



CASPA-ADM – a mission concept for observing thermospheric mass density

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CASPA-ADM stands for Cold Atom Space Payload - Atmospheric Drag Mission

The 7-month study was supported by the ESA contract ESA RFP/3-16170/19/NL/FF/ab.

The objectives of the study were to

- identify a science case that can be addressed by an accelerometer based on cold-atom interferometer (CAI) technology
- develop the minimum viable mission concept for that science case

As CAI accelerometers have not yet been flown in space, CASPA-ADM would also serve a technology demonstrator from which, e.g., future gravity missions could benefit.

Introduction

The thermosphere

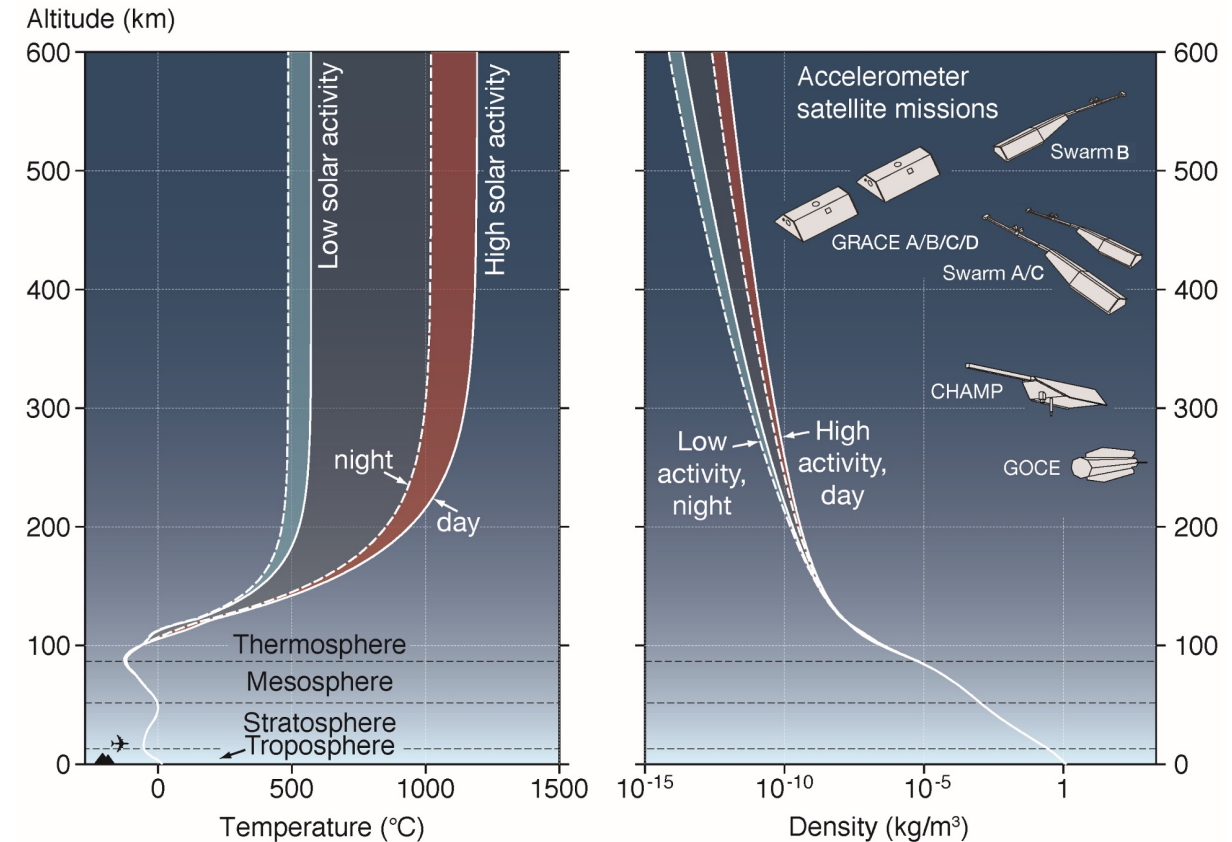
- Region between 90 and 1000 km altitude
- Characterized by large temperature variations
- Highly driven system
 - Solar flux
 - Geomagnetic activity
 - Gravity waves

Orbit prediction for active satellites and space debris

- Drag is dominant force and largest source of uncertainty below 600 km
- Lifetime predictions, collision risk assessment/avoidance

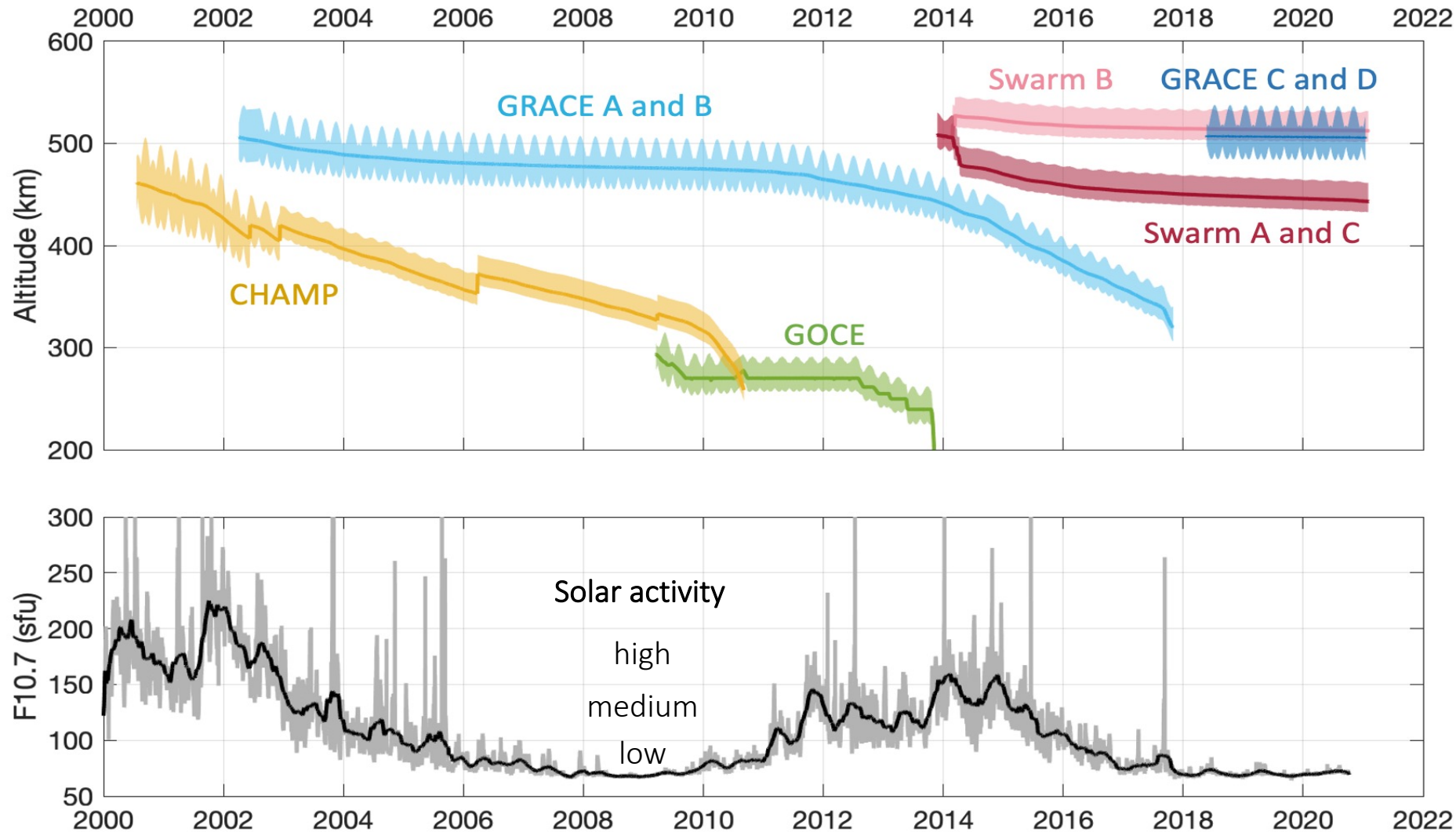
High-resolution, in-situ observations of thermosphere density

- 1970s and 1980s → Atmospheric Explorer missions
- Since 2000 → Missions of opportunity



Source: Doornbos (2011)

