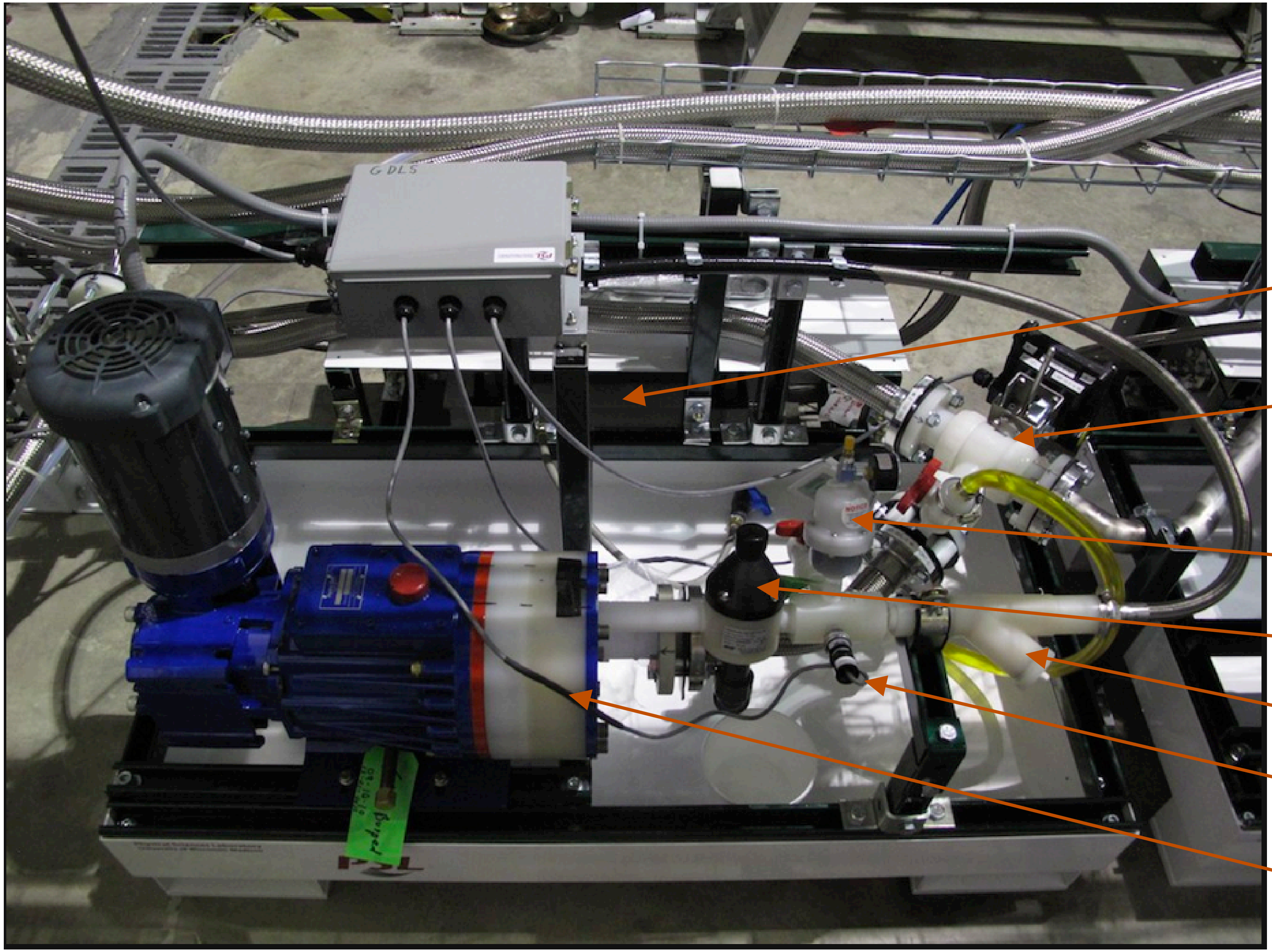
The pumping system was not easy to build.





GDLS pump station with PVDF components.

Two additional pumping stations with SS components are also used.



