Navigation

SS-2004

Summary of previous lectures

- Part A – Fundamentals
  - Introduction
  - Historical review
  - Mathematical fundamentals
  - Physical fundamentals
  - Maps

Outlook

- Part B – Methods of positioning
  - Terrestrial navigation
  - Celestial navigation
  - Terrestrial radio navigation
  - Satellite-based navigation
  - Other navigation techniques

Chapter 6 – Terrestrial navigation

6 Terrestrial navigation / Contents

6.1 Introduction

6.2 Instruments and observables

6.3 Position determination

6.4 Drift determination and correction

6 Terrestrial navigation (1)

6.1 Introduction

6.1.1 Definitions

- Historical development
  - Origins: Determination of **location** by sight (on land, at sea)
  - Further development of **marine navigation** ➔ Use of terrestrial measurements for position determination
  - Today: Use of terrestrial navigation on land, at sea, and in the air
- Terrestrial navigation
  - Dead reckoning
  - Visual navigation
  - Generic position fixing

6 Terrestrial navigation (2)

- Dead reckoning
  - Principle navigation technique of ships and aircraft
  - Terminology
    - Reckoning for **dead water** ➔ without considering current
    - **Deduced** (ded.) **reckoning** ➔ computation of new position from previous one plus course and distance (rather unlikely)
  - **Relative positioning** w.r.t. previous positions
  - Repeated determination of **course** and **distance traveled**
  - **Difficulty**: Non-deterministic character of wind and current ➔ DR positions corrected for wind and current are "estimated" (contrary: Position **fixing**)
  - German terms: „Koppelnavigation“ / „Besteckrechnung“ („Besteck“ des Navigators: Zirkel, Lineal)

6 Terrestrial navigation (3)

- Visual navigation
  - **Fixing positions** w.r.t. **known and visible** landmarks
  - Use of **maps** (trajectory planning) and measurements performed with **instruments** (typical: compass bearings)
  - Typically applied in **marine navigation** ➔ “optical” instruments may be used during most phases of the voyage of a vessel
  - Special technique: **Piloting**
    - Marine navigation
      - **High-precision** navigation in restricted waters
      - **Pilot** ➔ exceptional knowledge of local terrain (no permanent crew member in case of large ships)
    - Aeronautic navigation
      - Fixing **locations** w.r.t. known and visible landmarks (no use of instruments)

6 Terrestrial navigation (4)

- Generic position fixing
  - Involves measurements performed with **nonvisual** instruments
  - Examples
    - Speed log: Speed measurement
    - Radar: Distance and direction measurement
    - Sonar: Depth measurement
    - ...
  - Not included: Terrestrial **radio** navigation (➔ Chapter 8)

6 Terrestrial navigation (5)

6.1.2 Units

- Range and distance measurements
  - Earlier times
    - Use of a wide variety of different range units
  - Today
    - **Meter** (➔ Système International, SI) and deduced units are dominant
    - Certain earlier units are still common
      ➔ Especially in the **English-speaking** part
    - Most important examples: **Foot**, **mile**

Relations of range units

Unit	Relations	Remarks/primary use
Inch [in]	0.0254 m	By definition
Foot [ft]	12 in or 0.3048 m	For heights and depths
Yard [yd]	3 ft or 0.9144 m	For distances
Fathom [fm]	6 ft or 1.8288 m	For depths
Mile		Mainly for distances on land
Milia passuum	about 1 470 – 1 480 m	Roman: 1 000 double steps
Statute	1 760 yd or 1 609.344 m	
Nautical mile		Mainly for distances at sea
International	1 852 m	By definition
UK	6 080 ft or 1 853.184 m	
USA	about 1 854.96 m	One arc minute in latitude

6 Terrestrial navigation (7)

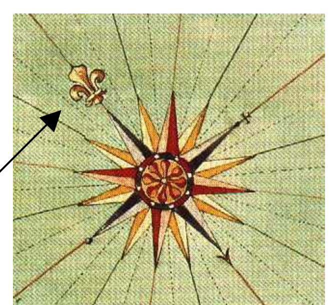
- Velocity
  - Meters per second [m/s] (➔ SI)
  - Kilometers per hour [km/h]
  - Miles per hour [mph]: 1 mph ~ 1.609 km/h
  - Nautical miles per hour [knots]: 1 knot = 1.852 km/h

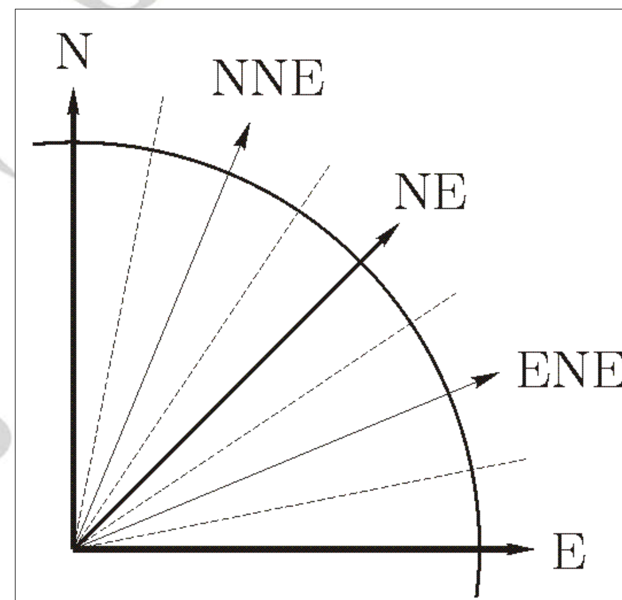
  - Origin of **knot**
    - Speed measurement of **vessels**
    - Use of a **wooden log** on a rope with knots at regular intervals
    - **Time measurement** and counting of knots ➔ Speed of vessel

6 Terrestrial navigation (8)

- Angular quantities
  - Today: Use of **sexagesimal** units
    - 360 degrees [°] for a full circle
    - 60 arc minutes per degree [´]
    - 60 arc seconds per minute [´´]
    - 1 arc minute in latitude ~ 1 nautical mile
  - Traditional (➔ magnetic compass)
    - **Graduation** of right angle (90°) into 8 points (German: „Strich“)
    - 1 **point** = 11.25°

North symbol





6.1.3 Terms

- Velocities
  - Velocity = **Vector** quantity defined by the speed into a given horizontal direction
  - **Speed over ground** (SOG)
    - Actual speed of a craft derived from sequential position fixes during a given time interval
    - For land vehicles: SOG = Indicated speed
    - For vessels and aircraft
      - SOG **differs** from the indicated speed relative to the surrounding water or air (true speed)
      - Reason: **Wind** and/or **current**
  - **Speed made good** (SMG): Average SOG (widely separated pos.)

