GEOMAGNETIC MEASUREMENTS FOR AERONAUTICS

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1. Introduction

Anybody who has been on the open sea without visual clues for orientation or, worse, trapped in the dark by a sudden failure of the lighting system, knows how easy it is to feel lost. If a navigation system is available, then there is a means to calming down and finding your way.

The geomagnetic declination allows one to do just that: navigate and find a way to destination with the aid of a specialized instrument called a "magnetic compass".

The principle function of the compass is to indicate the North direction on a graduated horizontal disk. This disk is free to rotate around a vertical axis and is actually moved by the torque exerted by the horizontal component of the geomagnetic field on a magnet inside it. The compass indicates the direction of Magnetic North, which is different from True North. The difference between the two directions is the magnetic declination.

For the compass to work accurately as a navigation device, various conditions must be met:

- The compass must work properly.
- The compass must not be perturbed by artificial magnetic fields or it must be compensated for them.
- The horizontal component of the geomagnetic field must be strong enough to drive the compass needle (a condition not met at and near the poles).
- Magnetic declination must be known at the location of the compass in order to determine True North from Magnetic North.

Aeronautics uses the magnetic compass extensively as a navigation tool. Of course, aircraft have other navigation devices, but the compass is still

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J.L. Rasson and T. Delipetrov (eds.), Geomagnetics for Aeronautical Safety, 213–230.

the primary direction indicator on small aircraft and is a very important back-up device on larger planes. Airport infrastructure must include the elements required to perform an aircraft check, and to calibrate or compensate onboard compasses. Airport infrastructure quality is not only nice buildings and runways, it also relates to more sophisticated facilities like the knowledge of the correct and up to date value of the magnetic declination.

This paper will focus on how the geomagnetic community can help aircraft operators and airport authorities with the proper operation and certification of magnetic compasses on board aircraft they own or those that pass through their facilities.

The list of services and products provided by the geomagnetic community follows:

1. Compass rose certification.
2. Runway azimuth determination.
3. Supply of isogonal information and maps.
4. Supply of magnetic declination data.

Compass rose certification is discussed extensively here, because the procedure is less well known among observatory personnel and if not done properly, becomes a very lengthy process as large numbers of measurements need to be made. Runway azimuth determination is more straightforward. They will be reviewed briefly.

Before starting the discussion of geomagnetic services and products, definitions of often used scientific and technical terms related to the subject of geomagnetism and magnetic navigation are defined:

- ***Azimuth***: The angle a direction makes from true North.
- ***Magnetic meridian***: The vertical plane containing the geomagnetic vector.
- ***Magnetic declination***: The azimuth of a horizontal direction in the magnetic meridian.
- ***Magnetic variation***: This expression is used instead of "magnetic declination" in maritime and aeronautical sectors.
- ***Secular variation***: The change of the magnetic declination over time at one location; usually expressed in arc minutes/year.
- ***Compass rose***: The graduated circle of the compass; by extension, the pattern painted on the compass calibration pad at an airport, or the pad itself.
- ***VOR***: Acronym for "VHF Omni directional Ranging"; an electronic aid located at various spots in the country for assisting in the navigation of aircraft.

- ***Heading***: The azimuth of the trajectory (speed vector) of a moving vehicle
- ***Isogonal map***: Map displaying the spatial distribution of the value of the magnetic declination as contour lines.
- ***Hard and soft magnetism***: "hard" refers to a magnet-like durable magnetization, which will remain after any external field has been removed. "Soft" refers to a magnetization existing only when an external field is applied.

2. Motives – Geomagnetism and the Commercial Sector

Surely the main motive for a magnetologist is the scientific curiosity. The investigation and the discovery of the internal and external magnetic processes going-on in the Earth and its physical manifestations are what push us all forward. However, the collaboration with the aeronautical community has its rewards also and we give below some additional reasons for going into this activity.

