FAI BALLOONING COMMISSION

COMMISSION INTERNATIONALE D'AEROSTATION

CALCULATION OF CORRECTED ABSOLUTE ALTITUDE

PART 1

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Regardless of what type of instrument is used, all altitude readings have to be corrected for a number of reasons. Here is first a theoretical summary of the nessecary corrections. Then follows a description of the procedure to follow when calculating the true geometrical altitude from the altitude indicated by an altimeter or in a barogram. Finally we will try to assess the overall total error in the altitude calculation.

A. THE THEORY

1. Internal temperature correction

Any instrument used must be corrected for the temperature in the instrument. The temperature in the mechanical or electronic parts of the instrument have an effect on altitude indication. This is usually corrected in the instrument and any remaining error is included in the correction chart for each individual instrument.

2. Instrument correction

Each instrument must have a calibration chart showing the correction to be applied as a function of indicated altitude. This correction may change and therefore the instrument has to be calibrated at regular intervals, usually every year, and a calibration chart must be supplied by an approved instrument workshop.

3. Pressure correction

An aneroid barograph is usually set at standard pressure and therefore the indication has to be corrected for actual barometric pressure at the position and time for the record attempt.

4. Ambient temperature correction

Finally the reading has to be corrected for the actual atmospheric temperature distribution at the time and location of the flight. This correction must not be confused with the correction for the temperature of the instrument mentioned above.

THE STANDARD ATMOSPHERE

All altitude instruments are designed to indicate altitude in a standard atmosphere. The actual temperature in the atmosphere can vary considerably from this ideal condition. The standard atmosphere is based on a pressure at sea level of 1013,25 hPa and a temperature of +15°C. The temperature at 11 000 m is -56,5°C. From 11 000 to 20 000 metres the temperature in the standard atmosphere is constant -56,5°C. The above figures mean that the surface temperature is +15°C and decreases with 6,5°C per 1 000 metres up to 11 000 metres. Any variation from these temperatures in an actual case makes it nessecary to apply a correction to the altitude reading.

5. Calculation of the temperature correction

The temperature correction can be calculated with the help of Gay-Lussac's law. He successfully claimed that the volume of a gas is proportional to the absolute temperature of the gas or,

$$V/T = k$$

"V" is the volume of the gas
"T" is the absolute temperature
"k" is a constant.

If we study a column of air with the base area A and the height H we can write the formula as,

$$A \times H / T = k$$

If we look at the standard atmosphere and compare it with the actual conditions, k is still constant and if we look at a column of air with the same base area in both caes, A will also be the same and all variables that remain will be H and T.

With index $_S$ for the ICAO STD and index $_a$ for the actual ambient air we get the following formula,

$$H_S/T_S = H_a/T_a$$

Or more convenient,

$$H_a = H_S \times T_a/T_S$$

The temperature in the atmosphere is varying. If we study the air mass in small vertical pieces we can write the formula as follows,

$$H = H_c \times T_{ma}/T_{ms} \qquad \text{Formula 1}$$

Or if we prefer to calculate the difference in temperature,

TEMPERATURE CORRECTION FORMULA

$$H = H_c \times [1 + \text{Average}(T_a - T_S)/T_{ms}] \qquad \text{Formula 2}$$

$H =$	the true geometrical height from mean sea level
$H_c =$	the altitude indicated on the instrument but calibrated for instrument errors and actual barometric pressure (QNH)
$T_a =$	actual atmospheric absolute temperature
$T_S =$	standard atmospheric absolute temperature

DEFINITION OF QNH

QNH is defined as "the pressure at mean sea level (MSL) calculated from the barometric pressure at ground level using the ICAO STD for the part between MSL and ground level".

