Cluster Confirmation and Extension (2017-2020)

Annexes

1 - ANNEX 1. Spacecraft orbit and separation

Cluster was the first 3D constellation of four scientific spacecraft. It was joined recently by NASA MMS mission launched in 2015. The four spacecraft are unique in their ability to obtain a three dimensional picture of plasma structures, to separate spatial and temporal features and to derive physical quantities never measured before such as plasma gradients (divergence of electron pressure tensor for example) and direct measurement of currents using the curl of the magnetic field. The spacecraft formation varies in size naturally around the orbit, which enables multi-point measurements of different regions at different scales.

A key aspect of the new science investigations over the various extensions has been the orbit evolution due to Sun-Moon gravitational perturbations. This has drastically changed Cluster's nominal orbital parameters over time and facilitated access to regions of near-Earth space that were not originally targeted by Cluster. For example, due to the increasing of perigee altitude, which will reach 5.7 R_E in 2018, high altitude phenomena such as the plasma jet braking region in the magnetotail will become an accessible scientific target for Cluster.

To summarise the evolution of the various orbital elements, we plot examples of orbits from various years of the mission in Figure 1, where the apogee-perigee line of apsides was starting around the equatorial plane (2001) then went southward (2009) and will be in the North hemisphere in 2021. At the same time the perigee altitude, starting around an altitude of 3 R_E (2001) went down to 240 km altitude (2011) and will reach 5.7 R_E altitude in 2018. The near-Earth magnetotail will be visited again at a distance around 16 Re from the Earth in 2017-2020.

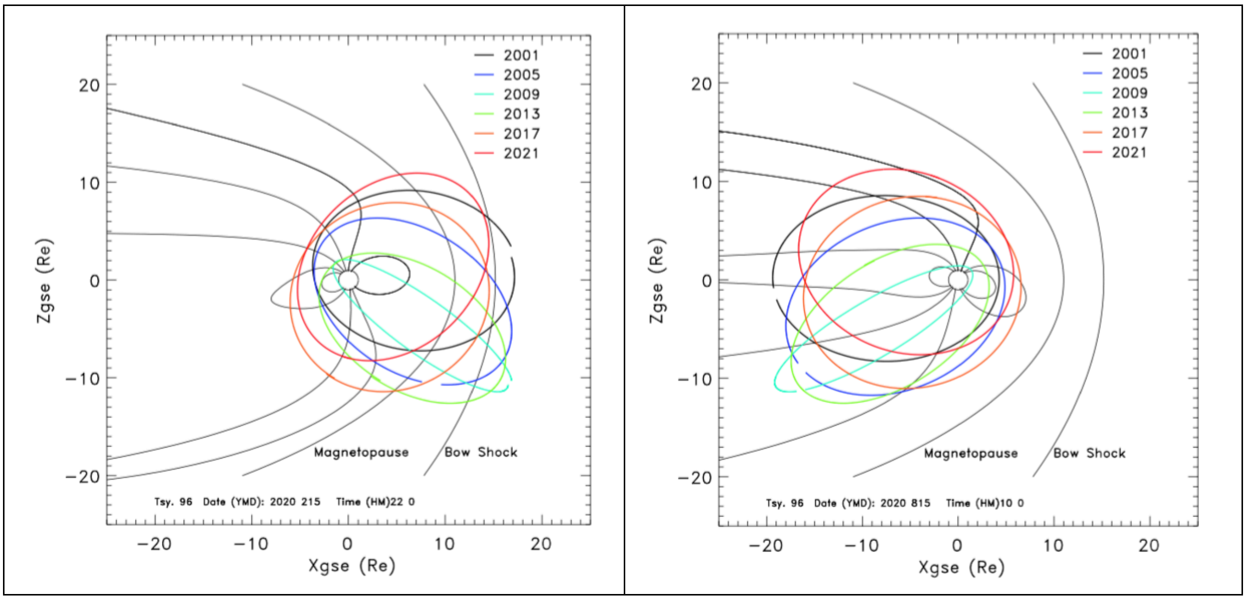

Figure 1 A broad sample of Cluster orbits from 2001 to 2021 in Geocentric Solar Ecliptic (GSE) coordinates. The nominal magnetopause and bow shock positions are shown as well as the magnetic field lines derived from the Tsyganenko 1996 model (date indicated at the bottom) and plotted as black lines. The orbit when the apogee is in the solar wind is shown on the left and when the apogee is in the magnetotail, 6 months later, is shown on the right.

Until 2011, about every 6 months the constellation was changed (separation and orientation) to match the scientific objectives defined by the Science Working Team. So far, this has enabled measurements in 3D at various scales from 100-10000 km in addition to a multi-scale approach to sample plasma processes at two scale sizes simultaneously with three spacecraft separated by ~7000-10,000 km and the last spacecraft separated from this plane by distances down to 3 km and up to 10,000 km. Since 2011, a number of configurations have been implemented to accommodate the Guest Investigators (GI) observations, as shown in Figure 2 (yellow dots). In late 2012 and mid 2016, we implemented the largest separations with Cluster: up to 36,000 km on the dawn and dusk flanks of the magnetopause. In early 2016, we achieved the smallest separation of 3 km targeted to study shock dissipation and particle acceleration at electron scales.

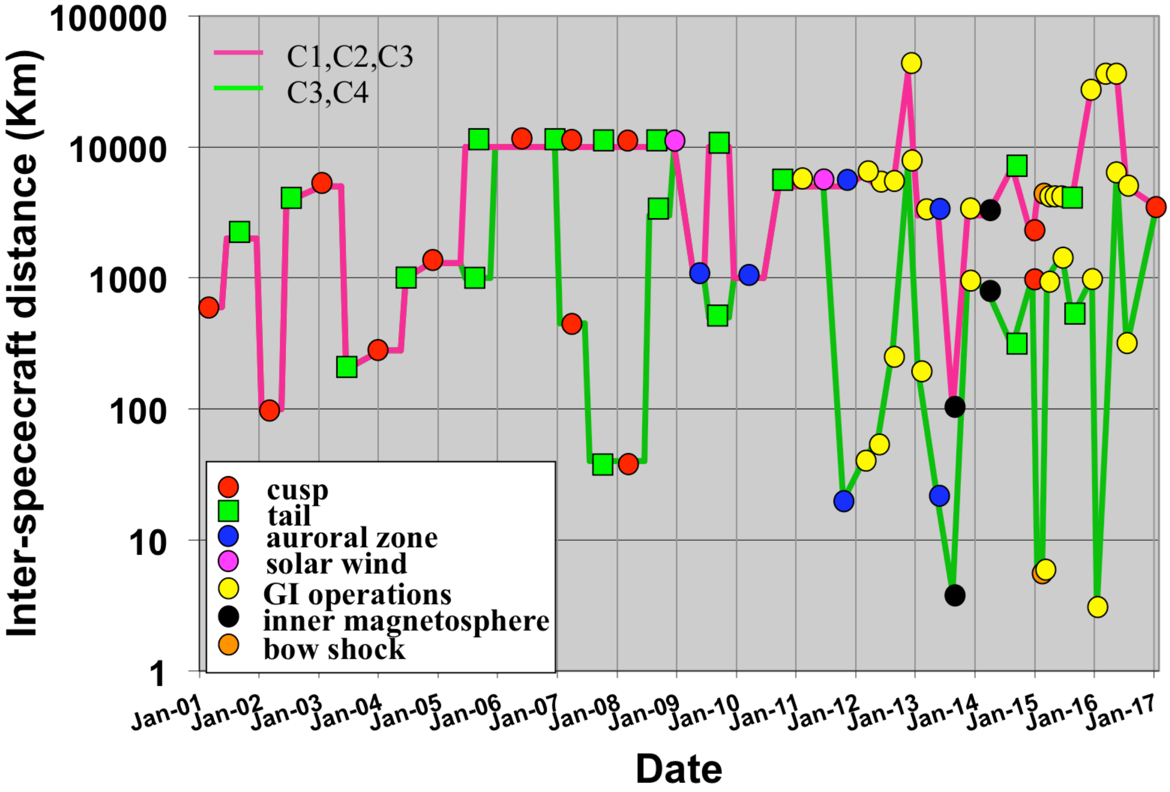

Figure 2 Inter-spacecraft separation strategy. Recent points marked in yellow represent GI observation operations.

A key feature of the Cluster mission is its ability to adapt the inter-spacecraft separation distances to the scientific region or physical process to be measured. At the start of the mission the fuel contained in the tanks of each spacecraft was around 60 kg and now after sixteen years in orbit, the remaining fuel is between 4 and 7 kg (Table 1). Despite this relatively small amount of fuel, we have significant flexibility in the modification of the spacecraft configuration by utilizing the so-called phasing manoeuvres to drift the spacecraft along their orbit tracks. Using 0.1 kg of fuel two spacecraft could be separated from each other by about 2h along the orbit, equivalent to 9000 km around apogee, in about 3 months. This is how we achieved up to 36,000 km separation between the spacecraft using between 0.1 and 0.6 kg of fuel. As indicated in Table 1, assuming an average of 0.3 kg per year, all spacecraft will still have more than 4 kg of fuel left at the end of 2020. Note that for a few years we no longer do manoeuvres on C4 as this is the spacecraft with the least amount of fuel.

Since the attitude of the spacecraft is now oscillating around 88-92 deg. (Figure 3) and will do so up to at least 2021 without any additional attitude manoeuvres, if one spacecraft runs out of fuel, we will be able to continue the mission, since it will have enough power to operate the payload; the other three spacecraft will be moved around it, as we do now for C4, to continue the mission.

In 2014, the analysis of the mission end of life showed that three spacecraft C2, C3 and C4 would re-enter the Earth atmosphere in 2024-2026 with a casualty risk well below the ESA threshold of 0.01 %. C1, however, would re-enter much later, in 2038, with a casualty risk above the ESA threshold. To prevent this to happen we conducted a manoeuvre in March 2015, using 0.6 kg of fuel, to make it re-enter in 2025 (Figure 4) and have a very low casualty risk, similar to the other Cluster spacecraft.

