MMS-SMART Science Data Products Guide: SCM

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1. Introduction

- The tri-axial search-coil magnetometer (SCM) with its associated preamplifier provides the three-dimensional measurement of the magnetic field fluctuations. The analog magnetic waveforms measured by the SCM are digitized and processed inside the digital signal processor (DSP) together with the electric field data provided by the spin-plane double probe (SDP) and the axial double probe (ADP). Both magnetic and electric field data are collected and stored by the central instrument data processor (CIDP) via the Fields central electronics box (CEB). Magnetic waveforms and spectra are available at different time resolution depending on the selected mode. The SCM waveform is sampled at 32 samples per second (S/s) in the survey mode[1], 8192 S/s in the burst mode and finally 16384 S/s in the high-speed burst mode. Onboard Fourier spectra computed by DSP are available from 0.2 Hz to 6 kHz with a time resolution of 16 s in slow survey, 2 s in fast survey. Finally the SCM calibration is checked at least once per orbit thanks to the onboard calibration signal provided by DSP and the SCM sensor temperature is measured by a thermistance (housekeeping data).

2. Instrumentation

- **Overview**

  The tri-axial search-coil magnetometer (SCM) provides the three components of the magnetic field fluctuations. The SCM consists of a tri-axial set of magnetic sensors with its associated preamplifier box. The SCM sensor is mounted on the same five meter boom as the analog flux-gate magnetometer (AFG), 4 meters from the spacecraft and 1 meter from AFG. The SCM preamplifier box is mounted on the spacecraft deck (outside of the central electronics box) near the base of the AFG/SCM magnetometer boom. The SCM preamplifier is connected to the digital signal processor (DSP) which digitizes and processes the three analog waveforms delivered by SCM. Once per orbit, the DSP injects to SCM a calibration signal. A thermistance mounted on the SCM structure provides the temperature of the SCM sensor (housekeeping).

- **Science background**

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[1] SCM waveforms are sampled at the same sample rate (32 S/s) for both slow and fast survey modes and stored in the same survey CDF file.

Electromagnetic waves are thought to play a key role in the fast processes of magnetic reconfiguration. Indeed, the magnetospheric plasma being collisionless at all scales, magneto-hydrodynamics models using a finite resistivity based on collisions between particles cannot be applied. Recent studies have shown that the collisionless magnetic reconnection can occur via the formation of two diffusion regions related to the scale where ions and electrons decouple from the magnetic field respectively. In particular, in the electron diffusion region, the acceleration and the heating of particles are thought to be strongly related to the wave activity (whistler waves, kinetic alfvén waves, lower hydrid waves, …). Other models addressing current driven instabilities as the cause of the fast magnetic field reconfiguration are strongly related to the generation of magnetic fluctuations with fastly growing amplitudes. Finally, coherent electromagnetic structures at the scale of the electron Larmor radius or down to few Debye lengths have been already detected in regions of acceleration and could play an important role in the acceleration and heating of electrons. In this context, it is crucial to be able to identify the nature of the observed waves (electrostatic or electromagnetic, frequency, polarization, direction of propagation, intensity, …). Finally as the four MMS satellites will be required to fly in a tetrahedral formation, it will be possible from the SCM waveforms to estimate the wave vector for a fixed frequency (k-filtering analysis) provided that the distance between these spacecraft is less than the wavelength to be measured.

- **Level-2 science requirements**

The SCM provides the three components of the magnetic fluctuations in the 1 Hz – 6 kHz nominal frequency range. The noise equivalent magnetic induction (NEMI or sensitivity) of the search-coil antenna is less than or equal to: 2 pT/sqrt(Hz) at 10 Hz, 0.3 pT/sqrt(Hz) at 100 Hz and 0.05 pT/sqrt(Hz) at 1 kHz. The SCM resolution at 1k Hz is 0.15pT.