The benefits for an observatory of commercially providing “services and products” are many and the experience and past history show that combining scientific and socio-economic activities really leads to a win-win situation. Here is why:

- Customers need and are ready to pay for what is delivered. The demand for products and services justifies the existence, ventures, and expenses of the geomagnetic community. This justification is regularly required by the political world, which often provides observatories with funding. They regularly assess the usefulness of observatories and hence their return on their investment weighing the money spent in maintaining an observatory against the service provided.
- The commercial relationship may actually result in the delivery of better services or products to the customer. Since there is a financial transaction, the observatory personnel may feel a stronger need to pamper the customers by providing highly accurate data, detailed customer information, and post-delivery services.
- An observatory delivering data and services free of charge may be unhappy if it later finds that it has been sold to a third party. Maybe you remember this advertisement for magnetic field sensors from Honeywell: "Buy this sensor, get the magnetic field for free". The magnetic field is free for anyone to observe, but the use of this information by a Honeywell sensor implies the coordinated and continuous effort of the whole geomagnetic observatory community, which comes at a cost.

- The commercial delivery of data and/or services allows the observatory to earn money. This is important since funding from governments is generally on the decline.

3. Inventory of products and services

3.1. COMPASS ROSE CERTIFICATION

3.1.1. *Compass Rose*

A compass rose or compass calibration pad is a spot on the airport grounds suitable for performing aircraft compass swings. Swings involve rotating the whole aircraft to known magnetic azimuths and, for each orientation, observing the compass deviations.

The compass needle directional indication is affected by ferrous, metallic components within the aircraft. To reduce the deviation effect, the aircraft compass must be checked and possibly compensated periodically by adjusting compensating magnets. This procedure is called "swinging the compass". During compensation, the compass is checked at, say, 30° increments. Adjustments are made at each of these points, and the difference between the magnetic heading and the compass heading is shown on a compass correction card (see Figure 112). When flying compass headings, the pilot must refer to this card and make the appropriate adjustment for the desired heading.

FOR	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
STEER	359°	30°	60°	88°	120°	152°	183°	212°	240°	268°	300°	329°

COMPASS CORRECTION CARD

Figure 112. Example of a compass correction card.

For an airport compass rose to be useful, the following elements are required:

- A large circular area devoid of magnetic perturbations and accessible to aircraft must be maintained. The horizontal dimensions of the largest aircraft that will be swung will determine the diameter of the area.
- Magnetic azimuth markings must be applied to this area so that the aircraft can be precisely oriented along them (Figure 112). Due to secular variation; the magnetic azimuth markings must be periodically updated.

- The true North direction should be marked.
- The compass rose must be certified for use.

The compass rose can be certified in a specified class if the magnetic perturbations, which affect magnetic declination, produce deviations (from a spatially averaged mean) that remain below a given value.

3.1.2. *Compass Rose Construction*

If there is no compass rose at the airport already, a location should be selected for one. A spot that is likely to be non-magnetic, that can accommodate the dimensions of the largest aircraft should be chosen with the aid of the airport staff. A special pad may be constructed for the compass rose, or the end of an infrequently used runway can be reserved (Figure 113).

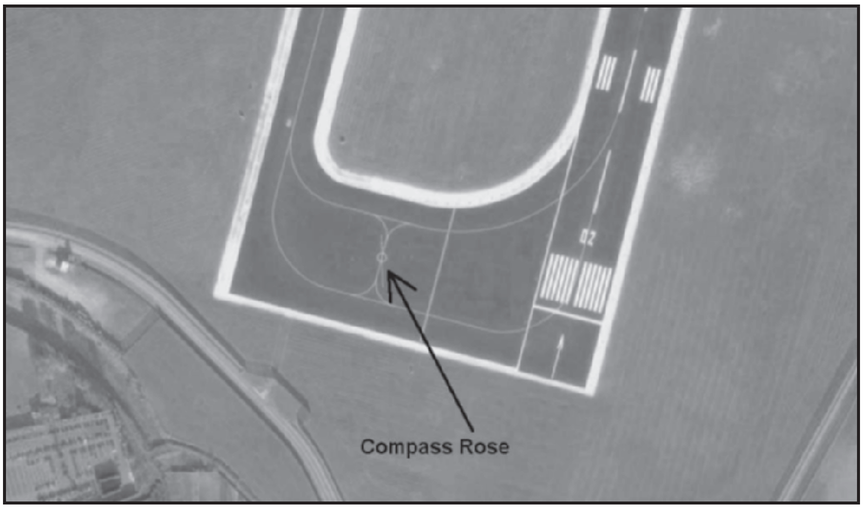

Figure 113. The compass rose at this international airport has been implemented near the end of the less frequently used runway.

