Capital Avionics, Inc.
8 Airport Road
Apalachicola, Florida 32320
PH: 850.370.1306
www.capitalavionics.com

AIRCRAFT HEADING SYSTEMS TEST AND MAINTENANCE – PART 1

OUTLINE

This document reviews the history and development of aviation compass/heading system maintenance practices. The objective is to focus on their accuracy and the efforts required to meet the requirements specified by OEMs and regulatory bodies. From this information decisions can be made, where applicable, to amend the current standards to better meet the current needs and those of the future.

HISTORY

Earliest aviation navigation consisted of the wet compass and pilotage. The wet compass consists of a bar magnet, suspended within a gimbal, and dampened with an inert liquid. Its accuracy was acceptable for circumstances where the pilot relied upon visual landmarks.

The wet compass soon became inadequate post WWI due to advances in aviation design and its replacement as the primary source of heading was the gyrocompass. Elmer Sperry designed an early gyrocompass for the marine environment, which was later, after redesign, used in aircraft. This basic system, consisting of a magnetic sensor (flux gate), providing long term magnetic heading to the gyroscope, which then provided a stable short-term heading to the pilot, became the cornerstone for aviation through three quartiles of the 20th century.

In the 1970s, new technology was beginning to be employed in aircraft. MEMS (Micro Electrical and Mechanical Systems) started to replace the iron spinning gyros and one example in the general aviation world was the Meggitt® AHRS installed in Piper Aircraft. This technology was followed by Laser Ring Gyros, Inertial Reference Systems and other advanced applications.

Today, there is an array of stable, reliable heading systems for most applications and budgets.

With that said, however, technological advancements in the testing, alignment and maintenance of compass systems have lagged their aircraft counterparts.

Developed as an adjunct to the wet compass, the sight compass is a standard wet compass that displays 180° from the actual heading to allow the technician facing the aircraft to view its heading. This technology, now more than 100 years old, is today one of the primary methods for determining aircraft headings of both the wet compass and gyrocompass systems.

The land version of the sight compass is the compass rose, which appeared with the sight compass as an alternative. It consists of painted lines at intervals, typically 30°, in an area deemed to be free of magnetic interference.

Capital Avionics, Inc.
8 Airport Road
Apalachicola, Florida 32320
PH: 850.370.1306
www.capitalavionics.com

The compass rose, together with the sight compass, comprise the industry's current options for most of the tests and alignment of aircraft compass systems.

There are additional methods which will be detailed here, but the fact remains that our industry relies significantly upon technology from the dawn of aviation.

The evolution of technical data and official guidelines for maintenance have been straightforward. Like evolution, however, you find earlier limitations and inaccuracies, without technical merit, embedded in the current standards.

One of the earlier, fundamental documents detailing the testing methods for aircraft compass systems is **Compass Swinging, Aircraft General Requirements for Mil-Std 765** published in 1962. Mil-Std 765A was published in 1967, with Notices 1, 2, 3, 4 and 5 in subsequent years. This standard was Cancelled, with no replacement, in 2014.

Mil-Std 765 et al was the precursor to subsequent OEM and official procedures and has been carried forward with surprisingly few changes over time.

In September of 2012, **AC 150/5300-13 Airport Design,** was released (now Change 1). It contains the latest FAA accepted procedures for compass rose construction and maintenance**.**

In August of 2017, the FAA released **AC 43-215 Standardized Procedures for Performing Aircraft Magnetic Compass Calibration.** This AC describes procedures for calibrating aircraft magnetic compasses.

Next, the above documents will be reviewed and their procedures analyzed for measurement accuracy and real-world acceptance by the aviation maintenance community. The goal is to establish a realistic and practical means of maintaining compass systems in today's aviation fleet and to prepare for future needs.

FUNDAMENTALS

We must first address the errors in measuring magnetic fields and their applications to aircraft. They are:

Local Environment

All compass roses must be tested for the uniformity of their magnetic fields to minimize errors in heading measurement. However, when testing aircraft using sight compasses, other sensing devices, and USGS calculated deviation values, the standard for what constitutes an acceptable environment becomes less strict.

It is therefore important that the testing location, at a minimum, meets the magnetic field tolerance specified by AC-150/5300-13, which is 0.5°, measured from 24" above the ground.

