紹介論文：

1. Harada, Y., et al. (2018). MARSIS observations of the Martian nightside ionosphere during the September 2017 solar event. Geophysical Research Letters, 45, 7960–7967. https://doi.org/10.1002/2018GL077622

2. Sánchez–Cano, B., et al. (2019). Origin of the extended Mars radar blackout of September 2017. Journal of Geophysical Research: Space Physics, 124. https://doi.org/10.1029/ 2018JA026403

原田裕己

Harada et al. (2018)
概要

- 2017年9月の太陽イベント発生中に、Mars Express搭載レーダーサウンダーMARSISが火星夜側電離圏について以下の特徴を観測した：

  (i) 下部電離圏の電子密度増加（グラウンドエコー消失）

  (ii) 夜側電離圏の最大電子密度が120 km高度で1-2x10^4 cm^{-3}まで上昇

  (iii)上部電離圏の磁場強度が増大

- MAVENの昼側電離圏観測と合わせて、太陽イベント中の電離圏の全球的な応答についての情報が得られる。

MEX-MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding)

- MEX in orbit since Dec. 2003, MARSIS operating since July 2005
- Capable of operating in two main modes, one for **ionospheric** science (Active Ionospheric Sounding, AIS, mode), the other for **subsurface** radar sounding (Subsurface, SS, mode)

(Jordan et al., 2009)

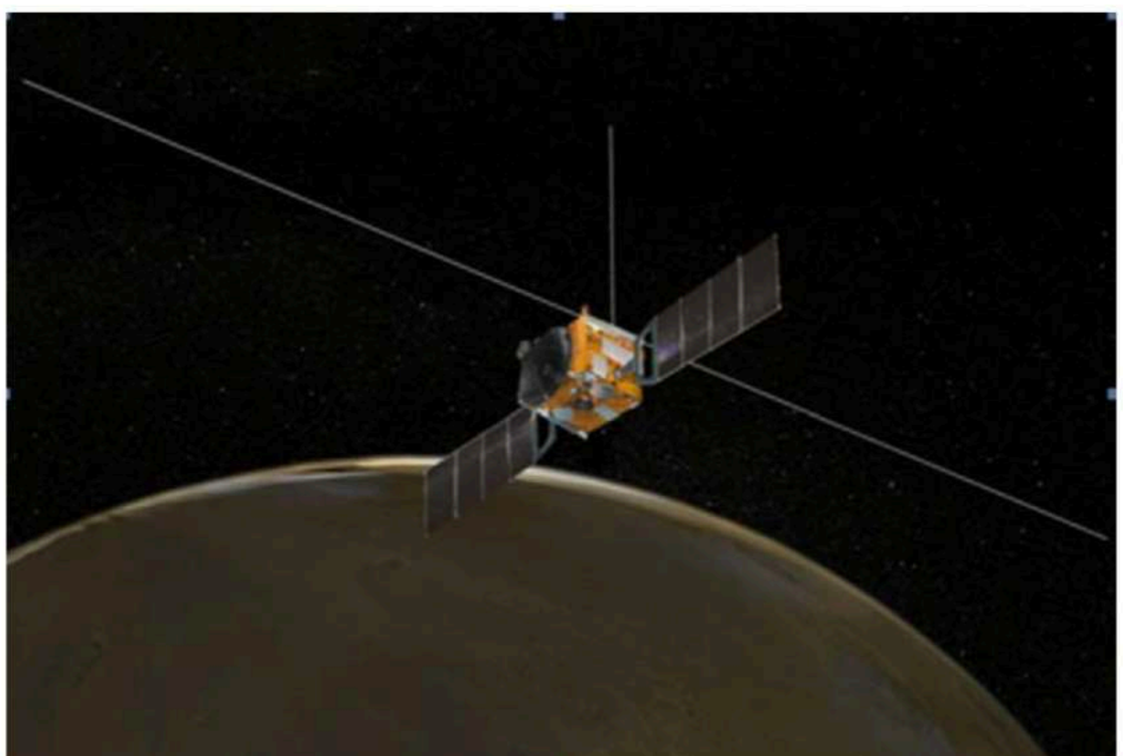


Fig. 2. MARSIS antenna configuration on Mars Express.

Table 1
MARSIS subsurface sounder parameters

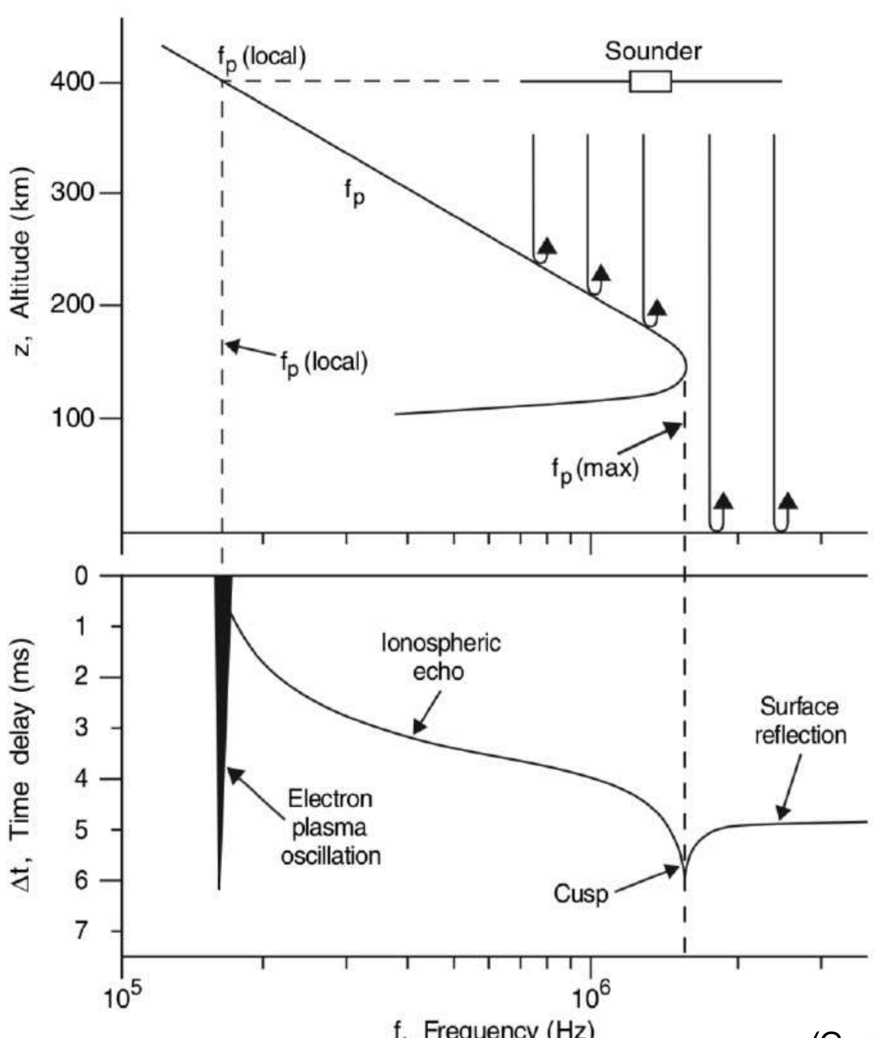
MARSIS subsurface sounder parameters Parameter	Description
Subsurface sounding altitude range	250–900 km
Dipole antenna length	40 m tip to tip
Monopole antenna length	7 m
Subsurface sounder frequency range	1.3–5.5 MHz (4 Bands)
Peak radiated power	1.5–5 W
Subsurface sounder pulse repetition rate	127 Hz
Subsurface sounder transmit pulse length	250 μs
Subsurface sounder wavelength	60–160 m
Bandwidth per band	1 MHz
Sounder free space depth resolution	150 m
Sounder dynamic range	40–50 dB
Nominal depth window	15 km
Number of processed channels	2 or 4
Number of simultaneous frequencies	1 or 2
Data quantization	8 bits per sample
Data quantization rate	2.8 megasamples per second
Data window duration	350 μs
Data rate output	18–75 Kbps
Data volume	285 Mbit per day
Dc operation power	60 W
Total mass	20 kg

