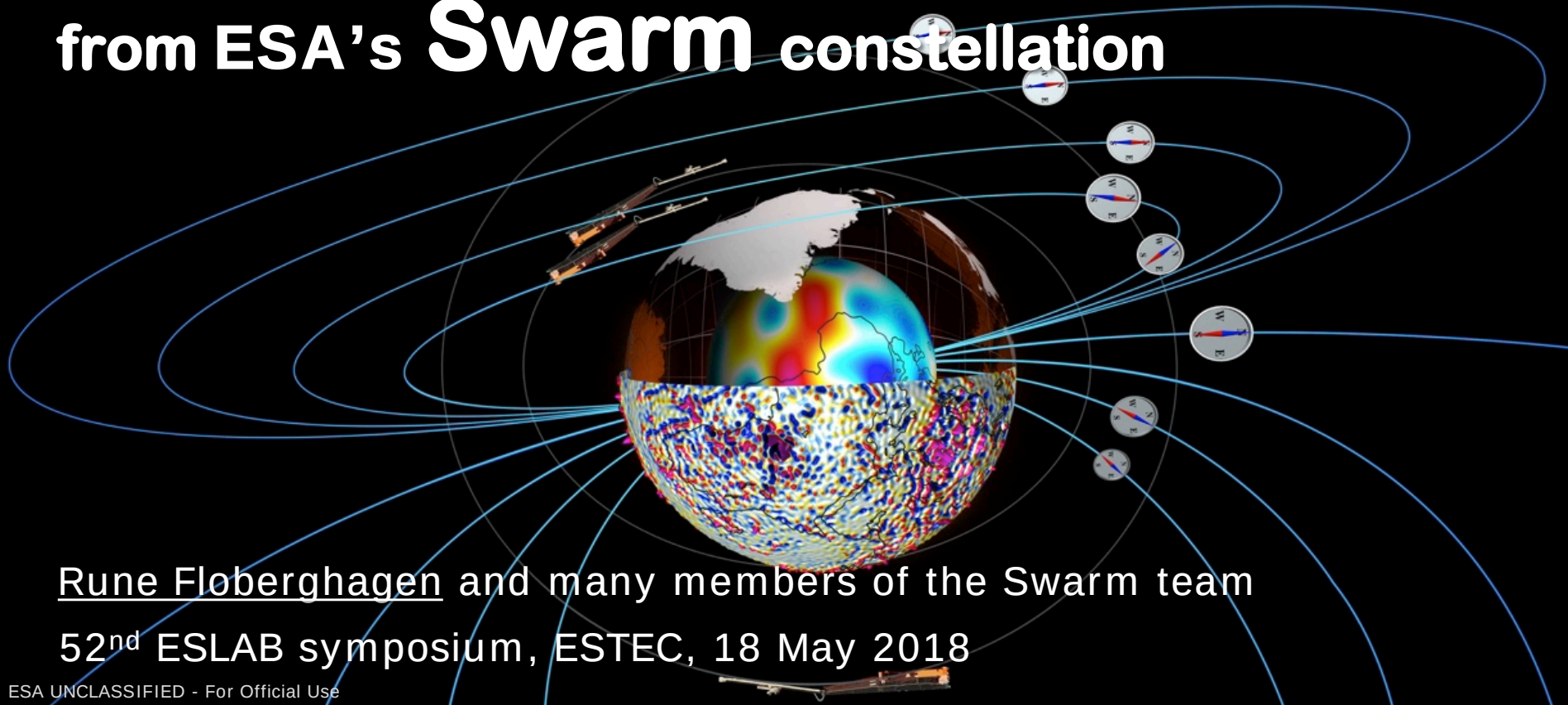
Geospace research contributions from ESA's Swarm constellation



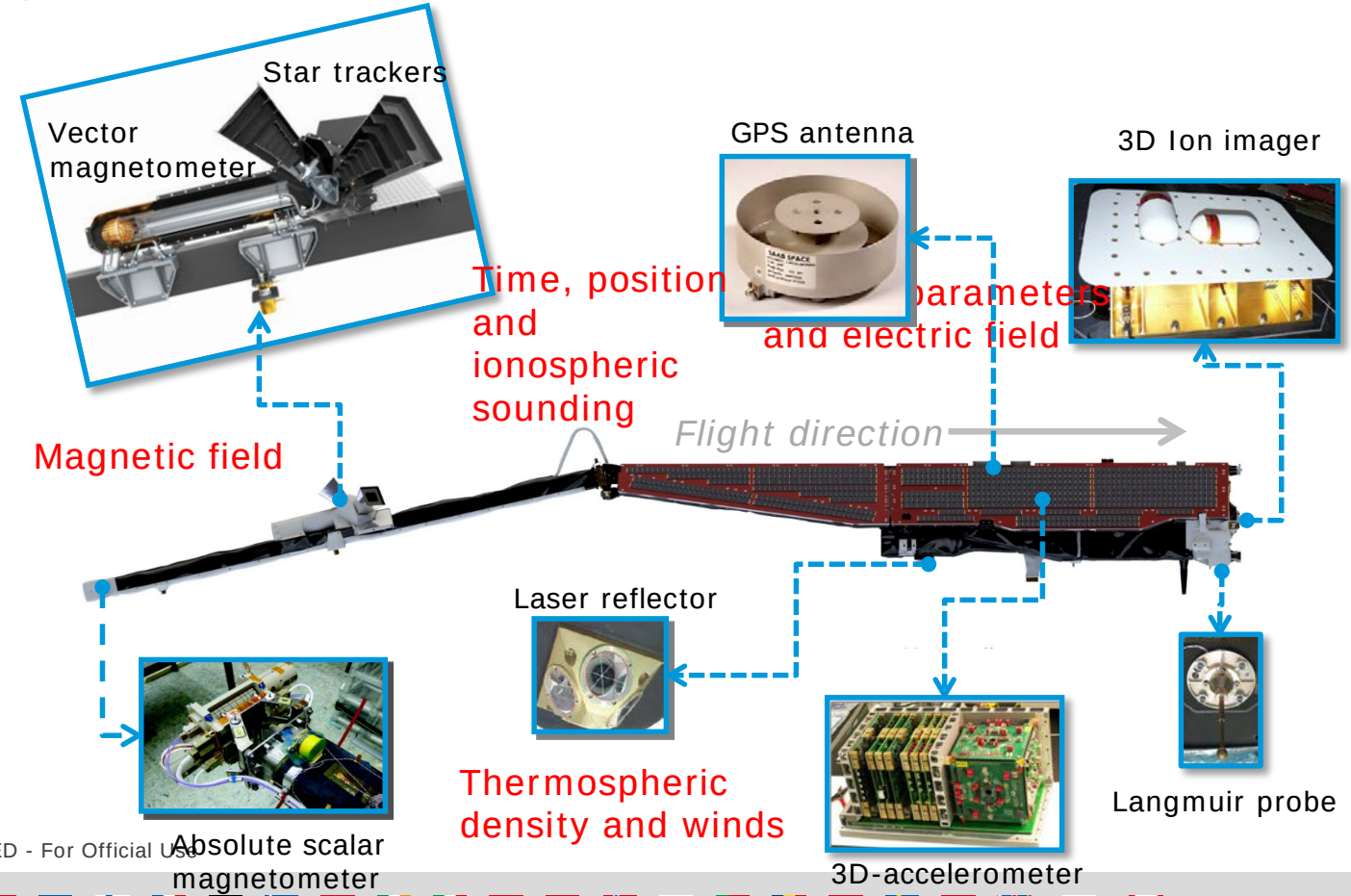
Rune Floberghagen and many members of the Swarm team

52nd ESLAB symposium, ESTEC, 18 May 2018

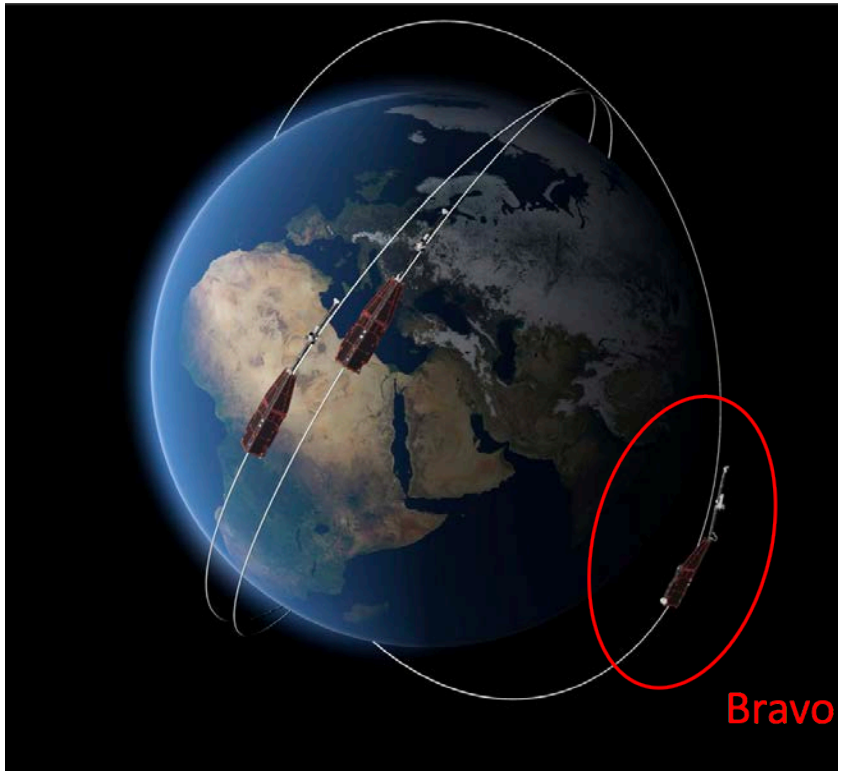
One true Earth (and Earth environment) Explorer…

…on a journey from the core to the magnetosphere and nearly everything in-between

Payload


Star trackers
Vector magnetometer
GPS antenna
3D Ion imager
Time, position and ionospheric sounding
parameters and electric field
Magnetic field
Flight direction
Laser reflector
Absolute scalar magnetometer
Thermospheric density and winds
3D-accelerometer
Langmuir probe

The upper satellite



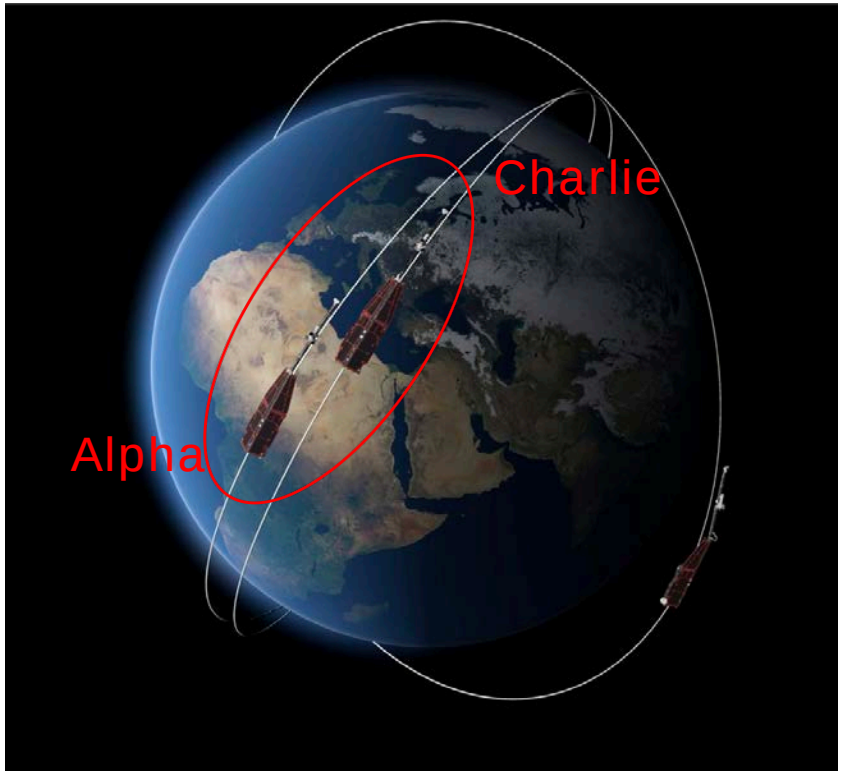
One satellite at higher altitude (approx 510 km)

Essential for signal and error separation

Different local time!

(Potentially very) long lifetime

The lower pair (“gradiometer”)



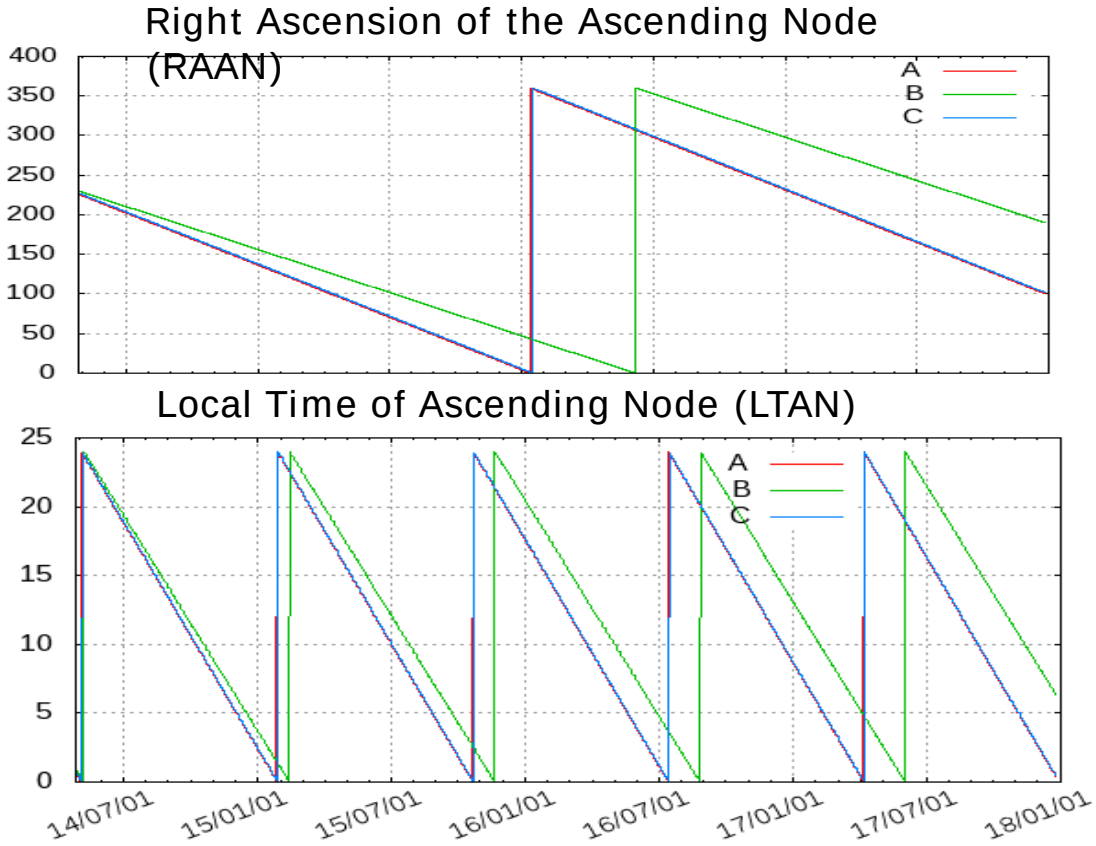
Two satellites at lower altitude (approx 460 km)

