SCARF - THE SWARM SATELLITE CONSTELLATION APPLICATION AND RESEARCH FACILITY

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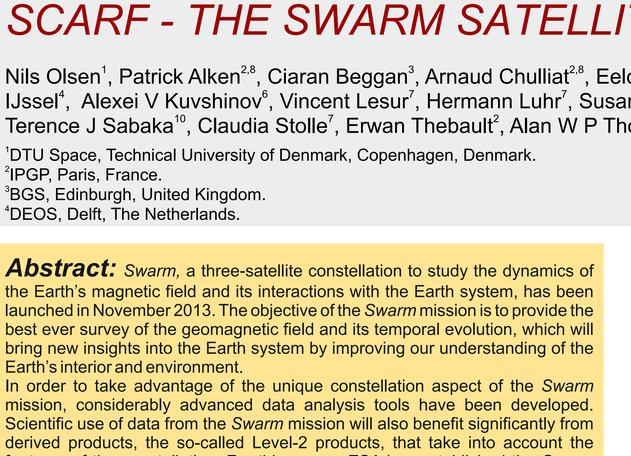
Abstract: *Swarm,* a three-satellite constellation to study the dynamics of the Earth's magnetic field and its interactions with the Earth system, has been launched in November 2013. The objective of the *Swarm* mission is to provide the best ever survey of the geomagnetic field and its temporal evolution, which will bring new insights into the Earth system by improving our understanding of the Earth's interior and environment.
In order to take advantage of the unique constellation aspect of the *Swarm* mission, considerably advanced data analysis tools have been developed. Scientific use of data from the *Swarm* mission will also benefit significantly from derived products, the so-called Level-2 products, that take into account the features of the constellation. For this reason ESA has established the *Swarm* "Satellite Constellation Application and Research Facility" (SCARF), in the form of a consortium of several research institutions.

A number of Level-2 data products will be offered by this consortium, including various models of the core and lithospheric field, as well as of the ionospheric and magnetospheric field. In addition, derived parameters like mantle conductivity, thermospheric mass density and winds, field-aligned currents, an ionospheric plasma bubble index, the ionospheric total electron content and the dayside equatorial zonal electrical field will be calculated.

All of the derived products will be available through the *Swarm* Payload Data Ground Segment (PDGS), located at ESRIN, the ESA Centre for Earth Observation in Frascati, Italy. The service provided by SCARF is expected to be operational for a period of at least 5 years.

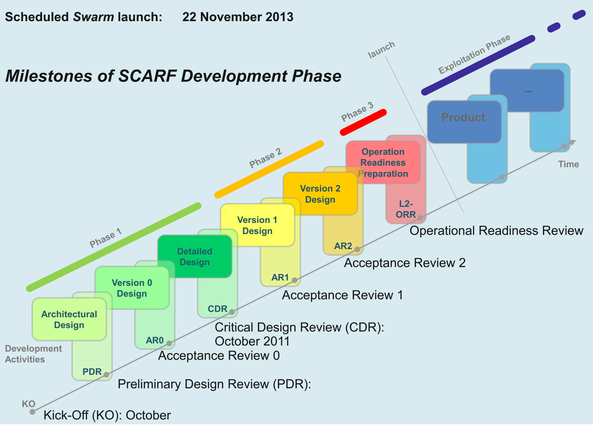
The Partners of SCARF



SCARF Development Phase: October 2010 - August 2013
SCARF Exploitation Phase: 2014 - 2019 (5 years)

Scheduled *Swarm* launch: 22 November 2013

Milestones of SCARF Development Phase



The Level-2 Data Products

Cat-1 Products

Complex algorithms to derive Level-2 products describing specific sources of the Earth's magnetic field. Product derived by SCARF since scientific experience is required to derive these products.

Science Objective	*Name*	*Description*
All. Needed for L1b processing	MSW_EUL_2_	Euler angles describing transformation from STR-CRF to VFM frame for satellites A, B, and C
O1: Core Field	MCO_SHA_2_	Spherical harmonic model of the main (core) field and its temporal variation
O2: Lithospheric Field	MLI_SHA_2_	Spherical harmonic model of the lithospheric field
O3: Mantle Conductivity	MIN_1DM_2_	1D model of mantle conductivity
	MIN_3DM_2_	3D model of mantle conductivity
	MCR_1DM_2_	1D C-response maps
	MCR_3DM_2_	3D C-response maps
O4: External Current Systems	MMA_SHA_2_	Spherical harmonic model of the large-scale magnetospheric field and its Earth-induced counterpart
	MIO_SHA_2_	Spherical harmonic model of the daily geomagnetic variation at middle latitudes (Sq and low latitudes (EEJ)
Precise Orbit Determination	SP3xCOM_2_	time series of position and velocity of the center of mass of each satellite
	ACCxCAL_2_	Accelerometer calibration parameters from the POD process
	ACCxPOD_2_	Time series of non-gravitational accelerations estimated by POD
O5: Magnetic Forcing of the Upper Atmosphere	ACCx_AE_2_	Time series of calibrated and pre-processed accelerometer observations and of aerodynamic accelerations from Satellite x. (x=A,B or C)
	DNSxWND_2_	time series of neutral thermospheric density and wind speed

