

Memo 9: Navigation

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Last revised: 2026-05-06

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1. Introduction

- As a bare minimum, we need:
 - Map
 - Compass
 - Timepiece
 - Speed
 - Altitude
- Practice poor situations, judging distance visually

2. The Earth

- The equatorial diameter of the Earth is 23nm more than through the poles (due oblate spheroid).
- True North and True South reflect the poles around the axis of rotation (which is 23.5°)
- Longitudinal lines join the poles (meridians of longitude)
- Latitudinal lines are parallel with the equator (parallels of latitude)
- ▸ The equatorial diameter of the Earth is 23nm more than through the poles (due oblate spheroid).
- True North and True South reflect the poles around the axis of rotation (which is 23.5°)
- Longitudinal lines join the poles (meridians of longitude)
- Latitudinal lines are parallel with the equator (parallels of latitude)
- The distance covered by travelling exactly one minute of latitude is one nautical mile (by definition)
 - covering this distance in a hour is one knot (by definition)
- You can derive the Earth's circumference by $360 \times 60 = 21600$ both arcminutes and therefore nautical miles
- "Departure" is the name given to the discrepancy in distance at varying latitudes
 - $\text{distance (nm)} = \Delta \text{ longitude (mins)} \times \cos(\text{latitude})$
- Great vs small circles: great circles must be equivalent to a slice through the sphere
- Rhumb lines cross all meridians of longitude at the same angle
 - All small circles are Rhumb lines
- Magnetic north varies from true north due geographical features
 - "Variation"
 - Lines of equal magnetic variation are "isogonals"

3. Time

- The sun appears to track along a great circle over the year at an angle of 23°27' to the equator
- The earth revolves anti-clockwise when observed from the true north pole
- The apparent day varies in duration due to the elliptical orbit around the sun
- The sidereal day is measured when observing a fixed point an infinite distance away
 - It is always 23 hours, 56 minutes and 4.091 seconds
- The mean day is merely a convenience unit

- 24 hour day
- 15° per hour
- Local mean time represents the subtle differences in perceived time in every location (where midday is defined as the sun directly overhead)
- Local standard time balances local mean time by deciding on a reasonable per-country time zone
- Time zones can be somewhat calculated by the assumption that 15° per hour is the earth's rotation rate

4. Mapping the Earth

- Maps are trying to achieve the following properties:
 - Conformity (orthomorphism): it is desirable to have latitudes and longitudes cross perpendicularly
 - Equivalence: the scale is consistent across the entire map
- Projections
 - Lambert Conformal Conic Projection
 - Place a cone over one hemisphere of the earth, such that the 45° latitude is tangent to the cone
 - A straight line on this projection is very close to a great circle
 - However the scale is only consistent at the points where the cone contacts the sphere. To counteract this, the cone can be submerged into the sphere, producing two intersectional circles, the "Standard Parallels". Distance is then accurate at both of these curves
 - Direct Mercator Projection
 - The earth is placed in a vertical cylinder of paper and projected as such
 - This projection is conforming
 - This projection is not equivalent, so is often only used for small areas especially near the equator so as to not affect navigation
 - Transverse Mercator Projection
 - The earth is placed in a horizontal cylinder of paper and projected
 - This projection is conforming
 - Again, this projection is not equivalent, so is often best for small areas especially near the poles
- Each map is overlaid with the lat/long grid with rectangles of 30 minutes
- Magnetic variation is shown on charts
 - To fly true north, fly magnetic north plus the variation
 - "West is best" (+), "East is least" (-)

5. Aviation Charts

- Two main chart scales used:
 - "half mil" (1:500000)
 - uses a Lambert Conformal Conic project
 - shows all airspace below FL195

