Physical phenomena used for direction determination in compasses

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Krajczyński Edward – Urządzenia nawigacji technicznej
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Types of directions

True direction – determined in relation to geographical North

Magnetic direction – determined in relation to magnetic North

Compass direction – determined in relation to compass North

Gyro direction – determined in relation to gyro North

Types of directions

Heading (steered course) – horizontal direction in which a ship actually points or heads at any instant, expressed in angular units from a reference direction, usually from 000 deg at the reference direction, clockwise through 360 deg. Heading is often designated as true, magnetic, compass or gyro

Course – direction in which a vessel is steered or intended to be steered, expressed as angular distance from North, usually from 000deg at north, clockwise through 360deg. Strictly, the term applies to direction through the water, not the direction intended to be made good over the ground. The course is often designated as true, magnetic, compass or gyro.

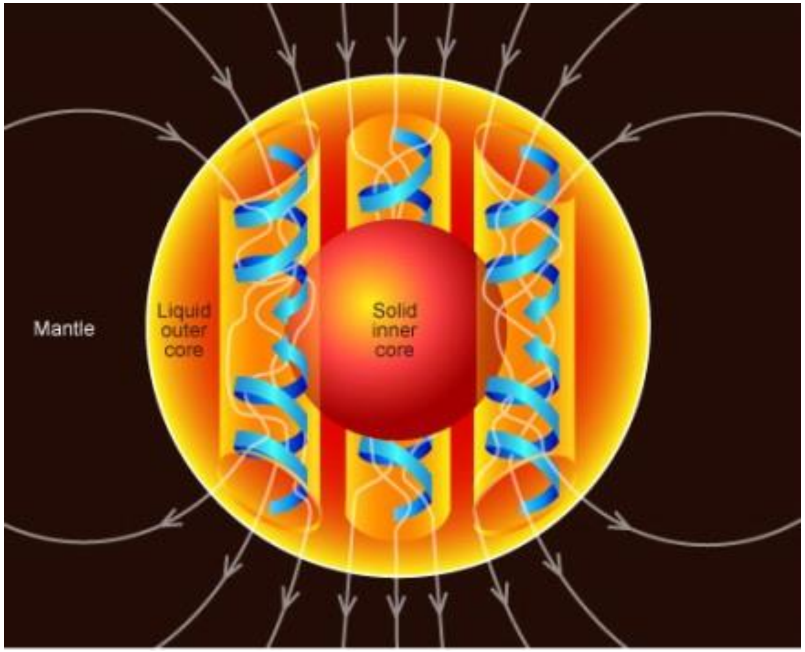
Types of directions

Course over ground – the direction of the path over the ground actually followed by a vessel.

Bearing – the horizontal direction of one terrestrial point from another, expressed as the angular distance form a reference direction. It is usually measured from 000 deg at the reference direction clockwise through 360 deg. A bearing is often designated as true, magnetic, compass, gyro or heading respectively.

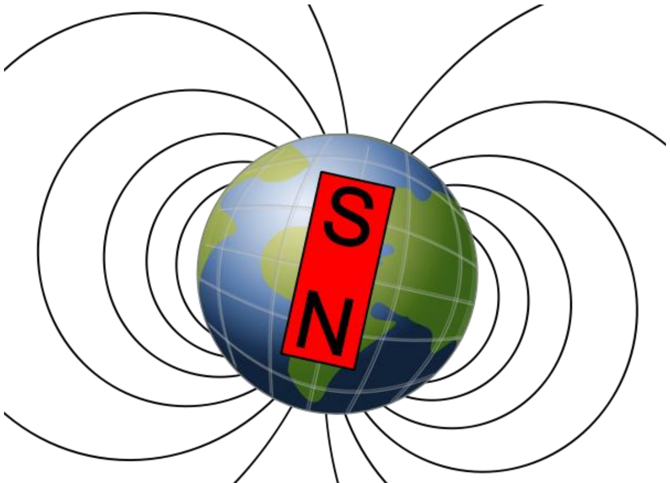
The Earth’s magnetism

The Earth's magnetic field is believed to be generated by electric currents in the conductive material of its core, created by convection currents due to heat escaping from the core. However the process is complex, and computer models that reproduce some of its features have only been developed in the last few decades.



The Earth’s magnetism

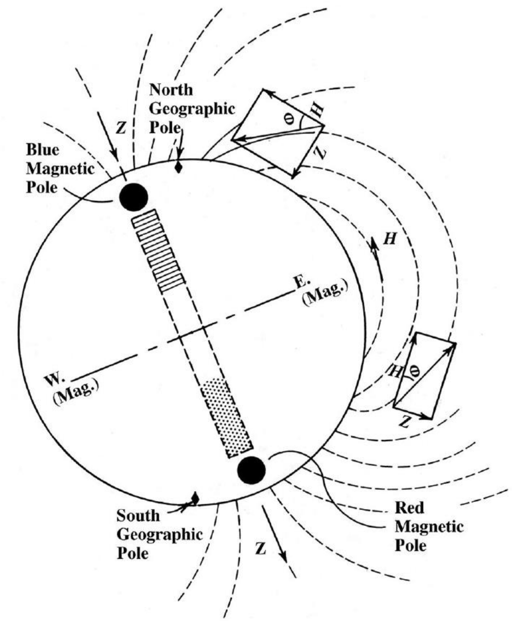
Approximately 90% of the Earth’s magnetic field can be explained by a strong, small magnet (dipole) in the centre of the Earth. This small magnet is directed towards the southern hemisphere and forms an angle with Earth’s rotational axis of approx. 11.5 deg. If we imagine the magnetic dipole extended to the Earth’s surface, this is called the magnetic axis, and it will cut the surface of the Earth at the **geomagnetic poles**. These poles form the basis for the magnetic coordinate system and the position in 2008 were N79.9° – W71.9°, S79.9° – E108.1°



The Earth’s magnetism

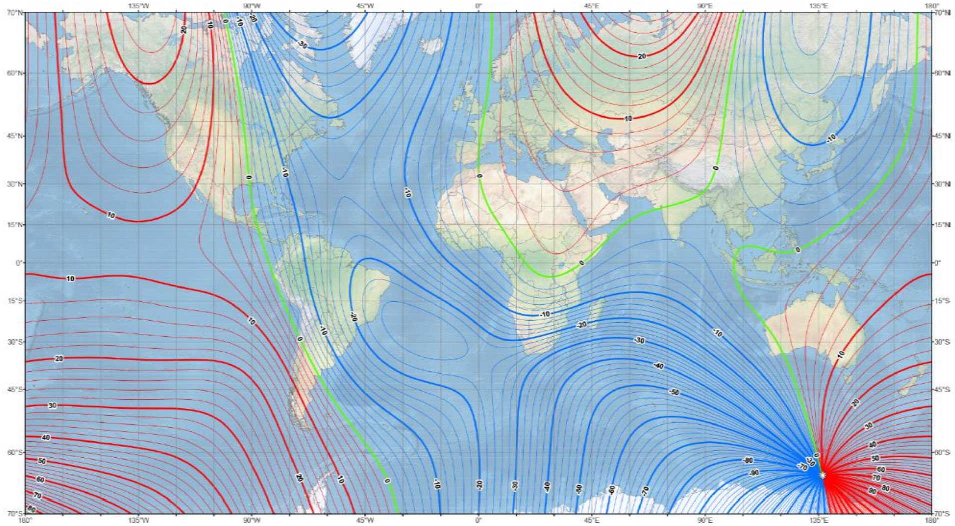
The definition of the **magnetic pole** is where the field lines are at the right angles to the Earth’s surface (geoid). The position of this place will vary somewhat, but is based on IGRF (International Geomagnetic Reference Field) calculated in 2008 to be:
N 84.2° - W124.0° (North of Ellesmere Island in the Canadian Arctic), S 64.5° - W 137.6° (in commonwealth Bay in the Antarctic)

Magnetic equator can be defined as the irregular imaginary line, passing round the earth near the equator, on which a magnetic needle has no magnetic dip. **Magnetic dip**, dip angle, or magnetic inclination is the angle made with the horizontal by the Earth's magnetic field lines



