MIRACLE and CHAMP: some results; MIRACLE and SWARM: some opportunities

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– **Main topics of this presentation:**

- How can we derive ionospheric electrodynamic parameters (currents, conductances, fields) from multi-satellite data
- How can ground-based data be used together with multi-satellite data for studies of ionospheric electrodynamics

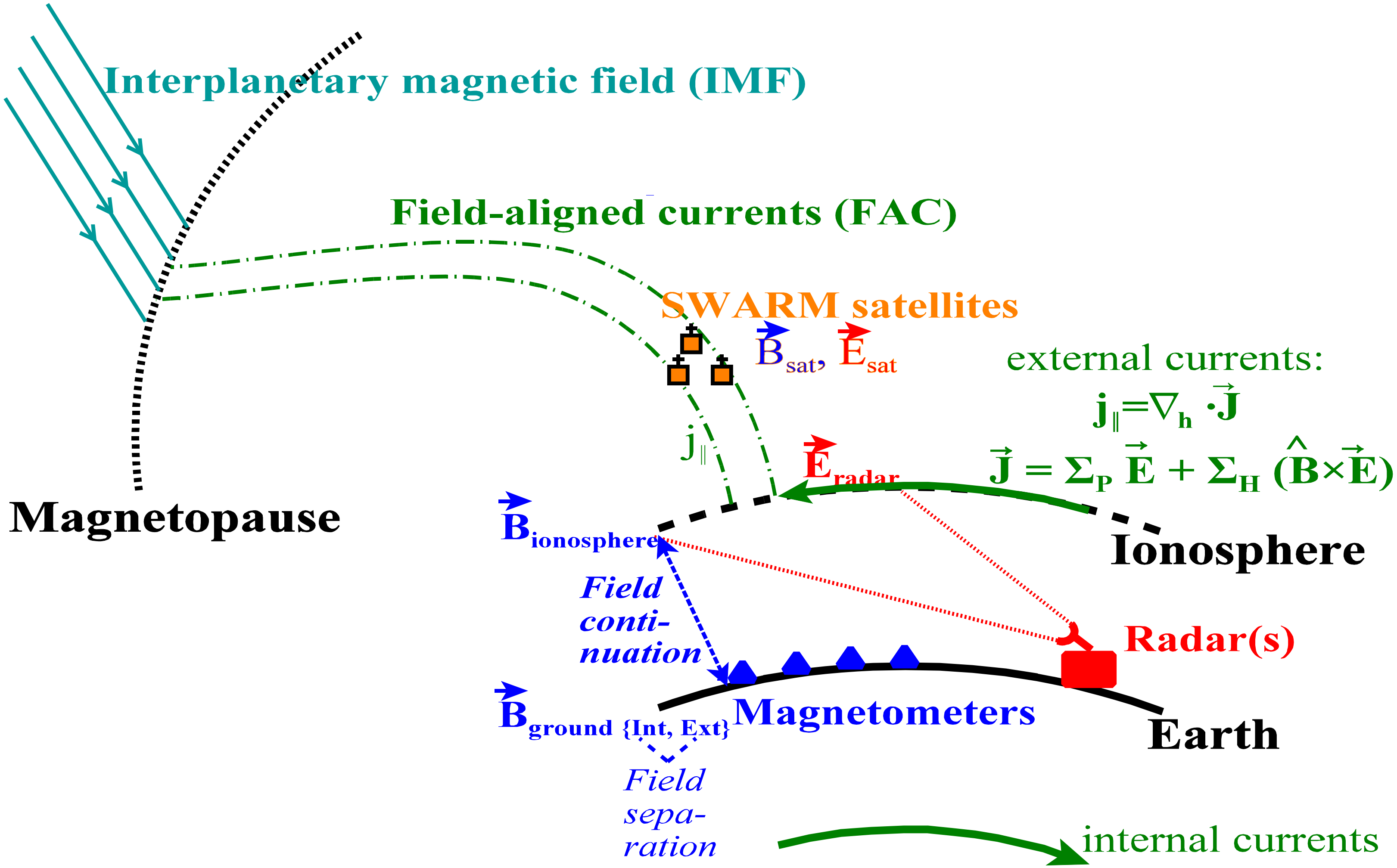
– **Structure of this presentation:**

1.) Introduction and basics
2.) Some CHAMP results using the 1D Spherical Elementary Current System (SECS) technique
3.) Some new opportunities with SWARM

- **Note**: In this presentation, **all magnetic fields mentioned are disturbance magnetic fields caused by ionospheric current systems**

1.) INTRODUCTION AND BASICS:

– Relevant current systems for ionospheric electrodynamics (schematic, thin sheet ionosphere model):