- “quarter mil” (1:250000)
 - Uses the Transverse Mercator projection
 - No airspace shown above FL55 or 5000ft AMSL
- Charts are updated yearly
 - It is illegal to fly without an up-to-date chart
- Chart features
 - Terrain
 - Note that no elevation is shown until it reaches 500ft
 - Obstructions
 - Note that no obstruction is shown until it is taller than 328ft AGL
 - Maximum Elevation Figures (MEFs)
 - Not safety altitudes
 - The highest terrain + the highest possible obstacle (either the highest mapped or highest terrain + 328ft)
 - Ceilined to the nearest 100ft
 - Danger areas (Dxxx)
 - With a ‘*’, these have applicable by-laws
 - Some are activated by NOTAM
 - Some have a DACS (Danger Area Crossing Service)
 - Some have a DAAIS (Danger Area Activation Information Service)
 - Restricted areas (Rxxx)
 - Prohibited areas (Pxxx)
 - HIRTA
 - GVS (Gas Venting Station, sometimes with upper altitude of validity)
 - Navigational aids
 - Instrument approaches
 - Ground aeronautical features
 - Airspace
 - Items of cultural significance to aid navigation
 - Major Pols
 - Good features: line features, water features, tall masts
 - Bad features: disused airfields, woods

6. Navigation Principles

- Dead Reckoning
 - “Track error” is the angular difference between the required track and the track made good
 - “Wind correction angle” (aka. “drift angle”) is used to compensate for wind velocities
 - “Track Made Good”: the actual a/c track across the ground
 - “Required Track”: the required path across the ground
 - “Heading”: the direction the aircraft is heading in
- Common time abbreviations:
 - ETD
 - ETA
 - EET: Estimated elapsed time, duration to destination

- ETE: Estimated time en-route, duration between waypoints
- ATD
- ATA

7. Navigation Factors

7.1. Altitude

- Maps and charts are always with reference to MSL
- We need to understand our altitude to understand if we are at increased risk
- We can follow the semi-circular rule (odd north east, even south west) to reduce the risk of conflict. +500ft under VFR.
 - Note that the semi-circular rule refers to magnetic track, not a/c heading
- Recall also the transition layer. When passing the transition altitude (3000ft in UK) change to SPS and fly a flight level
 - In the other direction, change at the transition level back to QNH
 - The transition layer is the layer of air between these two altitudes.
- Recall also that the altimeter reads a line of constant pressure!
 - Flying from high -> low pressure will over-read
 - This is compensated by each altimeter setting region using the lowest forecast QNH in the next two hours from the area
- Recall also that altimeters are calibrated to ISA, so any deviation from ISA will result in an altimeter error
 - Flying from high -> low temperature will over-read
- To calculate true altitude, we:
 - Compensate for pressure deviation from ISA, giving our pressure altitude
 - Compensate for temperature deviation from ISA, giving our true altitude
 - Pressure altitude can be read off by setting your altimeter sub-scale to the same as ISA, i.e. 1013hPa.
 - Alternatively, we can calculate it knowing that 30ft = 1hPa

7.2. Airspeed

- Instrument errors: the mechanical play in the instrument
- Position error: the difference in angle between the pitot and the airflow and similar causes
- CAS corrects for these errors, find a lookup table in the POH
- Environmental error
 - ASI is calibrated against ISA
 - To calculate TAS, use the CAS and pressure altitude on the whiz wheel
- For aircraft that exceed 300KIAS, we also need to compensate for air compressibility. This can be done on the whiz wheel

7.3. Bearing

- Charts have grid lines to true north
- Charts also show the magnetic variation for the area it covers by depicting isogonals by a dotted line
- Compass deviation must be accounted for, by the compass deviation card
 - Accounts for the effect of aircraft components on the compass
- The B field of the Earth dips inwards at the magnetic poles, which also decreases accuracy near the magnetic poles
- The compass is usually suspended in alcohol, so can be affected by any external acceleration that isn't downwards. Therefore, it must be read at a constant speed, constant heading, wings level
- To compensate for dip error when turning, remember UNOS (in the northern hemisphere), "Undershoot North(erly headings), Overshoot South(erly headings)"
- The compass is constructed with weight at the north and south indications, as such it cannot dip if flying east-west
 - Therefore if on an easterly heading and the a/c accelerates, the compass ring will swing northwards (and vice-versa)
 - Remember ANDS: accelerate north, decelerate south (in the northern hemisphere)
- Remember TVMDC (True Vikings Make Deadly Company)
 - True Heading, Variation, Magnetic Heading, Deviation, Compass Heading
 - Calculation goes from left to right, so invert if going the other way!
 - Drift always comes last!

