Event analysis on the origin of westward flows observed by the SuperDARN Hokkaido East radar during the recovery phase of geomagnetic storms

SuperDARN北海道陸別第一レーダーによって磁気嵐の回復相に観測された西向きフローの成因に関するイベント解析

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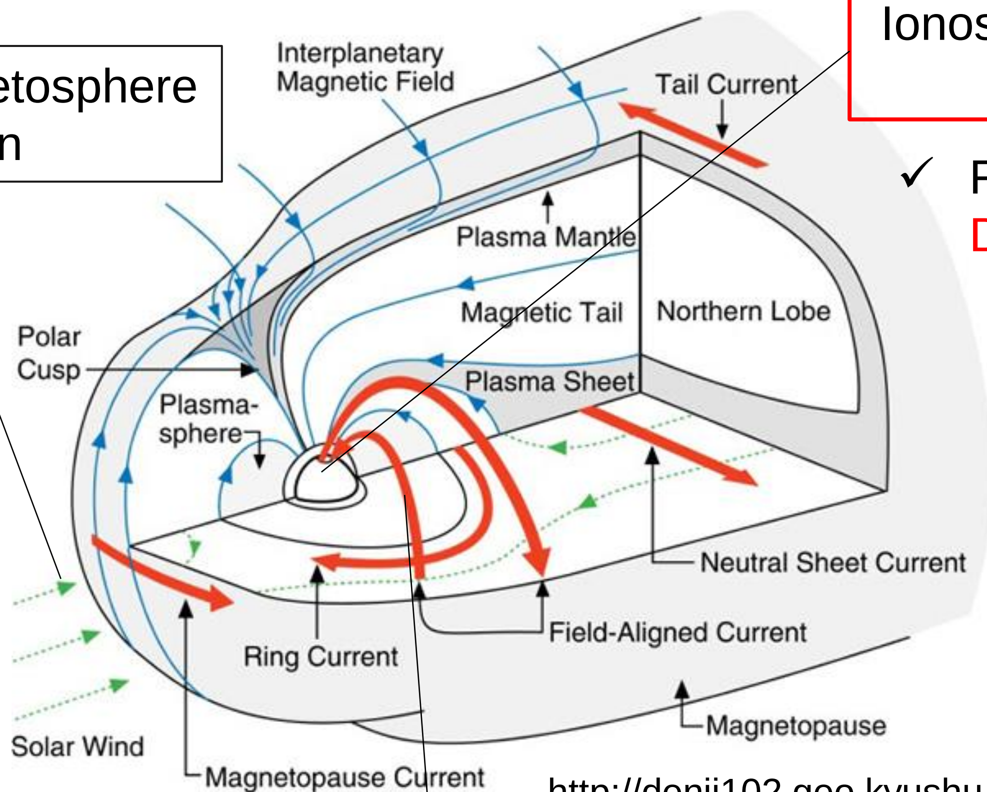
Outline

1. Introduction
2. Instrumentation and method
3. Result
4. Discussion
5. Summary
6. Future work

1. Introduction

- Ionospheric convection is determined by a variety of factors.

Solar wind-magnetosphere interaction



Ionosphere-Thermosphere Interaction

✓ Focusing on Disturbance Dynamo

http://denji102.geo.kyushu-u.ac.jp/stp/research.html

Magnetosphere-ionosphere interaction

1. Introduction

■ Disturbance Dynamo

➢ Dynamo action due the neutral wind caused by Joule heating in the polar regions.

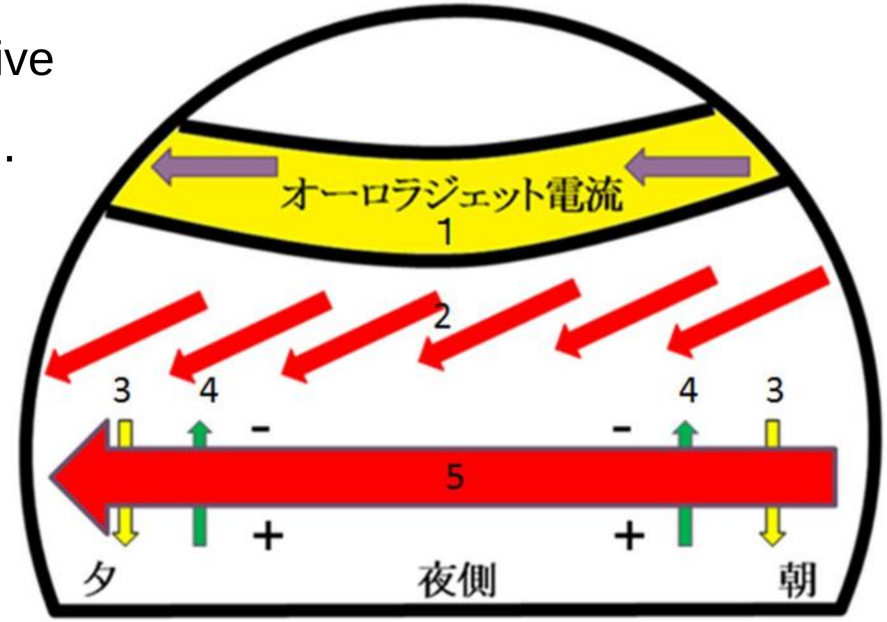
1) Joule heating generates a pressure gradient in the polar direction.

2) The balance between the Coriolis force and the pressure gradient produces a westward neutral wind.

3) Electric field **U** x **B** is generated and positive charge is accumulated in the equatorward.

4) Poleward electric field is generated.

5) Westward **E** x **B** drift occurs.

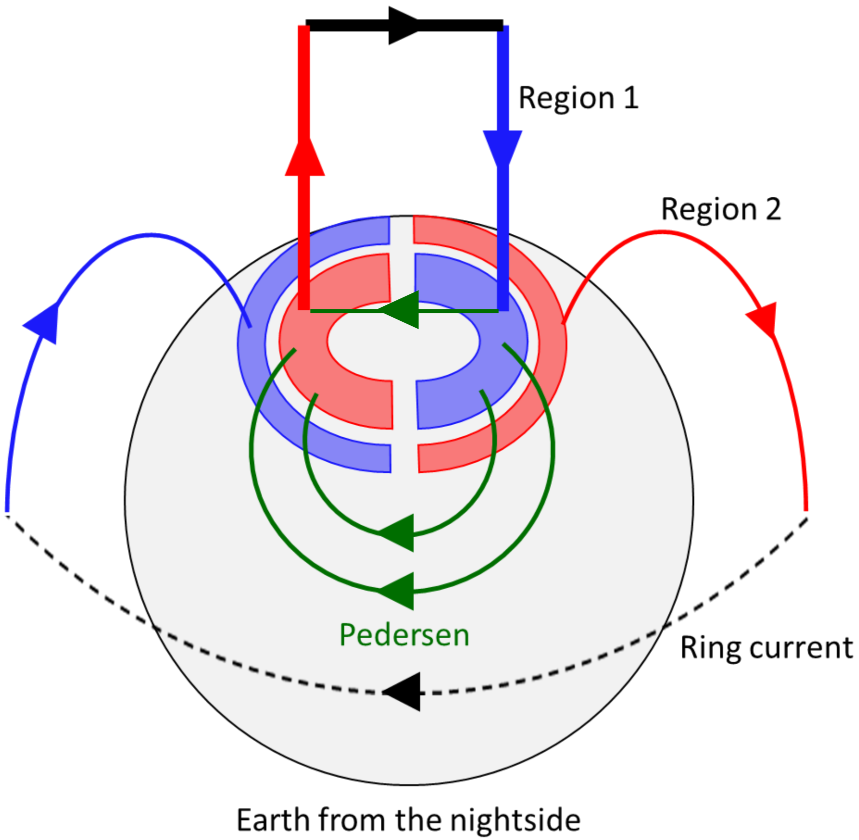


✓ The effect of the Disturbance Dynamo lasts for several hours after a magnetic storm occurs (Blanc and Richmond, 1980).

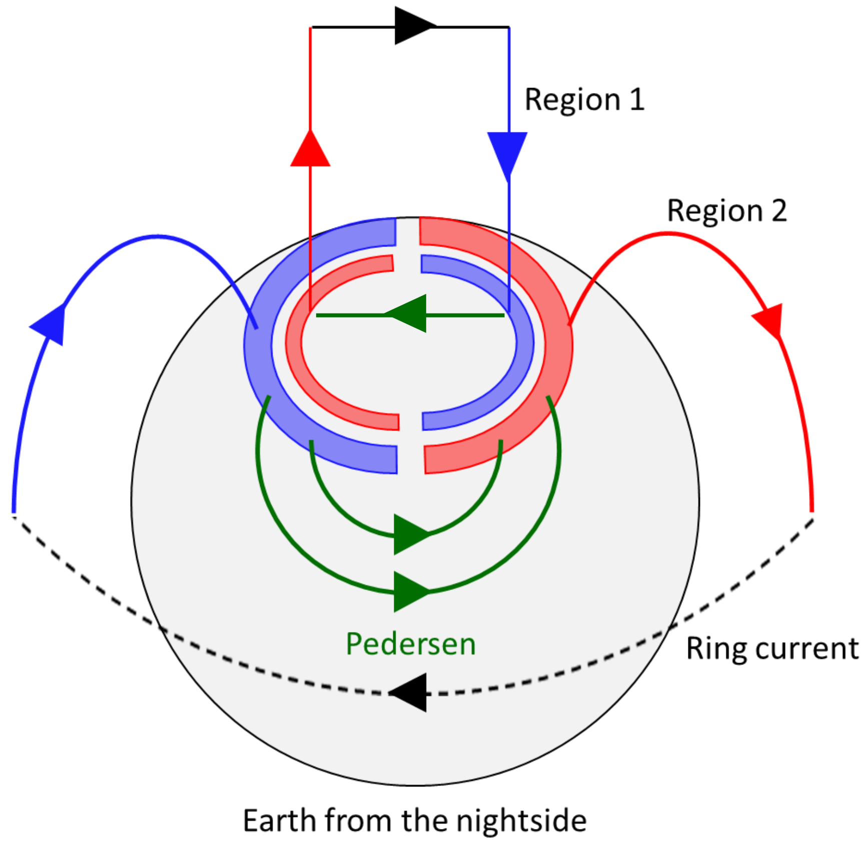
Zou修論 (2012)

1. Introduction

■ Penetration electric field



■ Overshielding



1. Introduction

■ Motivation

- The detailed effect of the Disturbance Dynamo on the mid-latitude ionosphere after geomagnetic storms is not clear.

- Past SuperDARN radar observations of Disturbance Dynamo (e.g., Baker et al. (2007), Zou & Nishitani (2014)) have not taken into account the effect of the magnetospheric electric field.

■ Purpose

- To study the characteristics of ionospheric echoes observed by SuperDARN Hokkaido East Radar during the storm recovery phase.

- To distinguish the effects of the disturbance dynamo from the effects of the magnetospheric electric field by comparing with the variation of FACs.

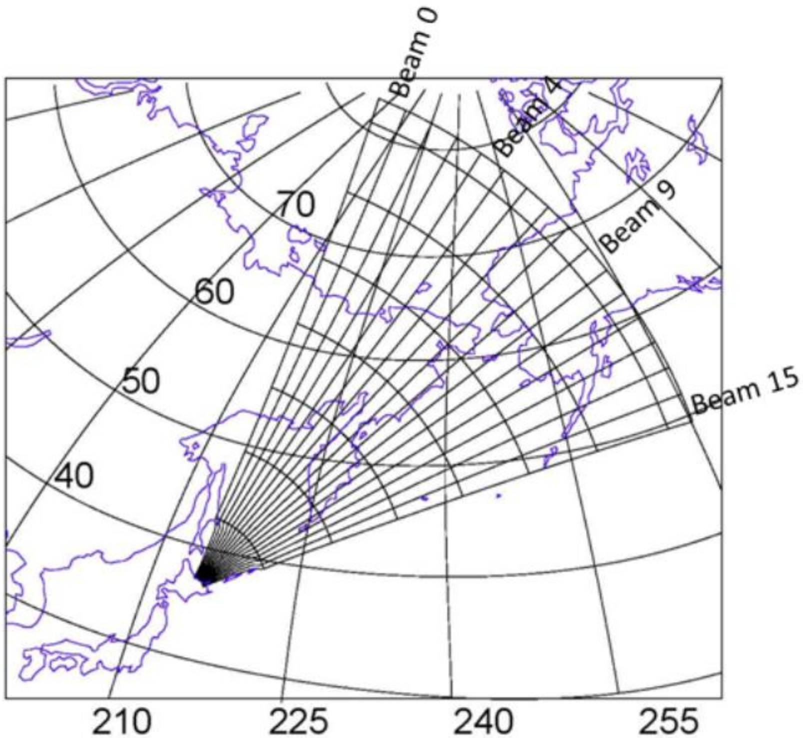
2. Instrumentation and method

- SuperDARN (Super Dual Auroral Radar Network)
  - A global network of ground-based HF radars.
  - Observing the line-of-sight velocity of ionospheric plasma.

- Hokkaido East Radar (HOK)

- It is located at the lowest latitude (37.3° N) of all the SuperDARN radars.

✓ It covers the mid-latitudes (40-60° MLAT).

