Cluster Active Archive

Users Guide to EFW data

Version 1.0

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CONTENTS

1. Introduction

The Cluster Active Archive (CAA) was created to archive all data from the Cluster mission. Emphasis is on providing the scientific community with calibrated science data. This document describes the CAA data from the Electric Field and Waves (EFW) instrument. It gives some brief information on the instrument, followed by a description of all EFW parameters available in CAA. Some important things to keep in mind when using the data are given in the caveats section. For those interested, there is also a section describing some of the processing details.

2. The EFW instrument

2.1 Instrument hardware

Details of the EFW instrument can be found in [Gustafsson et al., 1997]. Here only some of the characteristics are described briefly.

The detector of the instrument consists of four spherical sensors deployed orthogonally on 44 meter long wire booms in the spin plane of the spacecraft. The potential drop between two opposing sensors, separated by 88 m tip-tip, is measured to provide an electric field measurement. Since there are four sensors, the full electric field in the spin plane is measured. The potential difference between each sensor and the spacecraft is measured separately (and is often used as a high time-resolution proxy for the ambient plasma density, [cf. Pedersen et al., 2008]). The potentials of the spherical sensor and nearby conductors are actively controlled in order to minimize errors associated with photoelectron fluxes to and from the spheres. The output signals from the spherical sensor preamplifiers are also provided to the wave instruments (STAFF, WHISPER and WBD) for analysis of high frequency wave phenomena.

2.2 Probes and filters

The configuration of the four probes of the EFW instrument in the spin plane is shown in Figure 1. EFW measures individual probe potentials with a sampling frequency of 5 s^{-1}, as well as the potential difference between selected probe pairs with a sampling frequency of 25 s^{-1} or 450 s^{-1} depending on the telemetry mode. A schematic overview of the relevant signal paths is given in Figure 2. The individual probe signals, p1 to p4, are always routed through 7-pole low-pass filters with a cut-off frequency of 10 Hz before sampling. The probe difference signals, p12, p34 and p32 are normally routed through 10 Hz low-pass filters if sampled at 25 s^{-1}, and through 180 Hz low-pass filters when sampled at 450 s^{-1}.

Normally, the full spin plane electric field is computed using the orthogonal signals P12 and P34. However, a failure occurred on probe 1 on spacecraft 1 (28 December 2001), on probe 1 on spacecraft 3 (29 July 2002), and on probe 1 on spacecraft 2 (13 May 2007). After this time, it is not possible to use P12, but a workaround was implemented in the flight software to use P32 instead. This was fully implemented on 29 September 2003 on spacecraft 1 and 3, and on 24 November 2007 on spacecraft 2. In the intermediate period (Jan 2002 – Sep 2003 for SC1, Aug 2002 – Sep 2003 for SC3, and May – Nov 2007 for SC2), full resolution data will not generally be available. The 4-second resolution electric field data is not affected, since it uses data from only one probe pair as input.

The filters are normally connected to the sampled quantities as indicated in Figure 2. However, the 10 Hz filter on probe 3 on spacecraft 2 failed on 25 July 2001. As a workaround for this, the 180 Hz filter has been used for the difference signals sampled at 25 s^{-1}, which has no effect on the 4 second resolution data, and only a marginal effect on the full resolution data in those space environments where large amplitude electric field noise is present between 10 and 180 Hz.

