Measurement of Local Gravity for Force, Torque and Pressure Standards - Good enough for the requirements expected in 2050?

Speaker / Author: R.F. Jenkins

Emirates Metrology Institute
PO Box 853, CERT Technology Park, Abu Dhabi, UAE
e-mail: emi@qcc.abudhabi.ae
Phone: +971 2 406 6666   Fax: +971 2 406 6677

Abstract

The measurements of local gravity and air density are fundamental requirements when establishing measurement standards for Force, Torque and Pressure that are based on calculating the force due to the Earth's gravity on a known mass, in air. The Emirates Metrology Institute (EMI), established by the Abu Dhabi Quality and Conformity Council in April 2014, has several measurement standards which require the value of local gravity - or free-fall acceleration - to be known. The paper describes the method used to measure local gravity at the relevant locations in the EMI, with a relative expanded uncertainty (k=2) of 2.0 x 10^{-7}. The paper also outlines the approach taken for calculating the air-buoyancy force and associated uncertainty.

The paper proposes the way in which the best uncertainties for Force, Torque and Pressure standards can be achieved, and concludes that the requirements of the most demanding users of these standards will be able to be met for the foreseeable future.

1. Introduction

1.1 Force

The best method of realising the SI derived unit of Force - the newton (N) - is through deadweight machines, where a calculation is made of the force due to the Earth's gravity on a known mass, in air. The relationship between the quantities is given by the following equation:

$$F = m \times g \times \left(1 - \frac{\rho_a}{\rho_m}\right)$$

Equation 1.

Where F is the force on a body of true mass m and density ρ_m in air of density ρ_a at a location where the gravity is g.

Consideration needs to be given to the possibility of forces, other than those due to gravity and air-buoyancy, being applied to the mass - especially magnetic forces, friction forces, electrostatic forces and aerodynamic forces due, for example, to air conditioning. Consideration also needs to be given to changes in mass due to wear and chemical reactions, and these changes are quantified by recalibrating the masses at appropriate intervals.

The air density ρ_a is a function of atmospheric pressure, temperature and humidity. The most accurate way to calculate its value is to follow the CIPM 2007 method [1]. However, it is more convenient to use the approximate formula for air density [2] given in the following equation:

$$\rho_a = \frac{0.34848 \times P - 0.009 \times RH \times e^{0.061 \times t}}{273.15 + t}$$

Equation 2.

Where P is the pressure in hPa, RH is the relative humidity in %rh and t is the ambient temperature in °C. For the environmental conditions in the EMI laboratories, using this approximate formula gives a value in agreement with the CIPM 2007 method within a relative value of 2 x 10^{-4}, which is equivalent to a relative difference in F of only 30 x 10^{-9}.

Guidance concerning the evaluation of possible magnetic forces is also given in Section 9 and Annex B.6 of [2].

The density of the mass ρ_m will change with temperature, but this will have a very small effect on the calculated force. For stainless steel weights in air, an increase of 1 °C causes a relative reduction in F of about 7 x 10^{-9}.

Normally, the masses of the weights of a deadweight machine are adjusted to give nominal force values - so a machine may have a weight of 10 kN, for example. The mass value is calculated using the local value of gravity and an average value for air density. Corrections for changes in air density, due to changes in pressure, temperature and humidity, are not normally made and therefore these changes contribute to the uncertainty of the applied force.

As force is a vector quantity, it is important in the design and use of a deadweight machine to ensure that the axis of the force transducer being calibrated is aligned throughout its calibration with the vertical axis through the centre of gravity of the applied deadweights.

EMI has established force standards that are traceable to deadweight machines in National Metrology Institutes (NMIs) outside the UAE through comparisons made using force transfer standards (precision strain gauge load cells). The EMI 5 MN force standard machine uses reference force transducers in series with the device being calibrated and can apply compression and tension forces from 100 kN to 5 MN with a relative uncertainty (k=2) of 2 x 10^{-4}.