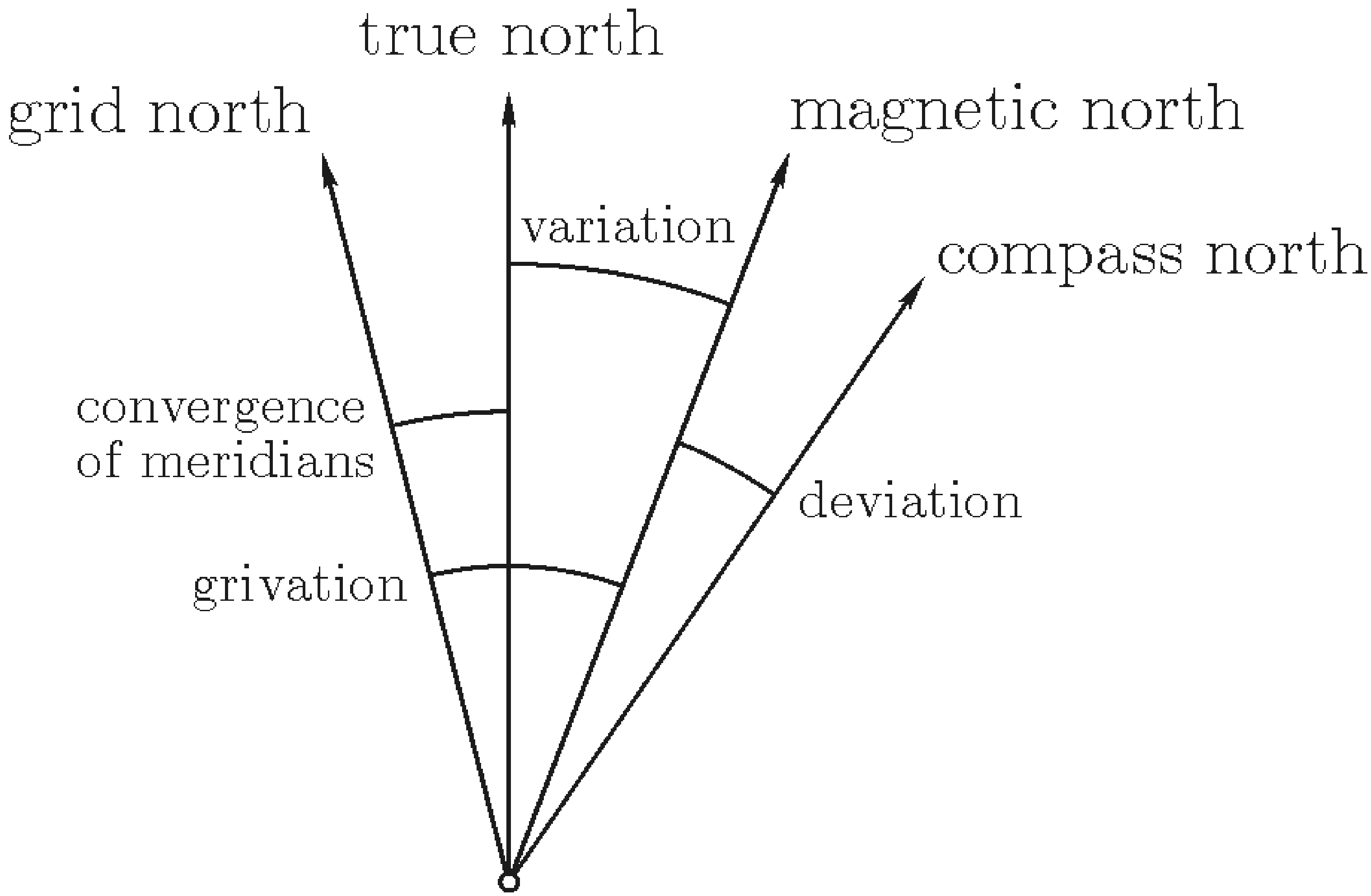
6 Terrestrial navigation (10)

- Angular quantities
  - **Direction**: (Horizontal) position of one point relative to another without reference to the distance between them
  - (German term: „Orientierte Richtung“)
  - Distinguish
    - **Bearing** … for terrestrial targets
    - **Azimuth** … for celestial targets
  - Directions are referred to reference directions
    - **True** north ... earth rotation axis
    - **Grid** north ... grid lines of a map
    - **Magnetic** north ... magnetic field of the earth
    - **Compass** north ... indicated north of a compass

6 Terrestrial navigation (11)

- **Transformations** between reference directions
  - **Variation**: Difference of true and magnetic north
    - First map with variation isolines (isogones) published around 1700 by the astronomer Edmund Halley
    - Variation changes with time ➔ Secular variation
    - Example: Graz 1°10' E 1991 (4' E)
  - **Deviation**: Difference of magnetic and compass north (➔ Calibration of vehicles)
  - **Convergence of meridians**: Difference of true and grid north (e.g. Gauß-Krüger, UTM projection)
  - **Grivation**: Difference of grid and magnetic north

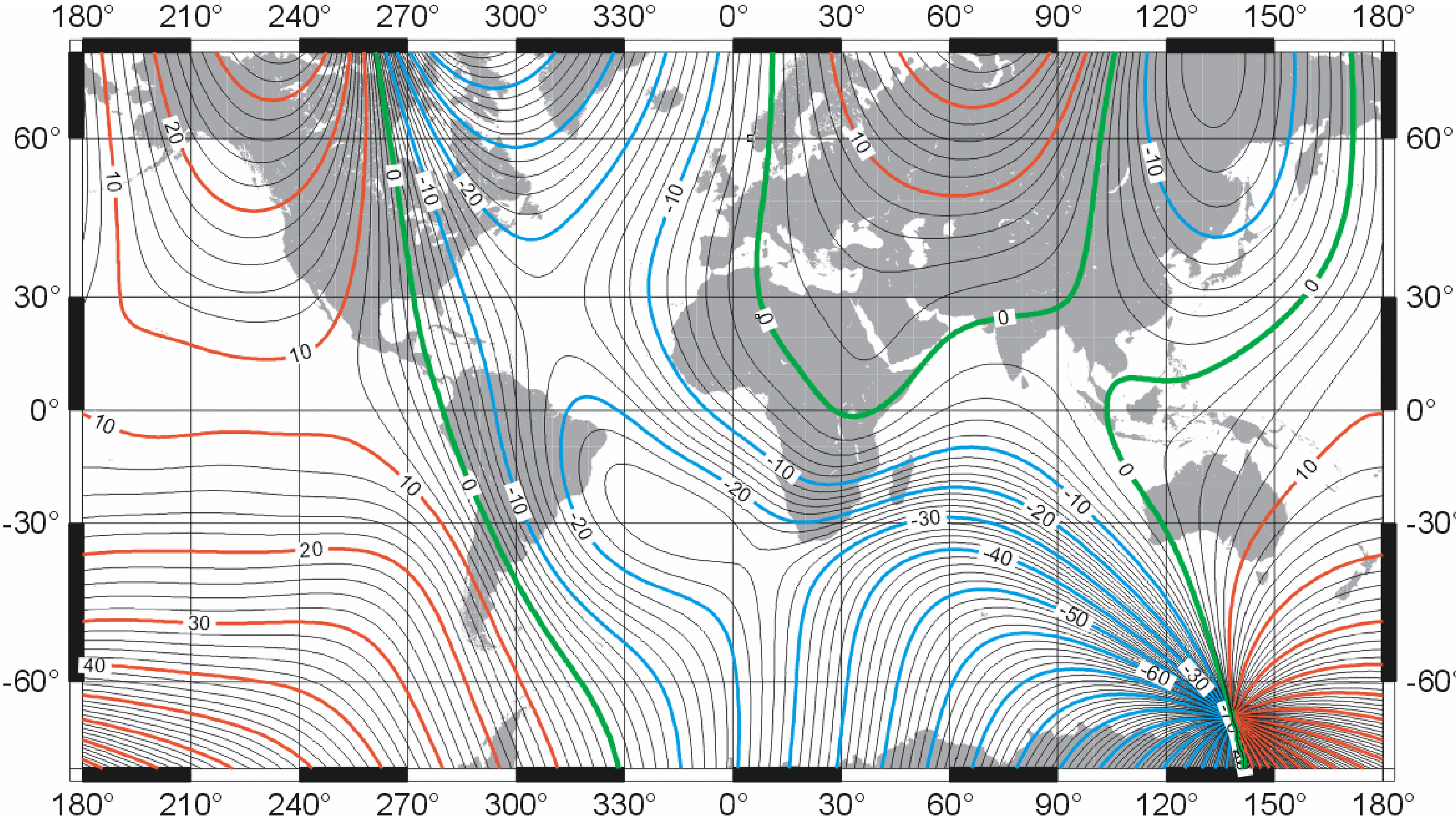
6 Terrestrial navigation (12)