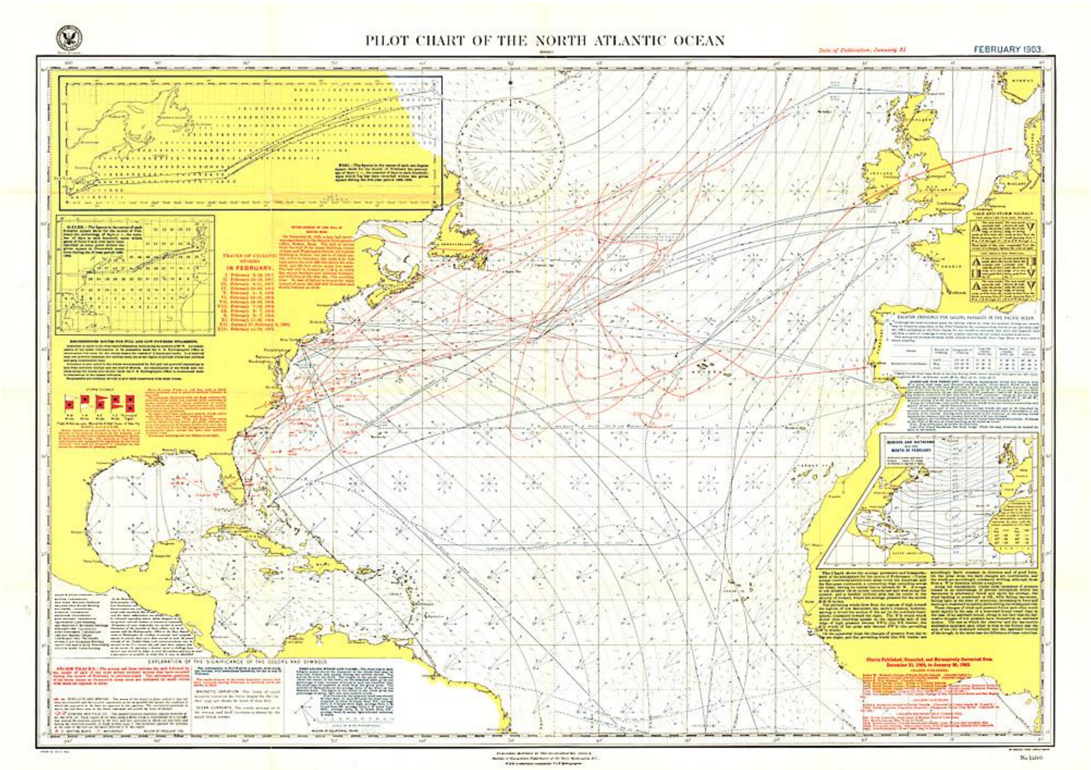
The Earth's magnetism

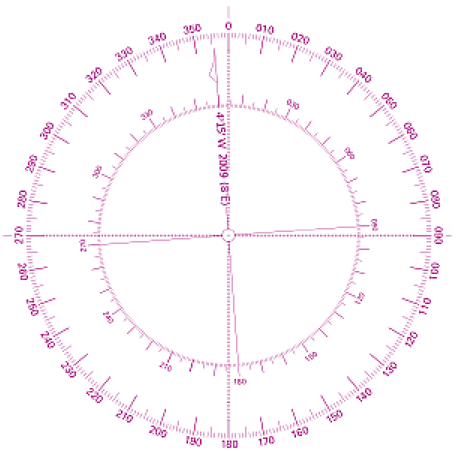
Since the magnetic poles of the Earth do not coincide with the geographic poles, a compass needle in line with the Earth's magnetic field will not indicate true north, but magnetic north. The angular difference between the true meridian (great circle connecting the geographic poles) and the magnetic meridian (direction of the lines of magnetic flux) is called **variation**. This variation has different values at different locations on the Earth.

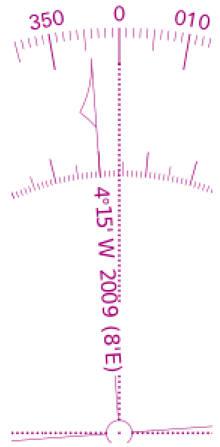


The Earth’s magnetism

In practice values of magnetic variation may be found on pilot charts and on the compass rose of navigational charts. Magnetic variation is sometimes called **magnetic declination**.







The ship's magnetism

A ship under construction or repair will acquire permanent magnetism due to hammering and vibration while sitting stationary in the Earth's magnetic field. After launching, the ship will lose some of this original magnetism as a result of vibration and pounding in varying magnetic fields, and will eventually reach a more or less stable magnetic condition. The magnetism which remains is the **permanent magnetism** of the ship.

The ship's magnetism

In addition to its permanent magnetism, a ship acquires **induced magnetism** when placed in the Earth's magnetic field. The magnetism induced in any given piece of soft iron is a function of the field intensity, the alignment of the soft iron in that field, and the physical properties and dimensions of the iron. This induced magnetism may add to, or subtract from, the permanent magnetism already present in the ship, depending on how the ship is aligned in the magnetic field. The softer the iron, the more readily it will be magnetized by the Earth's magnetic field, and the more readily it will give up its magnetism when removed from that field.

The ship’s magnetism

The magnetism in the various structures of a ship, which tends to change as a result of cruising, vibration, or aging, but which does not alter immediately so as to be properly termed induced magnetism, is called **subpermanent magnetism**. This magnetism, at any instant, is part of the ship’s permanent magnetism, and consequently must be corrected by permanent magnet correctors. It is the principal cause of deviation changes on a magnetic compass. Subsequent reference to permanent magnetism will refer to the apparent permanent magnetism which includes the existing permanent and subpermanent magnetism.

The ship’s magnetism

A ship, then, has a combination of permanent, subpermanent, and induced magnetism. Therefore, the ship’s apparent permanent magnetic condition is subject to change as a result of deperming, shocks, welding, and vibration. The ship’s induced magnetism will vary with the Earth’s magnetic field strength and with the alignment of the ship in that field.

The ship’s magnetism

Ship’s magnetic conditions create magnetic compass deviations and sectors of sluggishness and unsteadiness. **Deviation** is defined as deflection right or left of the magnetic meridian caused by magnetic properties of the vessel. Adjusting the compass consists of arranging magnetic and soft iron correctors near the compass so that their effects are equal and opposite to the effects of the magnetic material in the ship.

The ship's magnetism

Normally, a complete correction will be undertaken by a approved adjustor from the Ships Inspection Authorities. However, at sea things can happen which make it necessary to make a preliminary correction. The procedure will be as follows:

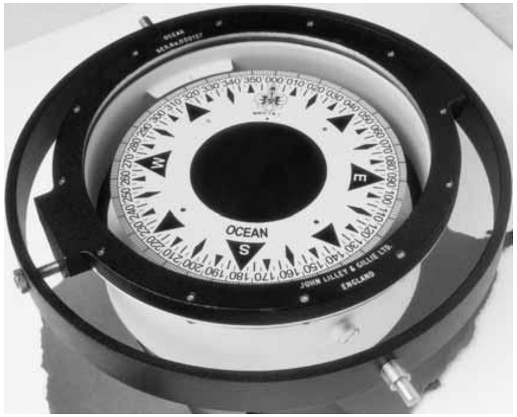
1. Undertake a couple of swings, as well as reversing to shake the ship free of semi-permanent magnetism
2. Remove the iron from the Flinders bar
3. Place heeling magnets under the compass halfway up the holding tubes
4. Turn the ship on to a magnetic southerly course and adjust the athwartships magnets until the deviation is zero

The ship’s magnetism

5. Turn the ship on to a magnetic easterly course and adjust the fore-and-aft magnets until the deviation is zero
6. Check the deviation for northerly and westerly courses
7. Turn the ship on to southerly course and move the quadrant spheres symmetrically so that the deviation becomes zero. Remember that the spheres must not be turned.
8. Turn the ship on to northwest and northeast. In the case of large deviation, halve the moving of the spheres.
9. Swing the vessel slowly round and note the deviation for every 10 degrees and write this into a deviation table and draw a curve.
10. Note the correction in the Deck Journal

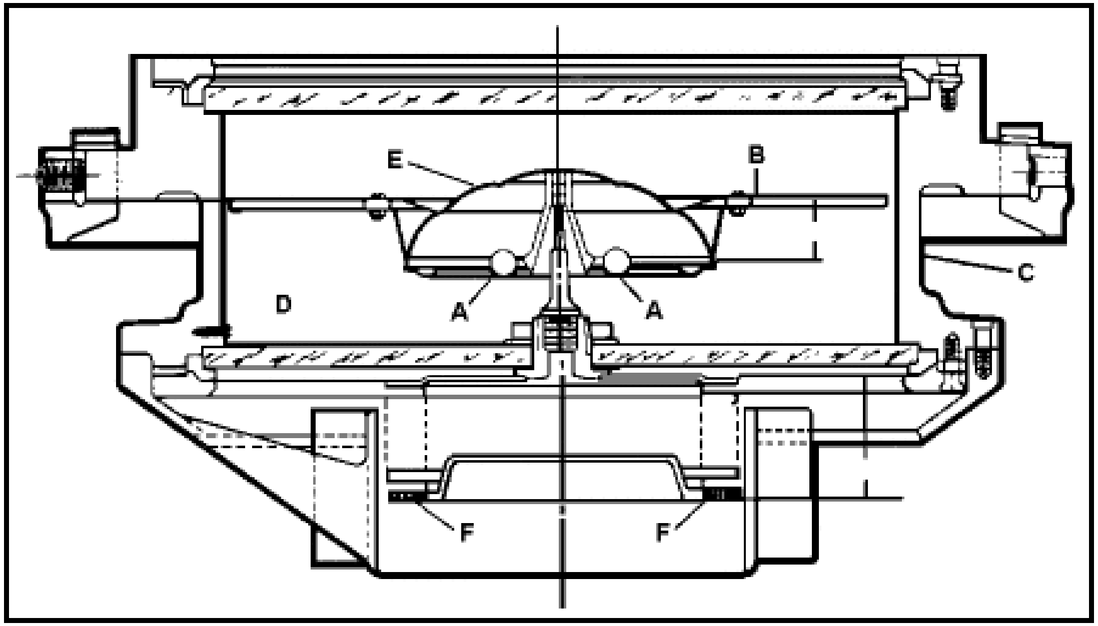
Magnetic compass

The principle of the present day magnetic compass is no different from that of the compasses used by ancient mariners. The magnetic compass consists of a magnetized needle, or an array of needles, allowed to rotate freely in the horizontal plane. The superiority of present-day magnetic compasses over ancient ones results from a better knowledge of the laws of magnetism and how it governs the behavior of the compass and from greater precision in design and construction.



