SCIENCE CASE FOR LEO QUANTUM MISSIONS: OP(C)M & Q-ACE

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WHY LOOK AT THE SCIENCE CASE FOR AN INSTRUMENT

- /// Space instrumentation is designed for a specific purpose in space
- /// This is especially true for new quantum technologies – these do measurements/processing in novel waves
- /// That quantum technologies are so specific – typically means they are focused at a particular mission
- /// The mission needs developing at the same time, as the instrument
- /// Also the mission has requirements, needs that the (quantum) instrument must meet
- /// This helps drive the development of the instrument, so it is designed with the needs of the target mission
- /// This talk looks at science and missions for two quantum measurements:
  - Optically Pumped (Caesium) Magnetometers – Magnetic Sensing
  - Cold Atom Interferometry – Accelerometer Sensing
- /// These are covered in next two talks

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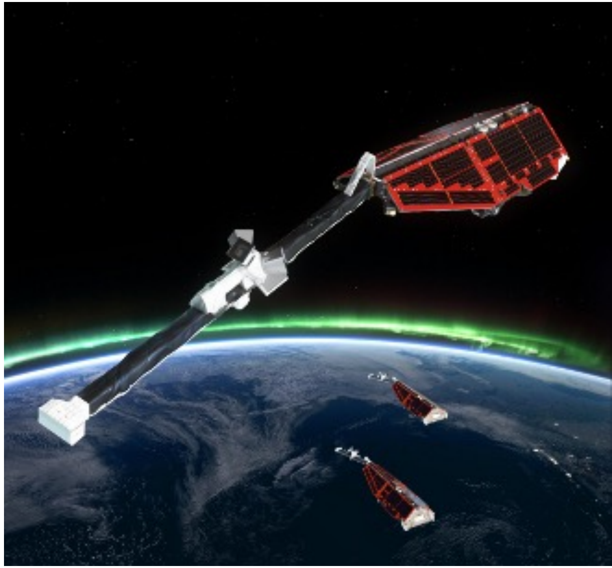
PRECISION SENSING OF MAGNETIC FIELDS FROM SPACE



/// History of precision sensing of magnetic fields from space (Europe)

- Ørsted,
- CHAMP
- SAC-C
- Cluster
- Swarm

/// Swarm is the most recent and ongoing mission, three (main) satellites

/// Swarm A and C at 460km altitude, parallel
– so gets across track measurements
– along track done over orbit

/// Swarm B at 530km altitude
– gives vertical measurements & at a different time of day

/// <0.5 nT error per measurement @1Hz

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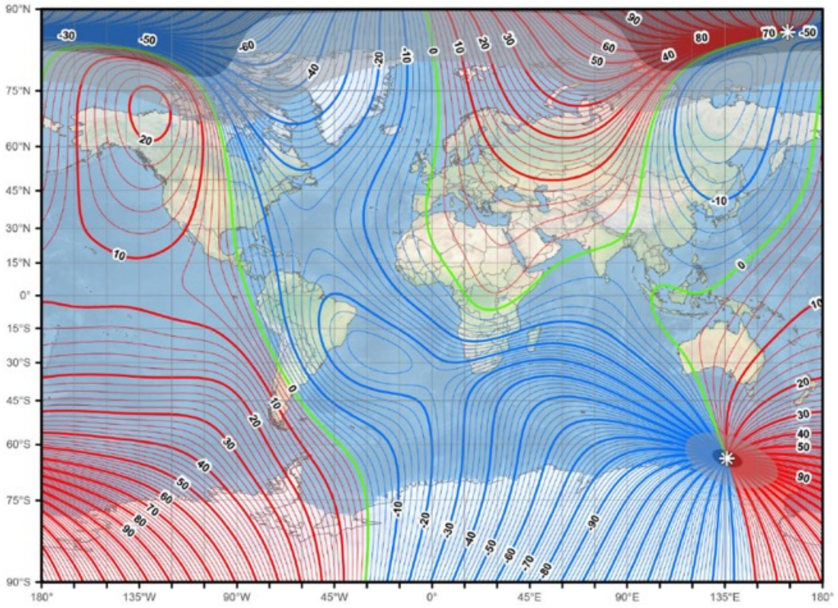
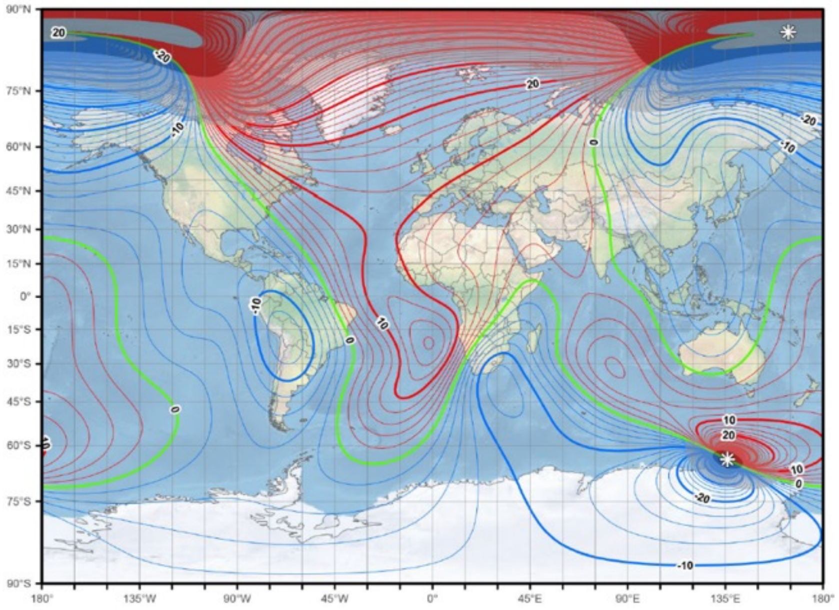
Ciarán Beggan @ BGS