- **Instrument characteristics**

The SCM sensor is constituted by three magnetic sensors mounted in a tri-axial structure. This structure is designed to ensure a precise alignment of the sensors with respect to the satellite axis. The orthogonality of the three mechanical axis of this structure is better or equal to 0.05 degree in order to satisfy the final +/- 1° required between SCM and spacecraft axis. Yet, it has been detected that the torque applied on the screws fixing each sensor on the SCM structure lead to a slight error of alignment. This error has been measured on each axis for each flight model (measured on FM2 to FM4, extrapolated for FM1) and used to build a correction matrix for each FM. This matrix could be used if needed in the SCM calibration program (see data products section).

The magnetic sensor consists of an optimized machined ferrite (ferromagnetic material with a high magnetic permeability) core of 10 cm length and 4 mm of diameter in order to amplify the external magnetic field. Then a primary winding with a large number of turns (more than ten thousands) is added to collect the voltage induced by the time variation of the magnetic flux. Finally a secondary winding with a smaller number of turns provides a flux feedback to flatten the frequency response of the antenna gain. This feedback circuit allows removing the resonance behavior associated with the primary winding and makes the response of the antenna smoother in phase and independent of temperature variations.

Internal electrostatic shielding is implemented around each antenna to minimize their sensitivity to electric fields. This electrostatic shielding is also reinforced by the multi-layer insulation (MLI) or thermal blanket added to ensure the thermal isolation of the sensors.

The three analog signals are routed to the SCM preamplifier via the SCM harness equipped by a silver-plated copper conductive shield braid. SCM preamplifier designed at LPP has been realized in multi-chip vertical technology (hydrid) by the French 3D+ company. It has two stages of amplification. The first stage has a low-noise input and a gain of 46 dB. The second stage has a gain of 31.5 dB and ensures low and high-pass filterings. A power supply regulation is also implemented as well as a calibration buffer in order to receive the onboard calibration signal provided by DSP.

The calibration signal is digitally synthesized by the DSP FPGA and filtered using a low pass filter to smooth the signal. It is applied to the feedback winding of the search coil. It consists of a sweeping sine wave with a frequency that doubles every 4 cycles from 0.125 Hz to 4096 Hz and then stops. This signal is analyzed to estimate any possible modifications of the SCM transfer function during the mission.

- **Limitations and operations**

Previous magnetospheric missions had usually a shorter spin period (few sec) than MMS (20 sec). As a consequence, the search-coil magnetometers used to get saturated around the perigee due to the strong spin modulation associated with the static Earth's magnetic field components. The SCM gain at the MMS spin frequency (50 mHz) is low due to the analogical high-pass filtering (inside SCM PA) around 0.1Hz. Therefore SCM is not saturated by the spin modulation which allows estimating two components of the DC magnetic field perpendicular to the spin axis along the orbit. However, SCM could be saturated by high frequency waves (500-1kHz) with amplitudes larger than 6 nT peak to peak.

Furthermore, remind that once or twice per orbit, in-flight calibration signal will be injected into the secondary winding of SCM in order to check the SCM transfer function. The whole sequence lasts about 90 sec and does not allow measuring the natural signal. That is why they are removed from survey data files leading to data gaps.

- **Heritage**

Similar SCM have been previously flown by LPP (or formerly CETP) on many earth-orbiting (GEOS-2, Cluster/STAFF, THEMIS/SCM) and interplanetary (Galileo, Cassini) missions. Multi-chip vertical technology has been already used for SCM preamplifier on THEMIS probes. MMS like search-coil have been also provided by LPP to equip the future Magnetospheric Mercury orbiter of the ESA/JAXA BepiColombo mission.

3. Data Products

- **Overview**

Descriptions of Quicklook products

Onboard FFT spectrograms from DSP corresponding to the square of magnitude (omni variable) given in nT^2/Hz are available at SDC website as PNG quicklook files.