Magnetic compass

A – magnets
B – compass card
C – compass bowl
D – fluid
E – float
F – expansion bellows

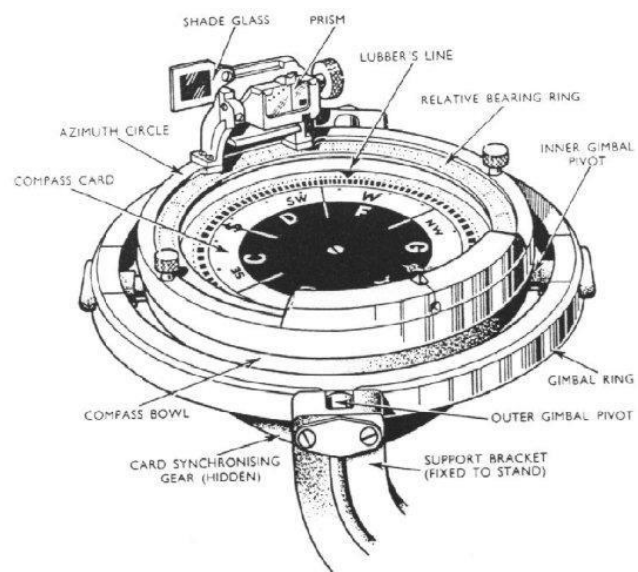


Magnets - four (two in older compasses) cylindrical bundles of magnetic steel wire or bar magnets which are attached to the compass card to supply directive force. Some newer compasses have a circular magnet made of a metallic alloy

Compass card - aluminum disc, graduated in degrees from 0° to 360° . It also shows cardinal and intercardinal points. North is usually indicated by the fleur de lis figure in addition to the cardinal point. Being attached to the magnets, the compass card provides a means of reading direction.

Compass bowl - bowl-shaped container of nonmagnetic material (brass) which serves to contain the magnetic elements, a reference mark, and the fluid. Part of the bottom may be transparent (glass) to permit light to shine upward against the compass card.

fleur de lis



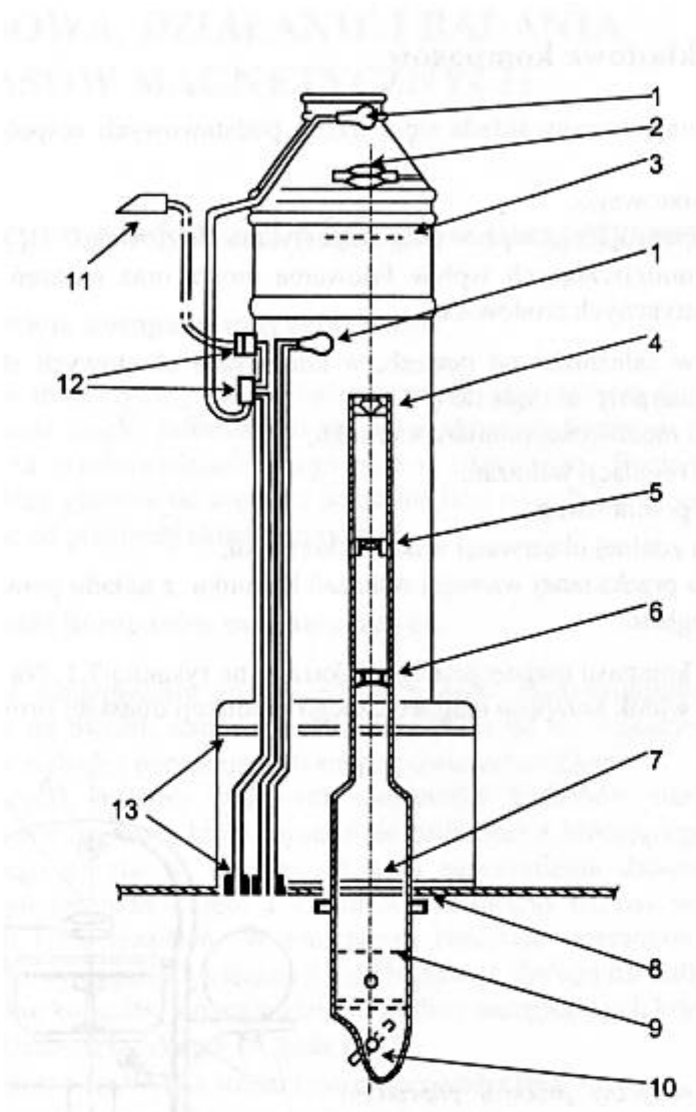
Fluid - liquid surrounding the magnetic element. According to Archimedes principle of buoyancy, a reduction of weight results in a reduction of friction, making possible closer alignment of the compass needle with the magnetic meridian. Any friction present will tend to prevent complete alignment with the magnetic meridian. Today's compasses contain a highly refined petroleum distillate similar to Varsol, which increases stability and efficiency and neither freezes nor becomes viscous at low temperatures.
Float - aluminum, air-filled chamber in the center of the compass card. This further reduces weight and friction at the pivot point.
Expansion Bellows - arrangement in the bottom of the compass bowl. This operates to keep the compass bowl completely filled with liquid, allowing for temperature changes. A filling screw facilitates addition of liquid, which may become necessary notwithstanding the expansion bellows.

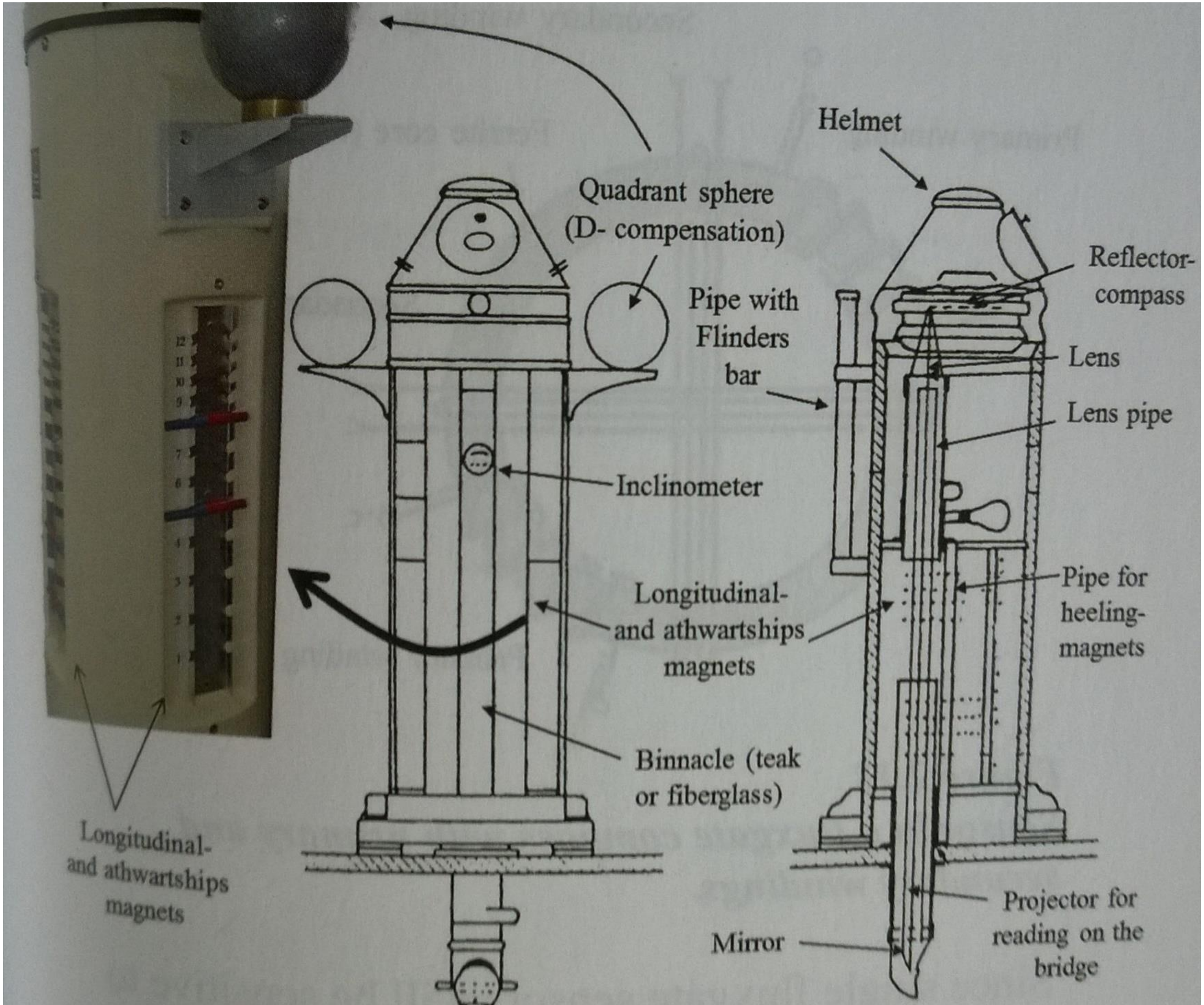
Lubber line - reference mark on the inside of the compass bowl. It is aligned with the ship's fore and aft axis or keel line of the ship. The lubber line is a reference for the reading of direction from the compass card. The reading of the compass card on the lubber line at any time is the "ship's heading."

