EM Induction from Space:  
The Swarm Satellite Constellation Mission and its Data Products

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\section*{Summary}

Determination of the electrical conductivity of the mantle and lithosphere using electromagnetic sounding is one of the scientific research objectives of the Swarm satellite constellation mission. After almost five years in orbit, high-precision magnetic field observations taken by the three \textit{Swarm} satellites resulted in improved global 1D (radially symmetric) conductivity models in the depth range down to 1600 km.

This talk will present the \textit{Swarm} satellite trio, its magnetic data products relevant for induction studies, and examples of their use for estimating conductivity-depth profiles.

\textbf{Keywords:} Geomagnetic Depth Sounding, Satellites, Mantle conductivity

\section*{Introduction}

Determination of mantle conductivity using magnetic satellite data has recently attracted increasing interest, thanks to the availability of high-precision magnetic measurements taken by low-earth-orbiting (LEO) satellites. An overview of the situation 20 years ago was given at the 14th EM Induction Workshop in Sinaia/Romania (Olsen, 1999). Since then much more high-precision magnetic satellites have collected more and more data, by the Danish Ørsted satellite (1998 – 2014), The German CHAMP satellite (2000 – 2010), and more recently by the \textit{Swarm} satellite trio. Kuvshinov (2012) gives a recent overview of how magnetic observations taken by satellites can be used for induction studies.

\section*{The Swarm Satellite Trio}

\textit{Swarm}, a satellite constellation mission comprising three identical spacecraft, was launched on 22 November 2013. Two of the \textit{Swarm} satellites, \textit{Swarm Alpha} and \textit{Swarm Charlie} are flying almost side-by-side in near-polar orbits of inclination $87.4^\circ$ at an altitude of about 455 km (in July 2018) above a mean radius of $a = 6371.2$ km. The East-West separation of their orbits is $1.4^\circ$ in longitude, corresponding to 155 km at the equator. The third satellite, \textit{Swarm Bravo} flies at a slightly higher (about 520 km altitude in July 2018) orbit of inclination $88^\circ$.

\begin{figure}[h]
  \centering
  \includegraphics[width=\textwidth]{swarm_satellites}
  \caption{The \textit{Swarm} satellite trio and its orbital configuration}
  \label{fig:swarm_satellites}
\end{figure}
Each of the three satellites carry an **Absolute Scalar Magnetometer (ASM)** measuring Earth’s magnetic field intensity, a **Vector Fluxgate Magnetometer (VFM)** measuring the magnetic vector components, and a three-head **Star TRacker (STR)** mounted close to the VFM to obtain the attitude needed to transform the vector measurements of the VFM magnetometer to a known coordinate frame. Time and position are obtained by on-board GPS.

**Figure 2:** Configuration of the various scientific instruments on board each of the three *Swarm* satellites (ESA/AOES Medialab)

### Swarm Data Products

For electromagnetic induction studies relevant *Swarm* data products include

- **MAGx_LR** 1 Hz calibrated and corrected magnetic vector and scalar measurements, interpolated to UTC seconds and provided in the North-East-Center coordinate frame for each of the three *Swarm* satellites;

- **MMA_SHA_2** Time series of Spherical harmonic model coefficients of the large-scale magnetospheric field and its Earth-induced counterpart. This product is determined by combing *Swarm*-satellite and ground observatory data;

- **MTI_SHA_2** Spherical harmonic expansion coefficients of the magnetic effect of the oceanic lunar $M_2$-tide.

A description of the *Swarm* data products can be found in Olsen et al (2013) and at [http://earth.esa.int/swarm](http://earth.esa.int/swarm) where also further information on how to obtain the data are given. All *Swarm* data products are freely available to everybody.

**As part of the preparation for the Swarm satellite mission a number of sophisticated and state-of-the-art 3-D inversion schemes have been developed and thoroughly tested, in order to properly process, analyse and interpret the *Swarm* magnetic observations Püthe and Kuvshinov (2013a,b); Velímský (2013); Püthe and Kuvshinov (2014).**

Examples of studies that directly use time series of *Swarm* magnetic vector field observations to determine mantle conductivity include the work by Civet et al (2015) and Martinec et al (2018).

An example of using derived *Swarm* data products like time series of spherical harmonic expansion coefficients of the magnetospheric and induced field for estimating mantle conductivity is the work presented by Püthe et al (2015).

A joint analysis of the magnetic tidal signal of the oceanic $M_2$ lunar tide in combination with time series of the large-scale magnetospheric and Earth-induced contributions has been performed by Grayver et al (2017) to determine the conductivity of the lithosphere and mantle at depths down to 1600 km. This novel approach combines advantages of the EM induction method (which is sensitive to conductive structures) with that of a geoelectric sounding (which is more sensitive to resistive structures).

Fig. 3 shows an example for a conductivity-depth profile determined from such a combination of satellite-derived data (Grayver et al, 2017).

See also the presentation by Grayver et al. “*Swarm* in global EM induction studies”, to be given at this EM workshop.