6 Terrestrial navigation (13)

TUG

Declination of the earth magnetic field = **magnetic variation**



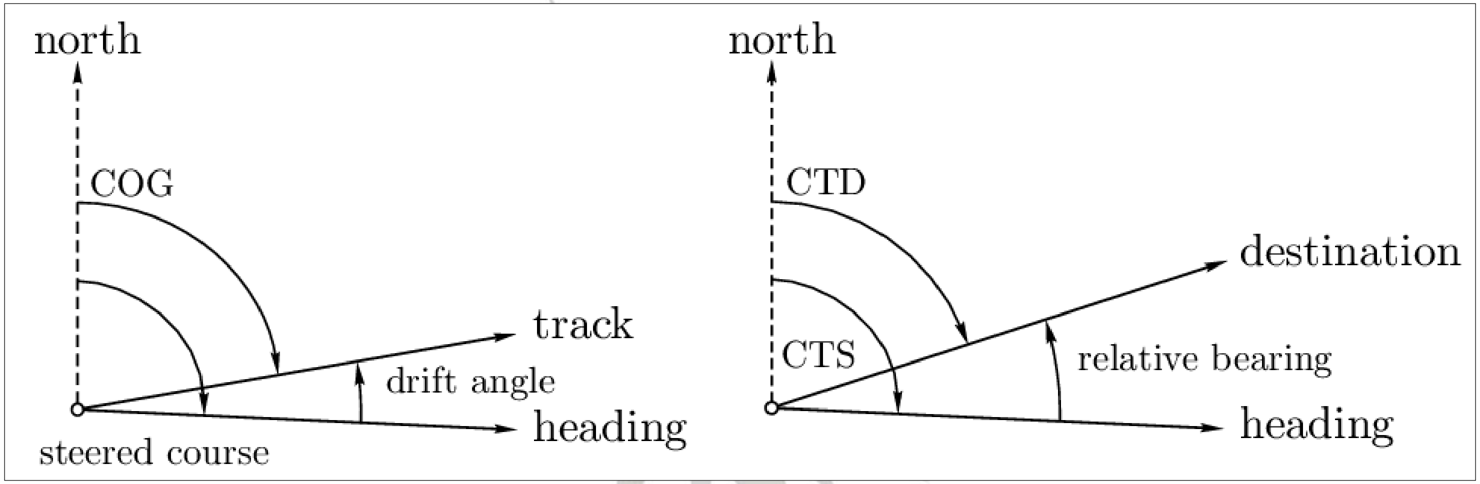
Source: http://www.ngdc.noaa.gov/seg/WMM/image.shtml

6 Terrestrial navigation (14)

- **Heading** = Instantaneous direction of the along axis of a craft
- Courses
  - Distinguish
    - **True** course („rechtweisender Kurs")
    - **Magnetic** course („missweisender Kurs")
    - **Compass** course
  - **Course types**
    - Course to destination (CTD) → nominal course
    - Course over ground (COG) → actual path of the craft
    - Course made good (CMG) → average COG
    - Course to steer (CTS) → to reach a destination

6 Terrestrial navigation (15)

- **Course transformations**
  - Drift angle = COG – steered course (heading)
  - Relative bearing = CTD – CTS



- **Direct waypoint navigation**
  - COG (or CMG) should correspond to the (local) CTD
    - ➔ Relative bearing cancels the effect of drift
    - ➔ Speed must be chosen appropriately (drift is a vector quantity)

6 Terrestrial navigation (16)

– Summary of terms of speed and course

Term	Meaning
True speed	Relative to the surrounding medium
Speed over ground (SOG)	Relative to the earth
Speed made good (SMG)	Average speed from a point of departure to the present position
Course to destination (CTD)	Nominal course
Course over ground (COG)	Actual track
Course made good (CMG)	Average course from a point of departure to the present position
Course to steer (CTS)	Differs from the CTD to correct for drift

6 Terrestrial navigation (17)

6.2 Instruments and observables

- **Types of observables used**
  - Ranges (distances)
  - Heights
  - Depths
  - Velocities
  - Directions
  - Time

6 Terrestrial navigation (18)

6.2.1 Ranges

- Odometer
  - Wide-spread use for dead reckoning in **land-based** applications
    - Rho-theta technique
    - Vehicle navigation systems (VNS)
  - **Principle**
    - Measurement of the **number of revolutions** of the non-propulsed wheels of a vehicle
    - Distance traveled = number of revolutions · wheel circumference
  - Problem
    - **Accumulation of systematic errors** with distance traveled

6 Terrestrial navigation (19)

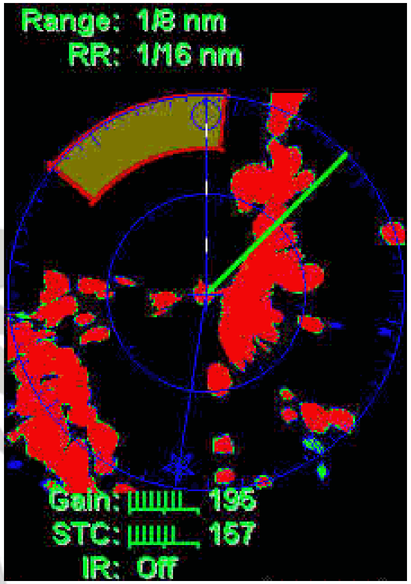
- Laser ranging
  - Acronym: Light amplification by stimulated emission of radiation
  - **Principle**
    - Frequency domain: Visual and neighboring bands
    - Emission of short laser pulse
    - Runtime measurement of pulse between emitter and reflector
    - Runtime ~ double distance
  - Use
    - Wide-spread use in electronic distance measurement (➔ surveying)
    - Support of radar in close-range navigation applications (e.g. harbor approach of vessels)

6 Terrestrial navigation (20)

- Radar
  - Acronym: Radio detection and ranging
  - **Principle**
    - Similar to laser
    - Frequency domain: **Microwaves** ➔ weather-independent
    - Strong transmission but weak reflection
    - Strength of reflected signal (**back scatter**) ➔ information about surface and attitude of reflecting objects
    - Rotating antennas provide distance and direction information
  - Use
    - Marine and aeronautic navigation
    - Collision avoidance
    - Traffic monitoring and control

6 Terrestrial navigation (21)

– Radar techniques
  - **Primary radar**: Only backscatter is recorded
  - **Secondary radar**: Remote equipment transmits answering pulses



– Positioning options
  - **Self-positioning**
    – Craft carries radar equipment
    – Support by external beacons is possible
  - **Remote positioning**
    – Position determination of remote vehicles by controlling station ➔ **Surveillance**

