Adverse Influences And Their Prevention In Weighing

Design And Working Principles Of Laboratory Balances
Specifications Of Balances
Influences On Balances & Weighing Samples

 V 1.3 August 2001

Abstract

The purpose of a weighing is the determination of the mass of an object. Usually, a balance serves as measuring instrument, on the platform of which the object to be determined is placed. Both participants in this process, the object and the weighing instrument, are subject to internal and external influences that potentially interfere with the weighing process and may deteriorate the weighing result.

This guide introduces the most frequent interferences and shows how to minimize their influence on the weighing. With these countermeasures it is possible to obtain high quality weighing results, even in difficult situations and with high resolution balances.

Design And Working Principles Of Top Loading, Servocontrolled Laboratory Balances

High resolving balances, i.e., balances with more than 100’000 displayed digits, almost exclusively rely on the electrodynamic compensation principle.

A first characteristic of this principle is that the weight force, namely the product of mass m of the weighing object and gravity g

$$G = mg$$

is not directly measured, but is compensated for instead.

Simply stated, the balance uses the same physical transducer principle as a loudspeaker. The difference between the balance and the loudspeaker is that with the balance, it is not the movement—a mere by-effect of this principle—that is of primary interest. The balance rather relies on the property of the electrodynamic principle by which a current flowing through a wire in a magnetic field produces a force. This force is equal to the product of the strength of the electrical current I, the strength of the magnetic flux B and the length l of the conductor, namely

$$F = IBl \quad .$$

If this compensation force is adjusted such that it is equal to the weight force, then the electrical current required is proportional to the mass on the weighing pan, provided the magnetic flux density, the length of the electric conductor and the gravitation remain constant. This is certainly true to a high degree; nevertheless, with high resolving balances, it is crucial to compensate for potential drifts.

The compensation current, carrying the information about the unknown mass, is now fed into an analog-to-digital converter. It produces a number which is the digital equivalent of the mass being weighed. This value is further processed by a digital signal processing unit to compensate for non-linearity, sensitivity deviation and temperature drift, before it is displayed.

We have not yet mentioned the mechanical guidance required to direct the weighing cell, enabling the weighing platform to support the weighing object; furthermore, the lever, providing mechanical advantage to transform the producible maximum force by the electrodynamic transducer to the weighing capacity of the balance. This guidance and the lever need to be rather robust to deal with accidental force impacts (shipment!), however, they must not introduce forces degrading the weighing value.

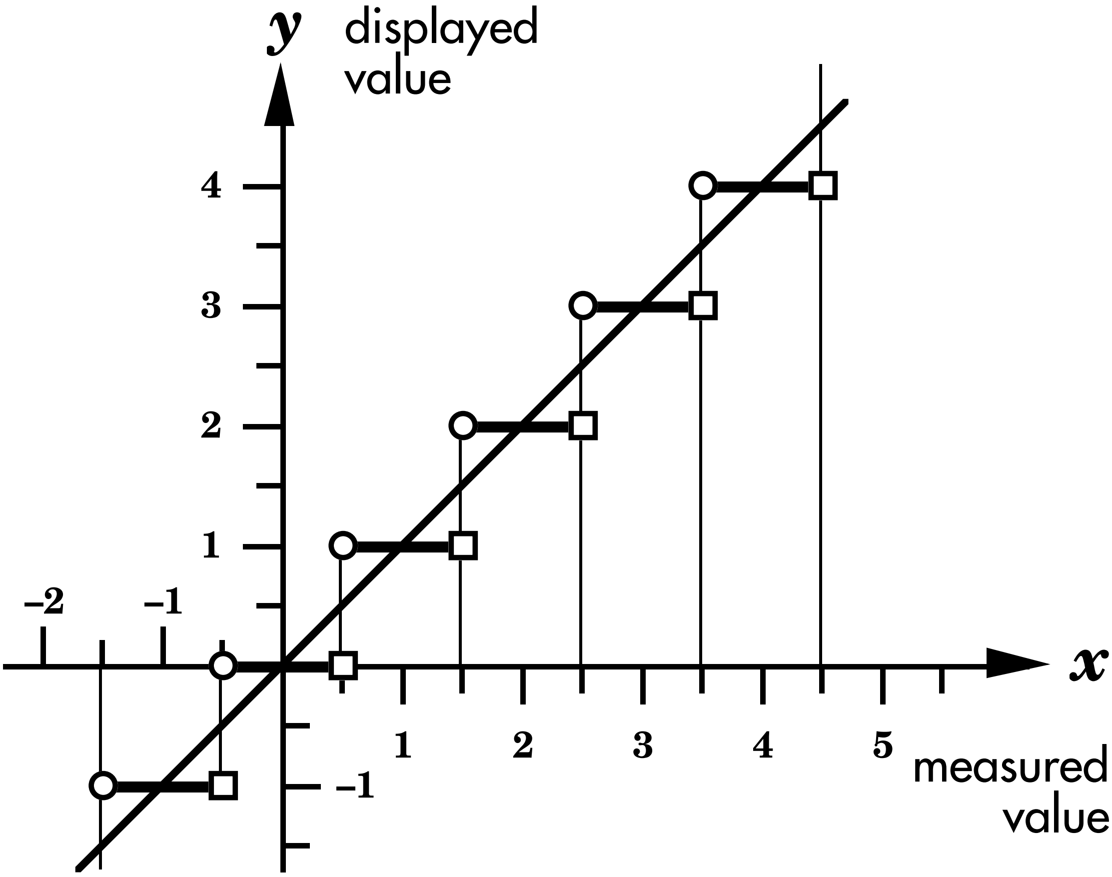
Specifications Of Balances

When discussing measurement deviations and uncertainties of laboratory balances, the following specifications are especially relevant:

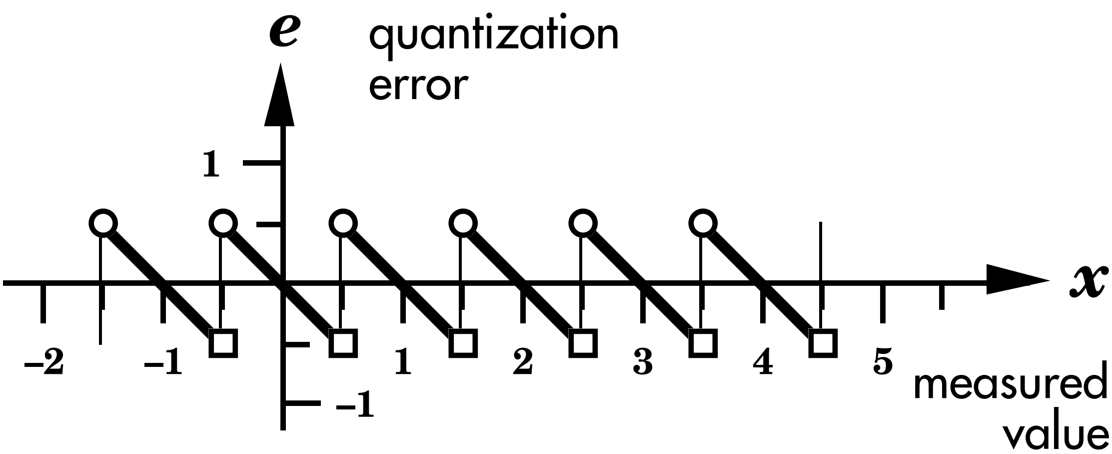
- readability
- repeatability
- sensitivity
- non-linearity
- temperature coefficient (of sensitivity)
- corner load deviation (eccentric load deviation)

Readability

Readability is the smallest increment between two displayed weight values.



Limiting the displayed value to one display step introduces the following quantization error:



Repeatability

Extent of random deviation of a sample weighing [1]). Repeatability is specified as a standard deviation.

The standard deviation is obtained through a measurement series, carried out with one and the same load and under identical conditions for the individual weighings, such as:

—same measurement method;
—same operator;
—same location;
—same ambient conditions;
—same point of time.

The conditions for the individual weighings shall not change, and the weighings shall be carried out within the shortest possible interval of time. The standard deviation can then be calculated from the measurement series as follows:

$$s_x = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \left(x_i - \bar{x}\right)^2} \quad ,$$

where $$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \quad .$$

Besides the properties of the balance, the weighing object and the environment influence repeatability. Therefore, unless otherwise stated, not only a load that barely affects repeatability is used, but the measurement series is also carried out under the most favorable ambient conditions.

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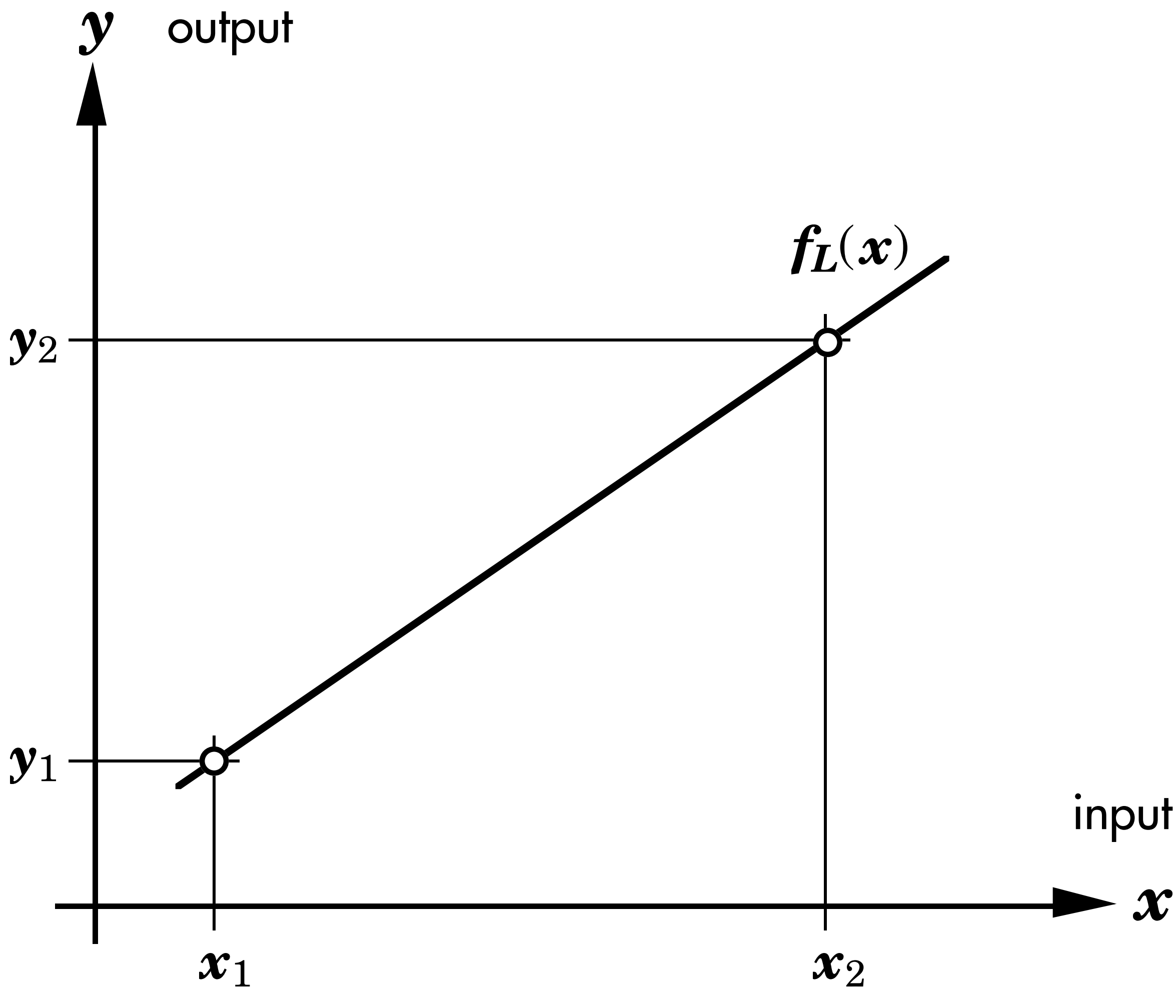
1) Single weighing: The difference between two readings, namely one with the sample and the tare, the other with the tare alone. If there is no tare container, the empty weighing platform takes its role.