Cat-2 Products

Algorithms leading to Level-2 products with minimum delay, e.g. for space weather applications. Near real-time capability. All Cat-2 products are provided in CDF format. Algorithms designed by SCARF, data processed by PDGS

Science Objective	*Name*	*Description*
O4: External Current Systems	IBIxTMS_2F	**CAT-2:** Ionospheric bubble index
	TECxTMS_2F	**CAT-2:** Time series of the ionospheric total electron content
	FAC_TMS_2F	**CAT-2:** Time series of field-aligned currents
	FACxTMS_2F	**CAT-2:** Time series of field-aligned currents
	EEFxTMS_2_	**CAT-2:** Equatorial Electric Field

Example of MCO core field model

Product name
SW_TEST_MCO_SHA_2R_19980101T000000_20030101T000000_0001.DBL

```
# Input core field model for generation of core field part of TDs-1 data set.
# n_mix = 1, n_max = 20.
# 51 Snap-shots derived from order-isog=6 spline models. There are isog-2 snap-shots
# per node-interval, plus one at each node i.e. every isog-1=5 snap-shot corresponds
# to a spline node.
# Gauss coefficient format F15.6
   1   20   51      6      5
                1998.00          1998.10          1998.20          1998.30          1998.40   ...
   1    0  -29576.796430  -29575.710728  -29574.634241  -29573.565540  -29572.502687   ...
   1    1   -1693.946980   -1691.838403   -1691.727136   -1690.611818   -1689.530903   ...
   1   -1    5122.038131    5119.921493    5117.798579    5115.670116    5113.536484   ...
   2    0   -2309.793580   -2311.180751   -2312.556466   -2313.920616   -2315.273200   ...
   2    1    3058.875059    3054.410796    3057.940221    3057.463661    3056.981523   ...
   2   -1   -2548.622966   -2550.872138   -2553.120633   -2555.368075   -2557.614120   ...
   2    2    1661.519141    1662.283484    1661.057810    1660.841342    1660.633302   ...
   2   -2   -492.677420    -493.890273    -495.107699    -496.328271    -497.550457   ...
   3    0    1334.483767    1334.478280    1334.480542    1334.490123    1334.506292   ...
   3    1   -2296.508319   -2296.832116   -2297.157839   -2297.482789   -2297.808768   ...
   3   -1   -209.481862    -208.913432    -208.340820    -207.764238    -207.183928   ...
   3    2    1247.909872    1247.812538    1247.717822    1247.625034    1247.533335   ...
   3   -2    278.291831     277.810544     277.325647     276.837327     276.345760   ...
   3    3    690.119217     689.327588     688.530698     687.727961     686.918823   ...
   3   -3   -513.031082    -513.626410    -514.209373    -514.780763    -515.341350   ...
   4    0    925.304661     925.054685     924.807330     924.562662     924.320544   ...
   4    1    793.136676     793.075020     793.614932     793.856362     794.099111   ...
   4   -1    279.222843     279.635146     279.650497     279.868796     280.089920   ...
   4    2    226.556805     225.788496     225.018553     224.246895     223.473365   ...
...
```

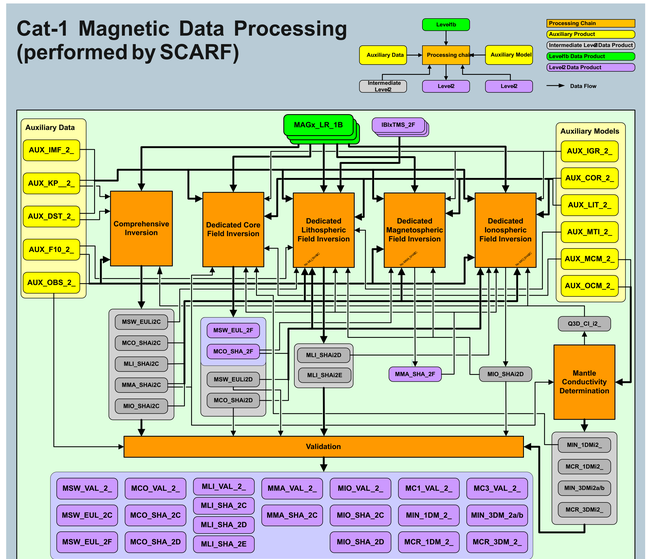
Example of ionospheric total electron content (TEC)

