# Cluster confirmation and extension (2017-2020)

## 1. Introduction

The Cluster quartet continues to reveal the science behind the interaction of the Sun and Earth's space environment by measuring key plasma parameters in 3D. The four Cluster spacecraft were launched in pairs on two Soyuz rockets in July and August 2000. The launches put the four spacecraft into a polar orbit that targeted some of the most important near-Earth regions: the solar wind, bow shock, magnetosheath, cusp, magnetopause, plasmapause and magnetotail. By providing unique, closely spaced, four point measurements in the Earth's magnetosphere, Cluster provides a 3D vision and temporal evolution of plasma structures and boundaries. It also enables an unambiguous determination of the various electric currents and gradients of key plasma parameters. The mission was originally funded to operate for two years, but has subsequently been granted extensions up to the end of 2018, subject to confirmation for 2017-18. This proposal seeks to confirm the current extension up to end 2018 and sets out the case for a further extension up to the end of December 2020.

The activities during each Cluster extension have not been simple continuations of the original science goals, but have been driven by exciting new science investigations. Due to the evolution of the orbit, Cluster has been able to sample regions of the magnetosphere that were not accessible in the initial stages of the mission, such as the auroral acceleration region, the inner magnetosphere and the sub-solar magnetopause. In addition, new science has been possible through collaborations with other missions. More recently, Cluster has implemented a pioneering Guest Investigator (GI) programme, the first in the field of space plasma physics, through which the scientific community is invited to propose their own science objectives and to request specific spacecraft and instrument operations needed to deliver that science. Following the success of the first GI Call, a second call was issued, and the resulting GI-led observations were implemented in 2015-2016

Due to the capability to change the separation distance between the spacecraft, and due to its evolving orbit, Cluster will address new science objectives that were not possible before. Furthermore, the recent launch of MMS will allow new synergies to be exploited for the first time. The science goals for the extension in 2019-2020 are the following:

- to characterise chorus waves at both low and high-latitude with only 3 km inter-spacecraft distance, in order to test competing theoretical models of how they are produced,
- to investigate bow shock/magnetosheath/magnetopause physics for the first time with a local solar wind monitor, in order to have precise information about solar wind driving,
- to measure the evolution of Kelvin–Helmholtz waves on the flanks of the magnetosphere by a unique constellation of spacecraft, in order to investigate their non-linear development, and whether they play a role in generating the "cold, dense plasmasheet",
- to open a call for early-career scientists to observe with Cluster during a 3-month interval.

## 2. Science Case

### 2.1. Mission impact and metrics

Cluster continues to make great discoveries in many regions of the near-Earth environment. The key technical breakthrough of the mission was to make the first 3D measurements using four identical spacecraft placed in a triangular pyramidal shape. Twice a year, the Cluster constellation is changed (separation and orientation) to match the scientific objectives defined by the Science Working Team (see Annex 1). In addition, the mission has engaged a broader scientific community by selecting GI proposals, which have driven changes of separation distances every few months over the past few years. Two calls for GI proposals were issued in 2010 and 2014 and the observations were implemented in 2011-2013 and

2015-2016 (see Annex 3). To cover various plasma scales simultaneously, the concept of multi-scales observations was introduced in 2005. Fluid and ion scales were then measured in various regions simultaneously. This year, to reveal for the first time the physical processes at electron scales, which dissipate energy in the collisionless bow shock (where the solar wind is slowed down on order to flow around the magnetosphere), Cluster observations were made with two spacecraft separated by an unprecedentedly small 3 km distance.

Cluster workshops are organised each year to discuss new data with the community, along with very well attended special sessions focusing on multi-point measurements at international conferences, such as the EGU, COSPAR and AGU. Last year, the 25th Cluster workshop was organised in Italy with about 130 participants from around the world. This year, the 26th Cluster workshop is organised together with the NASA THEMIS mission; this will be the 4th joint Cluster-THEMIS workshop after those in 2008, 2010 and 2012.