Descriptions of Level-2 products

Waveforms: SCM data are Bx, By and Bz components of the AC magnetic field given in physical units (nT) in GSE frame.

Onboard FFT spectrograms available in fast and slow survey modes from DSP: x, y and z components (in the sensor frame SCM123 see below for definition) as well as the square of magnitude (omni variable) given in nT^2/Hz.

- **Algorithms**

Description

The raw signal in telemetry units is converted in Volts. Then Volts must be calibrated to physical units (nT). Each antenna response is characterized by its own transfer function, giving the ratio V/nT and phase for a given frequency. These functions not being linear in frequency, a dedicated process must be applied to calibrate the raw waveforms.

Basically two methods of calibration exist:

(1) Perform the Fourier Transformation (FT) of the signal, on a given time period, then divide by the complex transfer function to take into account amplitude correction and phase shift; note that one has to fix a lower cut off frequency Fc as the transfer function goes to zero at null frequency. Finally perform an inverse FT to get the calibrated signal in the time domain.

(2) Deconvolve the instrument impulse response from the signal in the time domain.

The second method is implemented in the SCM calibration routine taking benefit from THEMIS heritage (while the first one has been used for the Cluster data). This method permits us to use optimized IDL convolution routines and gives better results in terms of computing time. The convolution is performed using a sliding window in order to provide a continuous calibration process. Calibration of a SCM mounted onboard a spinning spacecraft requires additional steps compared with laboratory calibration. Indeed the components of the DC magnetic field perpendicular to the spin axis are measured as a sinusoid with large amplitudes at the spin frequency Fspin. Since this DC field can be more than 100 times larger than the wave amplitude (~1 nT), in general it has to be removed from the raw signal before calibration to avoid undesirable effects. Furthermore the spinning motion at Fspin introduces a Doppler shift: a circular wave at frequency Fl turning in the opposite direction of the satellite is measured by the sensor as a wave at frequency Fl + Fspin whereas a wave turning in the same direction at Fr is measured as a wave at frequency Fr- Fspin. Therefore sensors mounted onboard a spinning spacecraft are not able to fully restitute spin-plane fluctuations with frequency around the spin frequency. Indeed any circular waves turning in the same direction as the spin rotation are not detected because their apparent frequency becomes null. This also means that the sensitivity of the experiment at low frequency depends on the polarization of the waves with respect to the spin axis. However, the MMS spin frequency being quite low (0.05 Hz), the SCM nominal frequency band (1Hz-6kHz) is not much affected by this effect.

We distinguish a few different steps in the SCM calibration process and refer to different coordinate systems as defined in the MMS and Fields document (Magnetometer Coordinate Systems.doc and MMS project alignment and coordinate system document 461-SYS-SPEC-0115B.pdf).