Sensitivity

The slope of the straight line, passing through two measurement points, usually obtained at no load and full capacity of the balance.

We have $$S := \frac{\Delta y}{\Delta x} = \frac{y_2 - y_1}{x_2 - x_1} \quad ,$$

where x represents the load, and y the displayed value. This is equivalent to the difference of the readings divided by the difference of the loads. Obviously, we expect from a balance a sensitivity (slope of the line) of 1g/g, 1kg/kg, or simply 1 (unity).



(In this and the following diagrams, "input" corresponds to the load on the platform, and "output" to the balance's displayed value.)

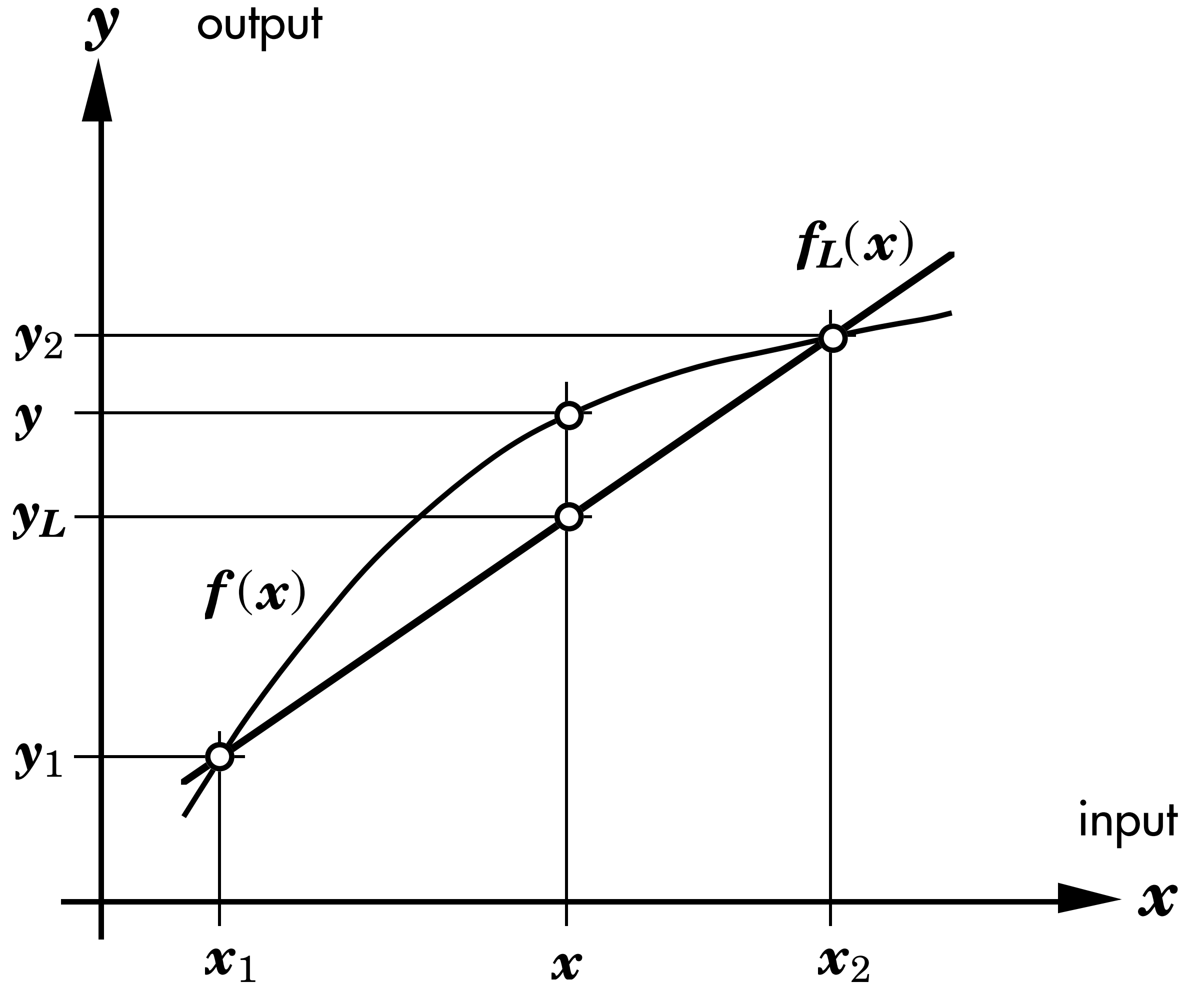
Non-Linearity

Deviation of measurement values from the straight line, passing through two measurement points, usually obtained at no load and full capacity of the balance.

$$y_{NL} := f(x) - f_L(x) = y - y_L \quad \text{(linearity deviation)},$$

with the straight line $y_L = f_L(x) = \dfrac{y_2 - y_1}{x_2 - x_1}(x - x_1) + y_1$,

where x are the loads, and y the readings.



Linearity deviation is often confused with sensitivity deviation. The definition of non-linearity is independent of the (global) slope of the straight line through the points at both ends of the measurement interval. Non-linearity states only the deviation of the characteristic curve from a straight line; the slope of this line is a matter of sensitivity.

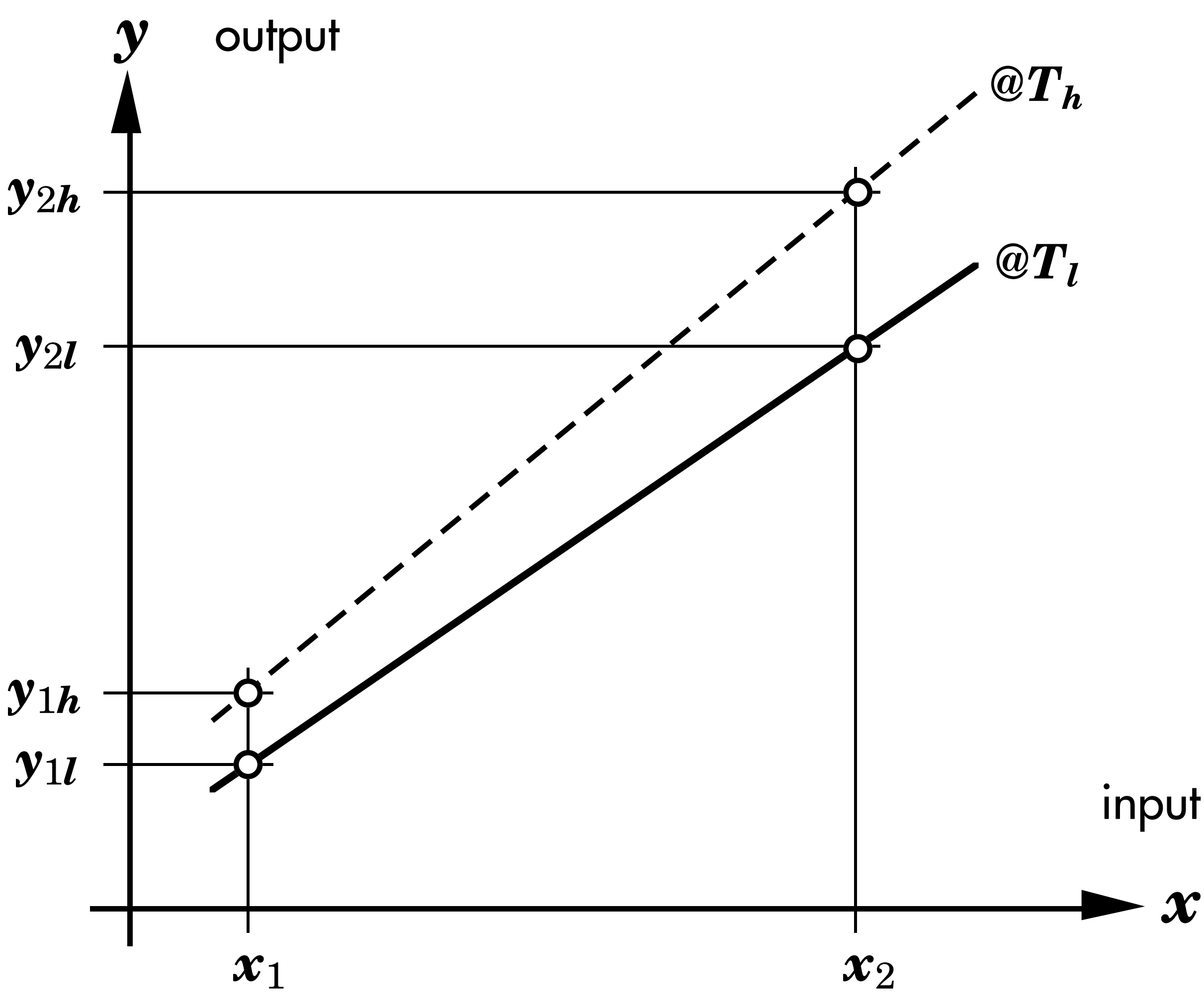
The sum of slope deviation and linearity deviation gives the deviation from the true measurement value.