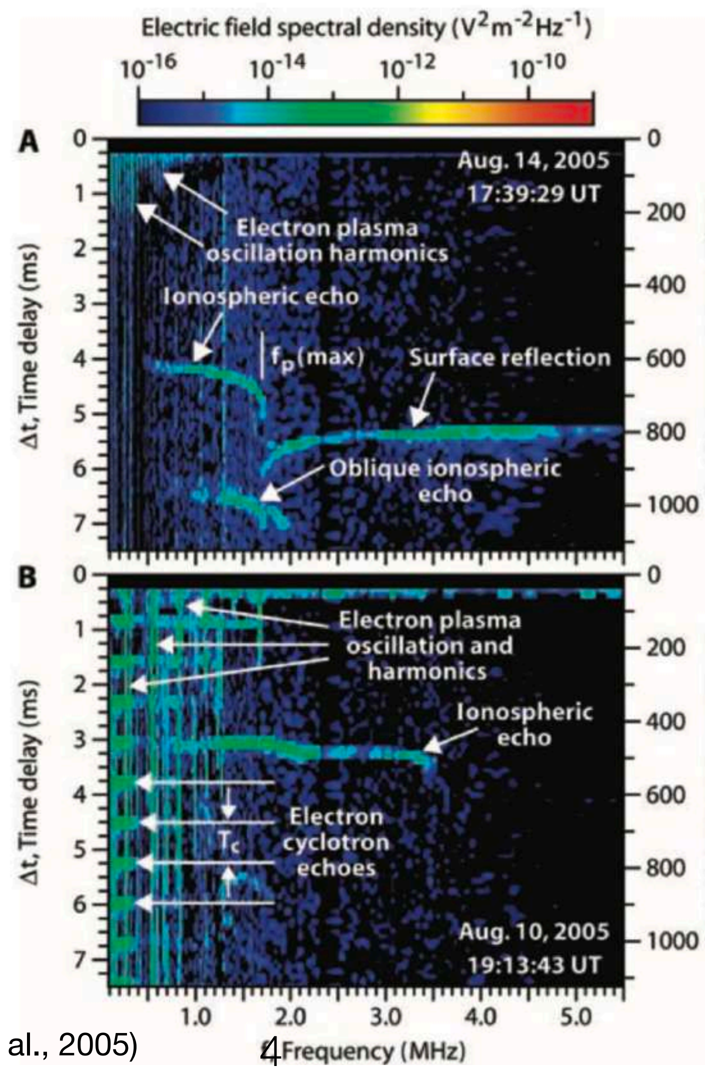
Table 2
Active ionospheric sounder parameters.

Ionospheric sounding mode	
Maximum altitude	1200 Km
Start frequency	100 kHz
End frequency	5.5 MHz
Number of frequencies	160
Transmit pulse length	91.43 μs
Minimum frequency step	10.937 kHz
Pulse repetition frequency	127 Hz
Frequency sweep repetition interval	7.38 s

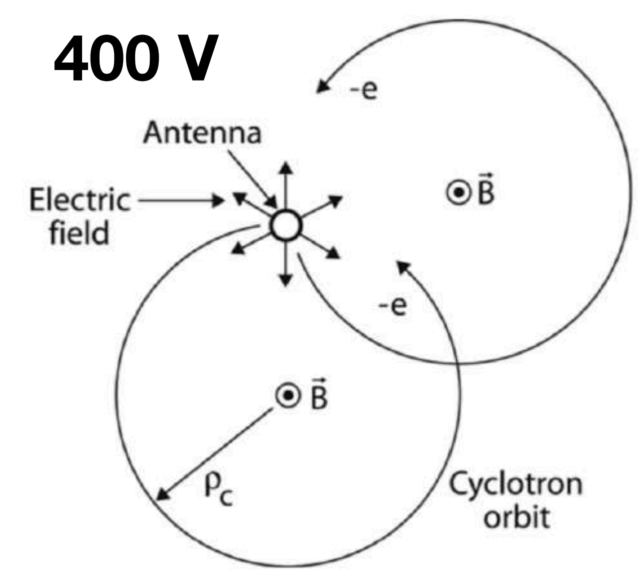
MARSIS AIS Measurements

- MARSIS AIS mode measurements provide:
  - electron density profile, $n_e(z)$, in the topside ionosphere <- ionospheric echo trace, $\Delta t(f)$
  - a measure of n_e in the bottomside ionosphere <- e-n collision damping of ground echoes ($\omega \sim \nu_{en}$)
  - local n_e <- electron plasma oscillation "harmonics" (waveform clipped in the receiver)
  - local $|B|$ <- "electron cyclotron echoes" (periodic return of electrons accelerated by the antenna)





(Gurnett et al., 2005)



(Gurnett et al., 2008)

MARSIS Ionogram Processing

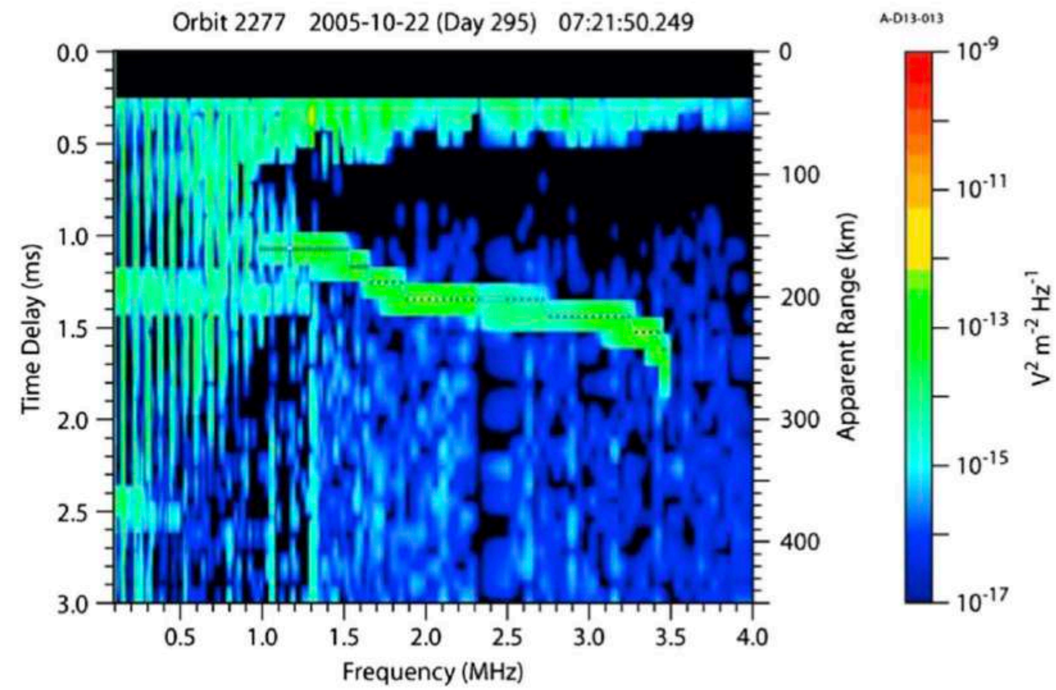
- An Autoplot based tool for efficient manual processing of ionospheric trace, f_{pe} harmonics, and e^- cyclotron echoes

- Ionospheric echo trace -> electron density profile

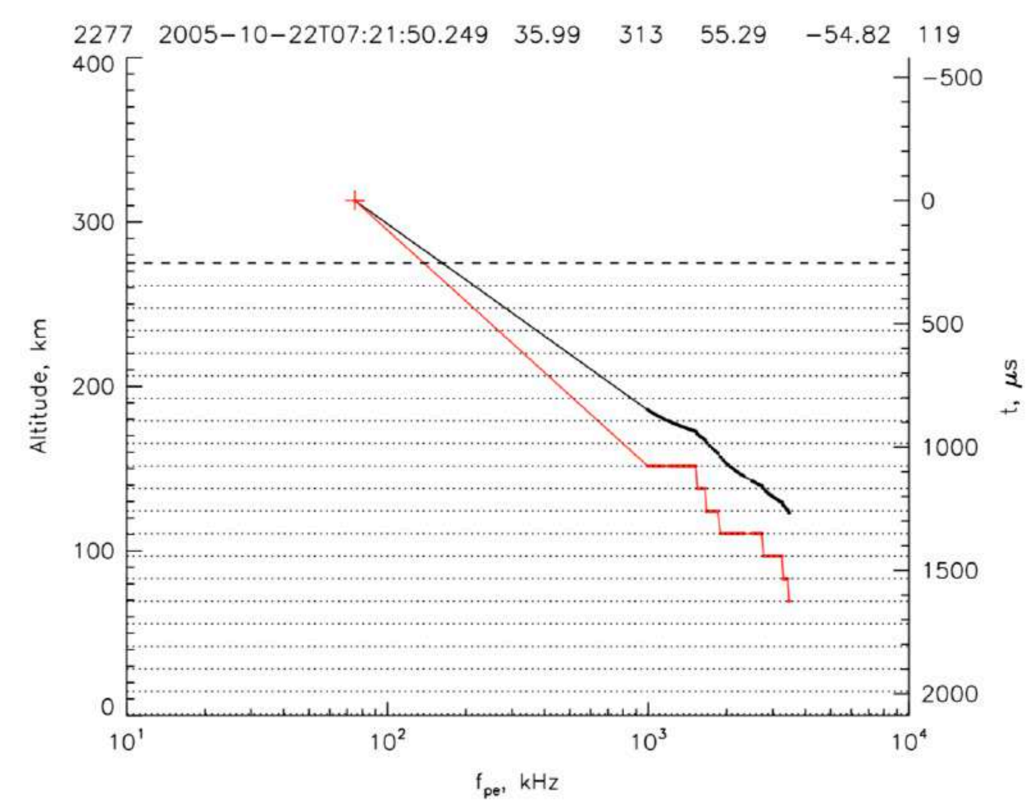
- Need to correct for dispersion:

$$\tau_i = 2 \times \int_{z_0}^{z_i} \frac{dz}{V_g} = 2 \times \int_{z_0}^{z_i} \frac{dz}{c\sqrt{1 - \left(\frac{f_{pe}(z)}{fs, i}\right)^2}}$$