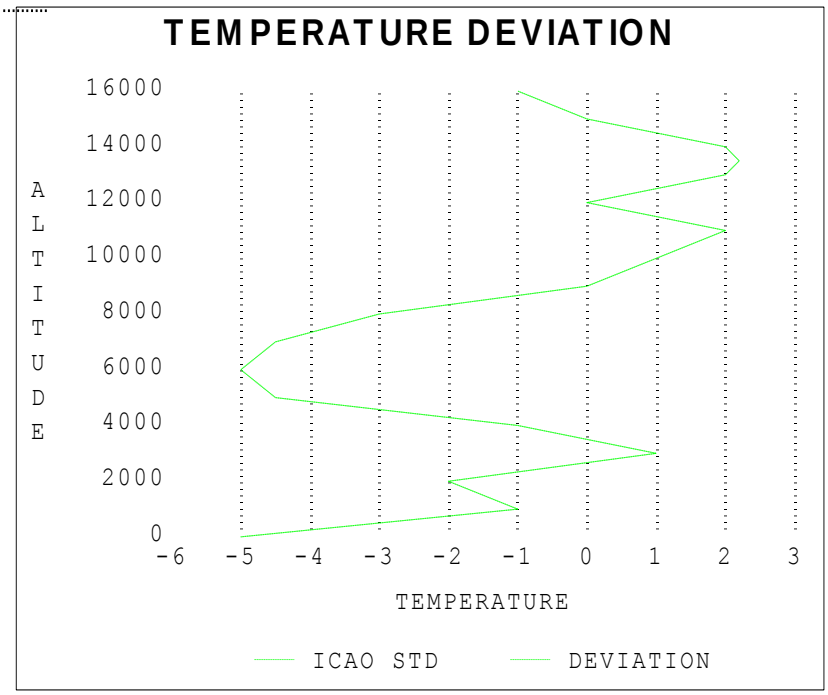
An altimeter set to QNH will therefore indicate true geometrical altitude when at ground level (assuming no instrument error). This is of course of interest to aviators in everyday life. They are interested in terrain clearence. In fact they are so interested that they add a correction of 4% per 10°C deviation from ICAO STD: We will soon learn why.

However the definition of QNH is of interest to those claiming a record. QNH has to be used when calculating the pressure correction. It also plays a part when calculating the temperature correction. If the QNH is obtained from a station at a high elevation the portion of altitude from MSL up to the elevation of the QNH station shall be disregarded when calculating the temperature correction as they already assumed a ICAI STD atmosphere up to the station elevation. This becomes important if we obtain the QNH from a station at say above 1000 metres. More about this later.

OBTAINING DATA FOR TEMPERATURE CORRECTION

The temperature correction must be based upon reliable data from the actual atmospheric conditions at the time when the aerostat reached the peak altitude. The meteorological services around the world sends up balloon-sondes from various places at fixed times, usually at noon and midnight UTC. Therefore it is possible to obtain a temperature diagram from a station not too far from the place of the record. At least in Europe the stations sending up balloon-sondes are sometimes up to 500 km apart. Nevertheless it is possible to obtain a diagram that is representative for the air mass at the location of the record altitude. If we can assess the temperature deviation from ICAO STD with a margin of 1° the formula 2 will show us that we are within 0,4%. The requirement is a total error of 1%.

The actual temperature distribution is usually obtained from the meteorological stations in the form of a table or a graph. The graph usually shows the ICAO STD temperature as a more or less vertical line and the actual temperature is snaking to the left (-) or right (+) or sometimes crosses the ICAO STD. Regardless of the presentation it is useful to make a simple diagram.



Calculate the shaded area from ground level up to the peak altitude. Area to the left of STD line is negative. Area to the right is positive. Use a paper with millimetre or 5 millimetre squares. Take the total area to the right and decrease by the total area to the left. Divide result by the distance on the paper from ground level up to peak altitude. See how many degrees the result of this calculation corresponds to. This number of degrees is the average temperature deviation Average(T_a - T_S) and may be positive or negative. Then use formula 2.

B. PROCEDURE TO FOLLOW

1. Required data

a Altitude reading from barogram or printout from electronic barograph or photo of altimeter at claimed altitude.
b Time and location of claimed peak altitude.
c Calibration chart for barograph or altimeter.
d QNH (barometric pressure) from one or two stations close to the location and time of the claimed peak altitude.
e Radiosonde diagram or equivalent.

All documents must be signed by the official observer or other authorized person.

2. Correction for instrument errors

a Find the indicated peak altitude registered in 1a. Check that the value is within the approved range for the instrument.

b The calibration chart or diagram (1c) will show the correction as a function of indicated altitude. Check that the calibration was made according to the time limits in the Sporting Code (No rule yet but should be within one year before the attempt or one month after the attempt). Check that the calibration is valid for the instrument actually used.

c In the calibartion chart, find the correction for the peak registered altitude.

d Apply the correction from the calibration chart.

$$H_{cal} = H_i + h \qquad \text{Formula 3}$$

H_{cal} is the calibrated altitude
H_i is the indicated altitude
h is the correction for instrument error.