6 Terrestrial navigation (22)

- Sonar
  - Acronym: Sound navigation and ranging
  - **Principle**
    - Similar to laser
    - Use of acoustic waves for range determination
    - Passive (recording only) vs. active (transmission + recording)
  - Use
    - Mainly for **underwater ranging** ➔ known propagation characteristics of sound in water
    - Passive sonar ➔ Surveillance
    - Active sonar ➔ Depth determination

6 Terrestrial navigation (23)

- Indirect ranging
  - Principle
    - Determination of ranges from vertical or horizontal **angle measurements** (➔ sextant)
  - Use
    - Typical: Onboard of boats and ships if no ranging equipment is available
    - Combination of angle measurement with compass bearing ➔ position fix
  - Example ➔ Labs

TUG

6.2.2 Heights

- Barometric altimeter
  - Measurement of **static air pressure**
  - Functional relationship between altitude and air pressure

$$p(h) = p_0 \, e^{-g h \rho_0 / p_0}$$

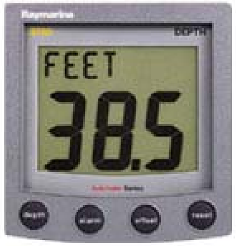
➔ Air pressure decreases with increasing altitude

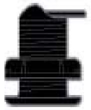
  - Typical use: **Aeronautic** navigation
    - Close to airports: use of current atmospheric parameters
    - Otherwise: standard atmosphere

- Radio altimeter ➔ according to radar principle

6.2.3 Depths

- Use: Marine navigation
- Techniques
  - Lead sounding
    - Traditional technique in seafaring
    - Lead-weighted line with depth marks
      - The weight is thrown ahead of the boat
      - The reading is done when boat passes over it
  - Sonar
    - Active sonar for depth measurements
    - Also denoted as “fish finder”





- Note
  - When using depth indications of nautical charts, consider the **vertical datum** of the chart

6 Terrestrial navigation (26)

6.2.4 Velocities

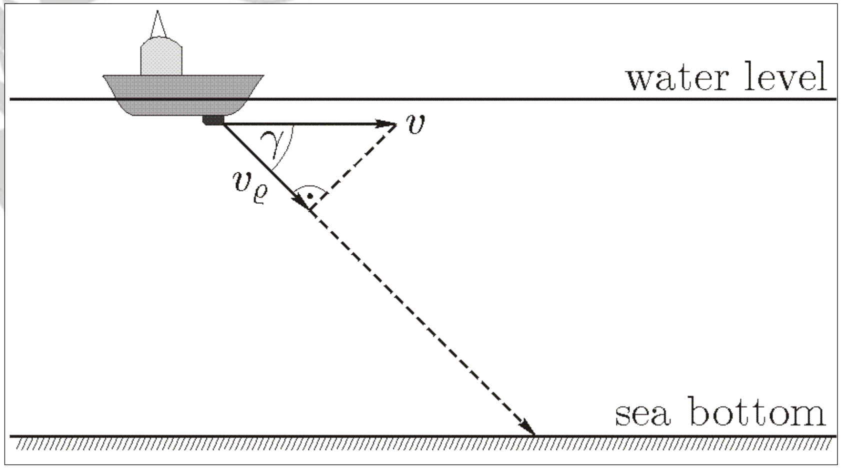
- Mechanical instruments
  - Odometer
  - Stream log: E.g., paddle wheel
  - Air-speed indicator: Pressure sensor (dynamic air pressure)

- Mach meter
  - Indicates the **speed of sound**, which decreases with increasing temperature (~height)

- Acoustic correlation sonar
  - Recording of **sea ground profiles** by two sonar transducers
  - Delay of profile ➔ speed of the vessel

- Doppler sensors
  - **Doppler sonar speed log**
    - Transmission of a sound wave towards the sea ground
    - Frequency shift of reflected signal is proportional to the radial velocity of the vessel w.r.t. the sea ground
    - Speed of sound in water: c_{sw} ~ 1500 m/s
    - **Doppler shift** relationship

$$\Delta f = f_r - f_e = -\frac{2v_\rho}{c_{sw}} f_e$$



  - **Airborne Doppler speed meter**

6 Terrestrial navigation (28)

- Differentiation of ranges
  - Determination of **radial velocity**
  - Basic relation

$$v_\rho = \frac{\rho_2 - \rho_1}{t_2 - t_1}$$

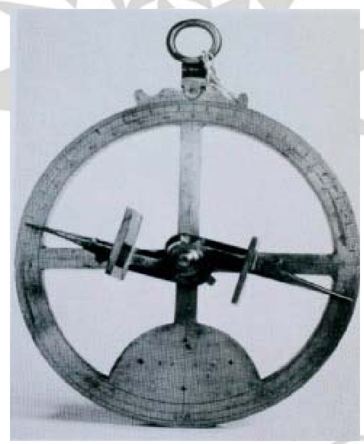
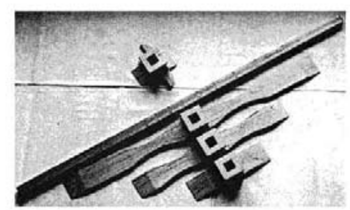
- Integration of accelerations
  - Basic principle of **inertial navigation**

$$\dot{\mathbf{x}}(t) - \dot{\mathbf{x}}(t_0) = \int_{t_0}^{t} \ddot{\mathbf{x}}(\tau)\, d\tau$$

6.2.5 Directions

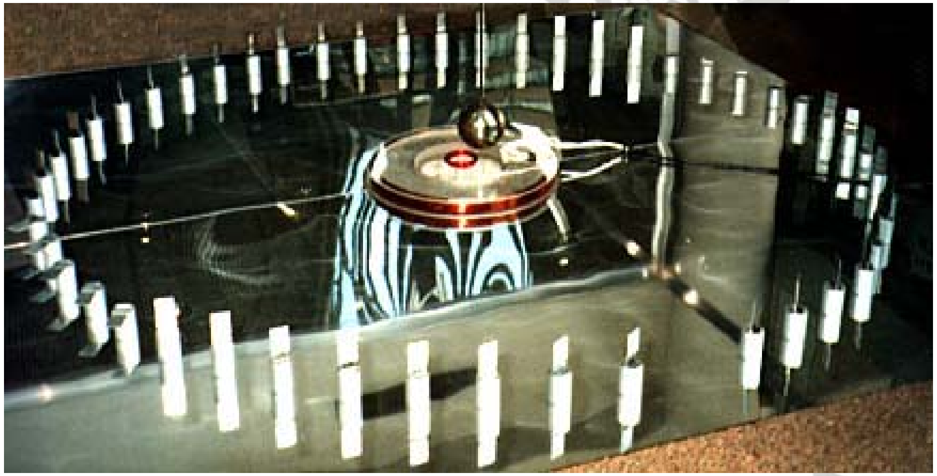
- Observations without instruments
  - Objects in visual range (also: in line, transit bearing)
  - Seaman's eye (visual sightings by experienced mariners)