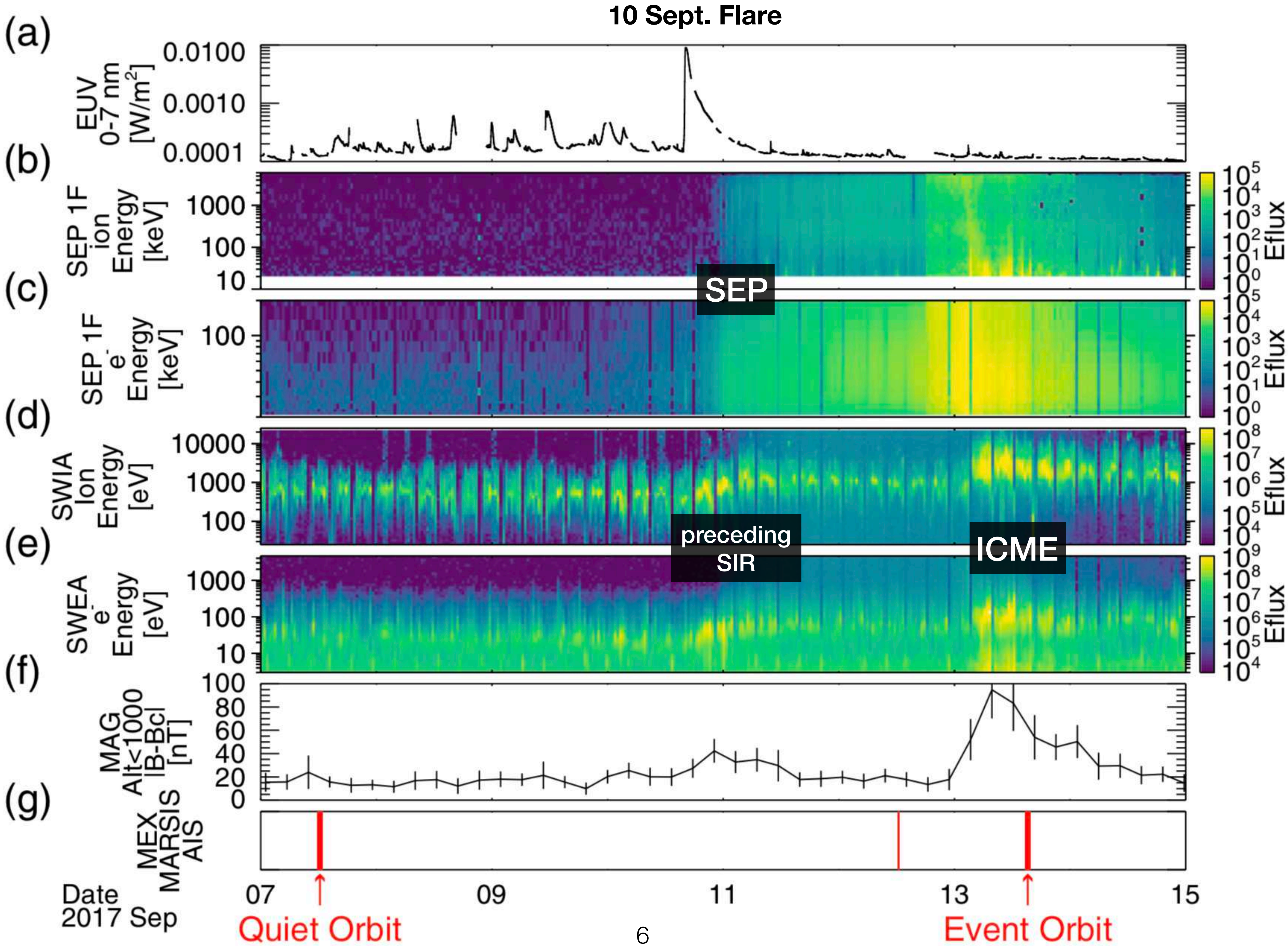
- A simple inversion routine (written in IDL) is provided in Morgan et al. (2013)



(Morgan et al., 2013)