Temperature Coefficient Of Sensitivity

The temperature coefficient of sensitivity is the normalized [2] sensitivity deviation of a balance, divided by the causing temperature change.

$$TC_{SENS} := \frac{\left(\frac{\Delta S}{S}\right)}{\Delta T} = \frac{\left(\frac{S_h - S_l}{S}\right)}{T_h - T_l} \quad ,$$

where $S_h := \frac{\Delta y_h}{\Delta x} = \frac{y_{2_h} - y_{1_h}}{x_2 - x_1}$ and $S_l := \frac{\Delta y_l}{\Delta x} = \frac{y_{2_l} - y_{1_l}}{x_2 - x_1}$.



[2] normalized: divided by its original undisturbed value

Corner Load Deviation (Eccentric Load Deviation)

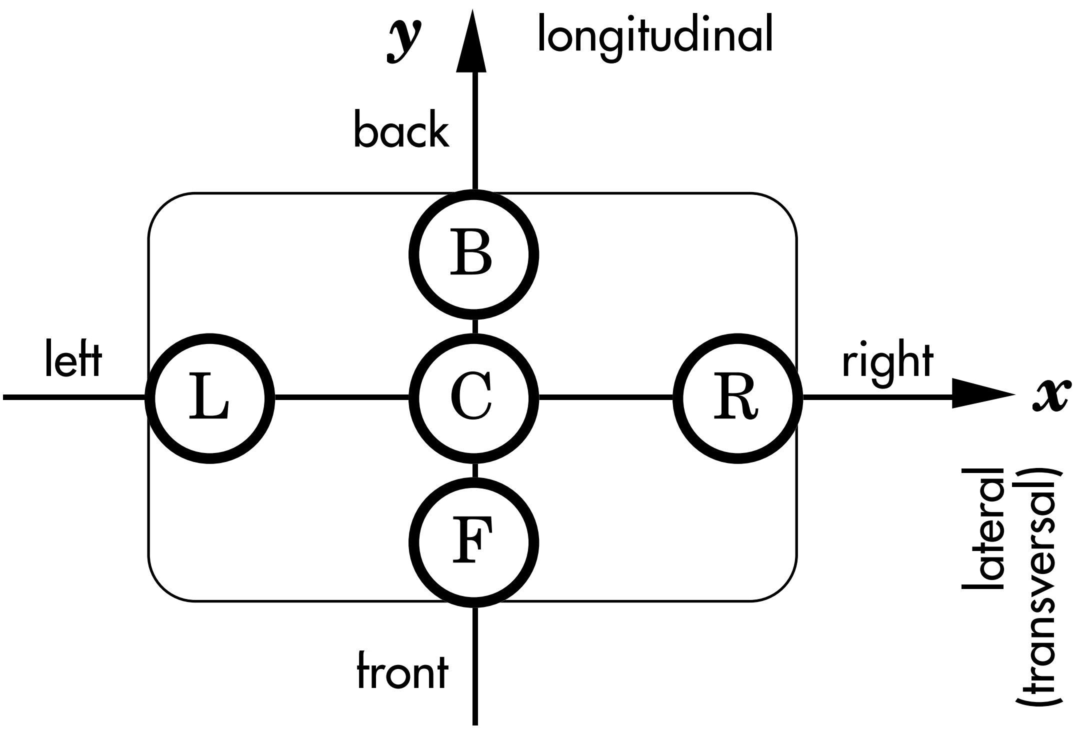
Deviation between two weighing values, obtained with the same load, where the load is placed once out of center (eccentrically), and once at the center of the weighing platform, with otherwise identical conditions.

$$y_{ECC}(x,r) := y(x,r) - y(x,0)$$

where x is the load, r the off-center distance, and y are the readings.

Usually, five weighings are carried out to determine corner load deviation: [3]

- one in the center of the platform (C)
- one each to the left and the right of the platform (L, R)
- one each to the front and the back of the platform (F, B)



3) OIML R-76 [1] and NCWM Publ. 14 [2] contain further details about where to place, and the amount of, the loads for this test. These requirements apply for approved balances.

Influences On Balances & Weighing Samples

Influences are physical quantities that are not of interest in the measurement, but which inadvertently, and often unknowingly, introduce systematic or random deviations into the measurement value. [4)]

At least three prerequisites are involved when carrying out a weighing: the balance, the weighing object (sample) and the environment. Neither the balance, nor the weighing object should be considered isolated objects; they always stay in interchange with their environment.

Although a balance is built to determine the mass, and only the mass, of the weighing object, it is impossible to prevent internal and external influences from disturbing the balance to a certain extent. This is also true for the weighing object; the environment tends to influence it even more. Although there are weighing objects that are fairly immune to external influences, such as dense metals with compact shapes and polished surface, most weighing objects are clearly subject to considerable environmental influence. There are samples that are very difficult to weigh, such as hygroscopic or volatile substances, or substances with low density, objects with extending shapes, porous surfaces or even consisting of an electrically non-conductive material.

In the following chapters we will systematically discuss the most important, often occurring potential influences on weighings, namely:

- Ambient Climate
- Air Draft & Pressure Fluctuations
- Radiation
- Mechanical Influences
- Electromagnetic Influences
- Long-Term Drift
- Air Buoyancy

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4) English translation from DIN 1319 [3].

Ambient Climate

- Temperature Difference Between Balance And Environment

Electronic balances are usually compensated against influences of ambient temperature. Even so, a change in ambient temperature may cause a deviation not only of its sensitivity (slope), but its zero point as well.

The remaining temperature coefficient of sensitivity of a properly adjusted precision balance amounts to 3…10ppm/K typically [5]), or to 1…3ppm/K typically if it is an analytical or micro balance. Although the temperature coefficient of zero point is usually not specified, this does not signify that zero point is independent of temperature. However, with most weighing operations, the zero's temperature coefficient is not of major concern, namely when taring is allowed before weighing. On the contrary, with all weighings where taring is not applicable, the zero's temperature drift must be taken into consideration [6]).

What is more, a balance, whose temperature differs by a few degrees from its environment, undergoes an acclimatization process, during which a change of the displayed value occurs that may amount to a value three to ten times of what might be expected from the static temperature coefficient. Such temperature transients predominantly occur when the balance is plugged to the power supply, because then the electronic components begin to dissipate power. Especially pronounced are these effects when a balance is moved from a cold environment (such as a car's trunk) to a warm one (such as a laboratory).

Such a transient interval may extend from one to multiple hours, depending on the type of balance. If an application requires the ultimate in resolution and accuracy from the in-

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5) ppm: abbreviation commonly used for parts per million = 1:1,000,000 = 10^{-6}; ppm/K = 10^{-6}/°C

6) With these applications, it is advisable to use an additional weight (reference weight) of approximately the same mass as the weighing object, and to determine its mass in advance. The weight difference between the weighing object and this reference weight is then determined. Thereby, if following weighings are performed against this reference weight, a potential zero drift, independent of its origin, can be eliminated.

strument, it is recommended to power a precision balance one or two hours before usage at the very location of measurement; if it is an analytical or micro balance, 6 to 12 hours are recommendable. For the same reason, an electronic balance should not be disconnected from the mains during measurement pauses, since reconnecting the balance triggers the warm-up phase again. Many balances provide a standby mode for this reason.

- Temperature Difference Between Weighing Object And The Environment Or Weighing Chamber

  The air inside the draft shield of balances exhibits a temperature rise above ambient temperature, because of power dissipated by electronic components. This warmer air escapes when the draft shield is opened, and colder air streams into the weighing chamber. This air draft exerts forces on the weighing pan and the object weighed. As a consequence, the displayed value gets distorted and unstable. Only after 15 to 30 seconds when the air draft has died out do these perturbations disappear. For the same reason one should neither reach with hands into the weighing chamber of a high resolving balance, nor touch the weighing object, nor place it on the platform with bare hands. A pair of pliers or tweezers should be used to do these operations.

  If a weighing object is not at the same temperature compared to its ambient air, an air draft emerges along the surface of the object, especially if the object possesses an extended vertical shape (such as a glass beaker). When the object is warmer than its surrounding air, this gives rise to an upstream, while an object colder produces a downstream current. Because of viscous friction, an upward or downward force acts upon the weighing object, making it seem lighter or heavier, respectively [4]. A mere few tenth of a degree are sufficient to offset the weighing value, or at least to degrade repeatability and prolong stabilization time. The effect fades away when the weighing object has acclimatized [7]).

- Humidity Difference Between Balance And Environment

  Analogous to temperature differences, a humidity change of the environment can cause deviations of the weighing value. Primarily, the zero point of the balance is affected, hardly its

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7) Acclimatizing a beaker may easily take half an hour or more.

sensitivity. The reason is that the weighing cell's mechanical components exchange humidity with their environment. For one thing, surfaces tend to adsorb 8) water films, for another thing, the bulk of certain components soaks in (absorbs 9) water. While effects of surface adsorption typically come to a close within an hour, bulk absorption, although weaker in strength, may extend over days, or even weeks before ending 10).

These effects are difficult to quantify, since they depend largely on the design of the weighing cell at hand. In case of doubt, the balance can be subjected to dry and moist environments to find out about the magnitude of humidity exchange.

- Humidity Exchange Between Weighing Object And Environment

  The effect caused by humidity difference between weighing object and its environment is approximately proportional to its surface; besides, rough surfaces tend to absorb larger amounts than smooth ones. A polished, clean metal surface, subjected to a humidity change of the ambient air from 40% to 80%rH, adsorbs per square centimeter of surface area a water film of about 0.1…0.4μg (this applies to calibration weights, for example). On the contrary, anodized aluminum will adsorb up to 40μg/cm^2 [5]. In any case, surface contamination plays a major role. Glassware is also known to adsorb water on its surface. The amount adsorbed is dependent on the quality of glass, its cleanliness, and its pretreatment. Glassware from soda-lime glass (soft glass), borosilicate glass (Pyrex/Duran), hard glass, or quartz adsorb, in this order, decreasing amounts of water [6].

