Precision Weighing at Sea

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Introduction

A key piece of any laboratory's analytical equipment is the precision balance used to weigh out reagents and samples with a high degree of precision, up to microgram in some cases. Aboard a research vessel at sea, however, a standard balance is completely ineffective because of ship's motion.

The JRSO employs two different dual-balance systems in order to counter ship's motion and allow for precision mass measurements at sea. Small masses, on the order of 1-100 mg, are weighed on Cahn Microbalances (Model C-29 or Model C-31). Larger masses, from 100 mg to ~100 g, are weighed on *paired* Mettler-Toledo XS-204 balances.

Basic Principle

Both the Cahn and Mettler-Toledo balances use the same basic principle to achieve precision mass measurements at sea: paired weights (reference and unknown) are put in similar conditions and allowed time to gather replicate measurements to overcome the movement of the ship. In the Cahn's case, the second weight is in the tare pan and counterweights the unknown pan.

For the rest of this document, the Cahn tare pan will be referred to as the reference pan to match the nomenclature for the Mettler-Toledo balances.

The balance is connected to a computer by an RS-232 connector and the net mass (red numeric LED in Fig. 1, below) is recorded over several minutes by computer and the average mass is calculated by JRSO-developed software.

Fig. 1. Cahn Model C-29 Microbalance. For masses 250 mg or less, the unknown pan is hung from the "A" support wire (as shown in the picture). The JRSO does not use the "B" wire configuration for heavier masses.

In the Mettler-Toledo case, a separate balance measures the reference mass and unknown mass, respectively. Each balance operates independently while the software receives their mass outputs and averages both. The averaged results are then combined to normalize the results to one gravity. The reference mass (left-hand balance in Fig. 2, below) is a standard reference mass; the unknown in the right-hand balance is in a moisture and density (MAD) vial.