In the next phase of development at EMI, consideration will be given to establishing deadweight force standards which can be used to calibrate force devices, and which can also be used as the reference for the hydraulic machine using the “Build-up” method (where force transfer standards are calibrated individually in a deadweight machine and then used in parallel to measure larger forces).

1.2 Torque

Once the unit of Force has been realised, the unit of Torque - the newton·metre (N·m) - is realised from the following quantity relationship:

$$T = F \times d$$

Equation 3.

Where T is the torque due to a deadweight force F being applied at an orthogonal displacement d from the torque axis (that is the force vector is vertical and the displacement vector is in the horizontal plane and at right angles to the torque axis).

The 1000 N·m torque standard machine at EMI (figure 1) uses deadweights to apply a torque in either a clockwise or anticlockwise direction. The torque is applied through a lever, of calibrated length, which is clamped to one end of the transducer being calibrated. The lever is supported by elastic flexure strips, set at right angles, which permit the application of torque to the transducer, but prevent the application of any shear forces and associated bending moments. Elastic flexure strips are also used at either end of the lever for the application of the deadweight force.

Figure 1. The 1000 N·m torque standard machine at EMI

The other end of the torque transducer being calibrated is clamped in a bush that has a manually-controlled drive unit and gear box. The axis of the bush is carefully aligned with the axis of rotation of the flexure strip support for the lever.

Strain gauges are bonded to all the flexure strips so they act as sensitive torque/bending moment transducers or "strain-controlled hinges". Before taking a reading from the torque transducer being calibrated, the manually-controlled drive unit is adjusted to achieve a zero signal from the strain-controlled hinges.

The torque standard machine can apply torques over a wide range - from 0.5 N·m to 1000 N·m - with a relative uncertainty (k=2) of 1 x 10^{-4}. At the lowest torque, the uncertainty is therefore equivalent to 5 x 10^{-8} of the maximum torque - or about 5 mg applied at 1 m.

The lever length is nominally 1 m for both the clockwise and anticlockwise directions and the mass of each deadweight has been adjusted to give a nominal force value, taking into account the local value of gravity and an average value for air density.

The uncertainty budget for the machine will therefore be the same as that for a deadweight force standard machine, but with an additional contribution due to the uncertainty of the lever length d and the small hysteresis effects in the material of the flexure strips.
The uncertainty of the lever length d includes the contributions associated with its initial calibration and also with the dimensional stability of its material with time. In addition, as with any dimensional measurement, the uncertainties are included for any departure in temperature

in use from the reference temperature given for the lever's calibration. The effects of dimensional changes due to elastic deflection under load are also considered.

1.3 Pressure

The method commonly used to establish pressure measurement standards, for both gas and oil, is to use a pressure balance, where a known mass is applied to a precision piston-cylinder assembly of known effective area. Publication [3] by the UK's National Physical Laboratory (NPL) provides a practical guide to the use of this type of equipment.

The unit of Pressure - the pascal (Pa) - is realized from the following quantity relationship for absolute pressure:

$$P = \frac{F + (D \times \tau)}{A} + P_{ref}$$

Equation 4.

Where P is the absolute pressure at the reference plane of the piston due to a deadweight force F being applied to the piston-cylinder assembly. P_{ref} is the reference pressure (the pressure due to the air surrounding the weights - at the reference plane of the piston). For oil pressure, the force due to surface tension is included, and is equal to the diameter of the piston D multiplied by the surface tension τ of the fluid in N/m. A is the effective area of the piston-cylinder assembly under the conditions of use, and can be calculated from the following equation:

$$A = A_0 \times [1 + (t - t_0) \times (\alpha_{pist} + \alpha_{cyl})] \times [1 + \lambda \times (P - P_{ref})]$$

Equation 5.