Coriolis meter glued to floor

Manual inlet valve

Pulse dampener

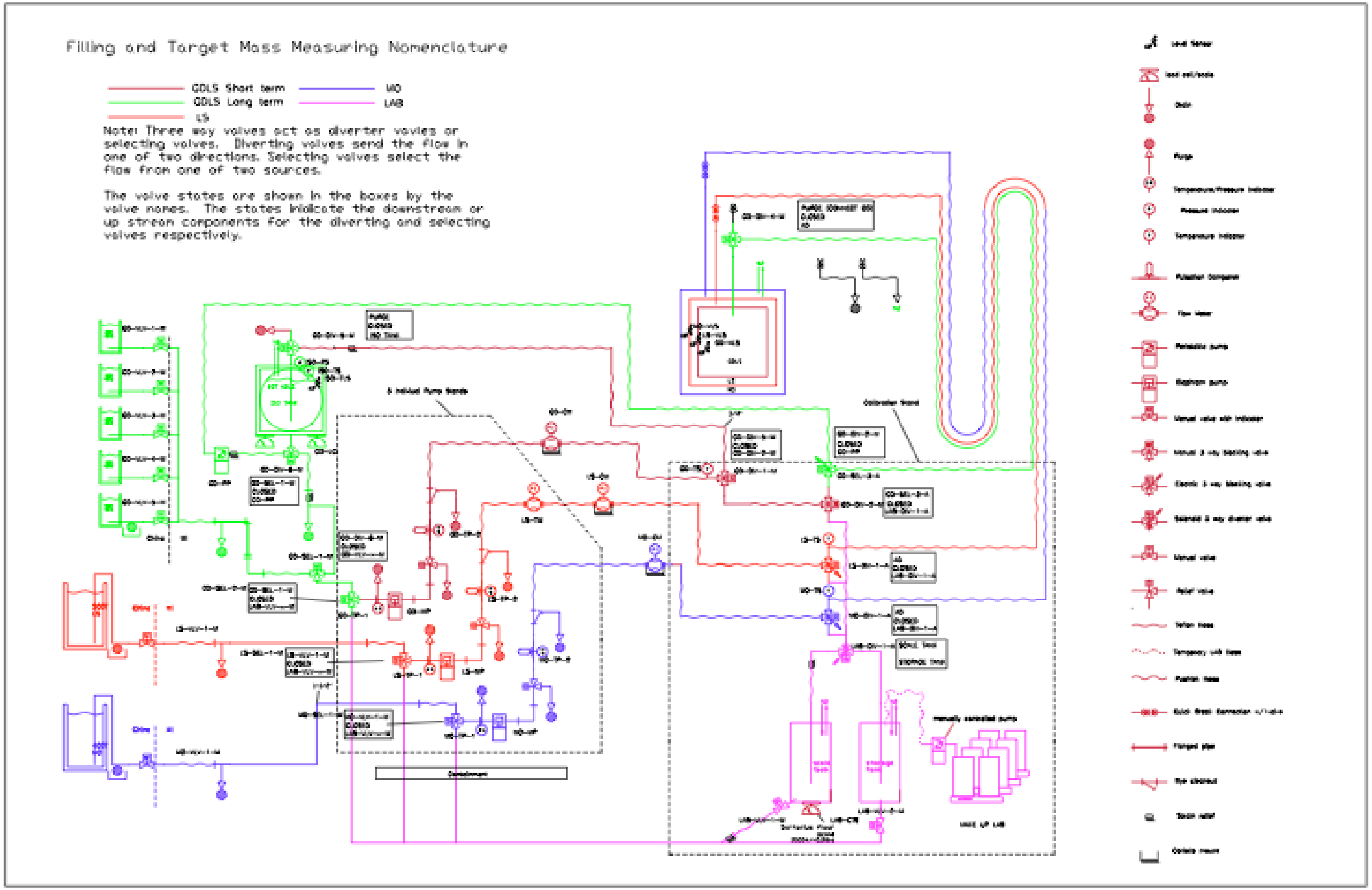
Pressure relief

strainer

Temperature, pressure sensors

3 poppet metering pump (Wanner)