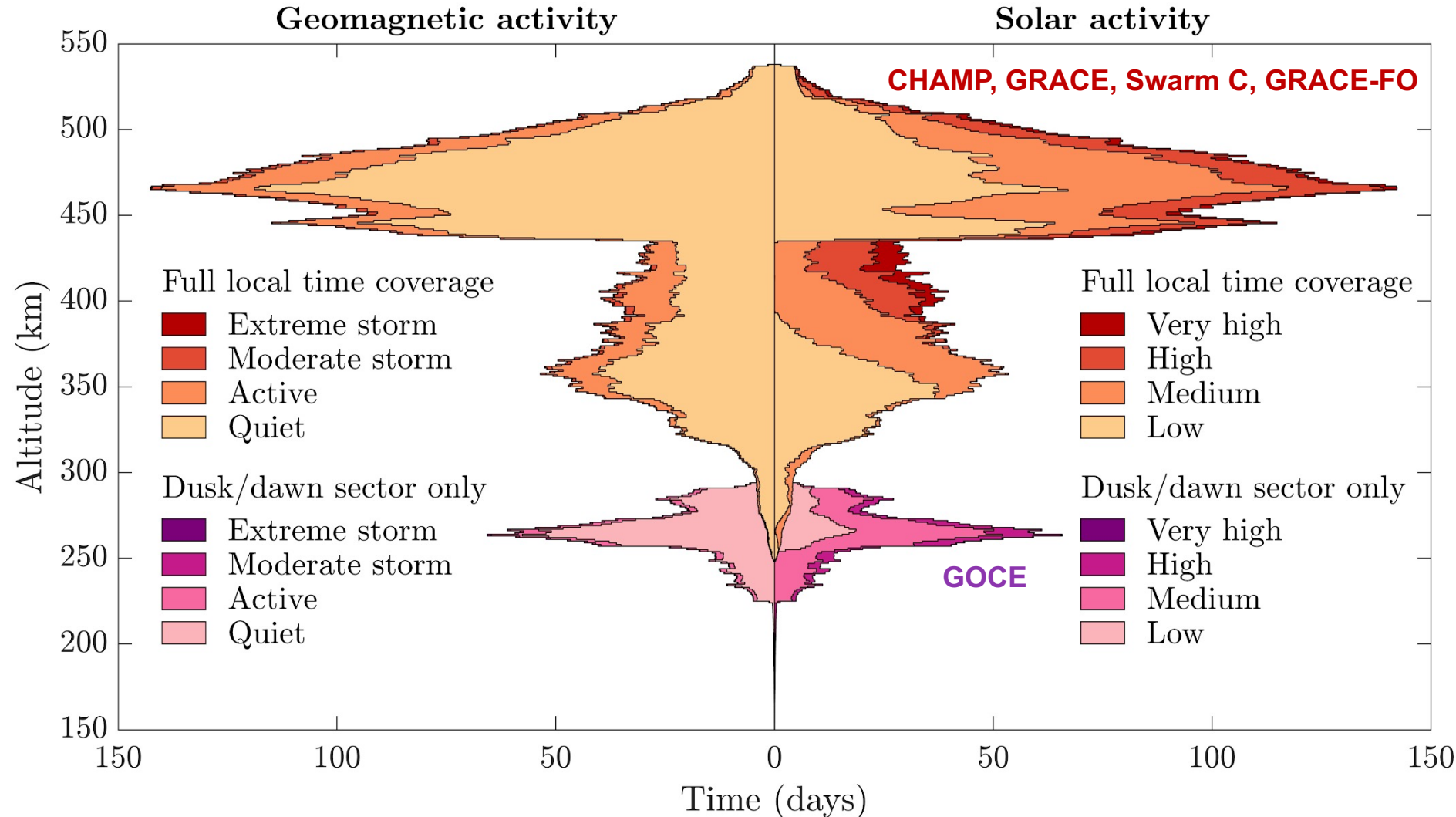
Density observations since 2000



Sampling from missions of opportunity is incomplete

- Most observations are at altitudes of 420–520 km
- Limited number of observations at altitudes below 420 km at medium–high solar activity (indicated by the F10.7 index)
- GOCE collected observations only in dusk/dawn sector
- Hardly any observations with full local time sampling at altitudes below 320 km

Density observations since 2000

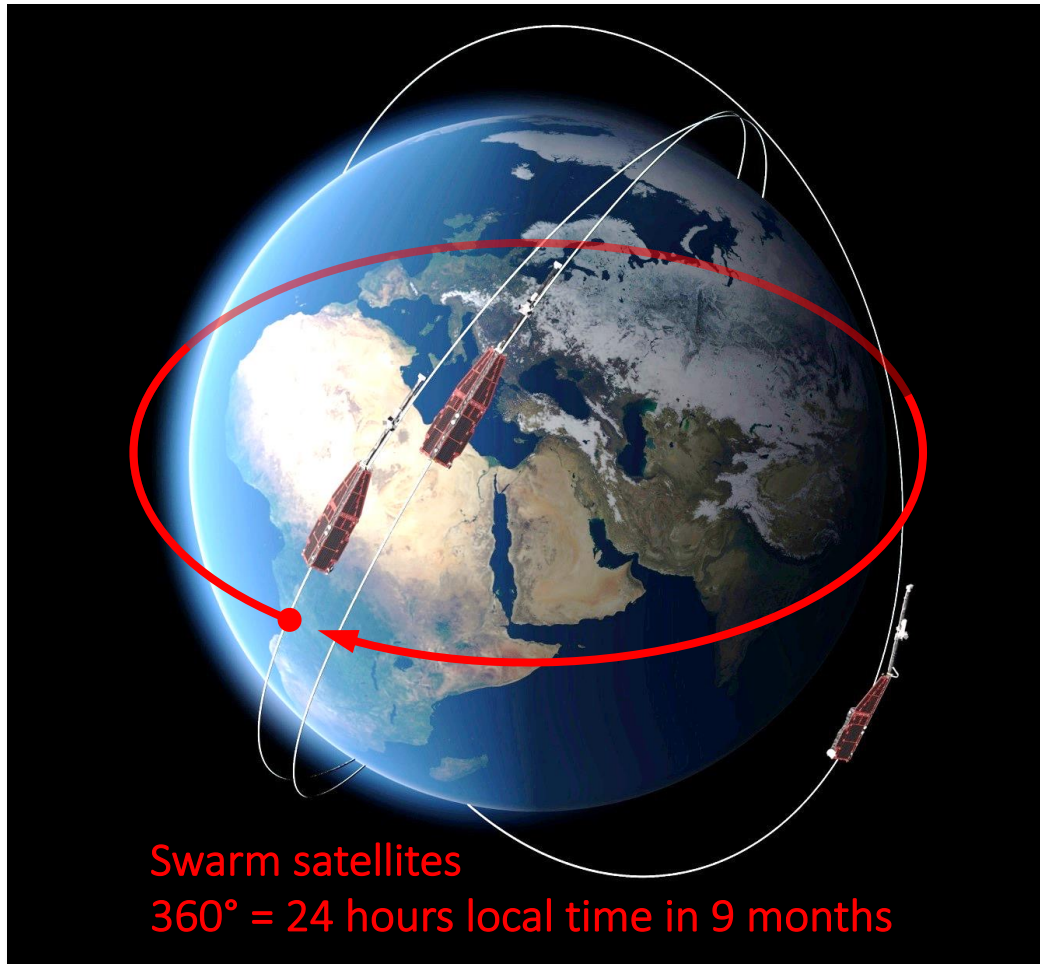


Sampling from missions of opportunity is incomplete

- This graph represents the same information as on the previous slide, but as a histogram of the number of observations per bin of 1 km altitude
- Most observations are concentrated at altitudes of 420–520 km
- GOCE is represented in a different color due to its limited local time coverage

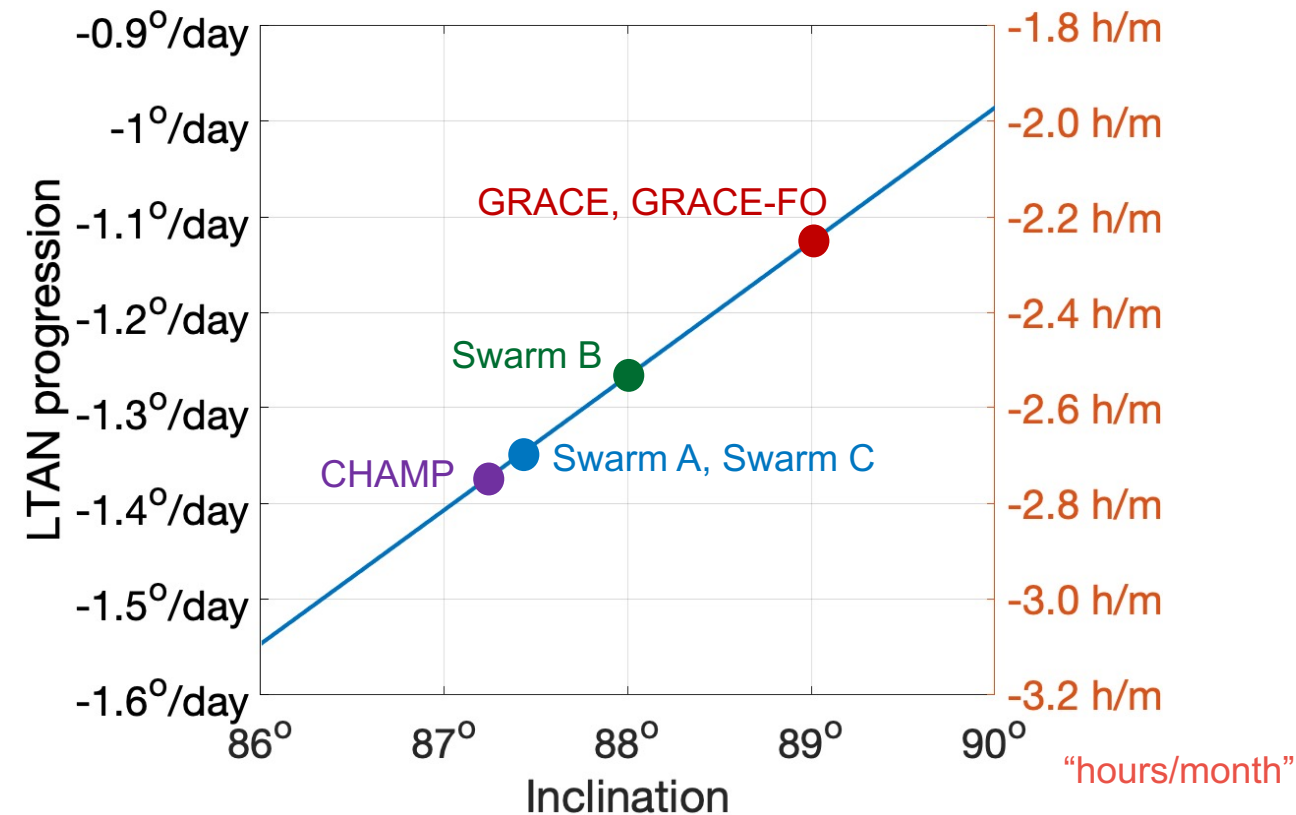
Missions of opportunity – local time

Precession of orbital planes



Source: ESA/ATG media lab

The missions of opportunity fly in near-polar orbits, which results in a very slow precession of the orbital planes. Hence, 8–11 months are needed to visit all local times.