When looking for a suitable site for a compass rose, before doing any measurements, an investigation of the site should be made to check for the presence of hard and/or soft magnetized bodies likely to give magnetic perturbations. Iron rebar, present in reinforced concrete, is often used for building runways and produces significant magnetic perturbations. Iron conduits for cables or fluids, located underground are also common sources of magnetic perturbation. Stepper motors inside guided cameras and other robotics often contain hard magnetized elements like magnets, and should be avoided.

When selecting a new compass rose site, and before starting expensive construction work, it is necessary to run a proton magnetometer survey, in order to determine the magnetic hygiene of the underlying terrain. A proton magnetometer is used first, because it is much faster to operate. Its output however is the modulus of the magnetic field and not magnetic declination. (The Tomlinson equation of section 3.1.7 on page 222 is useful to link both quantities.) The results of this first survey indicate if construction and certification can proceed or if another site must be found.

The choice of the spatial sampling interval is a delicate point in measuring the spatial features of the compass rose. Most authors (Civil Aviation Authority UK, 1993; Loubser, 2005) recommend a spatial sampling of 6 m, but some worry (Crosthwaite, 2005) that magnetic anomalies may “hide” between the 6 m separations of the measurement points. A solution exists if a closer spacing is chosen for the proton magnetometer measurements than for the declination measurements, especially if there is reason to believe that sharp, short wavelength magnetic perturbations exist in the underlying terrain. An example of spatial sampling is given in Figure 114.

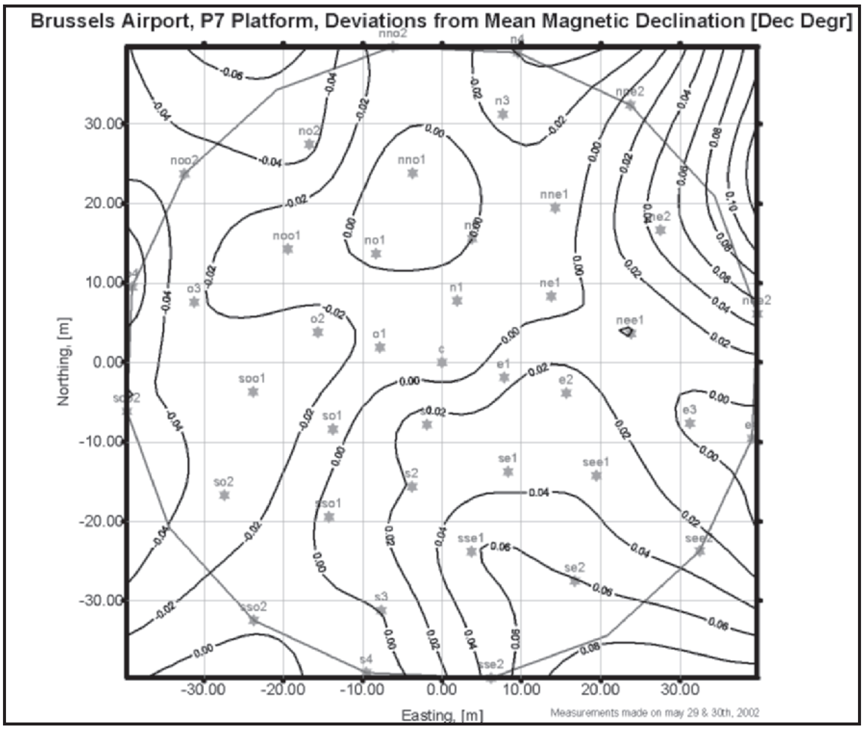

Figure 114. The compass rose and its different measurement stations as implemented at the Brussels International Airport. The isogonal lines show the deviations dD_i from the average value. According to this dD_i distribution, this rose qualifies for a Class 1 certification.

Some electronic navigation and landing aids produce strong electromagnetic radiation likely to perturb sensitive magnetic instrumentation, notably the proton magnetometer. The Instrument Landing System (ILS), for instance, sends out a powerful beam making valid proton precession measurements impossible in front of it. Therefore, it is not a good idea to establish a compass rose in close proximity to those facilities.

3.1.3. *Compass Rose Certification: Principles and Classes*

In an airport, a compass rose certification must be performed regularly in order to evaluate the magnetic cleanliness of the site and for keeping track of the changing magnetic declination.