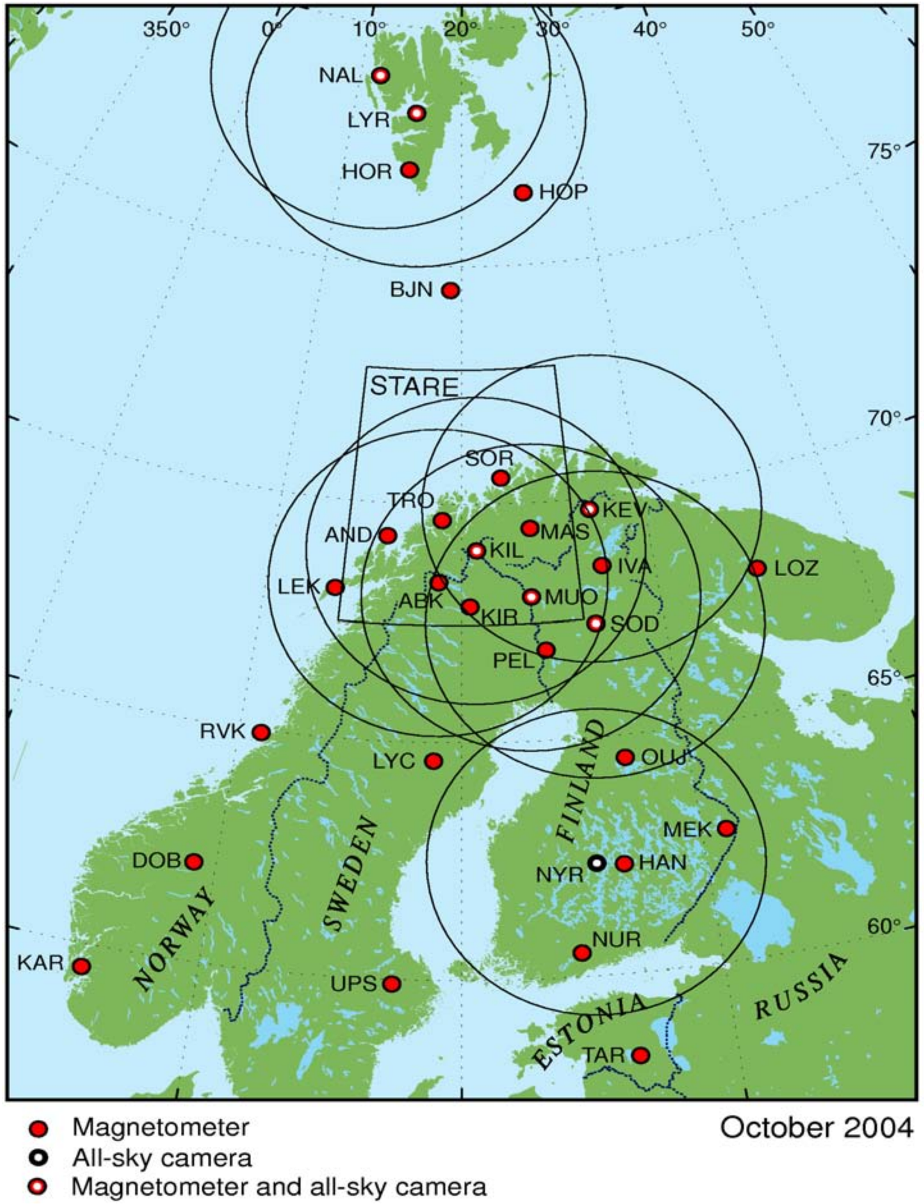


– Ground-based instrument network to perform integrated studies on ionospheric electrodynamics together with/ in support of SWARM:

MIRACLE network, consisting of:

– IMAGE magnetometers
– STARE radar (until March 2005)
– all-sky cameras

\+ other ground-based instruments (EISCAT, SuperDARN, Fabry-Perot interferometers, photometers, riometers, etc.)

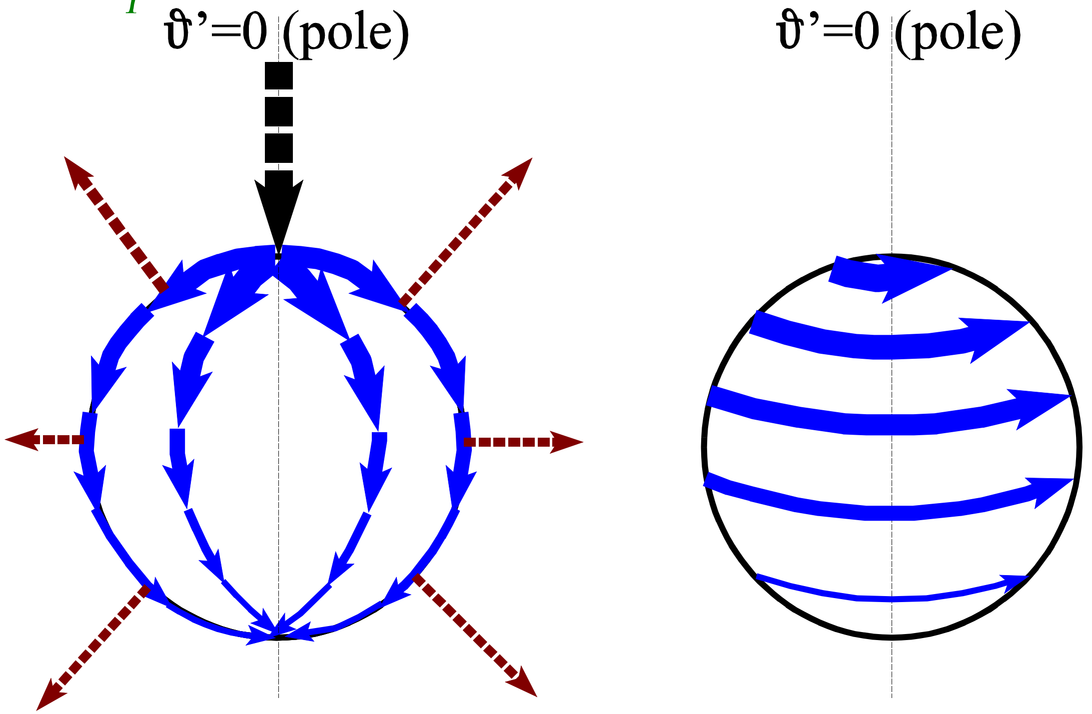


– Some basics:

a) *Curl-free* and *divergence-free* 2D spherical elementary current systems (SECS):