3. Correction for QNH differing from ICAO STD

a From (1b and 1d) find the QNH at the location and time of the peak registered altitude. Sometimes an interpolation between two or more values are required as it may be difficult to find official QNH for the time and location. For altitudes below 5000 metres it is recommended to find the correct QNH with a tolerance of ±0,5 hPa. This corresponds to an altitude error of 4 metres. For higher altitudes a tolerance of ±1,0 hPa is sufficient.

b For QNH above 1013,25 the correction is positive.
For QNH below 1013,25 the correction is negative.

The average pressure gradient varies with altitude. We are concerned with the pressure gradient close to the 1013,25 hPa surface. For QNH between 1035 and 1013,25 the pressure gradient is 0,121 hPa/metre. For QNH between 1013,25 and 990 the pressure gradient is 0,118 hPa/metre.

c For QNH above 1013,25 the corrected altitude is

$$H_c = H_{cal} + (QNH - 1013{,}25)/\ 0{,}121 \qquad \text{Formula 4a}$$

For QNH below 1013,25 the corrected altitude is

$$H_c = H_{cal} + (QNH - 1013{,}25)/0{,}119 \qquad \text{Formula 4b}$$

H_c is indicated altitude corrected for instrument errors and pressure

H_{cal} is calibrated altitude from paragraph 2

QNH is actual surface pressure in hPa

4. Temperature correction

a Calculate T_{ms}, the average absolute temperatur in ICAO STD atmosphere. For altitudes below 11000 metre, this is simply the ICAO STD temperature at half altitude plus 273,15 which is 0°C converted to °K. Use the following simple formulas,

$$T_{ms} = 288{,}15 - H_c/2000 \times 6{,}5 \qquad \text{Formula 5a}$$

(For peak altitude below 11 000 m)

$$T_{ms} = (11000 \times 252{,}4 + (H_c - 11000) \times 216{,}65) / H_c$$ Formula 5b

(For peak altitude above 11 000 m)

T_{ms} is the familiar average absolute temperature in ICAO STD

H_c is the corrected peak altitude

216,65 is the absolute temperature at 11 000 metres in ICAO STD

252,4 is the average absolute temperature below 11000 metres in ICAO STD

288,15 is the absolute temperature at sea level in ICAO STD

6,5 is the temperature lapse rate per 1000 metres in ICAO STD up to 11 000 metres

b Now calculate the temperature difference from ICAO STD in the actual atmosphere and insert the values in Formula 2.

Example: The average difference in temperature is -10°. The peak altitude corrected for instrument error and pressure difference was 8 000 m.

Formula 2 can be written: $H = H_c \times f_T$

The correction factor $f_T = 1 + \text{Average}(T_a - T_s)/Tms$

The absolute temperature at half top altitude is 262,15°K in the standard atmosphere. (Formula 5a).

Therefore in this case $f_T = 1 - 10/262,15 = 0,9619$

and $H = 8000 \times 0,9619 = 7\ 695$

This almost 4% reduction if the atmosphere is 10° colder than ICAO STD is a familiar rule-of-thumb to the proffessional pilot. His altimeter will indicate 4% too much in these circumstances and he will make a corresponding correction to his approach altitudes.

If we want the calculation to be painfully correct we now insert the resulting altitude, 7 695 metres, in formula 5a and do it all over again. The reason is that we used the uncorrected altitude to get the average temperature in the ICAO STD. This is of course not quite correct. If we do the calculation again we will get a slightly different f_T. The resulting corrected altitude will in this case be 7 696 metres. A difference of one metre and a small error compared to the overall tolerance. Hardly worth the effort. In fact we should also use the new altitude to find the average temperature in the actual atmosphere and we may get back to 7 695 metres.

For high altitudes it is sufficient to assess the difference in average temperature within 1°K. The resulting error will be less than 0,4%. The effect on overall error will be shown later.

Two other corrections may be considered however.

If the temperature diagram for the actual atmosphere shows a strong low level inversion and the peak altitude was reached at a time when the inversion layer had disappeared, then the inversion layer should be disregarded when calculating the average actual temperature.

