Separating magnetospheric, ionospheric and Earth-induced magnetic field contributions by joint analysis of Swarm satellite and ground observatory data

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Introduction

Models of the large-scale magnetospheric currents are either derived from satellite data alone (e.g. `CMMA_F` Level-2 data product) or from ground observatory data alone (resulting e.g. in the *Dst* and *RC* indices and `MMA_CHAOS`) or by joint analysis of both data sets (e.g., `MMA_C`). For all present models it is assumed that ionospheric currents are either absent or independent of geomagnetic activity (and thus can be accounted for by an ionospheric model (e.g., `MIO_C`) that is derived from quiet-time data).

However, it has long been noticed that the magnetospheric field as determined from ground data (e.g. *Dst* and *RC* indices) only accounts for 90% of that seen at satellite altitude, even if Earth-induced contributions are considered. This discrepancy has led to speculations about additional ionospheric currents between ground and satellite that depend on geomagnetic activity.

We investigate the existence of ionospheric currents of "ring-current geometry" (i.e., zonal currents) by simultaneous estimation of magnetospheric, ionospheric and induced currents using satellite and ground based data.

Data

- Satellite and ground observatory data for 2017, $< \pm 55°$ QD latitude, only night-time data (LT between 18 and 06)
- Swarm A, Swarm B, CryoSat, 15 sec sampling,
- Hourly Values from 106 ground observatories, interpolated to 90 min sampling ($\approx$ satellite orbit period)
- CHAOS-7 core and lithospheric field removed
- "observatory bias" accounted for by removing mean geomagnetic quiet night-time value for 1997 – 2023
- "quiet-time magnetospheric offset" (for *Dst* = 0) accounted for by adding P_1^0 magnetospheric field of amplitude $\overline{q}_1^0 = +15$ nT (to make observatory data compatible with satellite data)
- Vector components are rotated from geographic into dipole frame

Model parameterisation

$$\mathbf{B} = -\nabla V$$
$$V = V^{ind} + V^{iono} + V^{magn}$$

at ground:

$$V = a \sum \left[g_n^m \left(\frac{a}{r}\right)^{n+1} + \epsilon_n^m \left(\frac{r}{a}\right)^n + q_n^m \left(\frac{r}{a}\right)^{n+1} \right] Y_n^m$$

at satellite:

$$V = a \sum \left[g_n^m \left(\frac{a}{r}\right)^{n+1} + \tilde{\epsilon}_n^m \left(\frac{a}{r}\right)^{n+1} + q_n^m \left(\frac{a}{r}\right)^{n+1} \right] Y_n^m$$
$$= a \sum \left[g_n^m \left(\frac{a}{r}\right)^{n+1} - \frac{n}{n+1}\left(\frac{a+h}{a}\right)^{2n+1} \epsilon_n^m \left(\frac{a}{r}\right)^{n+1} + q_n^m \left(\frac{a}{r}\right)^{n+1} \right] Y_n^m$$

with

g_n^m : ground-induced contribution
ϵ_n^m : ionospheric contribution as seen from ground
$\tilde{\epsilon}_n^m = -\frac{n}{n+1}\left(\frac{a+h}{a}\right)^{2n+1} \epsilon_n^m$: ionospheric contribution as seen from satellite
q_n^m : magnetospheric contribution

Robust estimation of separate models:
q_n^m and g_n^m (from observatory-only data)
q_n^m and g_n^m (from satellite-only)
q_n^m, g_n^m and ϵ_n^m (from observatory and satellite data)
for $n = 1, m = 0, 1$ in bins of 90 minutes ($\approx$ satellite orbit period)

Note that any incompatibility of satellite and ground data (e.g. erroneous determination of "observatory bias") will contribute to an (apparent) ionospheric contribution.