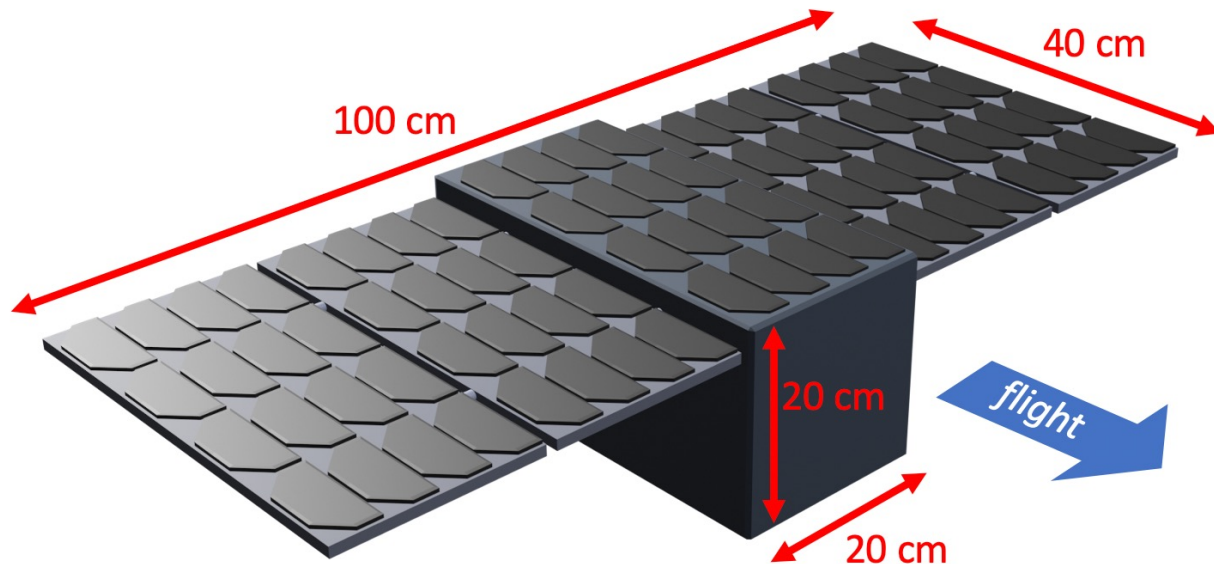
Mission objectives

Demonstrate CAI technology with a science case

1. Verification of gas-surface interaction models
2. Observation of atmospheric waves
3. Observe cross-track accelerations (secondary)

Fill the present gap in density observations

1. Region below 400 km altitude
2. Fast LTAN progression
3. Medium-high solar activity



Mission concept

- 16U CubeSat
- 40 U² solar arrays
- Approximate initial altitude 400 km
- 40° – 76° inclination
- Approximate launch window 2022 – 2028

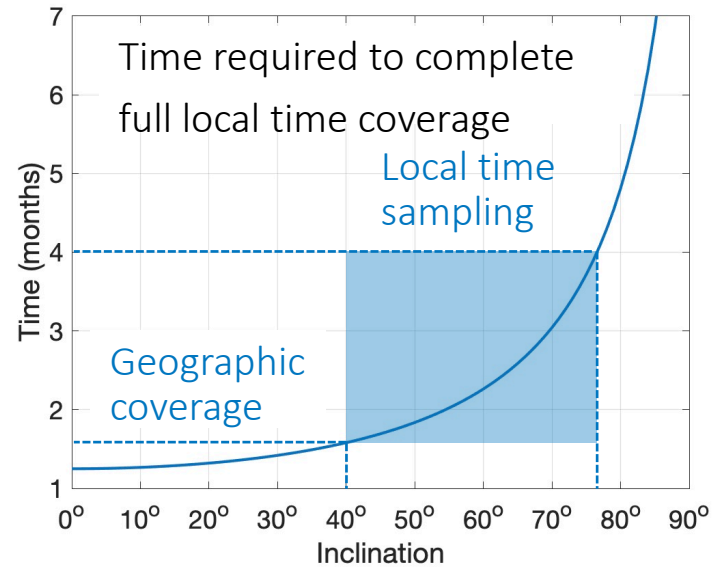
Note:

1 U = 10 cm x 10 cm x 10 cm

1 U² = 10 cm x 10 cm

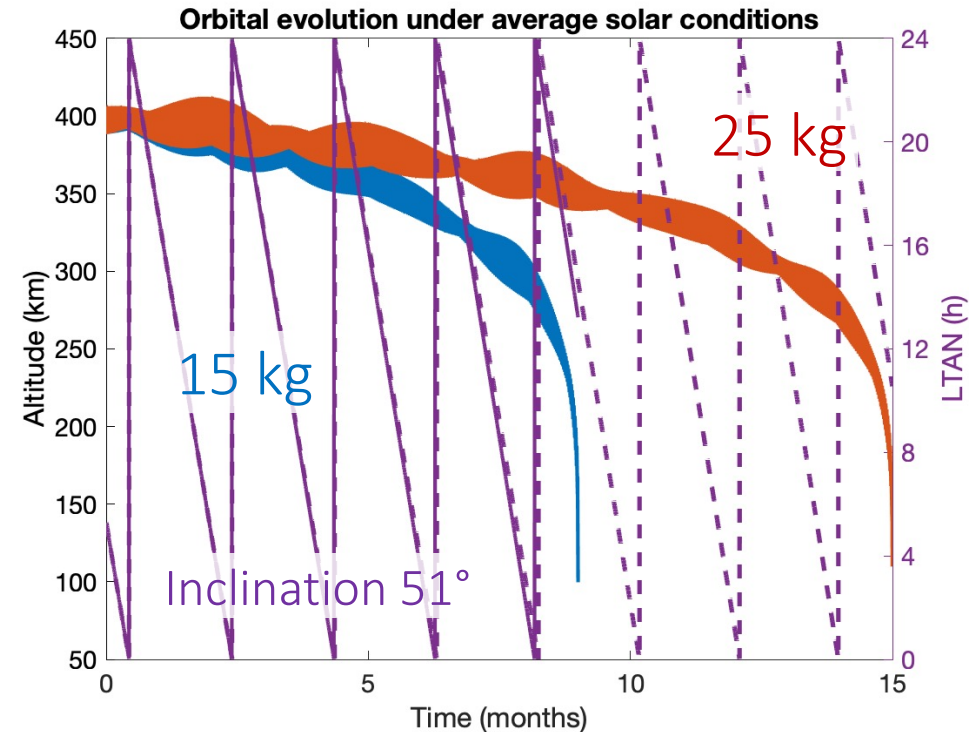
Scientific objectives require a measurement accuracy of 1% for mass density

Orbit selection



The target inclination in the range of $40^\circ - 76^\circ$ guarantees one full local time coverage every 1.6–4 months.

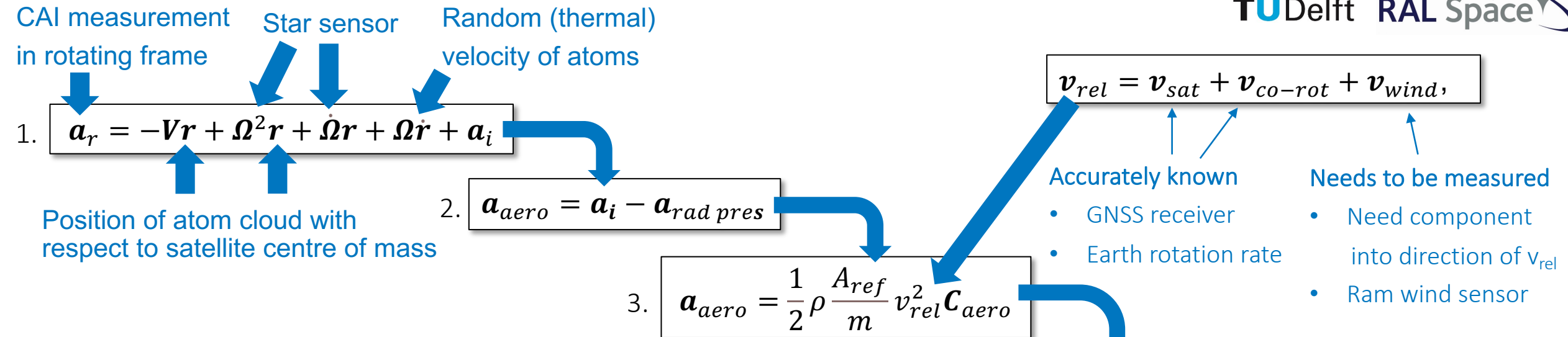
The inclination range is selected to achieve full local time sampling at least twice within the mission lifetime.



A 16 U CubeSat with a mass of 15–25 kg launched at 400 km altitude is expected to remain in orbit for 8–15 months at average solar activity.

An inclination of 51° is compatible with a launch from the ISS and would enable full local time coverage at least four times.

Observing mass density



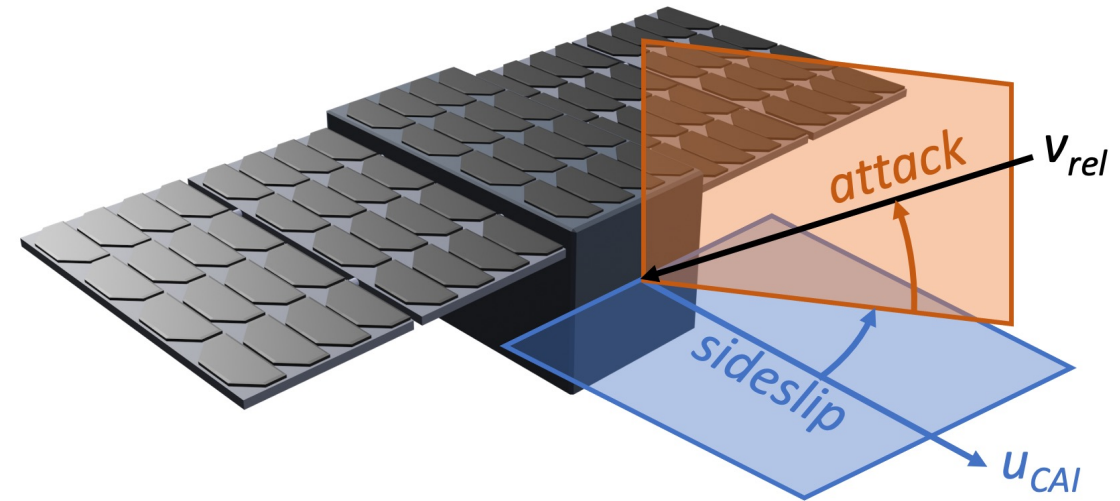
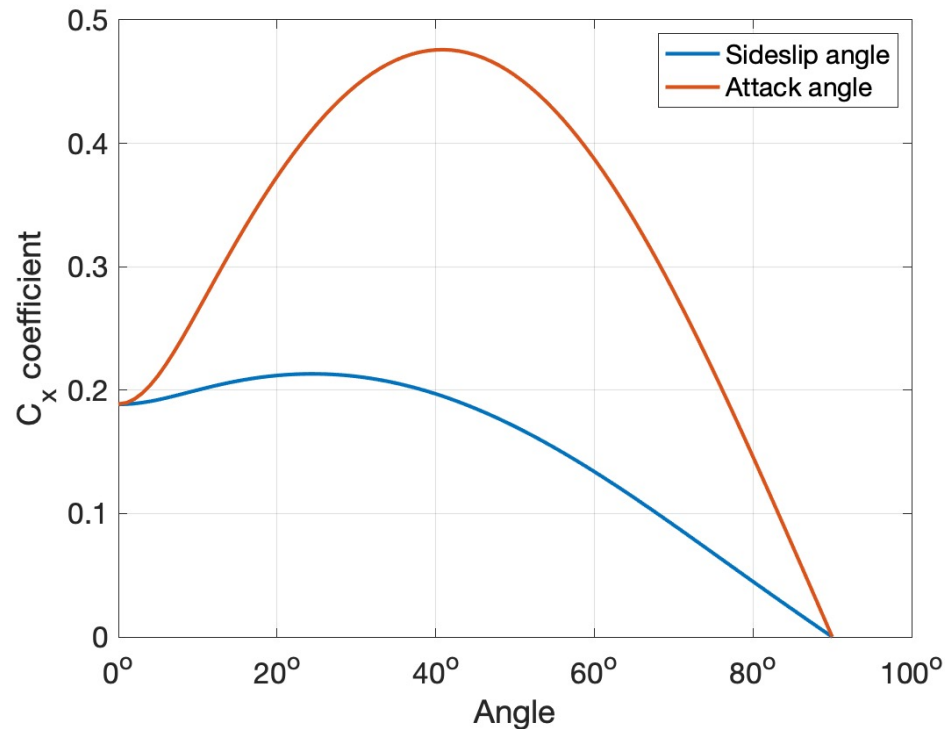
Outline of processing