Provides east-west differential observations essential for signal separation

Separation at equator approx. 150 km

Along-track separation of a few seconds to avoid collision at poles

Swarm Orbital Plane Evolution



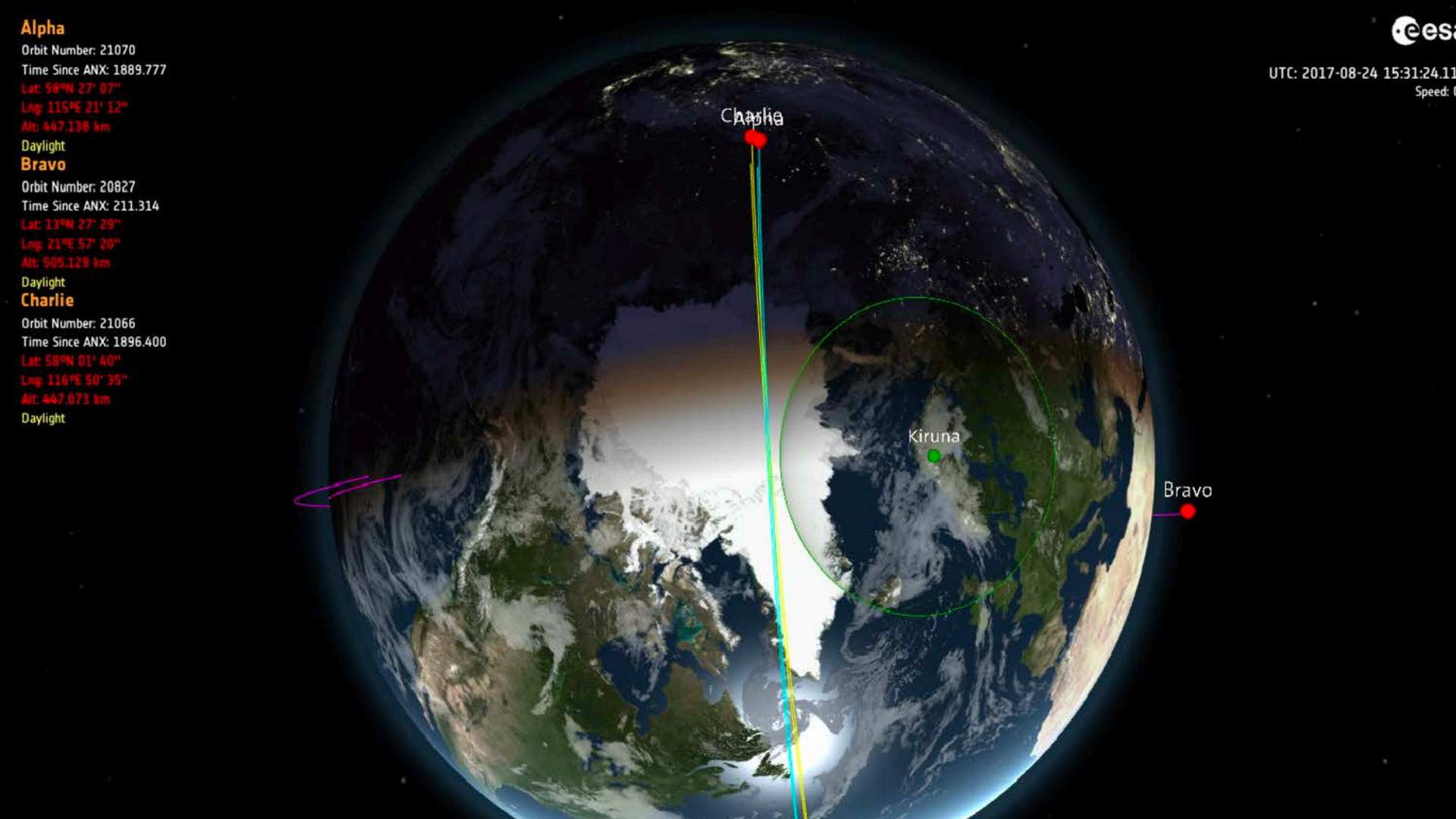
Rate of change:

Ω_{AC} : ~8.3 deg/month

Ω_{B} : ~12.5 deg/month

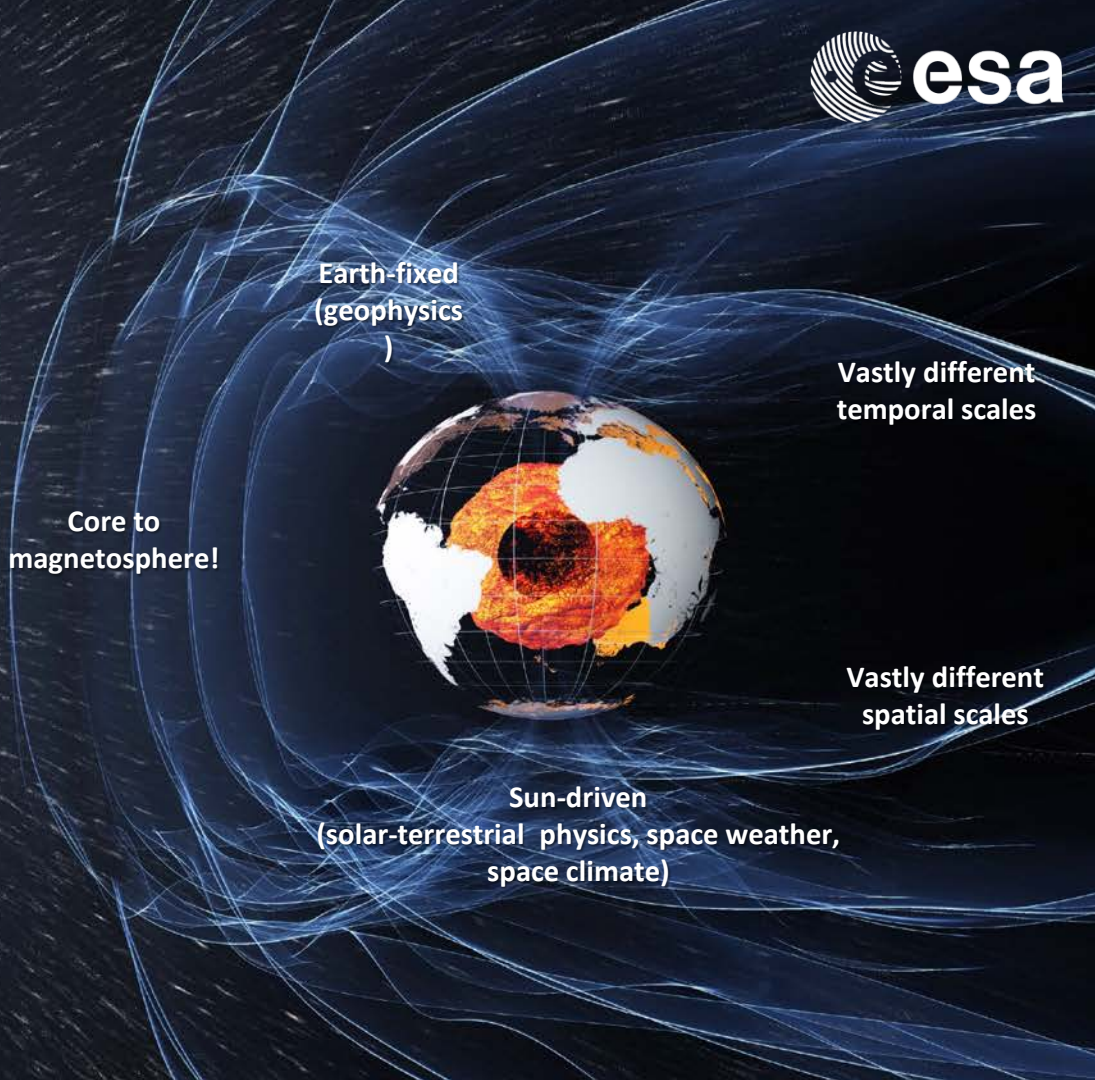
Full coverage (24h):

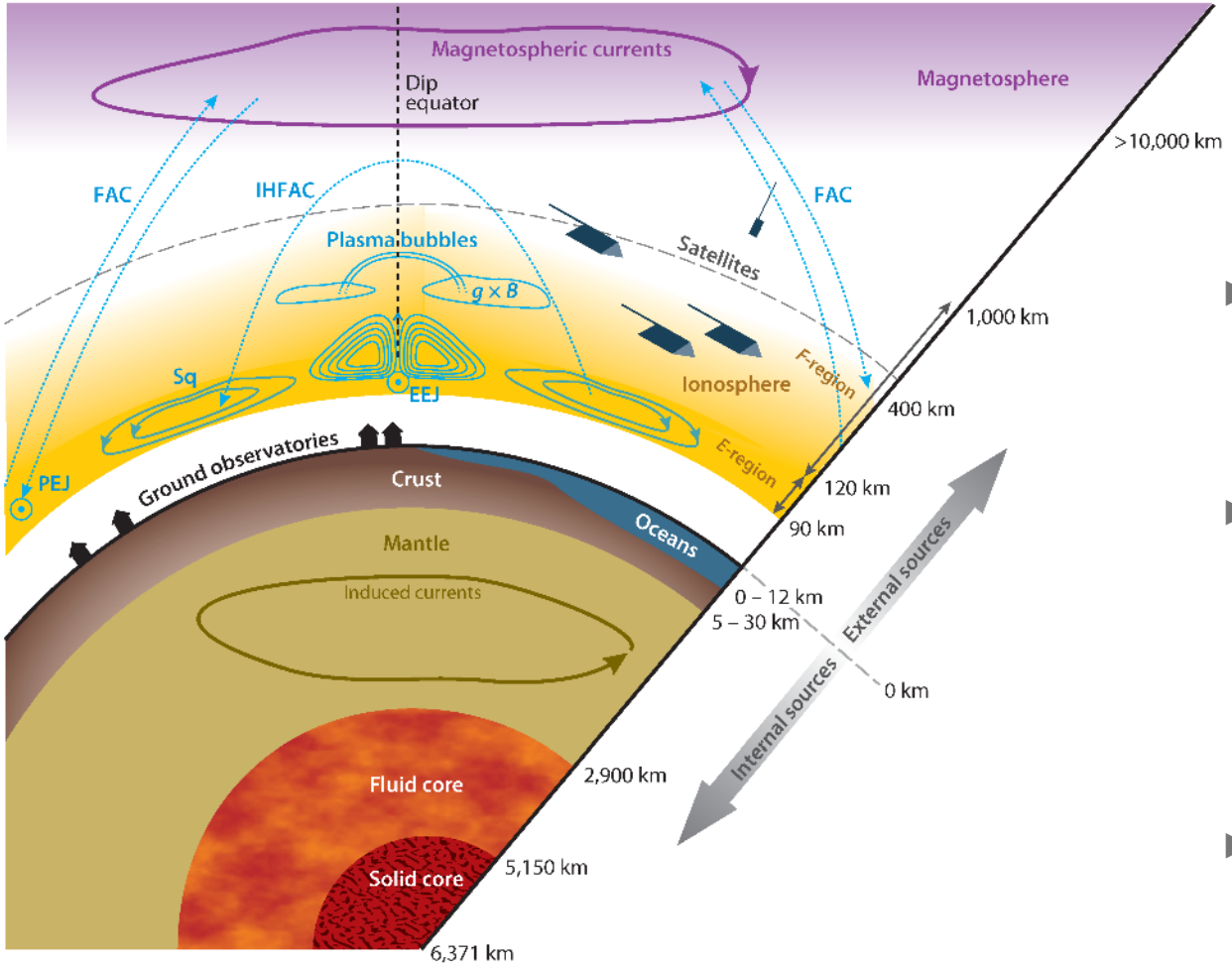
- 8.8 months A/C
- 9.2 months B


Alpha
Orbit Number: 21070
Time Since ANX: 1889.777
Lat: 58°N 27' 07"
Lng: 115°E 21' 12"
Alt: 447.138 km
Daylight
Bravo
Orbit Number: 20827
Time Since ANX: 211.314
Lat: 13°N 27' 29"
Lng: 21°E 57' 20"
Alt: 505.129 km
Daylight
Charlie
Orbit Number: 21066
Time Since ANX: 1896.400
Lat: 58°N 01' 40"
Lng: 116°E 50' 35"
Alt: 447.073 km
Daylight
UTC: 2017-08-24 15:31:24.11
Charlie
Alpha
Kiruna
Bravo

Swarm is growing fast: ~1000 partners worldwide; close to 200 papers since launch; products range, services and collaborations are increasing by the month

➔ A highly versatile mission





Swarm

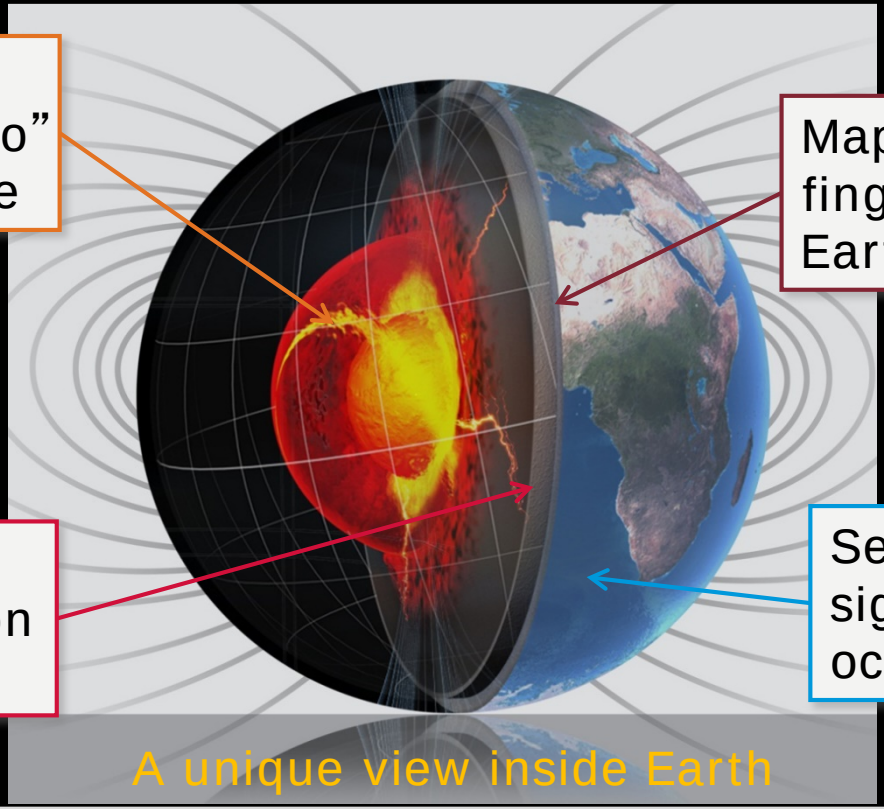
- is a true multi-point, multi-purpose explorer
- is a catalyser which brings Earth science and solar-terrestrial physics closer together
- is like nothing else up there