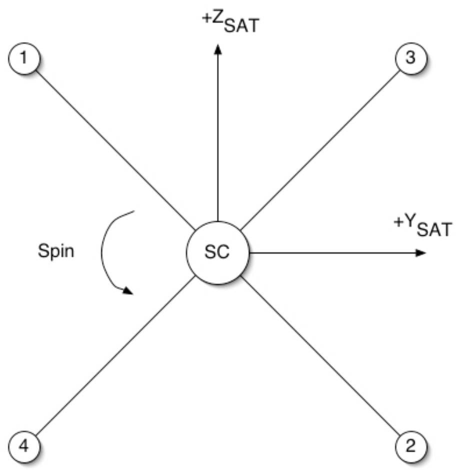

Figure 1. EFW probe configuration

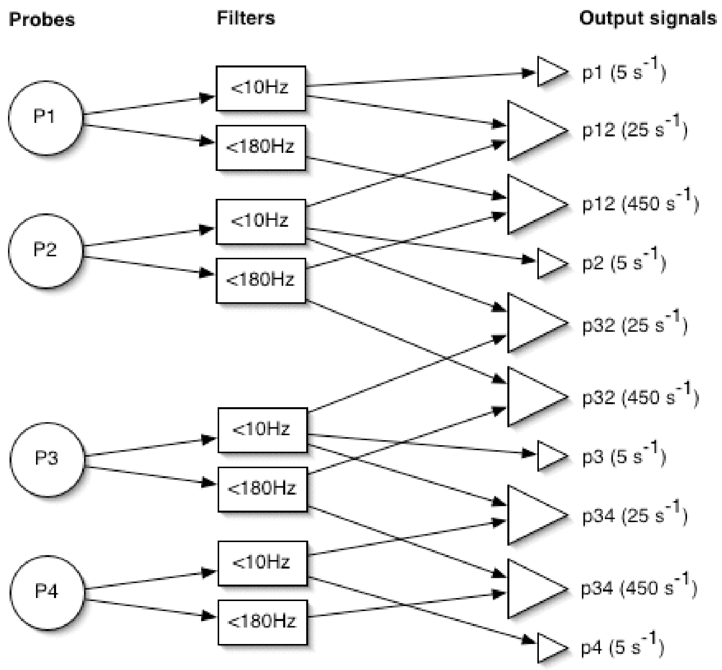

Figure 2. Probes, filters and sampled quantities

3. EFW parameters in the CAA

The EFW data delivered to the CAA are so far only based on the normal real time data. The EFW internal burst data are planned to be delivered to CAA at a later stage and are not presently described here. The overview data resulting from the on-board least squares fits are not delivered to CAA. The EFW parameters available in CAA are summarized the the following table, with a more detailed description following.

Level	Quantity	Sampling rate	Data format	Description
L1	P1	5 s^{-1}	Time_tag P1 (scalar)	Potential probe 1
L1	P2	5 s^{-1}	Time_tag P2 (scalar)	Potential probe 2
L1	P3	5 s^{-1}	Time_tag P3 (scalar)	Potential probe 3
L1	P4	5 s^{-1}	Time_tag P4 (scalar)	Potential probe 4
L1	P12	25 s^{-1} or 450 s^{-1}	Time_tag P12 (scalar)	Pot diff probes 12
L1	P34	25 s^{-1} or 450 s^{-1}	Time_tag P34 (scalar)	Pot diff probes 34
L1	P32	25 s^{-1} or 450 s^{-1}	Time_tag P32 (scalar)	Pot diff probes 32
L2	P	5 s^{-1}	Time_tag Spacecraft_potential (scalar)	Average potential selected probes, full resolution
L2	E	25 s^{-1} or 450 s^{-1}	Time_tag E_Vec_xy_ISR2 (vector)	Electric field, full resolution
L2	EINERT	25 s^{-1} or 450 s^{-1}	Time_tag E_Vec_xy_INERT (vector)	Electric field, full resolution, inertial frame
L3	P	0.25 s^{-1}	Time_tag Spacecraft_potential (scalar)	Average potential selected probes, 4 sec resolution
L3	E	0.25 s^{-1}	Time_Tag E_Vec_xy_ISR2 (vector) E_sigma (scalar)	Electric field and Standard deviation, 4 sec resolution
L3	EGSE	0.25 s^{-1}	Time_Tag E_Vec_xyz_GSE (vector)	Electric field, 4 sec resolution, inertial frame
L3	VGSE	0.25 s^{-1}	Time_Tag V_Vec_xyz_GSE (vector)	Convection velocity, 4 sec resolution, inertial frame

3.1 Level 1 quantities Pi and Pij

The Level 1 quantities are the raw data from the instrument, decommutated and converted to physical units. These data are not intended for the general user, but rather to the expert who wishes to do his/her own detailed analysis based directly on the raw data. The normal user should instead use the Level 2 and Level 3 data.

P1, **P2**, **P3**, **P4** are the potentials of the four individual probes, measured relative to the spacecraft.

P12, **P34** and **P32** are potential differences between pairs of probes. Nominally the instrument measures the potential differences **P12** and **P34**, but after the failure of probe 1 on spacecraft 1, 2 and 3, these spacecraft instead measure **P32** and **P34**.