Plumbing schematic



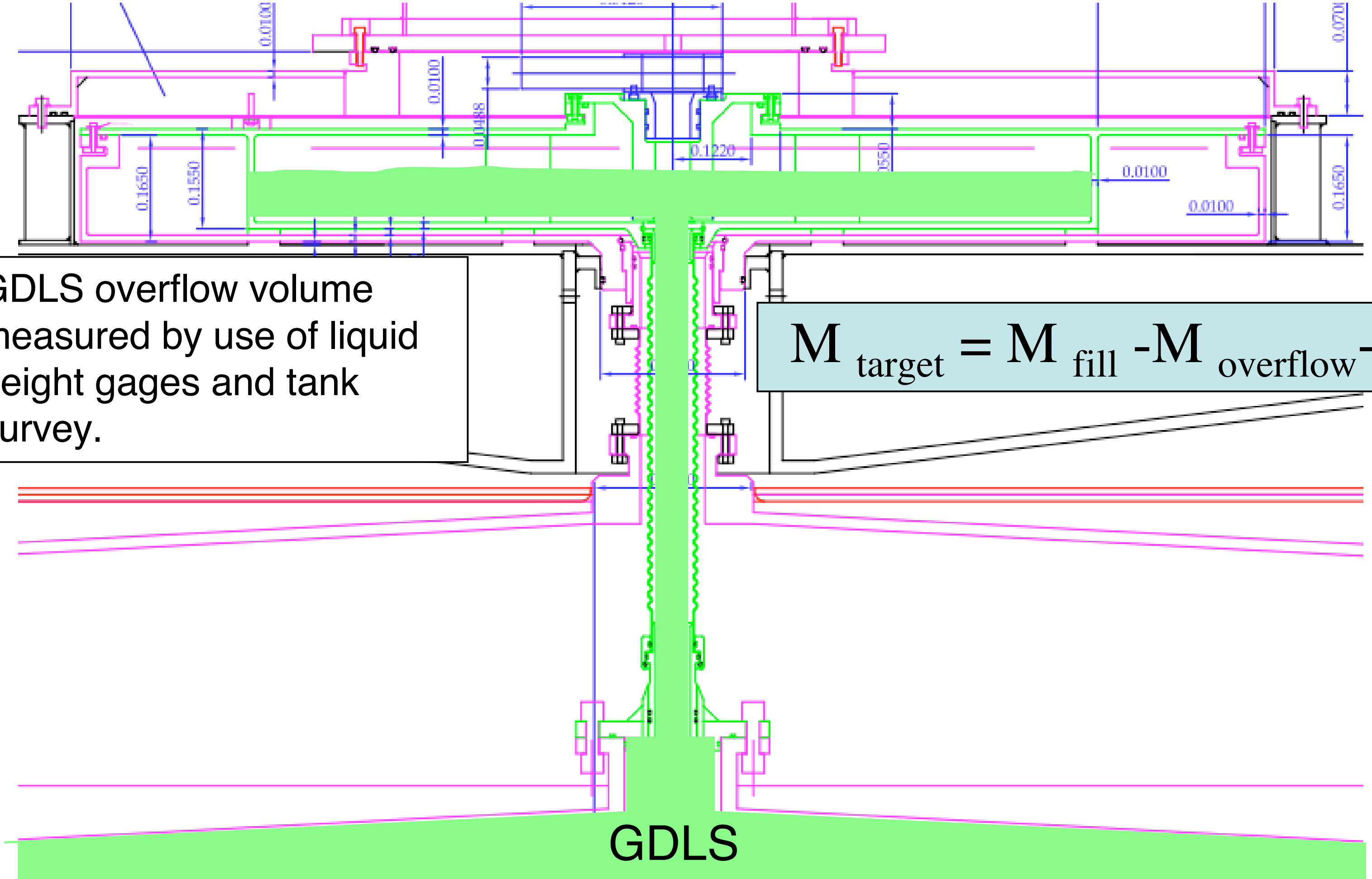
Filling and Target Mass Measuring Nomenclature

Note: Three way valves act as diverter vavles or selecting valves. Diverting valves send the flow in one of two directions. Selecting valves select the flow from one of two sources.

The valve states are shown in the boxes by the valve names. The states indicate the downstream or up stream components for the diverting and selecting valves respectively.