Gimbals - metal ring on two pivots in which the compass bowl is placed. The compass is also on two pivots which permits it to tilt freely in any direction and remain almost horizontal in spite of the ship's motion. The compass rests on the binnacle. An important concept is that regardless of the movement of the ship, the compass card remains fixed (unless some magnetic material is introduced to cause additional deviation from the magnetic meridian). The ship, the compass bowl, and the lubber line move around the compass card. To the observer witnessing this relative motion, it appears that the compass card moves.

Magnetic compass

1. Light
2. Lens
3. Compass card
4. Lens
5. Lens
6. Lens
7. Hole in the deck
8. Rubber gasket
9. Dimming glass
10. Mirror
11. Light
12. Waterproof plug socket
13. Gasket




Helmet
Quadrant sphere
(D- compensation)
Reflector-
compass
Pipe with
Flinders
bar
Lens
Lens pipe
Inclinometer
Longitudinal-
and athwartships
magnets
Pipe for
heeling-
magnets
Binnacle (teak
or fiberglass)
Longitudinal-
and athwartships
magnets
Projector for
reading on the
bridge
Mirror

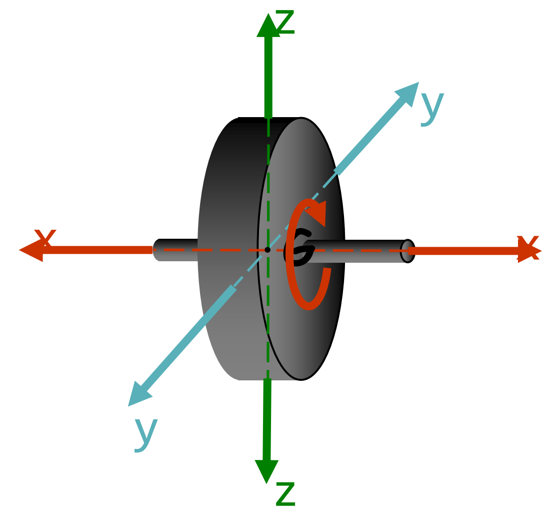
Gyrocompass

The gyroscope effect

A free gyroscope is a fast-rotating wheel which is mounted so that its axis can move freely in all directions. The wheel is then said to have 3 degrees of freedom (DoF) about:

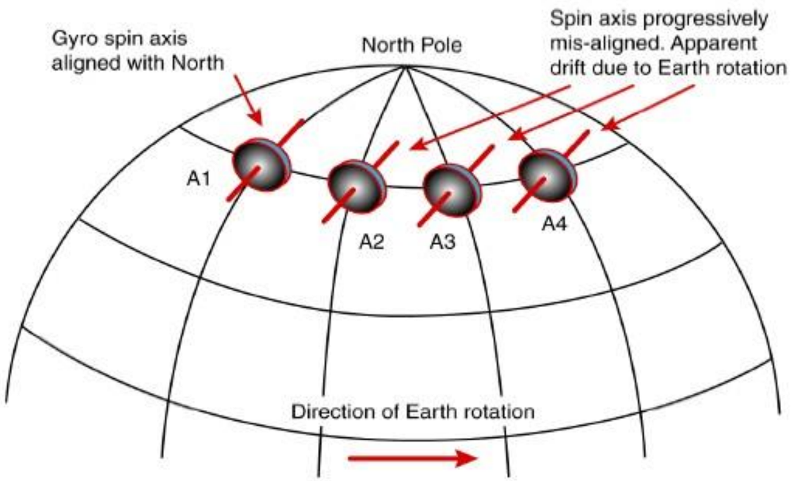
- Spin axis
- Horizontal axis
- Vertical axis

The mass of the wheel must be accurately balanced so that the centre of gravity lies in the geometrical centre



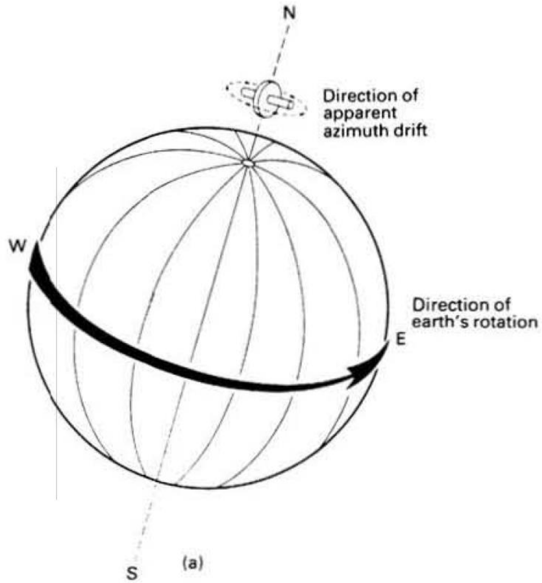
The gyroscope effect

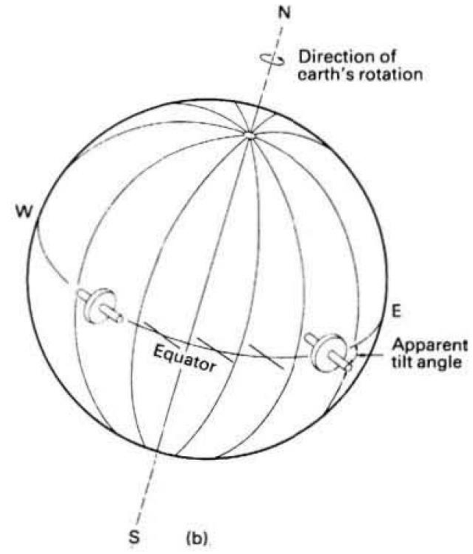
When a gyroscope is set into fast rotation it will achieve a large spin which makes the spin axis directionally stable in space (gyroscopic inertia). The direction of pointing will thereby remain permanently towards a point in space which is called the gyro star, if it is not exposed to an external moment of force. In relation to the Earth the axis will move as the Earth rotates.



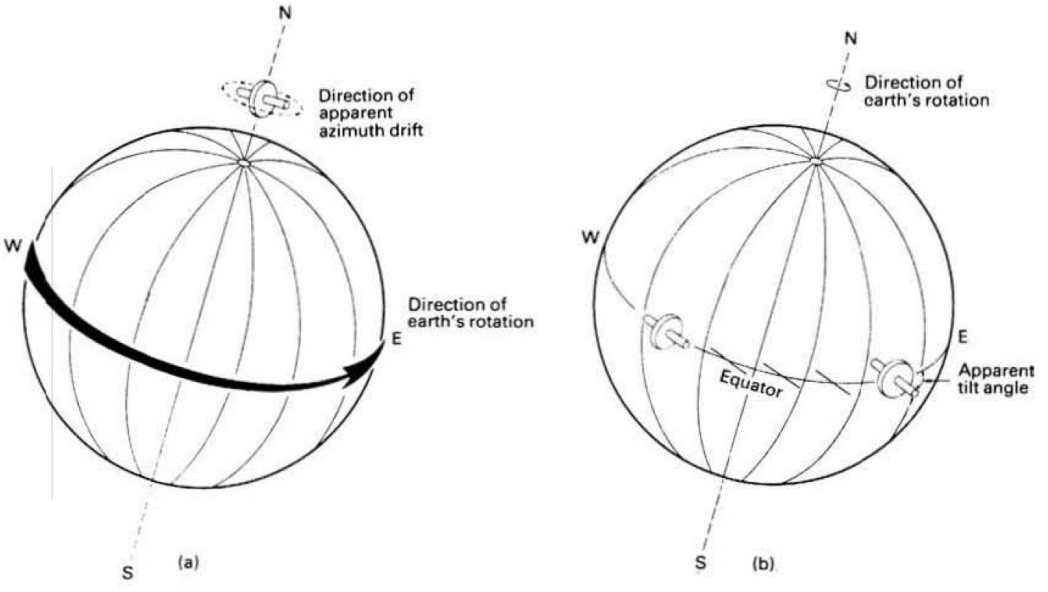
The gyroscope effect

If a gyroscope is placed at the equator with its spin axis pointing east-west, as the Earth turns on its axis, gyroscopic inertia will tend to keep the plane of rotation constant. To the observer, it is the gyroscope which is seen to rotate, not the Earth. This effect is called the horizontal earth rate, and is maximum at the equator and zero at the poles. At points between, it is equal to the cosine of the latitude.





If the gyro is placed at a geographic pole with its spin axis horizontal, it will appear to rotate about its vertical axis. This is the vertical earth rate. At all points between the equator and the poles, the gyro appears to turn partly about its horizontal and partly about its vertical axis, being affected by both horizontal and vertical earth rates. In order to visualize these effects, remember that the gyro, at whatever latitude it is placed, is remaining aligned in space while the Earth moves beneath it.