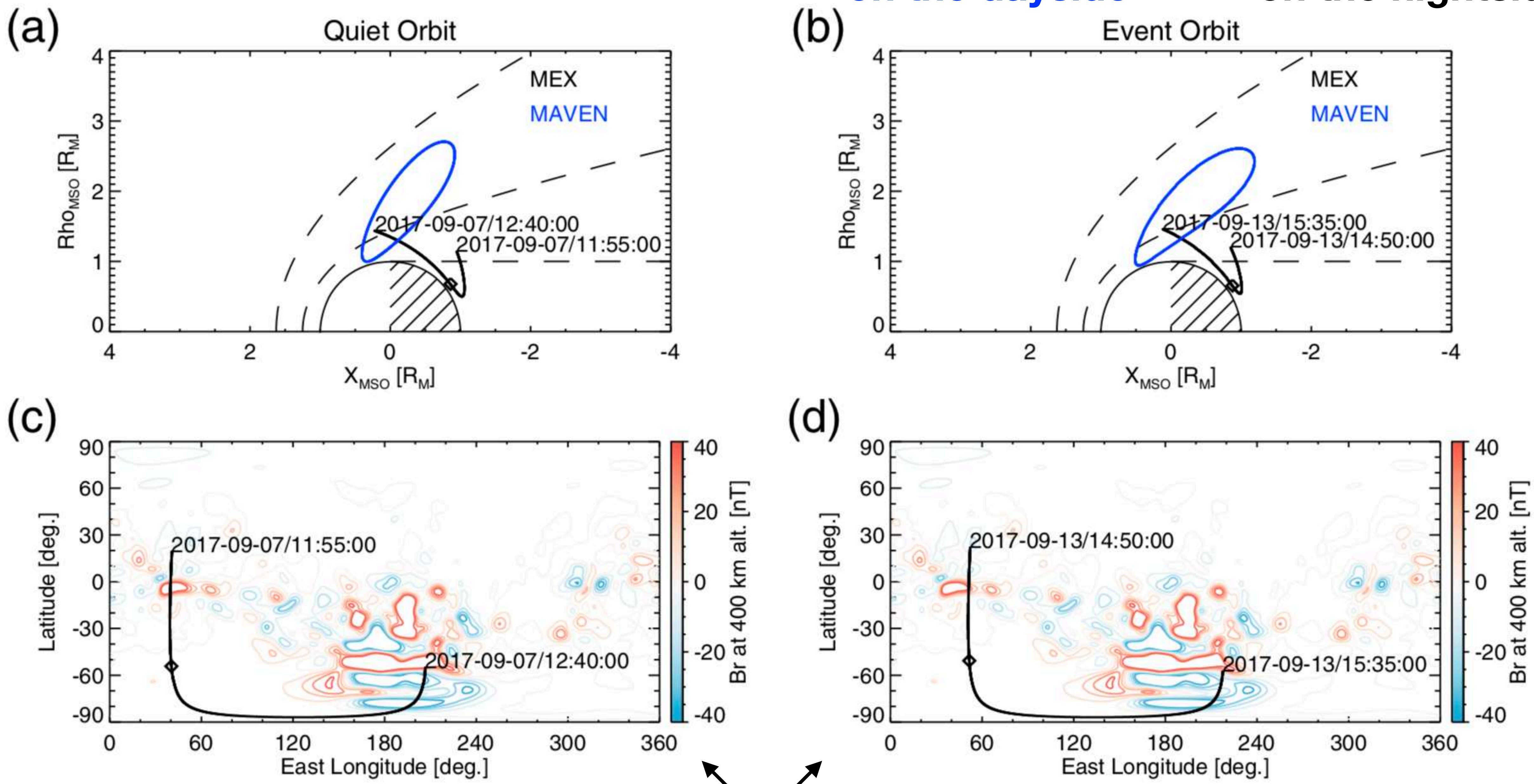


Sept. 2017 Solar Event Context



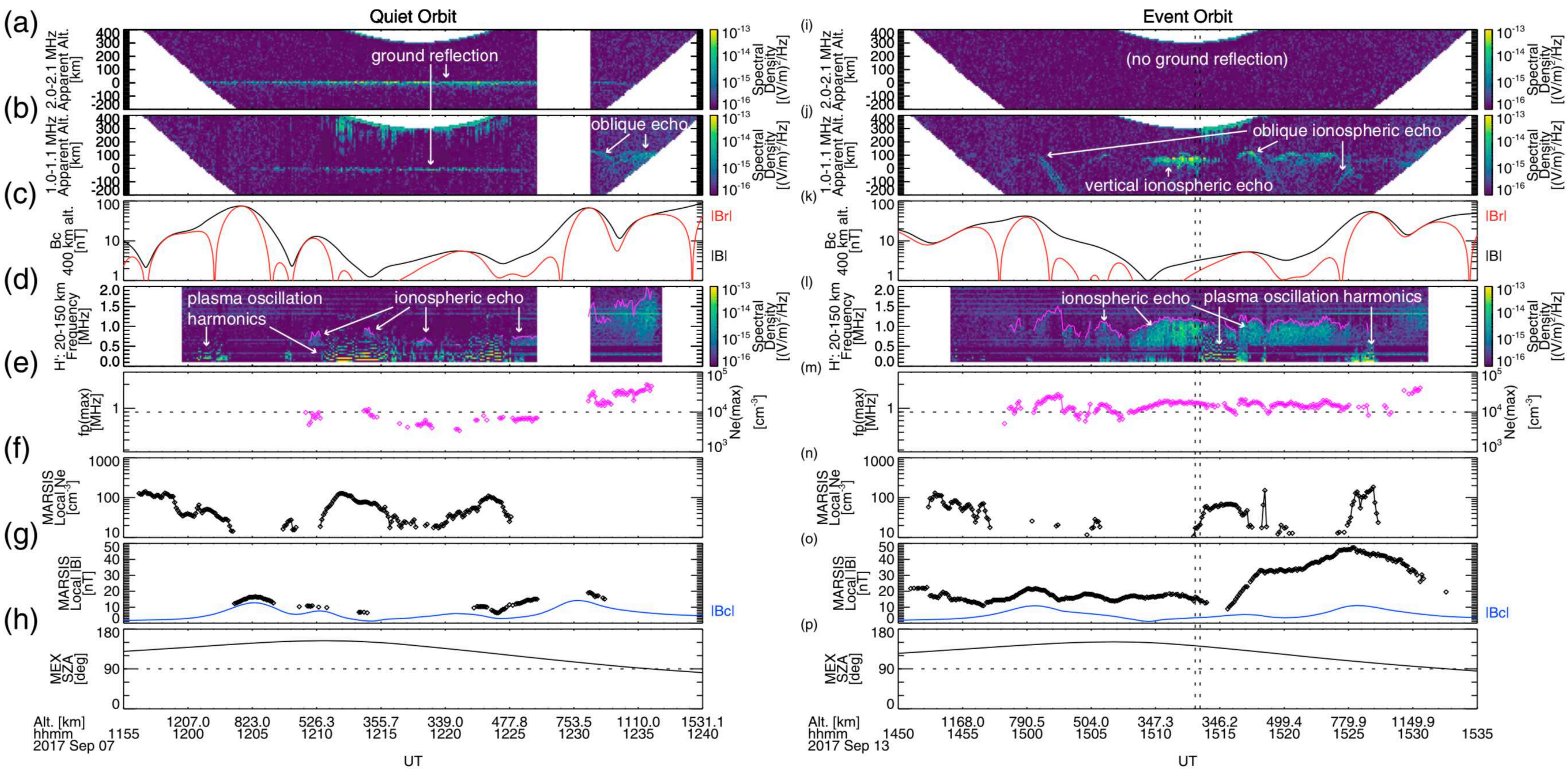
Orbit Geometry

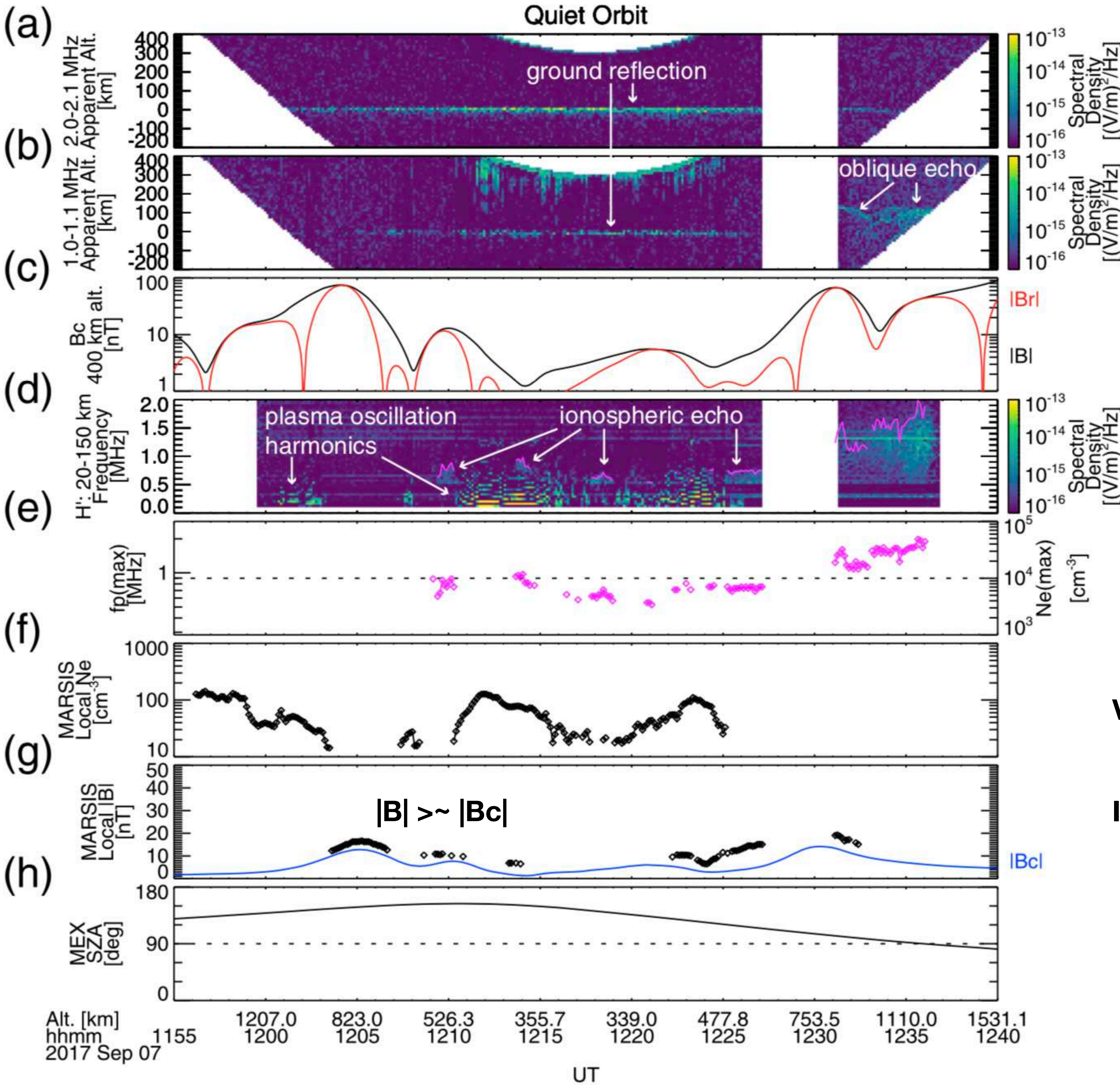
MAVEN periapsis on the dayside | **MEX periapsis on the nightside**