If the QNH was obtained from a station at a high elevation and the peak altitude was also obtained over high terrain, then the temperature difference shall only be calculated from ground level up to the peak altitude but the difference shall then be averaged out over the full altitude range. The reason is that the part below ground level is already considered to be in standard atmosphere as mentioned in the definition of QNH. See chapter A.5.

Example: The QNH is obtained from a station at 3 000 metres. The peak altitude is 10000 metres. The average temperature difference from 3 000 to 10 000 metres is 10° below ICAO STD.

Then the average difference is:$10 \times (10\ 000-3\ 000)/10\ 000 = 7$

The difference in reduction factor f_T will be:

0,9609 for 10° resulting in a corrected altitude of 9 609 metres

but 0,9726 for 7° resulting in 9 726 metres.

A significant difference.

C. CALCULATION OF THE PROBABLE ERROR

The overall error consists of several parts. Some errors are constant throughout the whole altitude range while some are a percentage of the peak altitude. The probable overall error is the square root of the sum of the squares of the part errors. Let us examine the parts one by one.

1. Reading error and System error. (dR)

A barogram can only be read to within 10 metres and then only with the help of a magnifying glass. Otherwise the error will be around 25 metres. An altimeter can usually be read within 10 metres.

If the peak altitude is registered from a radar transponder the reading is subject to a tolerance of usually 100 feet as the transponder only gives even 100 feet registrations.

If an electronic barograph is used the accuracy is usually found in the manufacturers handbook and is typically 10 - 15 metres througout the range of the barograph.

2. Calibration error. (dC)

If the calibration correction is derived from a barogram then this is subject to the same error as when reading any barogram. This part of the error is constant. The rest of the error depends upon the shape of the correction curve. If the correction to be applied is derived by interpolation between two readings, an additional error may occur. We assume that the calibration equipment is correct.

If an electronic barograph is used the correction may not be a smooth curve. It may be nessecary to apply the maximum error as a constant error throughout the whole measuring range.

3. Error in the pressure used for calculation. (dP)

It should be possible to obtain the QNH within 1 hPa. For records in the smaller categories where the peak altitude is just a few thousand metres it may be nessecary to get within ½ hPa. It should be possible as flights in these categories usually are short and the uncertainty in time and/or position is insignificant. A 1 hPa error is equivalent to 8 metres.

4. Error in the actual average temperature. (dT)

This is probably the largest error source, but normally it is possible to assess the average deviation from ICAO STD within 1°K.

A one degree error results in a 0,4% error in the altitude.

5. Summary

Example:

The reading error (dR) is 25 metres
The calibration error (dC) is 25 metres
The pressure error (dP) is 4 metres
The temperature error (dT) is 0,4% and the final calculated altitude is 10 515 metres.

The overall error is in this case:

$$\sqrt{(25^2 + 25^2 + 4^2 + 42^2)} = 55$$

The resulting altitude will in this case be 10 515 ± 55

This error is about 0,5% and well within the 1% margin stated in Sporting Code Section 1, 4.5.5.

Should the resulting error be over 1%, we have to try to make a better assessment of the individual errors and then we will try to eliminate some errors by using better data. If that does not reduce the overall error

below 1%, we have to make the best possible calculation and then reduce the altitude claimed by the error margin according to Sporting Code, Section 1, 4.5.5.

D. UNITS OF MEASUREMENTS AND CONVERSION FACTORS

Metric units have been used throughout this report. If other units are used, the following conversion factors should be applied before the formulas in this report are used.

Feet to metres: multiply by 0,3048
One foot is equal to 0,3048 metres

Inches HG to hPA: multiply by 33,86388 (33,8653)
29,92 corresponds to 1013,25

°Farenheit to °Celcius: reduce by 32, multiply by 5, divide by 9
32°F = 0°C, -40 °F = -40 °C.

°Farenheit to °Kelvin: Convert to °Celsius and add 273,15

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Changes compared to 1st edition February 1993

Mean substituted with average
ISA defined up to 20 000 metres
(Tma - Tms) substituted with Average(Ta-Ts)
Conversion factor Inches HG to hPA changed

Subjects for future additions to the report

Effect of humidity
Geopotential vs Geometric altitude
Calculating direct from a Balloon Sonde table