Where t is the temperature of the piston-cylinder assembly in use, and A_0 is the effective area of the piston-cylinder at the reference temperature t_0 (commonly 20 °C) and with $P = P_{ref}$ (i.e. no force applied). The linear thermal expansion coefficients of the piston and cylinder are α_{pist} and α_{cyl}, respectively, and λ is the pressure distortion coefficient of the effective area of the piston-cylinder assembly.

Having calculated the value of P at the reference plane of the piston, the pressure at any other horizontal plane can be calculated by measuring the distance between the planes and applying a head correction.

EMI has established deadweight pressure standards for gas up to 7 MPa and oil up to 500 MPa.

A bell enclosure over the weights of the gas standard enables the air to be evacuated and for the reference pressure P_{ref} to be reduced to about 5 Pa. The weights are applied under automatic control so that the vacuum can be maintained when they are changed.

For the oil standard, a precision barometer measures the reference pressure P_{ref} to enable the absolute pressure to be calculated.

Both the gas and oil pressure standards incorporate transducers to measure everything needed by the in-built computer to calculate the absolute pressure in accordance with equations 1, 2, 4 and 5 - namely: the air temperature, pressure and humidity; the temperature of the piston-cylinder assembly; the height of the piston above the reference plane and, where appropriate, the measurement of the pressure in the evacuated bell enclosure. The values for the other parameters required for the calculation are stored in the computer and can be re-entered following a recalibration. A very important parameter that has to be entered is the local gravity g.

In daily use, adjustment is made, if necessary, to ensure the axis of the piston-cylinder assembly is vertical. Also, any difference between the reference plane of the piston and the reference plane of the device being calibrated is measured and the value entered to enable the head correction to be applied.

This approach leads to the best uncertainties being obtained for the value of absolute pressure, although this value may differ from the nominal value by a relatively large amount compared with the uncertainty. This should not be a problem for most calibrations, as the actual value of pressure is used, together with the indicated value of the device being calibrated, to determine the device's metrological characteristics - such as repeatability, linearity and hysteresis - using appropriate regression analysis.

The alternative is to use small trim weights to obtain a value of pressure that is the same as the nominal value, within the required uncertainty. However, calibrations could not then be carried out so conveniently, especially gas calibrations in the absolute mode.

Another possibility might be to use a calibrated solenoid to apply a correction force and achieve values that are the same as the nominal values, within the uncertainty.

Figure 2 shows the 7 MPa gas pressure standard at EMI.

Figure 2. The 7 MPa gas pressure standard at EMI

2. Determination of local gravity

2.1 Calculation of value of local gravity

Section 2.7.5 of [4] gives the following formula for the calculation of g in m/s^2, at a location where the latitude is Ø (in radians) and the height above sea level is H (in metres):

$$g = 9.780\,327 \times \left(1 + 0.005\,3024 \sin^2 Ø - 0.000\,0058 \sin^2 2Ø\right) - 3.088 \times 10^{-6} \times H$$

Equation 6.

Equation 6 will almost always give results within 1×10^{-3} m/s^2 and usually within 5×10^{-4} m/s^2, i.e. within 1×10^{-4} of g and 5×10^{-5} of g, respectively.

The link “g-Extractor” in [5] uses the same formula, except that the constant for the height above sea level is -3.086×10^{-6} (not a significant difference).

The second website in [5] gives a method for calculating g that has a lower uncertainty. The method requires the value of the longitude to be known, as well as the value for the latitude and the height above sea level. The method also gives the uncertainty (k=2) for the calculated value of g. For various places in the UAE, the uncertainty given is 2×10^{-4} m/s^2.

Both methods of calculation were used to obtain the value of g for 10 reference stations in the UAE where it had been measured with an uncertainty (k=2) of better than 2×10^{-7} m/s^2.

None of the results obtained from equation 6 differed from the measured value by more than 1×10^{-3} m/s^2. Also, the results from the more accurate method of calculation were all better than those obtained from equation 6. However, for 8 of the 10 reference stations, the result from the more accurate method differed from the measured value by more than the uncertainty given for the calculation. The average magnitude of the difference was 3.3×10^{-4} m/s^2 with a maximum of 5.4×10^{-4} m/s^2, compared with a claimed uncertainty of 2×10^{-4} m/s^2. These results suggest that the uncertainty is significantly larger than the value claimed for the method of calculation - certainly for the UAE.