The Level 1 quantities, together with auxiliary information such as spacecraft spin phase and attitude are the basis for computing the scientific Level 2 and 3 parameters.

3.2 Level 2 quantities P, E and EINERT

The Level 2 quantities are scientific data from the instrument at full time resolution.

P is the average potential of all available probes, measured relative to the spacecraft. If all four probes are available, the average is done over all 4 probes. If only two or three probes are available, the average is done over 2 probes (**P1** and **P2**, or **P3** and **P4**). If only one probe is available, this quantity is the value of that probe. The number of probes used for **P** is given in the Parameter_caveats.

E is the electric field vector (Ex and Ey) in the spin plane, computed using 2, 3 or 4 probes. For a description of the coordinate system, see section 3.4. When 4 probes are available, the computation of Ex and Ey is straightforward. When 3 probes are available, the computation of Ex and Ey is also mathematically straightforward, but the electric field has larger errors since the measured components are not orthogonal. When only 2 probes are available, Ex and Ey contain only the measured component of the electric field along the x and y directions, and will thus have a strong spin modulation.

EINERT is the electric field vector in the spin plane in the inertial reference frame. It is computed from **Level 2 E** by subtracting the spacecraft motion induced electric field **v** x **B**. This computation is done at the CAA.

3.3 Level 3 quantities P, E, EGSE and VGSE

The level 3 quantities are scientific data from the instrument at 4 second time resolution (approximately spin resolution).

P is the average potential of all available probes, measured relative to the spacecraft. It is the time-averaged value of the **Level 2 P**, averaged over 4 seconds (see also section 3.2).

E is the electric field vector (Ex and Ey) in the spin plane, computed from a least-squares fit of a sine wave to one probe pair (**P12** or **P34**) over 4 seconds (approximately one spin). The least-squares fit is normally done on **P34**, if available, otherwise on **P12**. The result is two components of the electric field (Ex and Ey) and a measure of the standard deviation of the raw data points from a sine wave (Sigma).

EGSE is the full 3-dimensional electric field vector in the GSE coordinate system. It is computed from **Level 3 E** by first subtracting the spacecraft motion induced electric field v x B, then computing the third (non-measured axial) component of the electric field using the assumption **E.B** = 0, and finally transforming into the GSE coordinate system. It should be noted that these computations are only done when the magnetic field direction is more than 15 degrees away from the spin plane and | $\mathbf{B_Z}$ | is larger than 2 nT (otherwise the error in the third electric field component becomes too large). This computation is done at the CAA.

VGSE is the plasma convection flow velocity, computed from **Level 3 EGSE** and the magnetic field **B** as **VGSE** = (**EGSE** x **B**) / $\mathbf{B}^2$. This computation requires that **B** is more than 15 degrees away from the spin plane (to compute the full electric field vector) and that the magnitude of **B** is larger than 2 nT (to avoid division by zero). This computation is done at the CAA.

3.4 Coordinate systems

The EFW instrument measures the electric field only in the spacecraft spin plane. The preferred coordinate system for scientific studies involving the electric field is therefore a spin-plane oriented coordinate system. The **ISR2** (Inverted Spin Reference) system, also known as **DSI** (Despun System Inverted), is such a system. The x-axis is in the spin plane and pointing as near sunward as possible. The y-axis is in the spin plane, perpendicular to the sunward direction, positive towards dusk. The z-axis is along the (negative) spacecraft spin axis, positive towards the north ecliptic. [The coordinate system is called "Inverted" because Cluster is actually "inverted" with the spin axis pointing towards the south ecliptic.] The difference between **ISR2** (**DSI**) and the standard **GSE** (Geocentric Solar Ecliptic) is a rotation of between 2 and 7 degrees around the y-axis, which is due to the fact that the spacecraft is slightly tilted so as not to shadow the probes of the EFW instrument.

4. Caveats

Much effort has been spent on calibrating the data and removing spurious effects to give a useful database for scientific analysis. In spite of this, there will be data in the CAA which are not of optimum quality, and this section attempts to describe some of the potential problems in the data. It is important that anyone using the EFW CAA data for scientific analysis be aware of these issues to avoid misinterpretations of the data.