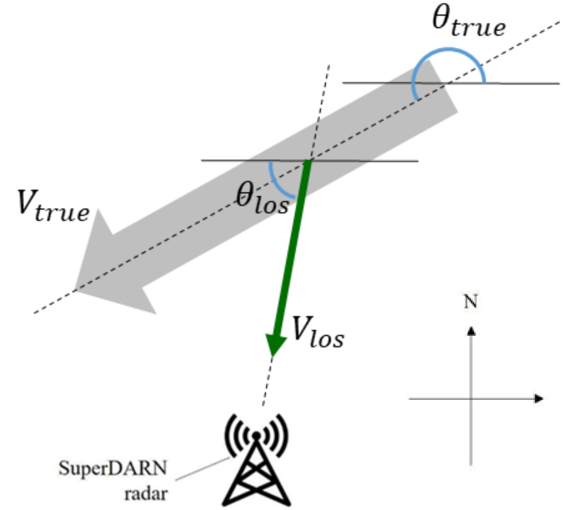


Zou修論 (2012)

2. Instrumentation and method

- **Beam swinging technique**

➢ A method for calculating the actual flow velocity from the line of sight velocity.



1. Assume that the plasma flow vector is constant at the same magnetic latitude in the radar field of view.

2. Derive $(V_{true}, \theta_{true})$ from the following equation.

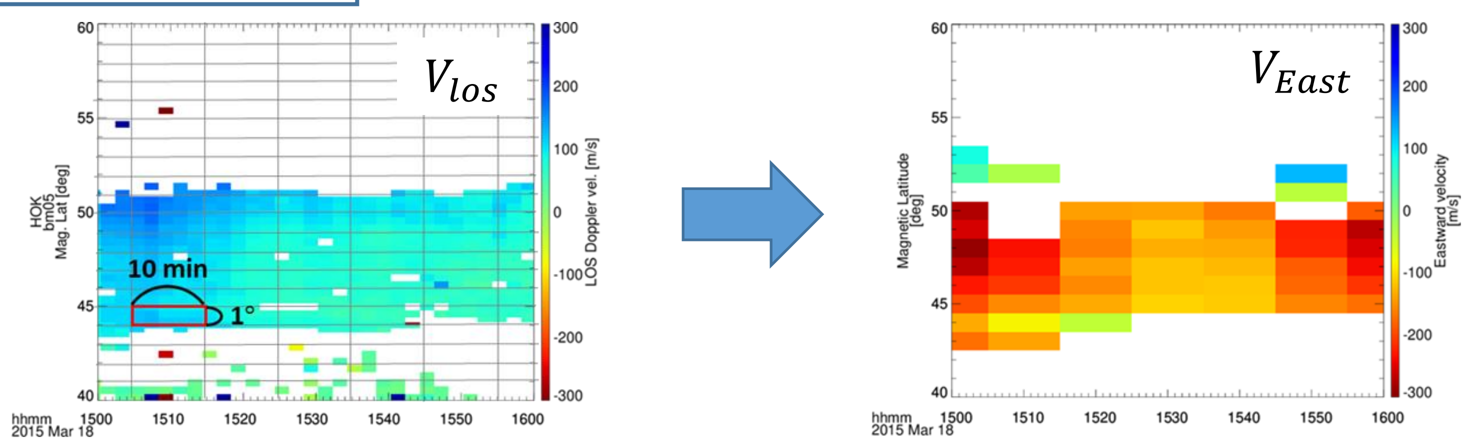
$$V_{los} = V_{true} \cos(\theta_{true} - \theta_{los})$$

V_{true}: Actual flow velocity
θ_{true}: Actual flow azimuth
V_{los} : line of sight velocity
θ_{los}: Beam Azimuth

3. Derive $(V_{true}, \theta_{true})$ from the following equation.

$$V_{East} = V_{true} \cos \theta_{true}$$

V_{East}: Eastward flow velocity

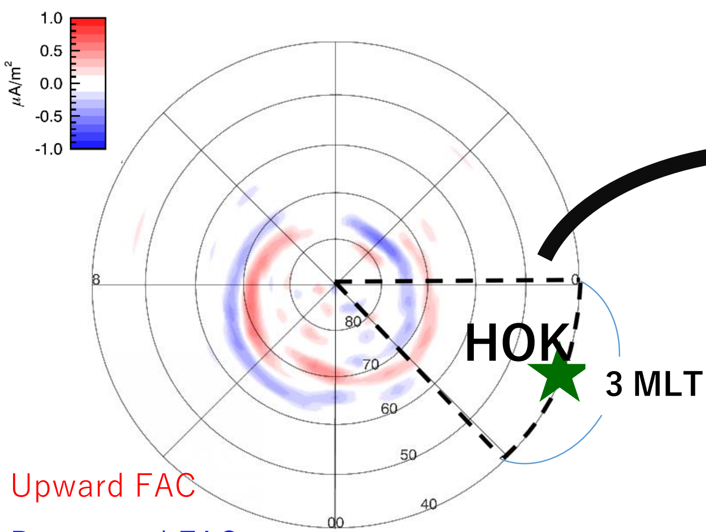


2. Instrumentation and method

■ AMPERE (Active Magnetosphere and Planetary Electrodynamics Response Experiment)

- AMPERE calculates the Field Aligned Currents (FACs) from magnetometer data on a network of Iridium satellites.

- Calculated the sum of the upward and downward FACs for each of the longitude range close to HOK.

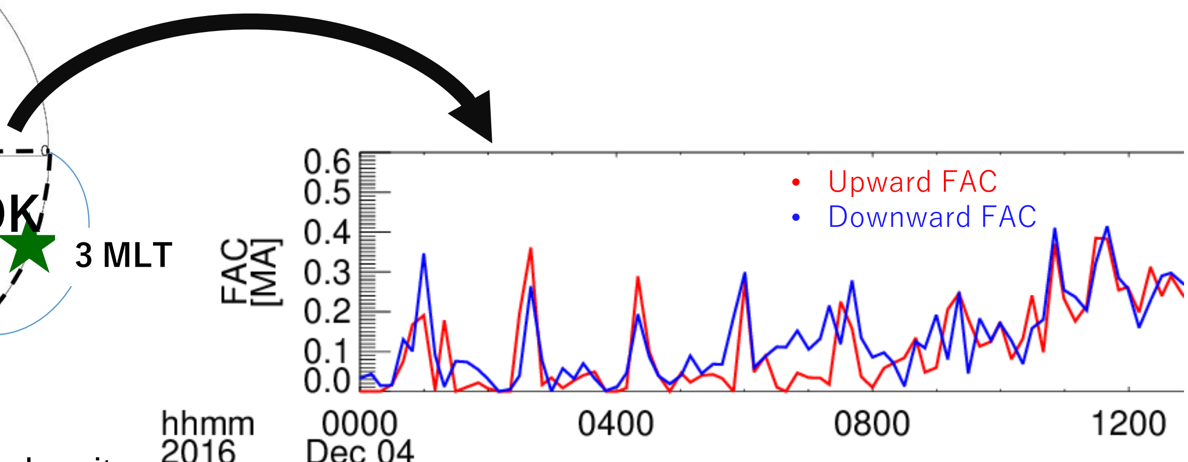


赤： Upward FAC

青： Downward FAC

10-minute average value of current density

http://ampere.jhuapl.edu/

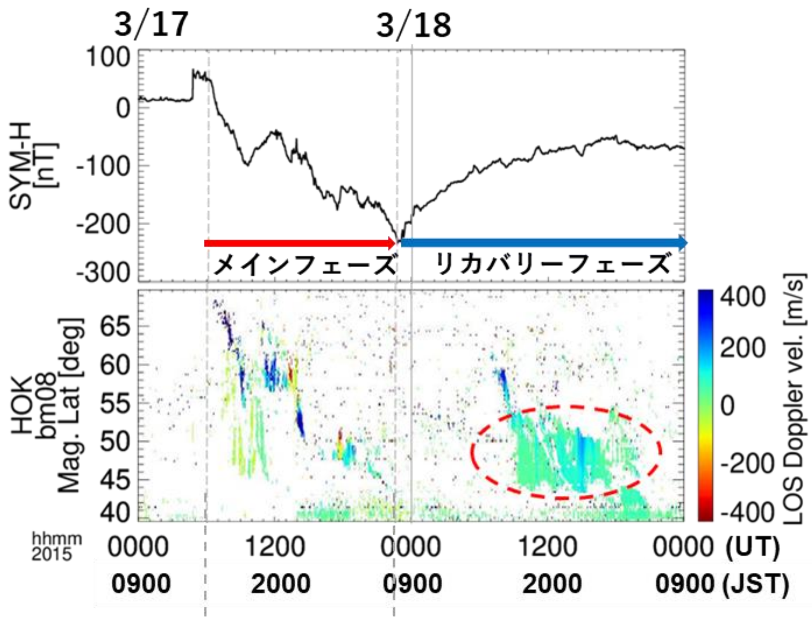


Sum of FACs of the longitude range close to HOK

3. Result　－Event selection－

■ We searched for echoes observed for several hours during the recovery phase of geomagnetic storms from 2012 to 2017.

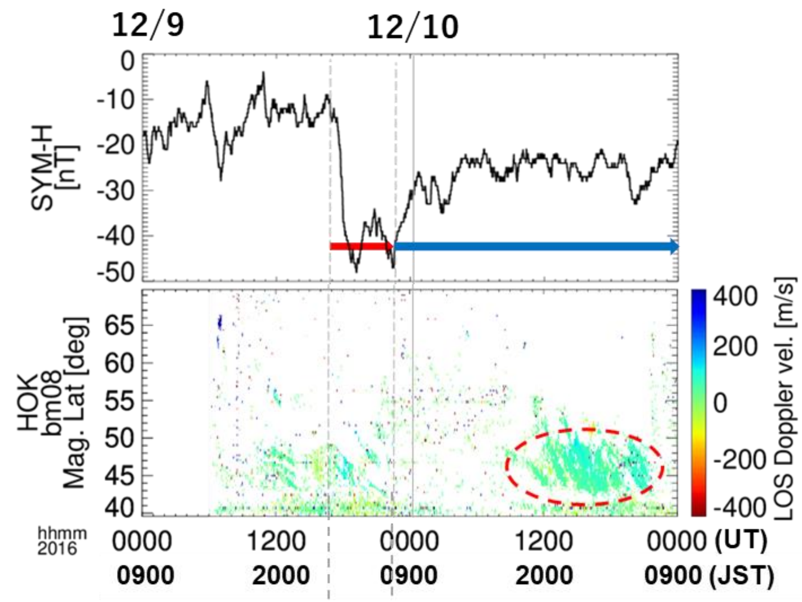
Event 1 (2015/3/18)



6:18 UT　　22:46 UT
(SYM-H: -233 nT)

✓ Echoes were observed from 10:00 to 18:00 UT (19:00 to 3:00 JST).

Event 2 (2016/12/10)



16:32 UT　　22:28 UT
(SYM-H: -47 nT)

✓ Echoes were observed from 12:00 to 20:00 UT (21:00 to 5:00 JST).

3. Result　－Event 1－

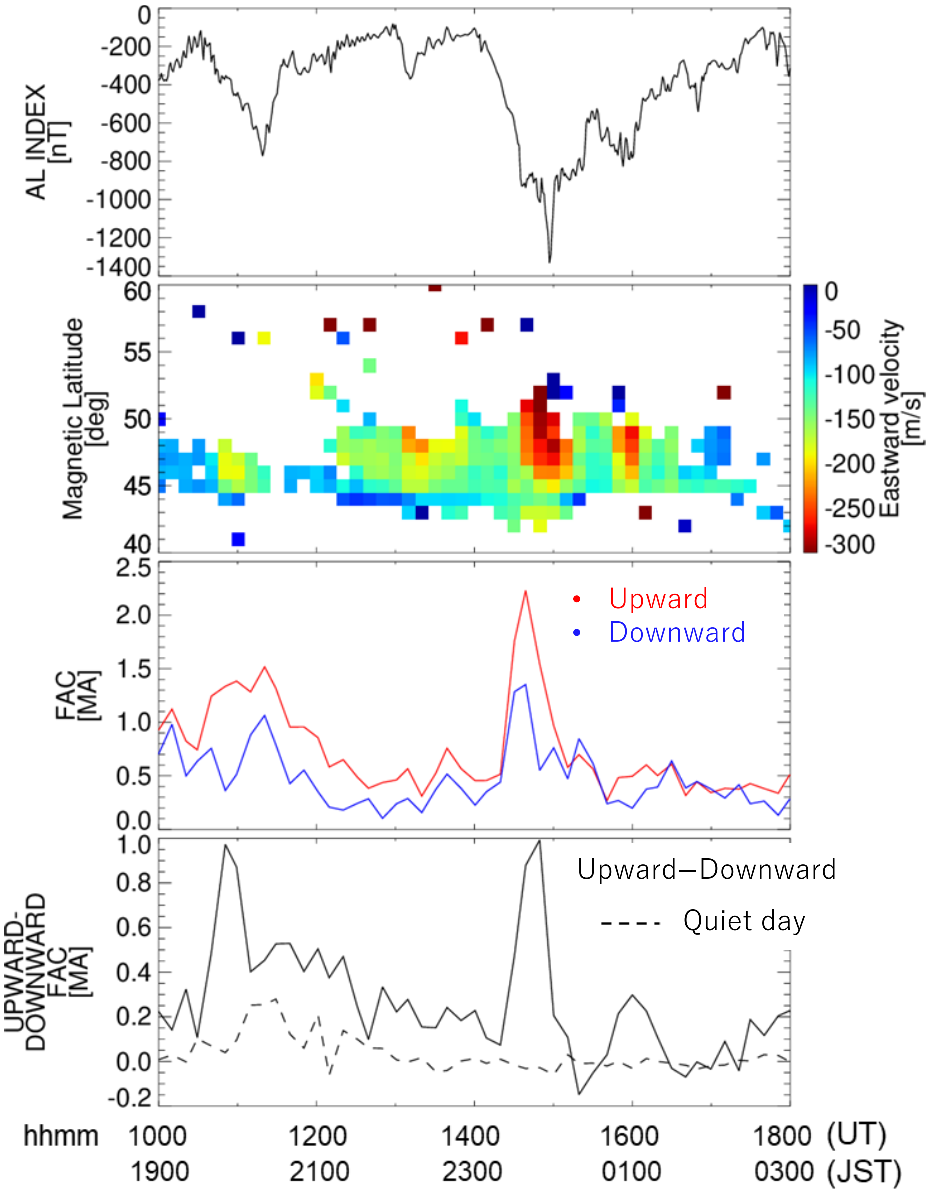
■ 2015-3-18/10:00-18:00 UT (19:00-3:00 JST)

● Plasma flow

- Westward flow of about 130 m/s continues for about 8 hours.
- Westward velocity increases to 300 m/s with a substorm expansion.