	Usable Fuel					
	Jun-16	Dec-16	Dec-17	Dec-18	Dec-19	Dec -20
C1	5.8 kg	5.7 kg	5.4 kg	5.1 kg	4.8 kg	4.5 kg
C2	5.9 kg	5.8 kg	5.5 kg	5.2kg	4.9 kg	4.6 kg
C3	6.6 kg	6.5 kg	6.2 kg	5.9 kg	5.6 kg	5.3 kg
C4	4.5 kg	4.5 kg	4.5 kg	4.5 kg	4.5 kg	4.5 kg

Table 1. Projected fuel usage up to December 2020. Usage of 0.3 kg/year/spacecraft for constellation changes is assumed.

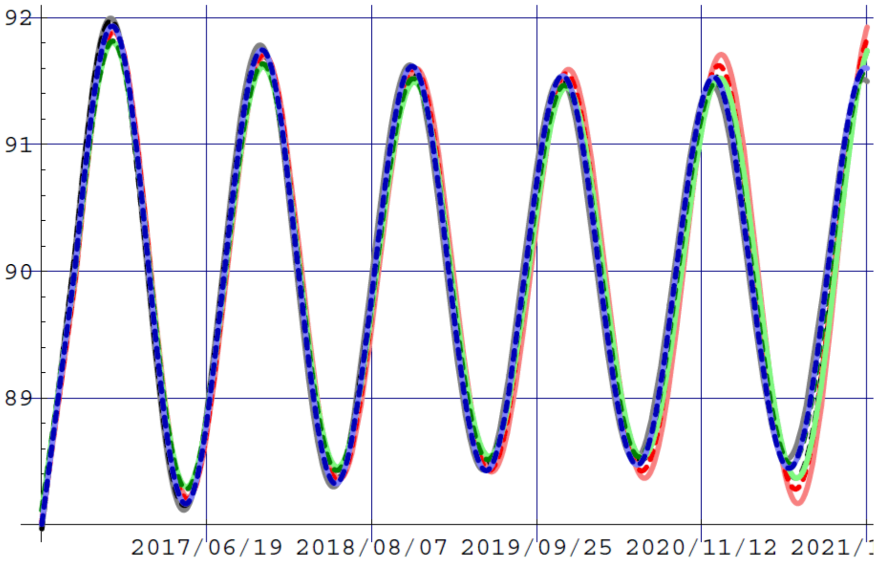

Figure 3: Solar aspect angle of the Cluster spacecraft from 2017 to 2021

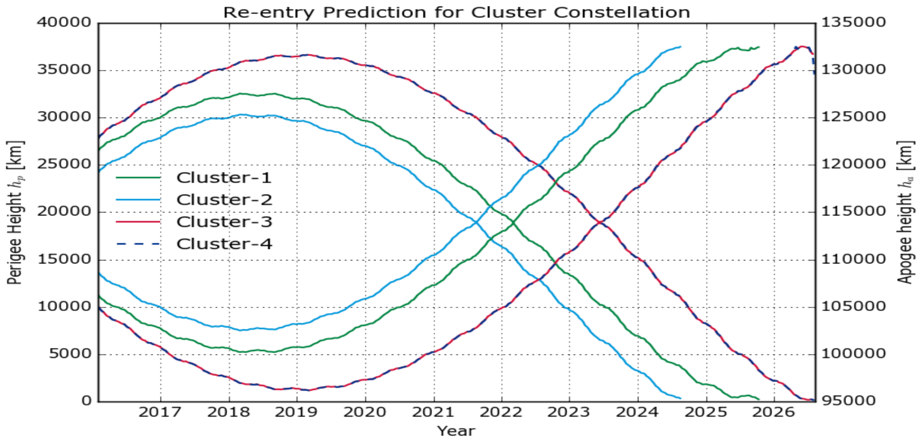

Figure 4: Perigee and apogee altitudes as a function of time. C3 and C4 curves are superimposed since there are approximately on the same orbit. Re-entry is expected in the Southern hemisphere between mid 2024 and mid 2026.

Solar array power degradation, which was significant during the passage through the inner radiation belt, has now decreased to almost zero (**Figure 5**). In the future, since the spacecraft perigee continues to increase the spacecraft will stay out of the proton radiation belts and the solar array should see minimal degradation. If we assume a degradation of 0.5 W/year in future years, the operations should not be impacted before the end of 2021.

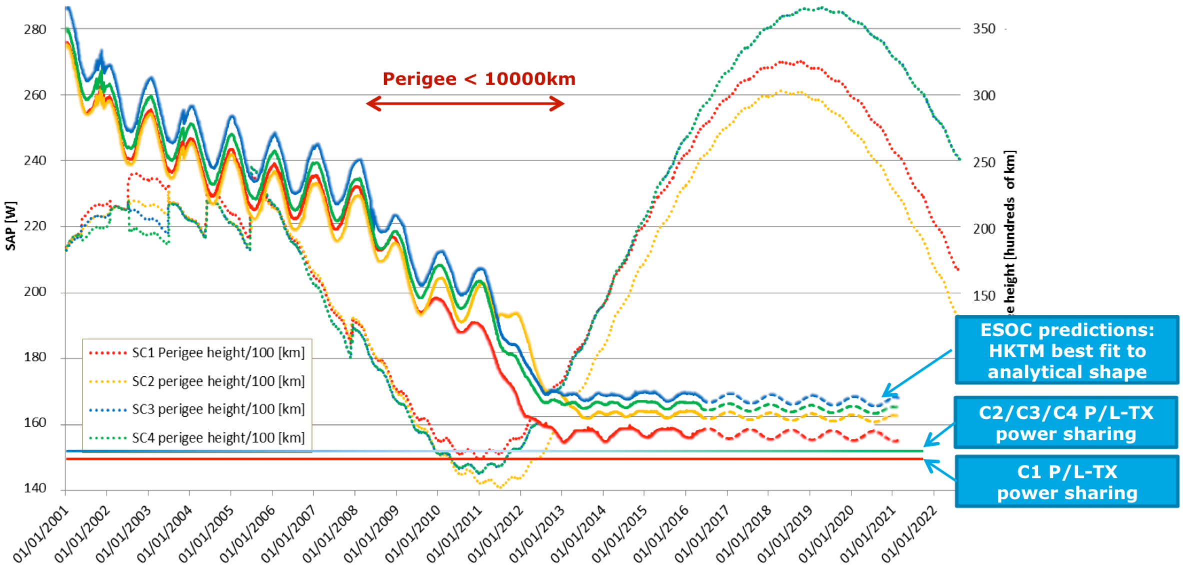

Figure 5: Solar array power of the four spacecraft as a function of time. From 2013, the solar arrays have not degraded much due to the perigee height above the radiation belts altitude. The perigee altitude is plotted in dotted lines and the scale is given on the right of the plot.

2 - ANNEX 2. Cluster Scientific Output

2.1 Publications

During the current extension, Cluster has continued its high publication rate (Figure 6). The chart below shows the publications for the entire mission, totalling 2357 up to the end of May 2016, with an additional 334 refereed papers over the last two years.

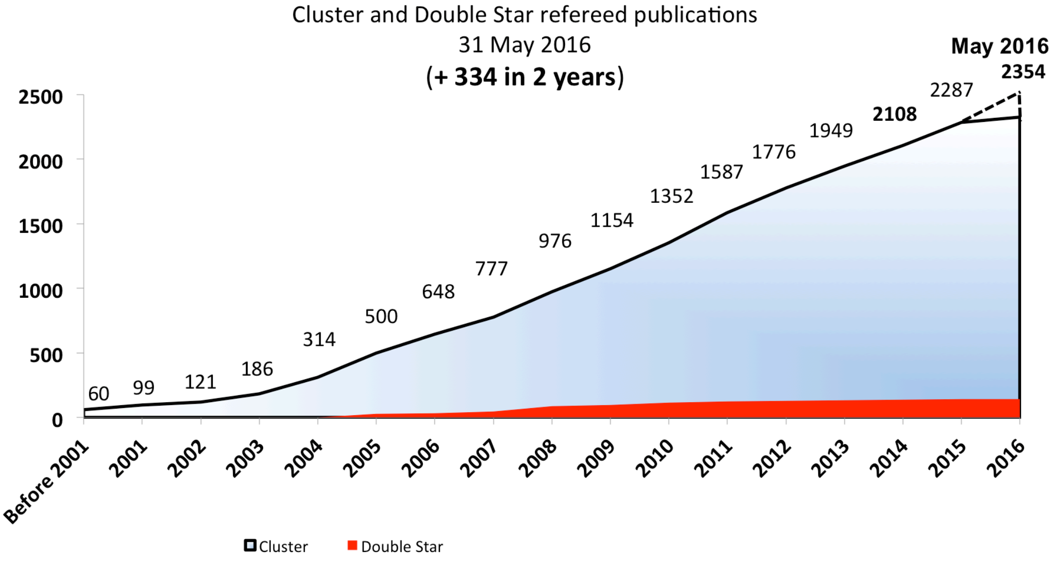

Figure 6: Referred publications of Cluster and Double Star up to and including May 2016.

The scientific community using the Cluster data is truly international, although dominated by the ESA member states, as shown in the breakdown of the Cluster and Double Star publications by region (Figure 7). There has been a clear increase in usage of the Cluster Science Archive data, introducing new scientists to the Cluster data, but also becoming the database of choice for Cluster scientists.

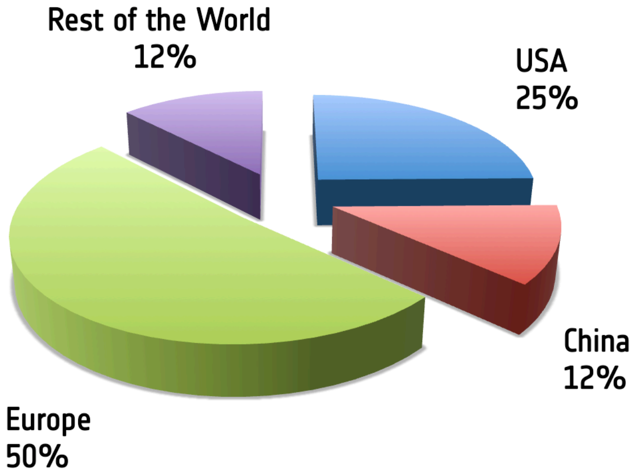

Figure 7: Breakdown of publications by geographical region.