The term “height above sea level” should be taken as the height above mean sea level (MSL) - the level of the sea over the long-term, averaging the effects of winds, tides and atmospheric pressure.

The *geoid* is the shape that the surfaces of the oceans would take under the influence of the Earth’s gravitation and rotation alone. The surface is extended through the continents using the hypothetical concept of very narrow canals. The *geoid* surface is irregular, unlike the *reference ellipsoid* for the Earth, but is much smoother than the Earth’s actual surface. The *geoid* is currently defined by the Earth Gravitational Model EGM2008.

The World Geodetic System ellipsoid, WGS84, is the *reference ellipsoid* currently used with the Global Positioning System (GPS). The surface of the *geoid* differs from the surface of WGS84 by between -106 m and 85 m. For the 10 UAE reference stations mentioned above, the elevation with respect to WGS84 is lower than the elevation with respect to MSL by about 33 m, varying between 26.5 m and 34.5 m.

The EMI Time and Frequency standards are based on three Cesium clocks. For time synchronisation, an accurate comparison is made between these clocks and the clocks on the GPS satellites, using a special temperature controlled antenna. The position (WGS84 latitude, longitude and altitude) of the centre of the antenna was measured using GPS over an extended period of time and the measured altitude was -18.878 m. The antenna is located on the roof of the EMI laboratory, some 9 m above ground level, which is about 6 m above the sea level nearby.

A second antenna (not temperature controlled) can be positioned near to the primary antenna, to be used in case of its failure. The position of the second antenna was measured separately, using the same GPS method as for the primary antenna. Using the coordinates of both antennas, the distance between their centres was calculated as 705 mm. A simple measurement with a tape measure gave a distance of 710 mm, with an uncertainty (k=2) of about 10 mm, due mainly to the estimation of the centres of each antenna, which were of different designs.

2.2 Measurement of value of local gravity

Neither method for calculating local gravity was considered accurate enough for the purposes of establishing high-level measurement standards for Force, Torque and Pressure at EMI. It was therefore decided to measure the value of g, either by a comparison measurement with a reference station where it was known, or by absolute measurement.

The history of absolute gravity measurement shows that, up to the 1970s, gravity could be compared with a better uncertainty than it could be measured absolutely. Developments since then have reduced the uncertainty of absolute measurement, at the best level, to about 1 μGal [6]. These measurements are made by using an atomic clock to measure the time taken for an object to fall a measured distance in a vacuum. The distance the object falls is measured using laser interferometry.

Portable instruments for measuring g absolutely using this "free-fall" method are commercially available [7] and give a measurement uncertainty of between 5 μGal - 10 μGal.

Note:
The Gal is the symbol for the unit of measurement used extensively in the science of gravimetry. 1 Gal is equal to 1 cm/s^2 (1 x 10^{-2} m/s^2), and so 1 mGal is about 10^{-6} g, and 1 μGal is about 10^{-9} g.

There have also been developments with instruments used for gravity comparison measurements. These instruments use the principle of elasticity, where a mass is suspended from a spring. The difference of g between two locations is obtained by measuring the change in the deformation of the spring when the instrument is moved from one location to another. The change in deformation can be measured indirectly by measuring the amount of external force required to bring the mass back to a reference vertical position. Because the elastic modulus of the spring changes with temperature, it is important that the spring is maintained at a constant temperature within very close limits.

It was decided to use an instrument of this type [8] to measure g at EMI by comparison with an absolute gravity reference station. The mass/spring system is housed in a temperature controlled chamber which is housed inside an outer chamber that is also temperature controlled. Any departure of the position of the mass from its reference position is measured by a capacitance displacement transducer. A DC voltage is then applied to the capacitor plates to produce an electrostatic force that restores the mass to its reference position. A change of g is related to the magnitude of the DC voltage.