7.4. Fuel Calculations

It is worth remembering that:

$$1 \text{ imp gal} = 1.2 \text{ US gal} = 4.5 \text{ l}$$

8. Navigation Planning

- Elect an alternate
- Consider marking waypoints with circles to avoid covering features
- Draw a line between waypoints
- Segment each leg into quarters
- Draw 10° fan lines
- Measure leg distances
- Measure true tracks
- Determine MSA (and max alt) for each leg
- Look at weather, particularly cloud bases, decide a planned altitude
- Calculate TAS (need CAS and temperature from F214)
- Calculate GS and true heading (need wind from F214)
- Find the magnetic variation and calculate the magnetic heading
- Adjust for deviation and calculate flown heading (if available)
- Calculate the leg times
- Calculate fuel usage, +5%, +diversion, +final resv (30m day, 45m night), +15m for taxi out and in

- Calculate W&B figures and endurance
- Select relevant ATSUs and frequencies
- Determine 0° level
- Determine sunset time
- Mark key features with an arrow in a different colour on the feature on the chart
- Mark beside each leg the track, distance and ETE

Then before you set off:

- Ensure you have all relevant charts and information
- Gain PPR if needed
- Check NOTAMs
- Check Wx

9. Practical Navigation

9.1. Departure

Don't:

- navigate straight away from take-off
- miscalculate leg times to account for unexpected climbs

Do:

- climb and get settled
- stay organised, including FREDA checks
- start navigating from the overhead, or from a nearby point

9.2. Turning Points

Don't:

- panic

Do:

- time noted in the PLOG
- turn
- transmit if needed
- test DI against compass
- tally: update the PLOG

9.3. En-route

Don't:

- Fixate on instruments
- Sit back and enjoy the view
- Fly feature-to-feature
- Expect flight times to be exact

Do:

- Look out
- FREDA
- Maintain heading
- Maintain altitude
- Maintain timeliness
- Revise ETA and heading
- Plan ahead

9.4. Destination

Don't:

- Get flustered
- Join "straigh in"
- Relax

Do:

- Listen
- Decide: on a join (overhead/downwind!)
- Complete: your PLOG, a/c log, your pilot log
- Refuel
- Refresh: eat

10. Correcting for Errors

- 1:60 rule: for each degree of track error, the aircraft will be 1 nm off track after 60nm
- track error = $\frac{\text{distance off track (nm)}}{\text{distance gone (nm)}} \times 60$
- Correct by twice the track error!!
 - Or, find the closing angle:
 - closing angle = $\frac{\text{distance off track}}{\text{distance to go}} \times 60$
 - then adjust heading by track error + closing angle

In the air, just use fan lines and quarter-leg markers. Correct angle by:

- from the $\frac{1}{4}$ marker: track error $\times 1.5$
- from the $\frac{2}{4}$ marker: track error $\times 2$
- from the $\frac{3}{4}$ marker: track error $\times 3$

11. Unplanned Diversions

- Need to be able to estimate distance, angle and time
- The width of a thumbnail is approx 5nm
- To divert around a hazard, you can use an equilateral triangle, i.e. turn 60° around the hazard, fly the time it would take to travel through it, then turn 60° again and fly the same time again
 - Mark this on the PLOG

To divert:

- Draw the new line
- Estimate the new magnetic track (use VOR roses if close by)
- Note the current time
- Turn onto the uncorrected heading
- Estimate the required heading and turn to it
- Calculate an ETA at both the destination and half-way point
- Check new MSA
- Check for airspace
- Adjust altitude
- Check for frequencies
- Correct as normal at the half-way point

Allowing for wind with a DI:

- Find the maximum wind correction angle:
 - $WCA_{\max} = \frac{60}{TAS} \times \text{wind speed}$
- Look at the angle and determine how far across laterally (crosswind) or vertically (headwind) the DI it is.
- Use this to approximate the trigonometric function to estimate the WCA.

On an EFIS, just use the track bug!