Revealing Earth's inner secrets

***A journey to the centre of the Earth* (Jules Verne)**

Understanding "Earth's dynamo" in the outer core

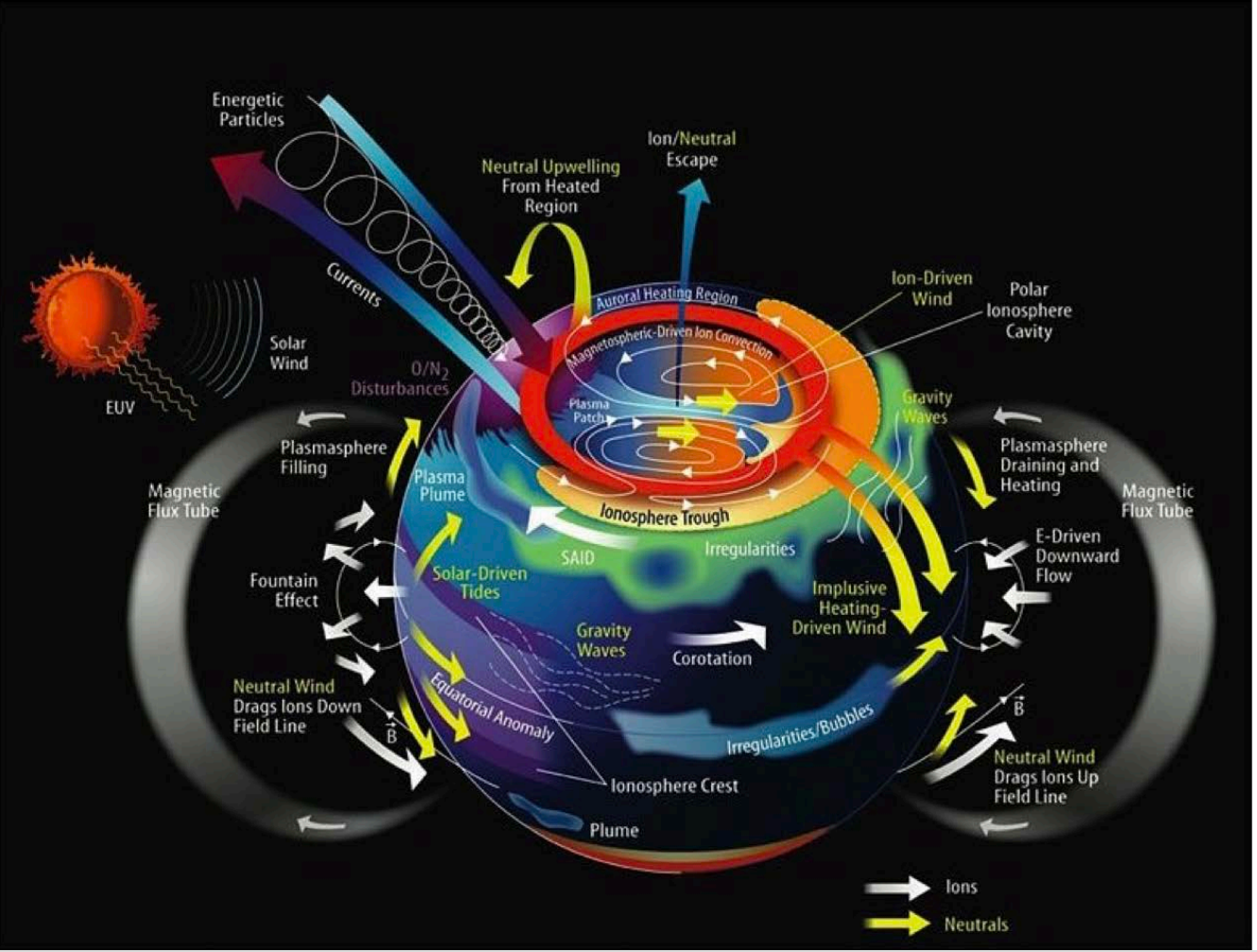
Mapping "magnetic fingerprints" in Earth's crust



Looking into the composition of the mantle

Sensing the weak signature of the ocean currents

A unique view inside Earth



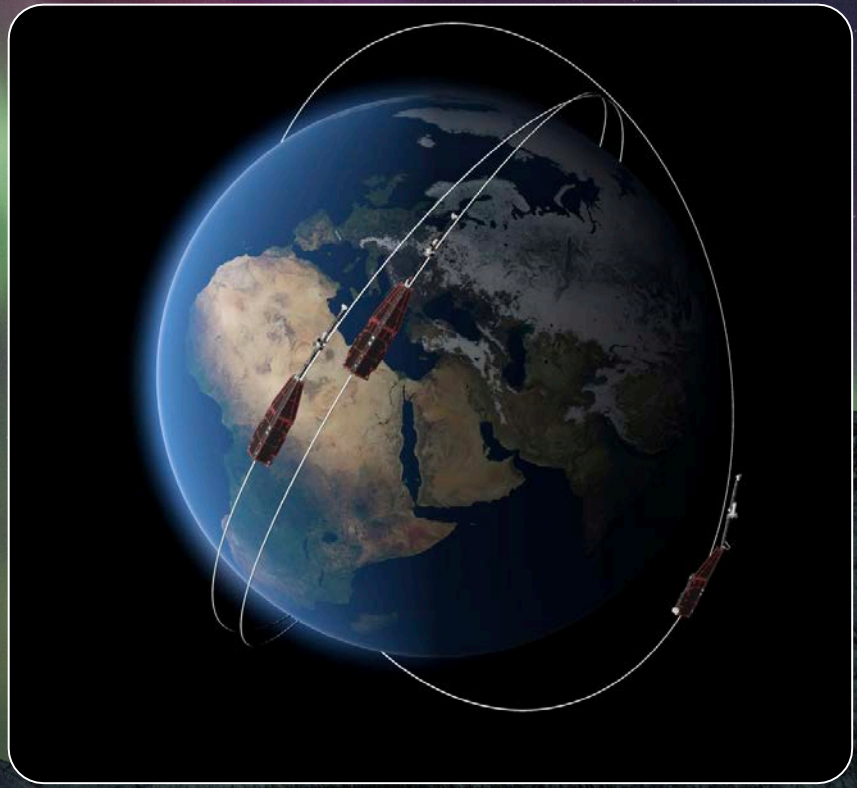
Courtesy: Joe Grebowsky, NASA/GSFC

Strength of the Swarm constellation

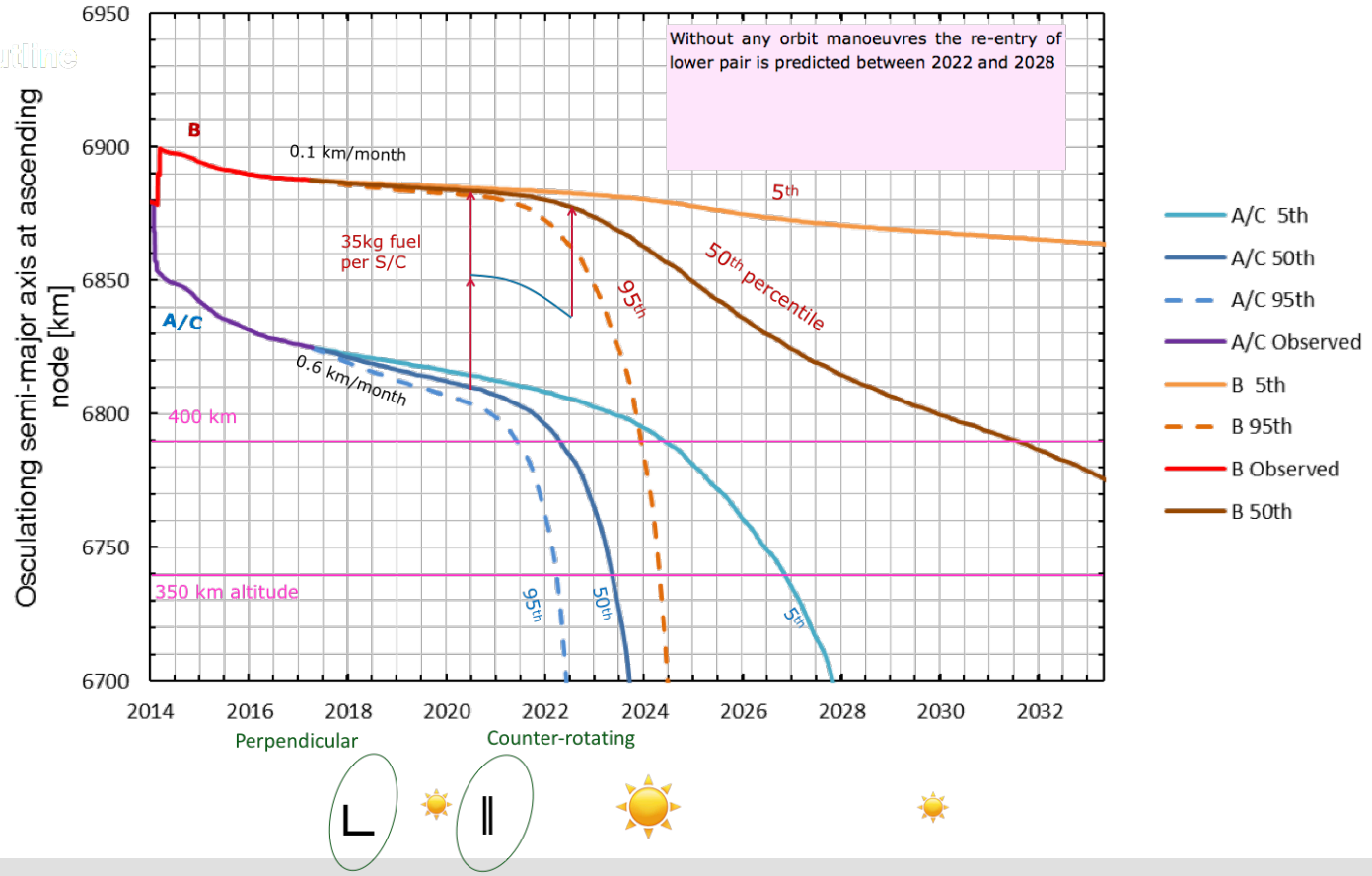
Highly **accurate** and **multi-point** observations make a **great combination** for the Earth and solar-terrestrial sciences

Swarm status

- Excellent performance
- No significant anomalies since 2014
- No signs of aging
- All redundancies in place apart from scalar magnetometer on Charlie
- > 60 kg fuel reserve on all s/c
- Extension approved through 2021

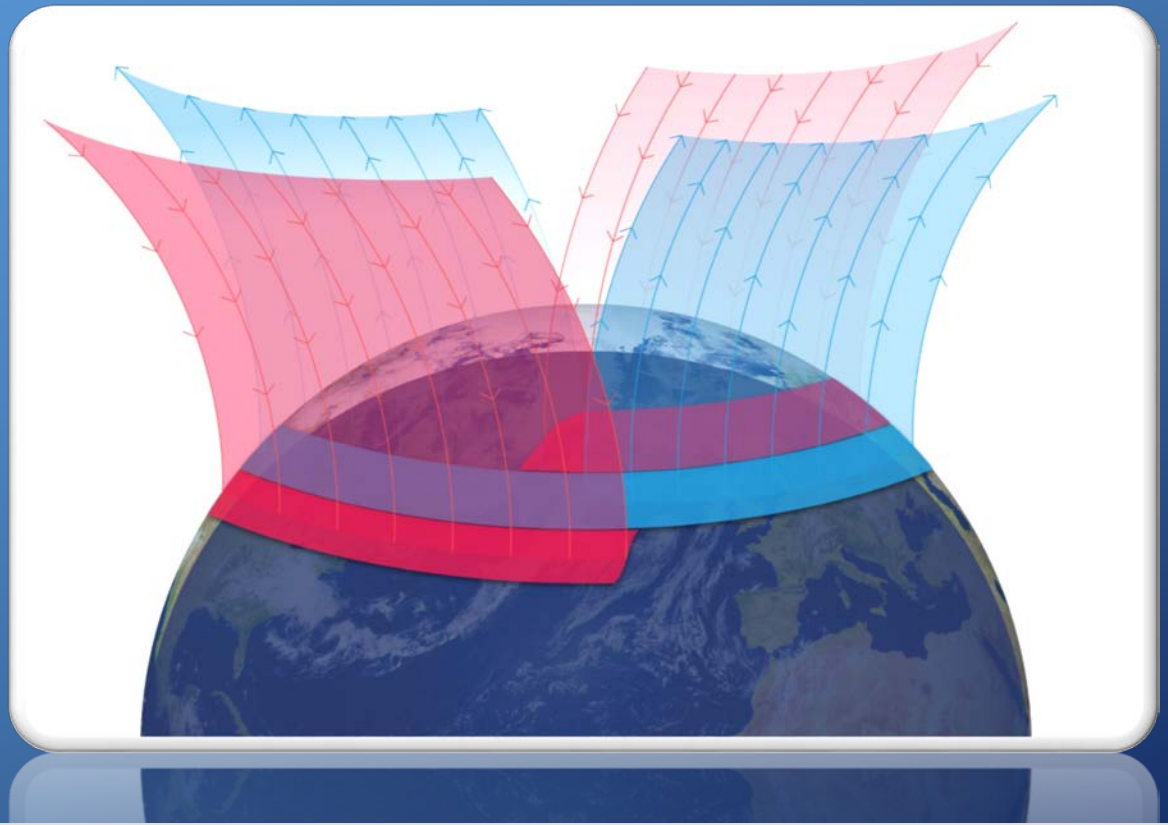


Lifetime perspectives

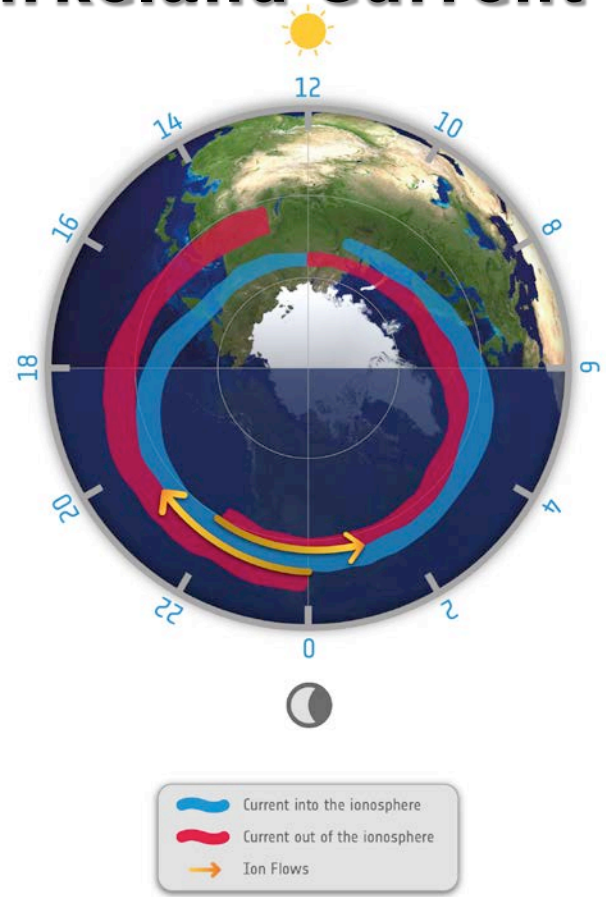


Selected Scientific Results

Improved understanding of MIT coupling



Birkeland Current Boundary Flows



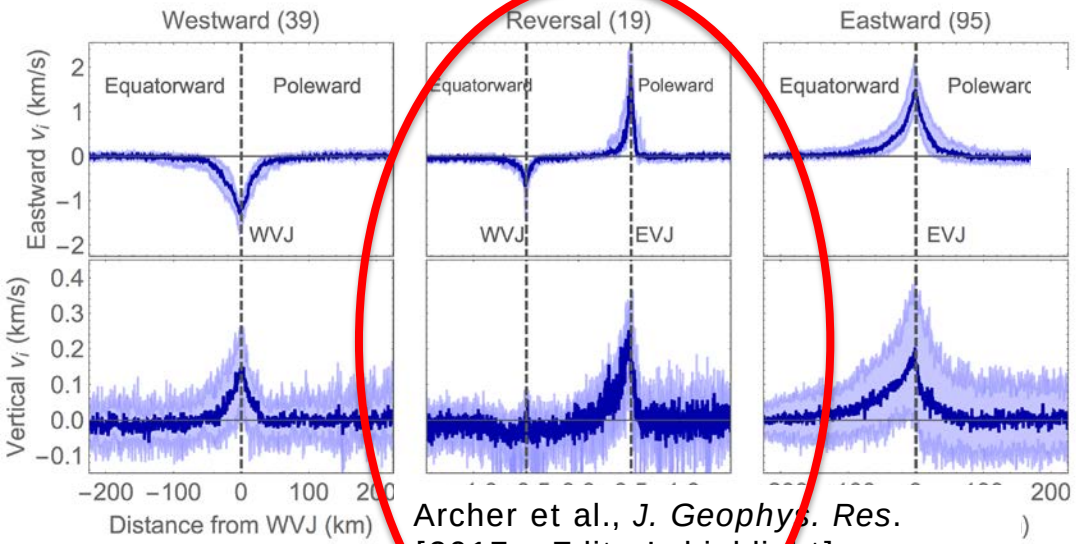
- study of quiet conditions (AE<200 nT)
- 20-100 km size latitudinal flow channels at the boundaries of R1/R2
- ~always present
- Effectively modifies the view on field-aligned currents that has been in place since the classical 1978 Iijima & Potemra paper

Birkeland Current Boundary Flows

- BCBF are fast flow channels along the boundary between R1 & R2 currents
- Fast ion flows are coincident with heated ions, ion upflow and likely also NO^+ production
- Upward current is coincident with aurora and heated electrons

Birkeland Current Boundary Flows

Archer et al. [*JGR*, 2017]