Results

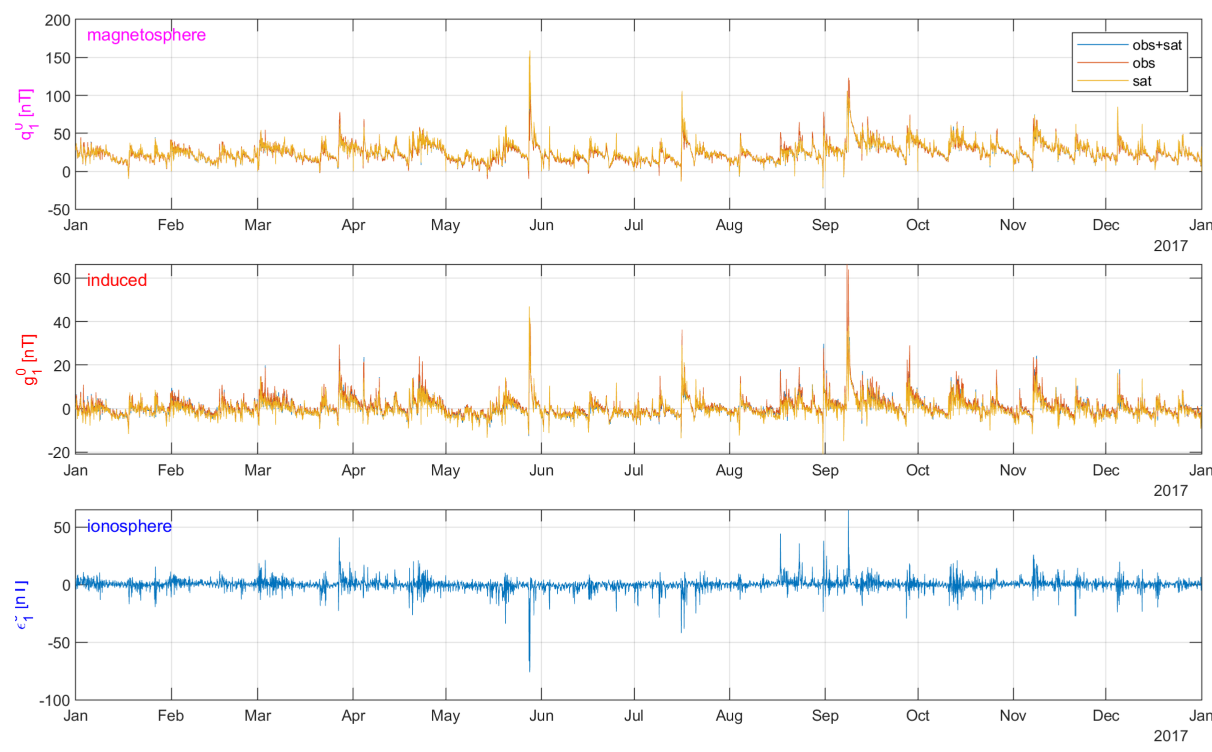
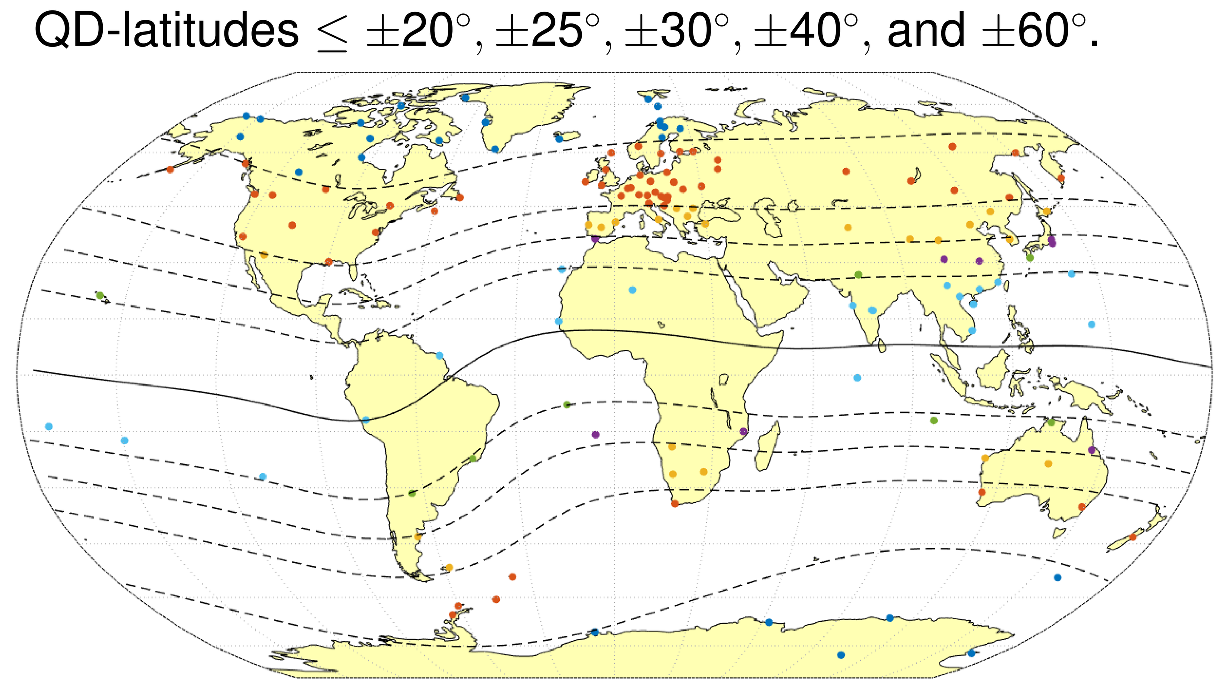