Therefore the magnetic declination D_i is measured at the N points of a grid covering the compass rose with the spatial separation/sampling agreed upon (generally 6m).

Those N measurements are corrected for the diurnal variation δD_i, thus providing N values D^*_i defined by:

$$D_i = D^*_i + \delta D_i ,$$

and the arithmetical mean is taken:

$$\overline{D} = \frac{1}{N}\sum_{i=1}^{N} D_i^* .$$

The deviations, with respect to the spatial mean dD_i , are then computed:

$$dD_i = D_i^* - \overline{D} .$$

The extremes dD_{max} and dD_{min} in the dD_i series are then easily found and the maximum deviation with respect to the mean value is defined:

$$MaxDev = \frac{\left(dD_{\max} - dD_{\min}\right)}{2}$$

The quantity *MaxDev,* expressed in units of degrees, is used in aeronautical quarters for evaluating the Compass Rose magnetic cleanliness. According to the *MaxDev* values, compass roses are divided into different classes with corresponding certification standards:

- Class 1 certification: MaxDev < 0.1°
- Class 2 certification: MaxDev < 0.25°

It should be emphasized that the natural, daily variation of the magnetic declination is about 10 arc-minutes (= 0.17°) on a quiet day in the mid-latitudes, and is even more elsewhere. This is why the daily variation of the magnetic declination should be removed from the D_i series, lest it introduce an unacceptable bias in the magnetic cleanliness data.

There are different approaches for measuring and certifying compass roses. The differences in methodology stem from the way the actual declination measurements are carried out (what instrumentation is used) and the way the diurnal variations are removed from the data. From section 3.1.4 to section 3.1.7 we review the different procedures known to us for performing the compass rose certification task.

3.1.4. *Compass Rose survey with the DIflux magnetometer and observatory data reduction*

The DIflux magnetometer is used almost universally in magnetic observatories and for repeat station work to make magnetic declination measurements. This instrument, essentially a non-magnetic theodolite equipped with a fluxgate sensor mounted on the telescope, allows error free measurements of the geomagnetic angles like declination and inclination. Additionally, it can easily be used for geodetic azimuth determination using astronomical sightings on the sun or stars (Rasson, 2005).

To reduce the diurnal variation of the compass rose data, using observatory data, a magnetic observatory must be close by. The observatory must be close enough so that the diurnal variation measured there is similar (within a few arc-minutes) to the one experienced at the airport. Each D_i measured on the compass rose is tagged by the time stamp t_i. Then $D_{obs}(t_i)$ is the declination measured at the observatory synchronously with the measurement D_i, and δD_i is the diurnal variation (supposed to be similar at both the observatory and the airport). We define the constant D^*_{obs} as the observatory data corrected for daily variation by:

$$D_{obs}(t_i) = D^*_{obs} + \delta D_i.$$

If we define:

$$\Delta_i = D_i - D_{obs}(t_i) = D^*_i + \delta D_i - [D^*_{obs} + \delta D_i] = D^*_i - D^*_{obs},$$

we see that this quantity is free from time variations and contains only the spatial information about the magnetic cleanliness of the compass rose. Δ_i can be used in lieu of D^*_i in the relationships of section 3.1.3 for computing the quantity *MaxDev* since the removal of the mean will eliminate the constant D^*_{obs}.

A distant azimuth mark should be chosen so as to be visible from all stations on the compass rose. This azimuth will be measured from the center station of the rose. Since the geometry and the orientation of the other station points is precisely known, the azimuth of the distant mark can be computed from the center station azimuth. This will allow the full measurement of the declination on all stations with only one azimuth measurement task to be performed.

The final product delivered to the airport authorities will be a list of the measured stations, the value of their dD_i's, and an isogonal map similar to the one in Figure 114. According to the results of the survey and the value of the MaxDev parameter, the report may also contain a certificate awarding a class 1 or class 2 status to the compass rose.

3.1.5. *Reciprocal sighting with two declinometers*

This procedure is described in aircraft instrument calibration manuals such as the CAP562 leaflet (Civil Aviation Authority UK, 1993). It has been accurately described in a to-be-published IAGA guide (Loubser, 2005) where a detailed analysis and error budget can be found. The procedure is based on the principle of taking reciprocal bearings with two declinometers (or datum compasses).