• written in spherical coordinate system $(r', \vartheta', \varphi')$ with $\vartheta' = 0$ at their "pole" $\vec{r}_0$

$$\vec{J}_{cf,el,sph}(\vec{r}') = \frac{I_{0,cf}}{4\pi R_I} \cot(\vartheta'/2)\ \underline{e}_{\vartheta'} \qquad \vec{J}_{df,el,sph}(\vec{r}') = \frac{I_{0,df}}{4\pi R_I} \cot(\vartheta'/2)\ \underline{e}_{\varphi'}$$



Curl-free elementary system (with associated FACs)

Divergence-free elementary system

– Expansion of any horizontal current system $\vec{J}$ in terms of SECS:

$$\vec{J}(\vec{r}) = \sum_{\text{Ionosph.}} \left(\frac{I_{0,df}(\vec{r}^{\,\prime})}{4\pi R_I} \cot(\tilde{\vartheta}/2)\ \underline{e}_{\tilde{\varphi}} + \frac{I_{0,cf}(\vec{r}^{\,\prime})}{4\pi R_I} \cot(\tilde{\vartheta}/2)\ \underline{e}_{\tilde{\vartheta}} \right)$$

$I_{0,df}(\vec{r}^{\,\prime})$, $I_{0,cf}(\vec{r}^{\,\prime})$: scaling factor of elementary current system with pole at $\vec{r}^{\,\prime}$;
$\tilde{\vartheta}$ and $\tilde{\varphi}$: coordinates of $\vec{r}$ in spherical coordinate system with pole at $\vec{r}^{\,\prime}$)

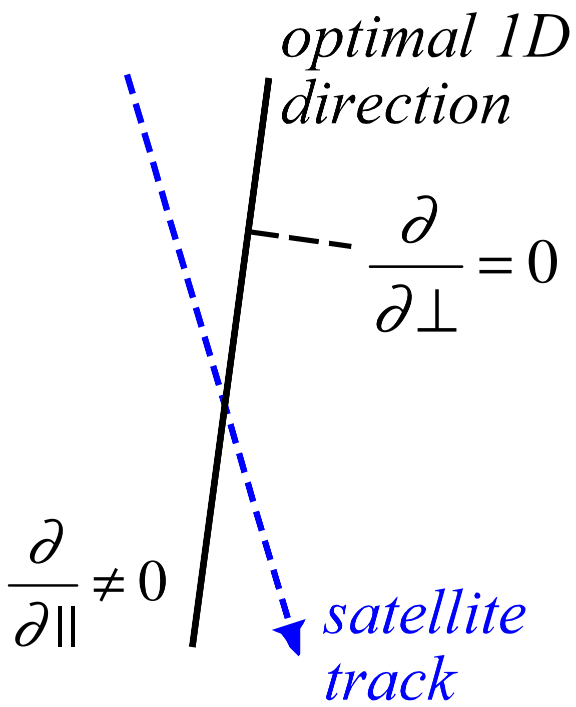
– Note: If the physical field to be expanded is known to be either divergence-free or curl-free
➠ only one type of elementary systems is needed, expansion will by definition produce exactly divergence-/ curl-free system!

– Example: Ground equivalent currents $\vec{J}_{eq} = \frac{2}{\mu_0}\ \hat{z} \times \vec{B}_h$ are divergence-free

- **For data of <u>single</u> satellites:**

  - Only data along a single line available
    - – 2D modelling not possible
    - ⇒ use 1D assumption, i.e., derivatives vanish along one horizontal direction
    - ⇒ use 1D SECS

  - <u>Notes:</u>
    - ☞ We can check from the magnetic data itself whether 1D assumption applies, or not
    - ☞ 1D direction does not need to be perpendicular to the satellite track
    - ☞ "Optimal 1D direction" can be inferred from magnetic data

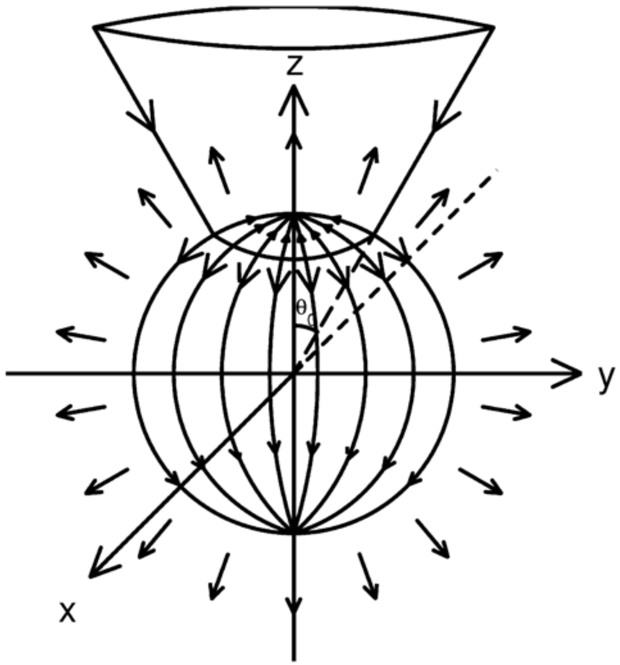


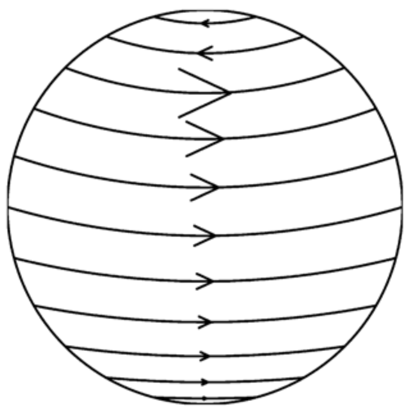
☞ ***b) Curl-free* and *divergence-free* <u>1D</u> spherical elementary current systems (SECS):**