● FACs

- Upward current is generally larger than downward current.
- The difference between the upward and downward currents increases with a substorm expansion.



3. Result　－Event 2－

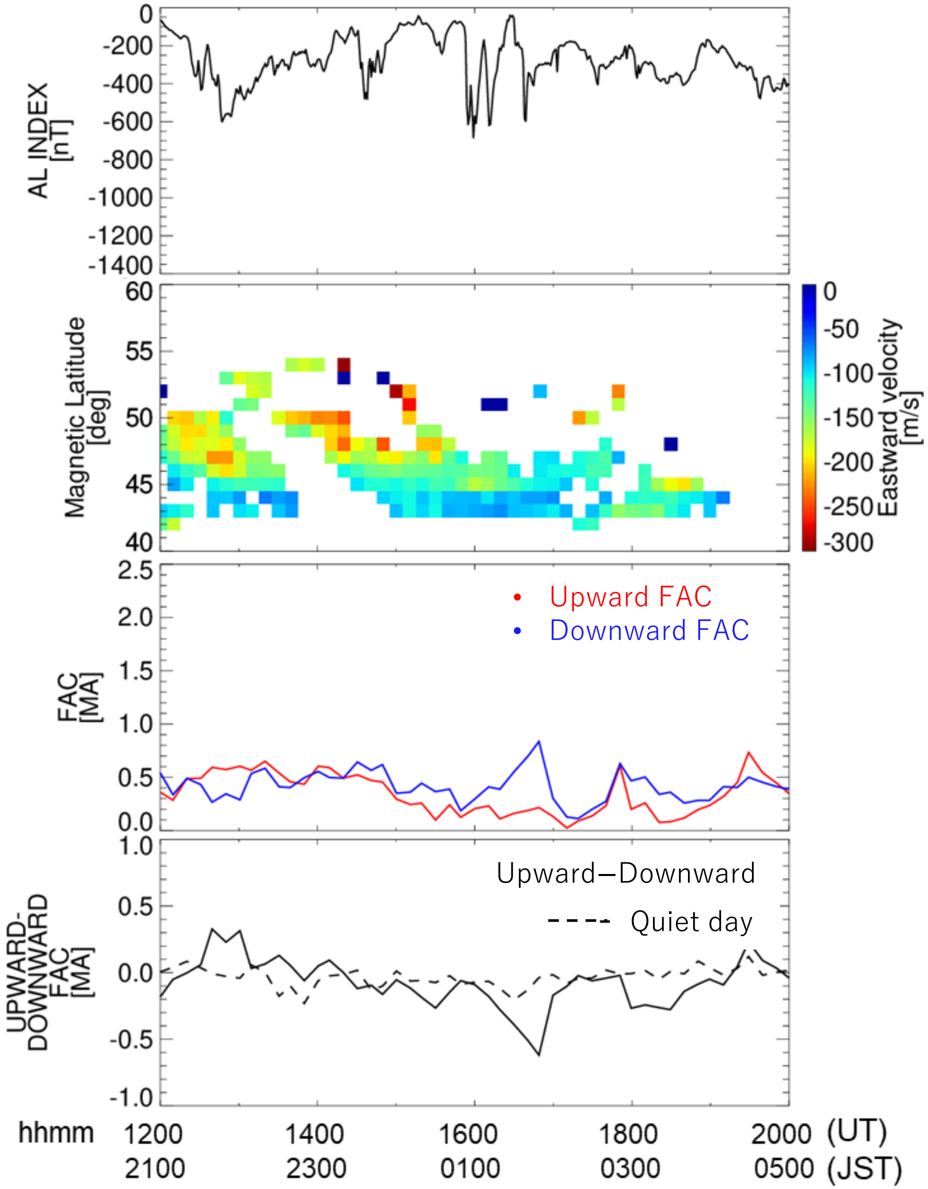
■ **2016-12-10/12:00-20:00 UT (21:00-5:00 JST)**

● **Plasma flow**

- Westward flow of about 130 m/s continues for about 7 hours.
- No clear relationship with substorm.

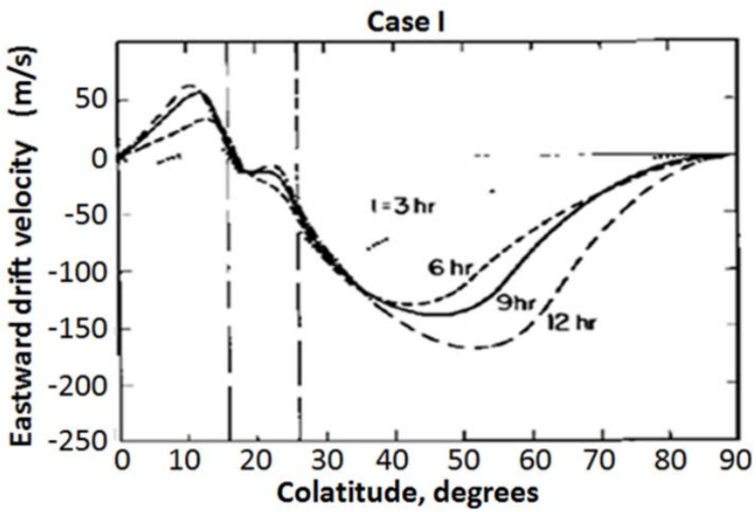
● **FACs**

- No significant difference between upward and downward FACs.
- No clear relationship with substorm.



4. Discussion　－Comparison with simulation－

■ Simulation of Disturbance Dynamo Effect (Blanc and Richmond, 1980)



Zonal plasma flow by Disturbance Dynamo after a geomagnetic storm

- After the onset of the magnetic storm, the flow velocity is gradually increasing.
- After 12 hours, the flow is about 150 m/s westward.

■ Characteristics of the flows observed in this study

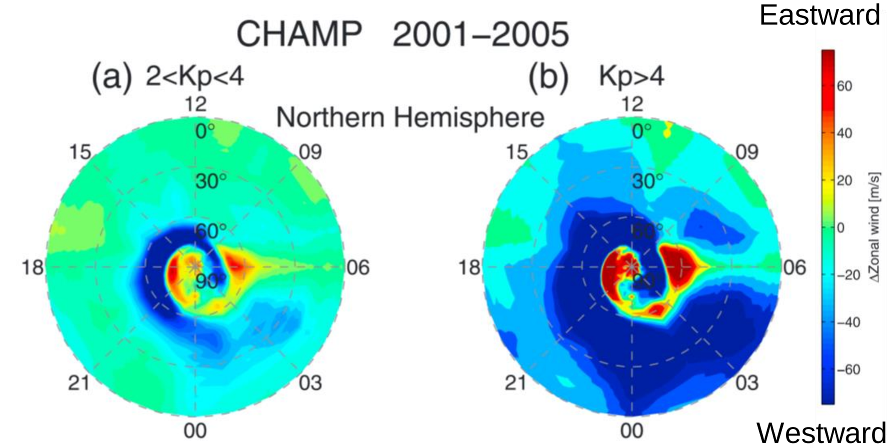
date	Direction	Average velocity at 45° [m/s]	Delay from SYM-H peak [h]	Duration [h]
2015/3/18	Westward	128	~11	~8
2016/12/10	Westward	125	~13	~7

- These are consistent with the features of the Disturbance Dynamo.

4. Discussion　－Comparison with neutral wind－

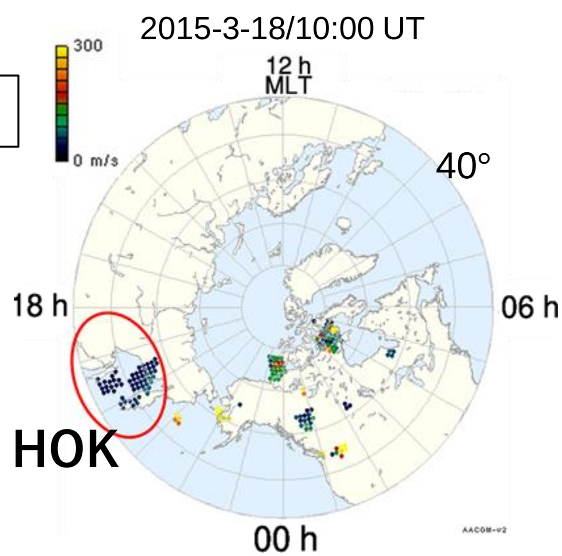
- Neutral wind
  - ➢ Westward winds expand to mid and low latitudes during geomagnetic disturbances.
- Plasma flow
  - ➢ Westward flow was observed from ~20 MLT in Event 1 and ~22 MLT in Event 2.

✓ They could be affected by neutral winds.

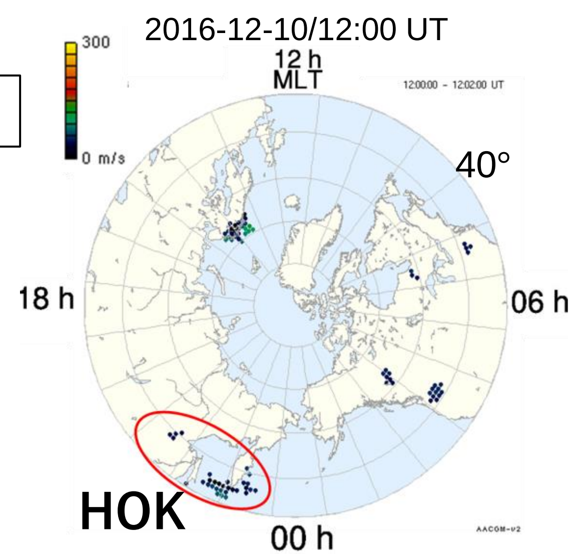


Zonal wind (Subtracted the quiet time values)
(Xiong et al., 2015)

Event 1



Event 2



Polar plots of SuperDARN observations when flows appeared.

4. Discussion －Comparison with FACs－

Event 1

- Mainly, the upward FAC was larger than the downward FAC.
- There was a temporary increase in velocity as well as an increase in upward FAC due to a substorm expansion.

➡ ✓ The Disturbance Dynamo and penetration electric field effects are mixed.

Event 2

- There was no significant difference between the upward and downward FACs.
- Westward flow of about 130 m/s was continuously occurring.

➡ ✓ Most likely affected by the Disturbance Dynamo.

■ Other possible source of flow

- SAPS
  - ➢ SAPS flow velocity threshold ：150~200 m/s (Nagano et al., 2015)
  - ➢ Average velocity at 45° N for each event ：~130 m/s

5. Summary

- We analyzed the mid-latitude ionospheric flows during the recovery phase of two geomagnetic storms using HOK and AMPERE observations.

- In both events, about 130 m/s westward flow lasting for several hours was observed on the night side, which was consistent with the trend of the Disturbance Dynamo.

- In the March 18, 2015 event
- The upward FAC was dominant and the effects of the Disturbance Dynamo and the penetration electric field could not be clearly discerned.

- In the December 10, 2016 event
- Even though there was no significant difference between the upward and downward FACs, there was high velocity westward flows.
- These flows are mainly due to the influence of the Disturbance Dynamo.

✓ We discussed the disturbance dynamo effects using the SuperDARN as well as other effects such as magnetospheric FACs using the AMPRRE data.

6. Future work

- Collect more geomagnetic storms to statistically study the effects of the Disturbance Dynamo on the mid-latitude ionosphere.
- Use data from other SuperDARN radars.
- Make comparisons with models of the neutral atmosphere to study the effects of the Disturbance Dynamo in detail.

Acknowledgments

- SuperDARN is a collection of radars funded by national scientific funding agencies of Australia, Canada, China, France, Italy, Japan, Norway, South Africa, United Kingdom and the United States of America.

- We thank the AMPERE team and the AMPERE Science Center for providing the Iridium derived data products.