World Magnetic Model (WMM)

- Use Gauss coefficients (weights) plus spherical harmonic equations
- WMM allows prediction of the magnetic field at any location and altitude
- Also make short term predictions (up to 5 years)
- Uses measurements from the night side (ionspheric field is quiescent)

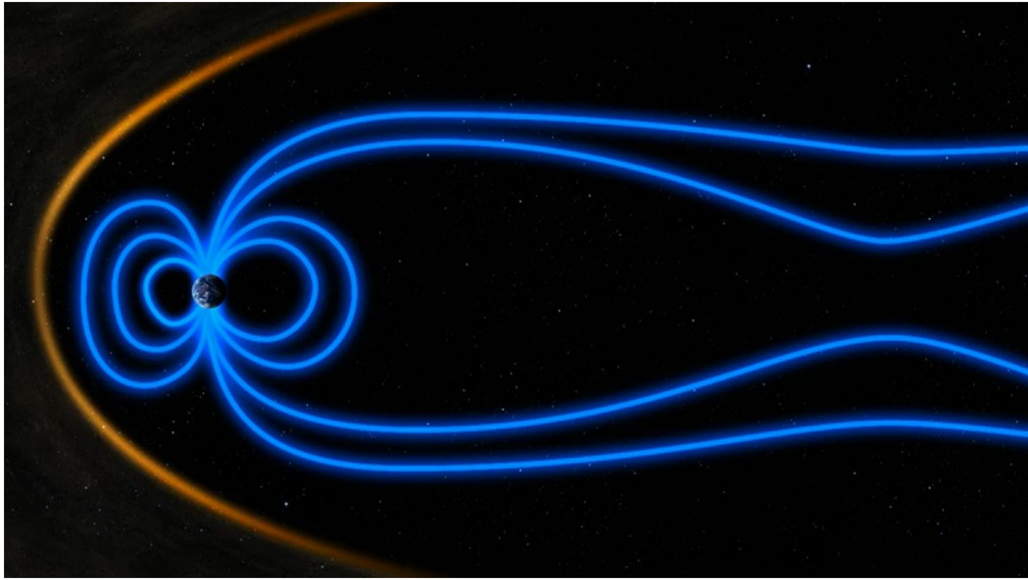




MAGNETIC FIELD RECONNECTION

- /// In 2021 Wei, Dunlop, Yang, Dong, Yu & Wang reported Intense dB/dt variation
- /// This utilises measurements both for Cluster (high altitude) and Swarm (Low Altitude)
- /// The magnetic field variation showed magnetic field reconnection
- /// Needed multiple measurements
- /// Demonstrated that interactions of the Earths magnetic field with the solar wind can be measured
- /// New era of measurement of the ionosphere