Nearly identical orbit configurations

MARSIS Observations





Visible ground reflection in radargrams

(nightside ionospheric echo: nominal occurrence rate ~9% Nemec et al., 2010)

peak Ne < 10^4 cm^{-3}

Variable local Ne <~ 100 cm^{-3}

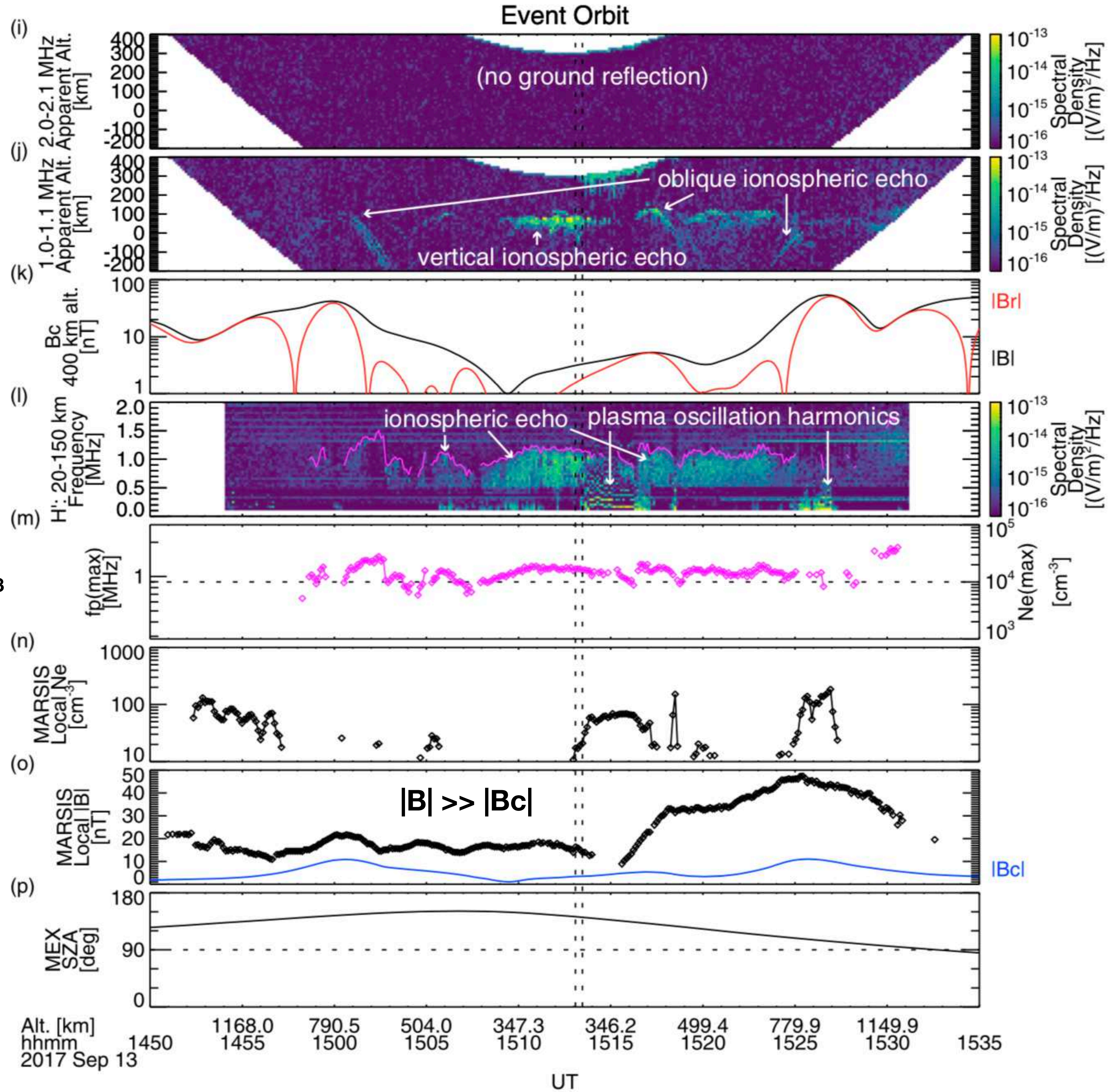
Induced B < 10 nT

Disappearance of ground reflection <= enhanced Ne in the bottomside ionosphere (Espley et al., 2007; Morgan et al., 2006, 2010, 2014; Němec et al., 2014, 2015, 2007)

peak Ne ~ 1-2x10⁴ cm⁻³ (cf. nightside peak Ne < 5x10³ cm⁻³ for 90% of the time)

Variable local Ne <~ 100 cm⁻³

Induced B up to ~40 nT



Nightside Electron Density Profile

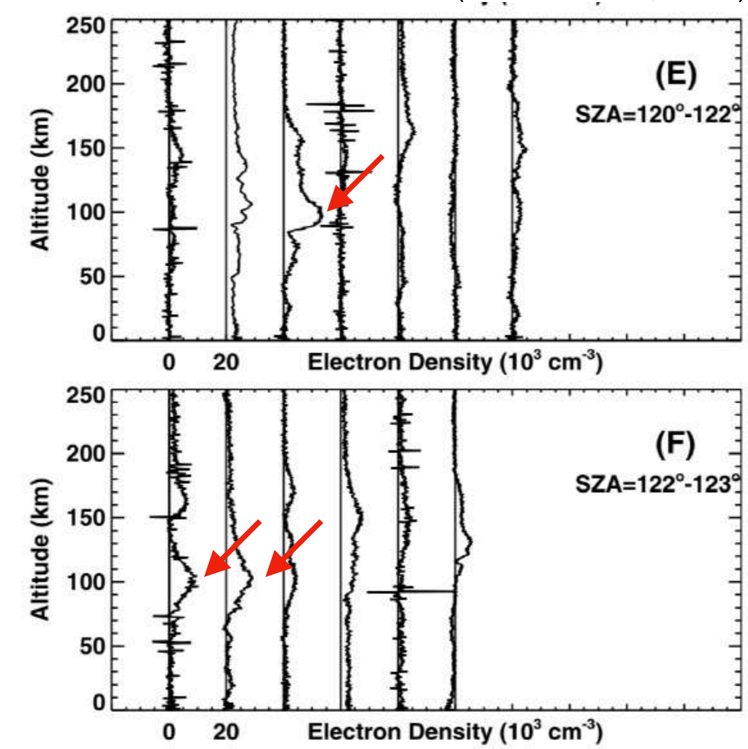
- Correct for dispersion by Morgan et al. (2013)'s inverse routine

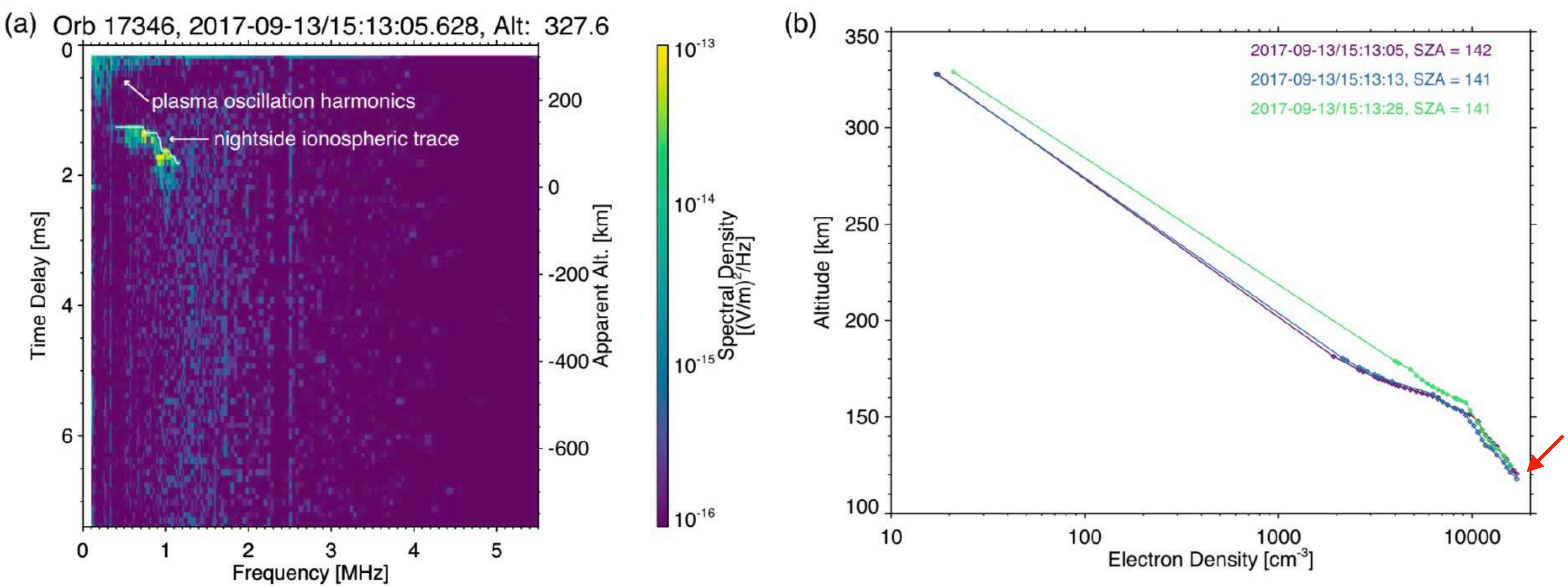
- Peak Ne (of 1.7×10^{4} cm^{-3}) at ~120 km altitudes

