Chapter 1
Introduction

Malcolm Wray Dunlop and Hermann Lühr

Abstract Two volumes, ISSI Scientific Reports, SR-001: Analysis Methods for Multi-Spacecraft Data and SR-008: Multi-Spacecraft Analysis Methods revisited, were published to document the growing toolset using the multi-spacecraft dataset being collected by Cluster.

Two volumes, ISSI Scientific Reports, SR-001: Analysis Methods for Multi-Spacecraft Data and SR-008: Multi-Spacecraft Analysis Methods revisited, were published to document the growing toolset using the multi-spacecraft dataset being collected by Cluster. Cluster was the first phased, multi-spacecraft mission, currently in its 19th year of full science operations, to maintain a close configuration of four spacecraft, evolving around an orbit covering many mid- to outer magnetospheric regions. Such a configuration allowed the estimation of plasma and field gradients, as well as wave vector determinations for the first time. A range of spatial scales were accessed through a sequence of orbital manoeuvres, predominantly from meso- to large scale spacecraft separation distances. Although covering a vast array of science targets, Cluster did not cover the small (sub-ion) spatial scales and did not access the low-Earth orbit (LEO) altitudes suitable for the upper ionosphere.

Since Cluster the Magnetospheric Multi-Scale (MMS) mission has now taken four spacecraft measurements on spatial separation scales of tens of kilometers, but still in equatorial orbits reaching the outer magnetosphere and solar wind. Swarm is the first multi-spacecraft, LEO mission, comprising 3 spacecraft in polar circular orbits at altitudes of 460 km and 510 km. Two Swarm spacecraft have maintained approximately east-west separations of 1.4° in longitude, corresponding to distances of typically 50 km in the high latitude regions, while the third has drifted relative to the other two in local time. Swarm established full science operations in April 2014

M. W. Dunlop (✉)
School of Space and Environment, Beihang University, Beijing 100191, P.R. China
e-mail: malcolm.dunlop@stfc.ac.uk

RAL Space, Rutherford Appleton Laboratory, STFC-UKRI, Chilton, UK

H. Lühr
GFZ-German Research Centre for Geosciences, Potsdam, Germany

M. W. Dunlop and H. Lühr (eds.), *Ionospheric Multi-Spacecraft Analysis Tools*, ISSI Scientific Report Series 17,
https://doi.org/10.1007/978-3-030-26732-2_1

and has been operating nominally since. Together with Swarm, other spacecraft arrays have been achieved at low orbit, such as the AMPERE experiment of the Iridium spacecraft array. The Iridium array comprises 66 active satellites in a set of crossing polar orbits covering all local times. These new measurements have allowed both local gradients and global currents to be mapped routinely, and a new set of methodology has arisen as a result.

The present volume (Multi-Satellite Data Analysis: Approaches for Deriving Ionospheric Parameters) documents a set of methods, modelling and analysis suitable for the low altitude (ionospheric) regions. It describes a range of approaches, from the gradient calculation for current density, to new global modelling of the geomagnetic field, through techniques for polar cap mapping.

We have organized the book by grouping chapters with common themes and start with two chapters on Olaf Amm's Spherical Elementary Current Systems (SECS) approach (see Preface). Following this, Chaps. 4–8 deal with field-aligned current (FAC) estimates; Chaps. 9 and 10 describe approaches for combining observations from different sources for deriving continuous maps for physical quantities, and Chaps. 11 and 12 are examples of Swarm constellation applications for deriving current or field distributions. During the late stages of this Working Group, ESA's Swarm project management set up a workshop as part of its Swarm DISC (Data, Innovation and Science Cluster) activity to assess the various field-aligned current estimating methods: Methodology Inter-Comparison Exercise (MICE), and this provided some form of rating of the various approaches. We have therefore included in Chap. 8 a summary of this exercise.

Chapter 2: Introduction to Spherical Elementary Current Systems is a review of the basic SECS method, covering its various applications to the study of ionospheric current systems, identified by both ground-based and satellite observations. The chapter concentrates on the general approach, starting with a review of ionospheric electrodynamics and a definition of the elementary current systems. The 1-D SECS approach is outlined. The details of its application to the Swarm electric and magnetic field data are left to Chap. 3: Spherical Elementary Current Systems applied to Swarm data; in particular describing the two dimensional (in latitude and longitude) maps of the ionospheric FACs and horizontal currents which surround the satellite path. Similarly the electric field and conductance can be obtained when data is available.

Chapter 4: Local least squares analysis of auroral currents, probes the first methodology into the form of structures using multi-spacecraft constellation data and highlights the technique for the two and three spacecraft data of Swarm. The chapter also discusses techniques for the geometrical characterization of auroral current structures with observations under stationary or weakly time dependent conditions.