ESA Video



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SWARM INSTRUMENTS

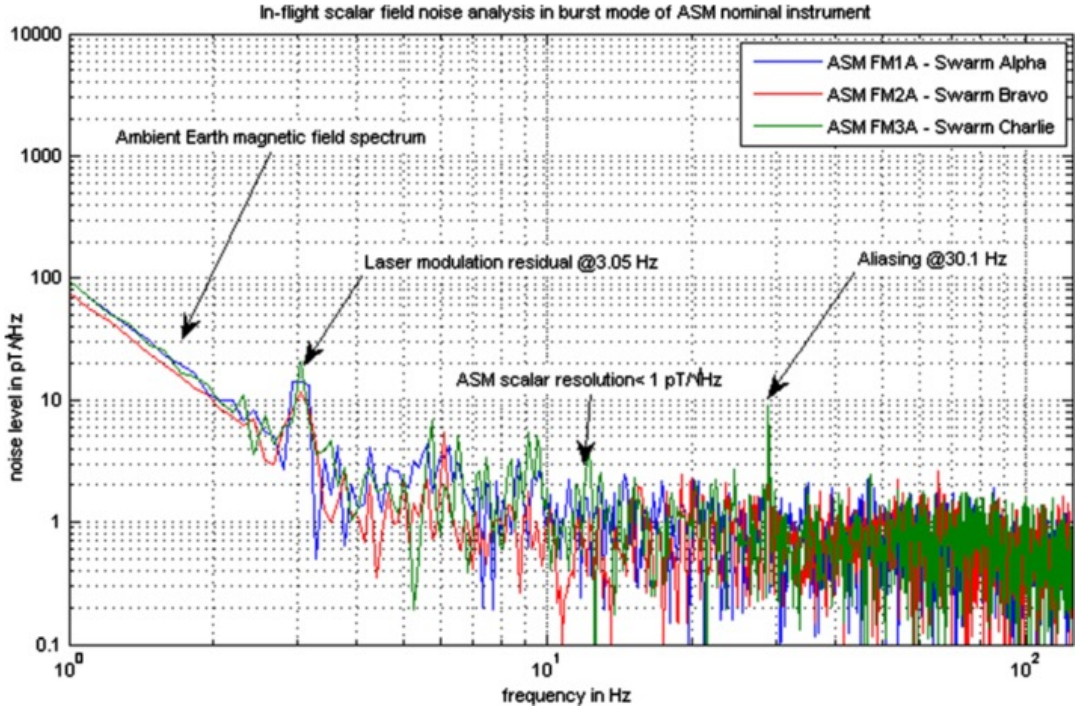
/// Vector Field Magnetometer <0.1nT vector measurements @ up to 50Hz

/// Absolute Scalar Magnetometer 1pT absolute measurement (65pT (1σ) max 1b level error)

/// Absolute Scalar Magnetometer in burst mode, 250Hz 1pT/√Hz

/// Absolute Scale Magnetometer is an Optically pumped Helium magnetometer – a quantum technology

/// Léger, Jager, Bertrand, Hulot, Brocco, Vigneron, Lalanne, Chulliat & Fratter



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SWARM STATUS & OP(C)M TECHNOLOGY

- /// Initial constellation formed on 17 April 2014
- /// Initial duration was 4 years, but in November 2017 this was extended to 2021
- /// It was then further extended to 2025
- /// The data it takes is important, but eventually the constellation will fail – what will replace it?
- /// Now if the time to look at the technologies needed for next generation of magnetic sensing missions
- /// Optically Pumped (Caesium) Magnetometer is a leading technology, but can it be made ready in time?
- /// Can OP(C)M compete with the current technology? How is it better?
- /// It's the mission concept, the target, that gives the requirements than the OP(C)M will need to be competitive

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THE CASE FOR THERMOSPHERE METEOROLOGY