Capital Avionics

Capital Avionics, Inc.
8 Airport Road
Apalachicola, Florida 32320
PH: 850.370.1306
www.capitalavionics.com

Magnetic Reference Errors

Every reference used will have one or more deficiencies that contribute to errors in magnetic heading. These include:

1. Errors due to mechanical friction and manufacturing tolerances
2. Interpretation errors where judgement in readout is required
3. Errors of compass roses from North migration and diurnal effects
4. Tolerances of solid-state sensors, repeatability
5. Tolerances of USGS Declination Angles (calculated)

Magnetic Reference Displacement from Level (0° Roll, 0° Pitch).

Any portable measuring device must have the ability to correct any physical dip angle error in relation to 0° Roll and 0° Pitch (level in relation to the ground). This offset will give rise to a sinusoidal heading error that mimics a magnetic effect. The magnitude of this component of heading error is proportional to the tangent of the test area dip (inclination) angle.

Example:

In a test area with a local dip angle of 63.4°, the tangent (slope) is 2.0. Any roll error from test equipment calibrated at 45° will be doubled. Therefore, 0.1°roll error in the measuring device equates to a heading error amplitude of 0.2°, not including magnetic offset error.

Likewise, in an area with a dip angle of less than 45°, the roll error will be reduced because the tangent of 45° is less than 1.

Magnetic North Pole Migration

The magnetic north pole is located near Ellsmore Island in Canade and is travelling in a Northwesterly direction towards Siberia at approximately 35 KM per year. This movement increases terrestrial headings by upwards of 0.1° per year and is important to consider when using terrestrial objects as magnetic references.

Diurnal Sun Effects

Magnetic field effects that repeat over 24-hour periods and typically are within 0.2° nominal. For the best accuracy of terrestrial references, the measurements are made at local noon.

Solar Flares and Disturbances

In addition to relatively predictable and smoothly varying diurnal variations, there can be transient, large-amplitude-variation magnetic storms originating from sunspot activity. These storms will vary in intensity in real time making any magnetic field measurements inconsistent and unusable.

Capital Avionics

Capital Avionics, Inc.
8 Airport Road
Apalachicola, Florida 32320
PH: 850.370.1306
www.capitalavionics.com

Latitude / Longitude and Geomagnetic North (inclination) Errors

The Earth's magnetic field varies with Latitude and Longitude along it's Geomagnetic Equator. As you approach the poles, the inclination angle increases, which increases the magnitude of the magnetic field vertical "Z" axis or **MAG_V**, and decreases the magnetic field horizontal "X" and "Y" axis or **MAG_H**. These changes in the relative strength of the two magnetic field components and the overall reduction in **MAG_H** for measurement purposes creates a heading difference ***between the two locations.***

Heading systems in aircraft all read the same headings, regardless of location, because only the frame of reference has changed.

Therefore, the location where the magnetic reference equipment is calibrated (latitude and longitude) can influence tests performed in distant latitudes and longitudes. For general measurement purposes, the effects are acceptable, but where precision values are specified, i.e. less than 0.5°, these errors may become an issue.

Alignment Error between the magnetic reference and the longitudinal axis of the test aircraft.

Reference Figure 1 below:

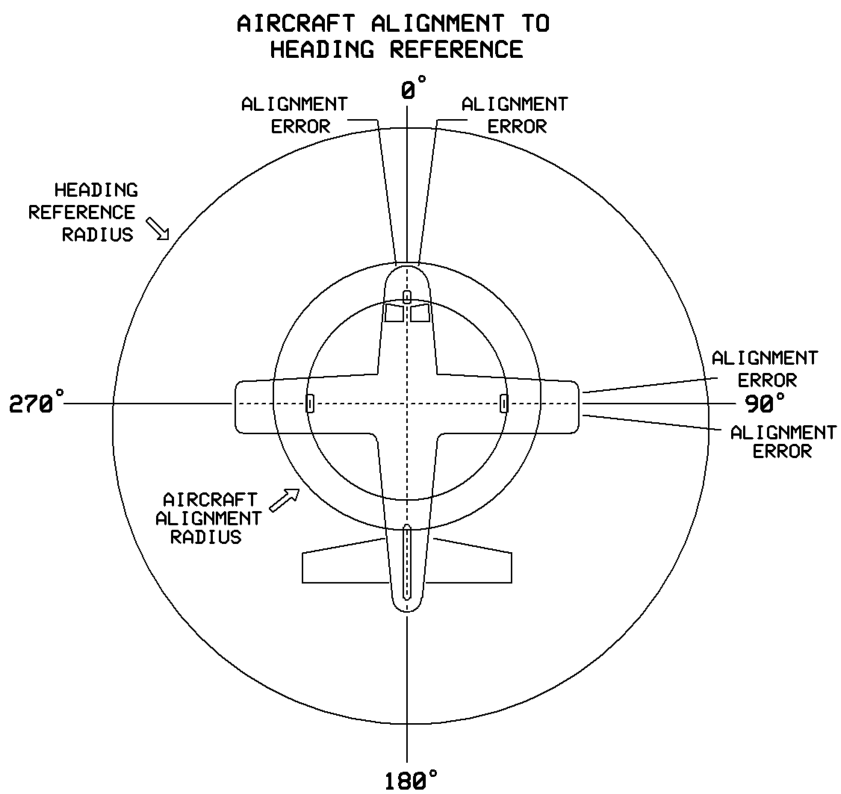


FIGURE 1

Capital Avionics
Capital Avionics, Inc.
8 Airport Road
Apalachicola, Florida 32320
PH: 850.370.1306
www.capitalavionics.com

Perhaps one of the largest errors in maintenance practices today comes from the methods used in our legacy protocols to align the aircraft with the heading reference. This heading reference can be a painted line (compass rose), visual alignment along the top or bottom of the fuselage (sight compass), laser beam projected on the fuselage or offset reference (digital compass), etc.

Because magnetic heading is presented to the pilot as a circle, a little refresh in geometry is useful here.

The circumference C of a circle is 2*Π*R or Π*D

Where: **C** = circumference

Π = 3.142

R = Radius of the circle

D= Diameter of the circle

Therefore, for a circle with a 120' diameter and 60' radius (like a compass rose), the circumference is about 377 feet or approximately 1 foot per degree of arc.

A good rule of thumb is that for every 5 feet of radius, 1 degree of arc is equal to 1 inch.

In Figure 1, the radius of the circle that can be aligned with the longitudinal axis of an aircraft would be defined by a circle that best encloses the landing gear and nose wheel where the landing tires are placed on one axis and the nose wheel is placed on the opposing axis.

Example:

Beechcraft Baron with 9' main wheel separation and 9' main wheel to nose distance equates to a circle with a 9' radius. Its circumference is ≈57' and 1° ≈ 2".

Note: Legacy compass roses have painted lines 4" wide and the latest AC 150/5300 specifies 6" lines bracketed by 1.5" white lines for a total of 9". The aircraft tires must be placed squarely in the center of these lines.

Mid-Level Business Jets with 4-6 passengers reside within a circle with a nominal radius of 15'. Its circumference is ≈94' and 1° ≈ 3".

Large corporate and small troop transport aircraft reside within a circle with a nominal radius of 24'. Its circumference is ≈151' and 1° ≈ 5".

For rotorcraft, the length of one skid would constitute the diameter R of the circle. One skid is placed parallel to the reference line for alignment.

Capital Avionics

Capital Avionics, Inc.
8 Airport Road
Apalachicola, Florida 32320
PH: 850.370.1306
www.capitalavionics.com

Example:
Mid-size helicopter with 12’ skid. Circle R is 12’, circumference is ≈75’ and 1° ≈ 2.5”.

Refer again to Figure 1. We now look at the larger circle that encompasses the entire fuselage. This would result from the use of the sight compass or digital compass where the entire fuselage acts as the radius.

Using this equipment, due to the extended radius for alignment, correspondingly tighter tolerances may be achieved.

However, what is lacking in current regulatory body and OEM maintenance practices are the misalignment tolerances allowed and how the technician is supposed to perform the alignment.

The only document readily available to industry with quantitative methods and tolerances, is Mil-Std 765A. This document has been suspended with no replacement. Therefore, we will review these practices as an example of what may be expected today. There are only two examples of acceptable methods provided therein.

- …radial bar must correspond to actual heading within 0.5°.
- Plumb bobs must be accurate to the centerline of the aircraft within 0.5 inches for every 15 feet of separation ***(equates to within 0.17° of reference)***.