4.1 Caveat 1: Solar wind wakes

The streaming solar wind creates a negatively charged wake behind the spacecraft, in the anti-sunward direction. As the individual probes enter and exit this wake, there is a dip in the probe potential, and thus a spike in the raw data signal twice per spin on each probe pair. In the de-spun electric field data this shows up as a negative spike in the sunward component Ex, four times per spin, once for each probe entering the wake. An algorithm has been developed to correct for these solar wind wakes in the Level 2 electric field data before submission to the CAA [see Eriksson et al., 2008]. While doing a good job, the algorithm is not always perfect, so the problem with solar wind wakes should be kept in mind as soon as spikes at four times per spin period are encountered in the data.

4.2 Caveat 2: Cold ion drift wakes

In the low-density plasma encountered in the tail lobes and above the polar caps, there is often a cold plasma component streaming essentially along the magnetic field lines, outward from Earth. This creates a negative wake on the anti-earthward side of the spacecraft, with similar consequences on the data as the solar wind wake. A difference compared to the solar wind, however, is that the ion drift wake is broader and more diffuse. It is often very hard to detect in the raw data since the effect is very similar to that of a real ambient electric field. The CAA production software attempts to remove all such ion wakes by looking at a combination of parameters, such as spacecraft potential, magnetic field direction, and the relation between different electric field components. At present there is no algorithm to correct the data so the bad data are removed from Level 2 and Level 3 data before submission to CAA. Since it is sometimes difficult to discern between these wakes and a real electric field, analysis of the electric field should be done with caution in regions where cold plasma ion drift occurs. When ASPOC is operating, the spacecraft potential is kept at a much lower value and the problem of wakes due to cold ion drift is much less severe. More information on these wakes can be found in [Eriksson et al., 2006] and [Engwall et al., 2006].

4.3 Caveat 3: Plasmasphere

During comparisons of electric field measurements done by EFW and EDI in the inner magnetosphere, it was found that the EFW data sometimes measures a spurious field of the order of 1-2 mV/m, mostly in the sunward direction. The raw data signal is often non-sinusoidal. The cause of this field is not yet understood, but an empirical algorithm has been developed to detect and remove the bad data. The algorithm uses a comparison between the measured electric field and the expected field if the ambient plasma were to co-rotate with Earth, and is applied only in regions of high density as indicated by the spacecraft potential. Also here, there is no correction applied to the data, but they are removed before submission to CAA. Users studying the electric field in the inner magnetosphere should be aware of this problem, since the removal of data is not always perfect.

4.4 Caveat 4: Whisper operations

The WHISPER instrument regularly emits waves of certain frequencies to detect resonances frequencies in the ambient plasma. These active soundings are seen in the EFW raw data, and are removed automatically by testing for a “sounder active” flag in the telemetry. There are some remaining effects at the start and end edge of the active sounding periods, mainly seen as small spikes in the Level 3 potential data [see CAA-EFW-ICD-0001, appendix 5, for details]. The WHISPER active soundings are done regularly, often at a repetition period of 52 s or 104 s, so they should be easy to separate from real variations in the data.

4.5 Caveat 5: ASPOC operations

The ASPOC instrument attempts to keep the spacecraft potential at a low value, primarily to enable low-energy ion and electron measurements by the particle instruments. In the absence of ASPOC the spacecraft potential often reaches several tens of V in the low-density plasmas encountered by Cluster. With ASPOC operating, the spacecraft potential is brought down to the order of 5-8 V. A positive side-effect of this is that the electric field measurements are most often improved since the wake effects associated with large spacecraft potentials in the polar cap (see section 4.2) are drastically reduced. A newly discovered effect is that with ASPOC on, the sunward offset in the magnetosphere is move variable than with ASCPOC off (see section 5.2). This is not yet understood.

The spacecraft potential is often used as a proxy for ambient plasma density variations (see Pedersen et al., 2008). The data quantity in the CAA is the probe potential measured with respect to the spacecraft potential, which is most often a negative quantity. More negative probe potential <=> more positive spacecraft potential <=> lower ambient plasma density. This works only when ASPOC is off and the spacecraft potential is allowed to float freely. Any use of the spacecraft potential to determine plasma density should take into account whether ASPOC was operating or not. ASPOC is not operational on spacecraft 1.