/// Thermosphere

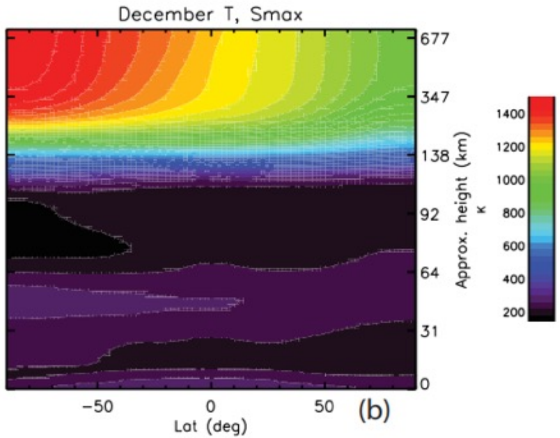
- Between ~90km up to 500-1000km
- Is very thin, satellites orbit in upper half of this range
- Absorbs most of solar radiation in EUV band, and temperature structure strongly driven by this
  - Hence T~600-800K (solar min) to T~1100-1500K (solar maximum)
  - Day/Night can vary 200K – so very strong driver

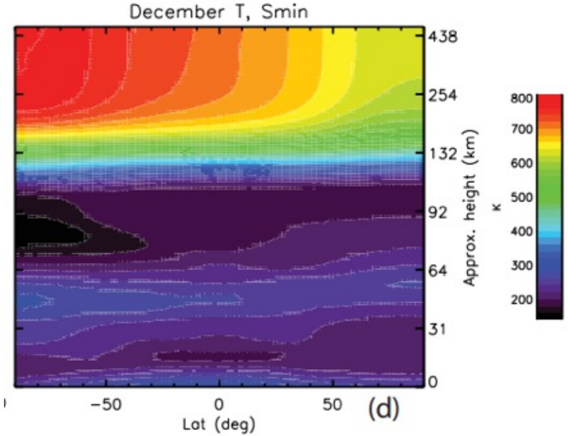
/// Space weather can cause large changes to thermosphere

- Geomagnetic storms following large CMEs can lead to density increases of up to ~750%
- Solar flares can also cause large changes to density (up to 200%)

/// Driving of thermosphere from below is important

- Tides, planetary waves and gravity waves can affect the thermospheric state at higher altitudes
- Tides in lower thermosphere (~100 km) can affect ionospheric structure at F region peak (~300 km)





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CURRENT STATUS OF THERMOSPHERE METEOROLOGY

/// Generally reasonable understanding of the physics of the thermosphere, and the thermospheric climatology - large body of published works

- Several models exist, which do reasonable job of simulating climatology and events (eg geomagnetic storms). Best are Whole Atmosphere Models (e.g WAM,WACCM-X, GAIA) since they are physics-based and include coupling wit the lower atmosphere

/// Available thermospheric observations:

- Density from accelerometers such as GOCE, CHAMP. GRACE – relatively sparse
- Temperature from space missions e.g SABER, GOLD, ACE/FTS and ground based (Fabry-Perot interferometers) – not NRT; limited spatial coverage
- Wind inferred from accelerometers – but with high errors

/// So data exists, but spatial coverage is often poor, and lack of availability of observations in near real time makes operational use difficult

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WHY MEASURE SPACE WEATHER

- /// Weather of the thermosphere is also known as Space Weather
- /// Space Weather is a priority to the UK (see UK Severe Space Weather Preparedness Strategy)
- /// Space Weather is driven by solar effects, e.g. solar flare on the thermosphere, can raise its temperature hugely
- /// This has given power cuts
  - March 13, 1989, Québec – 9 hour power cut
- /// More important for satellites
  - Space X lost 40 of 49 on 3/2/22 due to solar flare
  - Often satellites are initially launched into low earth orbit in the thermosphere, before they raise their orbit to an operational altitude. Space X satellites could not come out of safe mode, due to density of atmosphere
- /// Understanding thermosphere weather *is* understanding space weather