Table 1 shows the refereed publications for the entire mission, currently totalling 2354 (up to the end of May 2016). In the last two years, 338 new papers have been published.

| **Year** | <2003 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Papers** | 121 | 65 | 128 | 186 | 148 | 129 | 199 | 178 | 198 | 235 | 189 | 173 | 159 | 179 | 67* | **2354** |

**Table 1. The 2354 refereed papers from the Cluster and Double Star missions presented per year. *2016 up to May. Less than 100 of these papers are based solely on Double Star data.**

The productivity of the Cluster mission continues to rise thanks to the open access of all high-resolution Cluster data through the online Cluster Science Archive (CSA). CSA accounts more than 1900 registered users as of June 2016. On a monthly basis, approximately 200 different users access the CSA to download data or to view data with the help of various visualization tools. However, the real number of users per month is certainly somewhat higher because several institutes have centralised access to the CSA and all requests come via a single user identity (either fixed IP or fixed username). The CSA attracts users because it is continually adding new high-quality, high-resolution data from all the Cluster instruments. Moreover, it includes various visualization tools that help users to browse data before downloading them. It also supports complementary datasets from CNSA-ESA Double Star mission and the FP7 MAARBLE and ECLAT projects. This is the first time in space physics that all high-resolution data have been calibrated, processed and archived. One should note that the CSA services are fully based on the development done by the Cluster Active Archive (CAA) in years 2006-2014, itself complementing a more basic archive, the Cluster Science Data System.

Among the key results and discoveries that were published using the four Cluster spacecraft in the last two years, we can list those that have appeared as ESA website stories (in chronological order) (see Annex 2 for more detailed information):

- solar wind breaks through the Earth's magnetic field
- first observations of an unusual magnetic storm
- origin of the high latitude auroras revealed
- electric fields in black aurora explained
- first simultaneous measurements of field aligned currents with Cluster and Swarm
- physical mechanism behind the generation of equatorial noise waves
- a new method to capture magnetic nulls in magnetic reconnection
- two pathways for Earth atmosphere leak.

In 2016, Professor Stephen Fuselier, Cluster Co-Investigator and executive director of the Southwest Research Institute (USA) 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; its rates and sites, anti-parallel and component reconnection, and novel energetic neutral atom observations at the nose of the magnetosphere. This high-profile award is the latest attributed to a Cluster scientist.

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, with 70% of downloads made in years 2014-2015.

## 2.2. Confirmation of scientific performance for 2017 and 2018

During the confirmation period (2017-2018), Cluster will continue its key role in advancing our understanding of the near-Earth space plasma environment. The key aspects of the last extension presented in 2014 were to:

- characterise the jet braking region with Cluster at multi-scales
- determine the extent of the exterior cusp in longitude and investigate its dawn-dusk asymmetries
- study the magnetosphere-ionosphere coupling in conjunction with Swarm at 60-90 deg. orbits
- understand magnetic reconnection and plasma acceleration at multiple scales simultaneously using MMS, THEMIS, and Van Allen Probes constellation missions.

There are no changes to these science goals and Cluster is capable of delivering them as presented in the 2014 extension case. The Cluster orbit continues to evolve with its perigee altitude reaching 6.7 Earth radii ($R_E$) in 2018. This will allow the transition region between the tail and the inner magnetosphere to be visited and plasma jet braking at multi-scales to be addressed. The inclination of the orbit is now stable, at around 130°, and Cluster will cross the exterior cusp in longitude to investigate its dawn–dusk asymmetries. The Cluster and Swarm orbits evolution is as predicted in 2014. The Swarm A/C and Swarm B spacecraft will be separated in azimuth by 60° and 90° in 2017 and 2018 respectively. The Swarm nominal mission up to the end of May 2018 will be sufficient to achieve the objective listed above.

Cluster is collaborating with other solar-terrestrial missions such as MMS, THEMIS and the Van Allen Probes. MMS was launched as expected in March 2015 and is focusing on the reconnection process at small electron scales. This is very complementary to Cluster with its measurements at multi-scales, from electron to fluid scales; Cluster-MMS conjugate observations have already been initiated. To enhance these collaborations, well attended workshops are organised regularly: the 1st Cluster-MAARBLE-Van Allen Probes workshop took place in September 2014 and the 4th Cluster-THEMIS workshop will be organised in November 2016. In the coming years, we plan to organise a Cluster-MMS-THEMIS workshop. In summary, the science goals of the extension 2017-2018 remain valid and the spacecraft and instruments are fully capable of supporting these goals (see Section 3).