- As it will be difficult to accommodate the CAI accelerometer in the small satellite, the atom cloud is likely not in the satellite center of mass. Hence, the measured accelerations need to be corrected for gravity gradient and rotational effects.
- The acceleration due to radiation pressure needs to be modelled and removed.
- The magnitude of the velocity of the spacecraft relative to the atmosphere needs to be known, which includes wind to be measured by a ram wind sensor.
- The CAI accelerometer will measure the acceleration along the single laser axis, which is roughly aligned with the flight direction. Thus, we need to project the aerodynamic acceleration onto this direction (unit vector $\mathbf{u}_{CAI}$).

4.
$$a_{CAI} = \mathbf{a}_{aero} \cdot \mathbf{u}_{CAI} = \frac{1}{2}\rho \frac{A_{ref}}{m} v_{rel}^2 \mathbf{C}_{aero} \cdot \mathbf{u}_{CAI}$$

$$\mathbf{C}_{aero} \cdot \mathbf{u}_{CAI} = \mathbf{C}_{aero} \cdot \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = C_x$$

Observing mass density



The x-component of the aerodynamic coefficient (C_x) as a function of attack and sideslip angles, illustrated in the right panel. Starting from angles of 0° , the C_x coefficient increases for attack and sideslip angles up to 40° and 25° , respectively, as the cross-sectional area exposed to the atmospheric flow increases. Thus, flying at a small angle with respect to the atmospheric flow increases the signal to be measured by the CAI accelerometer. However, the ram wind sensor will then measure the wind into the wrong direction. It was estimated that deviations of the laser axis from the direction of the relative atmospheric flow up to 12° are acceptable.

Instrument and purpose

CAI accelerometer

- Measure non-gravitational acceleration

GPS receiver

- Geolocation of measurements
- Validation of CAI measurements

Neutral mass spectrometer

- Measure atmospheric composition and temperature

Star cameras

- Orientation of measurements/aerodynamic coefficient
- Correction for effects due to measuring in rotating frame

Ram wind sensor

Measure in-track wind

Signal range and required accuracy

Signal range 0.03–11.8 $\mu\text{m/s}^2$ within 300–400 km altitude
Noise level 0.01 $\mu\text{m/s}^2$ / $\sqrt{\text{Hz}}$

Multi-frequency measurements
12+ channels
Code and carrier phase observations part of telemetry

Mass range 4–32 amu
Composition accuracy 10% (1 σ)
Temperature accuracy 3% (1 σ)

Accuracy 50" (1 σ)

Alignment with relative velocity direction within $\pm 12^\circ$
Range < 2000 m/s
Accuracy 40 m/s (1 σ)

CAI accelerometer

Volume of CAI accelerometer → **minimum 16 U CubeSat**

- 3 U for CAI laser and control system
- 8 U for CAI physics package

Average power load on system → **40 U solar arrays**

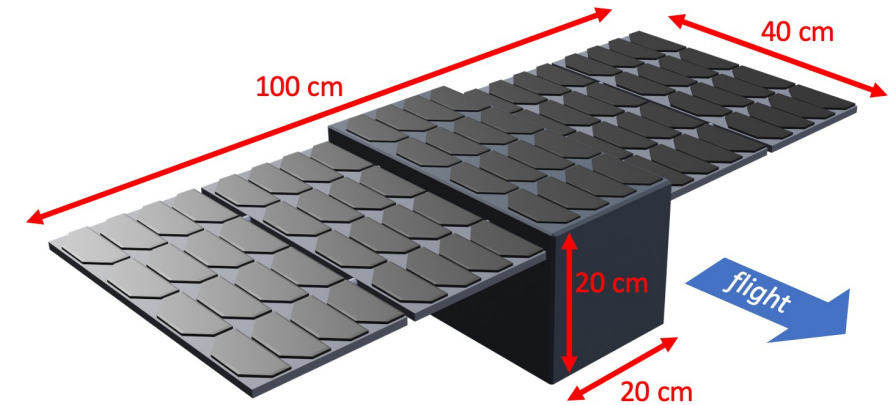
- 80 W average load during CAI accelerometer operations
- 5 W average load when CAI accelerometer is idle
- 6 orbits required to charge batteries assuming 40 U solar arrays area

Intermittent operation of CAI instrument → **to save power**

- One shot every 2.5 s (more than 1 s dead time between shots to reduce power load)
- Operate CAI accelerometer 2–3 times for at least for 1.5 orbital revolutions every day

Satellite operations

- Roll the satellite towards the Sun to maintain pointing of laser axis and maximize power
- Other instruments are operated without interruption (including mass spectrometer and GNSS receiver)



CAI accelerometer

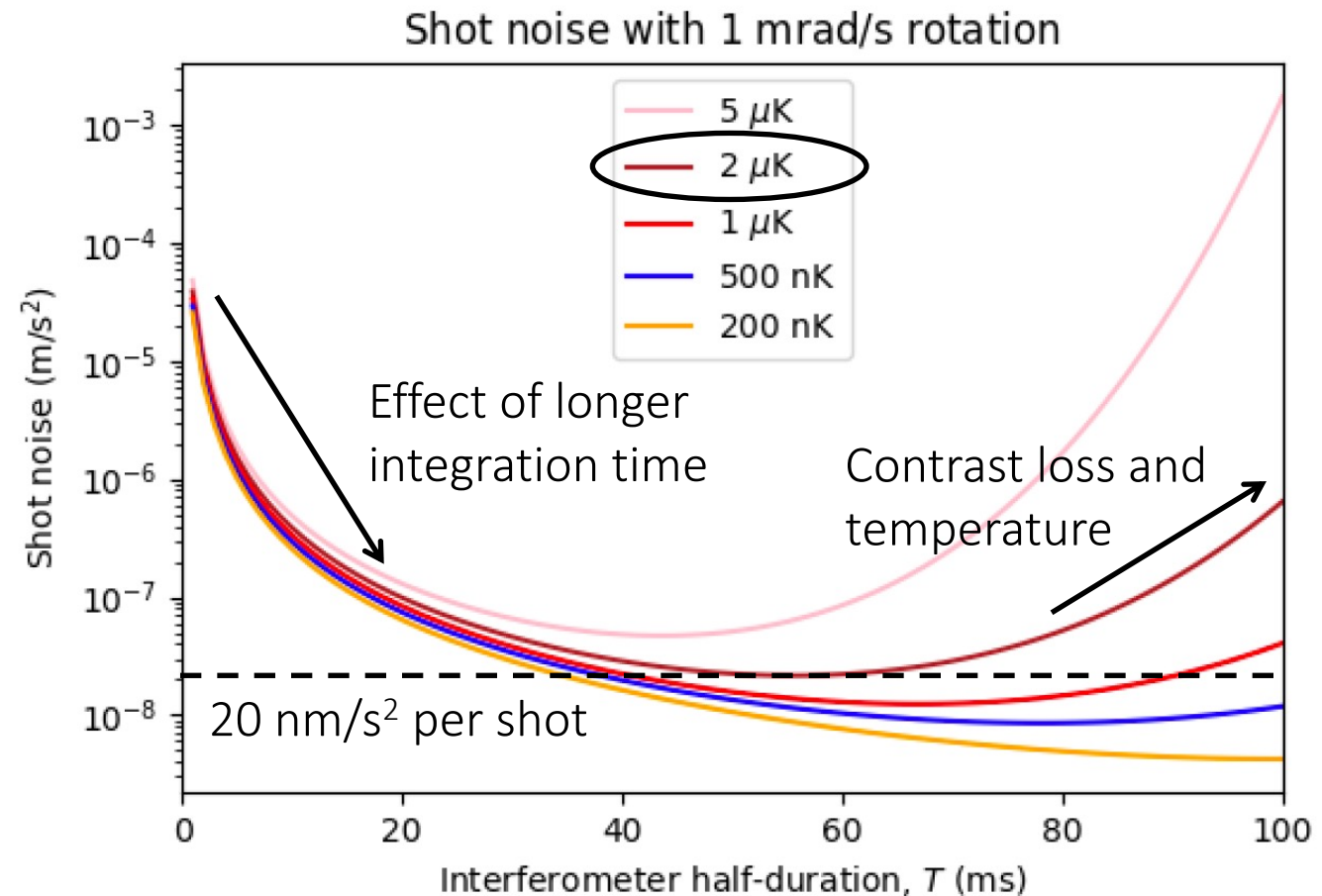
The figure shows the measurement accuracy projected from the commonly achieved performance in research labs taking into account

- contrast loss due to satellite rotation
- atom loss due to non-zero temperature

An accuracy of 20 nm/s^2 per shot is achieved for an interrogation time of 56 ms when atoms are cooled to $2 \mu\text{K}$, which can be achieved with the (relative simple) molasses cooling

Averaging over 4 shots within 10 s (one shot every 2.5 s) results in a precision of 10 nm/s^2 . The time per shot takes into account