12. Lost Procedures

- Don't be ashamed
- Consider the risk factors:
 - Poor flight planning
 - Errors in planning
 - Flight errors
 - Poor visibility
 - Landmark misidentification
 - Forced off-plan by ATC
 - Misuse of navigation equipment
- If you are lost:
 - Don't panic
 - Note the time
 - Consider a radar service
 - Speak to 121.500 MHz, squawking 0030.
 - Check the DI against the compass
 - Note down any error and try to establish where an error may have been made
 - Check PLOG for errors
 - airspeed/heading mismatch?
 - Calculate endurance
 - Check daylight remaining
 - Adopt a slow, safe cruise
 - Read from ground -> chart
 - Find ground features first, then locate on the chart
 - Consider using radio nav aids
 - Use your mobile phone to call someone

- As last resorts:
 - Follow a line feature
 - Land the aircraft
 - Consider a number of low passes before choosing a field

13. Special Navigation

- Navigation at night
 - Objects appear closer than they are
 - The yellow areas on charts represent the appearance at night of towns
 - Winds are more substantially different between surface and aloft due to the diurnal effect
 - Forced landings
 - Don't try to land on roads (this isn't the US!)
 - Use local knowledge
 - Pick a dark area: hopefully it won't have buildings
 - Use your night vision: turn off internal a/c lights
 - Use landing light near to the ground
- Navigation at minimum level
 - Not recommended
 - Distance judgement is off
 - Feature shapes are distorted
 - Some features may be hidden behind high ground
 - Consider using low safe cruise
 - Make use of the "transit" navigation method
- Navigation over featureless terrain
 - Best avoided
 - Use a line feature by preference
- Transit navigation method
 - Uses a cross-cut of distant visible features to establish position

14. Radio Basics

LF/MF:

- Consider ground wave and sky wave propagation in LF/MF bands
- You can also get coastal refraction
- Aircraft components can couple and affect the antenna and receiving equipment
- ADF uses two cross-polarised antennas. Banking the aircraft affects the processing of this data.

VHF:

- LoS
 - $\text{LoS (nm)} = 1.23 \times (\text{sqrt aircraft altitude (ft)} + \text{sqrt ground antenna altitude (ft)})$
- Designated operational coverage (DOC)
 - Found in AIP ENR 4.1.1.1
- Morse idents

15. RADAR

- Primary radar
 - Detects metal
 - Detects weather (clutter)
- Secondary radar
 - Transponder
 - A: squawk code
 - C: A + altitude
 - S: ADS-B

16. Radio Navigation

- VHF DF is rarely available these days given RADARs prominence
 - QDM: mag to station
 - QDR: mag from station
 - QUJ: true to station
 - QTE: true from station
 - Two bearings needed to get a position
 - Accuracy classes:
 - Class A $\pm 2^\circ$
 - Class B $\pm 5^\circ$
 - Class C $\pm 10^\circ$
 - Class D $> 10^\circ$
- ADF
 - Long range beacons require a beat frequency oscillator (BFO) for ident
 - Short range beacons can be identified on the ADF setting
 - Bearings are magnetic as they are relative to the DI
 - Remember SID: Select, Identify, Display
 - Cone of silence in the 80° above the NDB
 - During the day, approx $\pm 6^\circ$ error
- VOR
 - Remember SID: Select, Identify, Display
 - Cone of confusion in the 100° above the VOR
 - Error is approx $< 5^\circ$
- DME
 - UHF time-of-flight
 - Sometimes can be slaved to the NAV radios
 - Remember SID: Select, Identify, Display
 - Distance is euclidean, so does consider altitude!
 - GS and time are only accurate if flying to/from the station
 - However you can use this to fly a DME arc by keeping GS as 0

17. GNSS

- Causes of positional errors:
 - Atmospheric delays
 - Satellite clock errors
 - Orbit uncertainty
 - Multi-path errors
 - Receiver noise
 - Therefore, positional accuracy of between 10-30m
- Errors are corrected over time by satellite link from a ground measuring station
- Dilution of precision
 - Positional accuracy depends on satellite positions relative to the receiver
- Receiver Autonomous Integrity Monitoring (RAIM)
 - Ensures that the receiver sees enough satellites
 - Can detect (and sometimes exclude) erroneous data

18. Moving Maps

- Types
 - Panel mounted
 - Portable (phones, etc.)
- Alerts can link into headsets if compatible
- Mobile data may not always be available
- Temperature sensitivity
- Be familiar with them and their configuration!
- Tracks can be incredibly accurate, could meet someone mid-air if a magenta line follower!