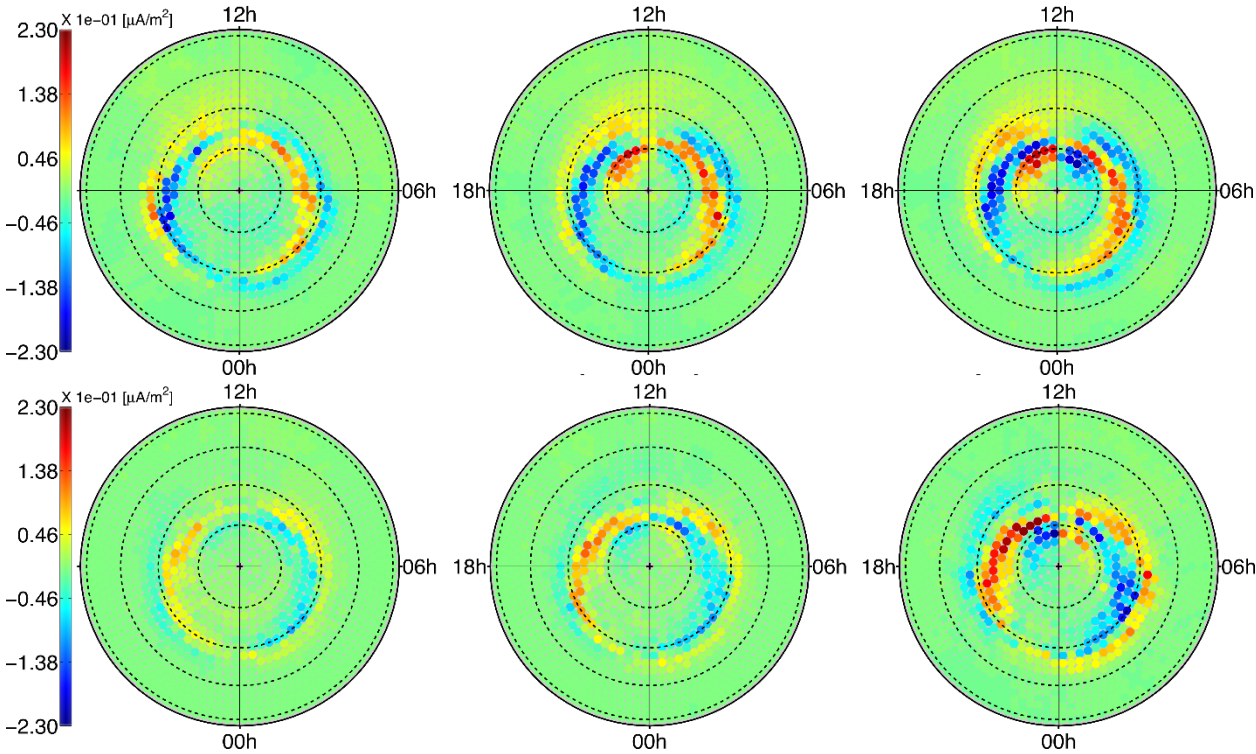
Archer et al., *J. Geophys. Res.* [2017 – Editor's highlight]

Birkeland current climatology: Ap ≤ 7 nT

local winter equinox

Northern hemisphere

Southern hemisphere

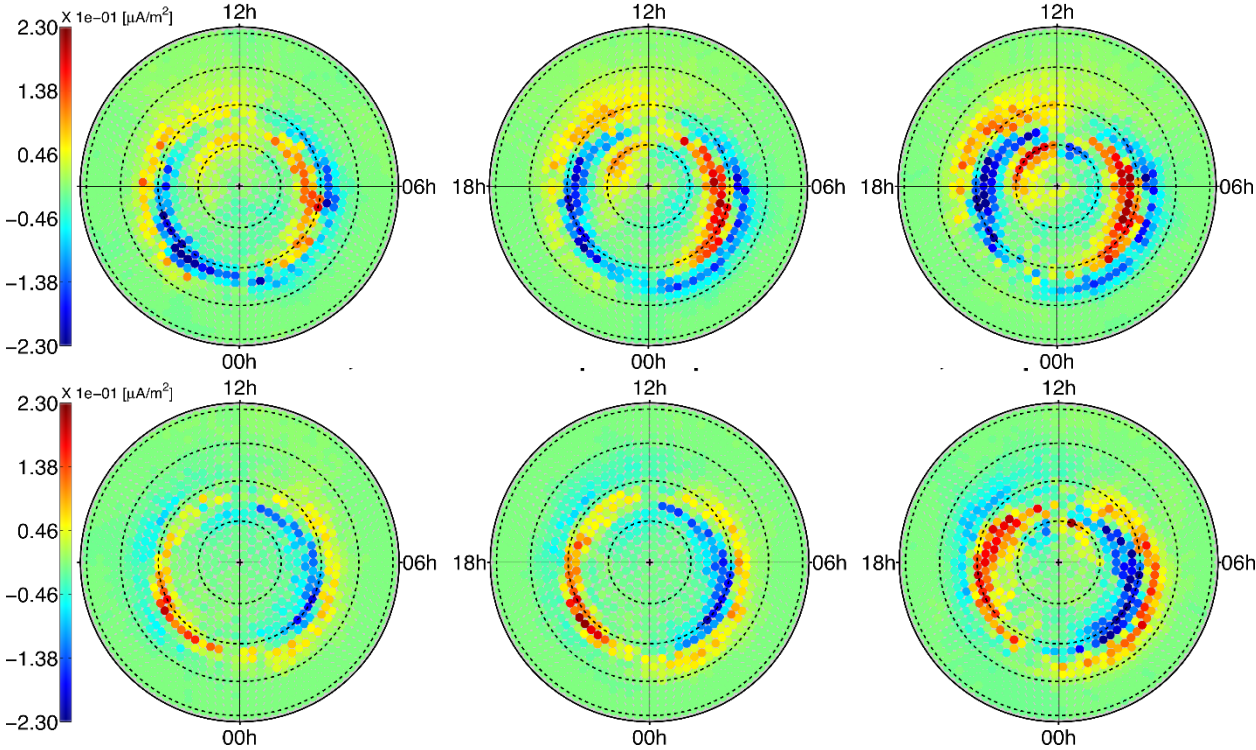


Birkeland current climatology: Ap ≥ 8 nT

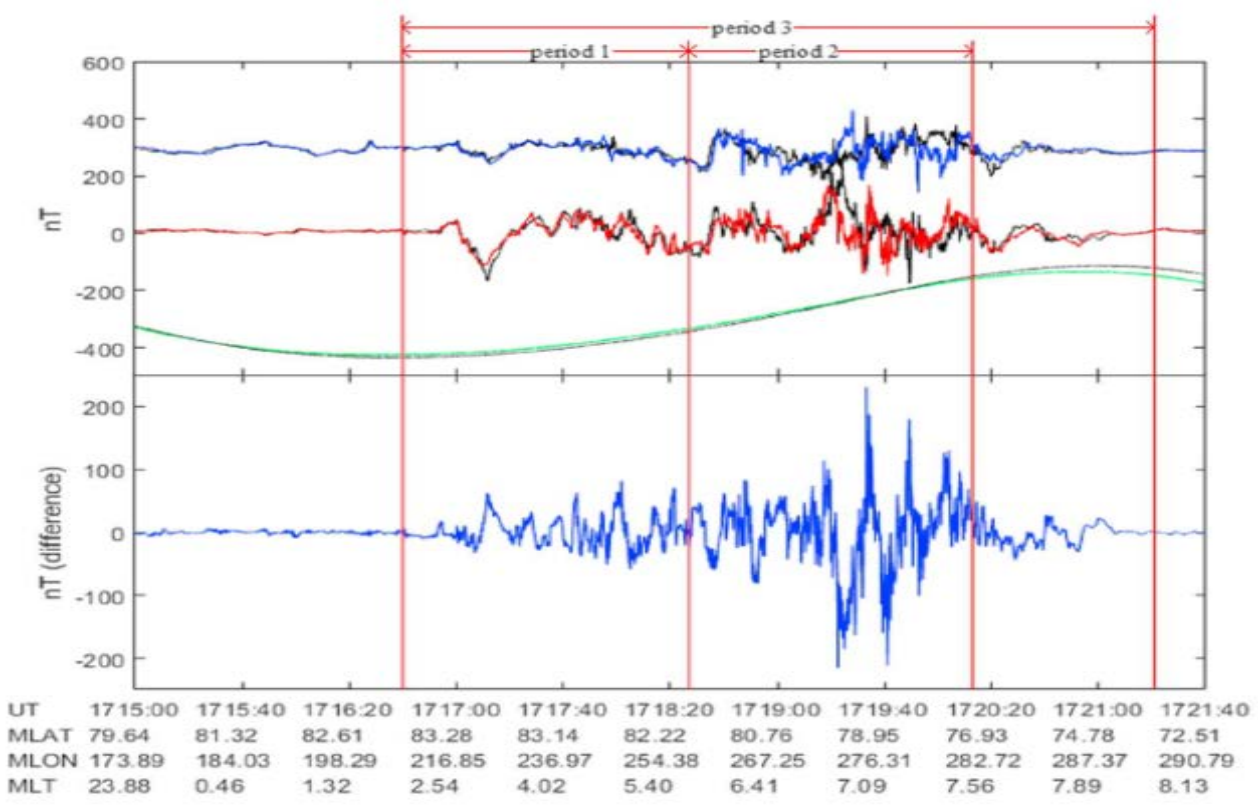
local winter equinox

Northern hemisphere

Southern hemisphere



High cadence data – FAC system crossing



- Pakhotin et al. (2018) JGR: quiet-time northward IMF Bz auroral system crossing by Alpha and Charlie; transverse magnetic field perturbations

- Two regimes: (1) quasi-static period and (2) dynamic/" Alfvénic" period with large residuals

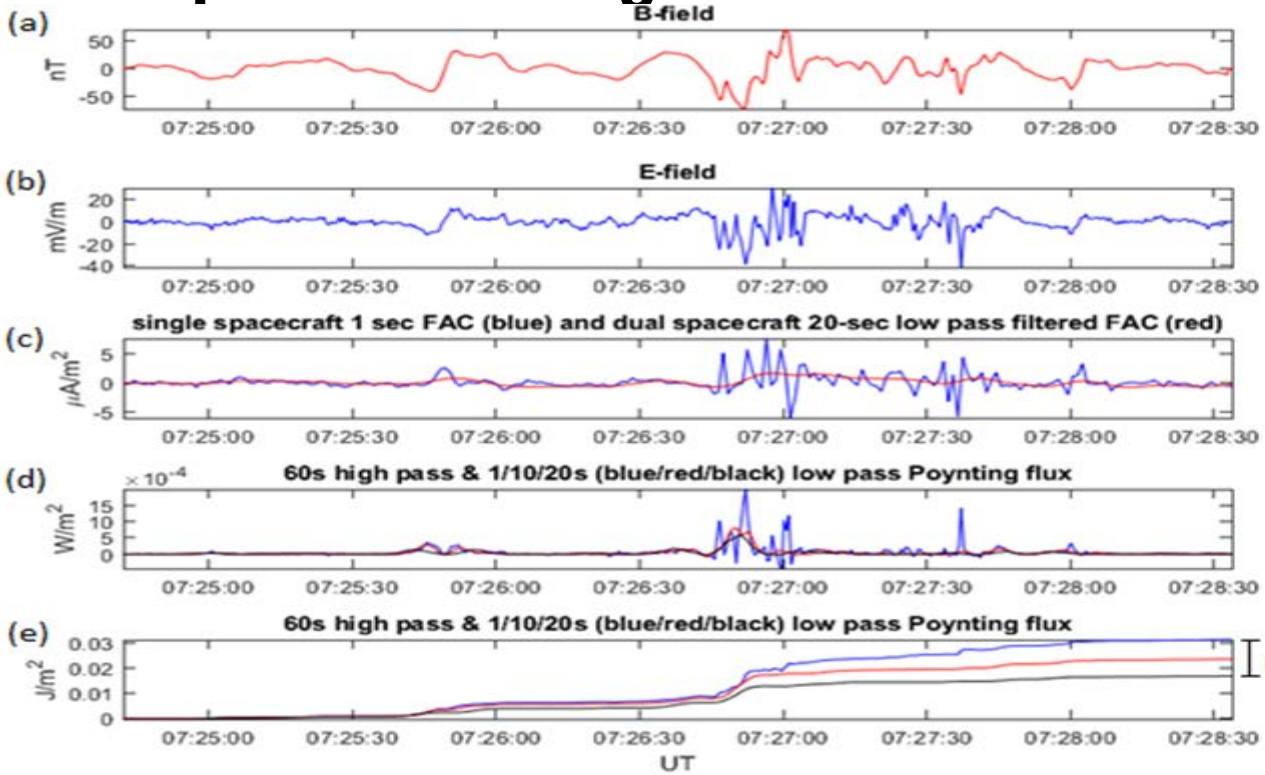
- Spacecraft only 10 sec apart along-track

Courtesy of: I. Pakhotin, Univ Alberta

What is the scale dependence in magnetosphere-ionosphere coupling?

- **In terms of field-aligned currents?**
- **In terms of energy transfer?**

Poynting flux under-estimation as a result of low-pass filtering



B-field

E-field

FAC

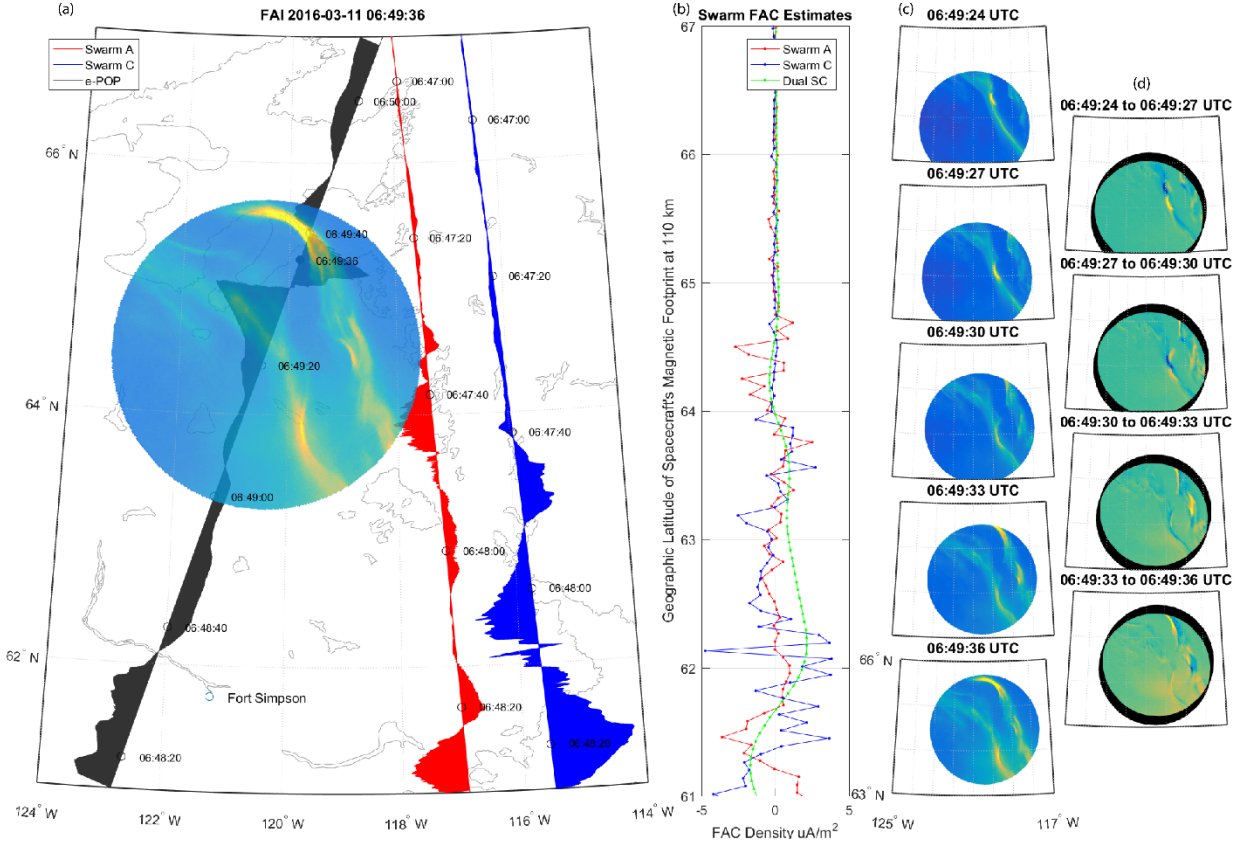
Poynting flux, S

Integrated S

Swarm and FAC system analysis

- Swarm high-cadence E and B field measurements allow diagnosis of physical processes that control magnetosphere-ionosphere coupling
- Alfvén waves and FACs appear to be well-described by the same physical paradigm of incidence, ionospheric reflection and interference at multiple scales
- Around half the Poynting flux appears to be carried by small-scale (<150 km) electrodynamics
- Filtering at 20-sec time scales removes the signatures of these electrodynamics from the Swarm field-aligned current products
- In order to fully understand MIC these smaller scales should not be ignored