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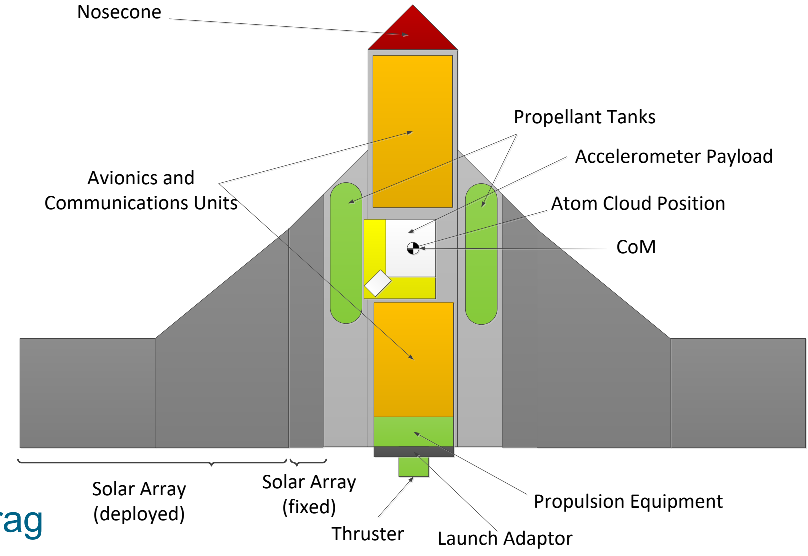
QUANTUM ACCELEROMETER CLIMATE EXPLORER (Q-ACE)

- /// Concept mission studied by large UK team (TAS,e2v,RAL,MetOffice,Franhofer) under NSIP(UKSA) 2 years
- /// 12 satellites (3 planes, 4 satellites per plane), polar orbit
- /// Typically 6 passes a day
- /// Elliptical orbit (250-500km)
- /// Satellite instrument (quantum accelerometer) measures drag
- /// Hoped to add temperature measurement (hard as thermosphere is *very* thin)
- /// This gives atmospheric density
- /// Data ideally downloaded ideally in 1h (challenging!)
- /// This would give the basis for a real time model (and forecast) for thermosphere (density & hopefully temperature)



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PLATFORM STATUS AND MISSION

/// Electric Propulsion to maintain orbit (similar to GOCE)

/// Needed to use particular ground station network (polar) for regular download – not clear how viable

/// Attitude control, was *very* complex, needed to work both at low altitude (high drag) and high altitude (very little drag)

/// Quantum Accelerometer ~100kg ➔Satellite ~1000kg

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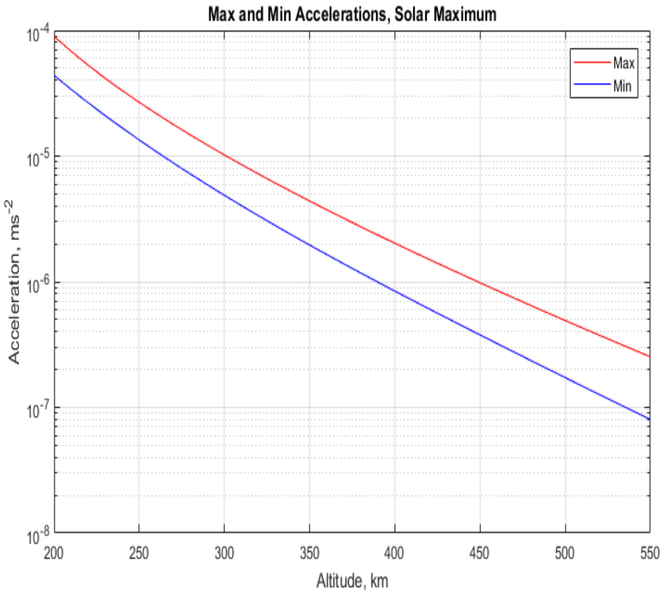
PROPRIETARY INFORMATION

THALES ALENIA SPACE OPEN

ThalesAlenia Space

QUANTUM ACCELEROMETER REQUIREMENTS

- /// The mission concept, gave requirements for the payload
- /// Maximum drag $1\times10^{-5}ms^{-2}$ (target $3\times10^{-5}ms^{-2}$)
- /// Need range, down to below $1\times10^{-7}ms^{-2}$
- /// Accepted two axis (along track, and either across or vertical) Three axis was better
- /// Lifetime 5/11 years (solar cycle is 11 years, and thermosphere is very sensitive to solar cycle)



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CONCLUSIONS

/// One can’t study an instrument without known what it needs to do

/// This is especially important for Space Missions

/// And more critical for quantum technologies – that are typically aimed at a specific mission

/// This is why in both talks that follow

- Tristan: Quantum Accelerometers for Space
- Mark: Optically Pumped (Caesium) Magnetometers

The studies for both, the science case was an important part – this is needed to give focus

/// Hence both studies on the instruments, included making the science/mission case

/// This case though is also needed for the community to know *why* the technology is proposed

/// E.g. We need YOUR support!

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