- Visual instruments
  - Astrolabe
  - Cross staff
  - **Sextant** ➔ Labs

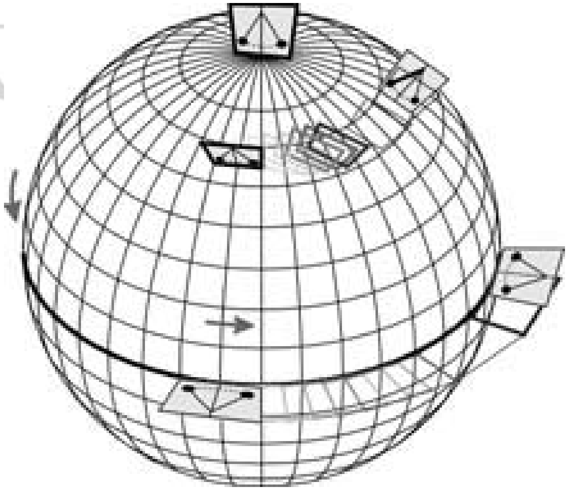




- Compasses
  - **Magnetic compass**
    - “Conventional” compasses
    - Electronic compasses (**flux gate**)
      - Three-dimensional properties of the magnetic field
      - Determination of horizontal bearing using inclination sensors
      - Drawback: Energy supply required (contrary to conventional)

- **Gyroscope and gyrocompass**
  - **Gyroscope**: Basic principle (➔ mechanics)
    - Fast spinning, freely mounted body preserves plane of rotation despite of external forces (cf. **Foucault pendulum**)



http://www.abc.net.au/surf/pendulum/default.htm

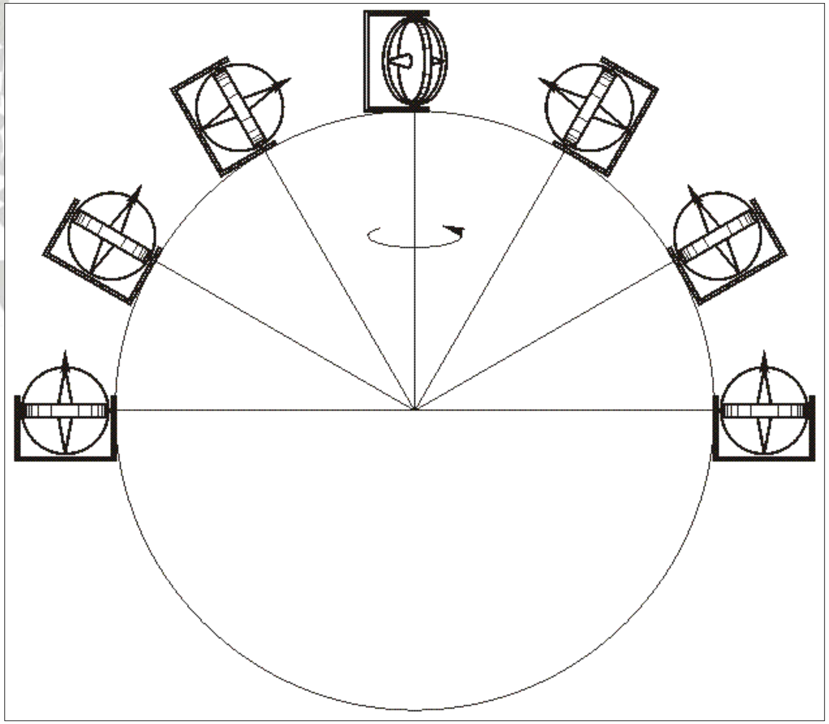


http://www.frombork.art.pl/Ang23.htm

6 Terrestrial navigation (32)

- Types of mechanical gyros
  - **Free gyro**: Spinning body is freely suspended in two gimbals
  - **Forced gyro**: Spinning body is suspended by only one gimbal ➔ Precession of spin axis

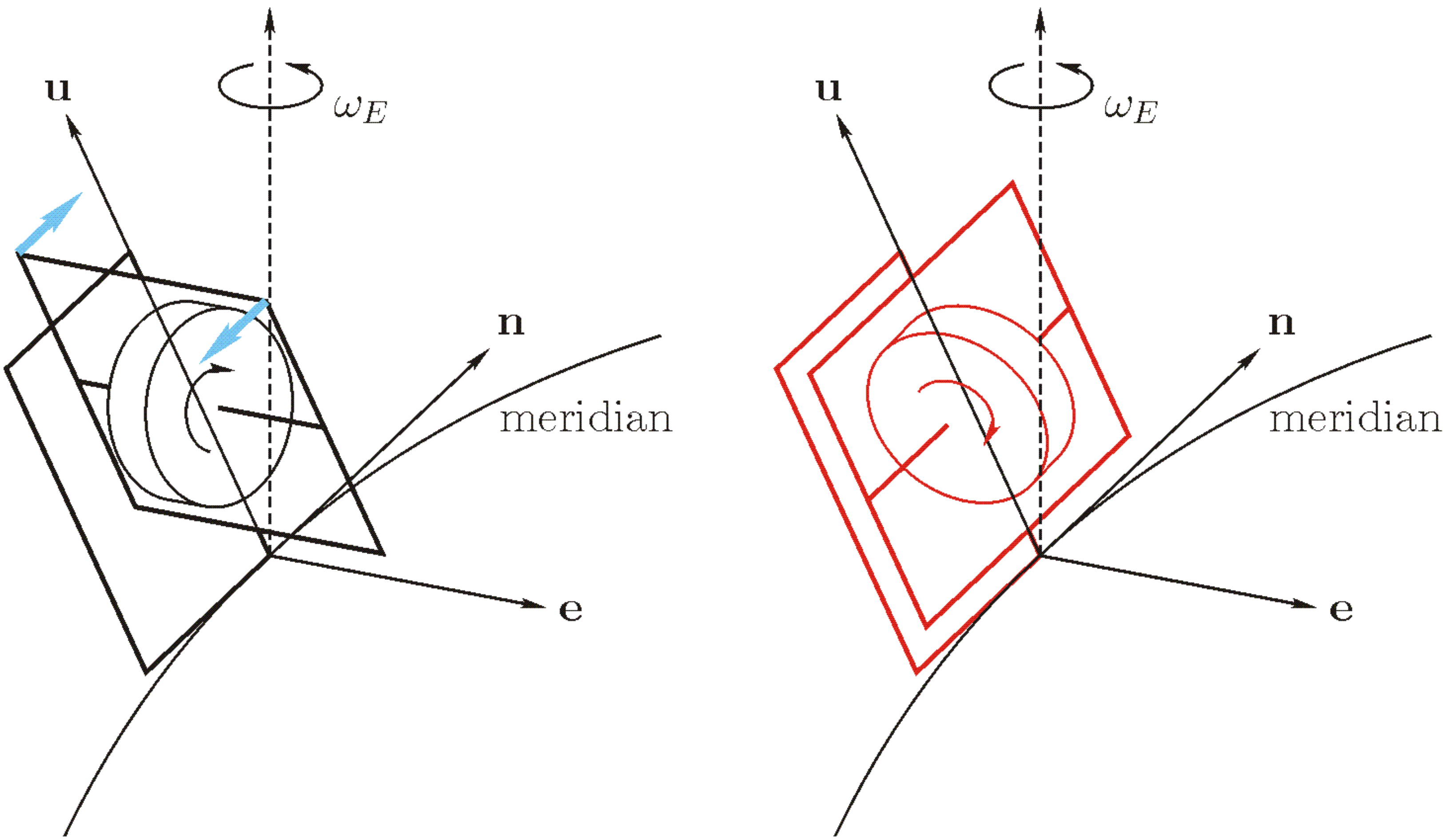
- **Gyrocompass**
  - Provides bearings w.r.t. true (astronomic) north
  - Realization: Forced gyro (**declination gyro**)
  - Precession aligns spin axis with meridian plane