One declinometer is set up in a fixed position throughout the survey, while the second one is moved from point to point on the grid of survey points on the compass rose. At each point the two declinometers are simultaneously aligned with magnetic North and readings are taken. The two declinometers are then aligned with each other and readings are again taken of the bearings (reciprocal bearings). The two readings, taken in opposite directions, will differ from each other by 180°. Therefore, if 180° is subtracted from one reading, and the two readings are then subtracted from each other, this difference should be a measure of the effect of local magnetic disturbances of geological or other origin. If the readings are taken at a time when the magnetic field is disturbed (magnetic storm or daily variation), the readings on the two declinometers will be affected identically if they are taken within one minute of each other. Thus, when the difference between the two readings is taken, this disturbance effect is cancelled.

This procedure obviates the need for a neighboring magnetic observatory and the subsequent correction of the survey data for the daily variation. It also obviates the need for a distant azimuth reference mark during the survey. Its use is therefore to be advocated in regions devoid of magnetic observatories. However, it imposes the availability of 2 dedicated observers and 2 dedicated and expensive declinometers, not part of the standard equipment at a magnetic observatory.

3.1.6. *USGS method*

This procedure is also suitable when nearby magnetic observatory data is not available. It is normally performed with a datum compass, but could also be done with a DIflux magnetometer. The diurnal variation is estimated by performing a sequence of measurements over the compass rose points including frequent re-measurements over the same center point. These closure measurements at the center point allow the extraction of daily field variations during the whole measurement task and its subsequent correction. This method requires one observer and one helper. The helper is employed for several hours and is supplied by the airport.

The procedure is fully explained in the paper by Berarducci in this volume.

3.1.7. *Tomlinson method*

This procedure, invented by L. Tomlinson of Eyrewell Observatory in New-Zealand, relies on the measurement of the sole field modulus. Therefore the use of the quick proton magnetometer survey allows a rapid estimation of the magnetic cleanliness of the compass rose.

By using the assumption that the magnetic anomalies underlying the compass rose have the simple structure of a magnetic dipole, Tomlinson (Tomlinson, 2000) arrives at a relationship linking the field modulus dF_i and the magnetic declination dD_i deviations required for the MaxDev parameter computation as explained in section 3.1.3 on page 219:

$$dF_i = \left|0.858 \times H \times \sin I \times \sin(dD_i)\right|,$$

where H is the horizontal field component and I is the magnetic inclination. Therefore, the MaxDev parameter can be replaced by a $MaxDev_F$ parameter valid for a single airport, according to the values of H and I there (Table 24).

Table 24. Values of the parameter $MaxDev_F$ in nanoteslas for different locations (year 2004). The Class 1 certification corresponds to magnetic declination deviations smaller than 0.1° and the Class 2 for deviations smaller than 0.25°.

Location	I [°]	H [nT]	$MaxDev_F$ Class 1 [nT]	$MaxDev_F$ Class 2 [nT]
North magnetic Pole	90	0	0	0
Resolute Bay CA	88.2	1790	3	7
Dourbes BE	65.5	19970	27	68
Skopje MK	58.7	24290	31	78
Ohrid MK	57.7	24740	31	78
Kanoya JP	45.0	32780	35	87
Huancayo PE	1.1	25950	1	2
Kakadu AU	-40.3	35440	34	85
Eyrewell NZ	-68.6	21110	28	70
Terra Nova Bay Ant.	-83.0	7830	11	29
South magnetic Pole	-90	0	0	0

Obviously, a problem exists for equatorial sites where sinI ~ 0, (which puts the parameter $MaxDev_F$ at an unrealistically low level). The Tomlinson method is not valid in regions near the magnetic equator (Tomlinson, personal communication). At polar sites where H ~ 0, the same low value is obtained, but a compass should not be used there anyway.

It should be mentioned that the Tomlinson procedure has been accepted by the New Zealand Civil Aviation Authority as the basis for an alternative method of testing aircraft compass roses (Tomlinson, 2000).

In any case, the Tomlinson method can be used over a well delimited region as a way to:

- get alternative information on the magnetic cleanliness of the compass rose,
- get higher spatial resolution than other methods (Crosthwaite, 2005) thanks to its quicker measurement protocol,
- obtain guidance when surveying using a different procedure.

keeping in mind that the Tomlinson procedure is not valid in regions situated on the magnetic equator.