Reference

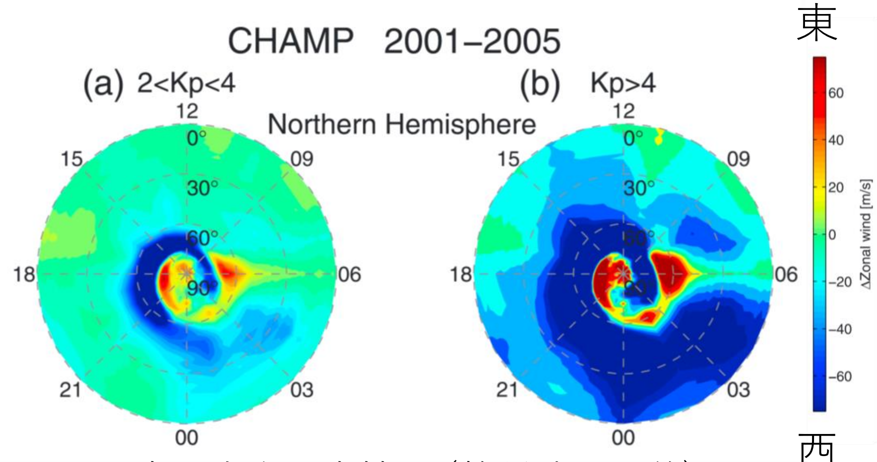
- Nishitani, N., Ruohoniemi, J.M., Lester, M. *et al.* Review of the accomplishments of mid-latitude Super Dual Auroral Radar Network (SuperDARN) HF radars. *Prog Earth Planet Sci* **6,** 27 (2019). https://doi.org/10.1186/s40645-019-0270-5

- Waters C.L., Anderson B.J., Green D.L., Korth H., Barnes R.J., Vanhamäki H. (2020) Science Data Products for AMPERE. In: Dunlop M., Lühr H. (eds) Ionospheric Multi-Spacecraft Analysis Tools. ISSI Scientific Report Series, vol 17. Springer, Cham. https://doi.org/10.1007/978-3-030-26732-2_7

Appendix

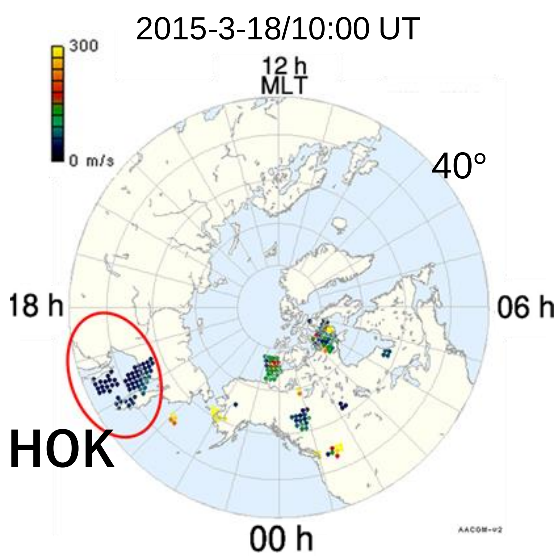
■ Comparison with neutral wind

	Kp index	MLT starting to observe flow
Event 1	4＋	~20 MLT
Event 2	3＋	~22 MLT

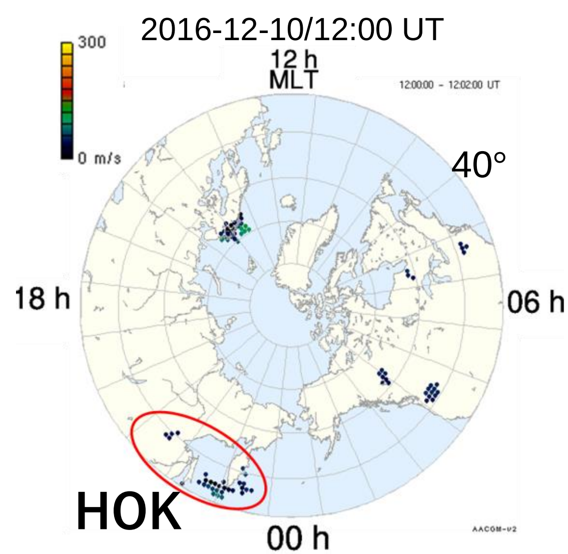


東西方向の中性風（静穏時との差）
(Xiong et al., 2015)

Event 1

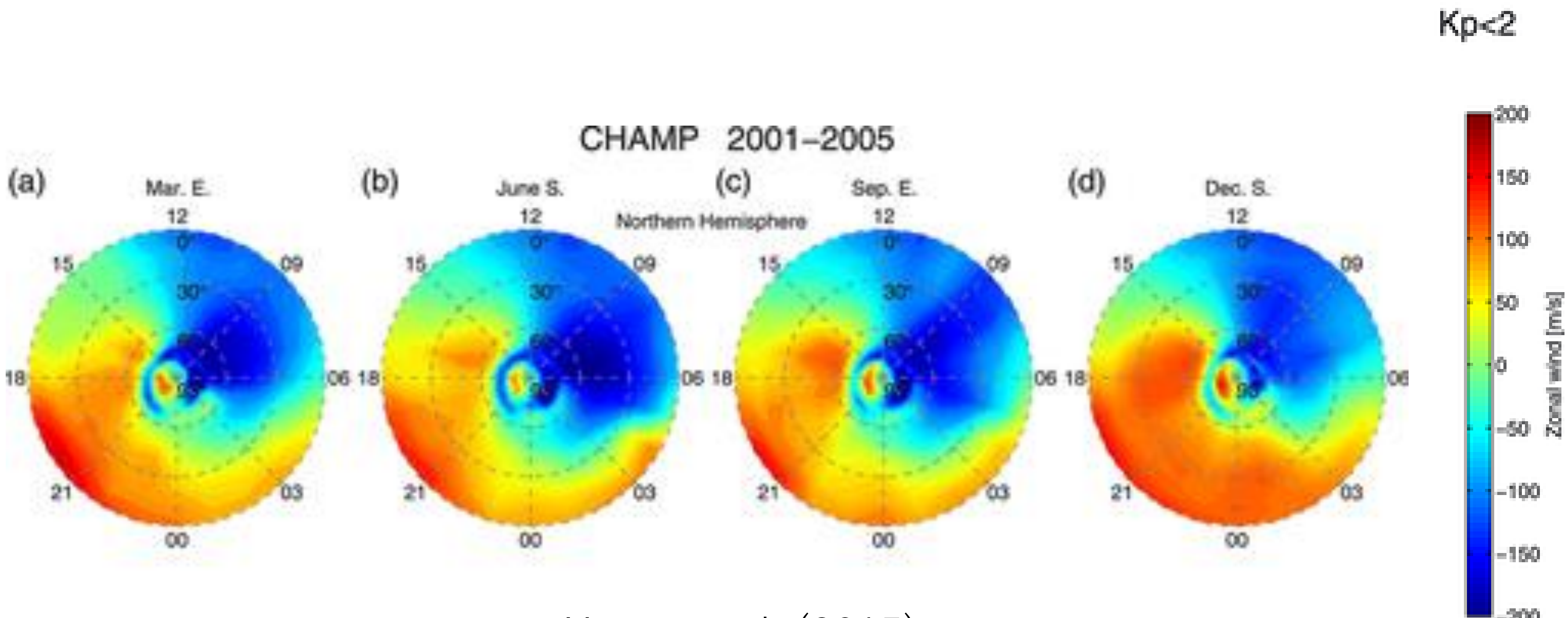


Event 2



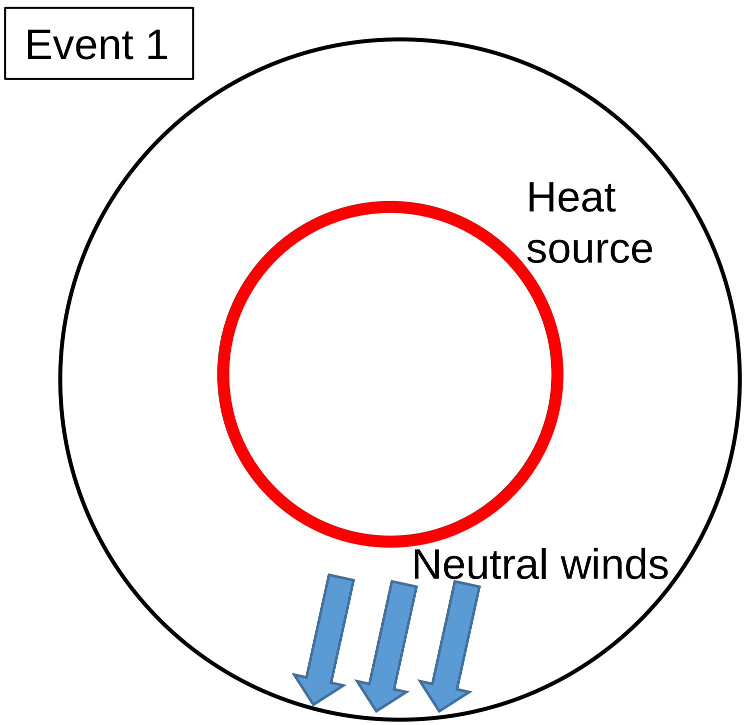
フローが観測され始めた時のSuperDARN観測の極域プロット

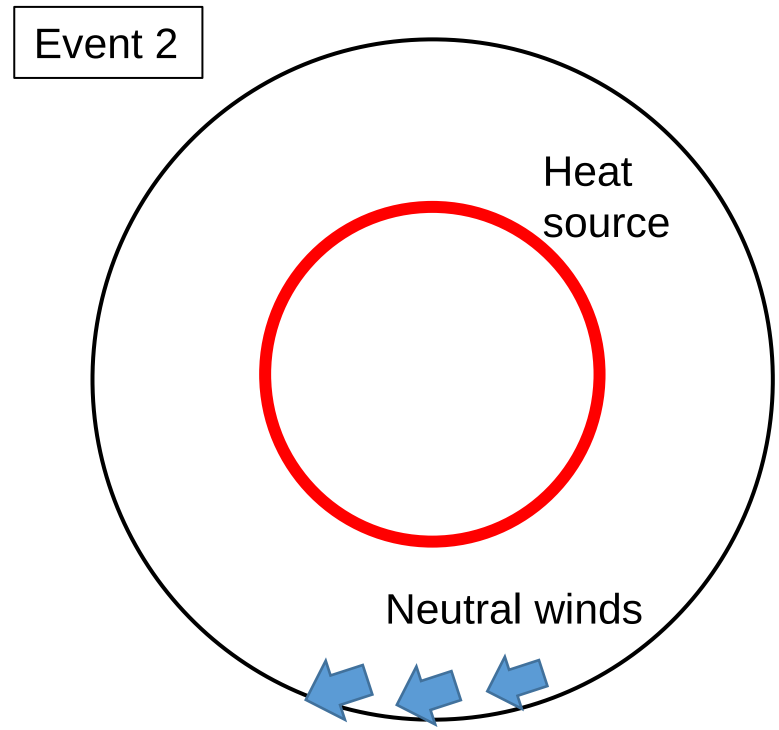
■ Neutral wind at quiet time



Xiong et al. (2015)

■ Why was the flow velocity the same for Event 1 and Event 2?

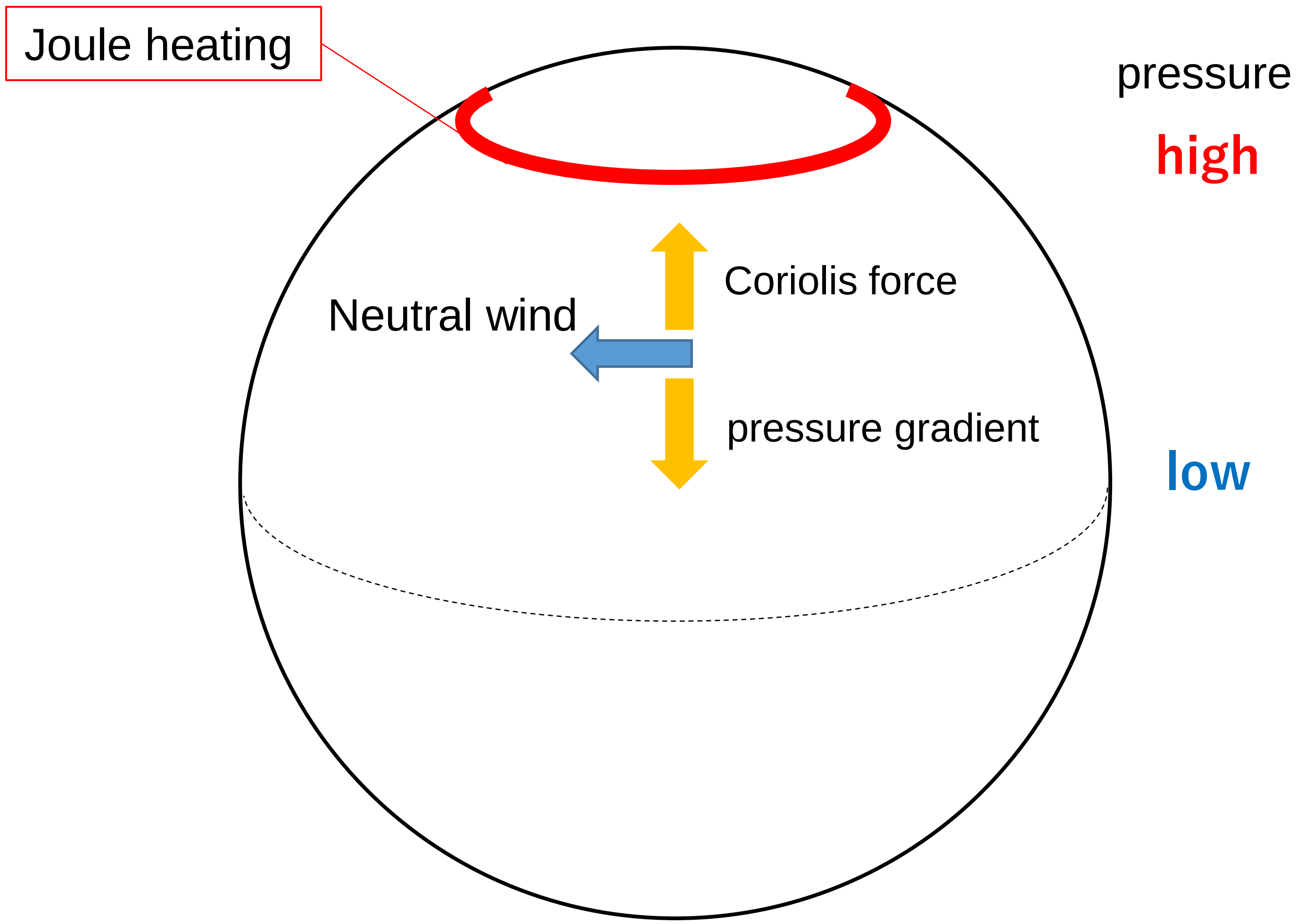




Event 1…The absolute value of the neutral wind speed is large, but the change to the westward direction is small.

Event 2…The absolute value of the neutral wind speed is small, but the change to the westward direction is large.