- Modern gyros: **Laser** sensors

6 Terrestrial navigation (33)

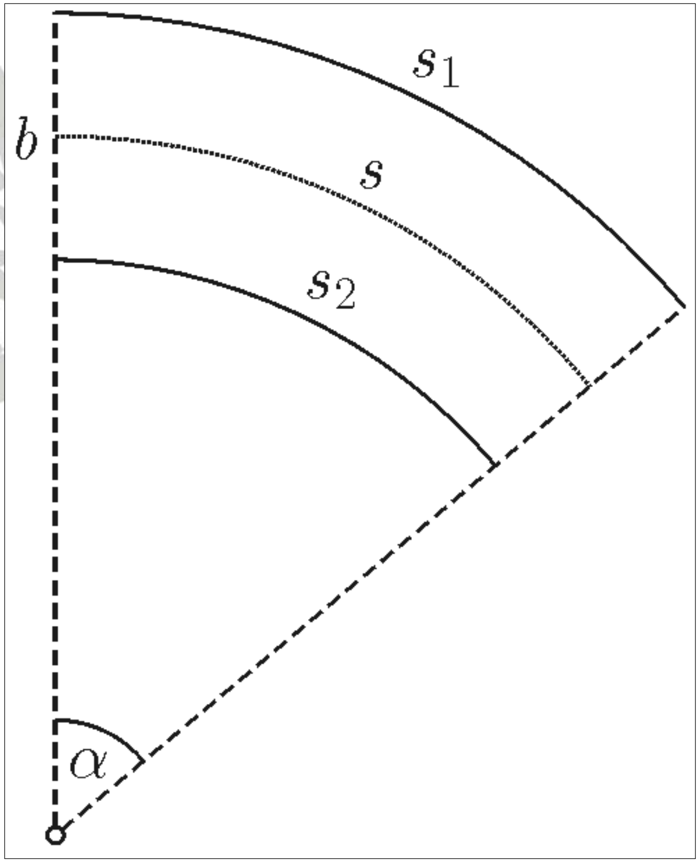
- Precession of the declination gyro



- Differential odometer
  - Two odometers attached to opposite wheels of a vehicle
  - Basic relations

$$s = \frac{s_1 + s_2}{2}$$

$$\alpha = \frac{s_1 - s_2}{b}$$



6 Terrestrial navigation (35)

6.2.6 Time

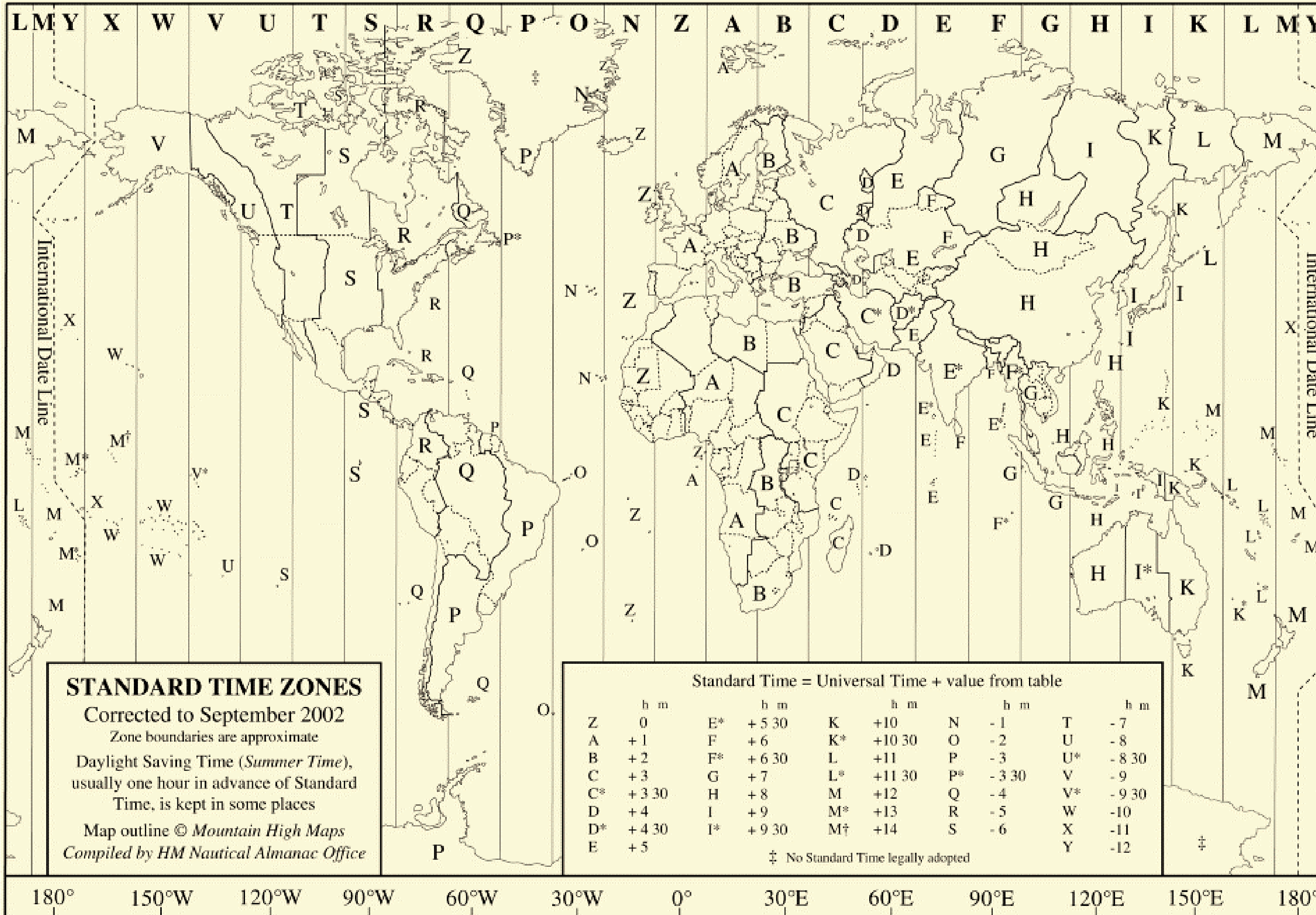
- General remarks
  - Time determination is an **integral part of navigation**
  - Geodetic coordinates ➔ **Longitude determination** implies time
  - Essential for many range and speed determination tasks

- Time systems
  - Earth rotation
    - Solar time
    - Sidereal time
  - Planetary motions
    - Dynamic time
  - Periodic atomic processes

6 Terrestrial navigation (36)

- Absolute time
  - Greenwich meridian
  - Local meridian or time zone
  - Time standard: **Universal time coordinated** (UTC)
    ➔ based on atomic clocks
  - **Measurement**
    - Clocks
    - Broadcast time signals (e.g. DCF-77)
    - Radio navigation systems (e.g. GPS, Loran-C)