Gyroscopic precession

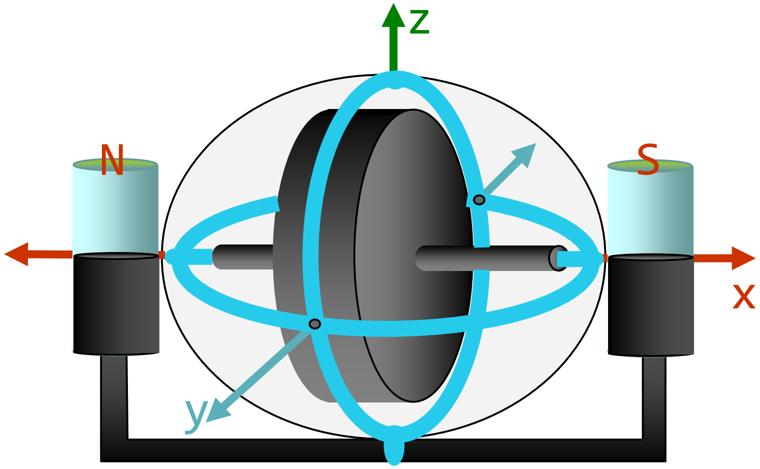
The gyroscope has a special characteristic when the axis is exposed to an external force. In such cases, the movement of the spin axis is called **precession.** Precession movement is 90 degrees in the direction of the external force.

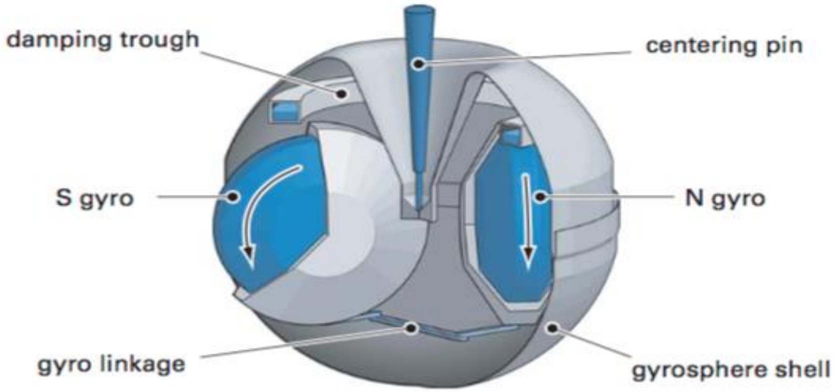
The direction in which the precession works depends on the direction of rotation of the gyroscope, as well as the direction of of externally applied force. If we have a vertical force we will have a horizontal precession

Gyroscopic precession

In principle there are two main types of gyroscope, or sensitive element as the gyro element itself is called:

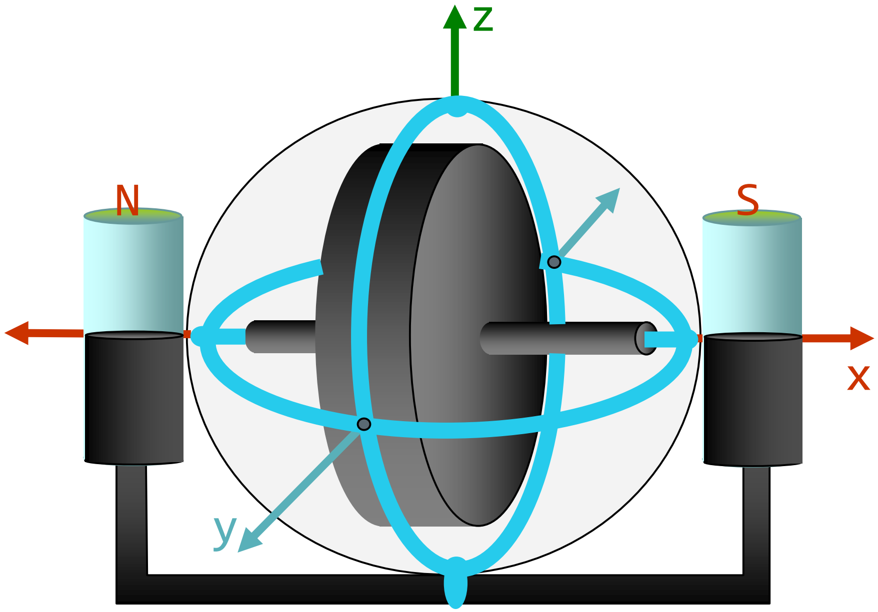
- Top-heavy gyroscope
- Bottom-heavy gyroscope





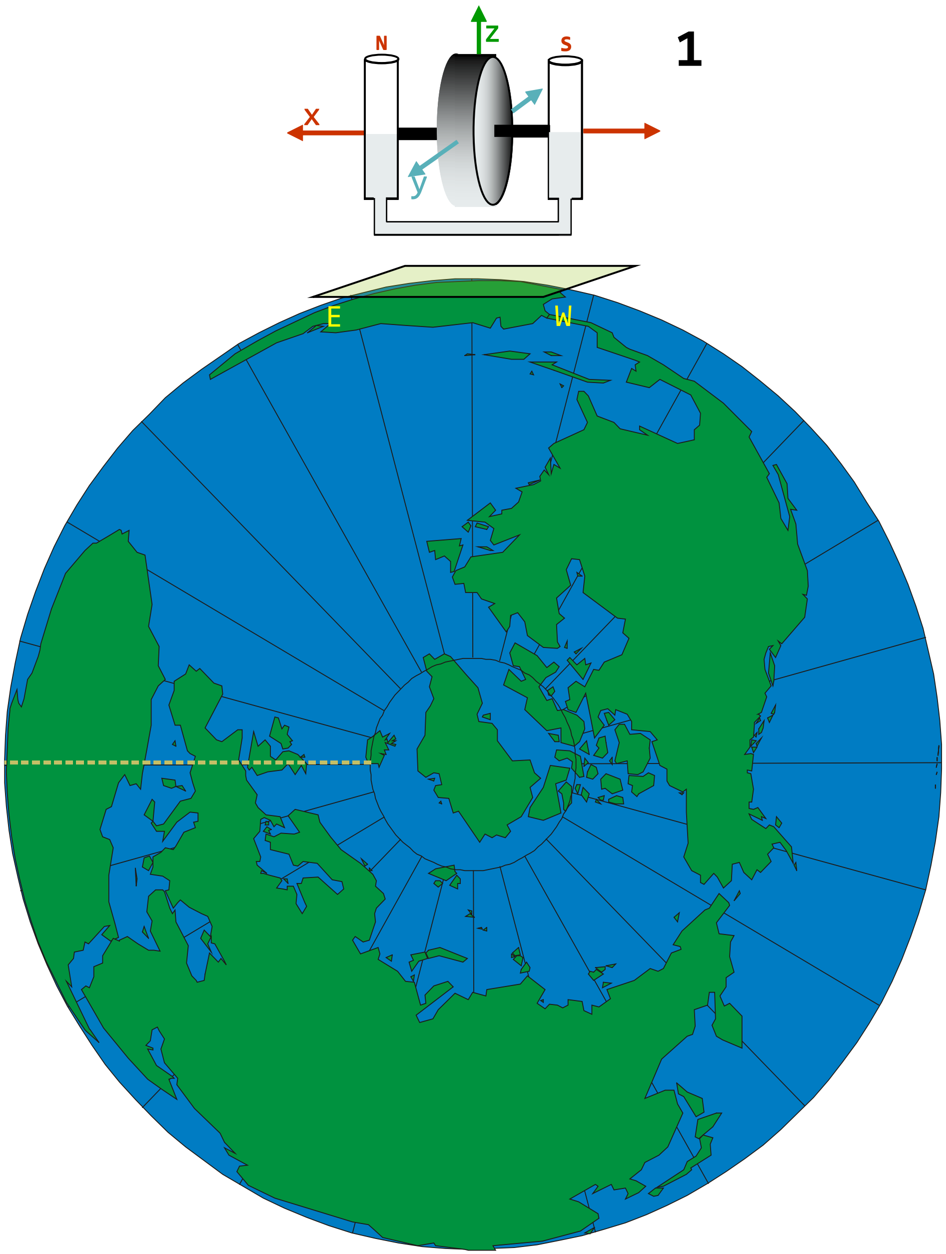
Top-heavy gyroscope

In order to obtain a force that can precess the gyro axis toward north, a container with mercury is mounted on the axes. The system is called mercury or Hg control.