Another key aspect of Cluster publications is the high level of publications in journals with a wider focus than space physics in the Earth environment, such as Physical Review Letters, Physics of Plasmas or the Astrophysical Journal. This demonstrates the use of Cluster data for a better understanding of physical processes ubiquitous across the Universe (**Table 2**).

Journals	
Nature/Science	25
Astrophysical Journal (incl Lett.)	51
Physical Review Letters	67
Space Science Reviews	94
Physics of Plasmas	60
Journal of Geophysical Research	762
Geophysical Research Letters	217
Annales Geophysicae	476
Other	602

Table 2. Breakdown of publications in particular journals.

2.2 Scientific Recognition.

During the current extension, Professor Stephen Fuselier, Cluster Co-Investigator received the prestigious 2016 European Geosciences Union Hannes Alfvén Medal for his fundamental contributions to understanding the physics of the interaction of the solar wind with Earth's magnetosphere, comets, and the interstellar medium. He has published many fundamental papers using Cluster data in particular on reconnection rate and sites, anti-parallel and component reconnection, and energetic neutral atoms at the nose of the magnetosphere. Several other high profile scientists have been awarded international prices based on their work on Cluster data (see previous extension document)

2.3 Publication highlights

Up to date information can be found at the ESA Cluster web pages: http://sci.esa.int/cluster/ but also at http://en.wikipedia.org/wiki/Cluster_II_(spacecraft). Cluster articles are frequently picked up by the wider media, such as spacedaily.com, astronomy.com and also National Geographic. The Cluster Science Archive data are becoming the main data source for Cluster publications, both for case studies and the growing number of larger scale surveys and statistical studies.

The Cluster Active Archive book entitled *Studying the Earth's space plasma environment*, Astrophysics and Space Science Proceedings, Laakso, Harri; Taylor, Matthew; Escoubet, C. Philippe (Eds.), 492 p., Springer, 2010) has been very popular. Since October 2009, 11632 chapters have been downloaded, making it one of the 2015 top 50% most downloaded eBooks in the relevant Springer eBook Collection. 70% of downloads were made in years 2014-2015.

Please find below a selection of scientific highlights since the last extension review in fall 2014.

Solar wind breaks through the Earth's magnetic field

When two plasmas of different origins and having magnetic fields with different orientations collide, the magnetic fields can be "clipped off" and "reconnected" so that the topology of the magnetic field is changed. This magnetic reconnection can give energy to eruptions on the solar surface, it can change the amount of energy from the solar wind entering the magnetosphere which then creates aurora, and it is one of the obstacles to storing energy through processes in fusion reactors.

In their paper, published in Physical Review Letter, Graham et al., showed that electric fields parallel to the magnetic field are the main process that accelerates and heats electrons in magnetic reconnection. They used data when Cluster was crossing the dayside magnetosphere and could combine for the first time electron data coming from two very closely spaced spacecraft (30 km) to obtain high time resolution of the electron distribution function (1s).

https://www.sciencedaily.com/releases/2014/06/140609122025.htm

Graham, D.B., Yu.V. Khotyaintsev, A. Vaivads, M. André, A.N. Fazakerley, Phys. Rev. Lett., 112, 215004 (2014)

First observations of an unusual magnetic storm

The Sun is a variable star, experiencing 11-year-long cycles of activity which impacts our planet and near-Earth space. Forecasting the changing space weather and the effects it will have on Earth remains a challenge, as illustrated by an unusual magnetic storm that was observed by Cluster and one Double Star spacecraft. The Coronal Mass Ejection (CME) observed on 21 January 2005 was one of the fastest of solar cycle 23. When it arrived at Earth, it did not trigger a superstorm, since the interplanetary magnetic field was mainly northward. However the dense solar filament had some effects similar to superstorms such as the superfountain in the equatorial ionosphere, magnetotail streching and strong joule heating in the polar ionosphere. This analysis was based on SOHO, Double Star and Cluster data but also on numerical simulations and other spacecraft.

http://sci.esa.int/cluster/54573-a-mixed-up-magnetic-storm/#

Kozyra, J. U., et al. (2014), Solar filament impact on 21 January 2005: Geospace consequences, J. Geophys. Res. Space Physics, 119, doi:10.1002/2013JA019748.

Origin of the high latitude auroras revealed

Auroras are the most visible manifestation of the Sun's effect on Earth, but many aspects of these spectacular displays are still poorly understood. Usually the auroras form an oval centred around the magnetic pole of each hemisphere. Sometimes, however, high latitude auroral arcs are formed and cross the oval to form a “theta” letter. Cluster observations, together with NASA IMAGE observations, have shown for the first time the direct evidence that theta aurora is formed by plasma population originating from the magnetotail. Up to now it was not clear if these particles were coming from the solar wind through the magnetopause or from the magnetotail. The first images of theta auroras were taken by Dynamics Explorer 1 in 1982, more than 30 years ago. The process of magnetic reconnection on the night side of Earth causes a build-up of ‘trapped’ hot plasma in the higher latitude lobes.

http://www.esa.int/Our_Activities/Space_Science/Cluster/Origin_of_high-latitude_auroras_revealed/#

Fear, R.C., S.E. Milan, R. Maggiolo, A.N. Fazakerley, I. Dandouras, S.B. Mende, Direct observation of closed magnetic flux trapped in the high-latitude magnetosphere, Science, 19 December 2014: Vol. 346 no. 6216 pp. 1506-1510, DOI: 10.1126/science.1257377

Electric fields in black aurora explained

A black aurora is opposite to an aurora where electrons are accelerated away from Earth, instead of towards Earth in a classic aurora. The black auroras are seen as black stripes in between auroras. The first observations of the dynamical behaviour of black auroras were made by the four Cluster spacecraft and reported back in 2001. It was shown that the electron population of the ionosphere becomes more and more depleted in these dark regions.

Cluster observations showed that intense electric fields were observed in the centre of a "black" aurora. The Cluster data were reproduced successfully by a simple current system model, showing that the depletion of electrons in the black aurora produced the strong electric fields to maintain continuity in the current system.

http://sci.esa.int/cluster/55764-heart-of-the-black-auroras-revealed-by-cluster/#

Russell, A.J.B., T. Karlsson, A.N. Wright, Direct Magnetospheric signatures of ionospheric density cavities observed by Cluster, J. Geophys. Res. Space Physics, DOI: 10.1002/2014JA020937

First simultaneous measurements of field aligned currents with Cluster and Swarm

For the first time ever, two of ESA's space missions – Cluster and Swarm – have joined forces to simultaneously measure the properties of Earth's magnetic field at two different altitudes.

The satellites found a number of striking similarities in the behaviour and structure of the field-aligned currents detected at each altitude, despite their vastly different locations. Field-aligned currents (FACs) flow along Earth's magnetic field lines, transferring energy from region to region. The Cluster data showed that the large-scale measurements beamed back from an altitude of 500 km were remarkably similar to those gathered at 15 000 km in both form and scaled current strength – in fact, it is highly likely that both missions sampled the same large-scale FAC. Such studies will allow to better understand FACs and their consequences on the magnetosphere and ionosphere.

http://sci.esa.int/cluster/56098-seven-esa-satellites-team-up-to-explore-earths-magnetic-field//#

Dunlop, M.W., J.-Y. Yang, Y.-Y. Yang, C. Xiong, H. Lühr, Y.V. Bogdanova, C. Shen, N. Olsen, Q.-H. Zhang, J.-B. Cao, H.-S. Fu, W.-L. Liu, C.M. Carr, P. Ritter, A. Masson and R. Haagmans (2015), Simultaneous field-aligned currents at Swarm and Cluster satellites, Geophys. Res. Lett., 42, doi:10.1002/2015GL063738

Physical mechanism behind the generation of equatorial noise waves

Back in 1966, a NASA satellite known as OGO-3 discovered 'noisy' plasma waves at an altitude of around 18 000 km above the Earth. The waves were observed very close to the equatorial plane of the planet's magnetic field – the geomagnetic equator. The location of the electric and magnetic fields of these waves, together with their unstructured nature, led to them being termed 'equatorial noise'. This 'noise' turned out to be one of the most frequently observed emissions in near-Earth space, being detected by many spacecraft as they fly over the geomagnetic equator.

The Cluster spectral observations, together with observations of particle distributions, allowed the researchers to calculate the growth rates of the waves. This study clearly showed that these waves were produced by so-called ion ring distributions. The Cluster spacecraft were able to measure these distributions, and models used by the scientists definitively showed that they are responsible for the excitation of the waves.

http://sci.esa.int/cluster/56143-cluster-solves-the-mystery-of-equatorial-noise/#

Balikhin, M.A., Y.Y. Shprits, S.N. Walker, L. Chen, N. Cornilleau-Wehrlin, I. Dandouras, O. Santolík, C. Carr, K.H. Yearby, B. Weiss, Observations of discrete harmonics emerging from equatorial noise, Nat. Commun., 7, 7703, 2015

New method to capture magnetic nulls in reconnection

Magnetic reconnection is a fundamental plasma process converting magnetic energy into particles' kinetic and thermal energy. In a three-dimensional (3-D) regime, such reconnection often occurs at magnetic nulls, where the magnetic strength becomes zero and the particles get unmagnetized. Investigating the properties and topology of magnetic nulls, therefore, can help us to understand the initiation of the reconnection process.

Up to now magnetic nulls were only found when they were located within the tetrahedron formed by the four spacecraft. A new method, the first order Taylor expansion, enables now to find the presence of magnetic nulls not only within the volume defined by four point measurements but also nearby, outside of the Cluster constellation. A re-visit of the Cluster database has enabled to dig out a much larger number of X lines skimmed by the ESA flotilla.

http://onlinelibrary.wiley.com/doi/10.1002/2015JA021082/abstract

Fu, H.S., A. Vaivads, Y.V. Khotyaintsev, V. Olshevsky, M. André, J.B. Cao, S.Y. Huang, A. Retinò, and G. Lapenta (2015), How to find magnetic nulls and reconstruct field topology with MMS data?, J. Geophys. Res. Space Physics, 120, 3758–3782, doi:10.1002/2015JA021082

Two pathways for Earth atmosphere leak

Earth's atmosphere is leaking. Every single day, around 90 tonnes of material escapes from our planet's upper atmosphere and streams out into space.