Swarm and ePOP (“Swarm Echo”)

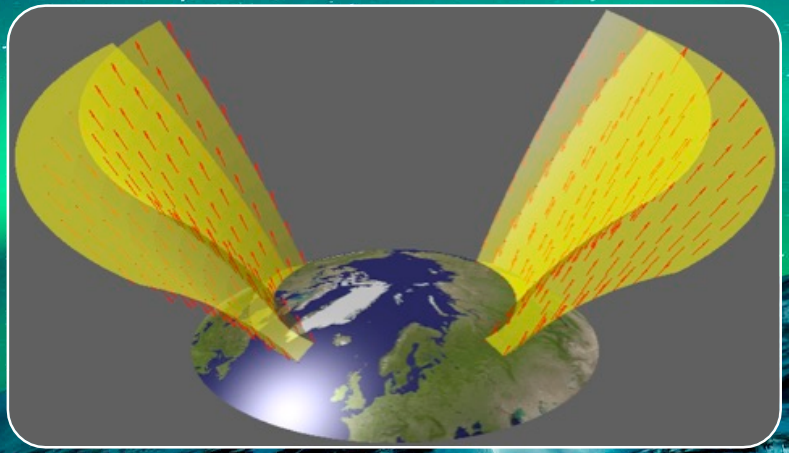


Discoveries by Swarm

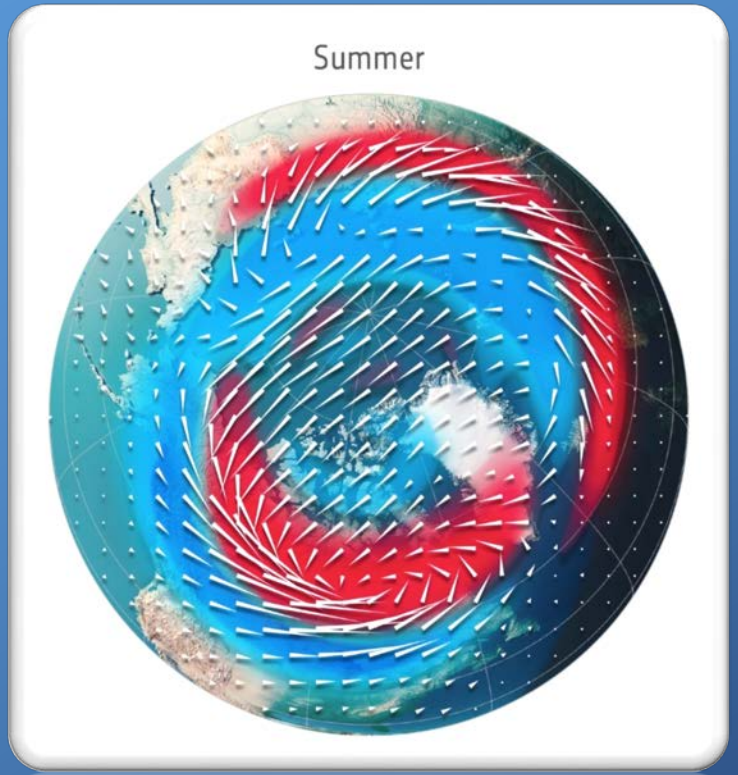
3

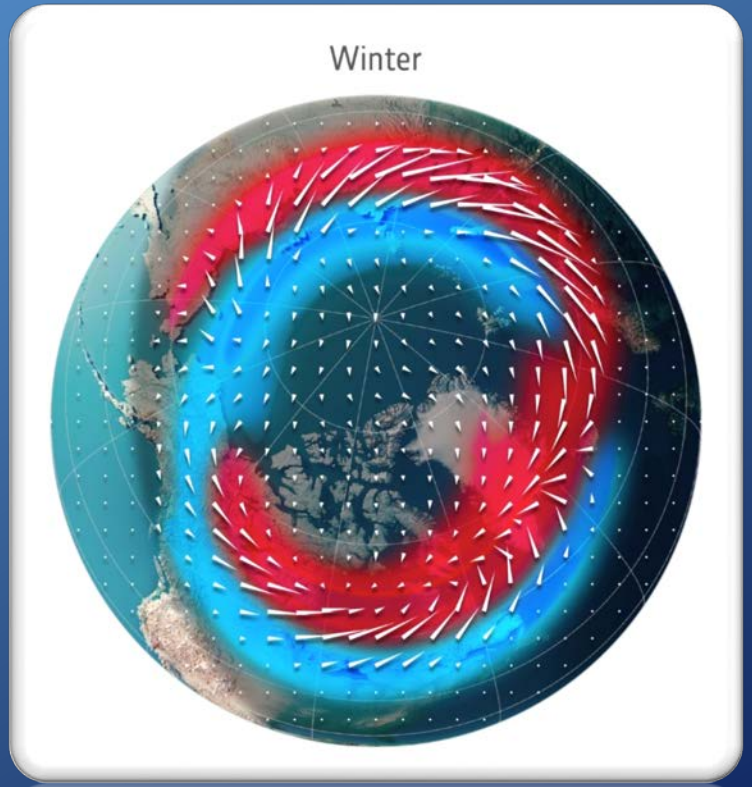
Electric currents in the polar cap

- How do currents close in the polar caps? Close to Earth or really far out and away?
- Long-standing scientific debate now solved by Swarm



Swarm resolves the 3D current structure!



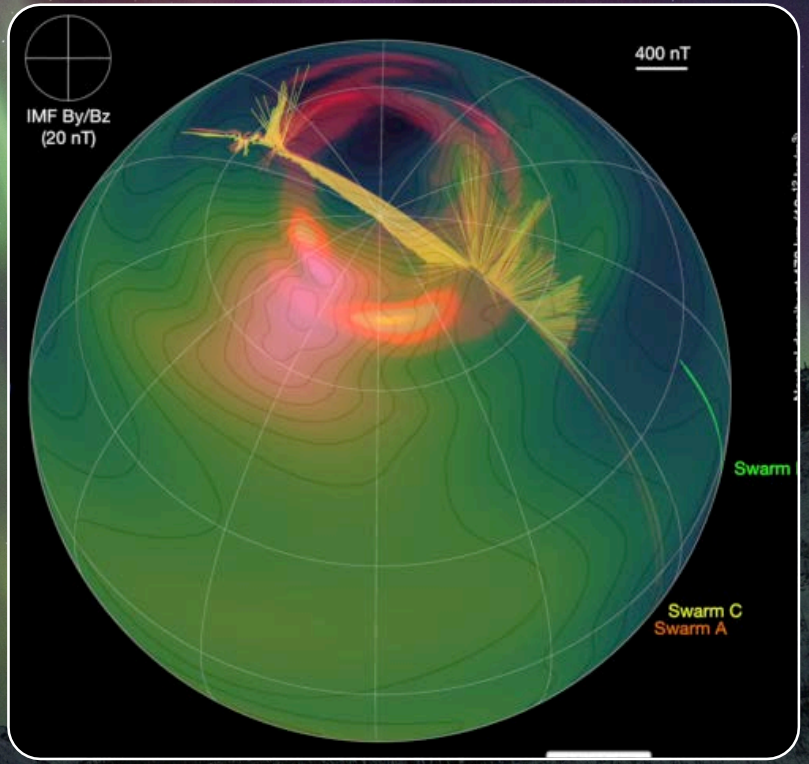


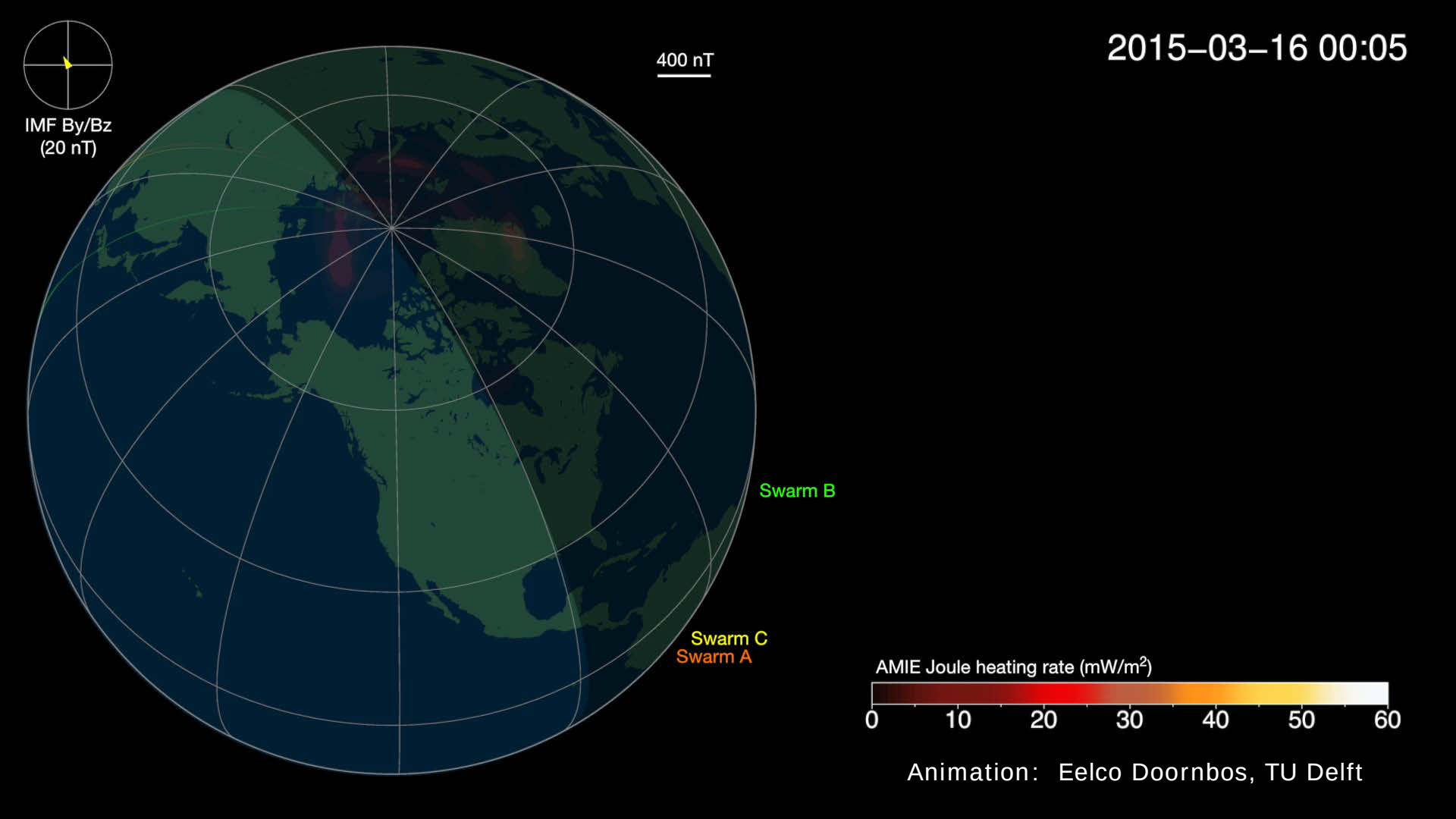
Discoveries by Swarm

4

Space storm

- Detailed evolution of a storm in geospace
- Shows how the solar wind drives (Joule) heat into the upper atmosphere and how it responds



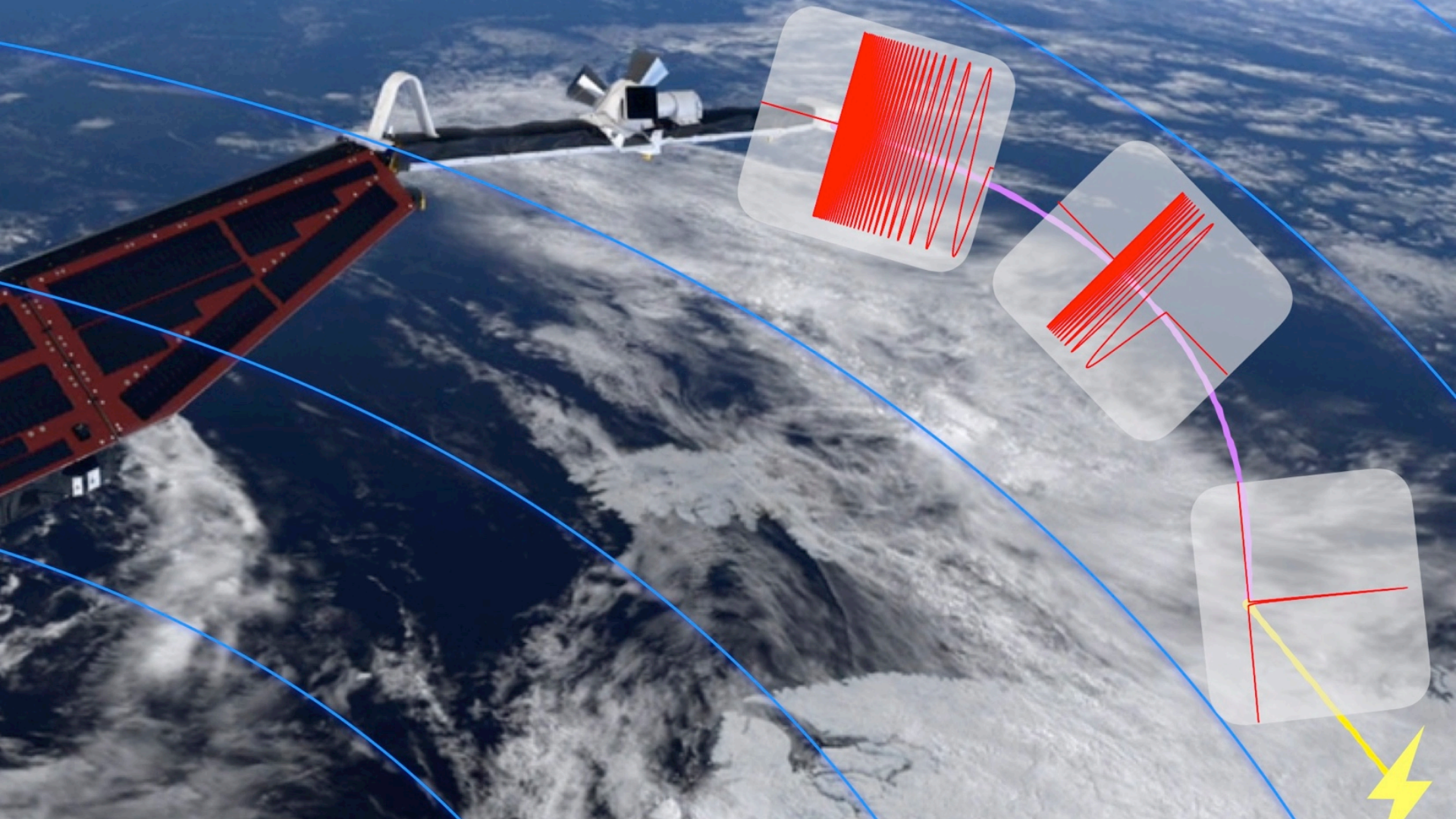

IMF By/Bz
(20 nT)
400 nT
2015–03–16 00:05
Swarm B
Swarm C
Swarm A
AMIE Joule heating rate (mW/m2)
0
10
20
30
40
50
60
Animation: Eelco Doornbos, TU Delft