4.6 Caveat 6: EDI operations

EDI measures the ambient electric field by emitting a beam of electrons and detecting the drift step as the electrons gyrate around the ambient magnetic field. The emitted beam current contributes to increasing the spacecraft potential, particularly in a low density plasma. During some periods in the beginning of the mission, the emitted EDI beam current was larger than expected, in particular on spacecraft 2, so there is a tendency for the spacecraft potential to be larger than on the other spacecraft. Since the spacecraft potential is often used as a proxy for a measurement of the ambient plasma density, this could be misinterpreted as a lower density at spacecraft 2. It also affects the EFW electric field measurements in that there is a larger risk of saturating the measurements, which happens when the spacecraft potential reaches the order of 70 V.

5. Processing details

5.1 Data intervals and data files

The EFW data delivered to CAA are divided into files. There is one file per data product, and one file per time interval. The time intervals are normally 90 minutes in spacecraft nominal mode (the EFW Level 2 data have a time resolution of 25 s^{-1}) and 30 minutes in spacecraft burst mode (the EFW Level 2 data have a time resolution of 450 s^{-1}). A new file is normally started at each 90-minute (or 30-minute) boundary. New files may also be started when there is a change in instrument mode, or after a data gap. Sometimes a file may contain more than 90 minutes (or 30 minutes) if this means avoiding being followed by a short data file.

5.2 Least squares fits and raw data offsets

In the presence of a constant ambient electric field, the raw data signal is a sine wave where the amplitude and phase of the sine wave give the electric field magnitude and direction. Theoretically, the dc level of the raw data should be zero. But small differences between the probe surfaces and in the electronics create a dc offset in the raw data. If uncorrected, this dc offset would show up in the de-spun electric field data as a signal at the spin frequency.

The least-squares fits done on the raw data serve two purposes. Firstly, it gives a measurement of the electric field at the spin resolution, where only one probe pair is necessary. Secondly, it gives a possibility to find the dc raw data offset, which can then be used to correct the raw data before despinning the full resolution electric field. A least-squares fit to the raw data of the form

$$y = A + B \sin(\omega t) + C \cos(\omega t) + D \sin(2\omega t) + E \cos(2\omega t) + \ldots$$

is done once every 4 seconds, and gives the following output:

- The sine and cosine terms, B and C (the electric field)
- The dc offset, A
- The standard deviation of the raw data from the fitted sine wave, σ
- Higher order terms, D, E, ..., may be used for diagnostics of data quality

The electric field (computed from A and B) and the standard deviation σ are directly input to the CAA as **Level 3 E** (see section 3.3). The dc offset, A, is used for processing the Level 2 data. There are small differences in the dc level of the raw data from one spin to another, mainly because of real variations in the electric field Therefore the dc offset is smoothed before using in the Level 2 processing, using a weighted average over 7 spins. See also the description in [CAA-EFW-ICD-0001, appendix 6]. The value of the dc offset used for each spin is not presently available in the CAA data files, but the next version of the Level 3 E files will contain these data, one value per data point.

5.3 Sunward dc offsets and amplitude correction

After despinning, the electric field data (both Level 2 and Level 3) give the electric field as measured by the EFW instrument. This field contains some systematic errors, which need to be corrected for, namely an amplitude correction and dc offset removal.

The spacecraft potential, which is also the potential of the wire booms, extends out to a large distance from the spacecraft. The ambient electric field is thus “short-circuited” by the presence of the spacecraft and wire booms, so the EFW instrument measures only a certain fraction of the real ambient electric field. By simulations and comparisons with other data (mainly CIS), it has been determined that the measured electric field magnitude needs to be multiplied by a factor of 1.1 to get the real electric field (see also CAA-EFW-ICD-0001, appendix 4, and Cully et al., 2007]. The same value is used for all spacecraft and for the entire mission. The amplitude correction is done routinely in the CAA processing.

The spacecraft, wire booms and probes emit photoelectrons, which create a cloud of excess negative charge around the system, mainly on the sunward side. This will be measured by the EFW instrument as a spurious sunward electric field, generally referred to as the sunward dc offset, which needs to be subtracted from the data. The magnitude of this sunward dc offset is determined by comparisons with other instruments, mainly EDI and CIS. The offset varies slowly with time, with plasma region, and is slightly different for the different spacecraft. This offset is removed from the data before delivery to CAA. The value of the offset that have been subtracted from the data are given in the Parameter_caveats in the header of the CEF file.