– Similar peak Ne and slightly higher altitudes compared to Ne profiles derived from radio occultation during SEP events (Withers et al., 2008)

- Given the low peak altitude (<< 200 km), the primary ionization is most likely provided by electron impact ionization by precipitating solar particles

(Withers et al., 2008)





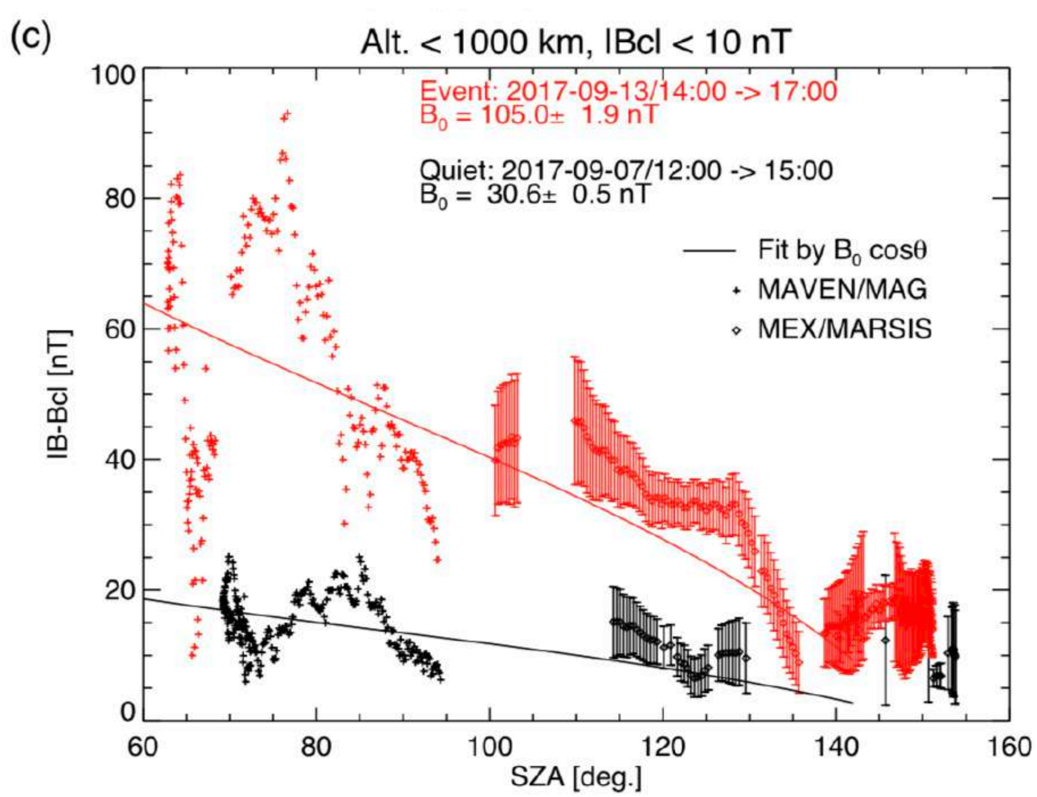
Enhanced |B| in the Ionosphere

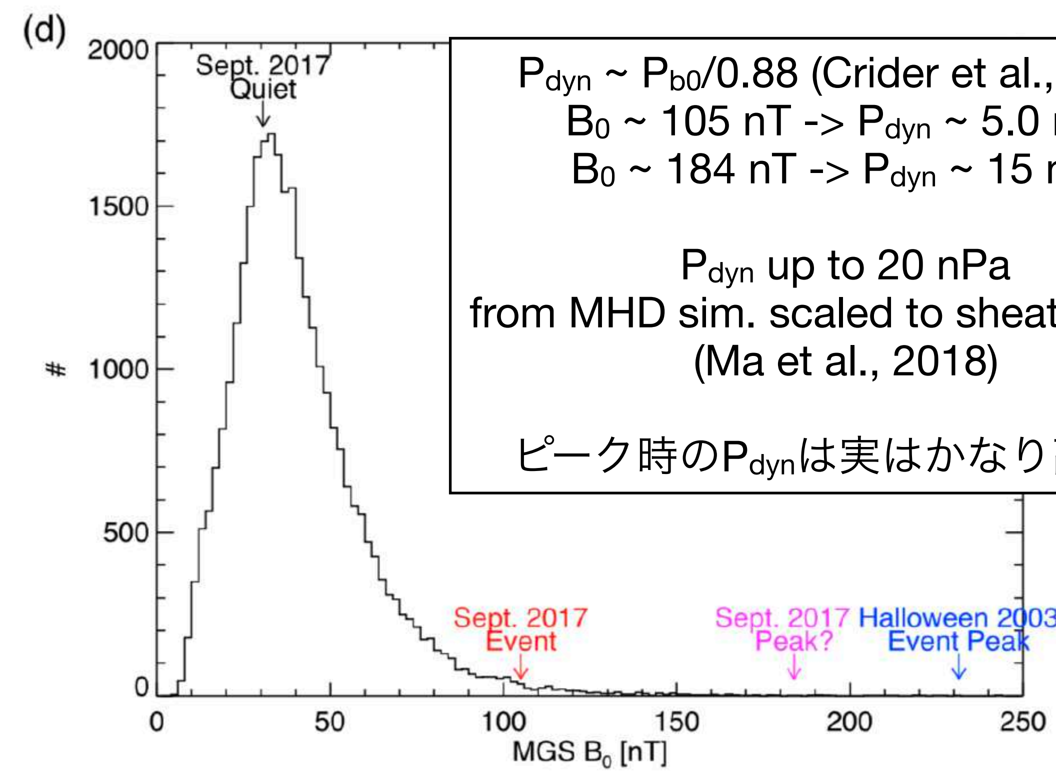
- Dayside (60° < SZA < 90°) observations by MAVEN/MAG and nightside (100° < SZA < 155°) observations by MEX/MARSIS indicate that the magnetic field intensity at <1000 km altitudes were globally enhanced during the ICME passage

- Extrapolation of B-SZA relation according to Crider et al. (2003) function infers subsolar B0 ~ 105 nT during the Event period

  - $B = B_0 \cos\theta$, where θ is the magnetic pileup boundary normal angle with respect to the Mars-Sun line derived from the conic fit by Vignes et al. (2000)

- A very rough estimate of peak B0 from MAG data implies B_0 up to 184 nT





$P_{dyn} \sim P_{b0}/0.88$ (Crider et al., 2003)
$B_0 \sim 105$ nT -> $P_{dyn} \sim 5.0$ nPa
$B_0 \sim 184$ nT -> $P_{dyn} \sim 15$ nPa

P_{dyn} up to 20 nPa
from MHD sim. scaled to sheath B data
(Ma et al., 2018)

ピーク時のP_{dyn}は実はかなり高い？

MGS subsolar magnetic field magnitude
(http://sprg.ssl.berkeley.edu/~brain/proxies/subsolfield)

Sánchez–Cano et al. (2019) 概要

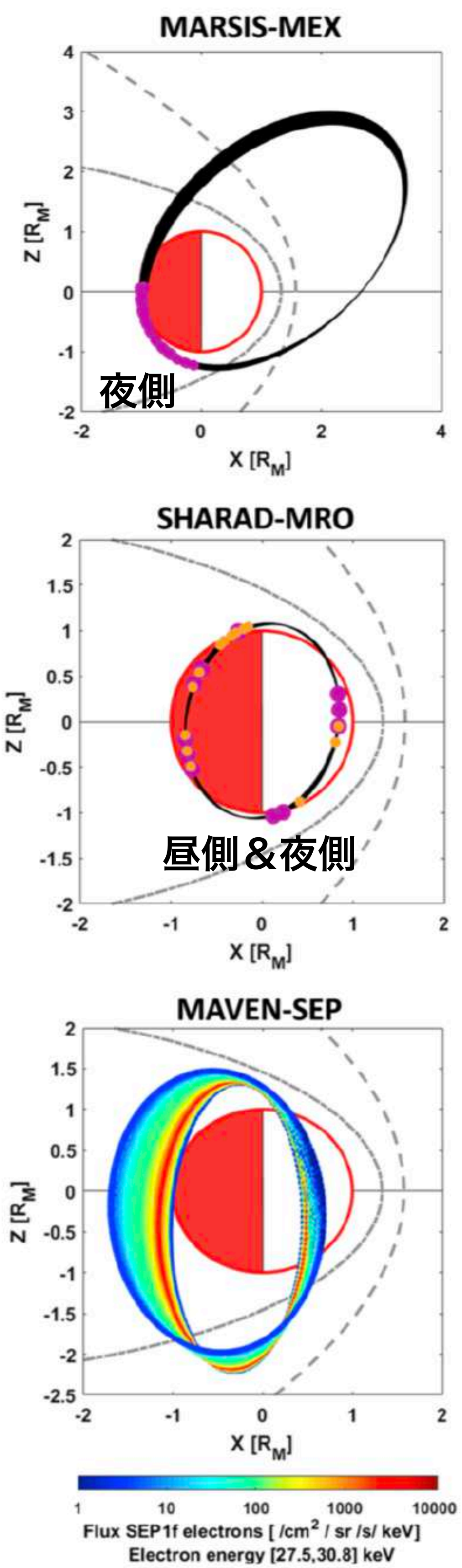
- 2017年9月の宇宙天気イベント発生中に、MEX-MARSISは0.1-5.5 MHzの周波数で10日間、MRO-SHARADは20 MHzで３日間、火星表面からのエコー消失（"radar blackout"）を観測した。