Figure: Time series of magnetospheric (q_1^0, top), Earth-induced (g_1^0, middle), and ionospheric (ϵ_1^0) coefficients for 2017, determined from observatory data only, satellite data only, and their combination.

Night-time ionospheric zonal currents ϵ_1^0 are weak / absent during quiet conditions, as expected due to vanishing *E*-region conductivity. Enhanced apparent contributions during active periods might be related to a) rapid changes, leading to inconsistency between 15 sec satellite and 1 hour observatory data sampling, or b) leakage from higher-degree (not included) coefficients.

RC index determined from observatory data covering different latitudes

We investigate whether the difference in latitude distribution between satellite and ground data can explain the apparent disagreement between *Dst* (resp. *RC*) and satellite-derived q_1^0.
We estimated 5 versions of *RC* from subsets of night-time observatory data, including observatories at QD-latitudes $\leq \pm 20°, \pm 25°, \pm 30°, \pm 40°$, and $\pm 60°$.



Using these 5 versions of *RC* for parametrising magnetospheric contributions, we derived 5 geomagnetic field models from one year of Swarm data (1. Jan – 31. Dec 2017) scalar (above $\pm 55°$ QD latitude) and vector (below $\pm 55°$) data (from dark regions and geomagnetic quiet conditions) and solved for a static internal field (up to SH degree $N = 40$), linear and quadratic time-dependence of the core field up to $N = 14$), and a "CHAOS-type" external (magnetospheric) field and co-estimated a linear dependence, $\hat{q}_{RC}$ with *RC*.

QD-lat	$\leq 20°$	$\leq 25°$	$\leq 30°$	$\leq 40°$	$\leq 60°$
$N_{obs} =$	20	28	36	59	114
$\hat{q}_{RC} =$	0.42	0.82	0.87	0.96	0.97
F_{polar}	5.04	4.55	4.42	4.08	4.03
B_r	2.43	2.20	2.07	1.64	1.56
B_θ	4.14	3.16	3.03	2.65	2.56
B_ϕ	2.42	2.40	2.39	2.36	2.36

$\hat{q}_{RC}$ systematically *increases* (approaching the expected value of $\hat{q}_{RC} = 1$) if ground observatories from higher latitudes are used to derive *RC*.

The rms misfit (in nT) to the *Swarm* satellite data *decreases*.

Conclusions: Using only low-latitude data *overestimates* the magnetospheric ring-current, resulting in $\hat{q}_{RC} < 1$.

Magnetic Field due to Current Loop at $R = 5a$

Why do low-latitude ground data result in an *overestimation* of the magnetospheric ring-current?