The instrument has a resolution of 1 μGal and an operating range of 8000 mGal. Its scale is adjusted following a calibration process where measurements are taken at absolute reference stations which have relatively large differences in the value of g (105 mGal).

A precision temperature sensor is mounted close to the spring and enables its temperature to be controlled at a reference temperature to within ±1 mK. The sensor measures the temperature of the spring with a resolution of 0.01 mK and applies a correction for the departure of temperature from the reference value. This correction will drift with time as the characteristics of both the spring and the temperature sensor (zero and span) change with time. The drift can be compensated for in the short term by using a measurement cycle that includes repeat measurements being made at the same location over a fairly short time interval. Over the longer term, the gravity meter should be re-calibrated at regular intervals using the method described in the previous paragraph.

The gravity meter incorporates sensors to measure the level of the instrument in two directions at right angles. A correction is then applied automatically for any tilt during use. An inbuilt GPS determines the location (WGS84) of the measurement, and the time of measurement - in Universal Coordinated Time (UTC) - to enable a correction to be applied for Earth tide effects, if required. The gravity meter can therefore be used for high precision land gravity surveys [9].

2.2.1 Measurement Protocol

Two gravity meters (identified as A and B) were provided by the Petroleum Institute (PI) in Abu Dhabi and were used to make the gravity comparisons on three consecutive days. The measurement cycle for each day included five measurement stations, as follows:

(Ref) (Abs) (EMI1) (EMI2) (Ref)

The *Ref* station was a specific location at the PI. *EMI1* and *EMI2* were the locations, at floor level, in the EMI Pressure and Force & Torque Laboratories, respectively, nearest to the locations where deadweights would be used to realise the measurement standards. The *Abs* station was an absolute reference station where the gravity had been measured using an absolute gravity meter. A different *Abs* station was used for each day's measurement cycle, and the details are given in table 1.

Table 1. Values of gravity and associated uncertainty at the absolute gravity stations

Station	**Location**	***g***	**Uncertainty (k=1)**
		mGal	mGal
1	Nazwa	978 846.767	0.004
2	Hatta	978 881.266	0.005
3	Al Ain	978 768.517	0.006

At each location, 10 consecutive measurements were made with each gravity meter. Each measurement was the average output of the gravity meter over a period of 4 min 16 s, so the total measurement time was 42 min 40 s. The average of these 10 measurements was calculated and no Earth tide correction was applied.

For the absolute gravity stations at Nazwa and Hatta, it was not possible to use the gravity meters at the reference location inside the enclosure. Consequently, measurements were made at ground level on opposite sides of the enclosure, about the same distance from the estimated centre of the enclosure. The average result was then used.

2.2.2 Measurement results

The linear drift with time of each gravity meter was determined from the 6 average results obtained at the *Ref* station (PI) over the three days of measurements. Figure 3 shows the linear least-squares fit for the results for gravity meter A, where the standard error for the fit is 0.034 mGal. The results for gravity meter B were very similar. The coefficients of the best-fit straight line then enabled a correction for drift to be applied to the measurements taken at all the locations. The values of g at floor level of the two EMI locations, for each of the three absolute gravity stations and for both gravity meters, were calculated from the drift-corrected measurements, and are given in table 2.