## 2.3. Science case for the extension interval 2019 and 2020

As demonstrated by the high publication rate, coupled with the solid usage of CSA and its continually growing user community, Cluster continues to engage and serve the space science community. Covering a range of latitudes and altitudes, Cluster remains a unique tool to investigate energy flow and mass transport within the Sun-Earth system. Endorsed by the Cluster Science Working Team (Annex 4), we propose to further extend the Cluster mission in order to provide new measurements to understand the Sun-Earth relation and the plasma processes governing it. The new science goals for the January 2019-December 2020 extension are:

### *2.3.1. Characterise chorus waves at both low- and high-latitudes with only 3 km inter-spacecraft distance*

Chorus waves are electromagnetic emissions observed in the Very Low Frequency (VLF) range, mainly on the dawn side of the Earth’s environment. They consist of brief rising or falling frequency tones that sound 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 chorus waves have been shown to accelerate electrons to extremely high energy (MeV). Chorus waves are thus an important element in the dynamics of radiation belts and the understanding of space weather.

In 2019-2020, we propose to answer two open questions: what is the source of high latitude chorus waves (locally generated, or originating at low latitudes)? and what is the generation process of chorus waves? To address the first question, we will take advantage of the evolution of the orbit which will now cross the high- and low-latitude chorus source regions with about 3 hours time delay. We would then separate one spacecraft from the others by 3 hours to simultaneously cover the high- and low-latitude chorus regions simultaneously (see Annex 5). To understand better the process of chorus generation and propagation, measurements at very-small scales are necessary. The chorus wavelength is about 30 km and to discriminate between different theoretical models we will separate Cluster 3 and Cluster 4 by 3 km. This will allow us to investigate spatial properties of the fine structure of chorus wave packets which was originally discovered by Cluster (Santolik et al., 2003, doi:10.1029/2002JA009791) and which is inherently linked to the generation mechanism. We used 3 km between Cluster 3 and Cluster 4 to study the bow shock in early 2016, but this scale has never been applied in the chorus source regions.

### *2.3.2. Investigate bow shock/magnetosheath/magnetopause physics for the first time with a local solar wind monitor*

Many physical processes occurring in the dayside boundaries of the magnetosphere (bow shock, magnetosheath, and magnetopause) depend strongly on the physical parameters of the solar wind just in front of the magnetosphere. The solar wind velocity, density and interplanetary magnetic field all influence the large scale properties of the bow shock and magnetopause, as well as the occurrence of transient smaller scale phenomena, such as hot flow anomalies, magnetosheath high speed jets, boundary waves, dynamic pressure transients, flux transfer events, etc. Accurate knowledge of the solar wind input is critical to study these phenomena.

Up to now, analysis of Cluster observations has relied on solar wind parameters measured at the Lagrange L1 point by the ACE or Wind spacecraft. These spacecraft are located at 220 $R_E$ or 1.4 million kilometres from Earth (Annex 6). The time it takes for the solar wind to travel from L1 to Earth varies depending on the solar wind speed and the orientation of the interplanetary magnetic field; it can vary from 30 min up to 1.5 hours. The calculation of the propagation time is difficult. The OMNIWeb system developed by NASA provides "best estimates" of solar wind conditions just upstream of Earth based on measurements near L1. Case & Wild (2012, doi:10.1029/2011JA016946) compared 10 years of solar wind measurements of ACE at L1 and Cluster near Earth. They found that the time difference between the OMNI estimate and the ACE-Cluster cross-correlation is in the range of ± 20 min and for a few cases larger. 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.

One key aspect of this extension is therefore to set up a local solar wind monitor within the Cluster constellation. We propose to change the spacecraft configuration by placing one spacecraft upstream with respect to the others. The near-Earth solar wind would then be measured with one spacecraft every time the other three 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. The fuel needed to drift one spacecraft with respect to the other by 8 hours is 0.2 kg (and another 0.2 kg to get back), if we use 6 months to reach the required constellation. This is perfectly feasible in view of the fuel left on the spacecraft (see Section 3).

#### *2.3.3. Investigate the evolution of Kelvin–Helmholtz waves on the flank of the magnetosphere with a unique constellation of spacecraft*

Kelvin–Helmholtz (K-H) waves form when shear flows appear in fluid, gas or plasma. In plasmas, this phenomenon is more complex as electromagnetic forces also play a role. K-H waves have been detected at the surface of the ocean or deep under the surface, and in the atmosphere of giant planets (Saturn, Jupiter). K-H waves in plasmas have been observed where the solar wind flows along the outer layers of the magnetospheres of Earth and Saturn, and in the solar corona, and must occur in many astrophysical contexts. Although K-H waves in fluids have long been studied, major open questions remain on the physical processes associated with K-H waves in magnetised plasmas. What is their evolution from birth to collapse? How is magnetic reconnection initiated within K-H rolled-up vortices? Do they enable solar wind plasma to enter into magnetospheres?