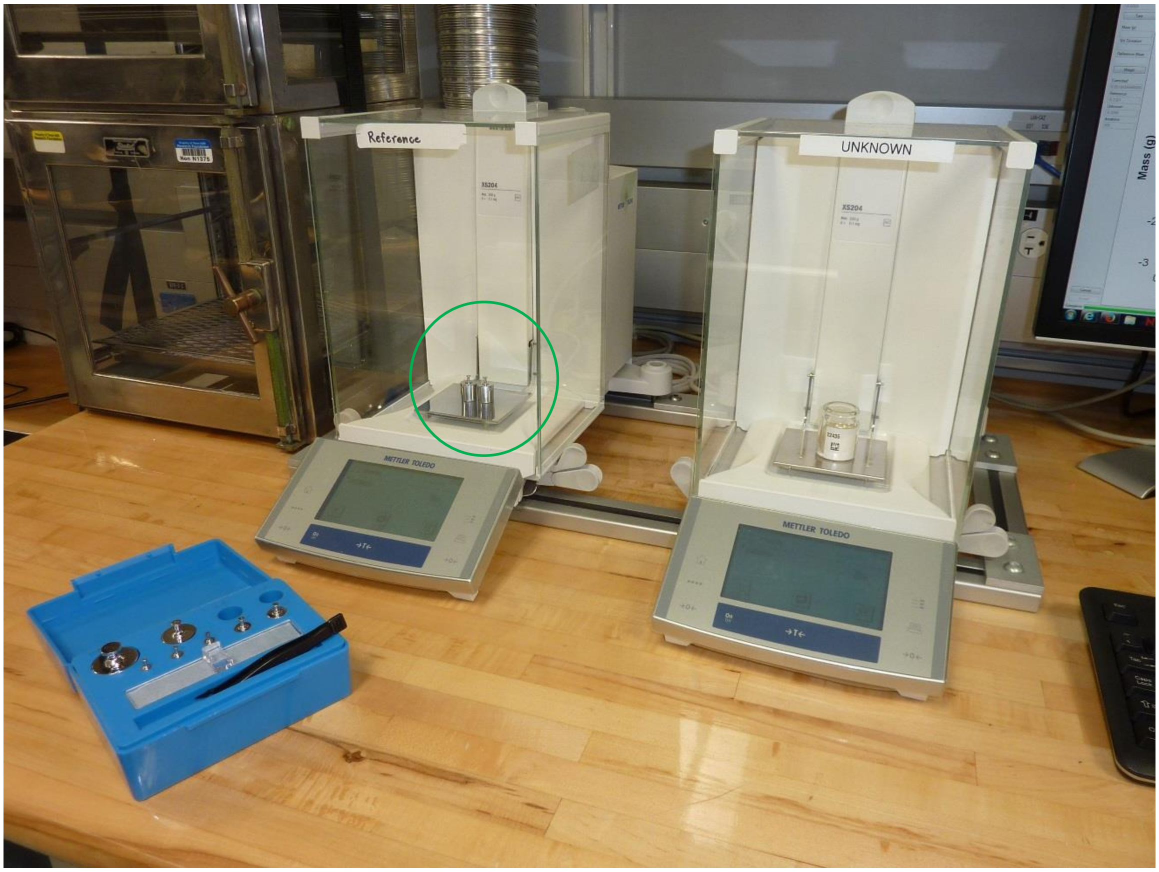

Fig. 2. Mettler-Toledo XS-204 balances. Note that the pan (circled on left) hangs from the back wall of the balance, instead of being suspended from below; this configuration is much more stable for use at sea.

Ship Motion Characteristics

Even in port on a calm day, the ship moves too much for a balance to work as it would in a shore-based laboratory. At sea, the ship is free to move in all three axes (X, Y, and Z) and around all three axes; the ship is constantly turning, tilting, and bobbing on the waves. Most of the movement seen in the balance software (Fig. 3, below) is due to short-period swells that last about 3 to 7 seconds, but the ocean has long-period swells that both have an effect on the mass measurement and are difficult for a human to sense. These swells can last for 5 minutes, 15 minutes, or even hours, and they are all superimposed on one another. Consequently, the ship is almost never experiencing 1 *g* acceleration, even if it seems still to a passenger; it is for this reason that one must relate the measurement back to a standard reference mass.