- Hygroscopic, Volatile Or Reactive Weighing Objects

  The body (volume) of a weighing object is capable of exchanging water, too, although at a much slower pace than its

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8) to adsorb: to accumulate gases, liquids, or solutes on the surface of a solid or liquid.

9) to absorb: To take something in through or as through pores or interstices.

10) Since magnet wire has a large surface and its insulation is prone to soaking, high resolving electrodynamic balances often are equipped with a sealed compensation coil.

surface. This effect often results in a never ending drift of the weighing value. The situation gets critical if the weighing object is obviously hygroscopic, volatile or hygroscopic. Alcohols that easily evaporate, but also water belong to this category. Ashes, salts and other substances are hygroscopic. Many substances react with the surrounding air, or the humidity in it.

As a rule, such substances should always be kept sealed to minimize any exchange with their environment. Suitable for weighing are containers with narrow necks, or sealable containers. Syringes, or containers sealed with (rubber) membranes also help reducing the exchange. Volatile fluids can also be kept under an oil layer, provided the density of the liquid to be protected is higher than the density of the cover substance. Reactive substances should be kept under inert gases or other substances that prevent reactions.

When gravimetrically calibrating pipettes, a moisture trap can lower the evaporation rate. This device consists of a glass cylinder with only a small opening, through which the dispensed liquid is dosed into a container.

If the exchange is not too pronounced, the repeatability of the weighing may be improved if the weighing operation follows always the same procedure and time pattern, including loading of the balance and reading of the display. However, this method cannot prevent a possible systematic deviation (bias) caused by a reading at an inappropriate instant, either too early, or too late.

With weighing samples that tend to a strong exchange, it is also possible to record their weight via the balance's data interface during a suitable interval of time before and after loading of the platform. Provided some conditions are met, a post processing of this data series may reveal the true weight.

Air Draft & Pressure Fluctuations

• Air Draft

Any air draft generates, through impact pressure or viscous friction, spurious forces onto the weighing platform and the weighing object; clearly these forces do not emerge from the mass of the latter. Especially if the weighing object possesses a large surface, one has to be prepared for such influences.

Air currents cause not only fluctuations of the weighing value, but may as well offset them.

Known for their notorious ability to produce air currents are air conditioners and fume hoods. During cold seasons, heaters and windows with large surfaces may give rise to air currents as well.

Disregarding extreme situations or sensitive weighing objects for the time being, one may expect to weigh trouble free without a draft shield down to a readability of 10mg. Around a readability of 1mg it is recommended, and from 0.1mg (analytical balance) it is indispensable to use a draft shield. Usually these balances already provide a draft shield that is fully integrated into their design, defining the balance's weighing chamber. From a readability of 10µg, it is highly recommended to further reduce the volume of the weighing chamber, if possible. To achieve a readability of 1µg (micro balance), the weighing chamber and the weighing pan area must be kept small. This is even more true for ultra-micro balances with a readability of 0.1µg.

Balance models with the same weighing capacity may be equipped with weighing platforms or pans of different size in surface, or for the same balance model different weighing pans may be available. With some balance models a smaller draft shield is offered as an accessory. It is recommended to use the smaller platform as well as the smaller draft shield, if the weighing object allows for it. This will reduce the settling time of the weighing value, and will improve its repeatability.

- Pressure Fluctuations

The inside volume of the balance housing, containing the weighing cell and the electronics, is connected by the load transfer mechanism to the weighing platform outside this housing. With balances equipped with a draft shield, the latter further isolates the weighing pan from the outside. Pressure changes in the environment of the balance lead to pressure differences between outside and inside of the balance. Since the feed through channel of the weighing platform cannot be hermetically sealed by a membrane—suffice it to mention the barometric distortion, as well as the guiding forces introduced by such a membrane—the balance's exterior and interior remain connected to each other [11]). These pressure differences generate compensation currents, which will exert flow forces onto the weighing pan or the weighing cell, disturbing the weighing value.

Air conditioners enhance already existing pressure fluctuations of the balance's environment [12]). Hence, air conditioners, or other equipment, producing pressure fluctuations, or doors being opened and closed, may degrade the balance's repeatability [13]).

Radiation

- Heat Radiation

The air contained within a balance's draft shield, and the balance itself, will begin to warm up if exposed to any form of heat radiation. Temperature differences, or varying temperatures of the balance or the weighing object cause perturbations already described in an earlier chapter. Therefore, a balance should never be placed in the path of a heat source.

The sun is one of the most frequent, especially strong and highly varying heat source. Nevertheless, light sources (spots) or other devices or equipment, emitting radiation, belongs also to this category.

- Operator Radiation

Surprisingly enough, even an operator's body may radiate sufficient heat during a weighing on an analytical or micro balance to perturb the weighing. With a surface temperature of about 30 degrees centigrade (or 300 Kelvin), a person emits enough heat to change the conditions in the weighing chamber within about half an hour. A zero point drift or

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11) This restriction drops with high capacity balances. The guiding forces as well as the barometric effects of membranes may usually be neglected against the reduced resolution of those balances.

12) Fitzgerald reports in [7] of a degradation of short-term air pressure changes between a thermostatically controlled laboratory (s=0.05mbar) and a climatized (s=0.11mbar).

13) Should you ever be involved in planning a laboratory that will house (high resolving) balances, then propose sliding doors instead of hinged doors, and make sure that the air conditioner produces neither strong air currents, nor pressure fluctuations.

fluctuation of the weighing value, or a reduction of the repeatability, induced by air currents, may become visible.

Mechanical Influences

- Gravitation

Most electronic weighing principles—including strain gauge and electrodynamic compensation weighing cells—do not measure directly the mass m of the weighing object; instead, they measure its weight force, which is caused by gravitation g [14])

$$G = mg \quad .$$

Gravitation, and with it the weight force and the weighing result, is dependent on location and, to a small extent, time. The weighing result is therefore a function of geographical latitude, altitude and the local anomalies of earth's gravitation. It would be rather annoying to know precisely enough the value of gravitation for every place where a weighing is to be performed. Therefore, modern day balances provide a calibration procedure to adjust the sensitivity of the balance in-situ with an internal or external calibration weight [15]).

This operation carried out, the user need not worry about gravitation anymore, unless the balance is moved and installed in a different place, possibly on a different floor, without adjustment [16]). If this floor lies higher by one story ($h = 3\mathrm{m}$), for example, the weighing looses sensitivity, according to

$$\left(\frac{dg}{g}\right) = \frac{-2}{r_E + h}\,dh \quad .$$

where r_E is the earth's radius (≈6000km). A loss of sensitivity of

$$\left(\frac{dg}{g}\right) \approx \frac{-2}{6000\mathrm{km}}\,3\mathrm{m} = -1\mathrm{ppm}$$

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14) g ≈ 9.81N/kg
15) to calibrate: compare the displayed value with a standard (caliber); to adjust: change the setting of the measurement such that the displayed value is equal to the one of the standard.
16) It is assumed, though, that the balance is leveled there again.

results. Hence, as a rule of thumb, for every story higher a balance is installed, its sensitivity reduces by one millionth [17]), equivalent to a vertical gradient of

$$\frac{\left(\frac{dg}{g}\right)}{dh} \approx -0.3\text{ppm/m} \quad .$$

The reader may now ask, whether massive objects in the very vicinity of the weighing object will influence gravity, and hence the weighing result?

As long as the object does approach the balance no closer than 1m, and its mass stays below 1.5 (metric) tons, the influence may be neglected. Such a mass would produce a relative change in gravity of approximately one hundred millionth in the worst case [18]).

- Inclination

The moving of masses in the very vicinity of a balance may have other consequences, though, besides influencing gravity. The floor or the bench, on which the balance rests, may give under the weight. A table, if it is too resilient, may even incline when loading the balance.

Inclining an electronic balance has two consequences:
One has to do with the weight force. If a platform is not exactly leveled , i.e., the measurement direction of the weighing cell is not perfectly perpendicular, then the balance does not measure the total weight force, but the normal force exerted on the weighing platform. This force diminishes proportionally to the cosine of the inclination angle

$$F_N = G\cos\alpha \quad ,$$

thereby reducing the sensitivity of the balance by the same ratio

$$S/S_0 = \cos\alpha .$$

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17) Or, the user performs highly sensitive weighing, extending over several hours with otherwise constant ambient conditions. Then it may be possible that he can observe the effects of the tides and the associated changes in sensitivity, amounting to typically 0.1…0.2ppm, with periods of 12 and. 24 hours.

18) See also [8]

The effect can be identified by its characteristic, that the indicated value deviates negatively if the balance is tilt either way, i.e., to the front or the back.

Firstly, since for small angles the cosine reduces merely with the square of this angle

$$\cos\alpha \approx 1 - \tfrac{1}{2}\alpha^2 + \dots \quad , \text{ for } \alpha << 1 \quad ,$$

the weight force diminishes only slightly. Secondly, the sensitivity of the balance may be adjusted in this off-leveled position. Because the calibration weight undergoes the same reduction of weight force, this deviation is thereby eliminated completely.

The same holds for that part of the weighing cell's dead load which is not mechanically balanced, but is electronically compensated for, as if it were a weighing load. A single taring of the balance eliminates this zero point shift.

The other consequence concerns balances containing a lever. It its center of gravity is not perfectly coincident with its pivot axis, the lever exhibits a mechanical torque proportional to the lever arm and the sine of the deflection angle

$$M_H = g m_H d \sin\alpha \quad .$$

This torque must be compensated by an extra force which is electrically produced. This changes the weighing value by a corresponding amount. This deviation may be eliminated by a single taring, too. However, as the sinus for small angles is approximately proportional to the angle

$$\sin\alpha \approx \alpha - \tfrac{1}{6}\alpha^3 + \dots \quad , \text{ for } \alpha << 1 \quad ,$$

the balance remains sensitive to tilt. To suppress this effect, the center of gravity of the lever is adjusted into its pivotal axis.

- Vibrations

Vibrations, translational as well as rotational, at the site of the balance may introduce deviations into the weighing value. The higher the readability of a balance, usually the more susceptible it is to vibrations.

The lower the frequency of a vibration, the more difficult it is for the digital filter of the balance to suppress this disturbance. As a rule of thumb, movements with frequencies below 0.1…1Hz become visible in the display, such that the weighing value cannot be read unambiguously. In these instances, the influence is clearly recognizable.