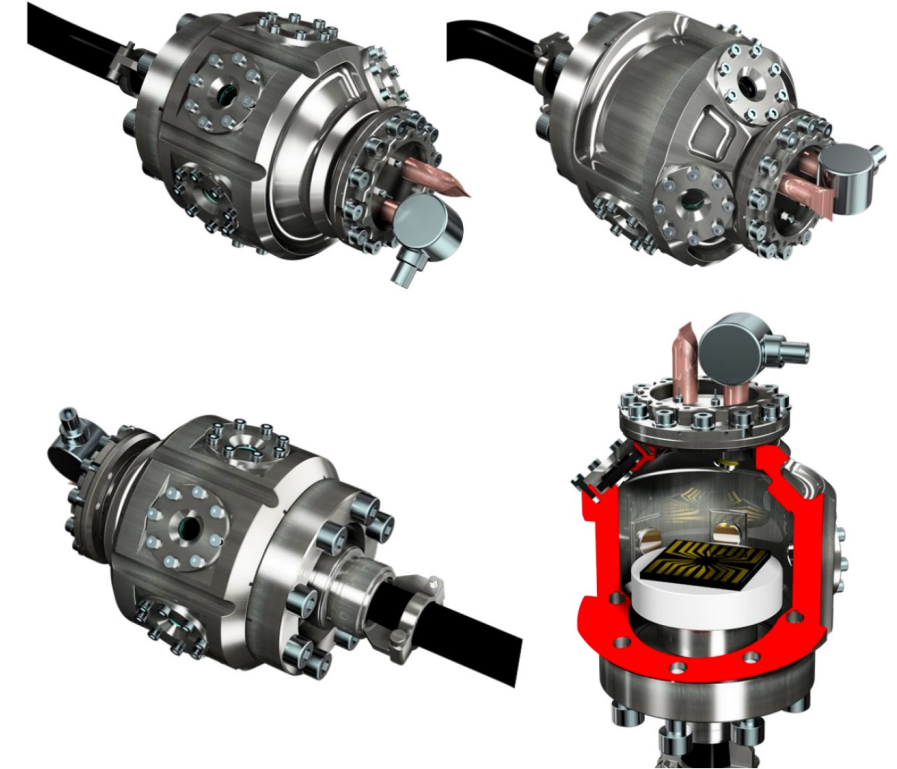
- atom preparation time
- additional dead time of 1.2 s to limit the power consumption



CAI accelerometer

Accuracy defining parameter	Value
Starting atoms (in MOT)	2×10^8
Atom temperature	$2 \mu\text{K}$
Atoms detected	2×10^6
Time between interferometer measurements	2.5 s
Averaging time	10 s
Shot noise	$2 \times 10^{-8} \text{ m/s}^2$
Noise after averaging	$1 \times 10^{-8} \text{ m/s}^2$

Other noise sources	Mitigation strategy
Vibration	Minimise moving parts, model full system, consider hybrid sensor
Magnetic fields	Passive shields, detailed model, consider active shielding
Instrumental noise	Careful design and accounting for systematics



Model of the vacuum chamber with the atom chip

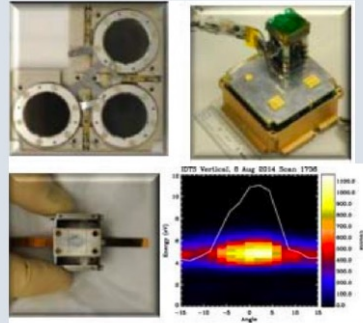
Scientific payload options

The picture below show a selection of the options that have been considered during the development of the mission concept as options for the scientific payload. The focus was on selecting existing solutions.



Mass Spectrometer

- UCL (UK) INMS used on the QB50 missions as well as the upcoming CIRCE (UK DSTL) & SOAR(H2020) missions
- Measures O, O₂, N₂, NO
- 0.3U Volume
- But no Ram wind sensor or He detection



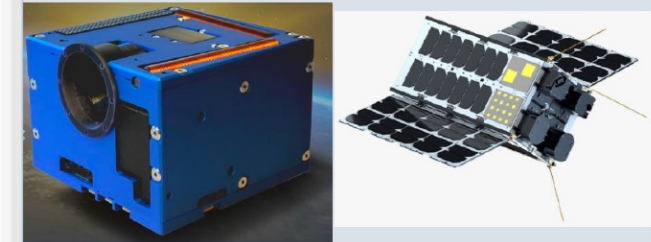
Ram Wind Sensor

- No European solution identified
- US NRL WINCS instrument suite combines mass spectrometer with Ram wind sensor
- Correct performance
- ± 2000 m/s
- 0.5U Volume



GNSS Receiver

- Recommendation from NanoMagSat
- Septentrio AsteRx2m – no space qualification but also true of alternatives
- Antenna for GPS-only use is the Sensor Systems S67-1575-14 antenna with has extensive flight heritage (including CASSIOPE)
- For GPS + GAL further work is required



ADCS Systems

- iADCS400 ADCS solution from Hyperion Technologies (left)
- M16P CubeSat bus from Nano Avionics (right) which includes an integrated ADCS solution
- Vibration and magnetic environments require further study

| Science objectives (SO)

Fill observational gap in the altitude range of 300–400 km at medium/high solar activity

Primary science objectives

SO1: Verification of gas-surface interaction models

SO2: Observation of atmospheric waves

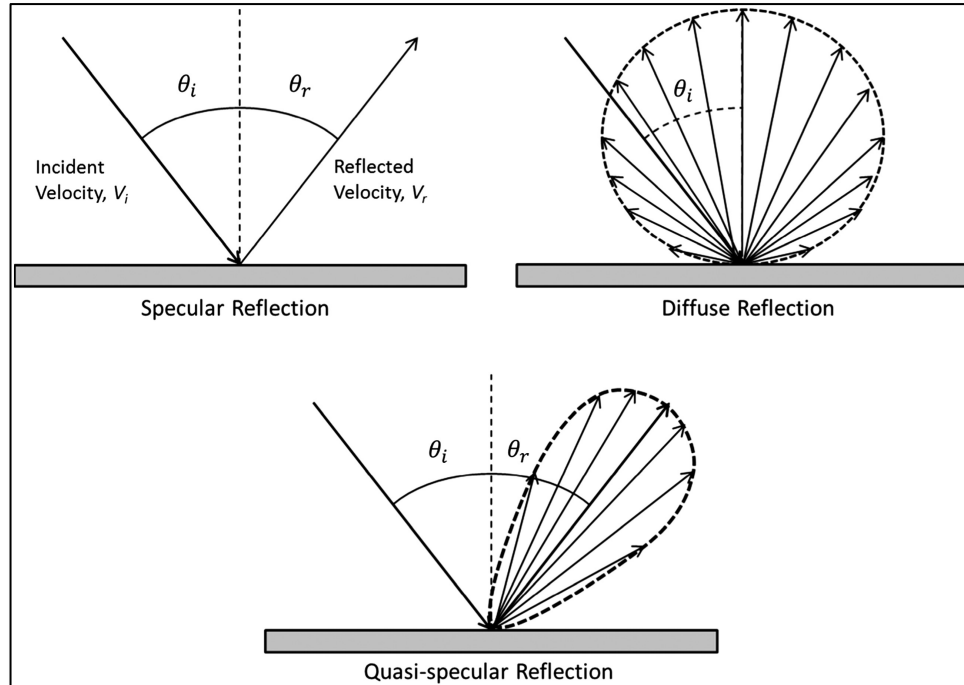
Secondary science objective

SO3: Observe cross-track accelerations (requires attitude manoeuvre)

Scientific objectives require an accuracy of 1% for mass density observations and simultaneous observation of atmospheric composition and temperature

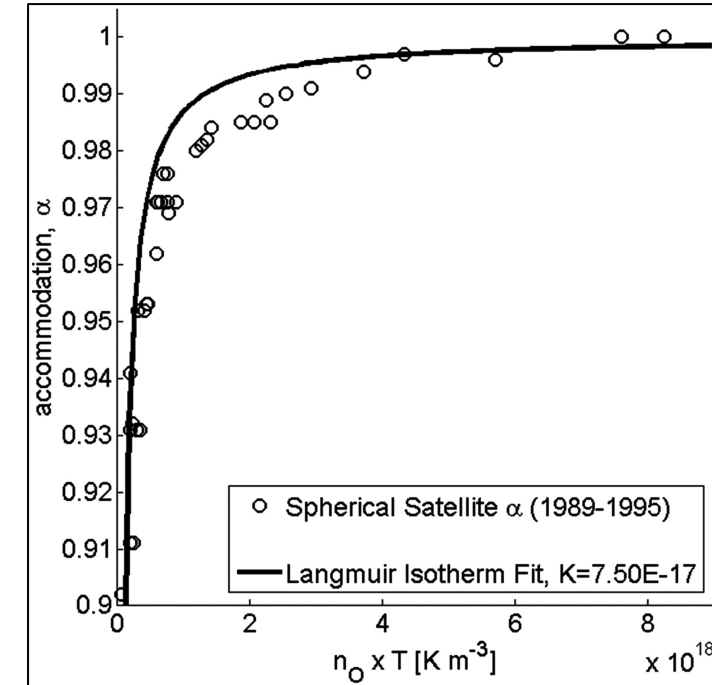
SO1: Gas-surface interaction models

Modes of reflection of particles



Source: Walker et al. (2014)

Particle-surface energy exchange



Source: Pilinski et al. (2010)

Even though significant advancements were achieved in the past decade, the accurate modelling of aerodynamic forces remains a challenge and uncertainties on the order of 10% are no uncommon. The combination of the CAI accelerometer and the mass spectrometer measurements will allow to verify model assumptions, e.g. on the angular distribution of the reflected particle (left panel) and the amount of energy exchanged between incident particles and the satellite surfaces (right panel), and consequently reduce the uncertainties in the modelling.

SO1: Gas-surface interaction models

The aerodynamic coefficient vector C_{aero} controls the scale of the density observations.