The photoelectron asymmetry responsible for the sunward dc offset by definition gives an offset in the sunward direction only. However, results of comparisons with other instruments have at times shown a small offset also in the duskward (Ey) direction, which is not yet well understood.

6. References

6.1 Online information

General information on the EFW instrument can be found on the EFW home page at

http://www.cluster.irfu.se

Information on EFW operations, both standard operations and anomalies (including detailed information on commissioning, calibrations, bias settings, internal burst operations and sweep operations), can be found on the EFW operations home page at

http://www.cluster.irfu.se/efw/ops

A chronological table of all non-standard operations and known instrument anomalies is available at

http://www.cluster.irfu.se/efw/ops/ns_ops.html

6.2 Printed information

The EFW instrument description paper is in

Gustafsson, G., R. Boström, B. Holback, G. Holmgren, A. Lundgren, K. Stasiewicz, L. Åhlén, F. S. Mozer, D. Pankow, P. Harvey, P. Berg, R. Ulrich, A. Pedersen, R. Schmidt, A. Butler, A. W. C. Fransen, D. Klinge, M. Thomsen, C.-G. Fälthammar, P.-A. Lindqvist, S. Christenson, J. Holtet, B. Lybekk, T. A. Sten, P. Tanskanen, K. Lappalainen, and J. Wygant, The Electric Field and Wave Experiment for the Cluster Mission, Space Sci. Rev., **79**, 137-156, 1997.

A short overview of the EFW data in CAA can be found in

Lindqvist, P.-A., Y. Khotyaintsev, M. André, and A. I. Eriksson, EFW data in the Cluster Active Archive, in Proc. Cluster and Double Star Symposium – 5th Anniversary of Cluster in Space, Noordwijk, The Netherlands, 19-23 September 2005, **ESA SP-598**, 5 pp., 2006.

The formal document describing the EFW data delivery to CAA is

Lindqvist, P.-A. and Y. Khotyaintsev, Cluster Active Archive: Interface control document for EFW, ESA document CAA-EFW-ICD-0001, Issue 3.1, 47 pp., 7 November 2007.

The latter two documents can be found online under the CAA documentation section at

http://caa.estec.esa.int/caa/instr_doc.xml

A description of the solar wind wakes and their removal is found in

Eriksson, A. I., Y. Khotyaintsev, and P.-A. Lindqvist, Spacecraft wakes in the solar wind, in Proc. 10th Spacecraft Charging Technology Conference (SCTC-10), Biarritz, France, 18-21 June 2007, available as http://space.irfu.se/aie/publ/Eriksson2007b.pdf.

A descriprion of the characteristics of polar wind wakes is found in

A. I. Eriksson, M. André, B. Klecker, H. Laakso, P.-A. Lindqvist, F. Mozer, G. Paschmann, A. Pedersen, J. Quinn, R. Torbert, K. Torkar, and H. Vaith, Electric field measurements on Cluster: comparing the double-probe and electron drift techniques, Ann. Geophysicae, **24**, 275-289, SRef: 1432-0576/ag/2006-24-275, 2006,

with detailed simulations presented by

E. Engwall, A. I. Eriksson and J. Forest, Wake formation behind positively charged spacecraft in flowing tenuous plasmas, Phys. Plasmas, **13**, 062904, doi: 10.1063/1.2199207, 2006.

An overview of how the spacecraft potential is used to determine plasma density is found in

Pedersen, A., B. Lybekk, M. André, A. Eriksson, A. Masson, F. S. Mozer, P.-A. Lindqvist, P. M. E. Décréau, I. Dandouras, J.-A. Sauvaud, A. Fazakerley, M. Taylor, G. Paschmann, K. R. Svenes, K. Torkar, and E. Whipple, Electron density estimations derived from spacecraft potential measurements on Cluster in tenuous plasma regions, J. Geophys. Res., **113**, A07S33, doi: 10.1029/2007JA012636, 2008.

The results of simulations of the electrostatic potential around the spacecraft and how the electric field measurements are affected may be found in

Cully C. M., R. E. Ergun, and A. I. Eriksson, Electrostatic structure around spacecraft in tenuous plasmas, J. Geophys. Res., **112**, A09211, doi:10.1029/2007JA012269, 2007.