More treacherous are vibrations in higher frequency bands, above 10 to beyond 100Hz. The digital filter is capable of eliminating these fluctuations without difficulty, and the display remains stable. However, the balance may, dependent on the weighing load, exhibit resonances at certain frequencies, which may lead to non-linear effects. This may manifest itself in zero shift, an influence not necessarily recognizable.

Vibrations at the place of installation should be suppressed, if possible; at least their intensity should be kept below 10mG [19] (with analytical or micro balances). If this cannot be realized at the location of installation, then a preliminary test with known weights should be carried out to reveal potential deviations caused by vibrations.

- Placement Of Weighing Object

As already mentioned, the weighing platform of a balance needs to be mechanically guided to avoid it—and clearly the weighing object with it—from overturning.

Smallest non-idealities, such as dimensional manufacturing tolerances, or deflections of this guidance, caused by loading the weighing cell, will alter the displayed weighing value, depending on the load's center of gravity relative to the weighing platform. Although the guidance gets adjusted, there will remain a residual deviation. As a consequence, the balance becomes sensitive to the location where the load is placed. Moving the load to a different position will result in a deviation of the displayed weighing value, called eccentric load (error) (also known as corner load [error] or shift error). The magnitude of this deviation increases, usually over-proportional, with the weight of the load and distance between its center of gravity and the center of the platform.

This behavior may or may not be specified; however, some Weights and Measures regulations do exist which require that the off-center deviation of an approved balance is smaller than one approval step at 1/3 of weighing capacity [20]. With an analytical balance, a corner load

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19) here, $G = 9{,}81\,m/s^2$, hence $10mG \approx 0.1\,m/s^2$

20) According to OIML, R-76 [1]. NCWM Publ. 14 [2] asks for a test weight of $^1/_2$ the capacity. These requirements apply for approved balances.

deviation of typically 0.1…0.2mg may be expected, at half-capacity and with the load placed entirely at the edge of the pan.

From the above it should become clear that it is advisable to place the weighing object always in the center of the platform. Should this not be possible, the second best solution is to place it always at the same location on the platform. Thereby, the influence of eccentric loading can at least be reduced.

Electromagnetic Influences

- Electrostatic Forces

According to Coulomb's law [21]), two electric charges exert a force on each other

$$F_E = \frac{1}{4\pi\varepsilon_0}\frac{Q_1 Q_2}{r^2} \quad , ^{22)}$$

which is proportional to the product of both electric charges Q and the square of the distance r between them.

A balance or weighing object carrying such electric charges will cause an electrostatic attraction force. The vertical component of this force is being measured by the balance. Because the force is unexpected, it will mostly go undetected, and wrongly being interpreted as weight force equivalent to a mass $\Delta m = F_{El}/g$, where g is the value of the local gravity.

How can an object get electrically charged in the first place? If two objects touching each other are separated, electrons from one object are left behind on the other. That way both objects get electrically charged: the electron donator positively, the electron acceptor negatively. According to this mechanism, a glass container can get electrically charged for example by gripping it with tweezers, by rubbing it dry with a cloth, or by shoving it on a surface. This charging mechanism is often called "triboelectricity", although no

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21) Charles Augustin de Coulomb, 1736-1806. French physicist who pioneered research into magnetism and electricity and formulated Coulomb's law.

22) Permittivity constant $\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m

friction is required per se for this process; separation is sufficient. Liquids and gases may become charged as well. For example, a liquid which is poured from one container into another can get charged by this process.

For charges to exist on bodies over an extended time without dissipating, the bodies—in our case balance and weighing object are of interest—need to be electrical insulators. Electrical charge can flow through the body (bulk) of a body, or it can flow along its surface. Many weighing objects possess virtually no body conductivity, and hence, are isolators. Containers and other glassware made from borosilicate glass [23]) are excellent electrical isolators. Even soda-lime glass (″window glass″) is still a good insulator. Many components of laboratory supplies are manufactured from plastic materials which are fairly good to excellent insulators.

Even though the bulk of a body is from electrically insulating material, electrical charge can still dissipate if the surface of the body provides sufficient surface conductance. While the electric bulk conductance of an object may be small, its surface conductance can be substantial at the same time. Because of the adsorbed water layer on the surface at normal air humidity and ubiquitous contamination (by salt and other chemicals), as a rule of thumb, most labware possesses sufficient surface conductance to dissipate electrical charges within short time.

This surface conductance depends largely on air humidity, especially when contamination is present. However, if air humidity falls below 40…45%rH (during wintertime, when heating is on), then chances are that electric charges will barely dissipate, if at all. This is especially true for clean equipment. Charges will manifest themselves such that repeated weighings of the very same object will produce different weighing values, or that a weighing value will never settle, i.e., it drifts during a long time (seconds, minutes). Due to a lack of an obvious reason, most often the balance gets blamed for this behavior—wrongly so.

If the ambient air humidity is extremely low, around 10…20%rH, as can be the case in laboratory glove boxes with controlled atmosphere, for example, electrical charges

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[23]) Duran, Pyrex

may stay for hours (!) on objects or on the balance. Despite of a biased weighing value, a drift might not be observable.

If recognized correctly, the effect may be overcome with simple measures. Firstly, a normal atmosphere with sufficient humidity (50%rH) should be provided, and the distance between attracting or repulsing charges should be increased. If this is not possible, or the suppression is not sufficient, the following countermeasures will help:

i) The weighing object is electrically charged:

In this case the weighing object should be raised in the center between the platform and the top of the draft shield (where present). A spacer can be used to achieve this. Because it gets also weighed, it should not be too heavy, and there should be no doubts about the constancy of its mass. This method increases the distance between the electric charge and the base of the balance.

Another countermeasure is to enclose the weighing object with a Faraday[24)] cage which is electrically as well as mechanically connected to the weighing pan. Thereby, all electric field lines—the innate cause for forces—will end inside the weighing object, the cage or the pan; no field line will leave this structure. Consequentially, the electric charges cannot exert any force to the outside, hence producing no weighing force, either [25)].

A remedy can be ionized air. It neutralizes the electrical charges. It is important that the ionized air current is electrically neutral, i.e., carries an equal number of positively and negatively charged ions. Ionized air can be produced with hand held piezo ionizers [26)]. Such devices are well suited for occasional applications . If the electrical charges occur systematically, and if a high throughput is required, electrically operated ionizers that produce a steady stream of

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24) Michael Faraday, 1791-1867. British physicist and chemist who discovered electromagnetic induction (1831) and proposed the field theory later developed by Maxwell and Einstein.

25) This situation is comparable to the one that Karl Friedrich von Münchhausen, a German baron (1720-1797) once experienced. Legend has it that he pulled himself by his hairs out of a swamp.

26) Piezo ionizer, such as "Zerostat 3" of Bellex International, or equivalent. For more information contact: Bellex International Corp., 501 Carr Road, Suite 100, Wilmington, DE 19809. USA. Phone (302) 761-9886; www.bellexinternational.com

ions are the choice [27]). The electrode of such ionizers can be installed next to the balance, such that the weighing object passes through the operating zone of the ionizer and gets discharged while loading it on the balance. In persistent cases the ionizer may be mounted directly inside the weighing chamber. Be aware, though, that the ion current exerts forces on the weighing object and the weighing platform, disturbing the weighing value. The ionizer must therefore be switched off during the weighing, and the decay of the air currents inside the draft chamber must die out, before the balance can be read.

ii) The balance is electrically charged:

A balance should always be grounded, i.e., electrically connected to earth potential. If this connection is not provided, the balance may accumulate electric charges. The weighing pan, electrically connected to the housing and chassis of the balance, assumes the same electrical potential as the balance. This causes the pan to be charged relative to its environment, and the pan suffers a force, usually uplifting.

Usually, the balance gets automatically grounded by connecting the power plug to the electrical outlet. If the power plug has only two prongs (no earth prong), or if the balance is powered from a battery, it is recommendable to connect a bare spot of the balance (a screw, for example) with a wire to earth [28]).

The glass windows of the draft shield are capable of accumulating electrical charges, too, thereby causing a force onto the weighing object or the weighing pan. To alleviate this situation, an analogous strategy as described in i) may be used, with the difference that the Faraday cage now needs to be electrically and mechanically connected to the frame of the balance (not its weighing pan). Thereby, field lines emerging from the outside (of the weighing object) are prevented from reaching the weighing object or the weighing pan.

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27) Electrically operated ionizers such as the "U-ionizer" from Haug. For more information contact: Haug North America, 1200 Aerowood Drive, Units 14 & 15, Mississauga, CA-ON L4W 2S7. Phone (905) 206-9701; haug@pathcom.com; www.haug.de

28) It is not recommended to use the earth prong of a power outlet, as a live line might be inadvertently hit. This puts the balance under high, lethal voltage!

iii) In some rare cases weighing object and balance may be electrically charged; then methods i) and ii) should be applied combined.

The Faraday cage need not be closed entirely; usually it suffices to intersect the space with an electrically conductive surface. For example, this could be a metal cup, into which the weighing object is placed. Should a screen be required on top of the weighing object, for example with tall weighing objects reaching near the top of the weighing chamber, then it may consist of a metal gauze. The mesh width should be smaller than the smallest distance between the objects to be screened.

- Magnetostatic Forces

Magnetic forces emerge between two magnetized bodies, or between a magnetized body and a magnetically permeable body. Although magnetic phenomenons are more difficult to describe than those in the case of electrostatics, we still may write approximately

$$F_M \approx \frac{M}{r^2} \quad ,$$

where M is the magnetization of a body, and r the distance between the magnetically active objects. Again, the force decreases with the square of the distance between the magnetized and the attracted body. A magnetically active weighing object will be affected by repelling or attracting magnetic forces. The vertical component of such a magnetic force acts on the weighing object. Because the force is unexpected it mostly remains undetected and is interpreted—wrongly so—as a weight force equivalent to a mass $\Delta m = F_{Mag}/g$, where g is the value of the local gravity.

Magnetically highly permeable [29)] elements are iron (Fe), nickel (Ni) and cobalt (Co), as well as their alloys. Metallic glasses and ferrites are also permeable.