- 夜側大気への電子降り込みについての数値シミュレーションを行い、数10 keV以上の太陽高エネルギー**電子**によって、~90 km高度に~10^{10} m^{-3}のピーク密度を持つO_2^+層が形成されることを示した。

- この様な層は観測されたレーダーエコー消失を説明できる。

- 電波吸収は70 km高度にピークを持つ。

MARSIS & SHARAD Observations



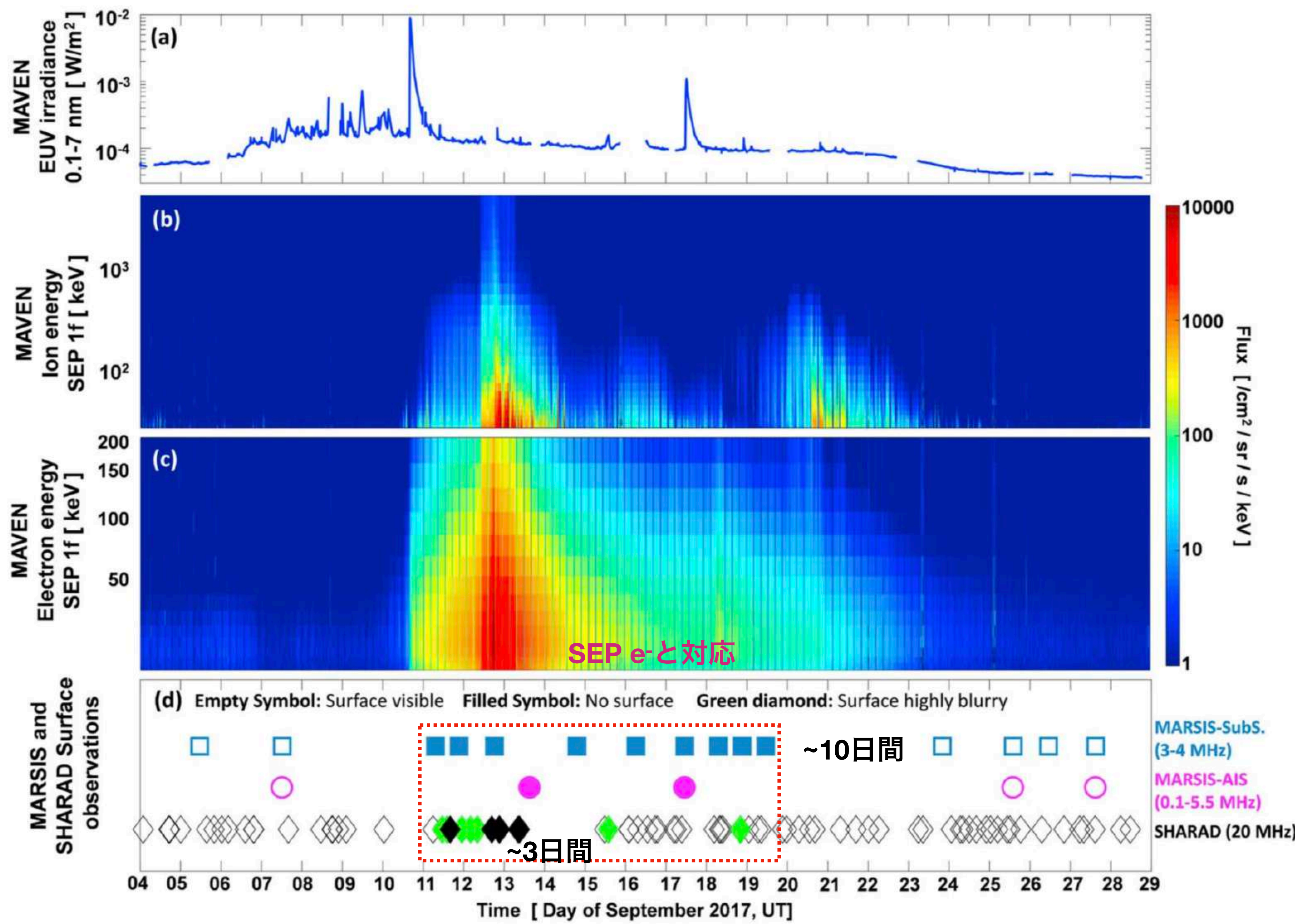


Figure 2. (a) MAVEN-EUV irradiance observations of wavelength 0.1–7 nm. (b) MAVEN-SEP ion differential flux spectra. (c) MAVEN-SEP electron differential flux spectra. (d) Each symbol denotes when MARSIS and SHARAD were in operation. Empty symbols designate the cases when the surface was observed, and filled symbols when was not observed. The exceptions are green diamonds that indicate the times when SHARAD observed a highly blurry surface.

Sample Radargrams

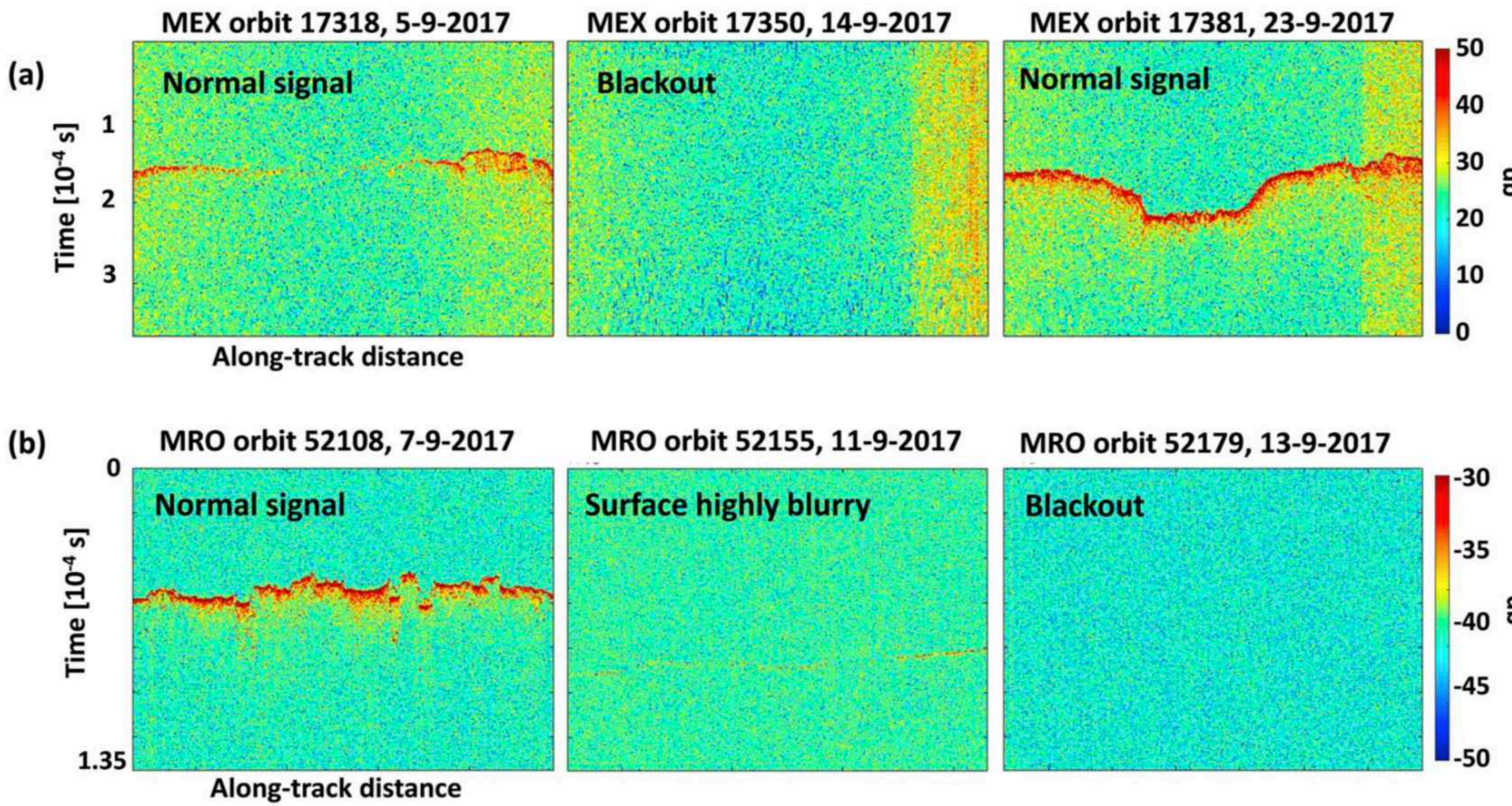


Figure 3. Radargram examples showing normal surface reflections, blackouts, and partial blackouts (surface highly blurry). (a) MARSIS radargrams. (b) SHARAD radargrams.