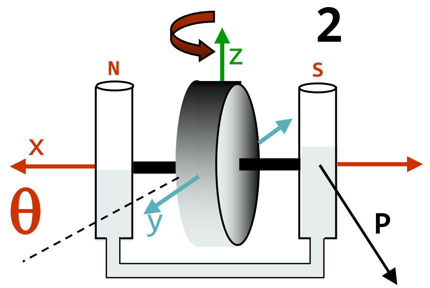


Top-heavy gyroscope

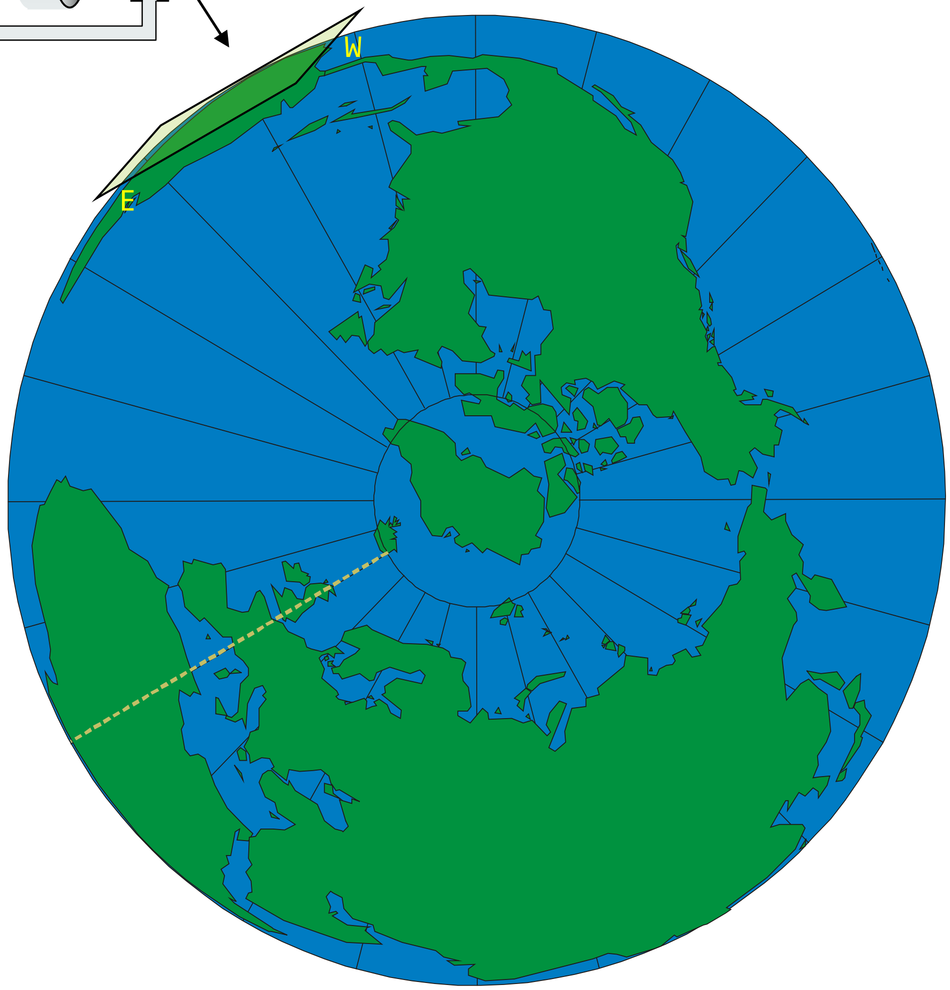
If we imagine that the north axis is turned eastwards when the gyrosope is started, ths axis will be raised when the Earth rotates toward east.



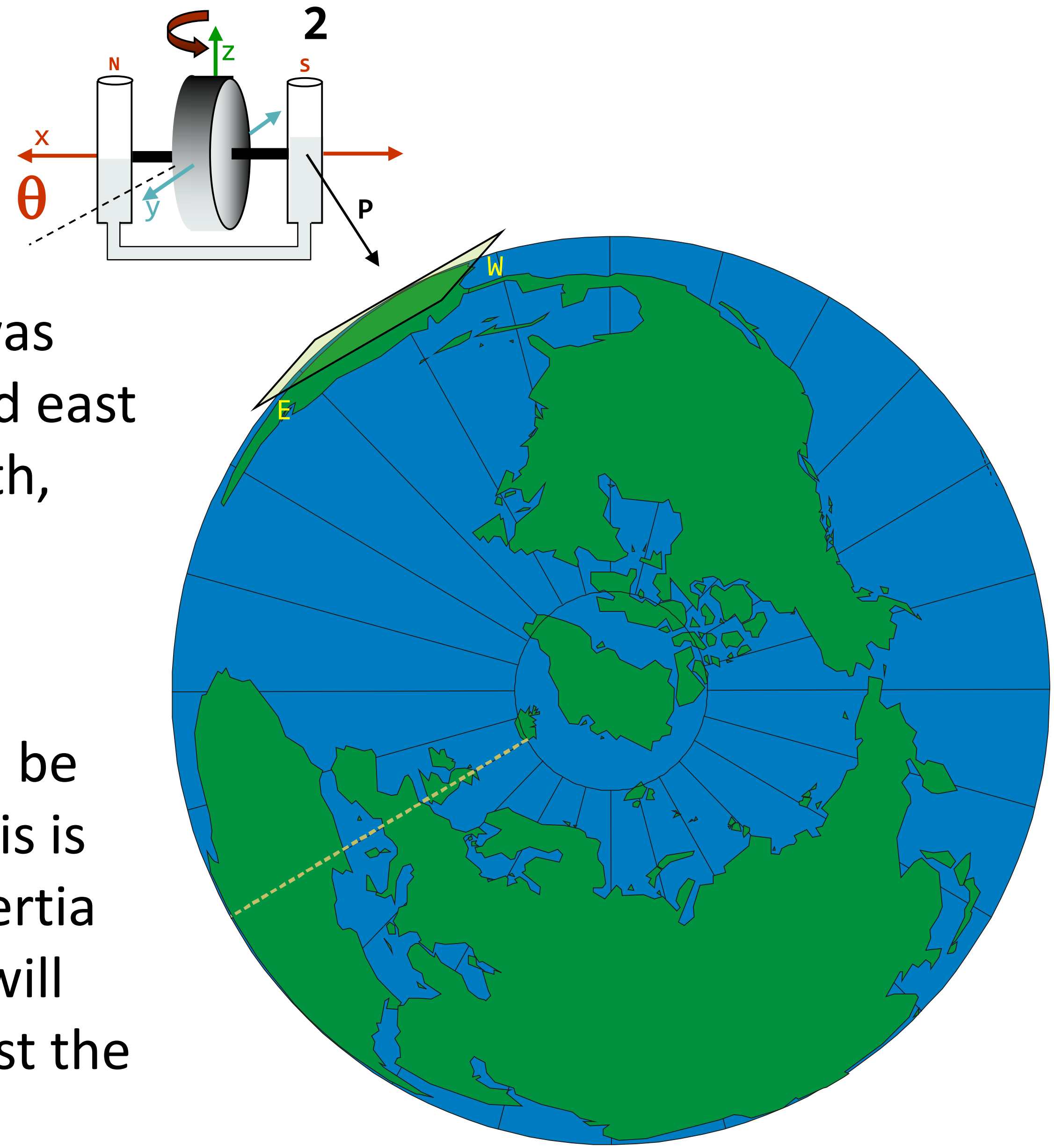
Top-heavy gyroscope



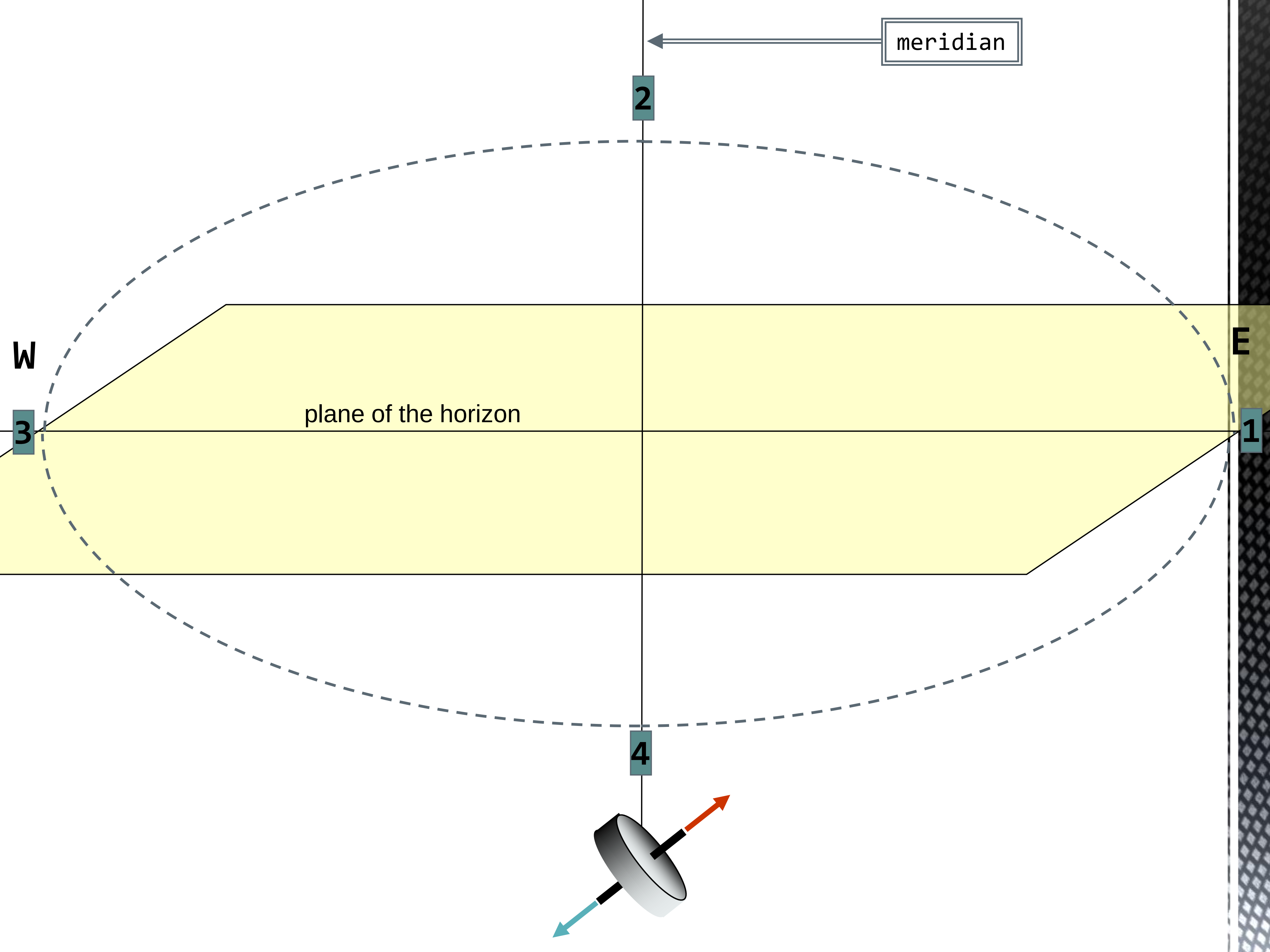
The container on the north axis will therefore be high and the mercury will run to the low container. This will in its turn lead to a greater vertical force on the low axis, which will again lead to a precesion of 90 degrees on this.