Magnetically "hard" materials can be magnetized, for example those from hard steel, and permanent magnetic materials, designed expressively for that reason. Magnetic fields emerge also from electromagnets or cables carrying high electric currents. Typical sources of magnetic fields, for

29) i.e., with a large relative magnetic permeability, $\mu_r >> 1$

example, are permanent magnets, also (mostly inadvertently or unknowingly) magnetizable objects such as screw drivers, knives, tweezers or other tools or objects manufactured from steel. Furthermore, equipment containing electromagnetic components, such as motors, valves, transformers, etc., should not be overlooked. Finally, we should not forget—although weak, yet omnipresent—earth's magnetic field.

In suppressing the influences of magnetic effects, we have to keep apart the following cases:

i) The weighing object is magnetized:

Most often the magnetized weighing object attracts magnetically permeable elements in its vicinity, including those of the balance. Although much thought is given to design balances without making use of permeable materials, it cannot be done without. The electrodynamic transducer, by its nature, must contain magnetically highly permeable material, as well as other components of the balance, such as calibration drive motors or magnetic screens. It may also happen that the balance stands on a partially or fully magnetically permeable support (iron table, iron reinforced stone table, or iron strengthened wood table), next to permeable equipment (steel enclosings) or other iron constructions. Be aware that weighing fluids in beakers that contain a stirring magnet belongs to this category as well.

The effect can be alleviated by placing the weighing object onto a non-magnetic, non-permeable (and not too heavy) body to gain distance [30]). This is the preferred method employed with balances that have no draft shield. Alternatively, the weighing object can be screened with a cage made from magnetically permeable material (soft iron or alloys such as mumetal), which itself rests on the weighing pan. Thereby, magnetic field lines are caught within the case (at least to the extent of the cage's screening capability) and can not reach the outside, which reduces forces onto the weighing pan.

Analogous to the countermeasures against electrostatic forces, the cage need not be closed entirely in every case. Depending on the situation, an iron sheet metal between

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[30]) Placing the weighing object onto a spacer made from a plastic material fulfills these conditions and may help. However, watch out now for electric charges that might be carried by the spacer or the weighing object, being electrically isolated from the weighing pan.

weighing object and weighing pan may sometimes help. However, contrary to electrostatic field lines, where a single layer of electrical conductor, independent of its thickness, provides a perfect screen, a magnetically permeable layer may not fully screen against magnetic fields. A thicker layer, or multiple separate plies, may be required to entirely suppress the magnetic field.

If none of the methods mentioned is applicable, or if they are not efficient enough, the weighing object should at least always be placed in the same position and with the same orientation. Certainly, this precaution does not away with a possible deviation of the weighing result, yet at least difference weighings should become more accurate and precise with this measure [31]).

ii) The weighing object is magnetically permeable:

In this case, sources of external magnetic fields should be removed, or if this is not possible, the balance should be screened with magnetically permeable material that is supported by the balance or its rest, not by the weighing pan. Here as well as above, the screen need not always cover the entire balance, it may suffice to use a permeable iron mesh. Be careful to use only magnetically soft [32]) material, i.e., material that cannot be magnetized.

- Conducted Electromagnetic Interference

Electronic equipment, especially those containing switches, relays or digital electronic components, or consuming high power (ovens, motors, etc.), may electronically disturb their supply mains. These disturbances will travel along the electrical supply lines to other equipment, potentially interfering with them. Balances—like other measurement equipment—are required to stand a certain amount of disturbance without a major change of the weighing value.

Be aware that these disturbances may also approach through data interface cables connected to peripheral devices, such as data processing equipment, PCs, etc.

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31) accurate: in agreement with the true value;
precise: not scattering when repeated.

32) ″Magnetically soft″ iron usually is also ″mechanically soft″.

Instruments of renown manufacturers are tested to be immune against these influences within the limits prescribed by regulatory bodies [33].

- Radiated Electromagnetic Interference

Similarly, electromagnetic disturbances may approach the balance through radiation. If an equipment contains the aforementioned components, it is highly probable that it may emit electromagnetic waves. Especially these days there are many devices that purposely emit radiation, such as cellular phones, for example.

A balance needs to stand a certain amount of electromagnetic radiation without a major change of the weighing value. The usual limit for field strengths is 3V/m in laboratory environment, and 10V/m in industrial environment.

Again, instruments are tested to meet international regulations that exist in this field [34].

Long-Term Drift

- Weighing Cell

Essential elements of the load transmission path, such as the parallel guide or the lever (when present), are made from aluminum, non-ferrous metals or steel alloys. Although these materials belong, in terms of dimensional stability and creep, to the most stable, it can not be avoided that with time (days, months, even years) creep and deformation processes happen, either spontaneously, or induced through climatic stimuli (especially temperature fluctuations), or through external implications (sometimes through regular use, surely through misuse). A common victim of these alterations is the lever transmission; as a consequence, the sensitivity of the balance changes.

The magnetic flux of a permanent magnet—despite its name—relaxes over time. This is caused by spontaneous thermic motion of molecules which change the directions of single magnetic domains; a behavior which cannot be suppressed. However, through proper magnetic and thermal pretreatment after assembly of the weighing cell, most of the

33) ####Norm für geleitete Interferenzen.
34) ####Normen für eingestrahlte interferenzen.

long-term drift, which manifests itself as logarithmic decay, can be forestalled. Since the electrodynamic transducer is based on the flux of a permanent magnet, the proportionality factor between current and force is affected. On the other hand, the compensation current can influence the permanent magnet field, since the current produces a magnetic field of its own, interacting with the permanent magnet.

Finally, we have to account for the fact that the geometry of the compensation coil, and of the permanent magnet system, does not remain infinitely stable, especially under the influence of temperature; this contributes to changes of the balance's sensitivity, too.

- Electronics

The balance's sensitivity depends on two electronic components that are essential for the analog-to-digital conversion (A/D) of the compensation current.

One of them is the reference voltage source, which establishes—as its name expresses—a high quality, i.e., extremely stable reference voltage. With the second component, a high quality, particularly stable resistor, the voltage generates a reference current. Clearly, this resistor requires outstanding properties, especially in terms of constancy. The reference current is required by the A/D converter to convert the compensation current. [35])

Analogous to mechanical components, both electrical components are affected by long-term drift. This will eventually alter the balance's sensitivity.

- Calibration Weight

The calibration weight is supposed to represent a known amount of mass, invariable with time.

A calibration weight may change its mass by loss or gain of material. A loss of mass may result through friction or corrosion, provided that the reaction products are volatile. A gain of mass is obtained when foreign particles (dust) settle on its surface, or by chemical reaction of the base material

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[35]) What has been said is also valid if instead of a current-A/D converter a voltage-A/D converter is used to convert the compensation current. Then the reference resistor is used to convert the compensation current into a proportional voltage; the reference voltage is fed to the A/D converter as reference.

with the ambient atmosphere, assuming the reaction products accumulate on the surface, or by adsorption of aerosols or gases. It has to be considered that friction does not lead to a mass loss in every case. Depending on the combination of materials, matter may accumulate on the rubbed weight [36]).

While in the early era of (analytical) balances, the calibration weights were predominantly made from brass, this material has been since replaced by stainless steel. Brass is afflicted by corrosion and is not very abrasion resistant, while steel tends to be magnetically permeable; both undesirable properties for calibration weights. Meanwhile, practically non-permeable stainless steel is used for manufacturing calibration weights. What is more, this material resists to wear, and its surface can be electrolytically polished which reduces its surface area and makes it smooth. Wear loss of external calibration weights, provided they are handled with caution, is negligible [37]). The wear of built-in calibration weights, moved by automatic actuators is usually insignificant over the lifetime of the weight or balance.

This is the reason, why a calibration weight—internal or external—can be used to adjust the sensitivity of the entire balance. Drifts from the weighing cell or the electronics, from changed gravity, or from any other source, are thereby cancelled.

Air Buoyancy

- Buoyancy

If a weighing takes place in a vacuum on earth, a body with mass m produces a weight force of

$$G = mg \quad .$$

Obviously, all weighing objects, with few exceptions, are weighed in their "natural" environment, i.e., in the atmosphere that surrounds the earth. According to Archimedes'

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36) Internal calibration weights of analytical balances, for example, kept in, and actuated several ten thousand times by aluminum guidances, tend to accumulate mass, if there is a change at all.

37) This is not necessarily the case for calibration weights in heavy use. See [9].

law [38], a body receives a buoyant force equal to the weight force of the fluid displaced. As every weighing object takes up a certain volume, it is a subject to a buoyancy force which is opposed to the weight force and diminishes the latter.

If we know the density ρ [39] of a weighing object, its volume can be calculated

$$V = \frac{m}{\rho} \quad .$$

Given the density of the fluid—we assume here a weighing in air, hence we will use the density of air a —we get for the mass of the replaced fluid

$$m_F = aV = a\frac{m}{\rho} \quad .$$

We can now write for the sum of all forces of the buoyant body (apparent weight)

$$G_A = mg - m_F g = mg - \left(a\frac{m}{\rho}\right)g = mg\left(1 - \frac{a}{\rho}\right) \quad .$$

Normalizing this apparent weight with the weight force observed in vacuum, we have

$$\frac{G_A}{G} = \frac{mg\left(1 - \frac{a}{\rho}\right)}{mg} = 1 - \frac{a}{\rho} \quad .$$

This is the ratio of the weight of a body of density ρ in air of density a , in relation to its weight in vacuum.

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38) Archimedes, 287?-212 B.C. Greek mathematician, engineer, and physicist.

39) With solid materials and materials containing sealed pores, density is obtained by the mass and the volume of the entire body, including its pores.
Bodies with open pores require a different approach. Only the mass and the volume of the solid part of the body is to be used to determine its density, neither the mass contained in its pores, nor their volume. This is valid under the condition that the pores stay in free exchange with the environment of the body.
If this is not the case, it is questionable to talk of an overall density, because density can then not be clearly defined in the first place. Furthermore, a (slow) exchange process between gas contained in the pores and the ambient may take place, influencing density, buoyancy, and hence the weighing result.

The air density at normal conditions is about $a = 1.2\text{kg/m}^3$ [40]). When weighing a heavy metal, copper for example, with a density of $\rho = 8950\text{kg/m}^3$, the buoyancy induced deviation amounts to

$$\frac{a}{\rho} = \frac{1.2\ \text{kg/m}^3}{8950\ \text{kg/m}^3} \approx 134\text{ppm}$$

—a figure certainly not to be neglected when dealing with high resolution mass determinations.