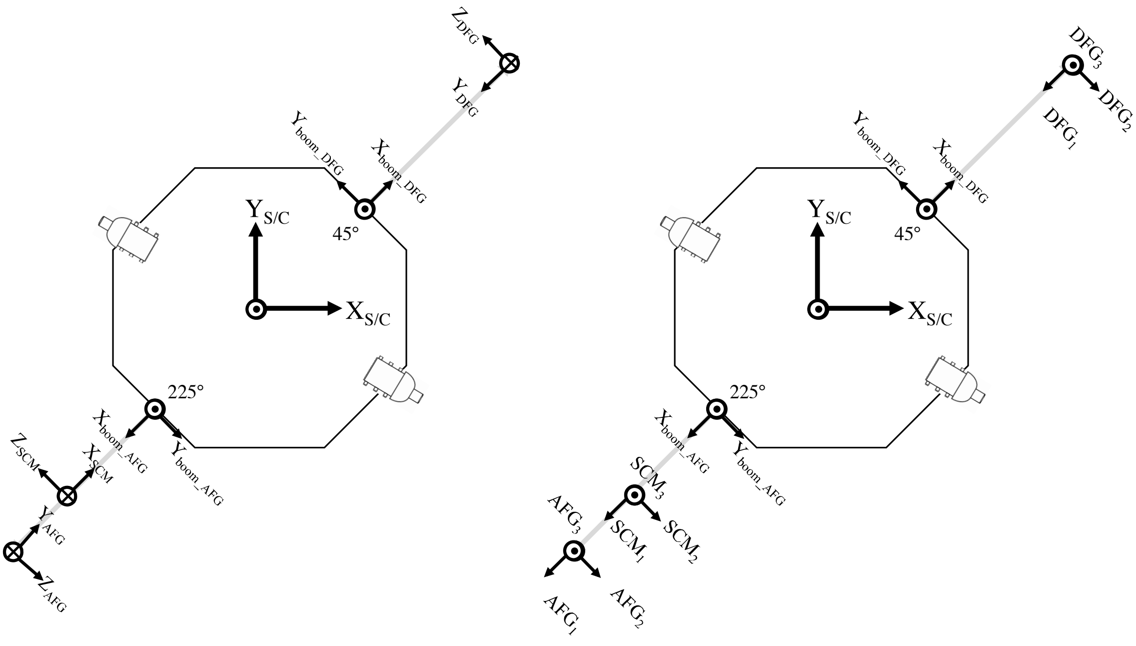

Figure 1: Nominal orientations of magnetometers with respect to the spacecraft, as represented in AFG/DFG/SCM XYZ coordinates (left) versus AFG/DFG/SCM Sensor Axis 1,2,3 coordinates (right).

step 0: waveform in counts unit, spinning SCM sensor system (SCM123)

Waveform is divided in gap-free batches at same sample rate. This step corresponds to raw data expressed in telemetry units.

NB: SCM data in this stage correspond to level 1A (L1A) SCM data.

For each gap-free batch, step 1 to 6 can be applied.

step 1: waveform in Volts, spinning SCM sensor system (SCM123)

The conversion factor from telemetry units to volts is applied to the data but the spin modulation is still present.

step 2: waveform in nT, spinning SCM sensor system (SCM123)

This step provides calibrated SCM data. Note that data are still in a spinning frame associated with the sensor coordinate system (SCM123).

The calibrated SCM data are obtained by the convolution of the uncalibrated data with the inverse Fourier transformation of the inverse of the SCM transfer function ($FT^{-1}[1/h(f)]$, h(f) being the SCM transfer function). SCM transfer functions for each MMS observatory are stored as a file provided by the LPP team. As for the Fourier method, a cut off frequency Fcut is fixed in order that 1/h(f) be well defined as h(f) goes to 0 as F goes to 0. Default values are 0.03 Hz for survey data and 0.5 Hz for burst and high speed burst data. Filtering responses which are needed to reduce the sample frequency (from 16384 S/s to 32 S/s in survey mode or 8192 S/s in burst mode) are taken into account at this stage as well as the analog low-pass filter (Bessel of 5th order at 6.5 kHz) of the DSP.

Then the convolution is performed using a kernel with a number of points fixed by the nk keyword. This routine is based on convol.pro routine from IDL package. The choice of the value of nk involves a trade-off between quality of the low-frequency calibration and data processing speed. Actually, Fcut being set, nk is computed for a given sample frequency in order to satisfy the following condition which ensures that the frequency resolution is accurate to calibrate the lowest frequency:

$\Delta f/fmin = \Delta f/Fcut = (1/T)/Fcut = 0.5 < 1$, where $T = nk/Fs$ is the duration of the sliding window and Fs is the sampling frequency. So for a given Fcut, nk has to be at least equal to the lowest power of 2 greater than 2*Fs/Fcut.

By default, an optimal value is chosen for each of the data modes, as a multiple of the sample frequency.

For survey mode (scsrvy mode with Fs=32 S/s nominally), nk=64*Fs.