Magnetic field at Earth's surface $r = a$ caused by a magnetospheric current loop in the equatorial plane:

$$B_\theta = \frac{\mu_0 I}{2R}\left[\frac{dP_1^0}{d\theta} - \frac{3}{2}\left(\frac{a}{R}\right)^2 \frac{dP_3^0}{d\theta} + \frac{3\cdot 5}{2\cdot 4}\left(\frac{a}{R}\right)^4 \frac{dP_5^0}{d\theta} - \ldots\right]$$
$$= \left[q_1^0 \frac{dP_1^0}{d\theta} + q_3^0 \frac{dP_3^0}{d\theta} + q_5^0 \frac{dP_5^0}{d\theta} + \ldots\right]$$

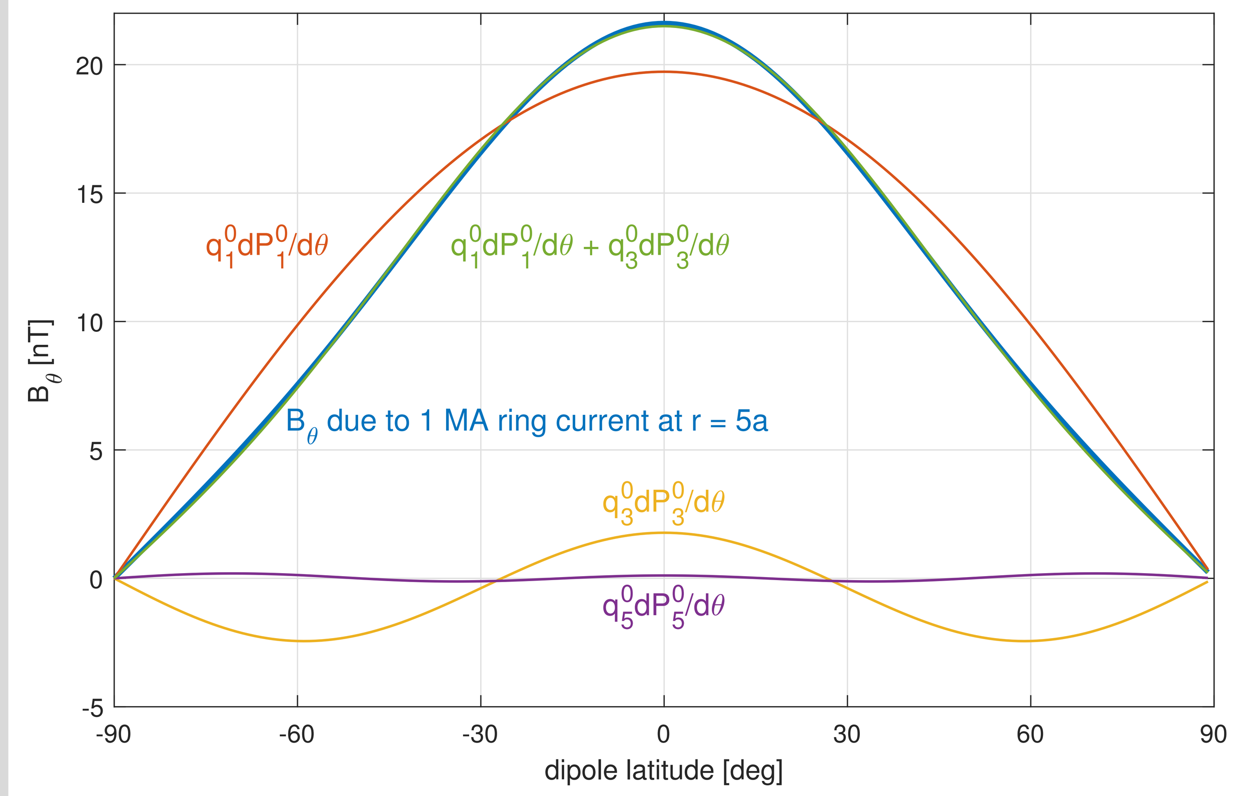


Figure: B_θ at Earth's surface ($r = a$) produced by $I = 1$ MA current loop of radius $R = 5a$ in the equatorial plane.

The P_1^0-approximation leads to smaller values at the magnetic equator compared to the true magnetic field. Consequently, using only low-latitude data to estimate a P_1^0 field results in an *overestimation* of the true ring current.