3.2. RUNWAY MAGNETIC AZIMUTH DETERMINATION

At the ends of aircraft runways, large 2 digit number markings are painted in white. These markings represent the magnetic azimuths of the runways in units of 10 degrees. They equal the number a pilot should read on his magnetic compass when his aircraft is correctly aligned with the runway during the landing procedure. Figure 115 illustrates such runway markings.

Figure 115. The beginning of runway 01 at Tete Airport (Mozambique). The number 01 is painted in enormous digits so that a pilot can clearly read it during his landing procedure. The painted number equals the magnetic azimuth of the runway in units of 10 degrees, i.e. the magnetic azimuth of this runway is 10°.

Table 25 gives the markings of several airports' runways in Mozambique, where the magnetic declination is high and varies considerably from place to place. Geodetic and magnetic azimuths are quite different and require regular updates.

Table 25. Listing of the main airports in Mozambique. The geodetic azimuth, magnetic azimuth, and the runway markings are valid for December 2004.

Airport	Geodetic Azimuth [dec. deg.]	Magnetic Azimuth [dec. deg.]	Magnetic Azimuth [runway marking]
Maputo int.	28.890	47.1	5
Pemba int.	340.741	347.0	35
Nampula	46.064	53.9	5
Lichinga	70.626	75.2	8
Tete	1.370	8.7	1
Beira int.	104.940	116.5	12
Quelimane	354.191	364.1	36

3.2.1. *Measurement Procedure of the Magnetic Azimuth*

The magnetic azimuth is the angle between Magnetic North and the runway axis. Figure 116 shows how to measure the magnetic azimuth of an airport runway with a DIflux magnetometer.

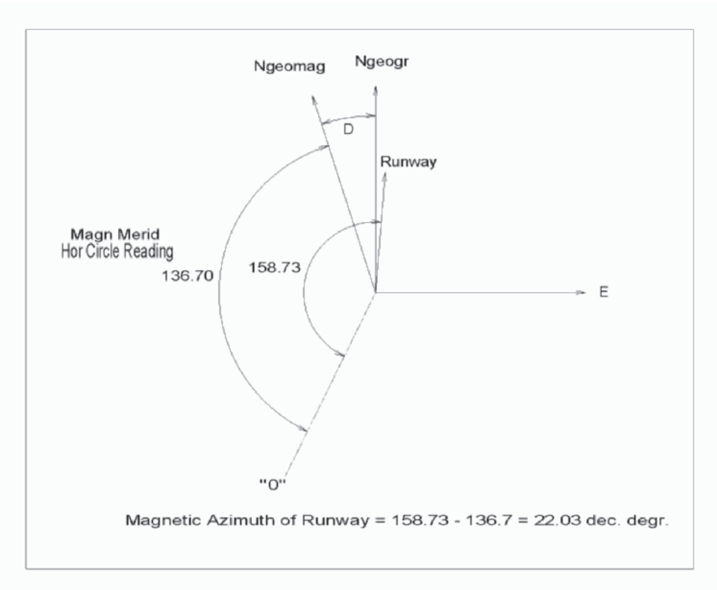

Figure 116. Magnetic azimuth measurement with a DIflux magnetometer. The indicated angles are the readings of the horizontal circle ("0" marks the direction of the starting graduation).

The tasks to be performed for runway azimuth determination are:

1. Perform a proton magnetometer survey of the runway location where the magnetic azimuth will be determined. If the runway is too magnetic, refer to section 3.2.2.
2. Determine trace of the direction of the magnetic meridian, T_{magmer}, by using the DIflux horizontal circle. The traditional 4 position DIflux D-measurement protocol is used with the instrument telescope horizontal and the fluxgate normal to the magnetic meridian. The trace is the same as would be used for positioning the DIflux for an I-measurement.
    - Measure the trace of the runway direction, T_{runw}, by sighting the runway center-line markings. An example of how to do such a sighting through the telescope of the DIflux is shown in Figure 117.
    - Compute the magnetic azimuth, $A_{mag,}$ of the runway:

$$A_{mag} = T_{runw} - T_{magmer.}$$

This procedure does not require the knowledge of the True North direction. Hence there is no need to perform astronomical, gyro, or GPS orientation measurements.

Figure 117. How to sight the runway center line markings through the DIflux telescope. A VOR antenna may be seen aligned with the runway at its terminus.