A Cluster study compared the two main atmospheric escape mechanisms Earth experiences — sporadic plumes emanating up through the plasmasphere, and the steady leakage of Earth's atmosphere from the polar ionosphere — to see how they might contribute to the population of cold ions residing at the dayside magnetopause. Both escape processes appear to depend differently on something known as the interplanetary magnetic field (IMF), the solar magnetic field that is carried out into the Solar System by the solar wind. Plumes seem to occur when the IMF is oriented southward (anti-parallel to Earth's magnetic field, thus acting as mentioned above). Conversely, leaking outflows from the polar ionosphere occur during northward-oriented IMF. Both processes occur more strongly when the solar wind is either denser or travelling faster (thus exerting a higher dynamic pressure).

http://sci.esa.int/cluster/58028-the-curious-case-of-earth-s-leaking-atmosphere/

Lee, S. H., et al., "A statistical study of plasmaspheric plumes and ionospheric outflows observed at the dayside magnetopause", 2016, Journal of Geophysical Research: Space Physics, 121, doi:10.1002/2015JA021540

3 - ANNEX 3. The Cluster Guest Investigator Programme

Following the Cluster Guest Investigator (GI) announcement of opportunity in 2010, and the successful execution of the GI observations in 2011-2013, a 2nd announcement of opportunity has been issued in 2014. This Announcement of Opportunity solicited new special operation proposals for observations in the Cluster extended mission, as described in the 2015-2016 extension document. The aim of the GI Programme was to open spacecraft science operations to the community for the period 2015-2016.

The 2nd AO was published in mid-February 2014 and the proposals were received in June 2014. The feasibility of these proposals was reviewed by the Cluster Science Operations Working Group, made up of Cluster Principal Investigators (PIs), Science Operations team members (Joint Science Operations Centre, JSOC), Mission Operations Team (European Science Operations Centre, ESOC) and ESA Cluster team. An evaluation was then sent to a Peer Review Committee (PRC) made up of two Cluster PIs , two members of the ESA Solar System and Exploration Working Group (SSEWG) and the project scientist. The PRC then formulated a recommendation regarding which proposals shall be selected. The ESA Director of Science and Robotic Exploration received the recommendations and appointed the new eight GIs in November 2014 (Table 3). At the time of writing this report, observations related to the last GI (C. Foullon) are being performed.

Guest Investigator	GI proposal title	Laboratory	Implementation period
Olga Alexandrova	Study of the dissipation range of solar wind turbulence	Meudon Observatory, F	February and March 2015
David Burgess	Ion pickup coupling in the solar wind associated with thruster operations	QMUL, UK	March 2015
M. Dunlop	Coordination of Cluster/Swarm for FACs	RAL, UK	June 2015
Yulia V. Bogdanova	Mid-altitude cusp properties, dynamics, small-scale plasma structure and ion outflow: simultaneous Cluster measurements at different MLT sectors	RAL, UK	November and December 2015
Yuri Khotyaintsev	Multi-spacecraft Investigation of Electron Scales at Bow Shock	IRF-U, S	January 2016
Primoz Kajdic	Magnetic reconnection in the solar wind: search for small-scale events	ESA/ESTEC, NL	February 2016
Xochitl Blanco-Cano	Upstream transients and their influence on the bow shock and magnetosheath	Mexico University, Mexico	April 2016
Claire Foullon	Magnetopause boundary layer: evolution of plasma and turbulent characteristics along the flank - repeats	Exeter University, UK	May-June 2016

Table 3: Cluster Guest Investigators selected in 2014.

4 - ANNEX 4. Recommendation from the Cluster Science Working Team

From: Cluster Science Working Team
To: SSEWG/SSAC/SPC

To whom it may concern,

This letter is in support of the case for the continued operation of Cluster in its current extension period, up to December 2018, and to further extend up to December 2020.

The Cluster mission and its four spacecraft remain unique in their capability in investigating local space plasma phenomena structural and temporal variations as well as the Sun-Earth system interaction as a whole and provide the space plasma community, via the Cluster Archive, with a unique and an invaluable data resource.

The new science goals for the January 2019-December 2020 extension are:

- characterise chorus waves at both low and high-latitude with 3 km inter-spacecraft distance
- investigate bow shock/magnetosheath/magnetopause physics with local solar wind monitor
- investigate evolution of Kelvin–Helmholtz waves on the flank of the magnetosphere
- open a call for early-career scientists to perform observations with Cluster during 3 months

The Cluster Science Working Team, as representative of the wider Cluster science community, strongly endorses the proposal for the continuation and further extension of the Cluster mission up to end 2020 and the subsequent support to the continuation and finalisation of the unique resource of the Cluster Archive.

Yours Sincerely

The Cluster Science Working Team

5 - ANNEX 5: characterise chorus waves at both low and high-latitude with 3km inter-spacecraft distance

Chorus waves are electromagnetic emissions observed mainly on the dawn side of the Earth's environment in the Very Low Frequency (VLF) range, from a few 100's of Hz up to 10 kHz, depending on the local magnetic field amplitude. They consist of brief rising or falling-frequency tones that sounds like the chorus of birds singing at sunrise. They are believed to be generated by energetic electrons (10-100 keV) in magnetic field minima, usually around the equatorial plane. Chorus waves can interact with radiation belt electrons and precipitate them in the atmosphere. On some occasions, these waves have been shown to accelerate electrons to extremely high energy (MeV) and can therefore be a source of energy to produce the radiation belts electrons. There are therefore important elements in the dynamics of radiation belts and the understanding of space weather.

First observations of chorus were done in the 1930s from the ground. But it was only in the 1970s, with the first satellite measurements, that chorus was measured near its source region, between the plasmapause and the magnetopause. Using the NASA Ogo 5 spacecraft, Tsurutani and Smith (1977) made a statistical study of chorus waves (Figure 8). They detected two type of chorus, one found near the Earth magnetic equator (latitude below 5 deg.) and the other one at high latitudes (latitude above 15 deg.). While equatorial chorus is found in the dawn sector from midnight to 09 h local time, high-latitude chorus is observed on the dayside between 09:00 to 18:00. The high latitude chorus is generally found in "minimum B pockets" near the polar cusp and magnetopause.

Using Cluster data, Vaivads et al. (2007) showed an example of chorus emissions at high latitude that was created locally around a minimum in B and propagated away from it. Although the time resolution of electron measurements cannot be compared with the chorus time resolution, it was shown that the flux of 10-25 keV electrons from the dayside plasmasheet decreased significantly when the chorus emissions were stronger. The chorus emission was explained by the opening of the closed field lines by reconnection and the rapid loss of field-aligned electrons. This electron anisotropy would then be the free source of energy for chorus emissions.

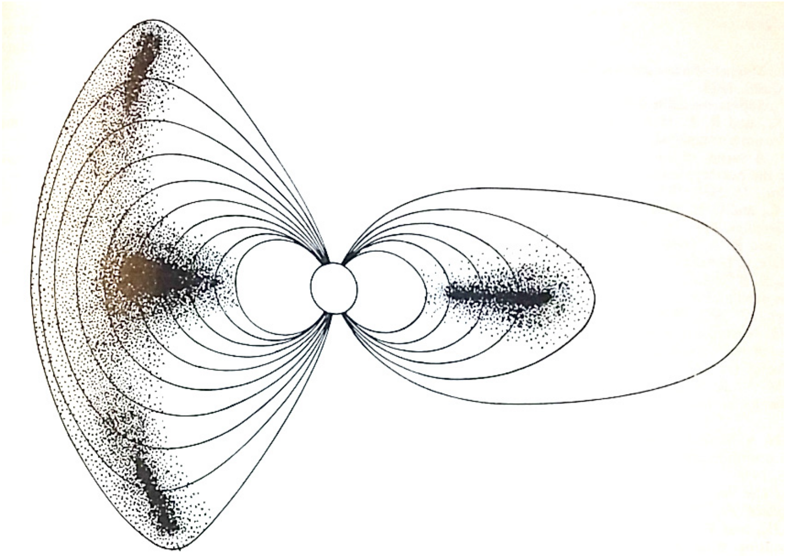

Figure 8: Sketch of the regions of the magnetosphere where chorus waves (dark dots) are observed (From Tsurutani and Smith, 1977).

A few years later, Menietti et al. (2009), using Polar data, showed an example of chorus emissions near the mid-altitude cusp, up to around 40 deg. of magnetic latitude. Using ray-tracing techniques they showed that these emissions could come from the equator and propagate to high-latitude. It is therefore not clear if the source of high-latitude chorus is local or is at the equator and the waves propagate to high latitudes.

Another aspect of chorus waves that requires further study is the propagation in the magnetosphere. The first observations of the motion of chorus sources was done for the first time using Cluster with the spacecraft close to each other near perigee. Santolik et al. (2003) showed that the source of chorus was oscillating within 1000-2000 km around the equator on time scales of minutes. Gurnett et al. (2001) observed a shift in frequency of chorus emissions between two Cluster spacecraft and Inan et al. (2004) explained it by the fast motion of the source region with respect to the spacecraft. A few years later, however, Chum et al. (2007) showed that the frequency shift could also be explained by a fixed source with varying emissions properties. Up to now it is not clear which mechanism is occurring and this is why new multi-spacecraft observations are necessary.

Cluster in a quasi-polar orbit is the only currently operating spacecraft mission which can really investigate all these open questions on chorus emissions. First, the inclined orbit that will reach again the high latitude regions of the magnetosphere in 2019-2020 allow now to cross the B-minimum regions near the cusp and a few hours later the dawn region in the equatorial plane (Figure 9). Therefore, by lagging a spacecraft with respect to the others by about 3 hours Cluster could also observe simultaneously the high-latitude region and equatorial region. This would allow to investigate the source of high latitude chorus without the ambiguity inherent to single point measurements.