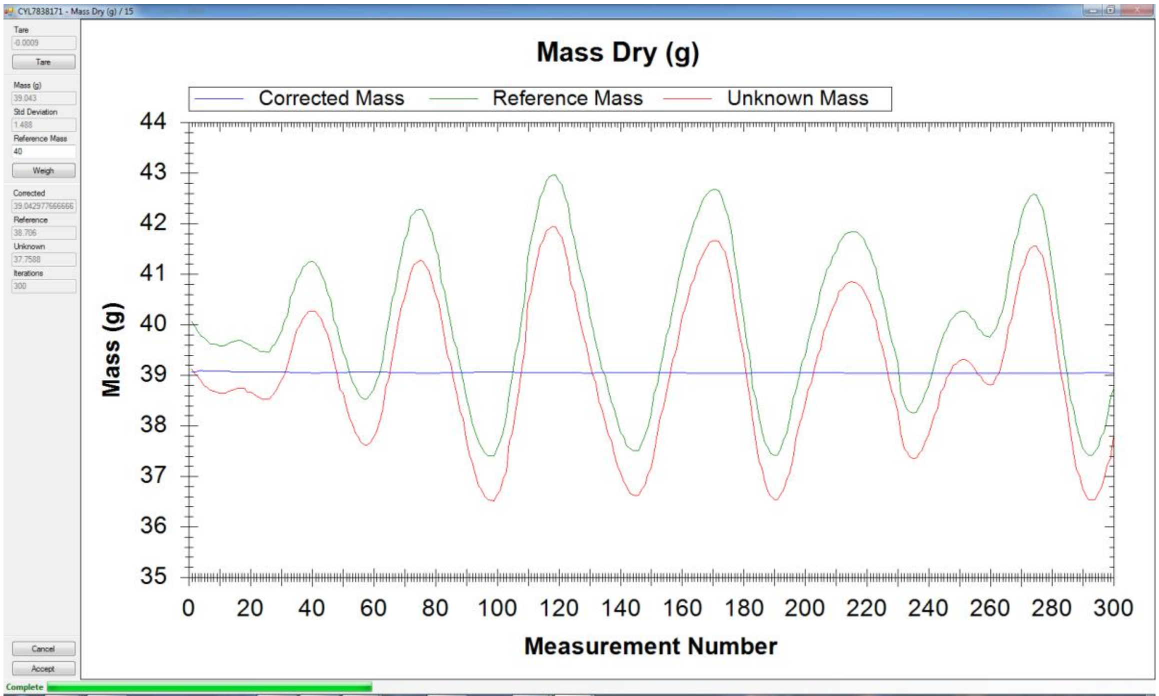

Fig. 3. Mettler-Toledo balance measurement screen. The reference mass was 40 g in this case (green trace). The peaks and valleys on the red and green traces are the short-term heave.

Requirements for Measuring Mass

In addition to following the guidelines from the manufacturer, the most important being to not overload the balance pan, the user must recognize the need to have the reference and unknown pans experience the same effects from ship's motion. Table 1, below, summarizes these requirements:

Requirement	Reason
Balances must be tared using the ship's dynamic weighing software (both balances)	The moment the balance was turned on, or the tare button pressed, the ship may or may not have been experiencing 1 *g* acceleration
Balance pans must be in close proximity	A distance greater than a few centimeters will impart differential acceleration on the two pans
Balance pans must be aligned along the same axis	If one balance were aligned port-starboard and the other forward-aft, they would not experience the same acceleration in the same timeframe
Balance pans must have close to the same load as each other	Larger masses have a larger spring effect and will not behave the same way as a smaller mass
Balances must record the mass measurements for sufficient time based on sea state	It is important to average the mass readings over time (primarily to average out the short-period swells)
Balance software must adjust the results based on the reference mass reading (internal to the Cahn)	The ship does not experience 1 *g* except for brief moments; it is always "climbing" (>1 *g*) or "falling" (<1 *g*)

Table 2. Requirements for measuring mass at sea.

Taring the Balances

It is necessary to tare the balance, both Cahn and Mettler-Toledo, by using the tare function in the JRSO software. Do **not** tare the balances using the tare buttons, because at the moment of that action, the ship's effective gravity is almost certainly not 1 *g*. The taring function measures the offset in mass between the reference and unknown pan and the exact value of the tare (shown on the screen in Fig. 3) is not important. A tare is good for a number of measurements but should be repeated whenever conditions change, or if something is spilled on the balance and then cleaned up. (Or some other event occurs to change the base mass value of a balance.)

Proximity and Alignment

The Cahn balance pans are by their nature always in proximity and in alignment to one another, as they are connected mechanically. For the Mettler-Toledo balances, the JRSO has mounted each pair of them close together as shown in Fig. 2, above, for the moisture and density (MAD) balances. It is important not to separate them more than 25-30 cm so that they experience acceleration as close to the same as possible as their paired balance.

Even Loading on the Balance Pans

The acceleration acting on the balance pans is countered by their mass and to get a precise result from the JR's balances, one must load the unknown and reference balance pans *roughly* evenly. Some margin exists because the pans themselves have mass that is added to the reference or unknown mass. The Cahn balances use stages strung on thin wire that weigh approximately 80-90 mg. The Mettler-Toledo balances have stages that are approximately 60 grams. Table 2, below, shows the differential between theoretical and actual mass with different scenarios of uneven loading.

Mass on Unknown Pan (g)	Mass Result for Unknown Pan (g)	Counter Mass on Reference Pan (g)	Absolute Mass Error (g)	Relative Mass Error (%)
0	0.0017	0	0.0017	N/A
1	1.0017	2	0.0017	0.2
3	3.0047	2	0.0047	0.2
5	5.0003	5	0.0003	0.0
15	15.0017	20	0.0017	0.0
35	**35.0147**	**25**	**0.0147**	**0.0**
55	55.0023	50	0.0023	0.0
105	105.0070	100	0.0070	0.0
0	0.0013	0	0.0013	N/A
1	1.0020	0	0.0020	0.2
3	3.0037	0	0.0037	0.1
5	5.0093	0	0.0093	0.2
15	15.0183	0	0.0183	0.1
35	35.0717	0	0.0717	0.2
55	55.1093	0	0.1093	0.2
105	105.2197	0	0.2197	0.2
0	-0.2510	100	-0.2510	N/A
1	0.8803	100	-0.1197	12.0