That is all. To those experienced with plumb bobs, especially in the ramp environment, this is not a practical method for alignment. Radial bars, the other option with their attendant errors, are rarely seen at airports.

This may explain the lack of guidance for alignment of aircraft to any reference line, whether terrestrial or generated by the test equipment. The result is a “best guess” scenario.

METHODS

COMPASS ROSE

One of the most popular methods of compass alignment, in use for at least 100 years. Compass roses are beginning to disappear from airports due to the cost of maintenance, periodic calibration and land requirements (AC-150/5300-13 dictates minimum distances which equate to between 1.6 and 26 acres).

Capital Avionics, Inc.
8 Airport Road
Apalachicola, Florida 32320
PH: 850.370.1306
www.capitalavionics.com

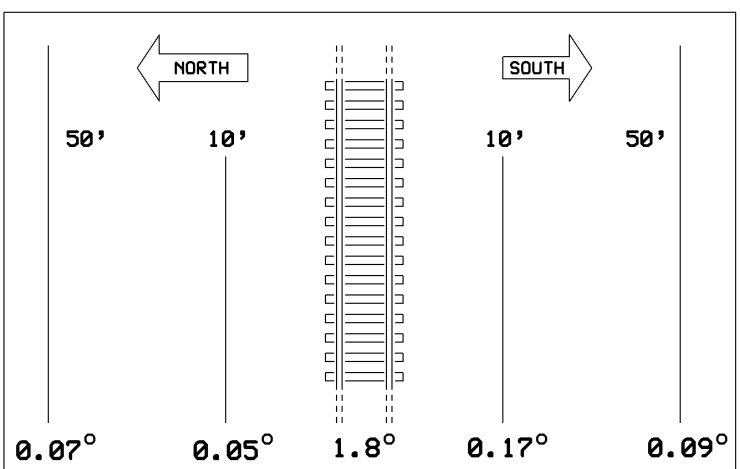
COMPASS ROSE Continued

ATTRIBUTES / ERRORS

Local Environment Effects	
Geomagnetic North	< 0.1°
Latitude and Longitude (inclination angle)	< 0.1°
Diurnal Effects	≤ 0.2°
North Pole Migration	0.1° x YSC*
***Y**ears **S**ince **C**alibration	
Sun Activity (low frequency of bursts)	+/- 0.3°*
* Not included in calculation	
Alignment	
Based upon 2.5” to 5” from centerline, proportioned for aircraft size, both axis	+/- 1.0°
Attitude Compensation	
Not applicable	0.0°
Magnetic Reference	
Per AC-150/2500-13	0.5°
Total Peak Error (3 years since calibration):	**2.2°**
Averaged Error, Expected	**1.65°**

Note: AC 150/5300-13 brings the requirements of Mil-Std 765A into the compass rose construction details without independent verification of their accuracy. Case in point is the 600’ distance from RR tracks. The results below speak for themselves and have been verified in multiple locations.

The average disruption measured from both sides of the tracks, 10’ offset and 32” above the ground is 0.11°, which is just above the rounding error of the test equipment. The average disruption at 50’ is less than 0.1°**.**



RR TRACK MAGNETIC INTERFERENCE - 32" ABOVE GROUND

Capital Avionics, Inc.
8 Airport Road
Apalachicola, Florida 32320
PH: 850.370.1306
www.capitalavionics.com

The point to be made is that magnetic disturbances cannot be calculated, guessed or visually recognized. The only way to determine a ramp's condition is to measure its uniformity with mass field or X/Y cartesian measurements.

SIGHT COMPASS

Possibly the most popular method of compass alignment, in use for at least 100 years. They are easy to use, maintain and provide a good balance of accuracy verses cost.

Mil Std 765A specifies an accuracy to 0.5°and friction not to exceed 1°.

Detailed in **AC 43-215 Standardized Procedures for Performing Aircraft Magnetic Compass Calibration**, we will look at one example.