For the first time, it will be possible to study these questions with a constellation of constellations (see Annex 7) that will acquire a unique collection of data sets that will shed new light on this universal process. Due to their different orbit evolutions, in June 2019, both Cluster, observing at multi-scales, and further downstream, MMS, observing at electron scales, will be able to observe the changes occurring in K-H waves over distances of more than 12 $R_E$ along the magnetopause. Cluster will observe the waves beginning to roll-up into vortices and as the vortices develop and collapse, MMS will study magnetic reconnection taking place in their twisted magnetic fields. The THEMIS constellation of three spacecraft will be located within the near-Earth magnetotail, able to monitor the magnetotail plasma sheet, and 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 at around 400 km of altitude will seek the signature of K-H waves in the high-latitude ionosphere, such as field-aligned currents associated with the relaxation of newly reconnected magnetic flux. .

#### *2.3.4. Open a call for early-career scientists to perform 3 months of observations*

Two Cluster announcements of opportunity (AOs) for a Guest Investigator programme have been addressed to the scientific community in 2010 and 2014. These AOs allowed scientists around the world to propose special operations to fulfil new scientific objectives (see Annex 3). This time, we propose a new type of call, to be addressed to early-career scientists (PhD level to PhD+ 3 years). They will be requested to propose a new science objective that could be met during a maximum 3-month observation interval. The selected early-career scientists will be "trained" to be a Principal Investigator (PI) and will interact with the instrument and operation teams at ESTEC, ESOC, ESAC and the Joint Science Operations Center (JSOC). They will participate in two Science Operation Working Group (SOWG) meetings, the first one to understand the work and the second one to do the operations planning. We propose to select 5-10 early-career scientists for them to work as a team on the best science objective proposed, with the aim of publishing common papers based on their observations. The call would create an exciting opportunity for leading early-career scientists to engage with an active science mission. It would produce new science, and has strong potential for outreach and education. The review of the proposals will be performed by the SOWG and a peer review committee, with members from the Solar System and Exploration Working Group. They will make a recommendation to the ESA Director of Science who will appoint the Cluster next-generation scientists.

### 2.4. Complementarity and uniqueness

The Cluster mission is unique since it is the only magnetospheric mission that uses a quasi-polar orbit. No other mission uses a flexible multi-scale, multi-spacecraft approach. The first and second new science objectives can only be performed by Cluster for these reasons.

The Cluster mission is highly complementary to other current magnetospheric missions (MMS, THEMIS, Van Allen Probes, Geotail) which all orbit in the equatorial plane, due to its quasi-polar orbital plane. The recent update of the standard magnetospheric model (Tsyganenko, JGR, 2014) relied heavily on Cluster high latitude observations alongside low latitude data from other missions. Our third science objective utilises this complementarity with several other missions. Over the coming years, the orbit of the MMS mission will become more and more aligned with the Cluster orbit, enabling Cluster and MMS to better sample inter-related regions of the magnetosphere simultaneously.

The quasi-polar orbit allows Cluster to make unique observations of the precipitation of solar wind particles into the polar ionosphere and of plasma leaving the polar atmosphere in ion outflows. These two processes are fundamental to the filling of the magnetosphere with plasma. An ion mass spectrometer allows Cluster to differentiate between hydrogen and oxygen ions, which is essential in order to characterise the outflows. Cluster has the most sensitive search-coil magnetometers currently flying, or likely to fly soon. Many research areas benefit from their excellent data, notably plasma turbulence. Another unique aspect of Cluster is its active plasma sounders which provide absolute knowledge of electron density in key regions. This enables excellent in-flight calibration of the electron and ion instruments.

### 2.5. Science Working Team recommendation

Based on this proposal, the Cluster Science Working Team strongly supports the confirmation of operations in 2017-2018 and the extension of Cluster operations in 2019-2020 (see Annex 4).

## 3. Spacecraft, Payload and Ground Segment Status

The Cluster payload is operated based on observational requests from the PIs via JSOC, which is responsible for coordinating the science operations for the Cluster Mission. The JSOC team and infrastructure are ready to support the extension through 2020.