For burst mode (scb mode with Fs=8192 S/s nominally) and high burst mode (schb mode with Fs=16384S/s nominally), nk=4*Fs.

Finally, a specific treatment is required at edges of each continuous waveform period (gap-free batches tagged in step 0). Indeed as the number of points becomes smaller than the size of the sliding window, different options can be selected in order to calibrate the beginning and the end (corresponding to nk/2 length) of the batch. By default, these edges for SCM L2 data are set to 0.

NB: SCM data in this stage correspond to level 1B (L1B) SCM data.

Table 1: Default calibration parameters for SCM L1B data in SCM123 frame.

SCM Modes	Fs (nominal, S/s)	Fcut (Hz)	nk	Edge option
Survey scsrvy	32	0.03	2048	mirror
Burst scb	8192	0.5	32768	mirror
High-speed burst schb	16384	16	65536	mirror

step 3: waveform in nT, in a fixed despun system (GSE)

Data are now calibrated and are projected to a fixed geophysics frame common to all instruments (GSE). An interpolated spin phase is used (the same for all magnetometers), which is calculated from the derived sun pulse data as well as common attitudes and ephemeris data from FDOA files. Please note that a high-pass filtering (F>Fmin) is also performed in order to remove any remnants of spin tone modulation.

NB: SCM data in this stage correspond to level 2 (L2) SCM data.

Table 2: Default calibration parameters for SCM L2 data in GSE frame.

SCM Modes	Fs (nominal, S/s)	Fcut (Hz)	nk	Fmin (Hz)	Egde option
Survey scsrvy	32	0.03	2048	0.5	zero
Burst scb	8192	0.5	32768	1.	zero
High-speed burst schb	16384	16	65536	32	zero

Error analysis
Error on measurements (nT)
Numerical precision

Constraints, limitations, assumptions
Calibration method: the kernel size choice leads to a fixed resolution (see above)
Windowing on the kernel (Hanning, etc)
Filters
Edge of finite time period
Data gap handling: continuous data block too short (<kernel size) leads to missing calibrated data.

- **Science parameters**

Survey data:

Survey data are measured all along the orbit and are downlinked with 32 S/s.

mms#_scm_srvy_l2_scsrvy_startTime_v0.0.0.cdf: SCM waveform in nT units during survey mode and in GSE

Variable name	Type	Dimension	Labels	Unit
Epoch	CDF_TIME_ TT2000	0:[]	TT2000	nanoseconds
mms#_scm_acb_gse_scsrvy_srvy_l2	CDF_REAL 4	1:[3]	Bx GSE, By GSE, Bz GSE	nT
mms#_scm_qf_scm123_scsrvy_srvy_l2	CDF_CHAR	0:[]		none

Burst and high-speed burst data:

Burst data are measured inside the region of interest at specific times at 8192 S/s.

mms#_scm_brst_l2_scb_startTime_v0.0.0.cdf : SCM waveform in nT units during burst mode and in GSE

Variable name	Type	Dimension	Labels	Unit
Epoch	CDF_TIME _TT2000	0:[]	TT2000	nanoseconds
mms#_scm_acb_gse_scb_brst_l2	CDF_REAL	1:[3]	Bx GSE,	nT

	4		By GSE, Bz GSE	
mms#_scm_qf_scm123_scb_brst_l2	CDF_CHAR	0:[]		none

Furthermore high-speed burst mode data are also measured inside ROI at 16384 S/s.

mms#_scm_brst_l2_schb_startTime_v0.0.0.cdf : SCM waveform in nT units during high-speed burst mode and in GSE

Variable name	Type	Dimension	Labels	Unit
Epoch	CDF_TIME _TT2000	0:[]	TT2000	nanoseconds
mms#_scm_acb_gse_schb_brst_l2	CDF_REAL 4	1:[3]	Bx GSE, By GSE, Bz GSE	nT
mms#_scm_qf_scm123_schb_brst_l2	CDF_CHAR	0:[]		none

The acquisition of Burst and High-Speed Burst data is triggered thanks to the Burst Trigger Scheme (see BADCO document).