The deviation resulting from buoyancy gets even severer when weighing watery solutions. We then get

$$\frac{a}{\rho} = \frac{1.2\ \text{kg/m}^3}{1000\ \text{kg/m}^3} \approx 1.2 \times 10^{-3} \quad ,$$

a deviation larger than 0.1%, a typical accuracy level of laboratory analyses.

Without buoyancy correction, it does therefore not make sense to determine the mass of a watery solution under atmospheric conditions accurate to more than 0.1%, using a balance that employs a force principle. With glasses (density $\approx 2500\text{kg/m}^3$) the limit is about 0.05%, with heavy metals (density $\approx 7000\ldots9000\text{kg/m}^3$) around 0.015%.

There are applications where the ratio of masses is of interest and where the absolute weight is not of primary concern. For example when preparing mixtures, it is not so important to know the absolute mass, it suffices that the ratio among the ingredients is correct. This is the case when weighing the components on the same balance, even if its sensitivity is offset or buoyancy is present. However, the restriction applies that all components must possess similar densities.

It does not make sense, either, to adjust the sensitivity of an (analytical) balance to one millionth, with the intention of performing high accuracy weighing, without applying buoyancy correction at the same time. Repeated weighings will produce the same precise, yet biased weighing results. If buoyancy correction is rarely applied, this may be caused by the fact that the buoyancy changes (mainly resulting from pressure change of the atmosphere) are about an order of

40) A method to determine the density of air is given in [10].

magnitude smaller than the nominal buoyancy effect itself, which thus remains hidden.

On the other hand, it is correct that the influence of sensitivity and buoyancy—the latter having the same effect on the weighing as the former—may be neglected if small samples are weighed (small in relation to the weighing capacity of the balance). In these cases, the measurement uncertainty is dominated by the contributions of repeatability and non-linearity. Furthermore, buoyancy correction need not be applied in those cases, where the weighing needs to be performed with an uncertainty not below 0.1%, provided, the weighing object has a density of at least 1kg/m^3.

- Conventional Mass

Clearly both the representation and dissemination of mass ("weights" or mass standards) are subject to the laws of buoyancy. There is a long history of measures taken to deal with the influence of buoyancy to reduce its influence, as it cannot be eliminated. To this end, OIML has conceived the concept of conventional mass [11]. *The main idea of this convention consists of the decision to forgo buoyancy correction in those cases, where a body has a density of 8000kg/m^3 and the weighing is carried out in air of density 1.2kg/m^3 [41]).*

If the density of the body is different from this conventional density (8000kg/m^3), then the body's mass is corrected for by adding mass to, or removing from, such that the weight difference [42]) compared to a reference standard of conventional density vanishes, provided the weighing is carried out in air of conventional density (1.2kg/m^3). A weight adjusted according to this procedure is said to have a *conventional mass* value—equal to the value marked on it—the (true) mass of the reference standard to which it was compared.

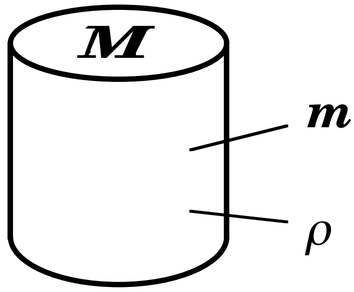
Clearly, this convention does not away with the physical phenomenon of buoyancy. However, since mass standards usually are manufactured from alloys of heavy metals with a density around 8000kg/m^3, buoyancy correction can be

41) Both densities of convention, namely the one for mass standards with ρ_K = 8000kg/m^3, and the one for air with a_K = 1.2kg/m^3, were established by the OIML [11].

42) not mass difference

greatly reduced, if not dropped altogether. Thereby the influence of buoyancy causes smaller deviations or uncertainties when disseminating masses.

As a further consequence of this convention, a standard with a density smaller than the conventional density actually possesses more, one with a larger density, possesses less mass than its conventional mass tells. The relationship between true mass m and conventional mass M of a body can be derived from the rules of this convention, namely



$$M = \frac{1-\frac{a_K}{\rho}}{1-\frac{a_K}{\rho_K}} m \quad ,$$

where M : conventional mass, m : (true) mass,
ρ : actual density of the standard

We give an example:

A mass standard of nominal value 1kg is to be manufactured from stainless steel of density ρ = 7960kg/m^3. How much steel is required?

Disregarding the OIML convention, the answer couldn't be simpler: $m = 1\ \mathrm{kg}$!

However, if we proceed according to the rules of the OIML convention, we interpret the nominal value as conventional value, hence $M = 1\ \mathrm{kg}$. That will be the value to be marked on the standard. We further have to respect the conventional densities

$$\rho_K = 8000\ kg/m^3 \quad ; \qquad a_K = 1.2\ kg/m^3 \quad .$$

Now we have to solve the above expression for m , the (true) mass

$$m = \frac{1-\frac{a_K}{\rho_K}}{1-\frac{a_K}{\rho}} M \approx \left[1 + a_K\left(\frac{1}{\rho} - \frac{1}{\rho_K}\right)\right] M \quad ,$$

and we can determine the mass required for the standard

$$m \approx \left[1+1.2\,\mathrm{kg/m^3}\left(\frac{1}{7960\,\mathrm{kg/m^3}}-\frac{1}{8000\,\mathrm{kg/m^3}}\right)\right]1\mathrm{kg} \approx$$
$$\approx \left[1+754\times10^{-9}\right]1\mathrm{kg} \approx 1\mathrm{kg}+754\mu\mathrm{g} \quad .$$

Hence, to manufacture this standard with a conventional mass of 1kg, we need 1.000000754kg of steel, somewhat more than its nominal value tells. The excess mass is to compensate for extra air buoyancy compared to a weight of conventional density (8000kg/m^3), which is caused by its slightly lower density than the conventional density [43].

[43] A more detailed description of the subjects of buoyancy and conventional mass can be found in:
Arthur Reichmuth: "Measuring Mass & Force With A Balance", Oct. 99, Mettler Toledo company brochure.

Conclusions

The first chapter of this paper presents the functional principles of a high resolution balance. The second introduces the relevant specifications by which a balance's performance is defined.

Following these introductory chapters, the most important and frequent external influences on weighing processes, each of which potentially degrading the weighing result, were introduced. Climatic influences on the balance and the weighing object were discussed, such as from temperature and humidity, as well as from air draft, pressure fluctuations and heat radiation. The influences of gravitation (providing the weighing force), inclination of the balance, vibrations of the support and other mechanical shortcomings are analyzed. Particularly dealt with are electrostatic and magnetic forces that are often present, yet invisible and hence seldom recognized. Long-term drift of a balance was also discussed. Air buoyancy, an omnipresent influence when weighing, and the related concept of conventional mass were commented on.

Wherever possible, precautions and suitable countermeasures to either eliminate, or at least to reduce the influence on the weighing process, were given.

Readers interested in the effects discussed in this paper are invited to perform some of the experiments that are described in the following appendix. These experiments are simple to carry out and will complement with practical experience and insight the theoretical statements about the mechanisms of influences given in this text.

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Influence Sources & Prevention In Weighing

Appendix
Practical Part: Experiments

 V 1.3 August 2000

Abstract

The experiments described below illustrate many of the physical influences discussed in the preceding chapters.

With few exceptions, they only require common equipment usually available in a laboratory. These experiments qualitatively and quantitatively demonstrate the detrimental effects that physical influences can have on every weighing, and some countermeasures can be tested for their effectiveness.

The following influences are covered: 44)

- Unequal Temperature Of Weighing Object and Environment, Draft Shield
- Evaporation
- Absorption
- Air Draft
- Heat Radiation
- Eccentric Load Deviation
- Weighing Object Electrostatically Charged:
  Charge In Lower Region Of Weighing Chamber;
  Countermeasures
- Weighing Object Electrostatically Charged:
  Charge In Upper Region Of Weighing Chamber
- Balance Electrostatically Charged
- Magnetically Permeable Weighing Objects
- Magnetized Weighing Objects

44) For best performance, it is advisable with all experiments to disable the autozero feature of the balance.
If the auto zero function cannot be disabled, a small preload can be put on the pan after taring, preferably a non-ferrous metal (for example a penny). Therewith, the displayed value is different from zero, which disables the auto zero. Hence, the balance must not be re-zeroed anymore in the course of the experiment, or the purpose of the preload is foregone.

Unequal Temperature Of Weighing Object and Environment, Draft Shield

Required Utensils

- Analytical balance, preferably 0.01mg readability, but 0.1mg will do, too
- 250ml glass beaker, ca. 15cm high, ca. 6cm diameter

Procedure

1) Install balance and let acclimatize. Disable the auto zero feature.
2) Put the previously acclimatized beaker on the weighing pan (or let it acclimatize there for about 1/2h…1h).
3) Re-zero the balance.
4) Grab the beaker and firmly enclose it with both of your bare hands during 1/2 to 1 minute [45]). The hands warm up the beaker.
5) Put the beaker back on the weighing pan.
   The beaker is now warmer compared to the air inside the weighing chamber. This causes an upward air current that raises along the wall of the beaker. Viscous friction due to this current exerts an upward force onto the beaker. Therefore, the weighing value will drift <u>to more negative values</u>, about 5…10mg, depending on the size and temperature of the beaker, and may strongly fluctuate in the beginning because of the current. Slowly, the amount of deviation will diminish. This relaxation can stretch well over 1/2h until the air current has fully died out.

One might argue whether really the air current is the reason for the drift. Could it not be the dust and sweat from the hands that is left on the outside surface of the beaker from holding it with bare hands, which are partially evaporating now?

If this were the cause, the weight should have increased. As a matter of fact, it had decreased (even though there might have been such residuals). Hence, the air current must be the reason for the effect.

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[45]) something, you should never do otherwise…

Evaporation

Required Utensils

- Analytical balance, 0.1mg readability
- Petri dish (dish and cover), diameter ca. 5cm
- Ethyl alcohol, methanol or any other readily evaporating fluid, in dispensing bottle
- Pliers or tweezers

Procedure

1) Install balance and disable the auto zero feature.
2) Put the Petri dish on the weighing pan.
3) Add some fluid: the weight value immediately drifts towards more negative values because of evaporating fluid.
4) Put the cover on the dish: the weight value stabilizes on a lower value, if the cover is tight.
   Usually, covers of Petri dishes do not seal thoroughly. The weight value continues to drift towards more negative values, although at a reduced rate.