Top-heavy gyroscope



The north axis which was initially directed toward east will move towards north, and we say that the gyroscope has become meridian seeking. The precession velocity will be maximum when the axis is in the north. Due to inertia in the system the axis will continue to precess past the meridian.

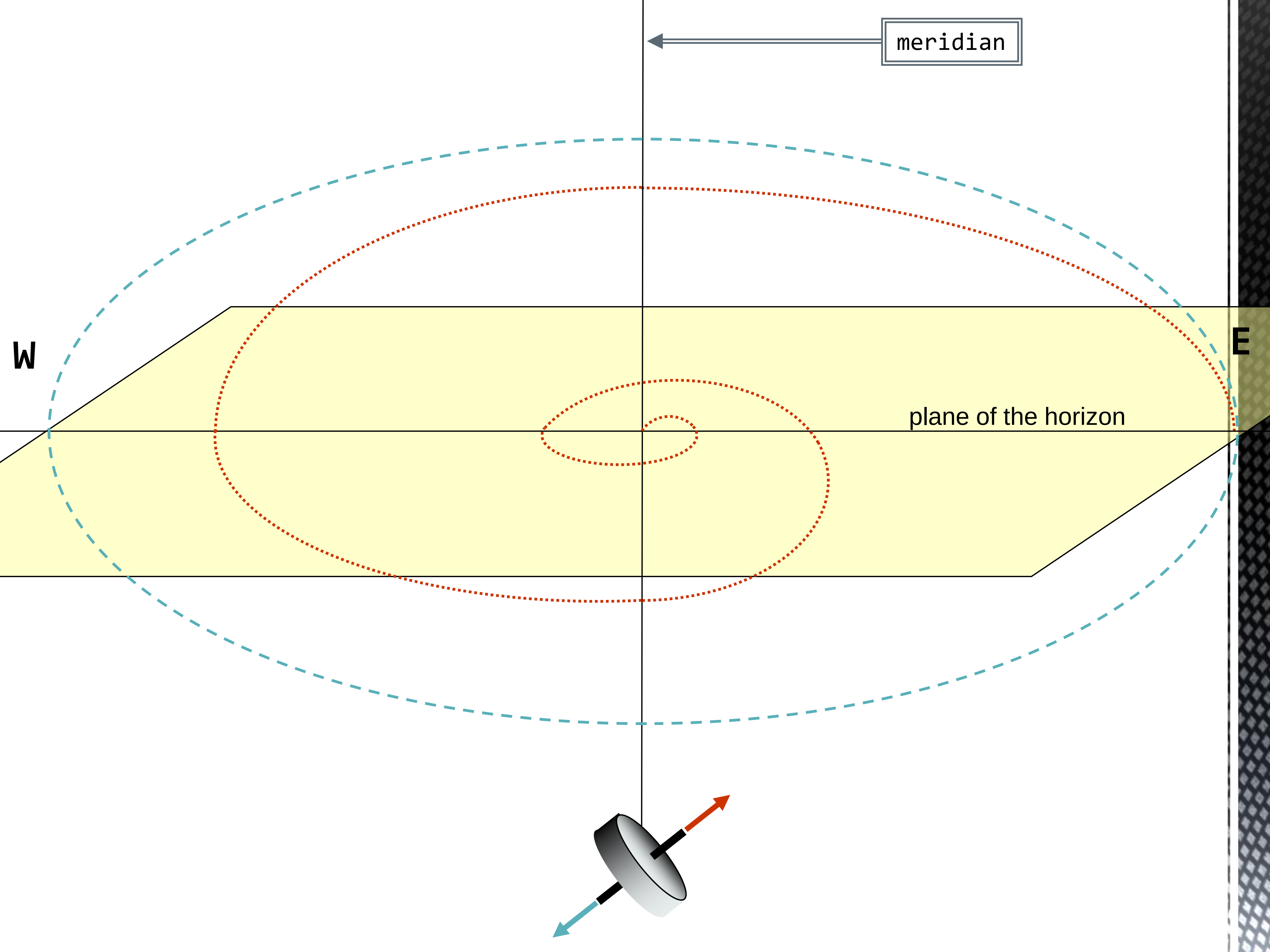

meridian
2
W
E
plane of the horizon
3
1
4

Top-heavy gyroscope

The north-seeking will initially be an unattenuated movement which means that the axis will not be stable in the meridian, but will swing for a period of approx. 84 minutes around the meridian.

We must therefore introduce an attenuation mechanism. In principle we can choose whether we will attenuate the pendulum movement in the vertical or horizontal axis. Both metods lead to that we have a spiral-formed attenuation curve which will put the axis in to the meridian.

In Sperry compasses it is achieved by placing a weight asymetrically in relation to the axis. This mean that the weight will perform pecession force on the axis when it tilts.


meridian
W
E
plane of the horizon

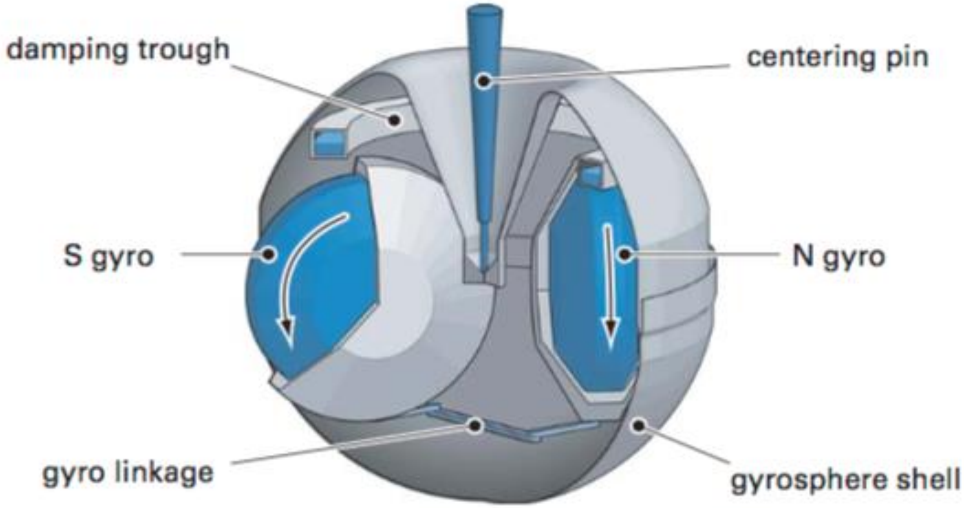
Bottom-heavy gyrscope

In compasses with the gyroscope encapsulated in a „gyro sphere”, it is usual to use a bottom heavy system. This is done in practise by placing the gyroscope lower than the centre in shpere, which will results in that the centre of gravity of the sphere will be lower than the centre of the sphere.

For the sphere floating freely in the liquid-filled container, if the axis is lifted as a result of the Earth’s rotation, the centre of gravity will be pushed outside the centreline of the sphere. In this case the buoyancy force will work in the sphere centre, while the force of gravity will work in the sphere’s centre of gravity which is placed lower than than the centre. Since there is a gyroscope in the sphere with fast spin, the „corrective” force will give a precession movement towards the meridian.

Bottom-heavy gyrscope

In the sphere there is also a liquid reservoir with continous piping. This is not a mechanism for force of gravity driven north-seeking, such as the mercury control was at the top-heavy gyoroscope. On the contrary the design is such that the oil filled reservoir system will work as an asymetrical weight that shall dampen the swinging movement around the meridian.