There are two data centres that are involved in the data production and delivery activities: the Cluster Active Archive (CAA) is responsible for the calibration, processing, production, and validation of all data and the Cluster Science Archive (CSA) which is responsible for the distribution and visualization of these data to scientists worldwide. The CSA has been opened to the public since October 2013. The total number of users is over 1900 with a steady increase of about 10 new users every month. The average amount of data downloaded in a month is around 2 Terabytes. Recently, quality indexes have been added to some data sets to help the user assess the quality of the data acquired in different magnetospheric regions. In addition to the science data, there are also raw data available, mainly used by PIs and CoIs. These data are transferred from the ESOC Data Disposition System to the CAA, which has developed a simple tool for users to access them. Eventually, these raw data will be archived at ESAC in the multi-mission RAWDAR system.

There is a complementary data system for Cluster, called the Cluster Science Data System (CSDS), which consists of data centres in Europe, USA and China. From a few hours to a few days after acquisition, CSDS provides the scientific community with key scientific and auxiliary parameters, derived from preliminary calibration files, in the form of various quicklook plots. Summary and prime parameter data are made available to scientists within a few months following acquisition. These data are also available through the CSA.

The archiving of the Double Star mission data has also made good progress. The complete high-resolution datasets from FGM (magnetometer) 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 current spacecraft status and performance is very good. Solar array power degradation, which was significant during the passage through the inner radiation belt, has now decreased to almost zero (Annex 1). During the proposed extension, the spacecraft perigee will remain above 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.

In 2014, the analysis of the mission end of life showed that three spacecraft C2, C3 and C4 will re-enter the Earth's atmosphere in 2024-2026 with a casualty risk well below the ESA threshold of 0.01%. C1, however, was going to re-enter much later, in 2038, with a casualty risk above the ESA threshold. Consequently, C1 executed a manoeuvre in March 2015 to change its re-entry to 2025 providing a similar very low casualty risk.

In June 2016 the remaining fuel on all four spacecraft ranges from 4.5 kg (C4) to 6.6 kg (C3). The fuel used for constellation manoeuvres requires around 0.1-0.2 kg/year on each spacecraft. C4 is not moved since it has less fuel than the others. If we assume a fuel usage of 0.3 kg/year (twice the current usage), we should still have between 4.5 kg (C4) and 5.3 kg (C3) at the end of 2020 (Table 1, Annex 1).

The payload is also in good health. In total, 37 instruments out of a total of 44 are operating and are fully capable of achieving the proposed science. All bulk plasma parameters are obtained by the payload on each spacecraft. For 2019-2020, it is quite possible that the two remaining RAPID energetic ion measurements on C2 and C4 will be unavailable but RAPID will be able to provide energetic electron measurements from all 4 spacecraft. The science objectives presented for 2019-2020 are fully achievable without the RAPID ion instrument.

The ground segment is stable and working reliably and will benefit from the evolution of the Cluster orbit, with its apogee returning to the Northern Hemisphere. After the Perth ground station closure, the increased visibility from other ground stations will still allow provision of a data volume of 115% equivalent orbit coverage in normal mode, outside of eclipses seasons.

## 4. MEOR Recommendations

A Mission Extensions Operations Review (MEOR) was held on 30 May 2016. The MEOR board confirmed that Cluster can deliver the expected science return in both the confirmation (2017–2018) and extension intervals (2019–2020).

## 5. National Funding Status and Prognosis

2017–2018: All instrument teams and data centres expect to be able to support operations during the confirmation interval. UKSA agreed to support the UK Cluster PIs from 2017 onwards. NASA funding for WBD operations stopped in September 2015 and these operations are continuing with the support of Czech Republic ground stations.
2019–2020: All instrument teams and data centres expect to be able to support operations.

## 6. Financial Request

The cost of Cluster operations for the confirmation period 2017-18 is XXXX M€ (at 2014 economic conditions as noted in ESA/SPC(2014)26), while it is expected that the 2019-20 extension costs will be broadly similar (corrected for inflation).

## 7. Conclusions

Due to the continued capability of the Cluster mission to carry out its science investigations as proposed, the SPC is requested to confirm the extension of Cluster operations until 31 December 2018. To take advantage of a number of new and unique science opportunities after this, the SPC is asked to approve the extension of the Cluster operations for a period of 2 years from 1 January 2019 to 31 December 2020.