- written in "global" (e.g., geographic) spherical coordinate system (r, ϑ, φ)
- obtained by integration of 2D SECS over all φ at a certain ϑ_0

$$\vec{J}_{cf,el,sph}(\vartheta,\vartheta_0) = \frac{I_{0,cf}}{2R_I}\, \underline{e}_{\vartheta} \begin{cases} -\tan(\vartheta/2), \vartheta < \vartheta_0 \\ \cot(\vartheta/2), \vartheta > \vartheta_0 \end{cases}$$

$$\vec{J}_{df,el,sph}(\vartheta,\vartheta_0) = \frac{I_{0,df}}{2R_I}\, \underline{e}_{\varphi} \begin{cases} -\tan(\vartheta/2), \vartheta < \vartheta_0 \\ \cot(\vartheta/2), \vartheta > \vartheta_0 \end{cases}$$





c) How to obtain the currents from the magnetic field measurements

- <u>Mathematically</u>: Solve inversion problem

$$\underline{\underline{T}} \cdot \underline{I} = \underline{Z}$$

where

$$\underline{Z} = \begin{pmatrix} Z_{1,r} \\ Z_{1,\vartheta} \\ Z_{1,\varphi} \\ \vdots \\ Z_{n_{obs},r} \\ Z_{n_{obs},\vartheta} \\ Z_{n_{obs},\varphi} \end{pmatrix} \qquad \underline{I} = \begin{pmatrix} I_{0,cf,1} \\ I_{0,cf,2} \\ \vdots \\ I_{0,cf,n_{el}} \\ I_{0,df,1} \\ I_{0,df,2} \\ \vdots \\ I_{0,df,n_{el}} \end{pmatrix}$$

$$\underline{\underline{T}} = \begin{pmatrix} T_{11,r,cf} & T_{12,r,cf} & \cdots & T_{1n_{el},r,cf} & T_{11,r,df} & T_{12,r,df} & \cdots & T_{1n_{el},r,df} \\ T_{11,\vartheta,cf} & T_{12,\vartheta,cf} & \cdots & T_{1n_{el},\vartheta,cf} & T_{11,\vartheta,df} & T_{12,\vartheta,df} & \cdots & T_{1n_{el},\vartheta,df} \\ T_{11,\varphi,cf} & T_{12,\varphi,cf} & \cdots & T_{1n_{el},\varphi,cf} & T_{11,\varphi,df} & T_{12,\varphi,df} & \cdots & T_{1n_{el},\varphi,df} \\ \vdots & & & \vdots & \vdots & & & \vdots \\ T_{n_{obs}1,\varphi,cf} & T_{n_{obs}2,\varphi,cf} & \cdots & T_{n_{obs}n_{el},\varphi,cf} & T_{n_{obs}1,\varphi,df} & T_{n_{obs}2,\varphi,df} & \cdots & T_{n_{obs}n_{el},\varphi,df} \end{pmatrix}$$

Z: vector of observations
I: vector of (internal and external) scaling factors
T: transfer matrix (describes magnetic field effect at observations points due to a single curl-free or divergence-free SECS)

– Method to solve problem: Singular value decomposition (SVD)

- **Properties and advantages of SECS:**

  - 1D/2D SECS are <u>complete basis functions</u> for <u>any</u> continuously differentiable 1D/2D vector field on a sphere
  - SECS are <u>local</u> basis functions
  - <u>Location of elementary system poles can freely be chosen</u>, adjusted to the geometry/ data availability of the specific problem
  - <u>No need to select globally smallest resolvable wavelength</u>, like in methods based on harmonic functions (spherical (cap) harmonic analysis, Fourier analysis)
  - SECS <u>naturally divide up curl-free and divergence-free parts of vector fields</u>, which often have different physical meaning
  - *Particularly for solving current systems from magnetic satellite data:*
    - Local and remote currents can be deduced <u>on the same spatial scale</u> ⇒ it makes sense to <u>combine</u> them for further calculations
    - <u>Satellite and ground-based magnetic data can be combined in the same inversion</u>, when both data available