Gyrocompass

Gyrocompass will have some common elements that can be characterised as:

- Sensitive element/gyro motors
- Voltage supply
- Follow-up system
- Compensation system
- Compass rose / display
- Junction box for peripherial equipment

Gyrocompass

The **sensitive element** consist of one or two gyro motors that can either be encapsulated in sphere or another form of encapsulation. The sphere is also suspended to reduce friction. This can be done by the element / sphere floating in „supporting" liquid, hung up on a needle or suspended by a wire. In addition, the whole arrangement will have a form of gimbals.

The **follow-up system** ensures transfer of the heading on the sensitive element to a compass rose or other form of display

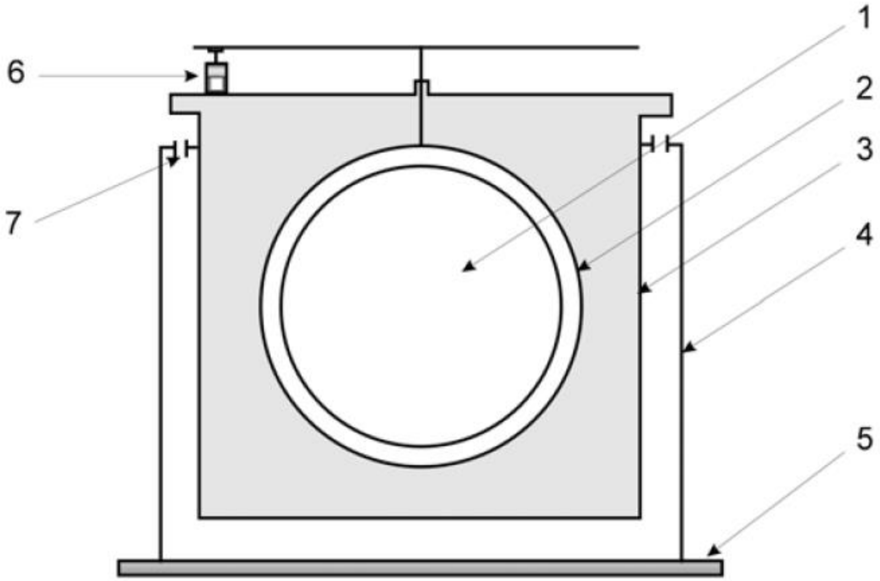
Gyrocompass

On some compasses there can be a **compenstation system** that actively adjust errors that are due to speed and latitude. This will normally be an electro-magnet that precesses the sensitive element toward the meridian. On such compasses there will be no need to use tables for correction of latitude error. However, it is important that the speed and latitude information that is fed into the system is correct

The **compass rose**, if such is found, is normally located on the top of the binnacle. The rose will be driven by small electrical motors that are steered from the follow-up system. Since many binnacles are placed in separate cabinets or rooms there is no need for an ordinary compass rose – there are therefore some producers that only have a digital read-out

Gyrocompass

1. Gyro sphere
2. Follow-up spere
3. Container filled with liquid
4. Casing
5. Base
6. Folow-up electrical motor
7. Gimbal



Gyrocompass errors

The total of the all the combined errors of the gyrocompass is called **gyro error** and is expressed in degrees E or W, just like variation and deviation. But gyro error, unlike magnetic compass error, and being independent of Earth's magnetic field, will be constant in one direction; that is, an error of one degree east will apply to all bearings all around the compass.

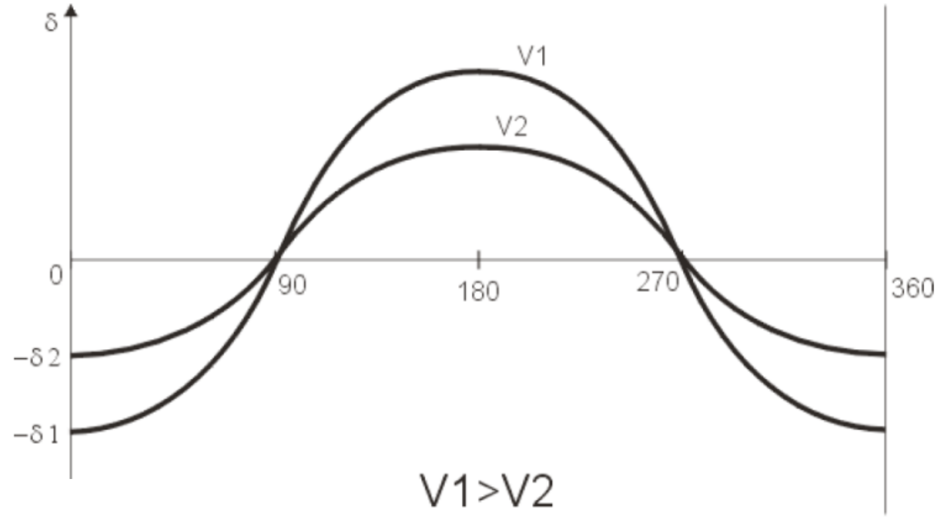
The errors to which a gyrocompass is subject are speed error, latitude error, ballistic deflection error, ballistic damping error, quadrantal error, and gimballing error.

Additional errors may be introduced by a malfunction or incorrect alignment with the centerline of the vessel.

Gyrocompass errors

Speed error is caused by the fact that a gyrocompass only moves directly east or west when it is stationary (on the rotating Earth) or placed on a vessel moving exactly east or west. Any movement to the north or south will cause the compass to trace a path which is actually a function of the speed of advance and the amount of northerly or southerly heading. This causes the compass to tend to settle a bit off true north. This error is westerly if the vessel’s course is northerly, and easterly if the course is southerly. Its magnitude depends on the vessel’s speed, course, and latitude. This error can be corrected internally by means of a cosine cam mounted on the underside of the azimuth gear, which removes most of the error. Any remaining error is minor in amount and can be disregarded.

Gyrocompass errors



Latitude	Northerly		Southerly		Speed of knots			
	Course Sign of course correction							
	-		+		4	8	12	16
55	0	360	180	180	0,4	0,9	1,3	1,8
	15	345	165	195	0,4	0,9	1,3	1,7
	30	330	150	210	0,4	0,8	1,1	1,5
	45	315	135	225	0,3	0,6	0,9	1,2
	60	200	120	240	0,2	0,4	0,7	0,9
	75	285	105	255	0,1	0,2	0,3	0,5
	90	270	90	270	0,0	0,0	0,0	0,0
60	0	360	180	180	0,5	1,0	1,5	2,0
	15	345	165	195	0,5	0,9	1,4	1,9
	30	330	150	210	0,4	0,8	1,3	1,7
	45	315	135	225	0,4	0,7	1,1	1,4
	60	300	120	240	0,3	0,5	0,8	1,0
	75	285	105	255	0,2	0,3	0,4	0,5
	90	270	90	270	0,0	0,0	0,0	0,0

Gyrocompass errors

Tangent latitude error is a property only of gyros with mercury ballistics, and is easterly in north latitudes and westerly in south latitudes. This error is also corrected internally, by offsetting the lubber's line or with a small movable weight attached to the casing.

Ballistic deflection error occurs when there is a marked change in the north-south component of the speed. East-west accelerations have no effect. A change of course or speed also results in speed error in the opposite direction, and the two tend to cancel each other if the compass is properly designed. This aspect of design involves slightly offsetting the ballistics according to the operating latitude, upon which the correction is dependent. As latitude changes, the error becomes apparent, but can be minimized by adjusting the offset.

Gyrocompass errors

Ballistic damping error is a temporary oscillation introduced by changes in course or speed. During a change in course or speed, the mercury in the ballistic is subjected to centrifugal and acceleration/deceleration forces. This causes a torquing of the spin axis and subsequent error in the compass reading. Slow changes do not introduce enough error to be a problem, but rapid changes will. This error is counteracted by changing the position of the ballistics so that the true vertical axis is centered, thus not subject to error, but only when certain rates of turn or acceleration are exceeded.

Gyrocompass errors

Quadrantal error has two causes. The first occurs if the center of gravity of the gyro is not exactly centered in the phantom. This causes the gyro to tend to swing along its heavy axis as the vessel rolls in the sea. It is minimized by adding weight so that the mass is the same in all directions from the center. Without a long axis of weight, there is no tendency to swing in one particular direction. The second source of quadrantal error is more difficult to eliminate. As a vessel rolls in the sea, the apparent vertical axis is displaced, first to one side and then the other. The vertical axis of the gyro tends to align itself with the apparent vertical.

Gyrocompass errors

On northerly or southerly courses, and on easterly or westerly courses, the compass precesses equally to both sides and the resulting error is zero. On intercardinal courses, the N-S and E-W precessions are additive, and a persistent error is introduced, which changes direction in different quadrants. This error is corrected by use of a second gyroscope called a floating ballistic, which stabilizes the mercury ballistic as the vessel rolls, eliminating the error. Another method is to use two gyros for the directive element, which tend to precess in opposite directions, neutralizing the error.

Gyrocompass errors

Gimballing error is caused by taking readings from the compass card when it is tilted from the horizontal plane. It applies to the compass itself and to all repeaters. To minimize this error, the outer ring of the gimbal of each repeater should be installed in alignment with the fore-and-aft line of the vessel. Of course, the lubber’s line must be exactly centered as well.