Absorption

Required Utensils

- Analytical balance, 0.1mg readability
- Petri dish (dish and cover), diameter ca. 5cm
- Dry (blue!) silica gel
- Spoon
- Pliers or tweezers

Procedure

1) Install balance and disable the auto zero feature.
2) Put the Petri dish on the weighing pan.
3) Add some silica gel: the weight value immediately drifts towards more positive values because of water absorbed by the silica gel.
4) Put the cover on the dish: the weight value stabilizes on a more positive value.
   Usually, covers of Petri dishes do not seal thoroughly. The weight value continues to drift towards more positive values, although at a reduced rate.

Air Draft

Required Utensils

- Analytical balance, 0.01

Procedure

1) Install balance and tare it.
2) Open the draft shield. Depending on the environmental air speed, the displayed weight value will fluctuate and possibly drift away as much as 1mg. In rooms with heavy air conditioning, this value may even be larger.

Heat Radiation

Required Utensils

- Analytical balance, 0.01mg readability
- Light source (spot)

Procedure

1) Install balance and let acclimatize. Disable the auto zero feature.
2) Direct the spot onto the balance. The displayed weight value will fluctuate and, depending on the situation, drift away.

Eccentric Load Deviation

Required Utensils

- Analytical balance, 0.01mg
- 100 or 200g weight piece
- Pliers or tweezers

Procedure

1) Install balance.
2) Put the weight piece on the center of the pan.
3) Tare the balance.
4) Shift the weight to the left, right, front and back. The deviation observed at these locations, compared to the center position, is the corner load deviation (expect about 0.1…0.2mg at 100g).

Weighing Object Electrostatically Charged: Charge In Lower Region Of Weighing Chamber

Required Utensils

- Analytical balance, preferably 0.01mg readability, but 0.1mg will do, too
- Short beaker (2…4cm), from borosilicate glass, thoroughly cleaned (electrically non-conductive!)
- Metal disk, 4…5cm in diameter
- High voltage generator [46])
- Electrostatic charge meter [47]) (if available)
- Short stub of blank metal wire (≈ 20cm)
- Pliers or tweezers

Procedure

1) Install balance and let acclimatize. Disable the auto zero feature.
2) Put the beaker upside down on the weighing pan, and put the metal disk on top of the beaker's bottom.
3) Re-zero the balance.
4) Deposit some electric charge on the metal disk
Confirm the presence of the charge with the charge meter (some kV).
Close the draft shield.
5) The displayed weighing value becomes more positive, about 5…10mg (depending on the beaker's conductivity and the deposited charge).
6) Touch the metal disk with the blank wire. This will dis-charge it. Test the absence of charge with the charge meter (≈ 0kV).

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[46]) Piezo ionizer, such as "Zerostat 3" of Bellex International, or equivalent. For more information contact Bellex International Corp., 501 Carr Road, Suite 100, Wilmington, DE 19809. USA. Phone (302) 761-9886; www.bellexinternational.com

[47]) Electrostatic Meter, such as "EOS 100" of Chapman Corp., P/N 83293, or equivalent. For more information:
Chapman Corp., 125 Presumpscot Street, P.O. Box 10700, Portland, ME 04104, USA. Phone (207) 773-4726.

7) The displayed weight value will travel towards zero and stabilize there, with a possible offset stemming from residual charge (on the beaker).

Countermeasures

Additional Utensils

- Metal can with cover, larger in diameter (6…8cm) and taller than glass beaker

Procedure

8) Put the metal can on the weighing pan.
9) Put the glass beaker upside down into the metal can, and put the metal disk on top of the beaker's bottom; the disk must not touch the metal can.
10) Re-zero the balance.
11) Deposit some electric charge on the metal disk. Confirm the presence of the charge with the charge meter (some kV). Close the draft shield.
12) The displayed weight value hardly changes, because the charge is screened by the metal can from interference; this prevents field lines from reaching the outside.
13) Should there remain any residual electrostatic force, putting the metal cover onto the can eliminates all of them.

Weighing Object Electrostatically Charged: Charge In Upper Region Of Weighing Chamber

Required Utensils

- Analytical balance, 0.01mg readability
- 250ml glass container, ca. 15cm tall, ca. 6cm in diameter, from borosilicate glass, thoroughly cleaned (electrically non-conductive!)
- Metal disk, 4…5cm in diameter
- High voltage generator
- Electrostatic charge meter (if available)
- Short stub of blank metal wire (≈ 20cm)
- Pliers or tweezers

Procedure

1) Install balance and let acclimatize. Disable the auto zero feature.
2) Put the glass container upside down on the weighing pan, and put the metal disk on top of the beaker's bottom.
3) Re-zero the balance.
4) Deposit some electric charge on the metal disk
   Confirm the presence of the charge with the charge meter (some kV).
   Close the draft shield.
5) The displayed weighing value becomes more negative, about 1…2mg [48]), because the electric charge is pulled towards electrically conductive structures on the top frame.
6) Touch the metal disk with the blank wire. That will discharge it. Test the absence of charge with the charge meter (≈ 0kV).
7) The displayed weight value will move towards zero and stabilize there, with a possible offset stemming from residual charge (on the beaker).

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48) Depending on the beaker's type, its conductivity and the amount of deposited charge; measured with the aluminum disk in about 2/3 of the height of the windshield.

Balance Electrostatically Charged

Required Utensils

- Analytical balance, preferably 0.01mg readability, but 0.1mg will do, too
- High voltage generator, or rubber gloves

Procedure

1) Install balance and let acclimatize. Disable the auto zero feature.
2) Re-zero the balance.
3) Deposit some electric charge on the outside window of the draft shield, at about half-height, by moving the voltage generator's electrode on the glass of the draft shield in circular motion. If the ambient air is dry enough, the charge may also be generated by rubbing the draft shield with rubber gloves. Confirm the presence of the charge with the charge meter (some kV).
4) The displayed weighing value will assume a <u>more negative value</u>, because the charge deposited on the draft shield attracts the weighing pan [49]). After that, the displayed value drifts to <u>more positive values</u> again, because the charge slowly dissipates.
5) If the environment is dry enough, try this:
   Open the draft shield. The displayed value will begin to fluctuate because of air currents; however, its mean value will tend <u>towards zero</u>, because the charge on the draft shield has been dislocated.
6) Close the draft shield again. If the air was dry enough, the electrical charge could hardly dissipate, i.e., it still resides on the draft shield. Hence, the displayed value drifts to <u>more negative values</u> again.
7) Slightly breathe upon the closed draft shield to cloud it over. The displayed value will tend <u>towards zero</u>, because temporarily, the breath's humidity provided enough electrical conductivity to dissipate the electrical charge.

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[49]) This will only work, if the ambient air is dry enough, say 50% or preferably less. Above that humidity, the residual surface conductivity of the draft shield is too high, which dissipates the charge quickly. It is important that the glasses be absolutely clean!

Magnetically Permeable Weighing Objects

Required Utensils

- Analytical balance, 0.1mg readability
- Iron rod or profile, ca. 10…15cm long (watch for weighing capacity and size of weighing chamber!)
- Permanent magnet (for example white board magnet)
- screwdriver, medium size or larger, magnetized [50]).
- Pliers or tweezers

Procedure

1) Install balance and let acclimatize. Disable the auto zero feature.
2) Put the iron rod on the weighing pan.
3) Re-zero the balance.
4) Open the draft shield and change the orientation of the rod (rotate counter-clockwise, for example). Close the draft shield.
5) The displayed value will change.
6) Open the draft shield and restore the original orientation of the rod. Close the draft shield.
7) The displayed value will return into the vicinity of its original value.
8) Bring the permanent magnet on the table towards the weighing object. The displayed value will become more positive (since the weighing object will be pulled downwards).
9) Put the permanent magnet on top of the draft shield: the displayed value will become more negative , but clearly to a lesser extent [51]).
10) Remove the permanent magnet, re-zero the balance, and bring the (magnetized) screw driver towards the balance: The displayed value will become more positive (since the weighing object will be pulled downwards).

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50) To magnetize a screw driver, glide a permanent magnet several times along the driver's blade. Be aware, though, that unless special demagnetized equipment is available to demagnetize the screw driver, it will stay magnetized forever.

51) Gaining distance is one of the methods to weaken the effect.

Magnetized Weighing Objects

Required Utensils

- Analytical balance, 0.1mg readability
- Permanent magnet (for example white board magnet)
- Iron rod or iron sheet metal
- 250ml glass container, ca. 15cm tall, ca. 6cm in diameter
- Pliers or tweezers

Procedure

1) Install balance and let acclimatize. Disable the auto zero feature.
2) Put the permanent magnet on the weighing pan.
3) Re-zero the balance.
4) Open the draft shield and change the orientation of the permanent magnet (rotate 90° counter-clockwise, for example).
5) The displayed value will change.
6) Open the draft shield, place the glass container upside down on the weighing pan, put the permanent magnet on the bottom of the glass container and orient the permanent magnet as at the beginning of the experiment.
7) Re-zero the balance.
8) Open the draft shield and change the orientation of the permanent magnet on top of the glass container (rotate 90° counter-clockwise, for example).
9) The displayed value will change, but clearly to a lesser extent than before [52]).
10) Re-zero the balance. Bring a permeable rod or sheet metal near the balance. The displayed value will become more positive (since the weighing object will be pulled downwards).

[52]) Gaining distance is one of the methods to weaken the effect.

Trapped Air Inside Containers

Required Utensils

- Analytical balance, 0.1mg readability
- Small bottle (≈50ml, preferably from glass) with small plastic snap-on (NOT screw) cover (a Kodak film container will do)

Procedure

1) Install balance and let acclimatize. Disable the auto zero feature.
2) Put the bottle and the cover onto the weighing pan; the container must be open.
3) Re-zero the balance.
4) Remove bottle and cover from the balance and firmly put the cover onto the container.
5) Put the covered bottle on the weighing pan.
6) The displayed value will be <u>larger</u> by one or several mg, depending on the size and the construction of the cover. This is because of trapped air in the cover, which gets compressed into the bottle when the cover is put in place. Thereby more air is contained in the bottle than in the open state, a fact the balance indicates.
7) Remove the covered bottle and uncover the bottle.
8) Put the uncovered bottle and the cover onto the weighing pan. The displayed value should return to zero.