Finally, to fully understand the process of chorus generation the measurement at very-small scales is necessary. Chorus wavelength is about 30 km and to discriminate between different theoretical models we need to make multi-point measurements at smaller scales. Previous Cluster results show that the characteristic transverse scale of the hot spots generating the individual chorus elements can be comparable to the wavelength (Santolik and Gurnett, 2003) but the fine structure of subpackets, which necessarily reflects properties of the generation process, occurs to be different in spatial points transversely separated by tens of km (Santolik et al., 2003).The goal is therefore to put C3 and C4 at 3 km distances while the other spacecraft will be at much larger distances. We used 3 km to study the bow shock in early 2016 and Flight Dynamics at ESOC are confident they can achieve it again now near perigee.

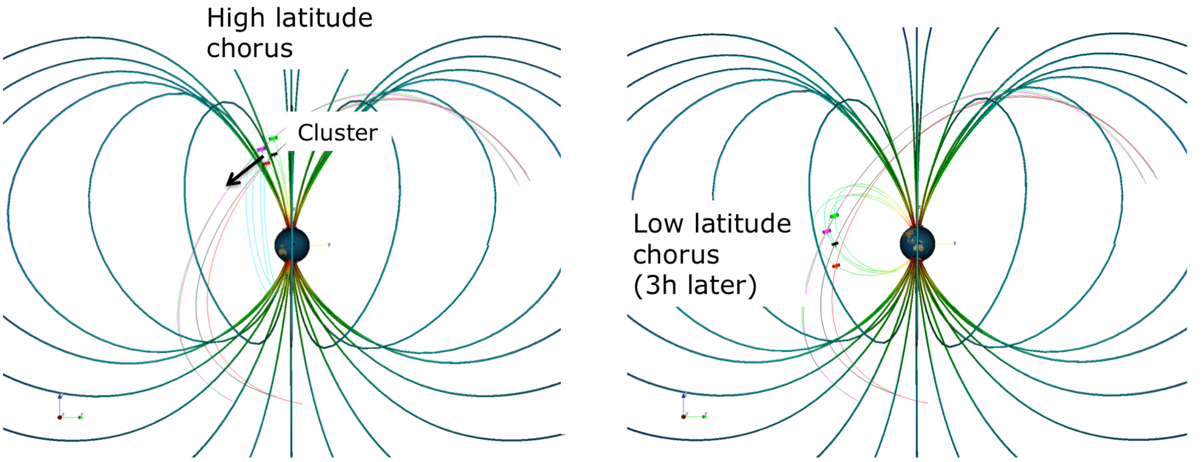

Figure 9: High (a) and low-latitude (b) chorus regions crossed by Cluster over 3 hours on 26 October 2019.

References:

Chum, J., O. Santolik, A. W. Breneman, C. A. Kletzing, D. A. Gurnett, and J. S. Pickett (2007), Chorus source properties that produce time shifts and frequency range differences observed on different Cluster spacecraft, J. Geophys. Res., 112, A06206, doi:10.1029/2006JA012061.

Gurnett, D. A., et al. (2001), First results from the Cluster wideband plasma wave investigation, Ann. Geophys., 19, 1259–1272.

Menietti, J.D., Santolik, O., Cetin Abaci, P. (2009), Chorus observations by the Polar spacecraft near the mid-altitude cusp, Planetary and Space Science, 57 1412–1418

Santolik, O., D. A. Gurnett, J. S. Pickett, M. Parrot, and N. Cornilleau- Wehrlin (2003), Spatio-temporal structure of storm-time chorus, J. Geophys. Res., 108(A7), 1278, doi:10.1029/2002JA009791.

Santolik, O., and D. A. Gurnett, Transverse dimensions of chorus in the source region, Geophys. Res. Lett., 30(2), 1031, doi:10.1029/2002GL016178, 2003.

Tsurutani, B. T., and E. J. Smith (1977), Two types of magnetospheric ELF chorus and their substorm dependences, J. Geophys. Res., 82, 5112 – 5128.

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6 - ANNEX 6: Investigate bow shock/magnetosheath/ magnetopause physics with local solar wind monitor

Many physical processes occurring in the dayside boundaries of the magnetosphere (bow shock, magnetosheath, magnetopause) depend on the physical parameters of the solar wind just in front of the magnetosphere. For instance, the solar wind velocity, density and interplanetary magnetic field influence the bow shock and magnetopause properties as well as the occurrence of transient structures such as hot flow anomalies, magnetosheath high speed jets, dynamic pressure transients, flux transfer events, etc. It is therefore essential when plasma structures in these regions are studied to have the most accurate measurements of the solar wind input.

Up to now Cluster observations relied on solar wind parameter measured at the Lagrange L1 point by the ACE or Wind spacecraft. These spacecraft are located at 220 Earth radii or 1.4 millions of kilometres (Figure 10). The time for the solar wind to travel from L1 to Earth vary according to the solar wind speed and the orientation of the interplanetary magnetic field: it can vary from 30 min up to 1.5 hour. The calculation of the propagation time is therefore difficult to perform. This difficulty has been the prime reason of the development of OMNIWeb (http://omniweb.gsfc.nasa.gov) by NASA. OMNIweb calculates the propagation time from L1 to the Earth bow shock using data from ACE and Wind using minimum variance analysis and cross-products methods.

Mailyan et al. (2008) compared various methods to estimate the propagation time for 200 magnetic discontinuity events. They found that the best method was using the orientation of the discontinuity and a constrained minimum variance analysis on the magnetic field. This method predicted an arrival time within 10 minutes for 71% of the events. More recently, Case and Wild (2012) compared 10 years of solar wind measurements of ACE at L1 and Cluster near the Earth. They found that the time difference between the OMNI estimate and the ACE-Cluster cross-correlation is in the range +/- 20 min with a few cases larger (Figure 11). These uncertainties in the OMNI data prevent effective analysis of the causes of short-lived phenomena, such as high-speed magnetopause jets lasting only a few minutes.

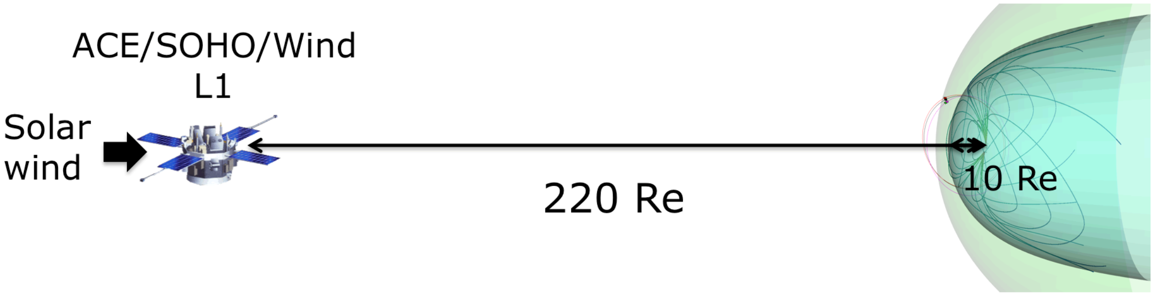

Figure 10: Solar wind monitors located at 220 Earth radii upstream of the Earth.

The proposal for this extension is therefore to set up a local solar wind monitor. We would propose to change the spacecraft configuration by placing one spacecraft upstream with respect to the others (**Figure 12**). The solar wind would then be measured during the whole period with one spacecraft when the three other Cluster spacecraft cross the bow shock, magnetosheath and magnetopause. A time lag of 8 hours between the local solar wind monitor spacecraft and the others would be necessary to achieve it. So far the maximum time of separation between two spacecraft was about 4h (for Foullon's GI in 2012 and 2016). The fuel needed to drift one spacecraft with respect to the other by 8h would be 0.2 kg (and another 0.2 kg to get back) using 6 months to reach the required constellation. This is perfectly feasible in view of the fuel left on the spacecraft. This local solar wind monitor with one spacecraft will suppress the propagation time uncertainty seen in the L1 measurements.

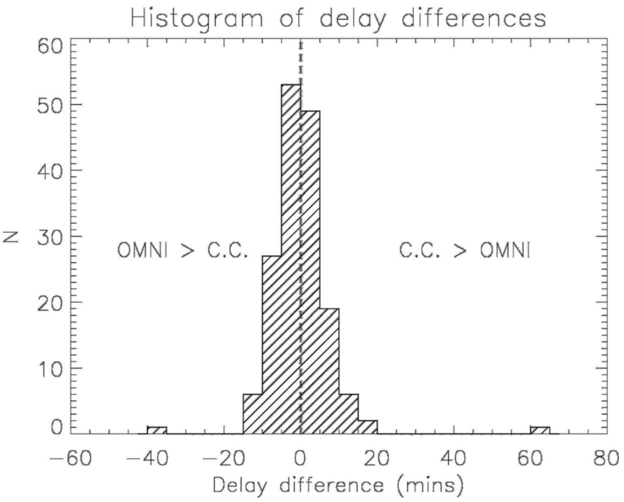

Figure 11: histogram of differences between the OMNI propagation delay from L1 to Earth and cross-correlation of ACE and Cluster data (from Case and Wild, 2012).