- Relative time ➔ time intervals
  - Measurement
    - Chronometer
    - Stop watch



	h m		h m		h m		h m		h m
Z	0	E*	+ 5 30	K	+10	N	- 1	T	- 7
A	+ 1	F	+ 6	K*	+10 30	O	- 2	U	- 8
B	+ 2	F*	+ 6 30	L	+11	P	- 3	U*	- 8 30
C	+ 3	G	+ 7	L*	+11 30	P*	- 3 30	V	- 9
C*	+ 3 30	H	+ 8	M	+12	Q	- 4	V*	- 9 30
D	+ 4	I	+ 9	M*	+13	R	- 5	W	-10
D*	+ 4 30	I*	+ 9 30	M†	+14	S	- 6	X	-11
E	+ 5							Y	-12

- Clocks
  - Quartz clocks ➔ **piezoelectric effect**
    - Voltage is produced between the two surfaces of a **solid dielectric** if a **mechanical stress** is applied and vice versa
    - Piezoelectric materials resonate within **narrow frequency bands** ➔ Stability around 10^{-6} per day
  - Atomic clocks
    - Atoms appear on **different energy levels**
    - A change of the energy level gives rise to a **radiation** with a frequency proportional to the energy difference
    - Under constant conditions, the **frequency** of the released radiation remains **constant**
      ➔ Stability of 10^{-13} to 10^{-15} per day

6.3 Position determination

6.3.1 Techniques

- **General**: Absolute (fix) vs. relative positioning
- **Techniques**
  - Dead reckoning
  - Multiple ranging
  - Multiple plotting (also: cross-bearing fix)
  - Generic position fixing
- **Solution**
  - Graphical using LOPs
  - Analytical
    - Rigorous
    - Approximate

6 Terrestrial navigation (40)

6.3.2 Non-simultaneous observations

- Situation
  - In many cases, multiple measurements to different targets cannot be performed simultaneously
  - **Low** requirements ➔ non-simultaneity can be ignored
  - **High** requirements ➔ running fix (also: transferred-bearing fix)
    - Correction of measurements for eccentricity
    - Correction of landmark positions
  - Position change is considered by **dead reckoning**

- Example
  - Bearing measurements to two landmarks A, B
  - Correction of position of landmark A

6.4 Drift determination and correction

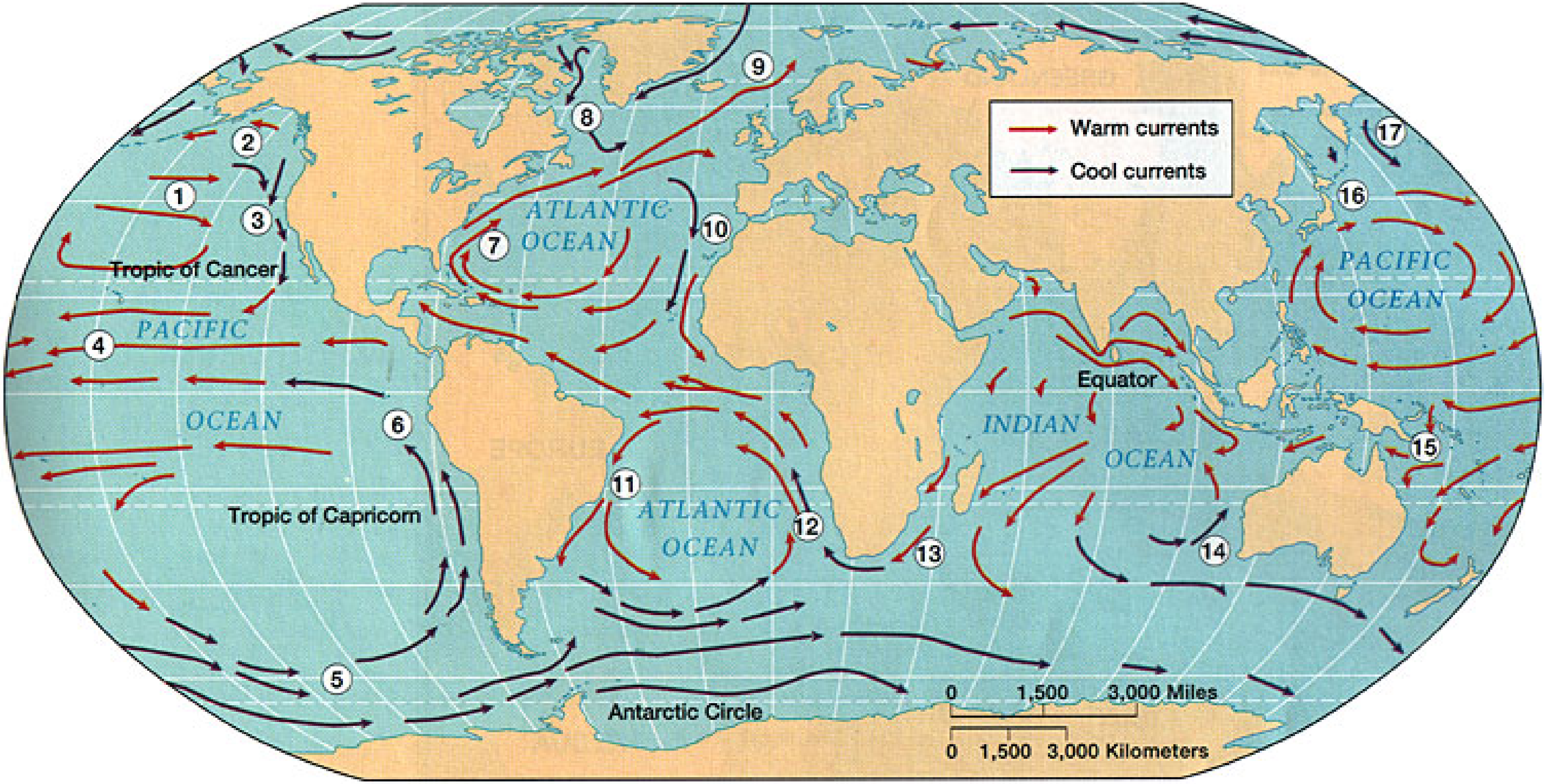
- General remarks
  - **Drift** = Displacement of a craft by wind and/or current
  - **Wind** (leeway) ➔ Aircraft and vessels (Predictable: Major wind systems, e.g. trade winds)
  - Tidal and other **currents** ➔ Vessels (Predictable: Main tidal currents, principle ocean currents, e.g. Gulf Stream)
  - Only **dead reckoning** is influenced by drift

- Drift components
  - Along track ➔ Impact on the chosen speed (➔ SOG)
  - Across track ➔ Impact on the steered course (➔ COG)
  - Drift correction requires drift determination as a first step