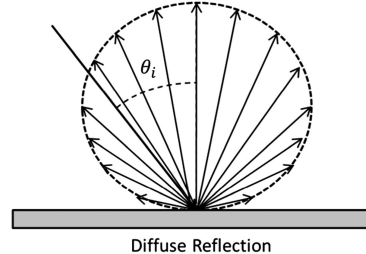
$$\mathbf{a}_{aero} = \frac{1}{2} \rho \frac{A_{ref}}{m} v_{rel}^2 \mathbf{C}_{aero}$$

Size and shape of the satellite

Diffuse reflection with incomplete accommodation (DRIA)

$$C_{D,i,j} = \left[\frac{P_{i,j}}{\sqrt{\pi}} + \gamma_i Q_j Z_{i,j} + \frac{\gamma_i}{2} \frac{v_{re}}{v_{inc}} (\gamma_i \sqrt{\pi} Z_{i,j} + P_{i,j}) \right] \frac{A_i}{A_{ref}}$$

$$C_{L,i,j} = \left[l_i G_j Z_{i,j} + \frac{l_i}{2} \frac{v_{re}}{v_{inc}} (\gamma_i \sqrt{\pi} Z_{i,j} + P_{i,j}) \right] \frac{A_i}{A_{ref}}$$



$$G_j = \frac{1}{2S_j^2}, \quad P_{i,j} = \frac{1}{S_j} \exp(-\gamma_i^2 S_j^2), \quad Q_j = 1 + G_j, \quad Z_{i,j} = 1 + \operatorname{erf}(\gamma_i S_j)$$

Sources: Sentman (1961), Doornbos (2011), Walker et al. (2014)

Atmospheric composition and temperature

$$v_{mp,j} = \sqrt{2 \frac{k}{m_j} T}$$

Most probably speed of a gas particle of mass m_j

$$S_j = \frac{v_{rel}}{v_{mp,j}}$$

Speed ratio of the most probable velocity and the flow velocity relative to the satellite

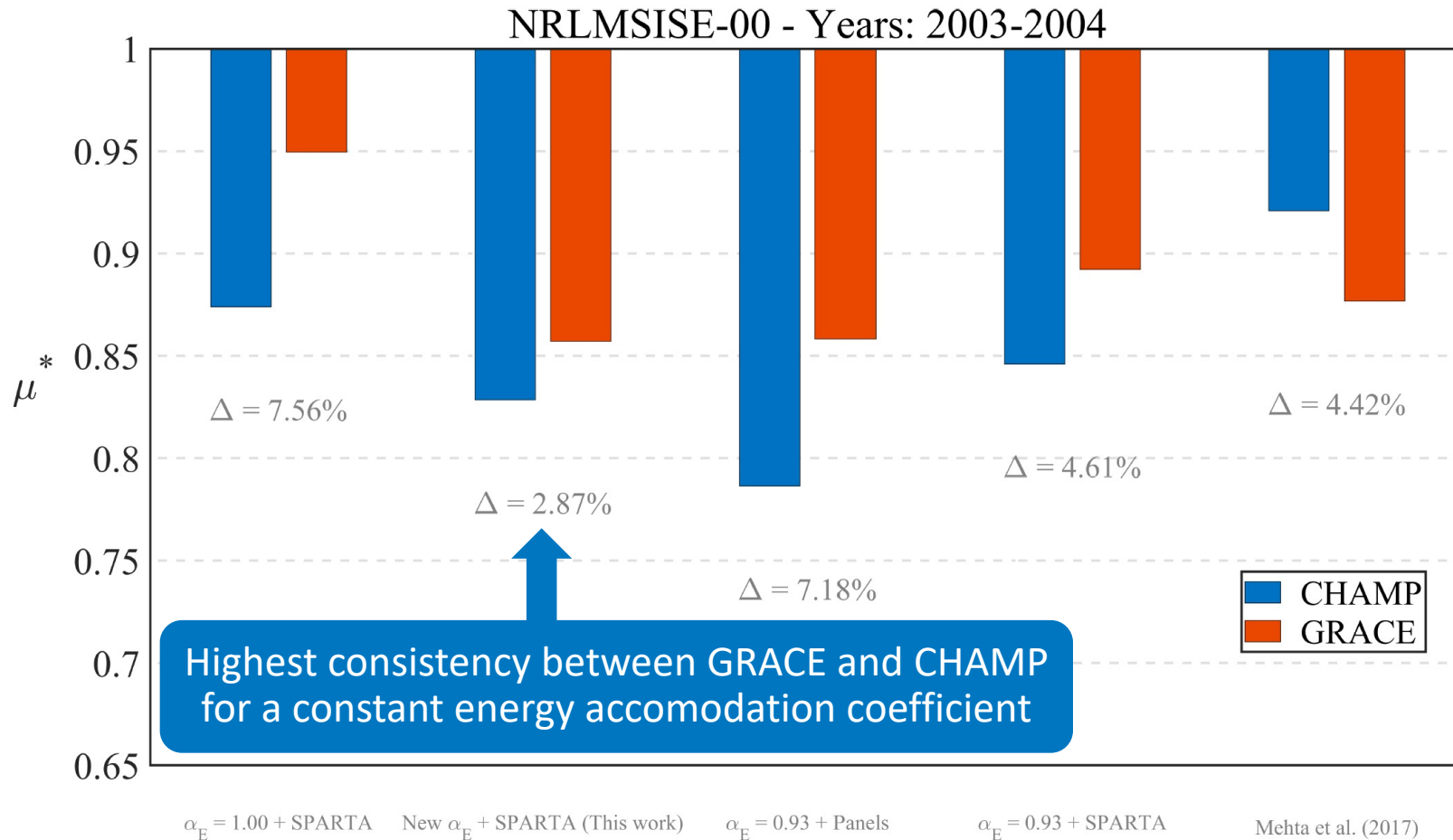
$$\frac{v_{re}}{v_{inc}} = \sqrt{\frac{1}{2} \left(1 + \alpha \left(\frac{4RT_w}{v_{inc}^2 m_j} - 1 \right) \right)}$$

Ratio of re-emitted and incident velocity

Energy accommodation coefficient
(function of number density of oxygen)

Example for the modelling a fully diffuse reflection with an incomplete accommodation of the kinetic energy of incident particles. This type of modelling is suitable for the altitude range from about 150 km, where free molecular flow begins, to about 400–500 km, where the number density of atomic Oxygen decreases to a level at which different model assumptions may be more appropriate.

SO1: Gas-surface interaction models



Source: March (2020)

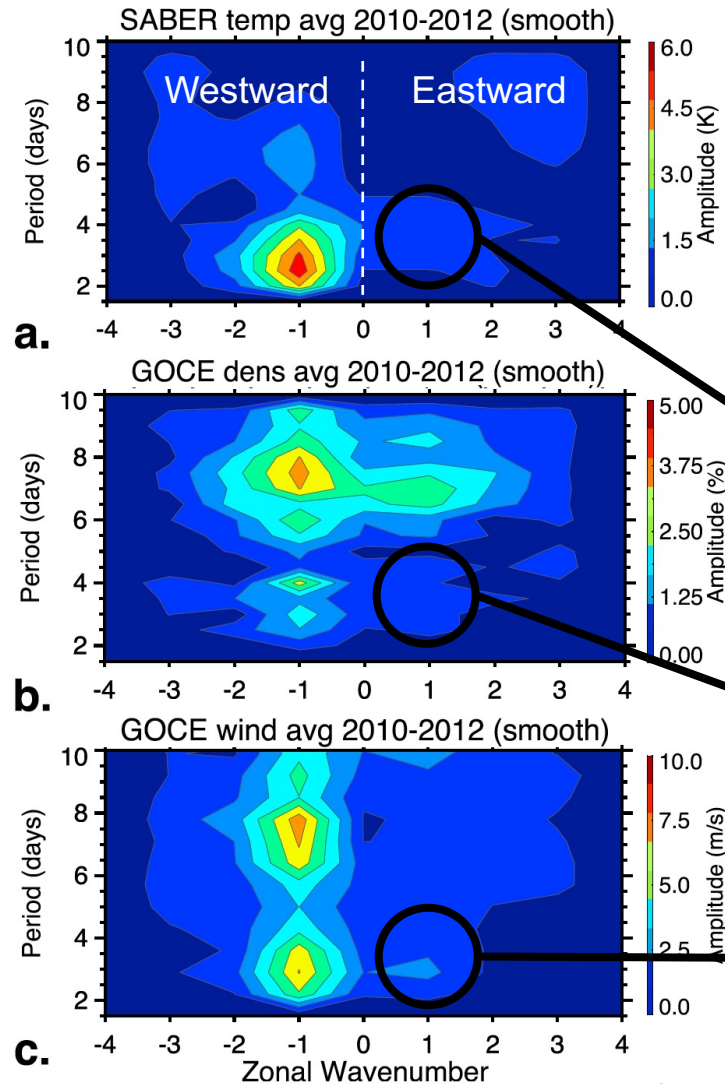
- The graph shows the average ratio of model and observed density of the CHAMP and GRACE missions in 2003–2004, when solar activity was high, for various gas-surface interaction model assumptions
- Even though a variable energy accommodation is expected in reality, a constant energy accommodation coefficient, derived from analysis of density and wind observations during satellite maneuvers, gives density observations that are more consistent between missions
- This demonstrates that variable energy accommodation models need to be improved

| SO2: Observing atmospheric waves

The following three slides present examples of atmospheric waves that CASPA-ADM would be able to detect.

Note that the magnitude of the atmospheric waves is on the order of a few percent of the density, which gives further justification of the requirement to observe density with an accuracy of 1%.

SO2: Observing atmospheric waves



Atmospheric tides

- Observed by the SABER instrument on board the TIMED satellite (radiometry)
- Observed by the GOCE satellite (accelerometry)