- **Validation**

Confidence in measurements

SCM transfer functions have been measured at the National Magnetic observatory of Chambon-la-forêt without their thermal blanket. The gain (resp. phase) differences at 1 kHz between different antennas of the same tri-axis are less than 0.1 dBV/nT (resp. 1.5°) and between antennas of different tri-axis are less than 0.3 dBV/nT (resp. 1.5°). Also, it has been checked that the gain (resp. phase) differences with and without a thermal blanket are no larger than 0.1 dBV/nT in gain (resp. 1°).

Comparison of other measurements

- Cross-calibrations (DFG, AFG) based on spin modulation @20s, 2 components in the spin plane.
- Cross-calibrations (DFG, AFG) based on common frequency range (0.1-4Hz: slow survey, 0.1-8Hz: fast survey, burst 0.1-32 Hz), 3 components.

From first comparisons, SCM gains have been found to be lower than DFG/AFG gains by about 10% and some slight misalignments (~0.5°) have been estimated. These corrections have to be confirmed and will be included in the next CDF version of SCM L2 data.

- Tests of synchronization with electric field waveform (SDP-ADP).

Validation of data against models

N/A

Quality control and diagnostics

1) A quality factor is given for each data point. This is a string of 3 characters where each letter refers to one SCM physical antenna in the SCM123 order (see Figure 1):

- 'G' : good data. Only these data points can be used for scientific analysis
- 'Z': data that are affected (L1B) or set to zero (L2) by convolution boundary effect,
- 'S' : saturated data (equal to VALIDMIN or VALIDMAX)
- 'X' : out of range data (<VALIDMIN or > VALIDMAX)
- 'B' : fillvalue/bad data (Not a Number : NaN)

2) Verification of transfer function, once per orbit using onboard calibration signal

The SCM calibration is executed at least once per orbit.The calibration signal sweep is broken into 4 segments with increasing sample frequencies and the whole calibration sequence lasts less than 90 sec. The frequency of the calibration signal doubles every 4 cycles from 0.125 Hz to 4096 Hz. Each segment will consist of four different frequencies as shown in the table.

Duration (Seconds)	**64**	**4**	**.3125**	**.078125**
Cal Signal Frequencies (Hz)	**.125** **.25** **.5** **1**	**2** **4** **8** **16**	**32** **64** **128** **256**	**512** **1024** **2048** **4096**
Sampling Rate (Samples/Second)	**16**	**256**	**4096**	**16384**

The SCM transfer function verification loop will

1. estimate the output amplitude for each frequency (using 4 cycles)
2. compute the 16 ratios (from 0.125 to 4096 Hz) between input and output signals and detect possible phase delay

3. compare gain and phase with the previous calibration transfer function values (first files being transfer functions measured at laboratory)
4. update if needed the SCM transfer function by generating a new SCM transfer function with corrected gain and phase for the corresponding frequency.

- **Caveats**

  For existing caveats see the 'CAVEATS' global parameter in each data file.

- **Data analysis and visualization - suggested techniques**

What to look for in the data

Period of intense wave activity / frequency range

- Onboard FFT spectrograms FFT and spectrograms of the waveform (nT^2/Hz)
- Integrated power (nT^2)

Wave polarization

- Projection in the Magnetic Field Aligned coordinate system (MFA)
- Polarization analysis (Samson or Means methods)

Direction of wave propagation

- Poynting vector calculation (Fourier and time domains)

Coherent structures

- B and E waveforms

Description of needs for each data product

DC magnetic field data are required for MFA projection

Electric field measurements required for Poynting vector calculation and coherent structure studies.

Description of what will be provided

Updated relevant routines from the THEMIS software package SPEDAS (IDL) will allow "on the fly" calibration of SCM waveform L1a data.