■ Mechanism of westward neutral wind generation

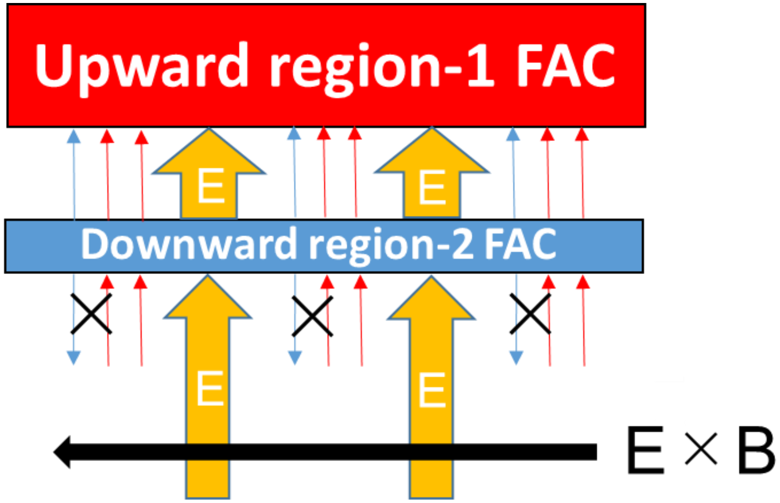


■ Mechanism of westward flow velocity increasing with increasing upward current

- Negative charge by upward FAC exceeds the charge of positive charge by downward FAC .
  上向き電流による負電荷のチャージが卓越。

- Poleward electric field penetrates to the equatorward of region-2 FAC.
  極方向の電場がリージョン2の低緯度側まで侵入。

- E x B drift enhances westward flow.
  E×Bドリフトによる西向きフローが強まる。



■ Simulation by Blanc and Richmond (1980)

- Maximum model height-integrated heating rates

⟶ 93 mW/m^2 at 79° MLAT

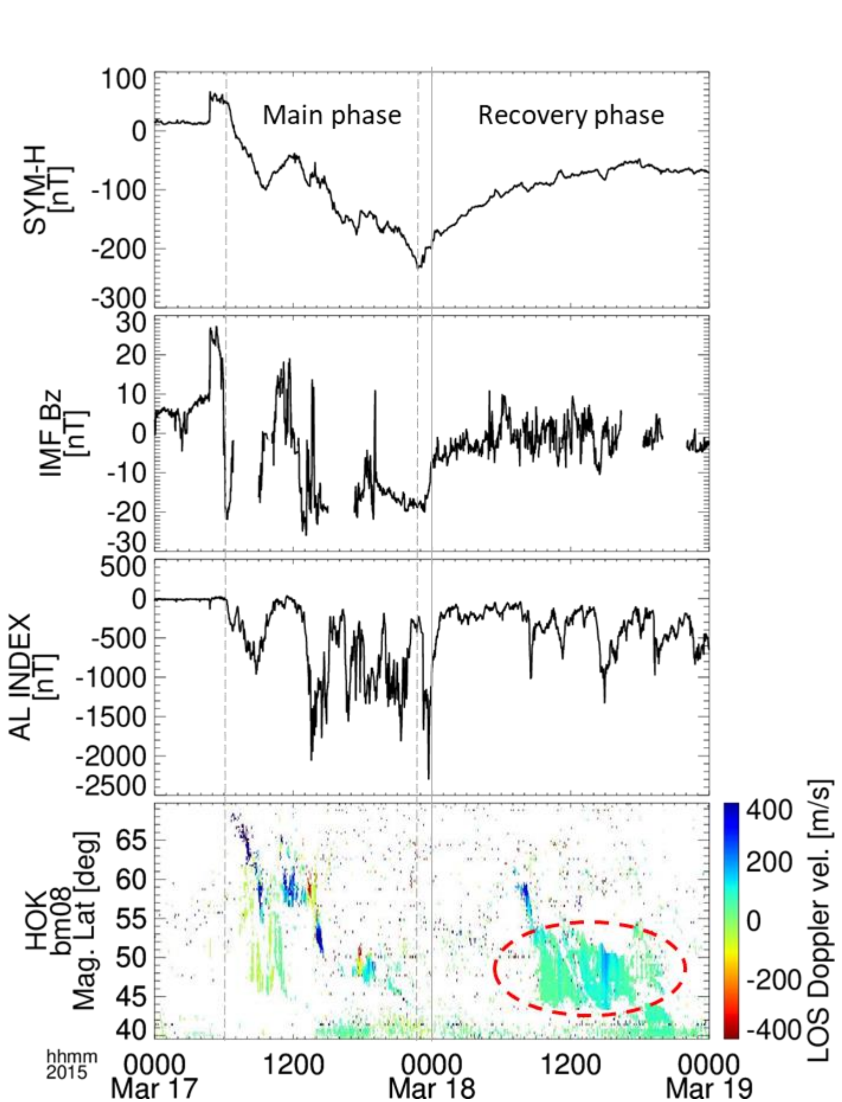
- Height-integrated Joule heating rates in the auroral zone during magnetospheric substorms

⟶ 50 mW/m^2 for 500 nT magnetic bays.

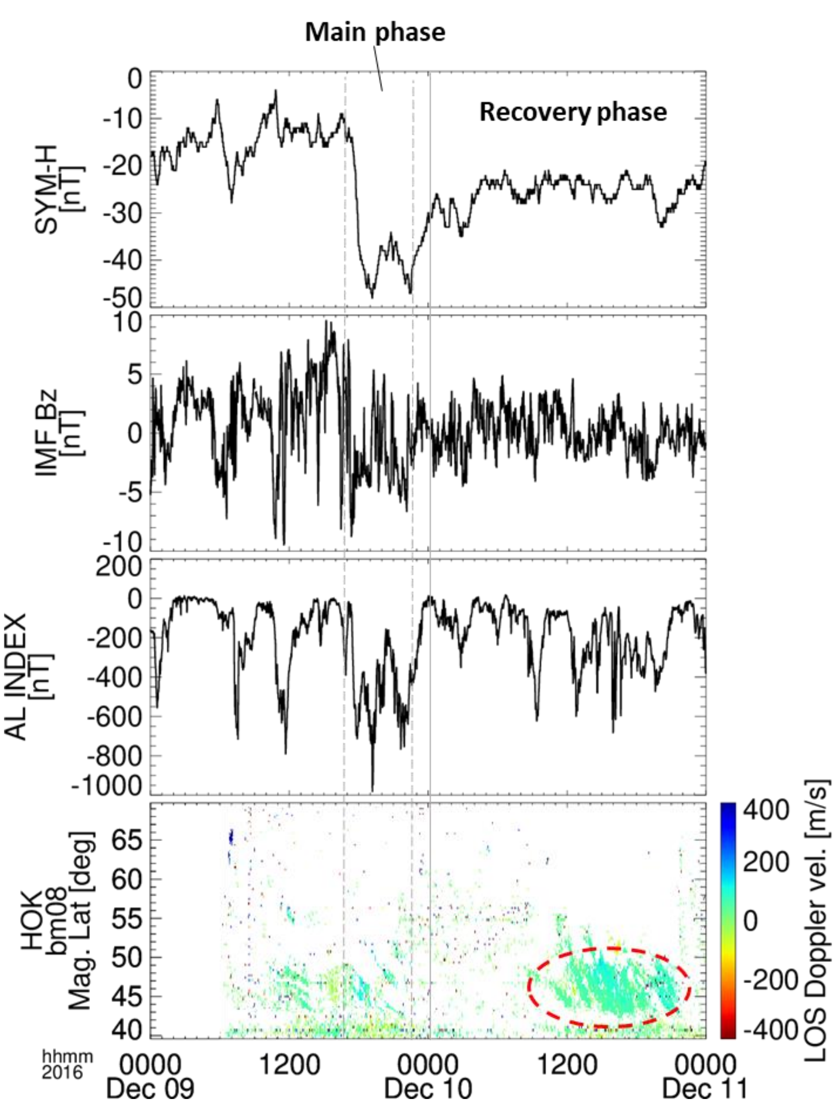
➡ Simulation probably corresponds to a large storm.

■ Overview of each event

Event 1

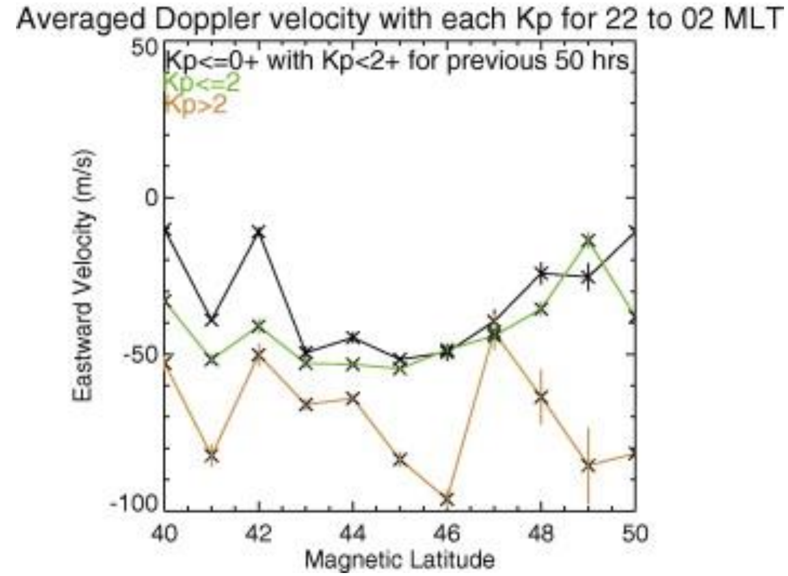


Event 2

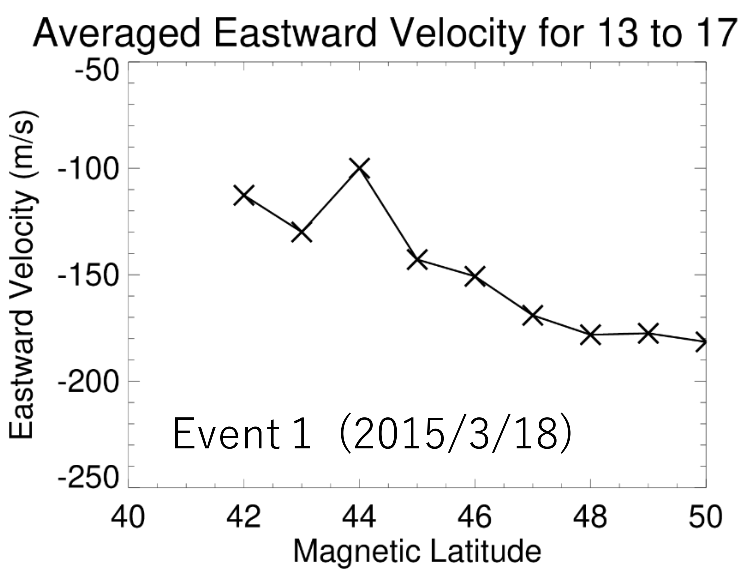


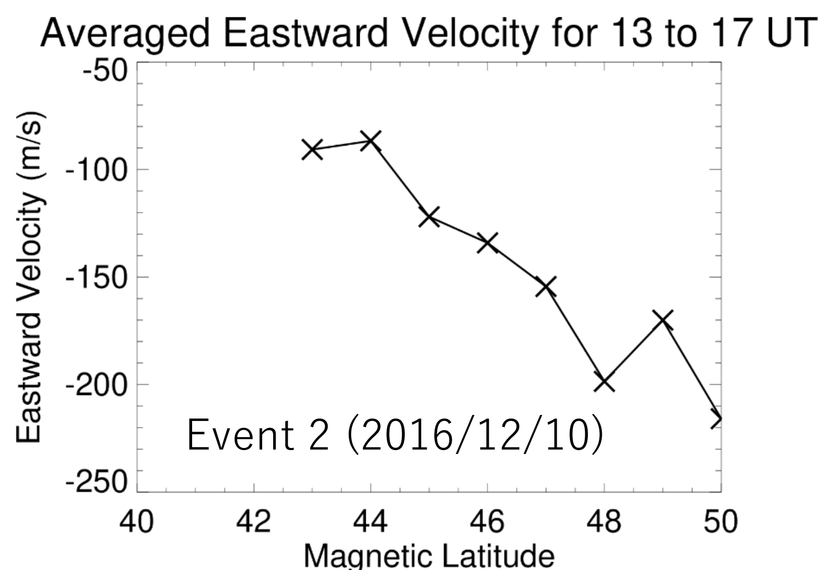
■ Comparison with quiet days

- **Drift on quiet days**
  - ➢ Westward drift of about **10 to 50 m/s**
- **2015/3/18**
  - ➢ Westward drift of about **100 to 180 m/s**
- **2016/12/10**
  - ➢ Westward drift of about **90 to 210 m/s**



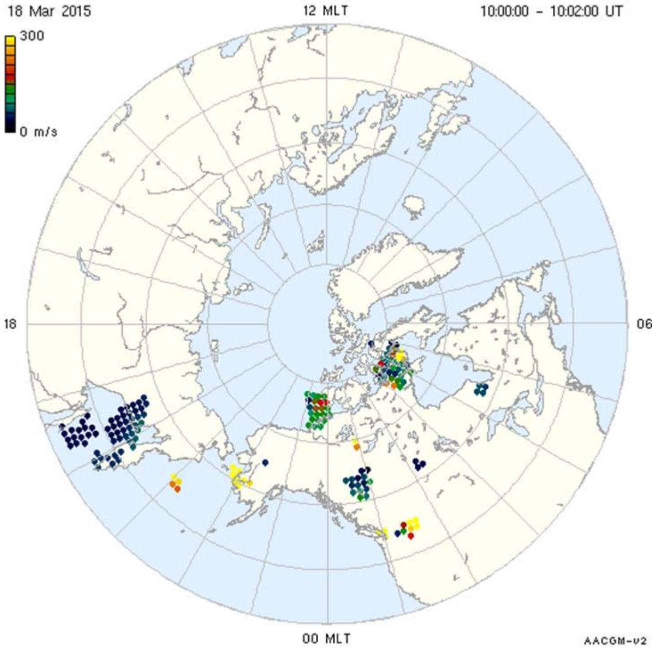
Zou and Nishitani (2014)