Chapter 5: Multi-spacecraft current estimates at Swarm, applies the older, established Curlometer technique, which has been previously used with the four-spacecraft constellation data of Cluster over the past two decades. The Curlometer directly estimates the current density from the curl of the magnetic field and this chapter focusses on the extension and application of the technique to the two and three spacecraft Swarm data. The chapter also reviews examples of the coordination of signals seen simultaneously between Cluster and Swarm and the application of the method to in situ estimates of current density in the Earth's ring current using other magnetospheric satellite data.

Chapter 6: Applying the dual-spacecraft approach to the Swarm constellation for deriving radial current density, reviews the standardized method, derived from the basic Curlometer concept, which is adopted by ESA for production of the Swarm Level 2 FAC products. As well as describing this method and possible errors, special emphasis is placed on the underlying assumptions and limitations on the approach, which include features associated with plasma instabilities and disturbances. The applicability of the method in different regions, depending on orbital constraints on the one hand and scale sizes on the other is discussed.

Chapter 7: Science data products for AMPERE, describes a methodology to analyze the magnetic field data measured by the global spacecraft array which is based on an orthogonal basis function expansion and associated data fitting. The AMPERE experiment uses magnetic field data from the attitude control system of the Iridium satellites and estimates data products based on the theory of magnetic fields and currents on spherical shells. The chapter discusses the application of the spherical cap harmonic basis and elementary current system methods to generate the AMPERE science data products.

Chapter 8: ESA Field Aligned Currents—Methodology Inter-Comparison Exercise, summarizes the MICE activity referred to above. The activity explored the possible evolution for the Swarm Level 2 FAC products by inter-comparing a number of different approaches on a test data base of Swarm auroral crossings. The chapter here describes the different strengths and assumptions in each method and outlines possible future activities. The known caveats on use of the methods are discussed in terms of the expected properties and scales of FACs.

Chapter 9: Spherical Cap Harmonic Analysis techniques for mapping high-latitude ionospheric plasma flow—Application to the Swarm satellite mission, introduces and describes a tool for mapping a variety of one, two, and three-dimensional parameters. The chapter outlines the theoretical basis through a discussion of the spherical cap coordinate system. The boundary conditions and basis-functions are discussed and practical considerations are summarized. The application of SCHA to the mapping of ionospheric plasma flow using a ground-based data set is also given and two-dimensional SCHA is shown applied to the mapping of Swarm ion drift measurements, as well as in conjunction with measurements from other instruments.

Chapter 10: Recent Progress on Inverse and Data Assimilation Procedure for High-Latitude Ionospheric Electrodynamics, discusses the development of this technique with an emphasis on the historical inversion of ground-based magnetometer observations. The method provides a way to obtain complete maps of high-latitude ionospheric electrodynamics; overcoming the limitations of a given geospace monitoring system. The chapter outlines recent technical progress, which is motivated by recent increase in availability of regular monitoring of high-latitude electrodynamics by space-borne instruments. The method description includes state variable representation by polar-cap spherical harmonics, where coefficients are estimated in the Bayesian inferential framework. Applications to SuperDARN plasma drift data, AMPERE measurements and DMSP magnetic field and auroral particle precipitation data are covered.

Chapter 11: Estimating currents and electric fields at low-latitudes from satellite magnetic measurements, presents techniques developed for processing magnetic measurements of the equatorial electrojet (EEJ) current to extract information about the low-latitude currents and their driving electric fields. The chapter presents a multiple line current approach to recover the EEJ current density distribution and emphasises the issues relating to the cleanliness of the satellite data and the minimization of the magnetic fields arising from other internal and external sources. The electric field determination uses a combination of physical modelling and fitting of the EEJ current strengths measures by the Swarm satellites. Such methods, which attain a global knowledge of the spatial structure of the low latitude currents, give insight into the atmospheric tidal harmonics present at ionospheric altitudes.

Chapter 12: Modelling the internal geomagnetic field using data from multiple satellites and field gradients–Applications to the Swarm satellite mission, reviews how models of the main magnetic field are constructed from multiple satellites, such as Swarm. The focus is on how to take advantage of estimated field gradients, both along-track and across track. The chapter summarises recent results from the Swarm mission dealing with the core and lithospheric fields. The aim is to inform users interested in ionospheric applications. Limitations of the current generation of main field models are also discussed pointing out that further progress requires improved treatment of ionospheric current systems, particularly at polar latitudes.

These chapters cover very different methodologies, but do have overlaps in techniques, and these have been referenced within and between each chapter. We thank all the authors for the substantial amount of effort needed to put this collection of work together.