3.2.2. *Problem solving*

The situation is not always straight forward. Two complications can arise:

1. The runway is too magnetic to perform a valid determination of the magnetic meridian.
2. The runway is not straight or it is not completely flat. This happens often at smaller airports. Sometimes one end of a runway is not visible from the other because the central section is elevated.

To solve the first problem, it is necessary to determine the geodetic azimuth of the runway $A_{runw.}$ This can be done by performing a sun shot. Then, the magnetic declination must be measured on a magnetically clean spot close to the runway (this spot is often a repeat station point as well). The magnetic azimuth of the runway A_{mag} is then computed as:

$$A_{mag} = A_{runw} - D_{runw}$$

For solving the problem of item 2, one should measure the magnetic azimuth on both extremities of the runway, and report this particularity to the airport authorities.

Figure 118. Aircraft landing at the Pemba Airport (Mozambique) while observers are in the process of doing runway azimuth measurements. While the observers could take cover, there was no time to dismantle and evacuate the DIflux and its tripod, visible at the lower left.

3.2.3. *Observer's security*

Some airports, usually small ones, will allow normal airplane traffic while magnetic measurements are being made on the runways. Working on the runways can therefore be dangerous. Even if the airport closes its runway for a period of time while measurements are being made, unscheduled or unauthorised aircraft movement may take place as a result of an emergency. Therefore, while on the runway, observers should keep contact with the control tower of the airport via a portable, short wave radio or cellular phone. In the absence of a reliable warning system, the firing of runway lights is a good indicator of an imminent landing. In any case, when on a runway, it is good to regularly scan the surrounding skies to detect incoming aircraft.

When confronted with an imminent landing, while doing runway geodetic or magnetic measurements, it is best to dismantle the instrumentation, including the tripod, and move everything well off of the runway. This requires a second set-up with precise location of the tripod and levelling the DIflux magnetometer after the aircraft traffic has ceased. If there is no time to dismantle equipment before the landing occurs, the observer may decide to leave all equipment on the runway, and take cover. The Figure 118 shows such a situation.

3.3. SPATIAL MAGNETIC DECLINATION DATA FOR PREPARING MAPS AND HEADING LISTS

To create detailed isogonal maps, full magnetic declination surveys are required. The detail of the maps will of course relate to the spatial sampling of the survey measurements. Using recent, and some past magnetic repeat station data and by extrapolating normal field maps, it is possible to "refresh" obsolete surveys and to produce detailed, up-to-date, isogonal maps (see more on the computation of normal fields in this volume).

It is also possible to compute magnetic field components, and hence declination, from total field aeromagnetic surveys using Fourier techniques. A few magnetic repeat stations covering the total field survey must be observed or extrapolated at both the total field survey epoch and at the planned map edition epoch (Le Mouël, 1970; Schmidt and Clark, 1998).

With up-to-date maps, aeronautical and airport authorities can compute the magnetic headings which are necessary to fly from one airport to another. This information can then be printed on aeronautical maps. See Figure 119.