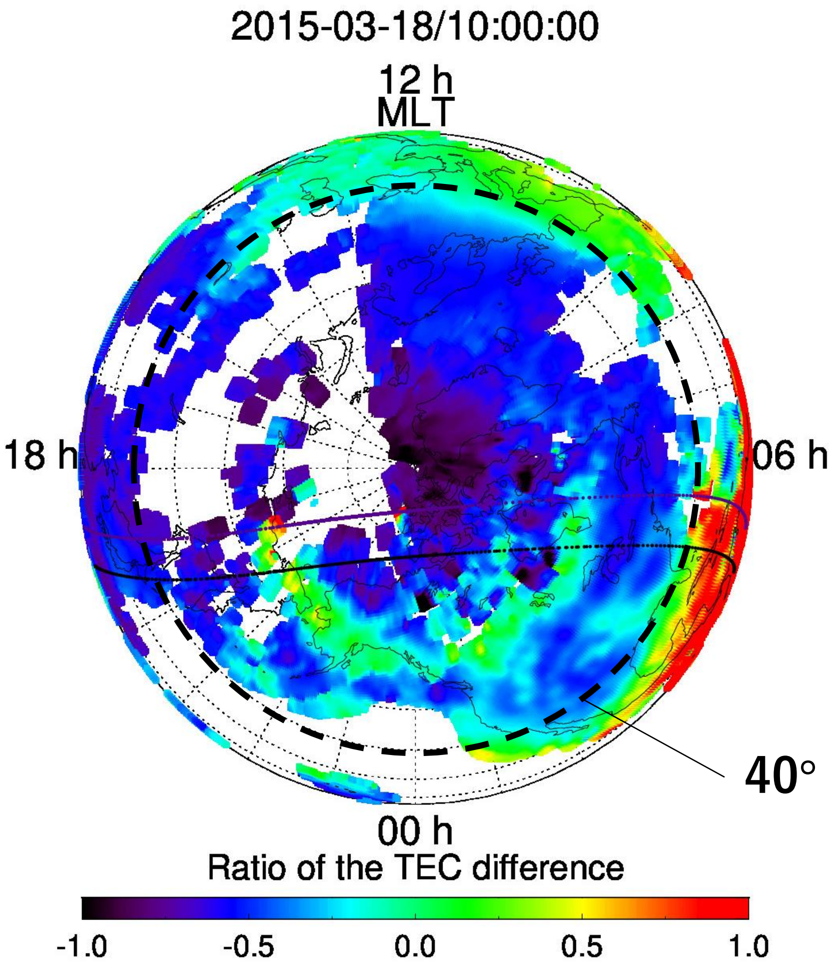




■ Comparison with rTEC

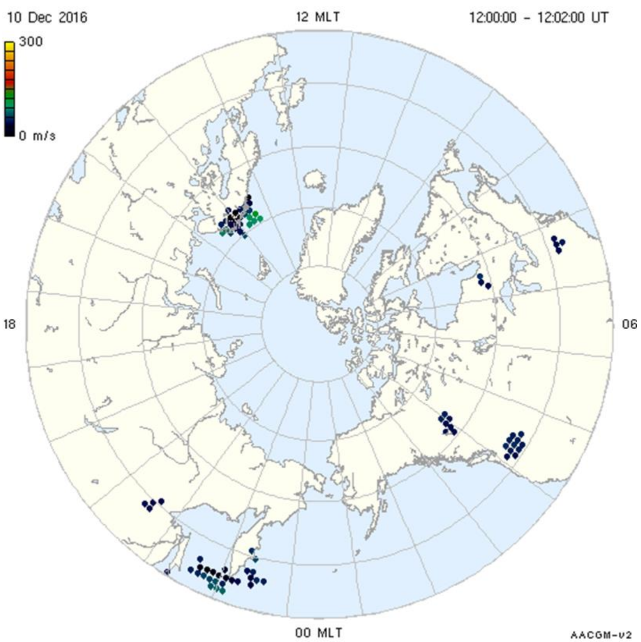
- 2015-3-18/10:00

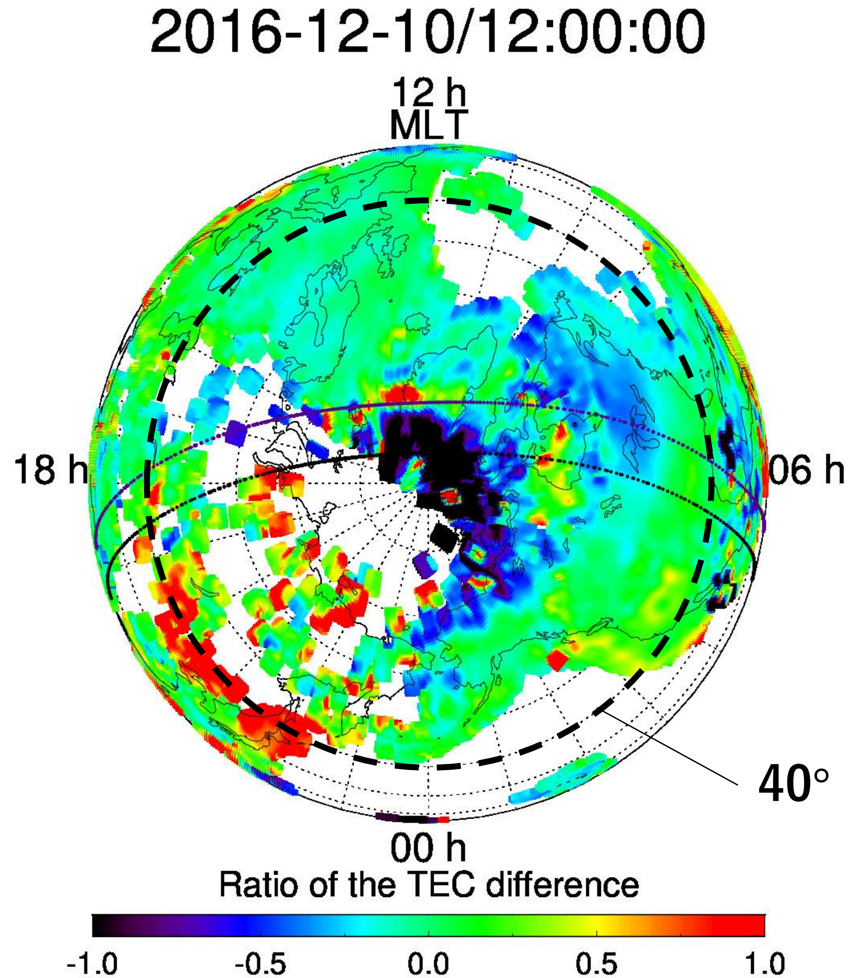




■ Comparison with rTEC

- 2016-12-10/12:00



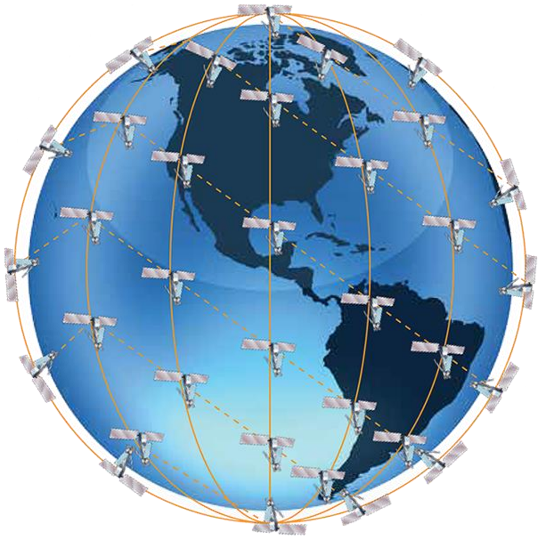


Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE)

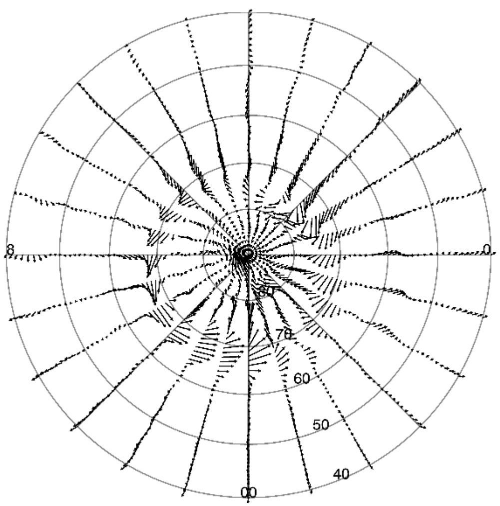
- To compare SuperDARN observations to Field Aligned Currents (FACs), we used the AMPERE observations.

- AMPERE provide near-real time magnetic field measurements using the Iridium satellite network.

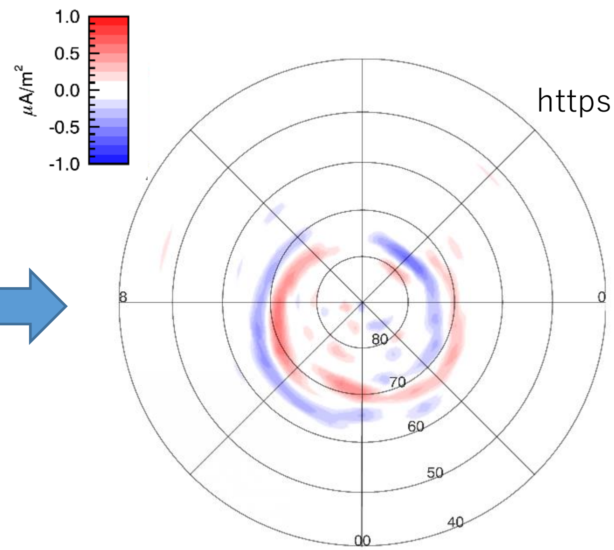
- Currents are derived from magnetic signatures according to Ampere’s law.



Iridium satellite network
https://www.polaris-as.dk/iridium-mariti



Magnetic perturbations



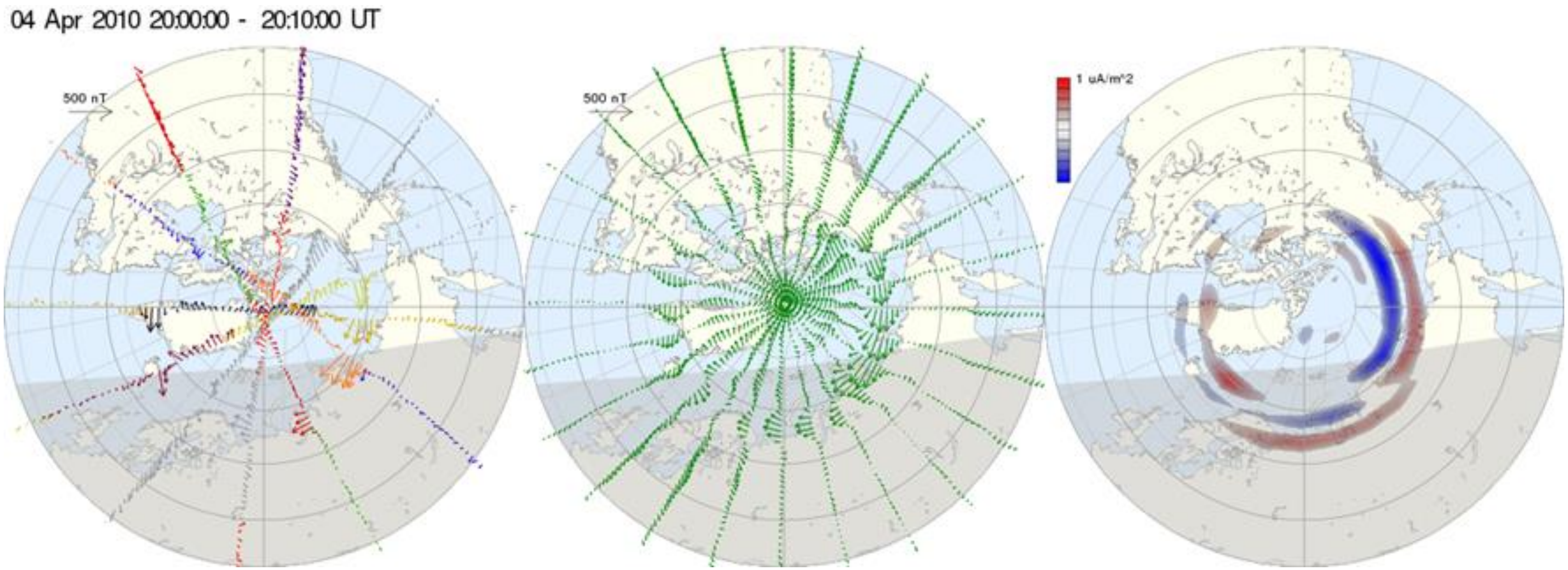
Current density

http://ampere.jhuapl.edu/

Red: upward current

Blue: downward current

■ AMPERE data products



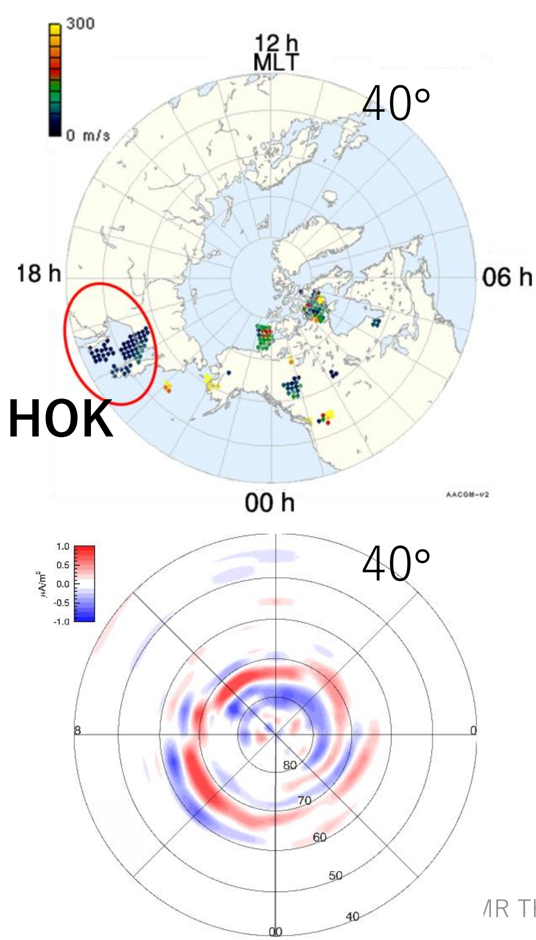
- Reduced magnetic field residual data showing the horizontal plane vectors (left)
- Spherical harmonic fit to the magnetic perturbations (center)
- Radial current (right)