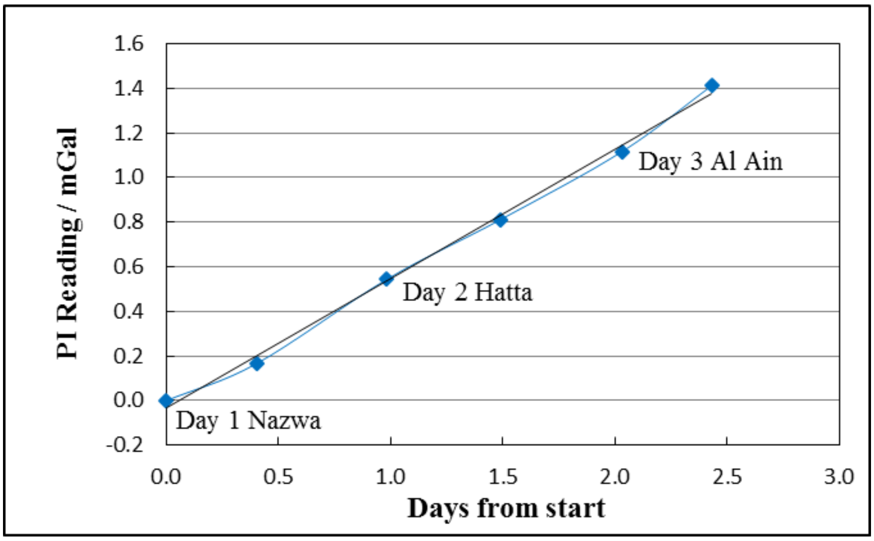

Figure 3. Drift of gravity meter A

Table 2. Results of the measurement of g at EMI at floor level

Location	Meter	Nazwa	Hatta	Al Ain
		Measured value of g / mGal		
EMI1	A	978 888.047	978 888.077	978 888.099
	B	978 888.049	978 888.091	978 888.123
EMI2	A	978 888.067	978 888.097	978 888.120
	B	978 888.069	978 888.111	978 888.143

2.2.3 Measurement uncertainty

Both [6] and [9] list the various factors that influence the value of g and therefore contribute to the uncertainty of its measurement. The two most important effects are the change with elevation, given in equation 6, and the change due to Earth tides, which can cause variations of ±150 µGal. Change with latitude should also be considered - at EMI's location, a change of latitude equivalent to a distance of 1 m gives a change of g of 0.6 µGal.

The standard error for the drift of the gravity meter gives a comparatively large contribution of 34 µGal; other contributions are the uncertainty of the value of g at the absolute gravity stations, the resolution of the gravity meter (1 µGal) and its short term repeatability (3 µGal), the effect of tilt (10.6 µGal for 30 arcseconds), and the effect of air pressure changes (-0.36 µGal/hPa).

As three absolute gravity stations were used, it was possible to check the calibration of each gravity meter by comparing the measured differences between the absolute stations with the known differences obtained by absolute measurements. This allowed an estimate to be made of the uncertainty due to scale error, which is proportional to the magnitude of the difference between the value of g at EMI and the value at the absolute gravity station. The uncertainty (k=1) was the highest when using the absolute gravity station at Al Ain, being 51 µGal for gravity meter A and 72 µGal for gravity meter B.

The estimated expanded uncertainty (k=2) for all the values given in table 2 is 0.16 mGal.

From the results at floor level, the values of g at the average location of the weights were calculated for the two EMI locations, and are given in table 3. The uncertainty was increased because a single value of g was used for all the weights used in each stack. As g had been measured before the installation of the equipment, an approximate calculation was made for the pressure standards of the attraction due to gravity between a weight applied to the piston-cylinder and the weights still located on their earth supports. The effect was about 7 µGal.

Table 3. Values of g at working level in EMI laboratories

Location	**Value of *g***	**Uncertainty (k=2)**	
	m/s^2	m/s^2	relative
EMI1 (Pressure Laboratory)	9.788 877 3	0.000 002 0	2.0×10^{-7}
EMI2 (Torque Laboratory)	9.788 879 6	0.000 002 0	2.0×10^{-7}

3. Determination of average air density

The masses for the 1000 N·m torque standard machine are adjusted to give nominal force values in newtons. They are used in a laboratory with the temperature controlled to 20 °C within ±1 °C and the humidity to 48 %rh within ±10 %rh. However, the air pressure is not controlled and, to minimise the uncertainty associated with neglecting changes in its value, it was necessary to obtain an average value for the calculation of an average value of air density in accordance with equation 1.