Discoveries by Swarm

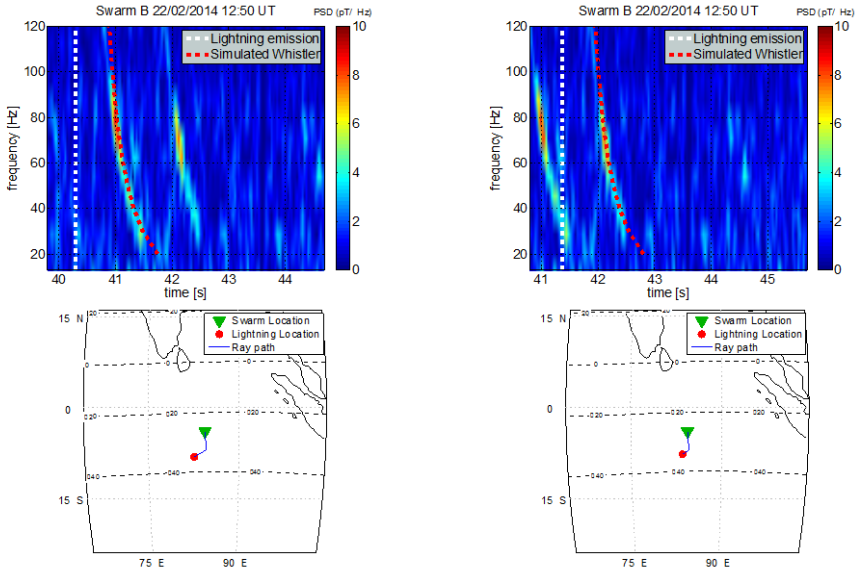
5

Thunderstorms

- Strong electrical charges also travels upwards
- Dispersed in the ionosphere
- Detected as a high-frequency magnetic signal
- Element of coupling between weather on ground and in space



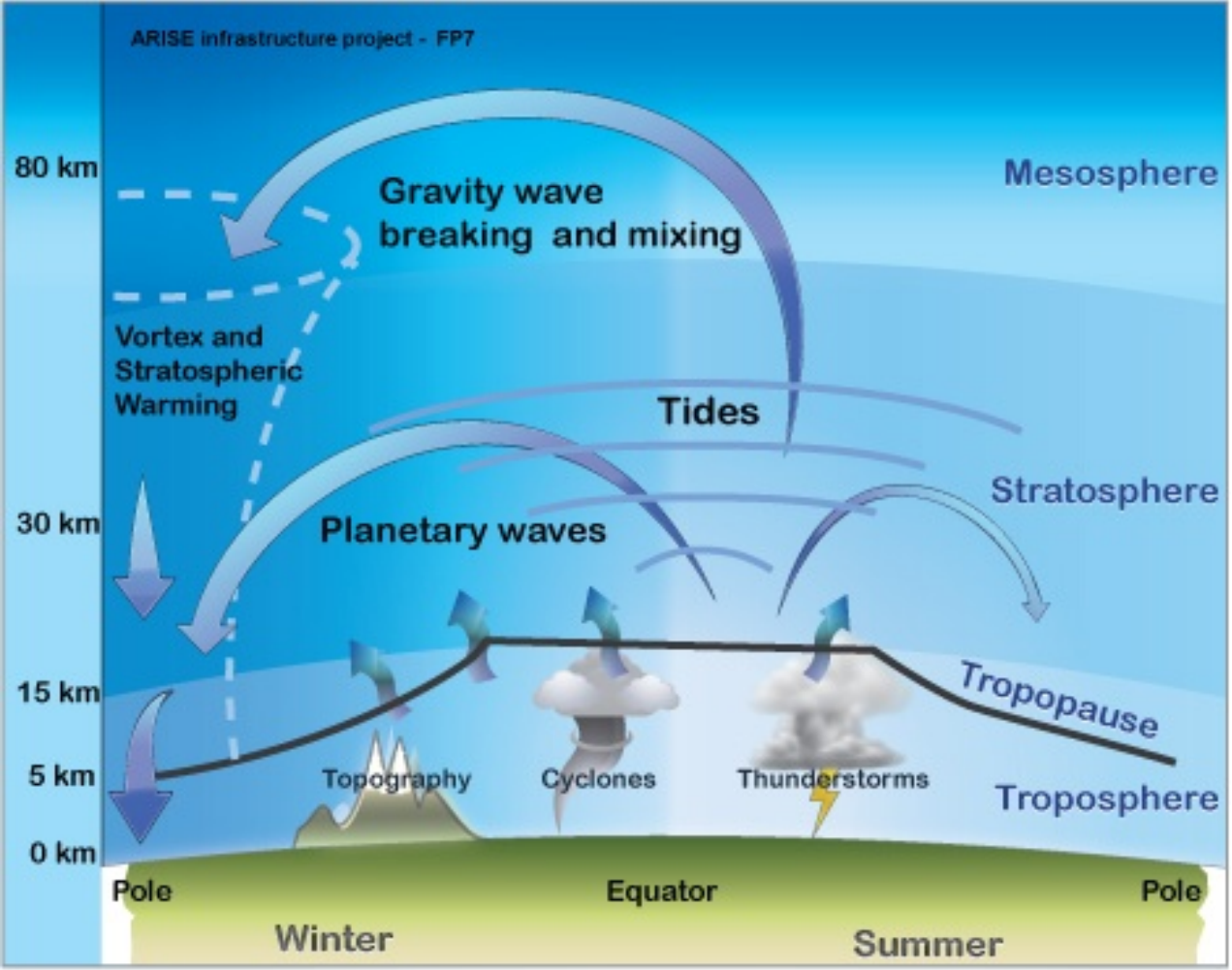
Unexpected new science avenues provided by the experimental **ASM burst mode data** of Swarm



IPGP/LETI

The ASM instrument has been run in a 250 Hz experimental mode over a few days, revealing « whistler » ELF intensity signals produced by lightning in the atmosphere. Such signals at such ELF frequencies **are poorly documented from space so far**, and **offer exciting possibilities for investigating propagation of such signals in the ionosphere**.

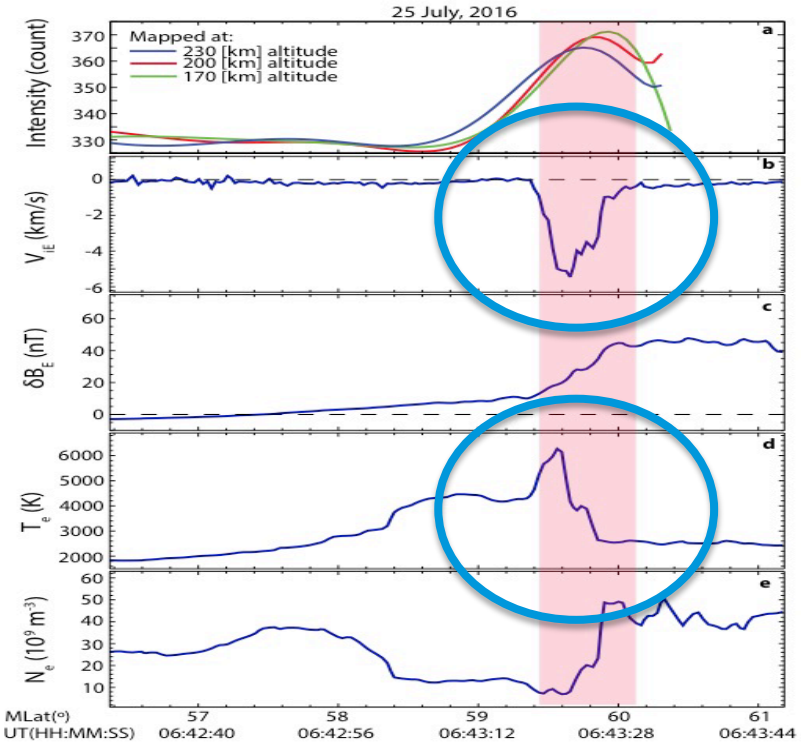
Simultaneous Detection of Extremely Low Frequency Lightning Whistlers by the Absolute Scalar Magnetometers on Board the Swarm Constellation



- Coupling between lower and upper atmosphere is becoming a hot topic
- We regularly observe cyclones and typhoons in Swarm EM data
- We are keen to collaborate on this!

“STEVE”

MacDonald et al. **New Science in Plain Sight: Citizen Scientists Lead to Discovery of Optical Structure in the Upper Atmosphere**, *Science Advances*, 2018.



Unique arc-like structure may result from Strong Thermal Emission due to a strong Velocity Enhancement (>4 km/s).

Equatorial density anomaly and equinoctial asymmetry: Informing models

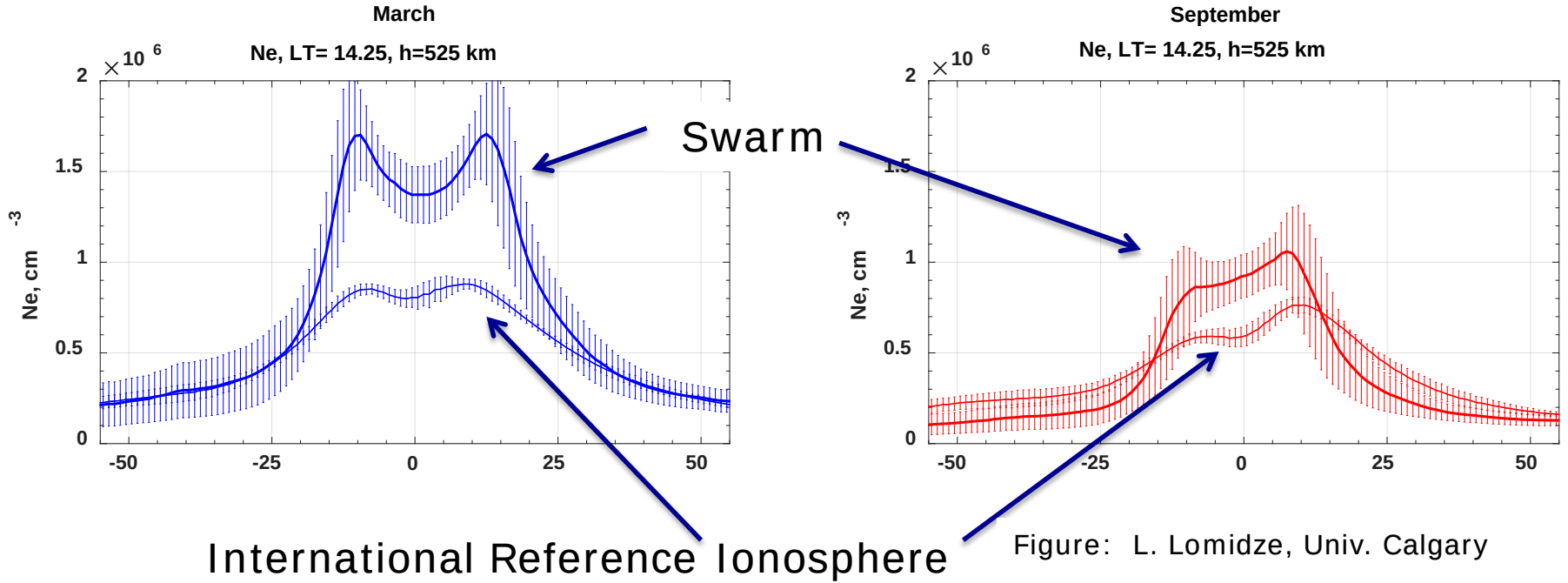
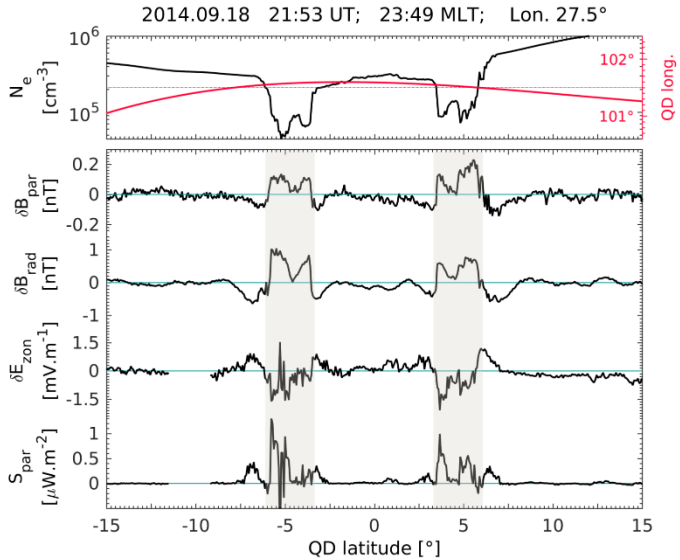


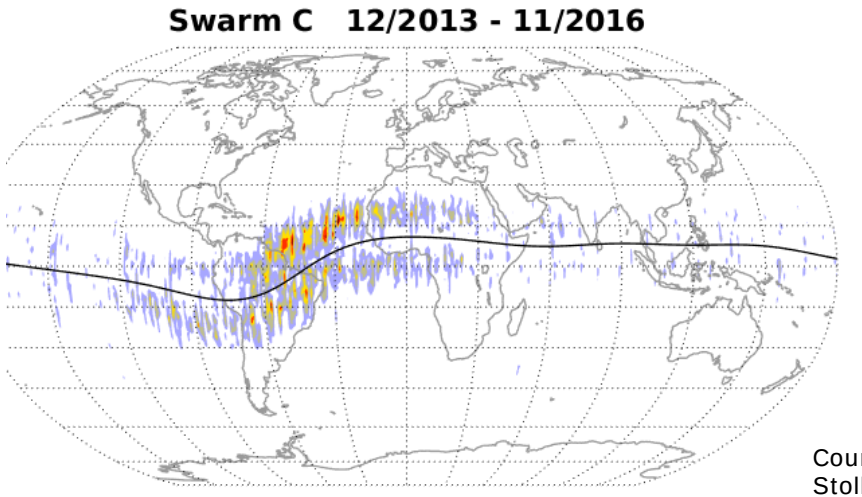
Figure: L. Lomidze, Univ. Calgary

Swarm makes it possible to monitor plasma irregularities in the equatorial regions of the ionosphere

Example of affected orbit (electron density, magnetic field, electric field)

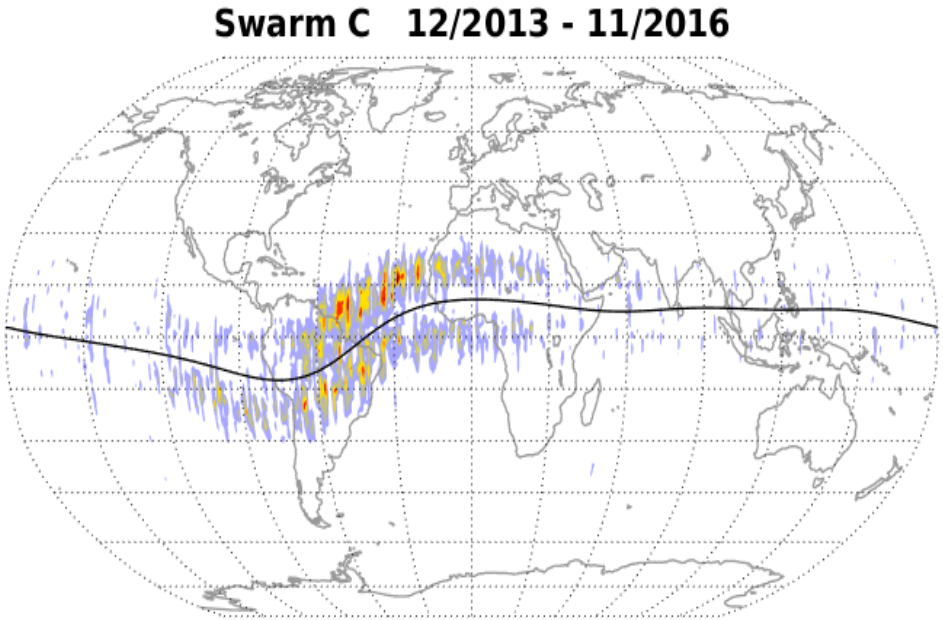


Occurrence of plasma irregularities detected in magnetic field and electron density