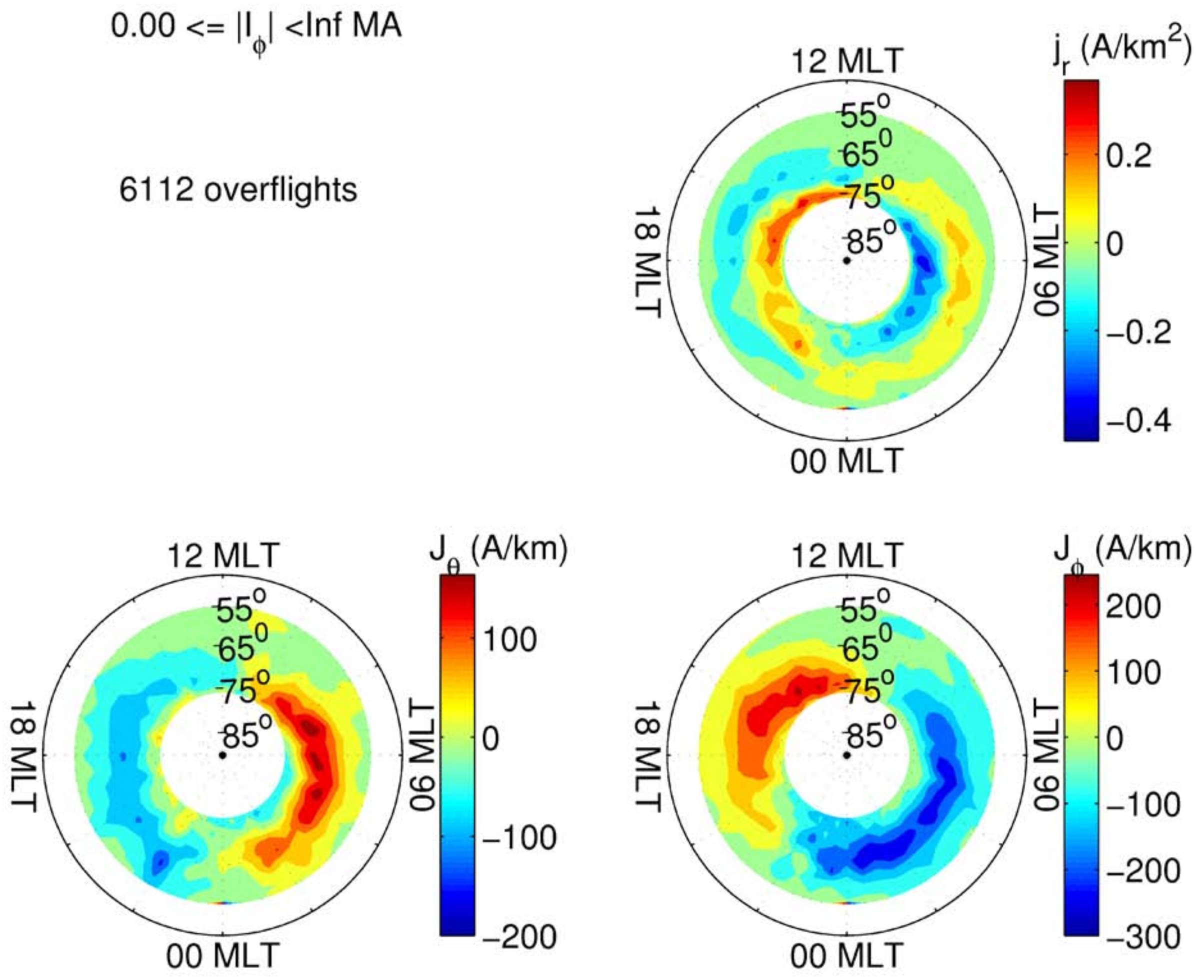
3.) SOME CHAMP RESULTS USING THE 1D SECS TECHNIQUE:

- Examples here:
  - Derivation of full current system ($j_\parallel$, J_ϑ, J_φ) on same spatial scale, global statistics
  - Derivation of the parameter $\alpha = \Sigma_H / \Sigma_P$, statistics between α and J_φ, global statistics

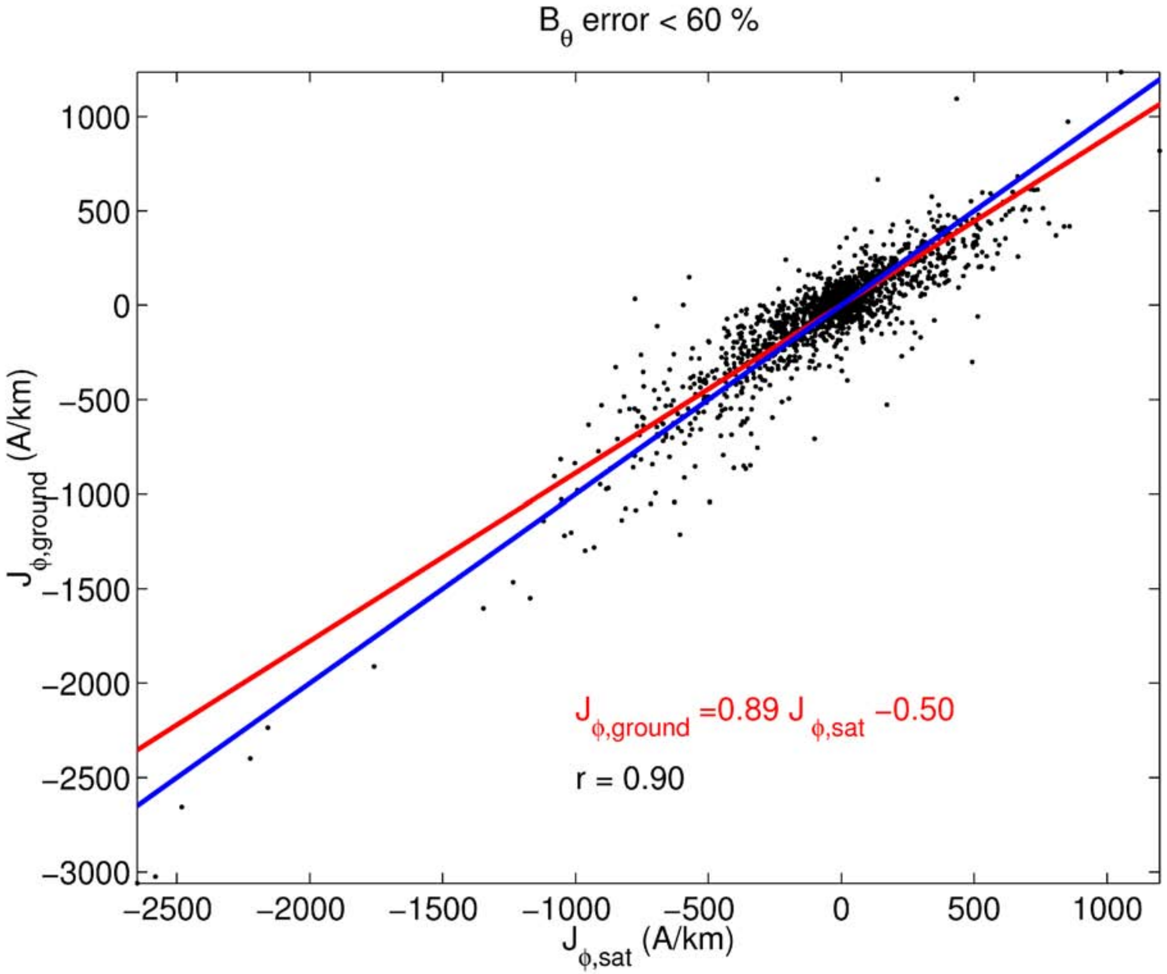
  - Notes:
    - ☞ α is an important parameter, as it tells about the energy spectrum of precipitating particles, and about the altitude distribution of ionospheric currents
    - ☞ α is also needed as an input parameter for the "method of characteristics" that infers Σ_H, Σ_P from magnetic and electric field data