Like all main airports, the International Airport at Abu Dhabi records the value of air pressure to give to pilots of aircraft before landing so that their altimeters can be set to indicate zero altitude at the local pressure. From 24 January 2013 until 17 April 2014, the values of atmospheric pressure were taken from information available on the website of the UAE National Center of Meteorology and Seismology. The information was taken at various times during the normal working day, between 07.00 and 17.00, and is given in figure 4. As Abu Dhabi International Airport is about 25 km from EMI, it was assumed that the average atmospheric pressure at the airport was representative of the average at EMI.

The average value of pressure over a complete year from 24 January 2013 was 1009.4 hPa. This value was used, together with the temperature and humidity set-points for the laboratory, to calculate the average air density ρ_a and hence the mass m required to give a nominal value of force F from equation 1.

The minimum and maximum values of pressure, 992.2 hPa and 1027.2 hPa, were used, together with the limits of the temperature and humidity control, to calculate the limits for ρ_a. The relative expanded uncertainty (k=2) for F, due to the uncertainty of ρ_a, was calculated as 2.8 x 10^{-6}, assuming a triangular distribution and including the uncertainty of the temperature and humidity measurements and the uncertainty associated with the use of equation 2.

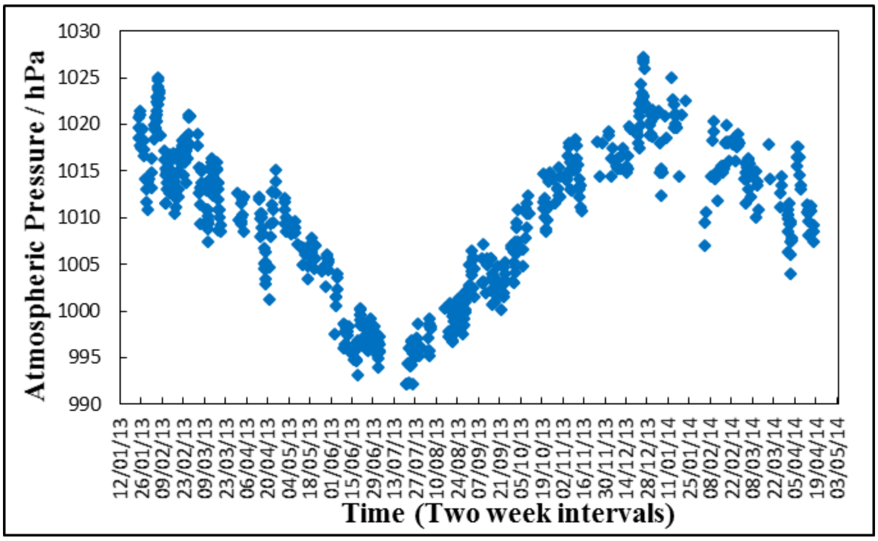

Figure 4. Variation of atmospheric pressure at Abu Dhabi International Airport

The values of atmospheric temperature varied in a similar way to the atmospheric pressure, but with minimum values of temperature occuring during periods of maximum values of pressure. The values of relative humidity varied over a wide range from 7 %rh to 99 %rh, with no pattern, throughout the year.

4. Conclusion

The work has shown that the measurement of g is not the limiting factor when establishing force, torque and pressure standards using deadweights. Also, taking an average value of air density is acceptable for current requirements. If ever the need arose, corrections for Earth tides could be made to g, and corrections made for changes in air density. However, especially for larger force and torque machines, it is likely that the uncertainty will be limited by the uncertainty of mass measurement.

The situation is very different for the work being undertaken on the watt balance to redefine the kilogram. The target relative uncertainty for the experiment (k=1) is 1 x 10^{-8} and this requires an equivalent uncertainty of g of a few parts x 10^{-9} - the most demanding requirement for the accurate measurement of force!

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