But it was rewarding to operate and very reliable

One final correction to the target mass is the volume of GDLS in the overflow tank. This mass must be subtracted from the delivered mass. Additional error is added because the height sensors have error and the overflow tank geometry is not known perfectly. The fraction α is determined by Monte Carlo and also contributes to total mass error.



GDLS overflow volume measured by use of liquid height gages and tank survey.

$$M_{target} = M_{fill} - M_{overflow} - \alpha M_{bellows}$$

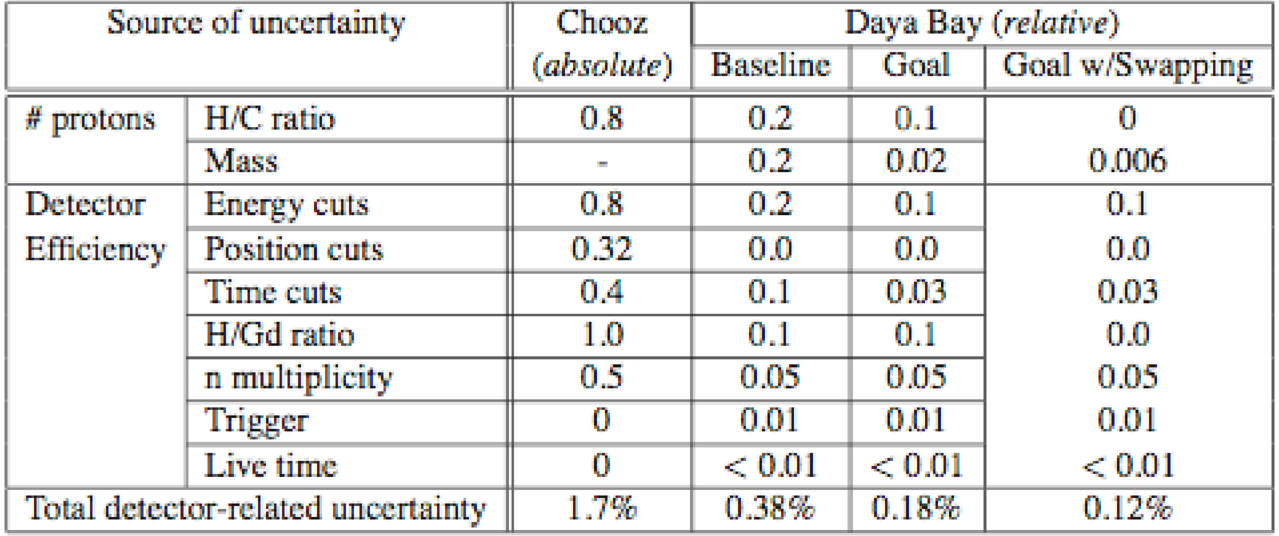
Conclusion

Two of the eight Day Bay detectors have been filled with these (preliminary) errors:

• Load cell drift	± 3 kg
• Calibration weight error	± 0.3 kg
• Barometric and temperature corrections	± 0.2 kg
• Overflow tank height and shape error	± 2.0 kg
• Bellows simulation factor error	± 0.1 kg
• plumbing operation error (1st AD only)	± 0.2 kg

<±6 kg or
< 0.03% Δm/m

Uncertainty table from TDR, october 2007



Source of uncertainty		Chooz (*absolute*)	Daya Bay (*relative*)		
			Baseline	Goal	Goal w/Swapping
# protons	H/C ratio	0.8	0.2	0.1	0
	Mass	-	0.2	0.02	0.006
Detector Efficiency	Energy cuts	0.8	0.2	0.1	0.1
	Position cuts	0.32	0.0	0.0	0.0
	Time cuts	0.4	0.1	0.03	0.03
	H/Gd ratio	1.0	0.1	0.1	0.0
	n multiplicity	0.5	0.05	0.05	0.05
	Trigger	0	0.01	0.01	0.01
	Live time	0	< 0.01	< 0.01	< 0.01
Total detector-related uncertainty		1.7%	0.38%	0.18%	0.12%

This performance exceeds baseline design and will reduce the overall experimental systematic uncertainties.