Courtesy of C. Stolle and the Swarm Science Team

Space Wx 1: Intense GPS scintillation leading to loss of lock



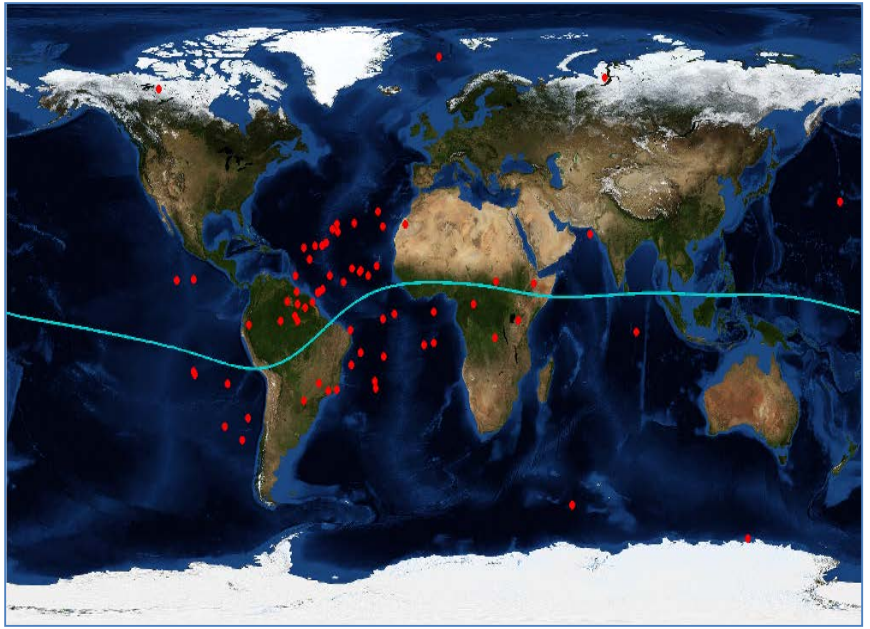
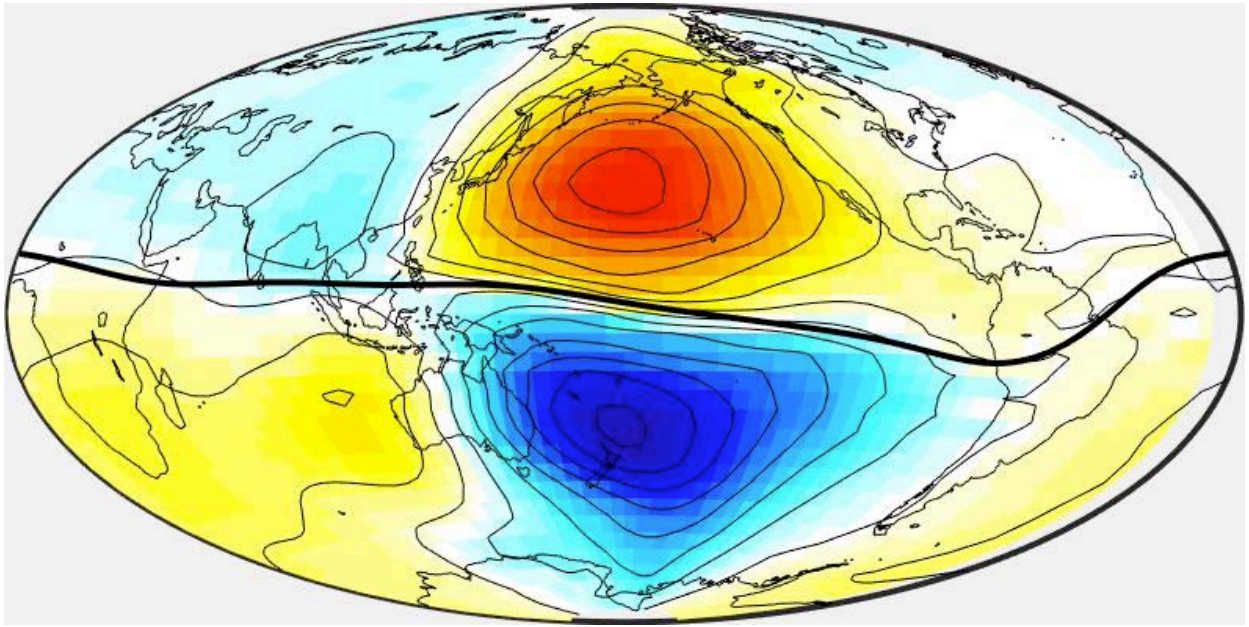


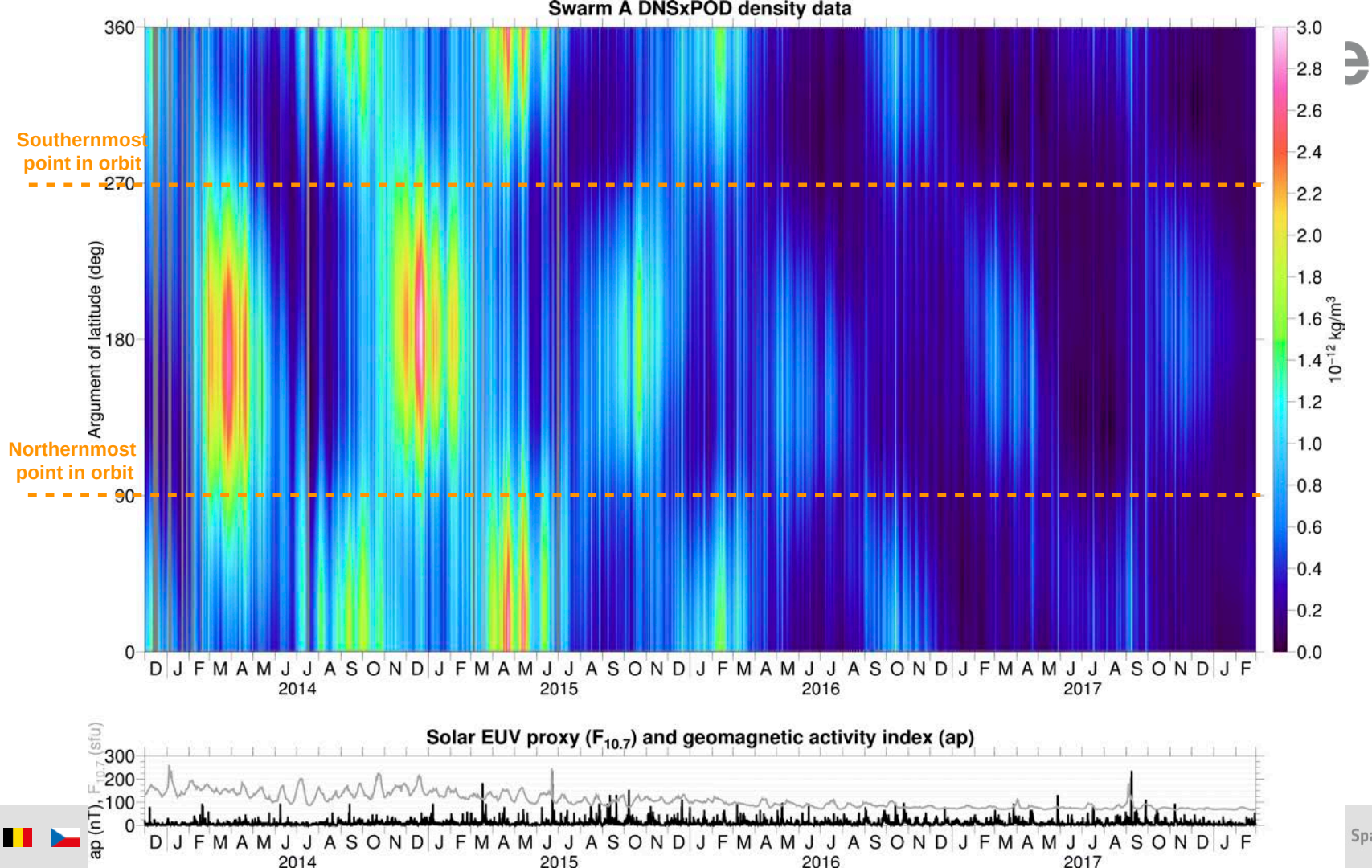
Figure: C. Stolle, GFZ Potsdam

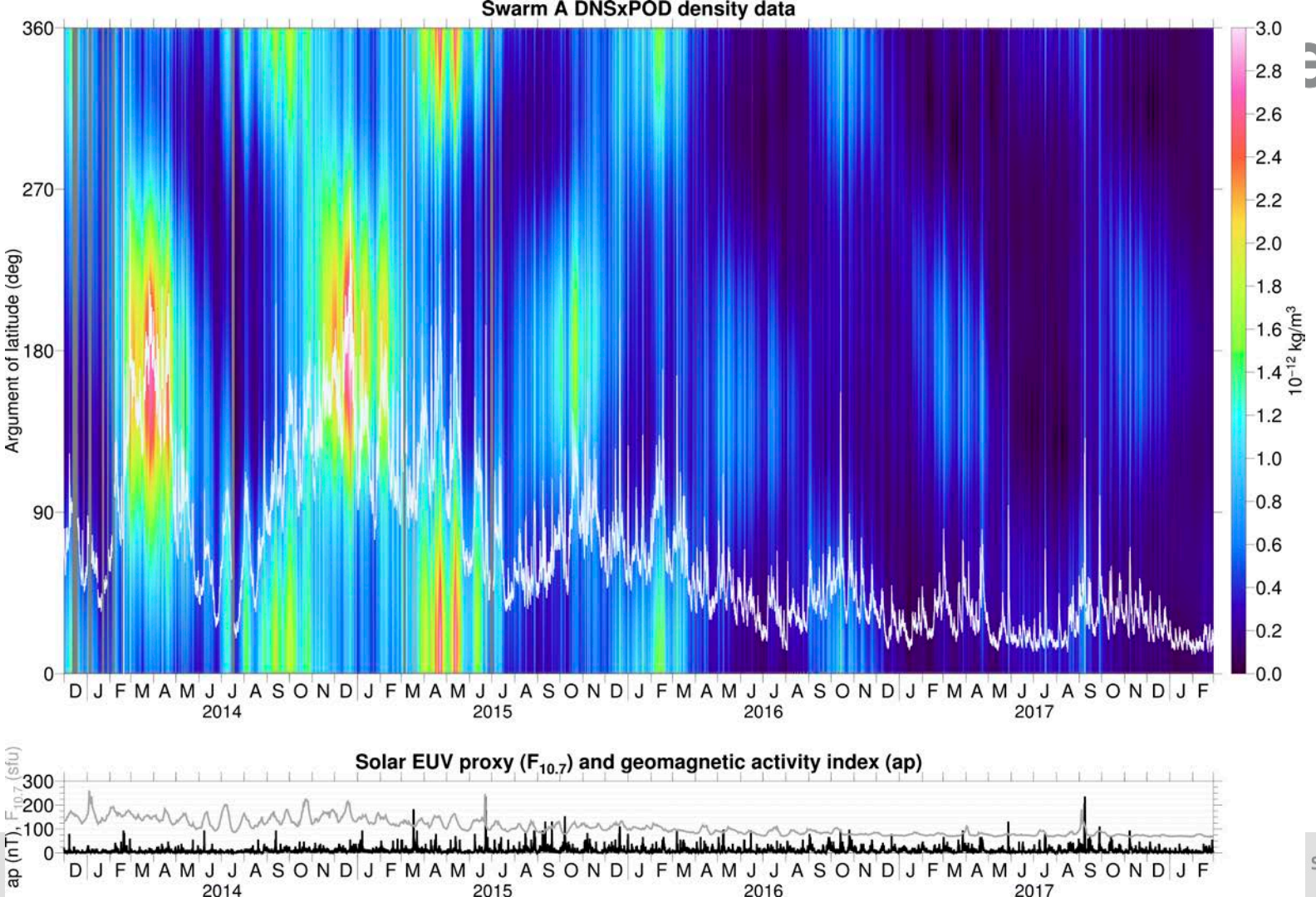
Swarm unravels the climatological variations of the Solar quiet ionospheric currents