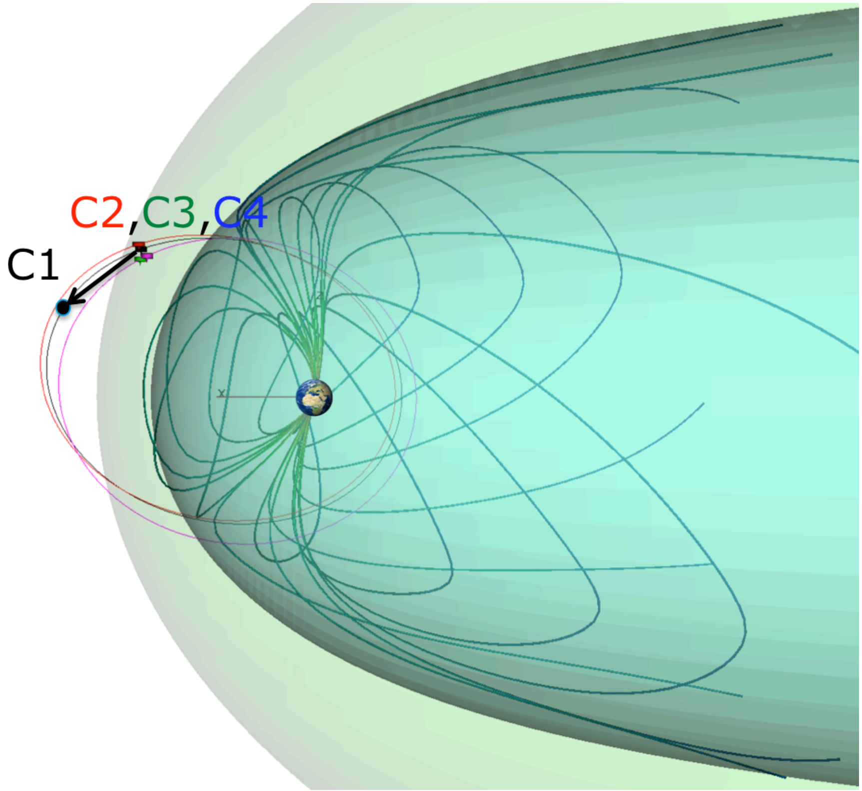

Figure 12: Cluster orbit with a model of magnetosphere (green lines). The magnetopause is in dark green color and the bow shock in light green. The shift (lag) of C1 by 8 h with respect to the other is indicated.

The THEMIS spacecraft had a similar configuration in the equatorial plane during a few years, with three spacecraft with an apogee around 10 R_E and the fourth one with an apogee around 20 R_E. The three inner spacecraft were therefore covering mainly the magnetopause and very rarely the bow shock region. With Cluster, we will be covering all regions from the bow shock to the magnetopause. Cluster would cross these regions at high latitudes, giving a complementary view to THEMIS and also addressing cusp processes.

The Geotail spacecraft could also be used as local solar wind monitor, it is however usually not at the same local time and latitude as Cluster and it is in the solar wind a maximum of 60% of the time. This new Cluster constellation will measure the local solar wind all the time during the crossings of the bow shock, magnetosheath and magnetopause and at approximately the same latitude and local time since the spacecraft are almost in the same orbit.

In addition such configuration could be used in the magnetotail 6 months later. In the magnetotail, a key unanswered question is what triggers magnetic reconnection in the plasmasheet. Is it internally driven in the plasmasheet or is it externally driven with changes happening in the lobes? By having three spacecraft in the plasmasheet and one in the lobes during a long period of time (hours) we will address the role of the lobes, for instance lobe magnetic pressure, that may be responsible for reconnection in the tail. For the tail, we would need around 16h delay between the three spacecraft and the single one that could be achieved by continuing the drift for another 6 months. This monitoring of tail lobes and simultaneously the plasmasheet can only be done with Cluster with its quasi polar orbit.

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7 - ANNEX 7: Investigate the evolution of Kelvin–Helmholtz waves on the flank of the magnetosphere with a unique constellation of spacecraft

Kelvin–Helmholtz (K-H) waves are ubiquitous in space and on Earth. They usually form when shear flows appear in fluid, gas or plasmas. For instance, such K-H waves have been detected at the surface of oceans or deep under the surface, in clouds, in the outer layers of the Earth and Saturn magnetospheres, in the Sun corona and in the atmosphere of giant planets.

In the Earth's magnetosphere, Cluster discovered that K-H waves can roll-up, turning into vortices (Hasegawa et al., 2004) (Figure 13) This phenomenon, by twisting the magnetic field inside the vortex, could initiate magnetic reconnection and allow solar wind plasma to have access to the magnetosphere (Nykyri et al., 2006). The twisting occurs when the waves are well developed and start to collapse. This is clearly shown in MHD simulations but the observations showing the evolution of the waves at separated points along the magnetopause have not been done yet.

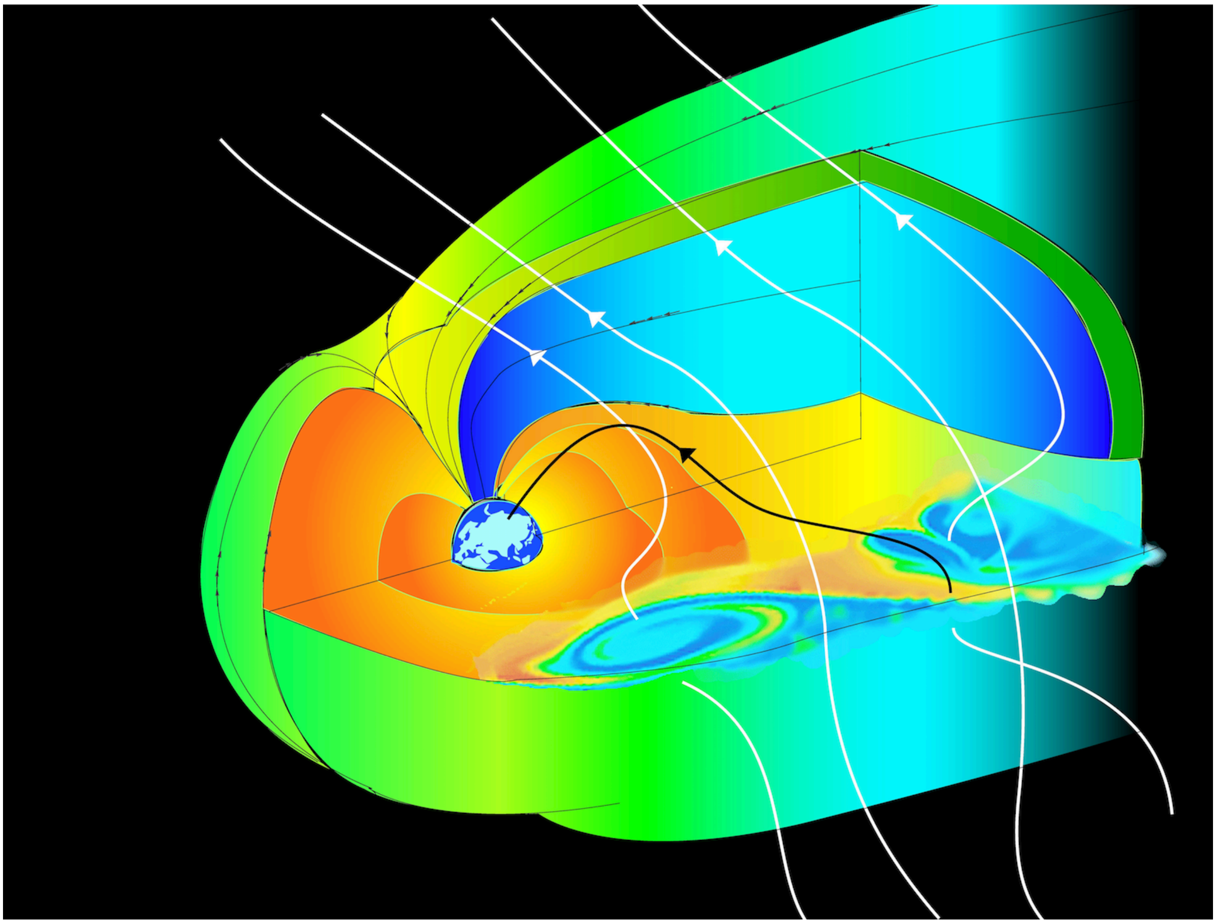

Figure 13: sketch of the magnetosphere with Kelvin–Helmholtz vortices generated on the dusk flank (from Hasegawa et al., 2004).

For the first time, it will be possible to study the evolution of K-H waves with a constellation of constellations. Due to their different orbit evolutions, in June 2019, both MMS, at small scales, and Cluster, at multi-scales, will be able to observe the changes occurring in K-H waves over distances of more than 12 RE along the magnetopause (Figure 14). Cluster could first detect the roll-up of the vortices and as the vortices develop and collapse, MMS will study magnetic reconnection taking place in their twisted magnetic fields. Simultaneously the THEMIS constellation of three spacecraft will be located in the near tail and monitor the density in the plasma sheet; the goal would be to detect if "cold dense" plasma sheet events (when the density is a factor 10 higher than usual) are produced by K-H waves. Swarm, with three spacecraft around 400 km of altitude will investigate the effect of K-H waves in the ionosphere, near the polar cap. This constellation of constellations will acquire a unique collection of data sets that will shed new light on this universal process.

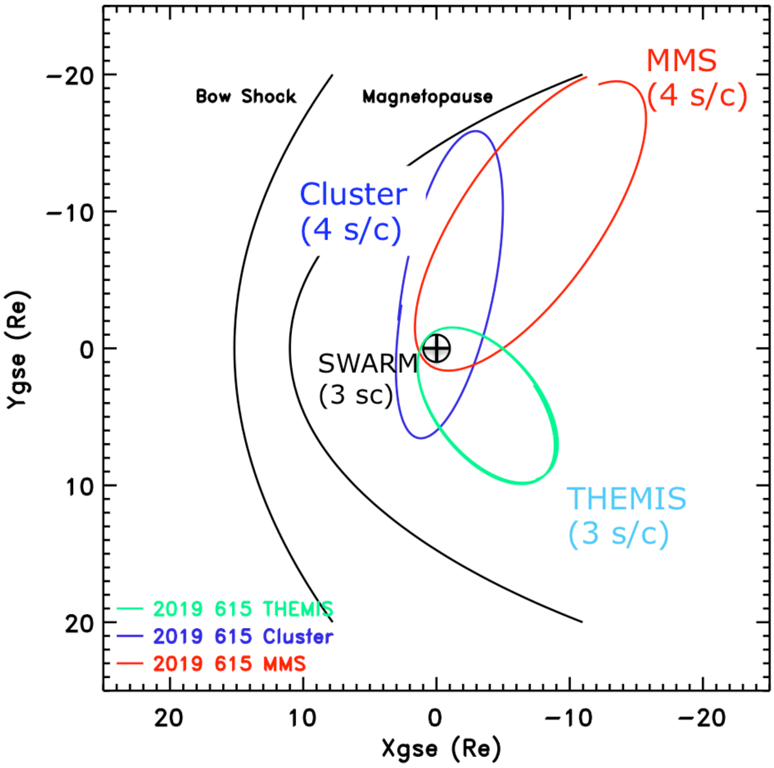

Figure 14: Cluster, MMS, THEMIS and Swarm orbits in June 2019.