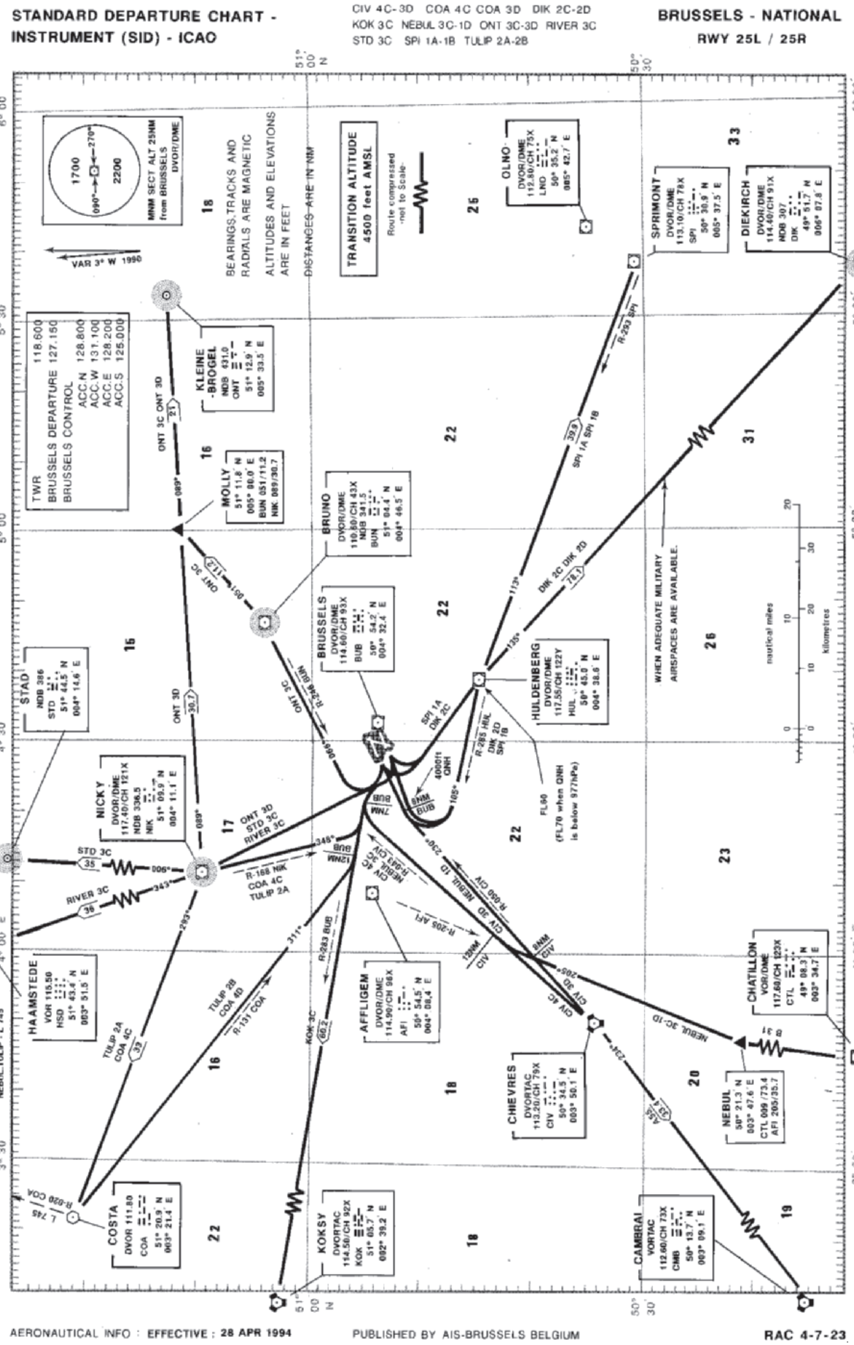

Figure 119. An aeronautical map (departure chart) with the indications of the magnetic headings to follow on the aircraft compass in order to connect from one airport to another.

3.4. SUPPLY OF DECLINATION VALUE (VOR STATIONS)

Extrapolated repeat station data is adequate to provide declination values at VOR stations. It can be extracted from an isogonal map. If no adequate isogonal map is available, or if the customer wants better than 0.1° accuracy of the magnetic declination at the VOR site, then an *in-situ* measurement session with the DIflux and Proton magnetometers should be made. The procedure is similar to that used at a repeat station. For the benefit of the geomagnetism program, the VOR declination measurement site could then become a part of a repeat station network.

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DISCUSSION

Question (J. Miquel Torta): Are these services compulsory for the airports? Are these services always done by geomagnetic observatory people?
How expensive can these kind of services be for the airport or in other words, how much can we charge them?
Answer (Jean Rasson): I am not sure if those services are compulsory in Spain, but I guess that in some countries they are by law. Anyway, an airport should be able to provide a compass rose calibration pad to its customers (the visiting aircrafts) as a basic service. Note that the recent increase in aircraft security awareness leads airport managers to a more rigorous approach in those matters.

I have heard that private companies are providing those services, but I never came across an advertisement for them. The armed forces of some countries have specialists in their ranks able to perform some of those services. But the vast majority of those services are provided by magnetic observatory staff.

About the charging policy for those services, many parameters come into play:

- Number of man/hour necessary to perform the task, including data reduction calculations back at the observatory
- Distance of airport to observatory
- Is the airport abroad?
- Is the airport a repeat station serving for your other researches?

In our case, for tasks performed at national airports, we charge the standard hourly rate according to the time spent and the rank of the staff involved, in addition to travel costs. When measuring abroad, we apply a flat rate (up to 8000 EURO) depending on the country where the work is to be done.