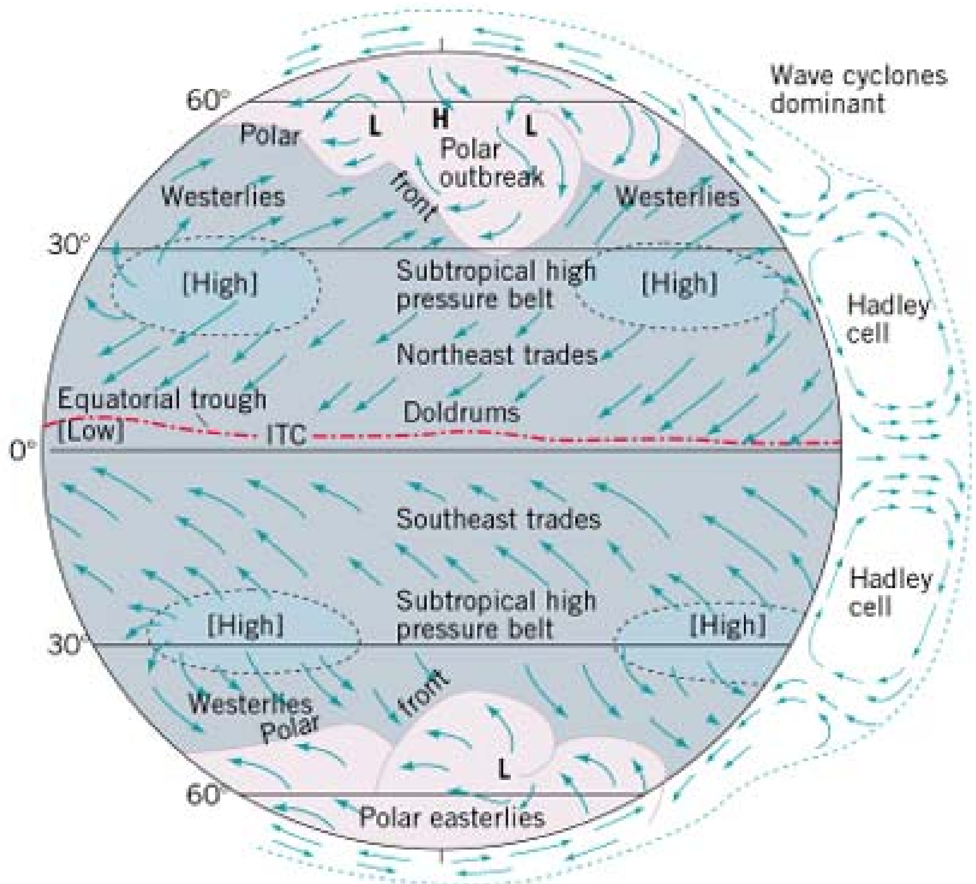
6 Terrestrial navigation (42)

- Drift determination
  - Components (actual values ➔ non-deterministic)
    - Flow direction
    - Flow strength
  - Options
    - Estimation
    - Measurement
    - Computation from position data
  - Solution ➔ **Speed triangle** (also: Wind triangle)
- Drift correction
  - Correction of future course and speed with previously determined drift parameters
  - Note: Drift parameters must be frequently re-determined

Main ocean currents



Main wind patterns



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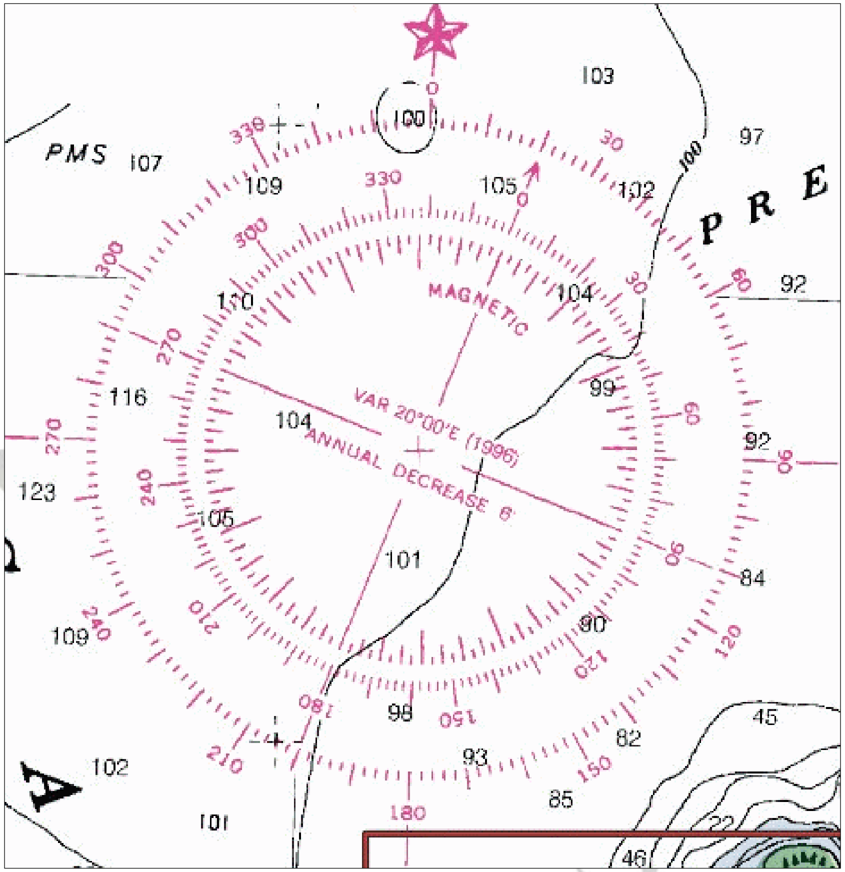
6 Terrestrial navigation / Labs (1)

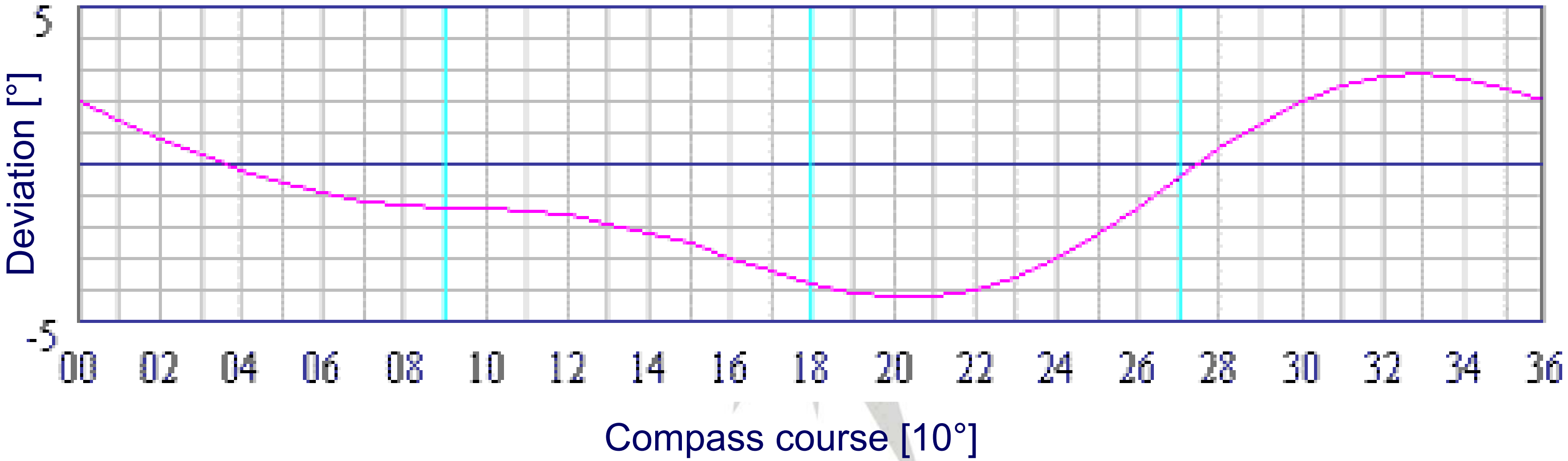
Example: **Compass rose** in a nautical map



Main use: Transfer of courses, correction of variation

6 Terrestrial navigation / Labs (2)

Example: **Compass deviation table**



http://www.sailingissues.com/navcourse3.html

Principle of the sextant