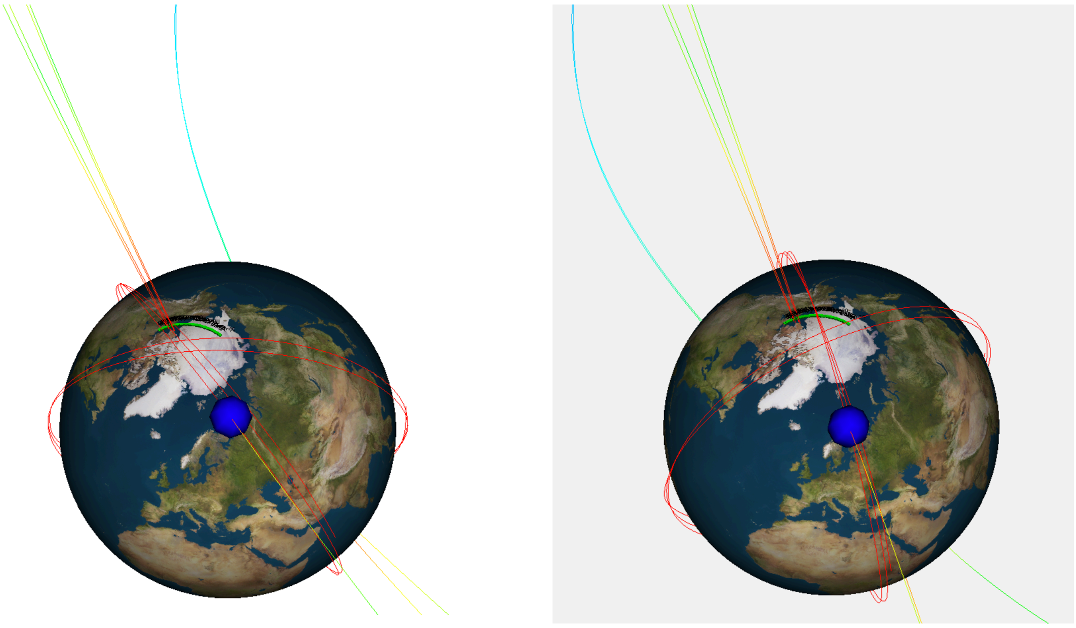

Figure 15 Swarm positions in June 2019. Left: A few orbits of Swarm B (blue dot) and Swarm A/C (spacecraft not shown since on other side of Earth)are shown, under the assumption that Swarm orbit continue to drift as now. Right: same as (a) but with a change of inclination in 2017 to keep the orbit planes of Swarm B and A/C separated by 90 deg. Cluster magnetic footprints are shown as a green line crossing the Swarm b orbit over the polar region.

Two options are being considered by Swarm: (1) keeping the drift of the orbit (left panel of Figure 15) or (2) changing the inclination of the spacecraft such as to keep the orbit planes between Swarm B and Swarm A/C around 90 deg. separation (right panel on Figure 15). It can be seen on Figure 15 that both options allow good conjunction with Cluster magnetic footprints (green line) and the Swarm B spacecraft. Note that Cluster, being far away from Earth, is moving slowly and its footprints take 4 h to go through the green line. Meanwhile, Swarm is making almost 3 full orbits around the Earth.

K-H waves can also be observed on the ground in the form of pulsations in ground-based magnetometers or convection vortices in SuperDARN radars. The spacecraft observations will therefore be complemented with ground based observatories that will cover the full Northern polar region and a good coverage of the Southern polar region. For instance the SuperDARN network is shown on Figure 16.

The small angle, less than 30 deg., between the apogee-perigee line of apsides of Cluster and MMS (Figure 14) will also be the perfect tool to study, a few month later, the tail of the magnetosphere and the dayside boundaries (bow shock, magnetosheath, magnetopause) from electron scales to ion, fluid and regional scales.

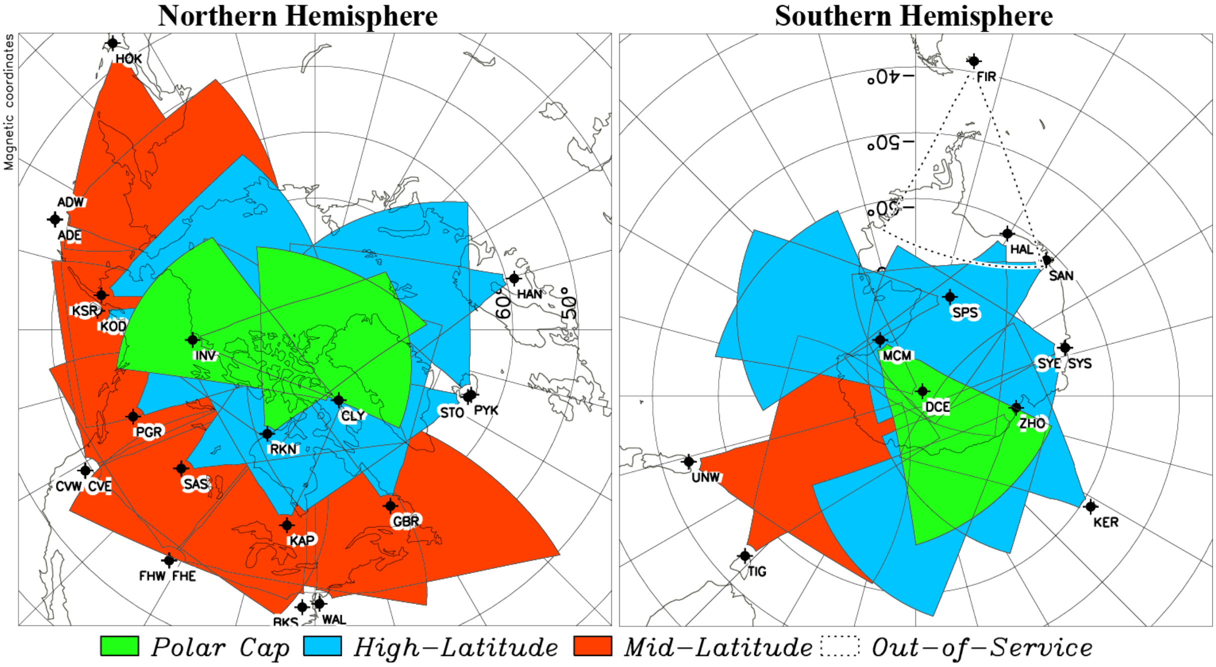

Figure 16: Radar coverage of the SuperDARN network. Left: Northern hemisphere radars. Right: Southern hemisphere radars

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8 - ANNEX 8. The Cluster Science Archive

The archiving of the high-resolution observations from the Cluster mission is a unique activity in space physics as this is the first time that any space agency has tried to provide scientists with access to all high-resolution calibrated data sets. Yet, this is still the only archive in the world to successfully do it.

The major challenge in space physics is to calibrate the in-situ instruments between four spacecraft as well as against different instruments (cross-calibration) of the wide range of plasma and field measurements. Each spacecraft carries 11 experiments, with three of these consisting of 2 instruments, making 52 instruments in total. For most of the instruments, the calibration must be done in flight by comparing observations between the four spacecraft and/or between different instruments on the same spacecraft. The calibration tables vary continuously and may be dependent on the environment. They vary along the spacecraft trajectory and many instruments are strongly affected by the presence of the spacecraft itself, making the final calibration of the observations very difficult and time consuming; many products have to be manually validated.

There are two archiving teams involved in the archiving activity and their tasks and responsibilities are split as follows:

- The Cluster Active Archive (CAA) is responsible for all technical aspects such as the calibration, processing, production, validation, and initial archiving of all data. The archiving tasks also include such issues as the definition and maintenance of the data format and the production of metadata.
- The Cluster Science Archive (CSA) which is responsible for the distribution and visualization of these data to the scientists all over the world. Once the CAA has ingested the validated files into its database, they are transferred into the CSA within one day. The CSA services can be accessed at http://www.cosmos.esa.int/csa.

The first preparations for the CAA started in year 2003, and the system specification review was held in November 2003. In 2004, all contractors (16 persons) were in place in the core team and the instrument teams, and two technical working groups started towards standardizing the data format and metadata dictionary. In May 2005, the archive held the implementation review where the archiving plans of the instruments and the technical implementation of the overall system were reviewed. In February 2006, the CAA became operational and opened its services to the scientific community. More recently the data access and visualisation system (CSA) was moved to the European Space Astronomy Centre (ESAC), Spain, which hosts most of ESA's astronomy and planetary mission archives. CSA was open to public in fall 2013 and since September 2014, the users have access to Cluster data only via CSA.

The technical tasks of the CAA are highly challenging, and in order to ensure and manage the overall activity, the following core management methods have been in place from the very beginning:

- Annual progress meetings between the CAA core team and instrument teams (ftp://ftp.cosmos.esa.int/pub/Cluster/MoM/CAA/ProgressMeetings/). The CAA team visits every instrument team once a year for a technical meeting where all archiving aspects are discussed in detail, including instrument calibration and cross-calibration, software development and maintenance, data production and validation, and documentation. These meetings are also used to discuss/evaluate the status of action items raised during previous progress meetings, CAA cross-calibration workshops and CAA operations reviews. The progress meetings have played a critical role for resolving a large number of problems and improvements in the archive data quality and user services.
- Bi-annual cross-calibration workshops (http://caa.estec.esa.int/caa/cross-cal.xml). The Cluster experiments are not independent but they are closely linked and are partially

overlapping in some cases. Therefore, it is very important that different experiments are cross-calibrated. This is highly challenging and therefore the teams gather together in cross-calibration workshops twice a year to discuss the status, progress and problems in the instrument calibration and data production. This activity is managed by the CAA core team. This is a unique activity in space physics which results in the production of the best quality datasets in space physics yet. It is one of the main reasons behind the popularity of the Cluster archive, resulting in a high number of users and subsequent scientific publications. The first dedicated book on the Cluster archive was published in 2010 and consisted of more than 30 refereed papers (The Cluster Active Archive: studying the Earth's space plasma environment, Astrophysics and Space Science Proceedings, Laakso, Harri; Taylor, Matthew; Escoubet, C. Philippe (Eds.), 492 p., Springer, 2010). This book has been very popular. Since October 2009, 11632 chapters have been downloaded, making it one of the top 50% most downloaded eBooks in the relevant Springer eBook Collection in 2015. 70% of downloads were made in years 2014-2015.