ATTRIBUTES / ERRORS

Local Environment Effects	
Geomagnetic North	0.0°
Latitude and Longitude (inclination angle)	0.0°
Diurnal Effects	0.0°
North Pole Migration	0.0°
***Y**ears **S**ince **C**alibration	
Sun Activity (low frequency of bursts)	0.0°
* Not included in calculation	
Alignment	
Based upon 2.5" to 5" from centerline, proportioned for aircraft size, both axis, 0.5° readout resolution, interpretation error of 1.0°at 0.021" per degree circumference, 1°peak friction error.	2.5°
Attitude Compensation	
Not applicable	0.0°
Magnetic Reference	
Calibrated errors at 0.021" per degree circumference	0.5°
Total Peak Error:	**3.0°**
Averaged Error, Expected	**2.0°**

STANDBY COMPASS CALIBRATOR

Described in AC 43-215, a **Standby Compass Calibrator** uses an apparatus with adjustable magnets to neutralize the Earth's magnetic field at the test location (near the wet compass) and creates a simulated field for calibration purposes. The aircraft remains stationary, and the test equipment must be calibrated and certified for use at the calibration site. One example, referenced in AC 43-215, is the **Firstmark Aerospace Standby Compass Calibrator.**

Capital Avionics

Capital Avionics, Inc.
8 Airport Road
Apalachicola, Florida 32320
PH: 850.370.1306
www.capitalavionics.com

STANDBY COMPASS CALIBRATOR Continued

The test apparatus is attached to the aircraft's wet compass after the aircraft has been pointed along a referenced (surveyed) north line and adjusted thereafter.

Specifications of accuracy were not readily available.

Total Peak Error:	**Not Specified**
Averaged Error, Expected	**Not Specified**

PORTABLE MAGNETIC STANDARD

As described in AC 43-215: *a test apparatus that contains a highly accurate digital compass that employs magneto-resistive sensors to sense the Earth's magnetic field in three dimensions and a remote indication system that allows attaching the compass to the aircraft and reading aircraft headings at the standby compass location. An internal laser provides a means for accurate alignment of the digital compass sensor with the aircraft. This apparatus is test equipment that must be properly calibrated and certified for use. One example of the equipment used in this method is the Capital Avionics CA-320 Digital Compass Set.*

Note that the CA-320 has been superseded by the CA-420, which uses similar magnetic-sensing architecture. Both models offer 0.5° and 0.1° resolution.

ATTRIBUTES / ERRORS

Local Environment Effects

Geomagnetic North	TBD
Latitude and Longitude (inclination angle)	TBD
Diurnal Effects	0.0°
North Pole Migration	0.0°
***Y**ears **S**ince **C**alibration	
Sun Activity (low frequency of bursts)	0.0°

* Not included in calculation

Alignment

Based upon minimum 15 feet radius circle (+/- 0.3")	0.1°

Attitude Compensation

Internal pitch/roll compensation	0.1°

Capital Avionics, Inc.
8 Airport Road
Apalachicola, Florida 32320
PH: 850.370.1306
www.capitalavionics.com

PORTABLE MAGNETIC STANDARD Continued

Magnetic Reference		
	0.5° Resolution 0.35° 2σ (95%)	0.35°
	0.1° Resolution 0.25° 2σ (95%)	0.25°
Total Peak Error:	0.5° Resolution	**0.55°**
	0.1° Resolution	**0.45°**
Average Error:	0.5° Resolution	**0.45°**
	0.1° Resolution	**0.35°**

Note: Geomagnetic and Latitude/Longitudinal effects have not been determined at the time of this publication.

AIR SWING PROCEDURE

As described in AC 43-215: *Air swings may be accomplished on the aircraft magnetic compass by comparing readings against those obtained from an electrically calibrated and compensated system or against readings obtained from an inertial navigation system (INS), Attitude and heading Reference System (AHRS), or a Global Positioning System (GPS) as long as the variation of the system used as a reference is known within 0.2°. Ensure the heading being used as a reference is being displayed as, or is converted to, MH.*

An air swing involves flying in smooth air on eight headings, comparing the wet compass with the reference magnetic heading, and adjusting accordingly.

ATTRIBUTES / ERRORS

The errors include interpretation since most magnetic references in the aircraft (horizontal situation indicators, etc.) resolve to nominally 1°. If the MH displays to 0.1°, it remains to be seen whether the aircraft can be stabilized to this resolution.

The +/- 0.2° tolerance for the reference magnetic heading (MH) is difficult to achieve when it is calculated that a 0.5” deviation along every 15 feet of fuselage longitudinal axis equates to 0.17°of heading error.