Filename SW_TEST_TECATMS_2F_20081119T000000_20081119T235959_0001.DBL

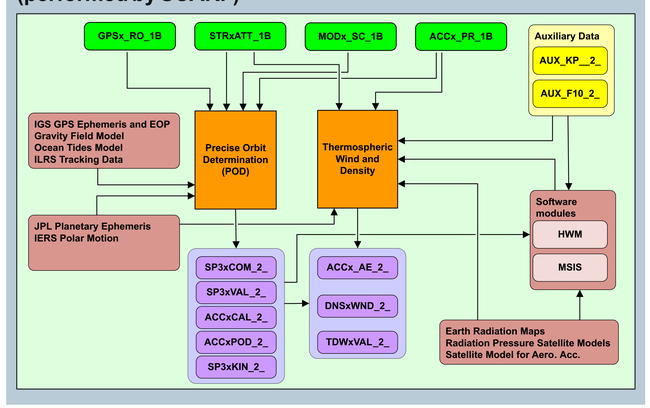
Each processed GPS-Swarm satellite link is uniquely defined by one row of 18 variable arrays, provided in CDF format

Variable	Description	Unit	Example
Timestamp	Time stamp in UTC (cdfepoch)	UTC	19-Nov-2008 00:00:06
Latitude	Geographic latitude	degree	16.3335
Longitude	Geographic longitude	degree	-18.7664
Radius	Geographic radius	m	6697840.4999
GPS_Position	X-,Y-,Z-coordinates (WGS84) of the GPS satellite	m	[2616227?.8499; -5620247.17084; 44794.0304]
LEO_Position	X-,Y-,Z-coordinates (WGS84) of the LEO satellite	m	[6697840.4999; -2067805.7800; 1883619.9080]
PRN	GPS satellite PRN	-	4
L1	GPS L1 carrier phase observation	m	-1893872.6910
L2	GPS L2 carrier phase observation	m	-1893875.5805
P1	GPS P1 code phase observation	m	20508459.0015
P2	GPS P2 code phase observation	m	20508461.8378
S1	GPS signal-to-noise ratio or raw signal strength on L1	-	300
S2	GPS signal-to-noise ratio or raw signal strength on L2	-	501
Absolute_STEC	Absolute slant TEC	TECU	8.0119
Relative_STEC	Relative slant TEC	TECU	27.5071
STEC_RMS	Root mean square error of relative slant TEC	TECU	0.3190
DCB	GPS receiver differential code bias	TECU	-14.6977
DCB_Error	Error of the GPS receiver differential code bias	TECU	0.8100

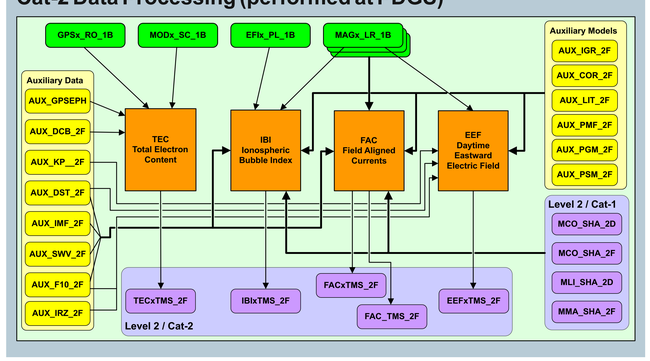
Cat-1 Magnetic Data Processing (performed by SCARF)



Cat-1 Processing of POD and Thermospheric Winds (performed by SCARF)



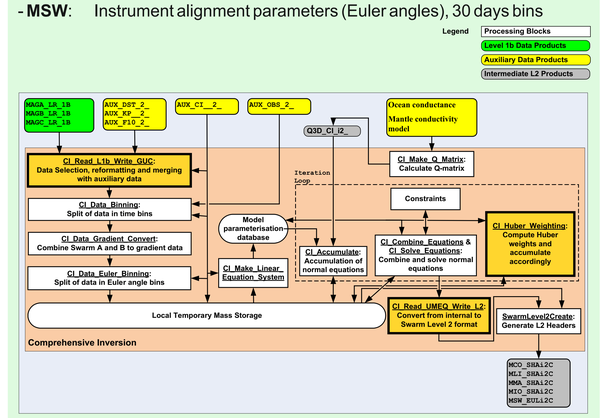
Cat-2 Data Processing (performed at PDGS)



The Comprehensive Inversion Chain

The Comprehensive Inversion takes Level-1b data (time series of magnetic field measurements) and estimates simultaneously the following L2 products:

- **MCO**: Core field up to degree n = 20, temporal resolution order-5 splines, 6 months knot separation
- **MLI**: Lithospheric field up to n = 150
- **MIO**: Ionospheric field in quasi-dipole frame, up to n = 60; m = 12, up to semi-annual and quarter-daily periodicity, induced contributions accounted for by pre-defined conductivity of 3D mantle + oceans
- **MMA**: Magnetospheric field up to n = 3; m = 1, induced field up to n,m = 6 1-hour bins for coefficients with n = 1, m = 0; 6-hour bins for all other coefficients
- **MSW**: Instrument alignment parameters (Euler angles), 30 days bins



Test of the Comprehensive Inversion Chain

Simulation of the magnetic measurements of a full Swarm Mission by generation of synthetic L1b data using sophisticated input models (of the core, lithosphere, ionosphere, magnetosphere plus induced contributions). The resulting L1b time series are subsequently inverted using the Comprehensive Inversion scheme and the estimated models are compared to the input models.

Assessment of the lithospheric field