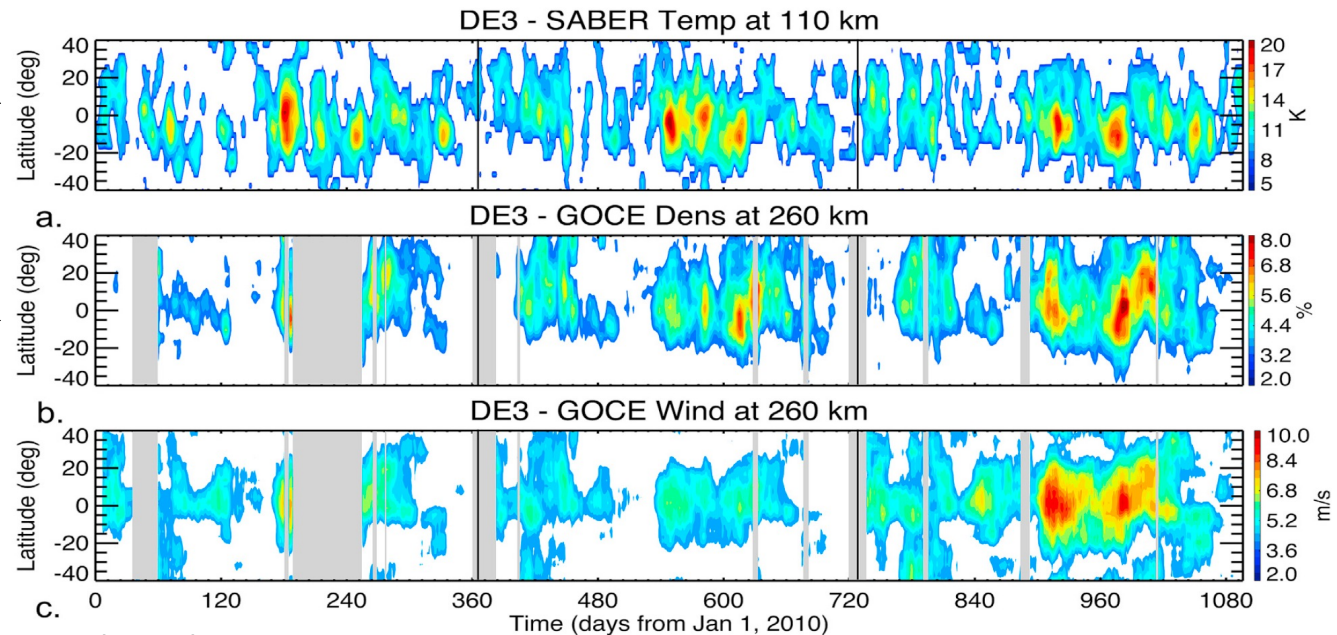
$$\psi_{n,s}(t, \lambda) = A_{n,s} \cos(n\omega t + s\lambda + \phi_{n,s})$$

Subharmonic index

Earth rotation rate

Zonal wave number

Longitude



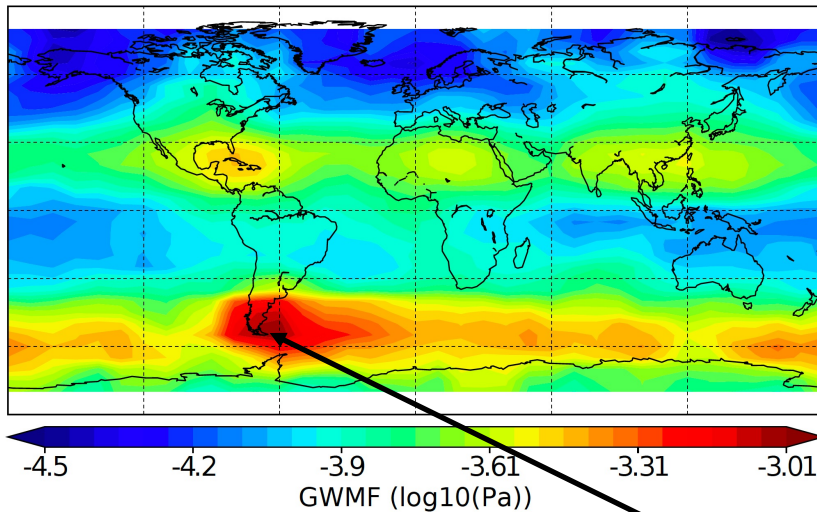
Source: Gasperini et al. (2018)

SO2: Observing atmospheric waves

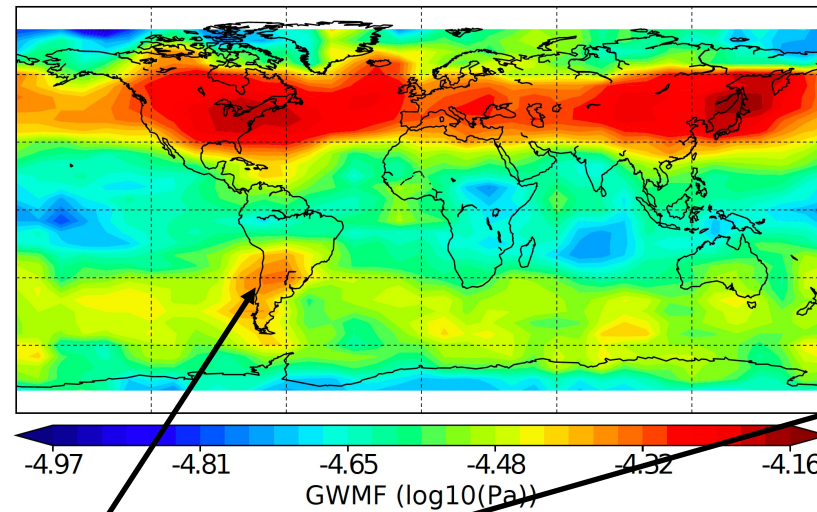
Gravity waves

- Observed by the SABER instrument on board the TIMED satellite (radiometry)
- Observed by the GOCE satellite (accelerometry)

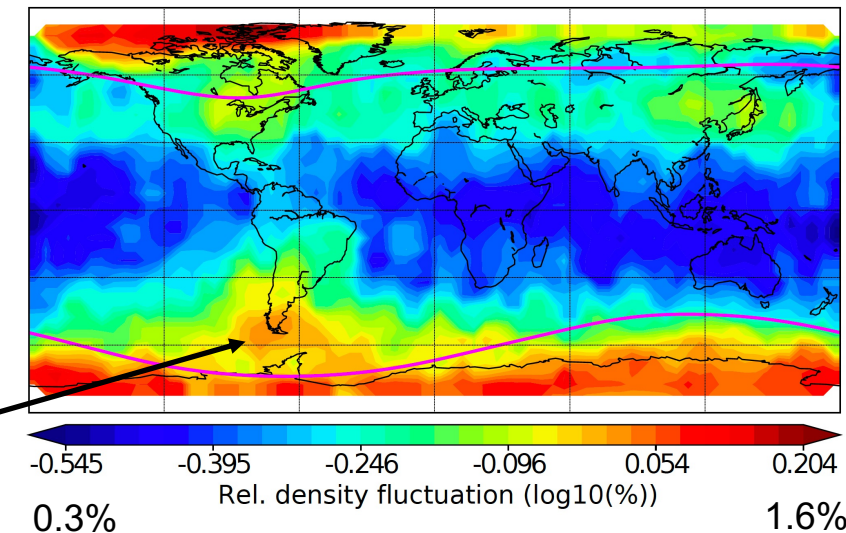
SABER observation at 30 km altitude



SABER observation at 75 km altitude



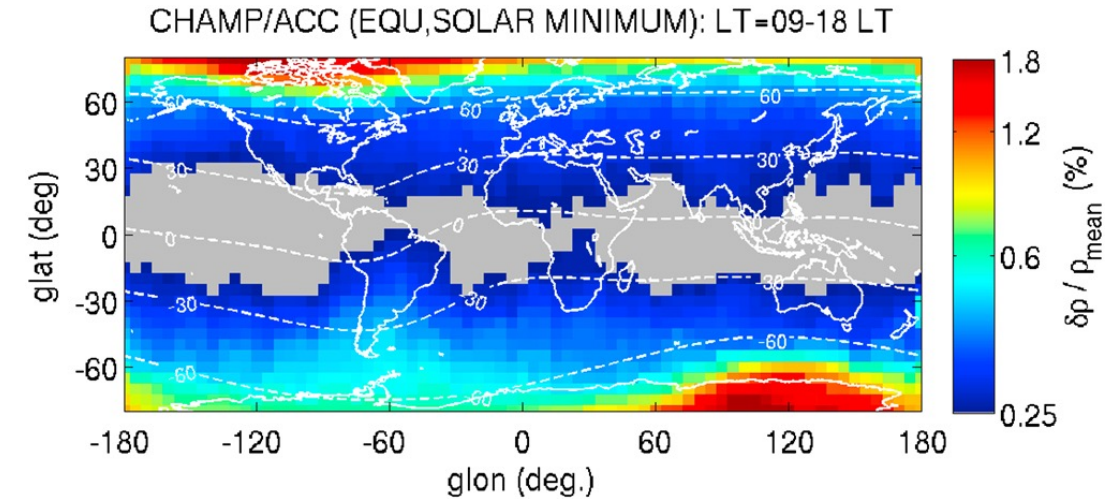
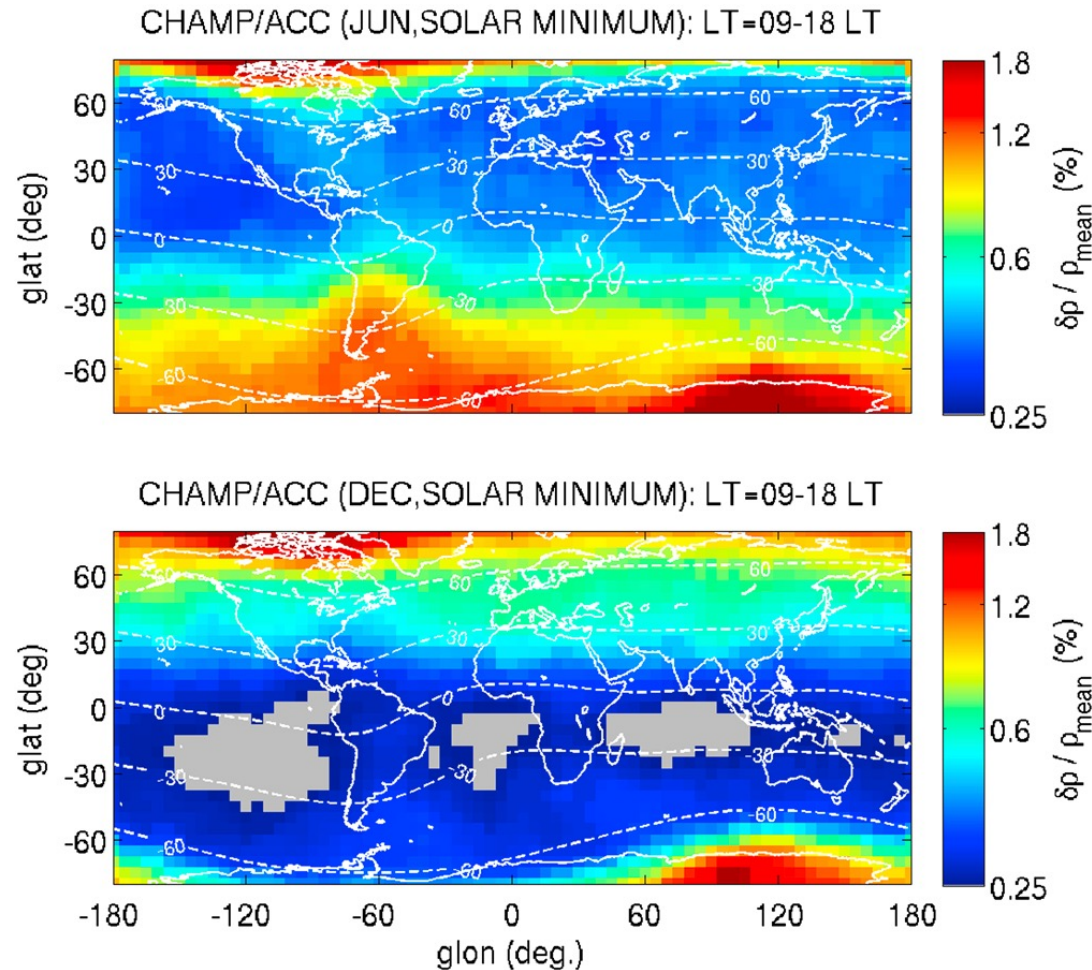
GOCE observation at 250 km altitude