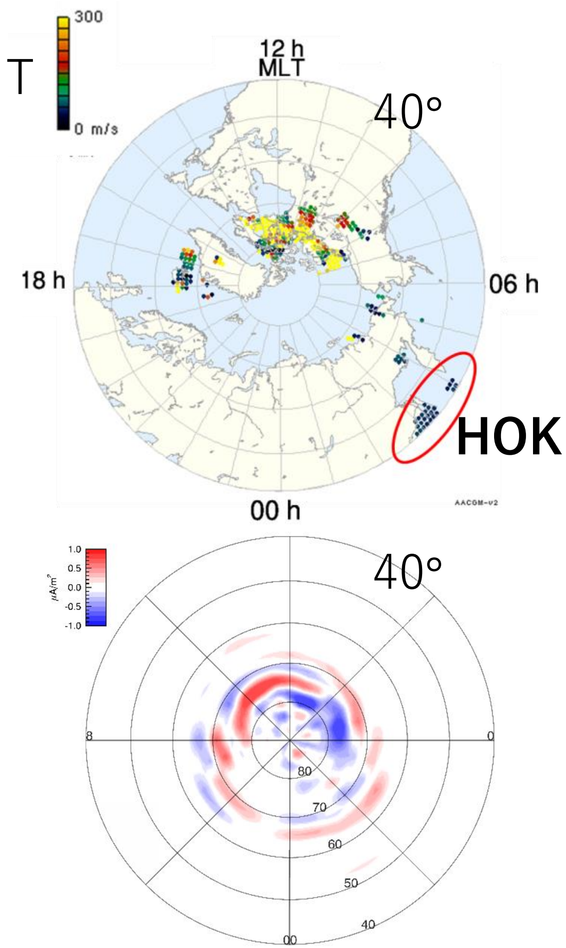
※ Current density of 0.2mA/m^2 or less is considered an error.

■ Polar map of SuperDARN and AMPERE observation (Event 1)

- Observation by SuperDARN radar (top) : Echoes spread to 40° MLAT (~100 m/s)
- Observation by AMPERE (bottom) : Region 2 FAC is located at about 60° MLAT

⇒ These flows are located equatorward of the shielding layer.

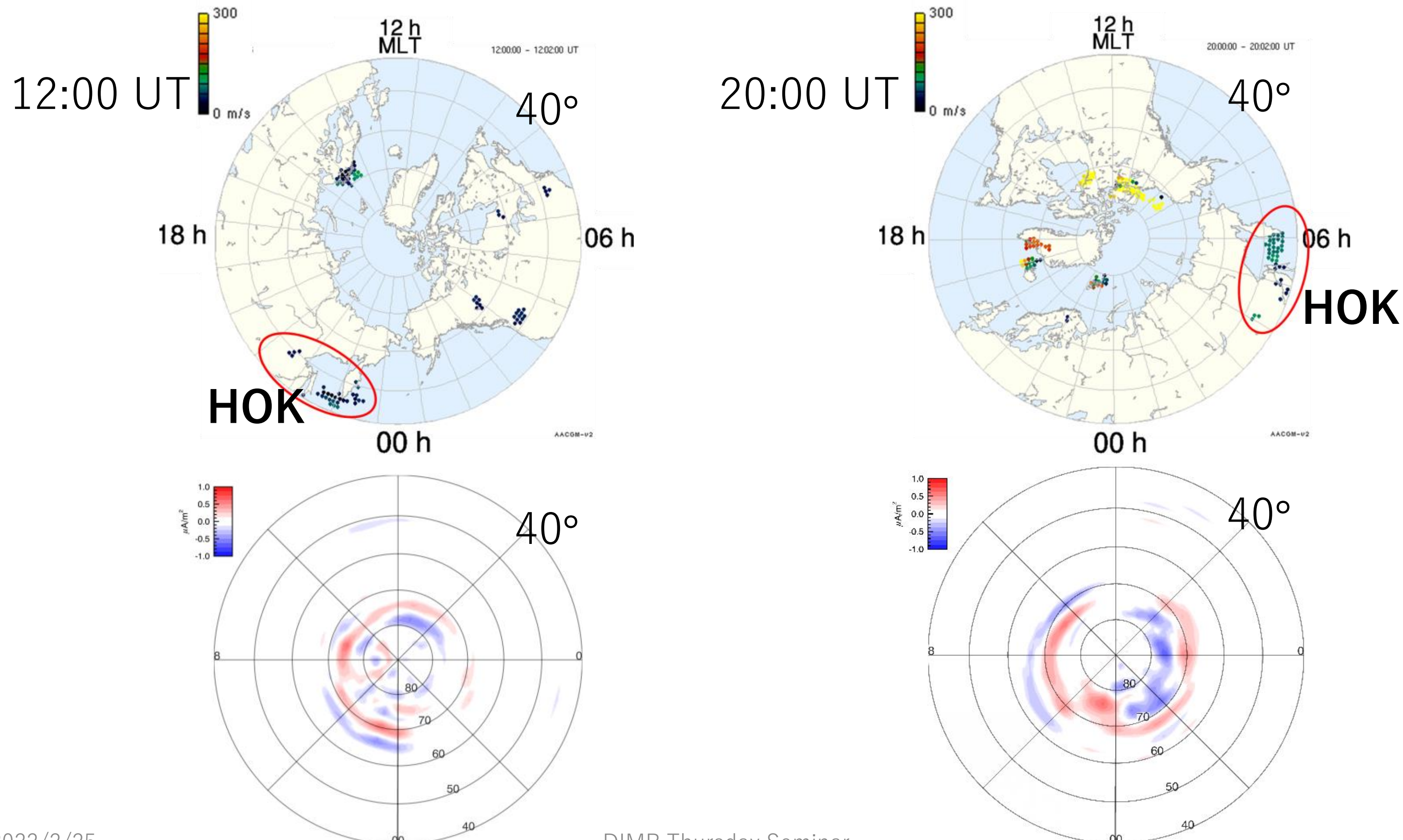




■ Polar map of SuperDARN and AMPERE observation (Event 2)

- Observation by SuperDARN radar (top) : Echoes spread to 40° MLAT (~100 m/s)
- Observation by AMPERE (bottom) : Region 2 FAC is located at about 60° MLAT

➡ These flows are located equatorward of the shielding layer.

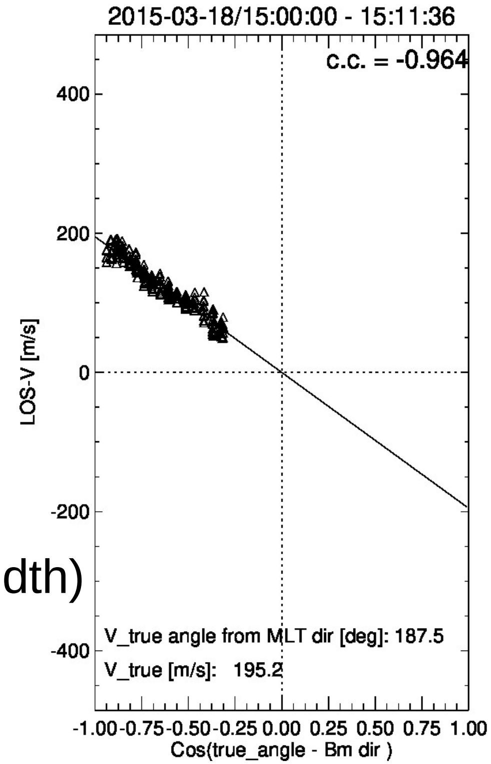


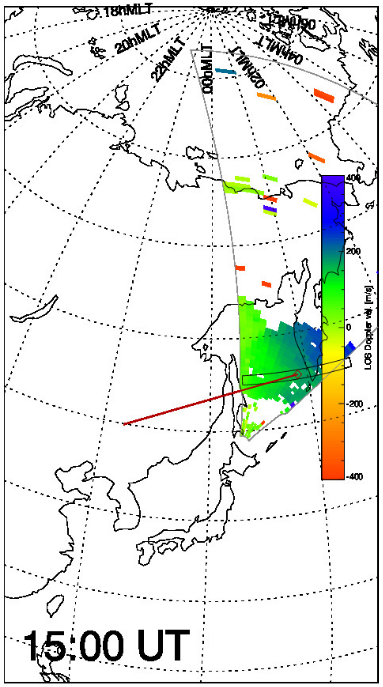
■ Beam swinging technique

$$V_{los} = V_{true} \cos(\theta_{true} - \theta_{los})$$

V_{true}: プラズマフロー速度
θ_{true}: プラズマフローの方位角
V_{los} ：視線方向のドップラー速度
θ_{los}: ビームの方位角

- Radar: HOK
- Latitude range: 1° from 40° to 60° MLAT
- Time resolution: 10 min
- Threshold
  - More than 10 data points
  - Correlation coefficient between V_{los} and $\cos(\theta_{true} - \theta_{los})$ is greater than 0.7
  - |Doppler velocity| ≤ 30−1/3×(spectral width)