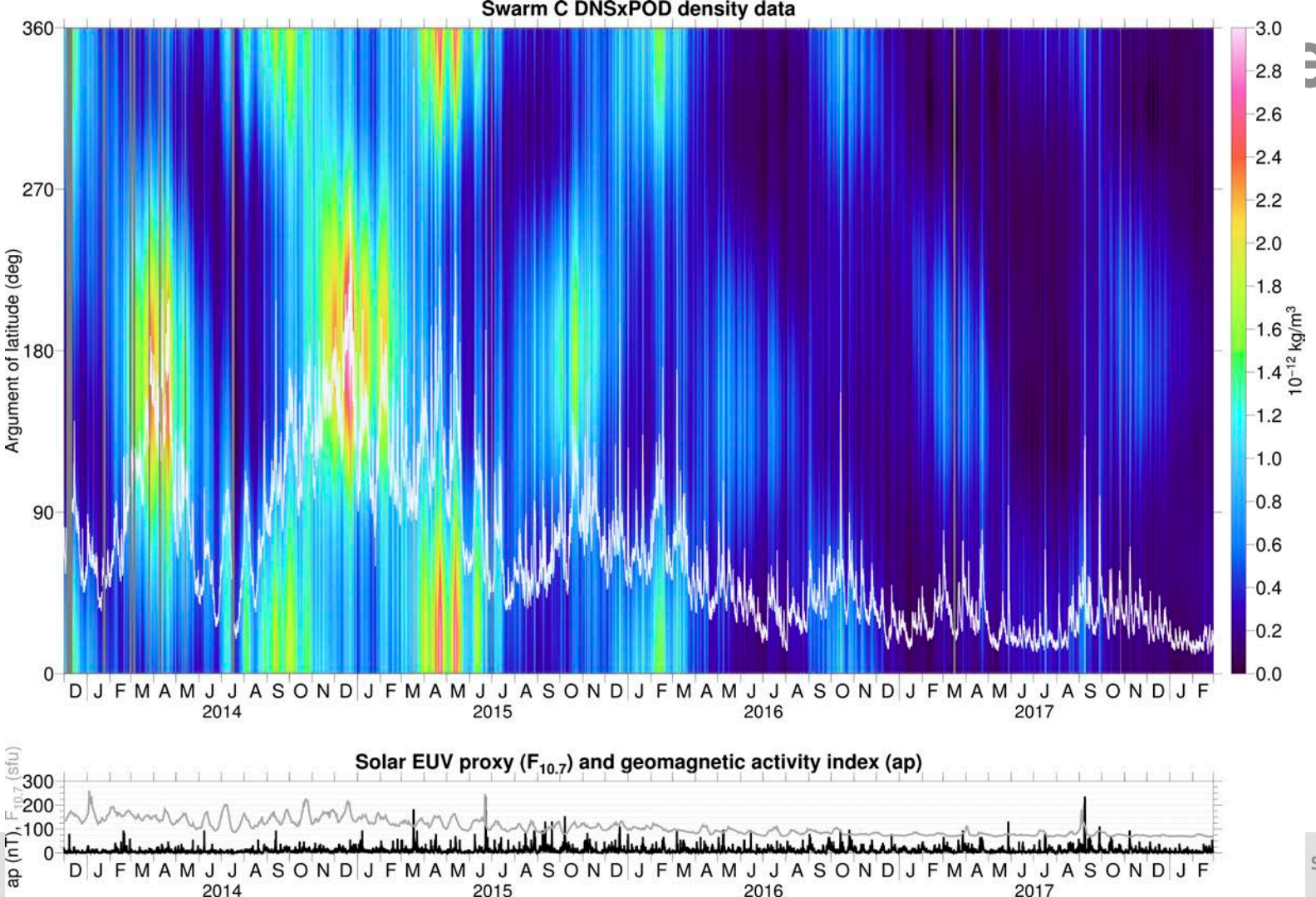


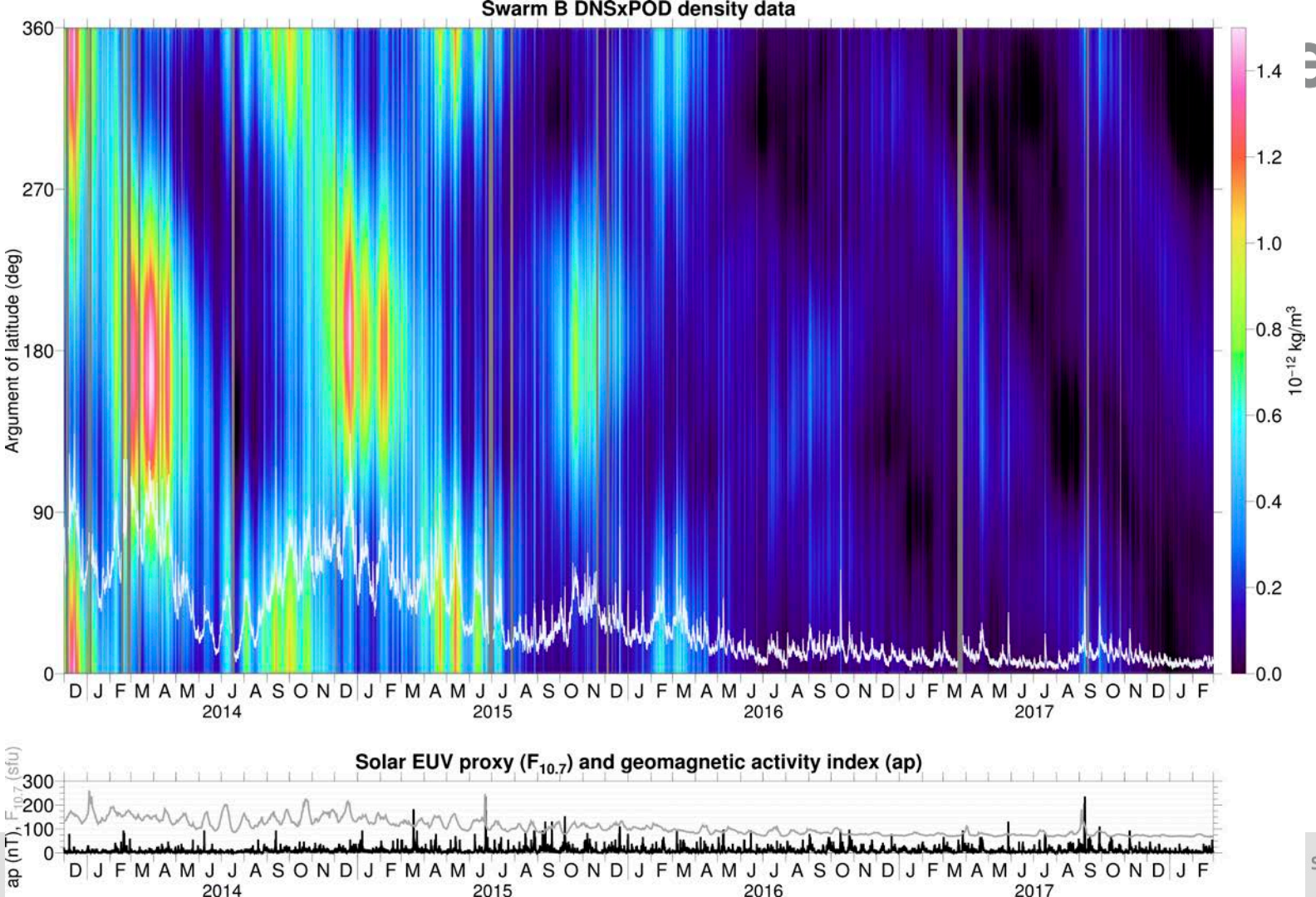
Courtesy of A. Chulliat
and the Swarm Science Team.

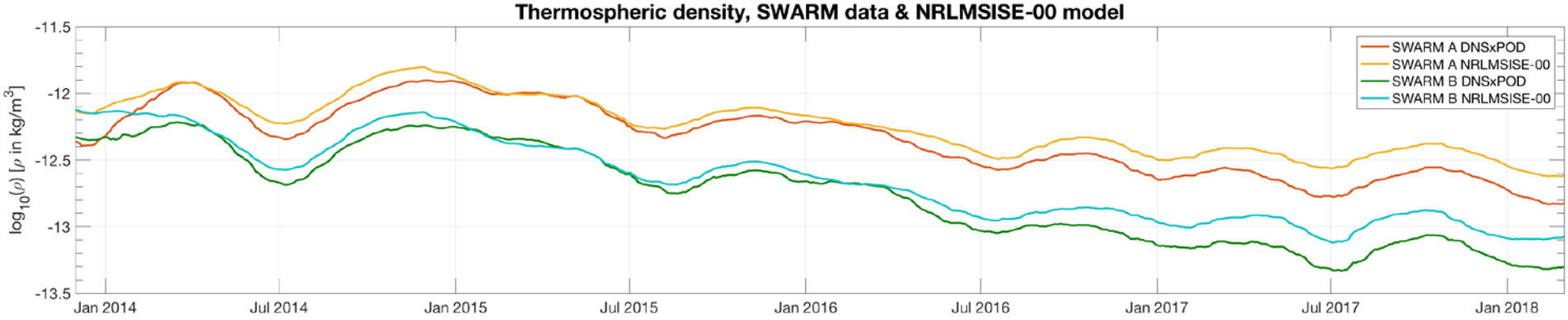
Equivalent currents in Spring (April 1). A 14.1 kA current flows between the contours.






Swarm C DNSxPOD density data
Argument of latitude (deg)
360
270
180
90
0
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10^{-12} kg/m^3
D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
2014
2015
2016
2017
Solar EUV proxy ($F_{10.7}$) and geomagnetic activity index (ap)
ap (nT), $F_{10.7}$ (sfu)
300
200
100
0
D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
2014
2015
2016
2017


Swarm B DNSxPOD density data
Argument of latitude (deg)
360
270
180
90
0
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10^{-12} kg/m^3
D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
2014
2015
2016
2017
Solar EUV proxy ($F_{10.7}$) and geomagnetic activity index (ap)
ap (nT), $F_{10.7}$ (sfu)
300
200
100
0
D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
2014
2015
2016
2017



Swarm A data/model density ratio μ_A=0.78763 σ_A =1.1677

Swarm B data/model density ratio μ_B=0.78401 σ_B =1.1891

Keys to an even better mission - I

Build **alliances** with stakeholders in Earth and solar-terrestrial science, including **satellite operators**, **space agencies**, **funding bodies**, **user groups** and **downstream services**

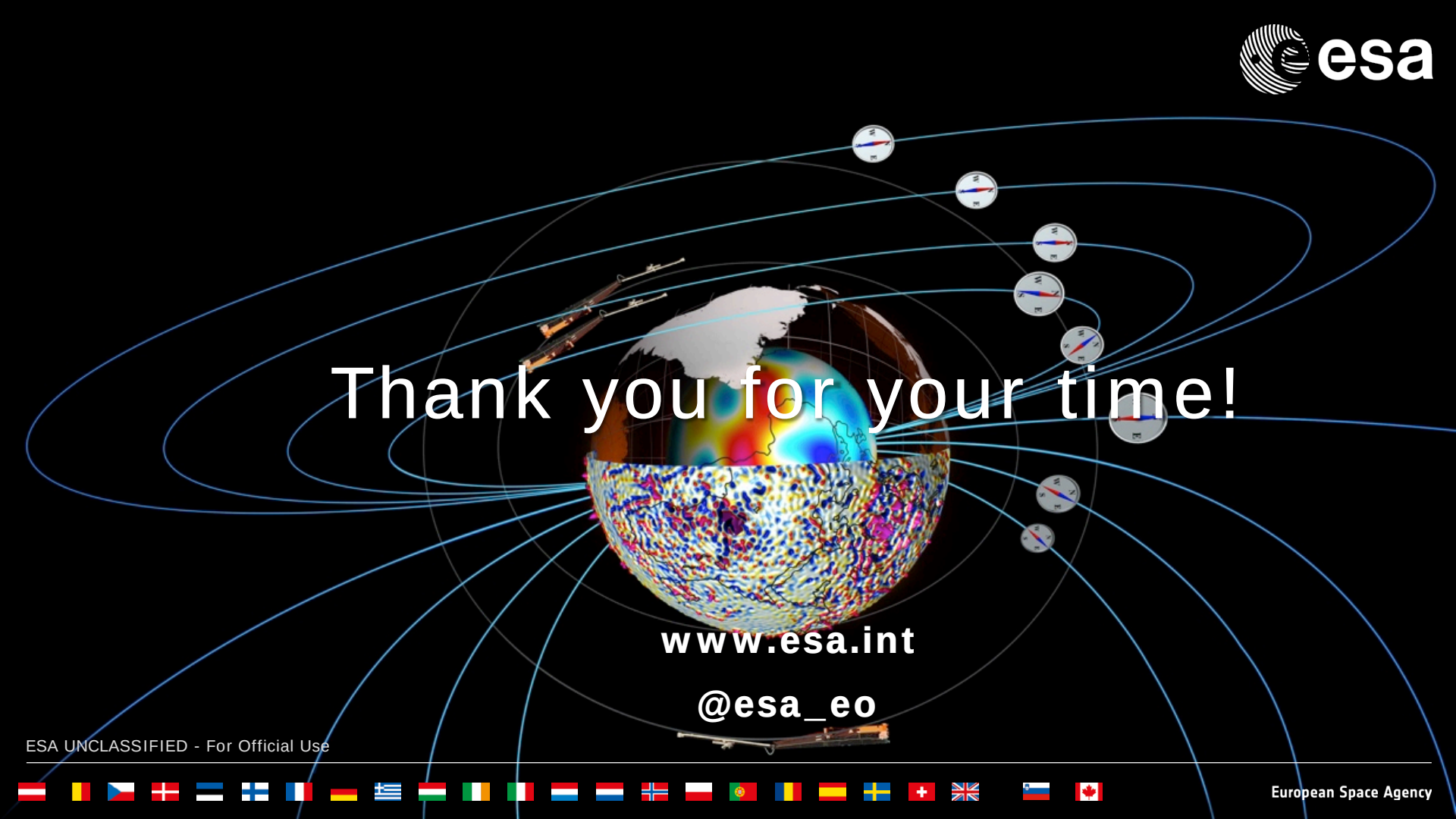
Keys to an even better mission - II

To initiate R&D **activities** addressing **ambitious** but **realistic challenges**, including cross-cutting and leading edge topics, and in a broad context.

Example a: From *Science with Swarm* to *Swarm for Science*

In summary, Swarm

- continues its exploration of the Earth and the space around it,
- aims at understanding the rapid dynamics of the outer core within its lifetime, and to produce the best-ever model of the upper sub-surface layers of our planet,
- wants to decipher the background near-Earth space climate, and also extreme weather events in space,
- has the health and on-board resources to do so for quite a while still,
- relies on strong community support and alliances to be able to achieve all of this

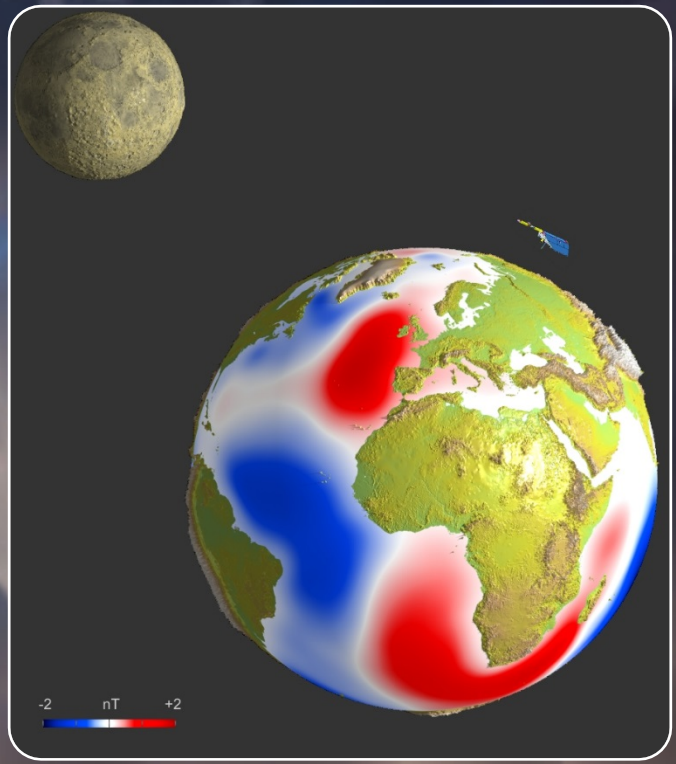


New Discoveries by Swarm

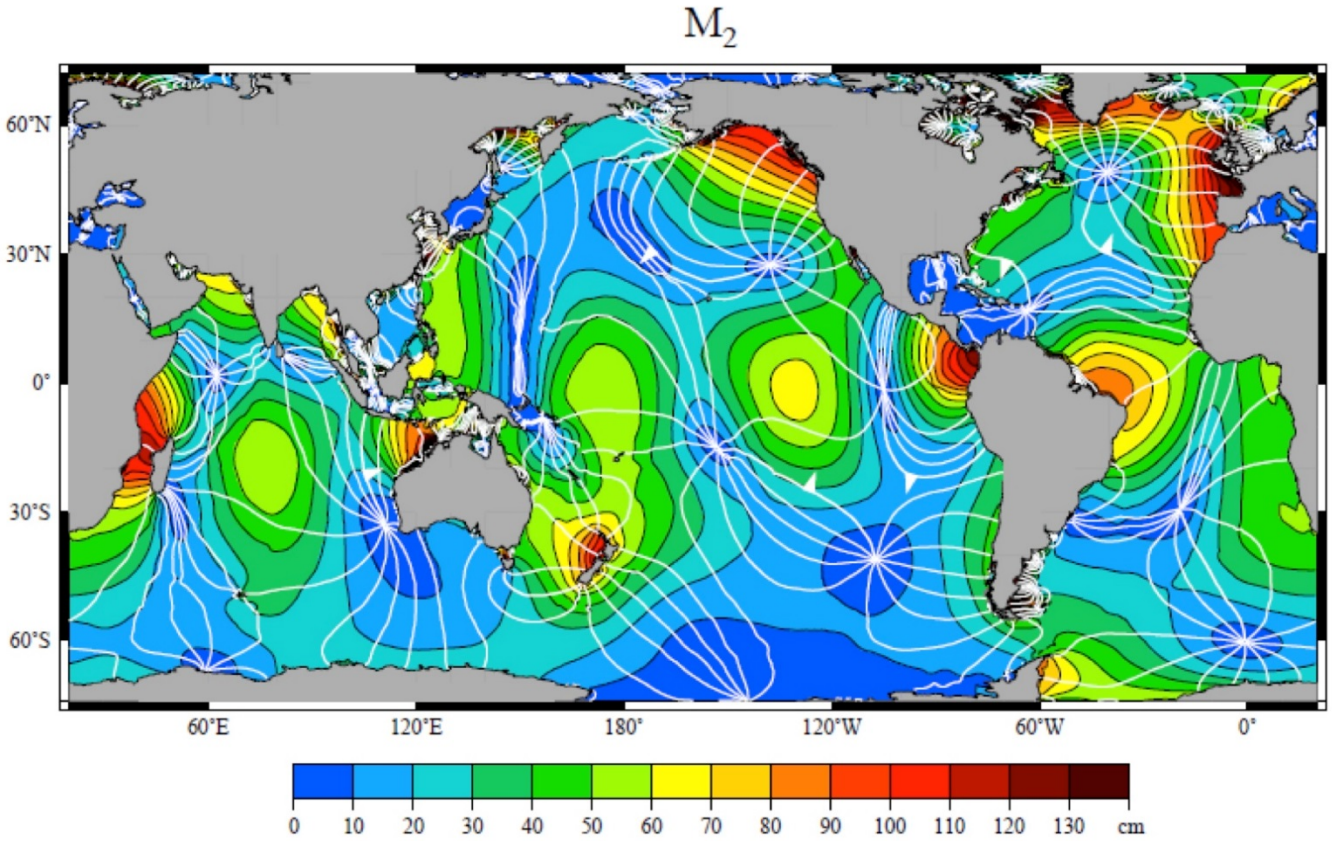
1

Ocean tides

- Signify depth-integrated currents
- Tiny signal, i.e. very hard to discover
- Implications for ocean and climate modelling



First, the lunar tide as we all know it…



Now, tides as Swarm sees them…

The magnetic north pole