- Annual operation review (http://caa.estec.esa.int/caa_stage/reviews.xml). Annual peer-reviews of the progress of the archive are held to examine the quality of the data products and the usability aspects of the services and to verify that key milestones have been met.

The coverage and range of Cluster products is continually improved, currently around 400 different datasets are available from each spacecraft, including high-resolution magnetic and electric DC fields and wave spectra and derived electron densities; full 3-D distributions of electrons and ions covering energies from a few eV to hundreds of keV; and various ancillary & browse products to help with spacecraft and event location. Recently, quality indexes have been added to some data sets to help the user asses the quality of the data acquired in different magnetospheric regions and under various operational conditions. All files are downloadable in either NASA Common Data Format (CDF) or in an ASCII format (called Cluster Exchange Format, or CEF). In addition around 400 different types of pre-generated instrument and cross-calibration plot files per spacecraft are available for data selection. Data volume (uncompressed) stands at around 500 TB, which, due to the highly compressible nature of the CEF file format, means that the storage requirement for these files reduces to only 90 TB.

Recent developments include software for accessing and interpolating parameters onto the same time line, a framework that has provided coordinate transform capabilities (see the tools at http://www.cosmos.esa.int/web/csa/software). Additional work continues on extending the Cluster archive graphics system family of plots with a family of particle distribution plots. Formats include energy-pitch angle plots, angle-angle plots, “Sauvaud” style pitch angle plots and classical wheel (or pitch angle distribution) plots.

Three different methods for downloading data exist: normal GUI using java client, command line tool and streaming interface. Using the last tool, users are able to stream data directly to their local machine, avoiding the normal procedure of creating a file at the Cluster archive first. A data-mining tool has also been developed recently and a beta version is available at http://caa.estec.esa.int/caa_dm/. The tool allows users to query any Cluster archive CEF parameter and complex expressions can be constructed to identify regions/periods of interest.
The archiving of the Double Star (ESA-China mission in collaboration with cluster) data has also made good progress. The complete high-resolution datasets from the magnetometer FGM on the two spacecraft have been cleaned and are available online since May 2015. Recalibrated datasets from PEACE (electron sensor) and HIA (ion sensor) have also been delivered. The CSA GUI has been re-designed to allow the selection of datasets from both Cluster and the Double Star missions. Note that this activity has no funding and is performed on a best effort basis.

The EU FP7 ECLAT (European Cluster Assimilation Technology) and MAARBLE (Monitoring, Analyzing and Assessing Radiation Belt Loss and Energisation) have finished and they both delivered data to the CAA, so they can be accessed via CSA as well. Several other EU FP7 projects (including HELIO and ESPAS) are planning to provide access to Cluster archive data within broader European-wide space physics data infrastructure projects.

Figure 17 shows some statistics of downloading activity. The top panel shows the number of different IP numbers which have downloaded data in a month. After the closure of the CAA, the number has been quite steady, between 150-200. However, this is not the actual number because one user may use different IP numbers and some institutes have a fixed system accessing the CSA. One should also note that some users may access the CSA only for visualizing observations and do not download data which is not shown in these statistics. The bottom panel shows the total volume of download every month. This is normally between 1-2 TB/month and the max value is ~10 TB so far. Again one important note is that some institutes maintained their local archive (with help of command-line tool, one can ensure the local database is always up-to-date) and so the data are not downloaded any more unless a new version of file has been ingested into the database.

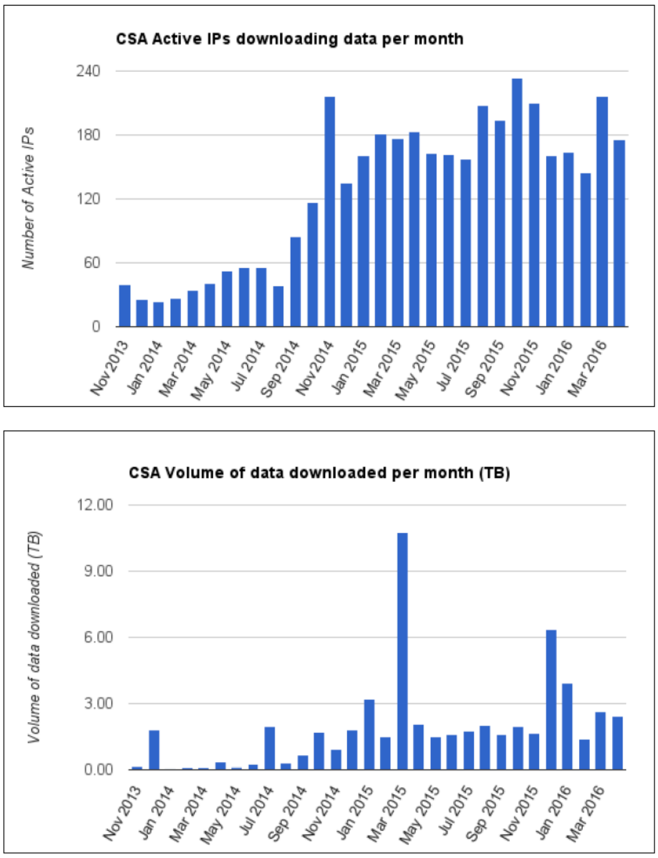
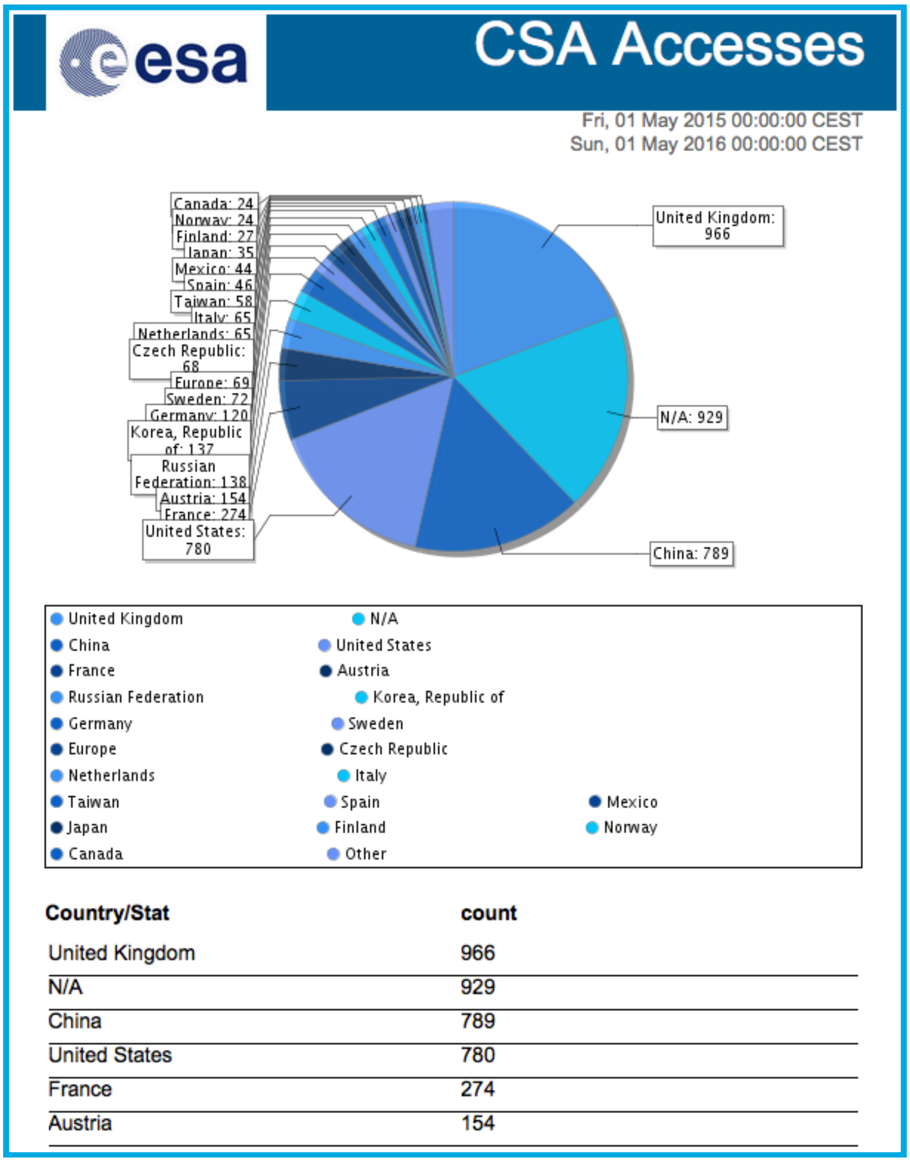


Figure 17: Monthly statistics of CSA usage. Top: number of different IP numbers that have downloaded data. Bottom: total downloaded data volume.

Figure 18 shows the distribution of countries of users who have accessed the CSA system (downloading, browsing, visualization etc) in the past 12 months. N/A is for the users who's country is not known (e.g. for .com, .net etc). It is seen that 40-50% of these users are from Europe, depending on who of the N/A users are from Europe. UK is the biggest user group, followed by China and USA. Chinese users may often use .com address and in reality they may be the biggest user group of the CSA services.



CSA Accesses

Fri, 01 May 2015 00:00:00 CEST
Sun, 01 May 2016 00:00:00 CEST

Country/Stat	count
United Kingdom	966
N/A	929
China	789
United States	780
France	274
Austria	154

Figure 18: Geographical distribution of CSA usage.