Note that q_3^0 of such a current loop has opposite sign compared to q_1^0. This is confirmed by SHA of hourly mean values from (night-time) ground observatory data:

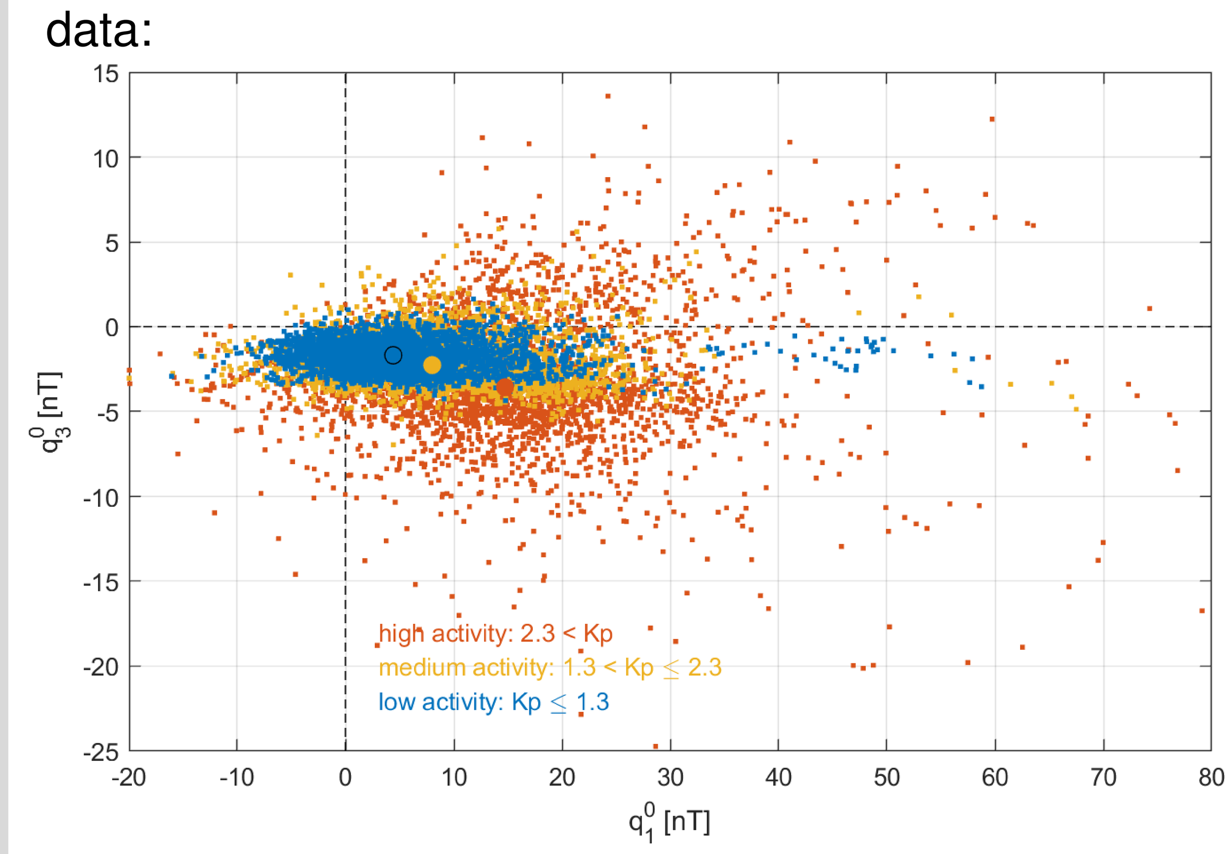


Figure: Scatter plot of q_3^0 vs. q_1^0 as determined from ground observatory data ($< \pm 60°$ QD latitude) for 2017. Note that average values (large dots) are *positive* for q_1^0 but *negative* for q_3^0, in agreement with the above theory.

Field modeling experiments

"CHAOS-type" field model for 2017 (data and parametrisation as described above) using *RC* (Model A). Model B is derived in exactly the same way but after removal of the magnetospheric (and induced) field predictions as given by the `MMA_C` model.

Number of satellite data points (N_{data}) and rms misfit statistics:

	N_{data}	Model A rms [nT]	Model B rms [nT]
F_{polar}	217,643	3.98	3.99
B_r	704,029	1.47	1.41
B_θ	704,029	2.55	2.29
B_ϕ	704,029	2.36	2.21

The lower non-polar rms data misfit of Model B indicates the existence of unmodeled magnetospheric contributions presently not captured by *RC* (Model A).