3	2.8303	100	-0.1697	5.7
5	4.8923	100	-0.1077	2.2
15	14.9240	100	-0.0760	0.5
35	34.9001	100	-0.0999	0.3
55	54.9717	100	-0.0283	0.1
105	105.004	100	0.0040	0.0

Table 2. Accuracy on Mettler-Toledo XS-204 balances with differential loading. All masses were reference masses whose values were known. Sea state was relatively calm (~ 1 m heave) and count was set to 300 (about 1 minute). 35 grams is bolded for emphasis. (Weight of the stage not included in the table.)

For the experimental conditions demonstrated in Table 2, the best accuracy was on the order of 1-2 mg when the reference and unknown balances had very similar mass loads. On the 35 gram experiment in the first section (bold text), note that the reference mass was 25 grams and that absolute error was about 15 mg, whereas the surrounding 15 gram and 55 gram lines, whose reference masses were within 5 grams of the unknown mass, had 0.2 mg error.

Measurement Time

Cahn C-29/C-31 Measurement Time

Both the Model C-29 and Model C-31 microbalances measure at approximately 1 Hz, so it is necessary to measure for at least 3 minutes to get enough measurement points to average properly. This is in a relatively calm sea state. Rougher sea states may require 5 minutes or longer; obviously at some point, the sea state is severe enough that masses cannot be determined.

Mettler-Toledo XS-204 Measurement Time

The above experiments were conducted on the Mettler-Toledo balances set to acquire 300 data points. As the XS-204 communicate at 5 Hz, this took about 1 minute. Even with a mild sea state of ≤1 meter, a shorter measurement time is not sufficient as it will not average across enough short-period heave cycles. If the sea state worsens, it may be necessary to measure for 3 minutes or even 5 on the Mettler-Toledo XS-204 balances. Measurement accuracy can easily be checked by measuring standard masses.

Normalizing to One Gravity

Cahn C-29/C-31 Microbalance

The nature of the mechanical geometry in the Cahn microbalances ensures that the results are normalized to one gravity because the reference and unknown pans experience nearly exactly the same acceleration. One must be careful to ensure both pans have similar masses for this to be true.

Mettler-Toledo XS-204 Precision Balances

A single XS-204 balance cannot normalize itself to one gravity acceleration, so for this reason a second balance is used. Provided the mass on the reference and unknown pans are close, the math in the balance software adjusts the unknown mass by the degree the reference mass is off from its true value. For example, if one is weighing an unknown mass using a 20 g reference mass, if the final averaged result of the reference mass is 18.5 g, the unknown mass must have 1.5 g added to its final averaged value (plus the tare differential) to get the true mass at 1 *g*.

Final Accuracy and Precision

The investigator or technician is encouraged to consider the precision needs of their measurement. If weighing 10 mg carbonate samples for the coulometer, it is necessary to measure to 0.1 mg (100 µg), at least, to have reasonable uncertainty in the carbonate measurement. If weighing samples below 10 mg, one should try to achieve 10 µg precision, but that may not be practical depending on sea state.

If weighing a buffer salt on the Mettler-Toledo balances, where the recipe calls for 75 g of reagent, one need only achieve 1 g precision with the measurement, as the 5 is considered by convention to be ±1 g.

If weighing a MAD sample for wet or dry mass (which in the end is measuring the water in the sample), and the moisture content is 25% of a 10 g sample (2.5 g water), 10 mg precision at least is warranted. In this example, 0.01 g uncertainty in 2.5 g of water will give rise to 0.4% error for both wet and dry masses. This will propagate: sqrt (0.4^2+0.4^2) = 0.6% overall error in mass of water.