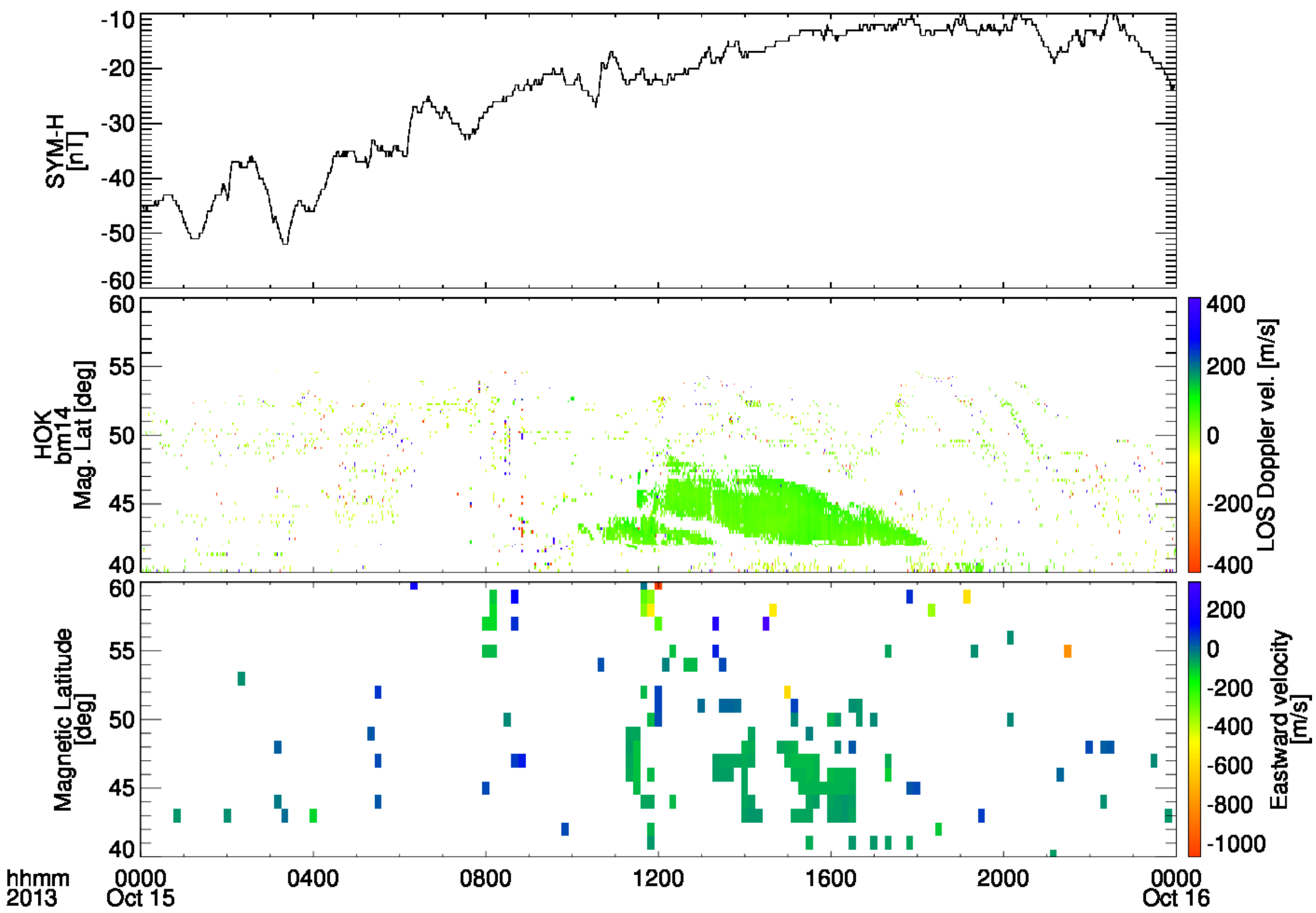


■ Data loss due to beam swinging technique

- 2013/10/15

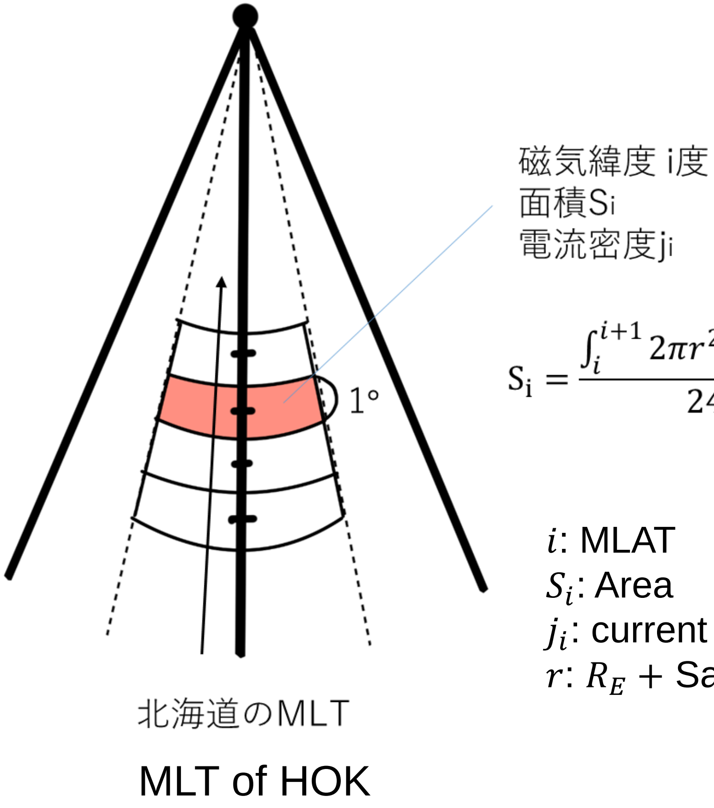
Before fitting

After fitting



■ Calculation of FAC

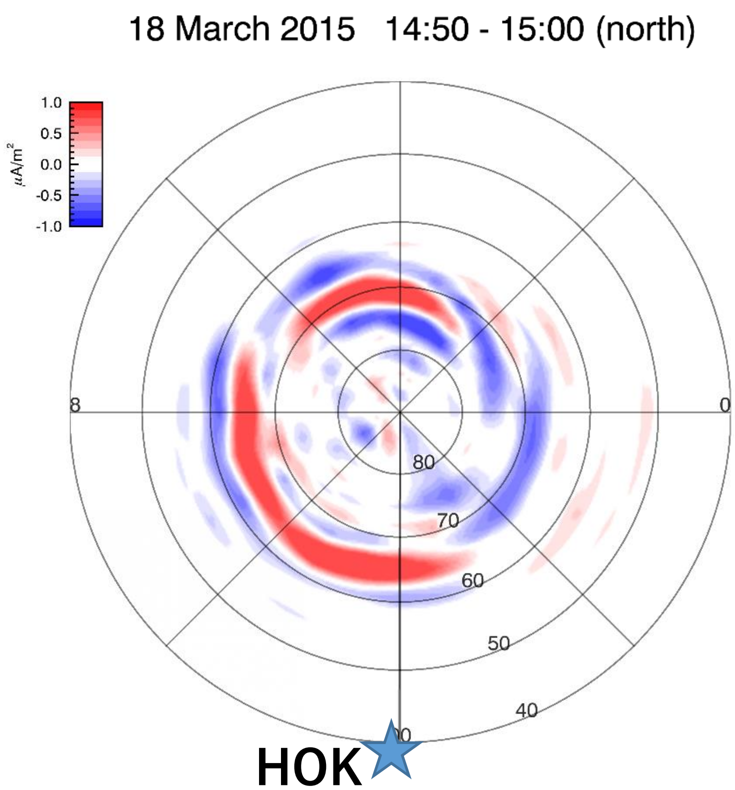
- Assume uniform current density over a range of 1MLT×1°.
  1MLT×1°の範囲の電流密度を一様と仮定
  - ➢ Current within a range: $I_i = j_i S_i$
- Add these together in the latitudinal direction from 40° to 89° magnetic latitude.
  これを磁気緯度40度から89度まで緯度方向に足し合わせる。

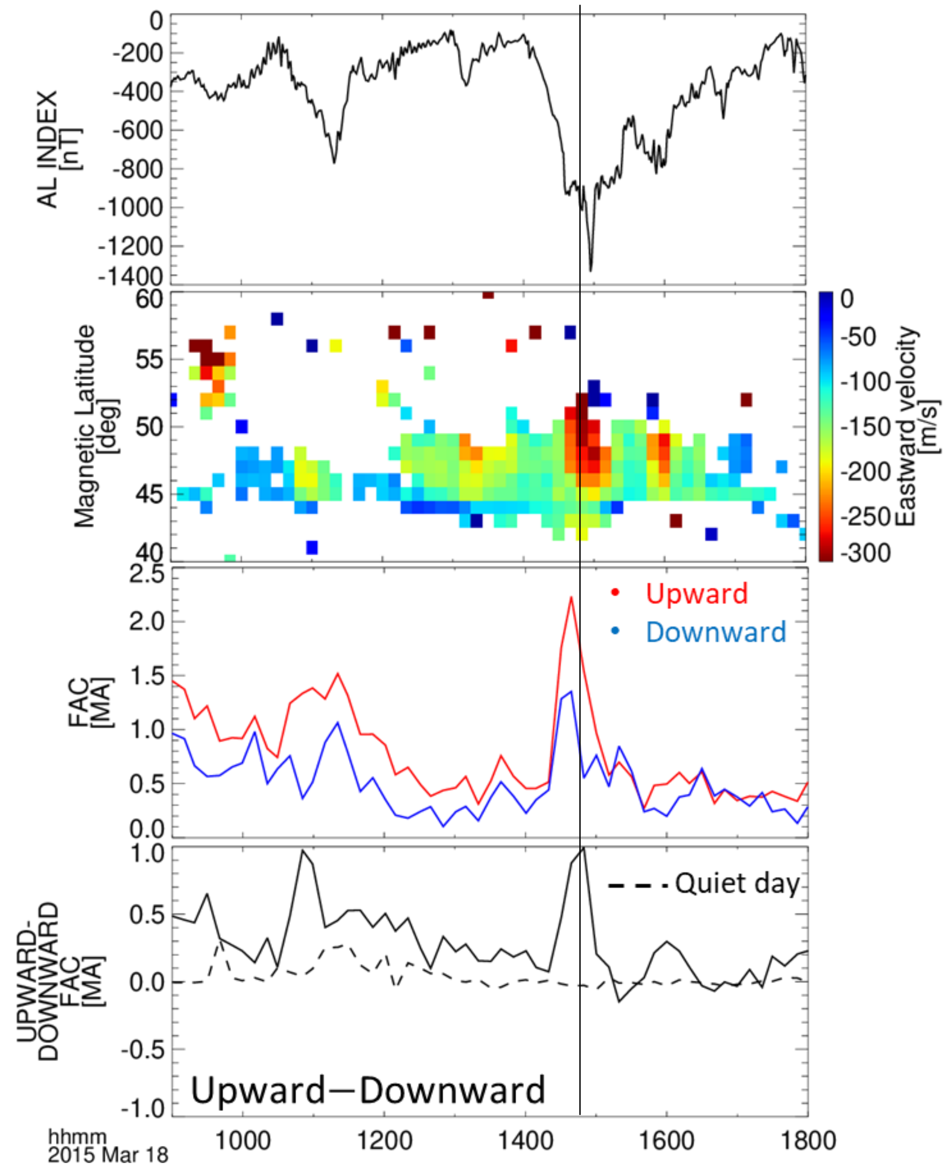


$$S_i = \frac{\int_i^{i+1} 2\pi r^2 cos\theta d\theta}{24}$$

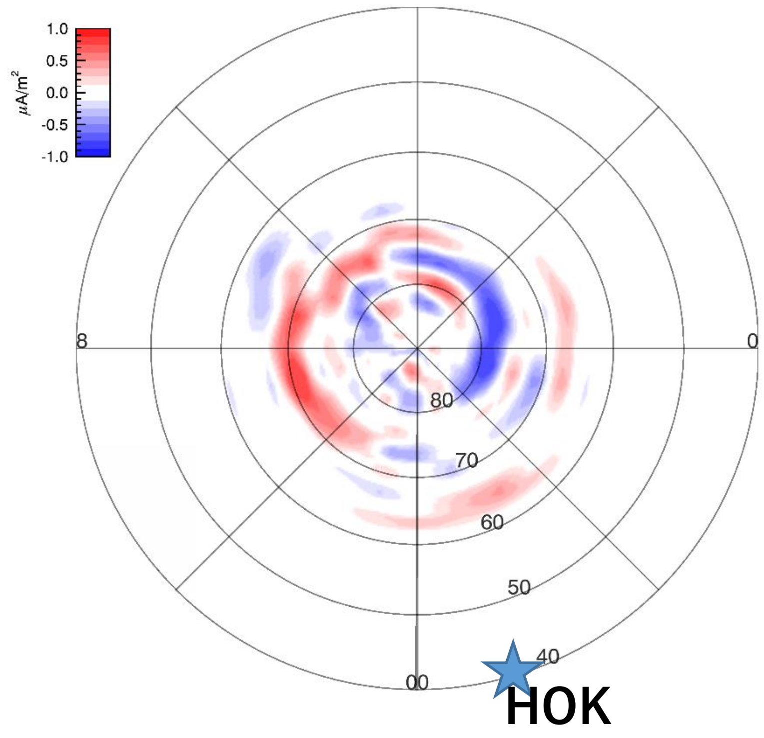
i: MLAT
S_i: Area
j_i: current density
r: R_E + Satellite altitude

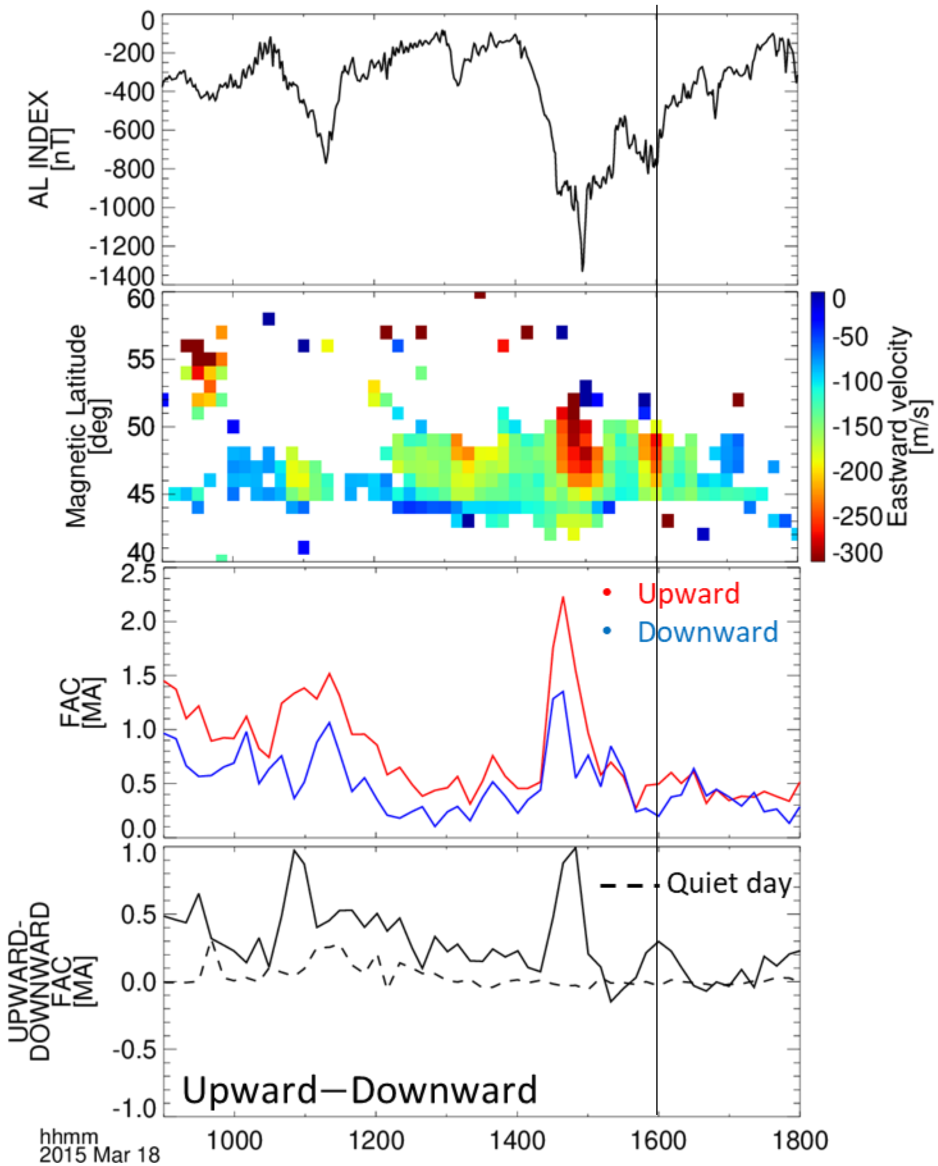
■ 2015-3-18/14:50





■ 2015-3-18/16:00





■ 2016-12-10/16:50