Source: Trinh et al. (2018)

Gravity wave hotspot

SO2: Observing atmospheric waves

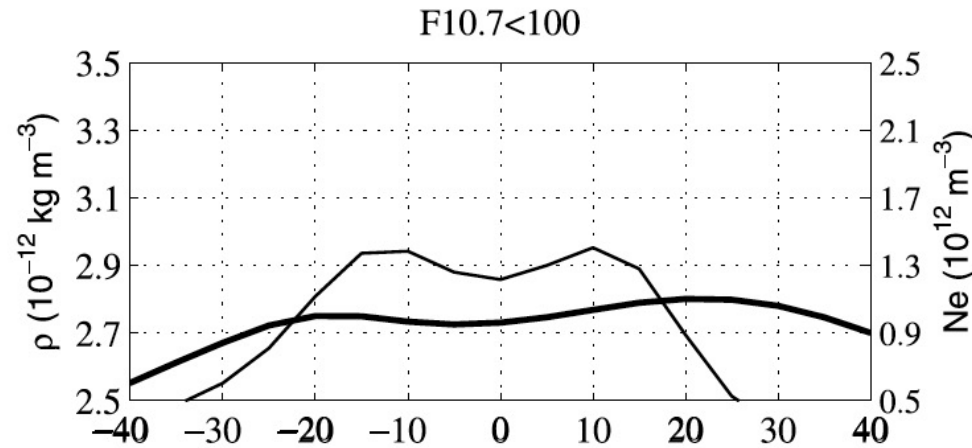


Gravity waves

- Observed by the CHAMP satellite (accelerometry)
- Magnitude is a few percent of the density

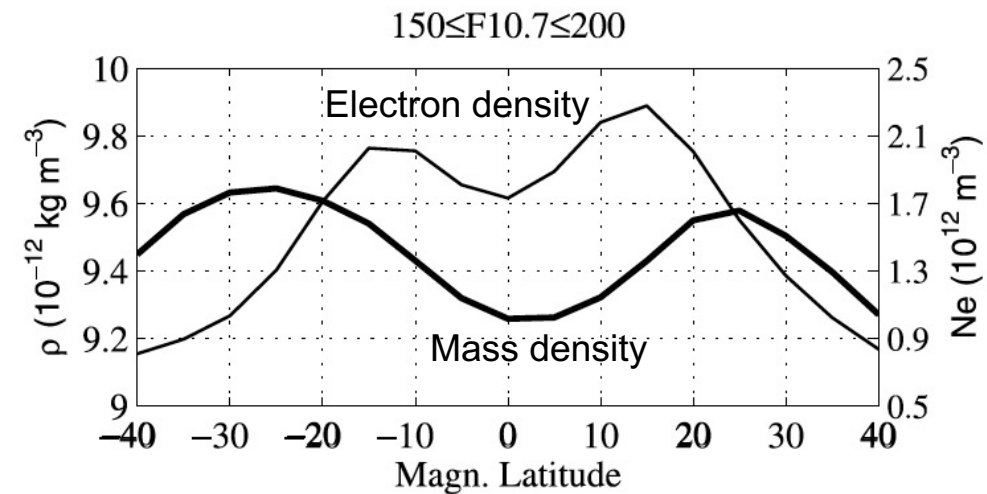
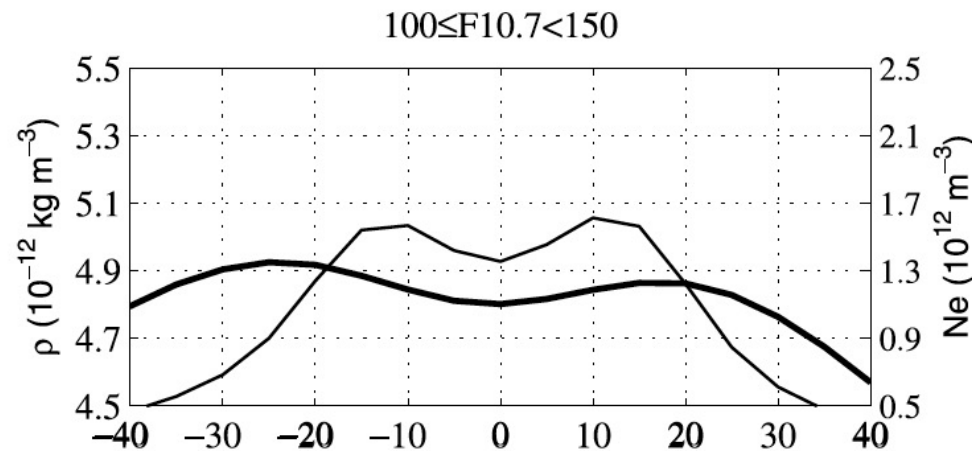
Source: Park et al. (2014)

SO2: Observing atmospheric waves



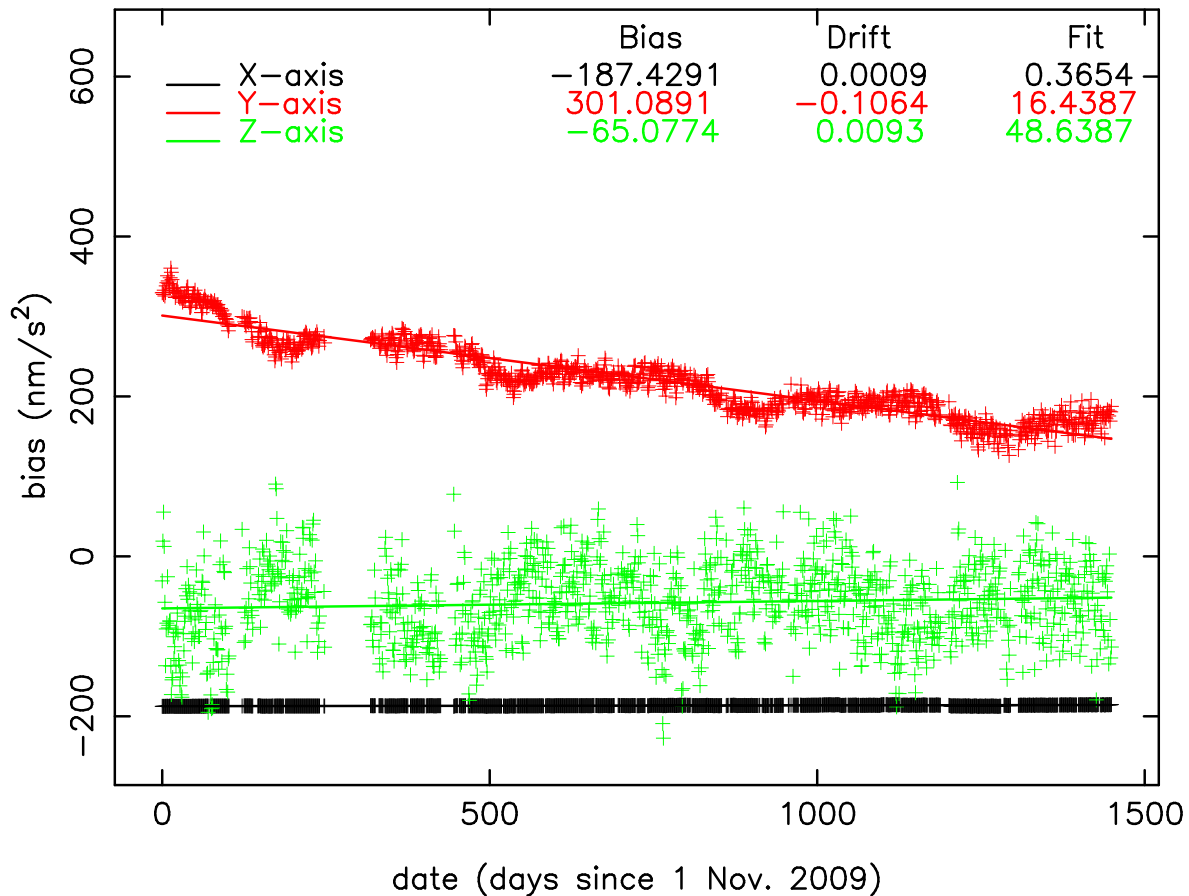
Equatorial mass anomaly

- Observed by the CHAMP satellite (accelerometry)
- Coupled to equatorial ionization anomaly
- Magnitude of a few percent



Source: Liu et al. (2007)

SO3: Observing cross-track acceleration



Source: Visser and van den IJssel (2016)

Estimation of accelerometer biases via POD

- Example: GOCE mission
- Estimated bias consists of
 - Trend (aging of accelerometers?)
 - Random noise (measurement noise of accelerometers and GPS receiver?)
 - Annual variations (force model errors?)

Clarifying the source of systematic variations observed in estimated biases will help to improve observations of the missions of opportunity.

To investigate the cross-track biases, the satellite would need to fly “sideways” as the CAI accelerometer measures only in one direction defined by the laser

Summary

Science objectives

1. **Verification of gas-surface interaction models**
 - Requires accuracy of 1% of mass density
 - Requires simultaneous observation of mass density, atmospheric composition and temperature, and wind
2. **Observation of atmospheric waves**
 - Requires accuracy of 1% of mass density
3. **Observe cross-track accelerations (secondary)**
 - Requires the ability to perform 90° yaw attitude manoeuvres

Fill the present gap in density observations

1. Region below 400 km altitude
2. Fast LTAN progression
3. Medium-high solar activity

Sensor suite

- CAI accelerometer (single axis, flight direction)
- GNSS receiver
- Star sensor
- Neutral mass spectrometer
- Ram wind sensor

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