a) Statistics of $j_\parallel$, J_ϑ, J_φ, based on 6112 passes with sufficiently good 1D condition:

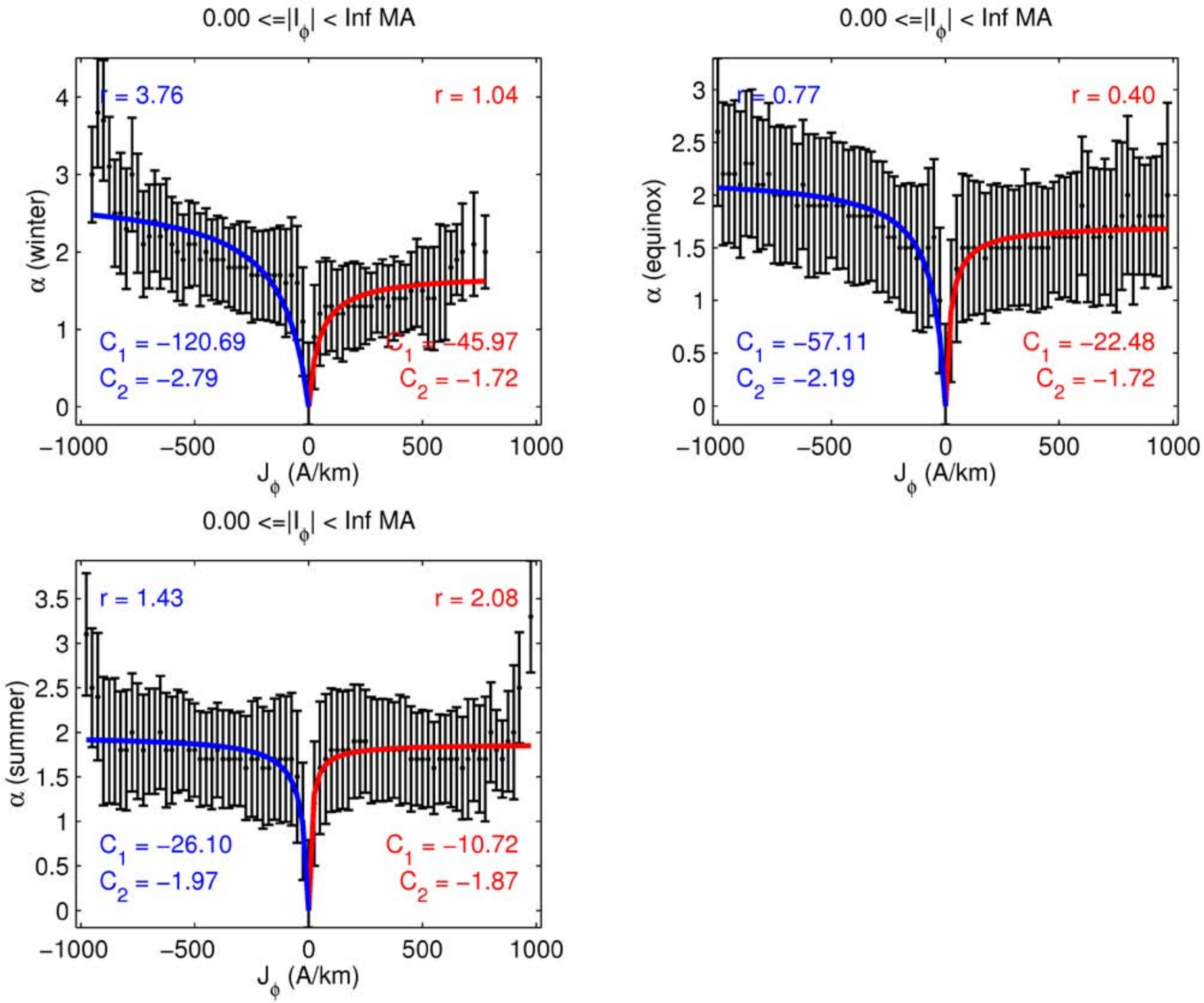
⇒ binning with respect to activity, season, IMF, etc. possible