Total Peak Error Referenced to MH of 0.2°:	**0.5°**
Average Error Referenced to MH of 0.2°:	**0.5°**
Average Error Referenced to MH of 1.0°:	**1.0°**

Capital Avionics, Inc.
8 Airport Road
Apalachicola, Florida 32320
PH: 850.370.1306
www.capitalavionics.com

ON-SITE TURNTABLE

Used with rotorcraft, an on-site turntable or rotating bearing placed at the center of a grid layout allows the rotorcraft to pivot around the circle with one wheel on the rotating surface. When coupled with an accurate secondary reference (like the center of the opposing tire axle), one can achieve alignment approaching 0.1°.

ATTRIBUTES / ERRORS

Local Environment Effects	
Geomagnetic North	0.0°
Latitude and Longitude (inclination angle)	0.0°
Diurnal Effects	0.2°
North Pole Migration	0.3° YSC*
*Years Since Calibration	
Sun Activity (low frequency of bursts)	0.0°
Alignment	
Based upon minimum 15 feet radius circle (+/- 0.3”)	0.1°
Attitude Compensation	
Internal pitch/roll compensation	0.0°
Magnetic Reference	
0.5° (AC 150/2500-13)	0.5°
Total Peak Error:	**1.1°**
Average Error:	**0.8°**

TERRESTRIAL REFERENCE WITH DECLINATION COMPENSATION

This method of determining magnetic north is often specified by avionics OEMs for electronic heading systems. A surveyed True North line is established and the aircraft is aligned to it. The calculated deviation is then applied to the established True North reference and compensated accordingly.

One source for the magnetic characteristics of a given local area is:
https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml#igrfwmm

This **Magnetic Field Calculator** provides field composition and declination angle.

Example:
For North Florida, the Declination angle is -4° 45’ 32” with an uncertainty of 0° and 20’ (0.33°) and is further dependent upon the geomagnetic activity level.

Capital Avionics, Inc.
8 Airport Road
Apalachicola, Florida 32320
PH: 850.370.1306
www.capitalavionics.com

TERRESTRIAL REFERENCE WITH DECLINATION COMPENSATION Continued

For information on activity level:
(https://www.ncei.noaa.gov/products/world-magnetic-model/accuracy-limitations-error-model)

ATTRIBUTES / ERRORS

Local Environment Effects	
Geomagnetic North	0.0°
Latitude and Longitude (inclination angle)	0.0°
Diurnal Effects	0.2°
North Pole Migration	0.0°
Sun Activity (low frequency of bursts)	0.0°
Alignment	
Because there is no terrestrial reference line for aircraft placement, one must be created that extends from the base of the transit-mounted True North reference towards the distant target. If a string is placed such as to extend this reference 120', this equates to ≈25" of arc per degree. Allowing 5" of True-North alignment error, the result is +/- 0.2°.	0.2°
Aircraft alignment to reference line based upon 2.5" to 5" from centerline, proportioned for aircraft size, both axis	1.0°
Attitude Compensation	
Internal pitch/roll compensation	0.0°
Magnetic Reference	
Survey 0.2° plus NOAA calculation 0.33°	0.53
Total Peak Error:	**1.93°**
Average Error:	**1.65°**

Capital Avionics, Inc.
8 Airport Road
Apalachicola, Florida 32320
PH: 850.370.1306
www.capitalavionics.com

SUMMARY

The legacy methods of compass alignment incorporate tolerances for which there are no effective solutions.

First, the alignment requirement where 0.5” of misalignment over 15’ of longitudinal axis equals 0.17°of heading error. Who has tried to do this on the ramp for every heading of the compass rose? Just determining the centerline of most aircraft within 0.5” is difficult. No procedures exist from governing bodies because there is no practical solution.

Second, OEM/industry heading tolerances specified between 0.25” and 0.5”, to be met, requires a precision that has no published methodology. Just the time of day easily creates 0.1° to 0.2° of heading error. Add practical, real-world alignment error and you have nothing left for the equipment tolerances when variations in the magnetic field are included.

Third, notice that this entire White Paper is dedicated to *wet compass* alignment procedures. There is no published guidance for the test and alignment of electronic compass systems. So, the industry simply uses guidance for wet compasses for electronic compass systems.

It is time to recognize the limitations of current legacy procedures and either to accept their broader tolerances, through published guidance, or provide alternatives that can produce the stated magnetic system accuracy requirements.