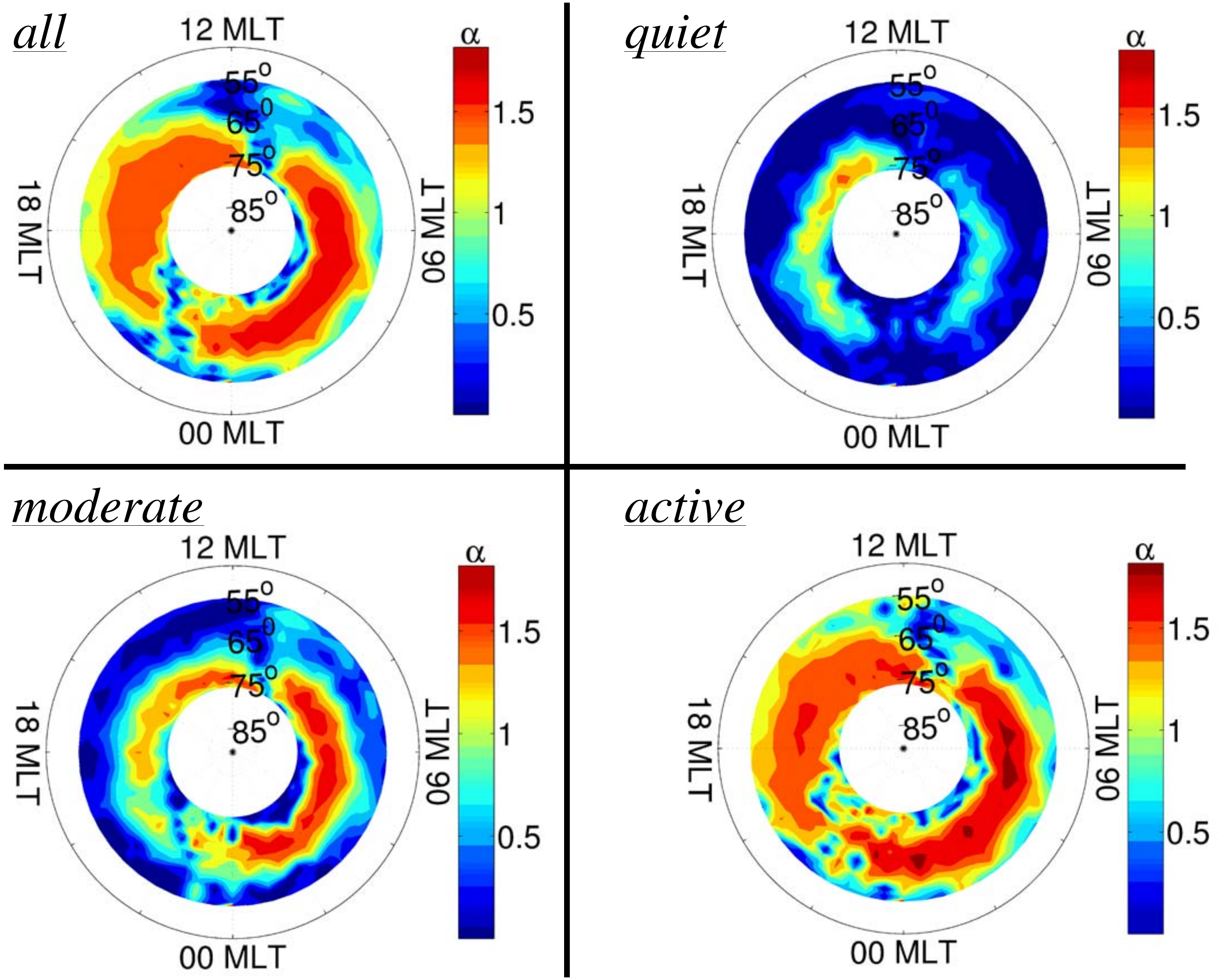
b) Confirmation of 1D SECS satellite results from Champ for J_φ with 2D SECS ground-based results from MIRACLE for $J_{\varphi,eq}$:



c) Statistical derivation of α as a function of $J_{\varphi,\left\{\substack{sat\\ground}\right\}}$:



d) Global maps of α, total and binned by activity level:



4.) NEW OPPORTUNITIES USING MULTI-SATELLITES:

– Major new possibilities with SWARM for ionospheric physics:

- 2-3 satellites available closeby ⇒ <u>gradients</u> of ionospheric parameters can be measured

- <u>electric field</u> data available, also with <u>gradients</u>

– Focus here on:

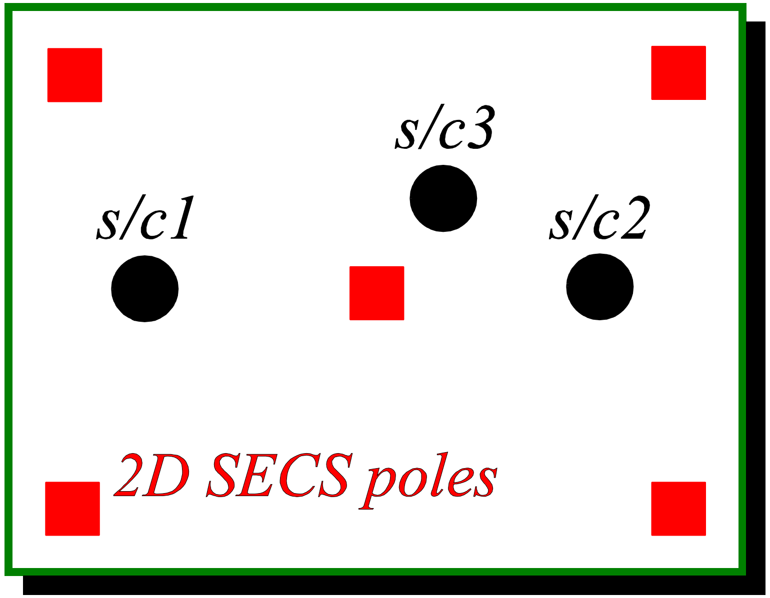
- Techniques to derivve local *and* remote currents (using SECS), and conductances with $\vec{E}$-field

(Other techniques, not discussed here:

- Derive local currents at the satellites only (by evaluation of $\nabla \times \vec{B}$))

a) Full 2D SECS technique:

– Properties:
  - evaluates both local and remote currents
  - assumption of stationary situation optionally
  - makes use of known current geometry
  - needs (at least) 3 satellites to work

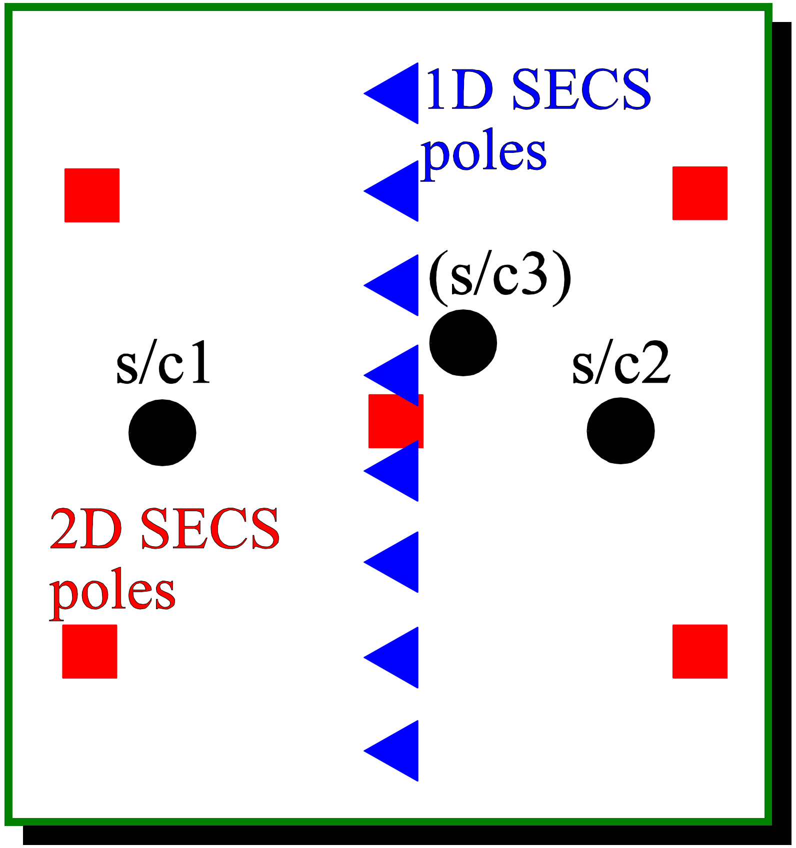


– Would be optimal for more satellites, *but* here:
  - If real situation is close to 1D, this is not well represented by only a few 2D SECS
  - However, we cannot put too many 2D SECS, as only 3 satellites are available for input data

⇒ probably better to use a hybrid 1D/2D SECS approach

b) Combined (hybrid) 1D/2D SECS technique:

– Properties like full 2D SECS method, but:
  - needs only 2 satellites to work
  - needs stationarity assumption for small number of satellites
  - basis system is partly linear dependent ⇒ should not matter in practise, but tests needed



– In both cases c) and d):
  - With knowledge of $\vec{E}$, Σ_H and Σ_P can simply be derived from $\vec{J}$ by inversion of Ohm's law:

$$\Sigma_H = \frac{(\vec{J} \times \vec{E})_r}{|\vec{E}|^2} \quad \text{and} \quad \Sigma_P = \frac{\vec{J} \cdot \vec{E}}{|\vec{E}|^2}$$

c) Further collaboration possibilities between SWARM and MIRACLE, *if* a planned new VHF radar for MIRACLE is realized:

– Ground-based data of $\vec{B}_G$, $\vec{E}_{radar}$, and estimate of α, can be used to infer 2D real current system and conductances independently from SWARM data (method of characteristics) ⇒ during MIRACLE overflights, *calibration of SWARM results possible*!

– With $\vec{E}_{radar}$ and $\vec{E}_{sat}$, studies of altitude dependence of the electric field *and* its gradients become possible

☞ Why the electric field can be altitude-dependent?

- Effect of inductive electric fields
- Effect of space charges in lower ionosphere
- Effect of significant field-aligned conductance in lower ionosphere
- Scale-dependence

➠ *coordinated analysis of satellite and radar electric fields important!*

5.) GENERAL CONCLUSION:

A LOT OF EXCITING NEW SCIENCE POSSIBILITIES ARE OPENING UP WITH SWARM, PARTICULARLY ALSO IN CONNECTION WITH GROUND-BASED EQUIPMENT!

– Method references:

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