Estimate of the Attenuation

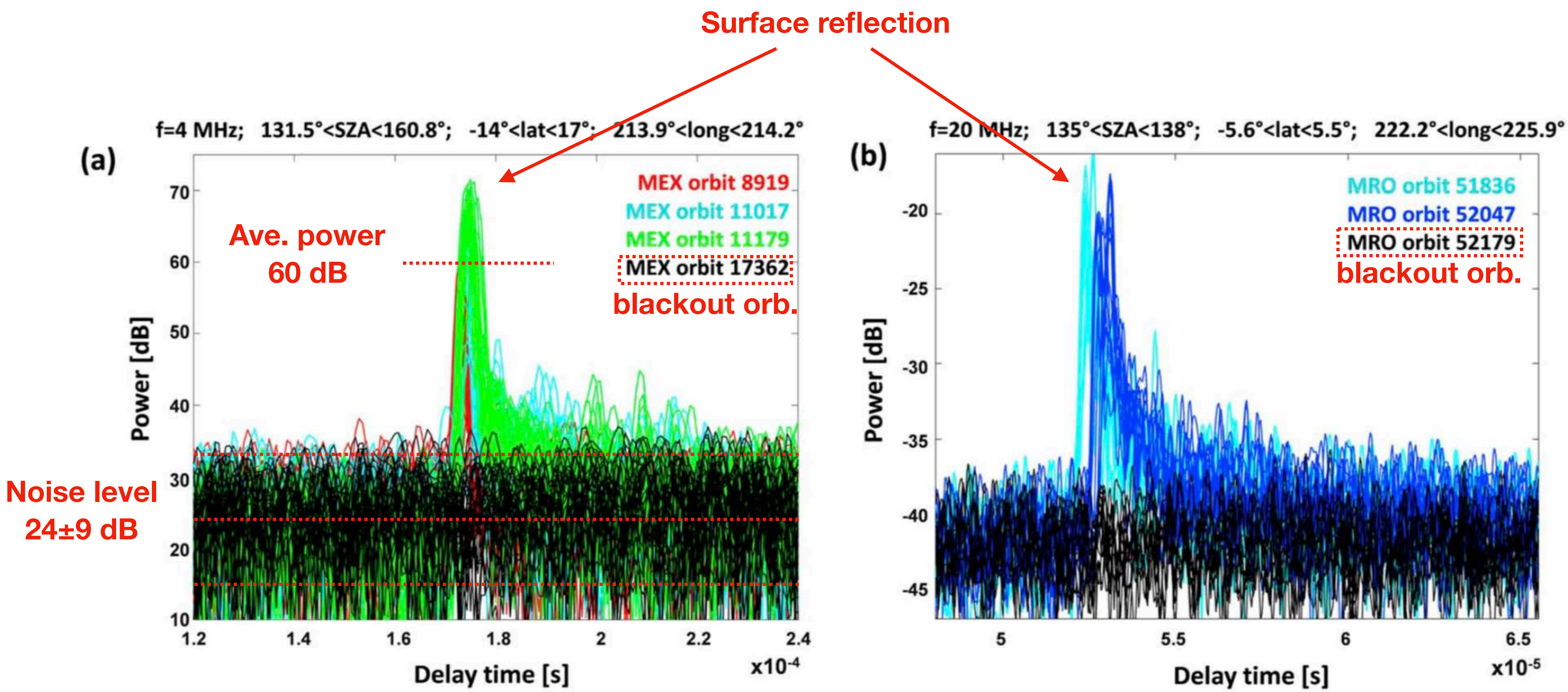


Figure 4. (a) MARSIS power signal versus delay time for several orbits over the same region. (b) SHARAD power signal versus delay time for several orbits over the same region.

=> >36±9 dB attenuation for 4 MHz round trip,
<u>>18±9 dB attenuation for one way</u>

(uncertainty propagation???)

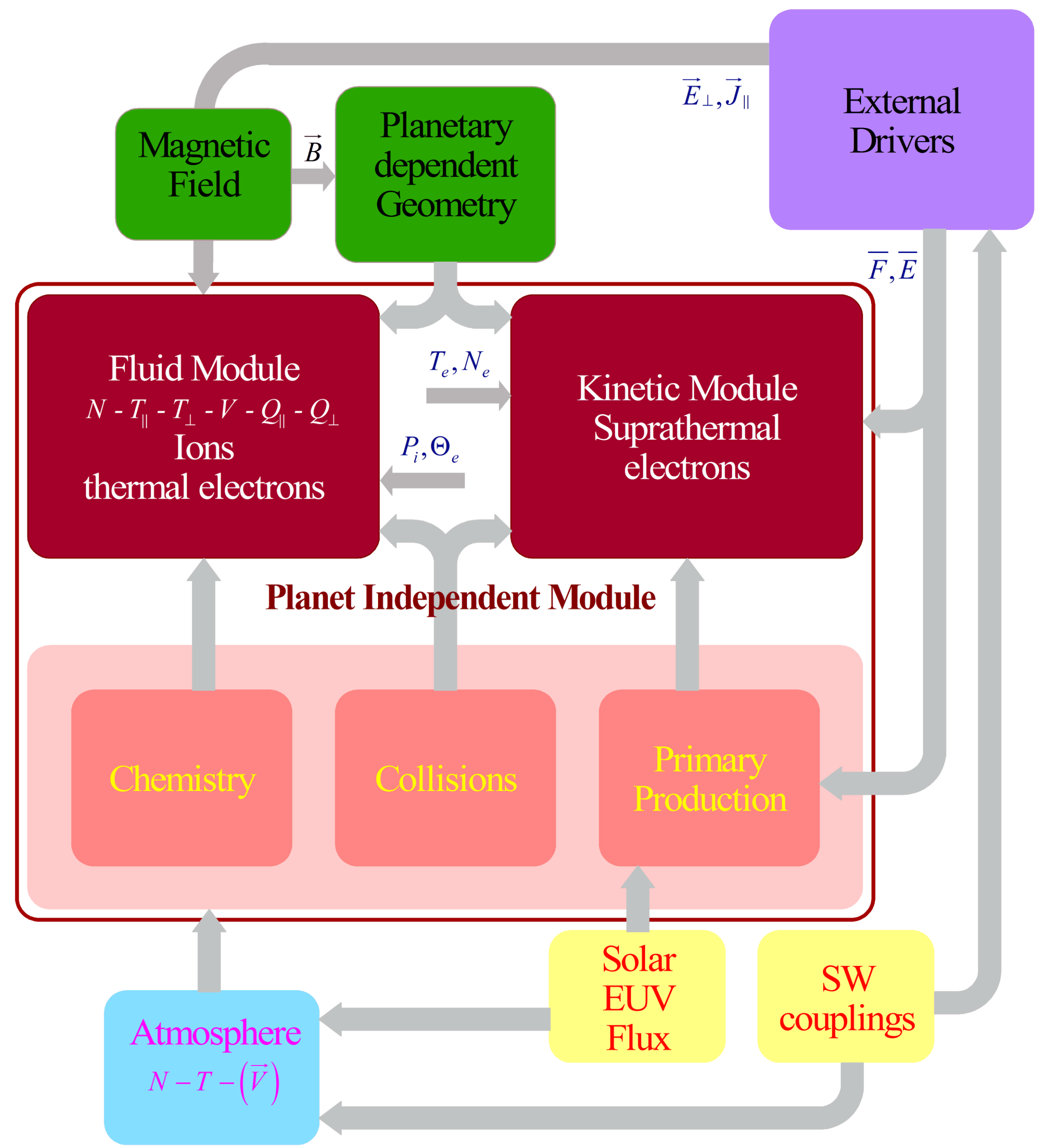
<u>>17±9 dB at 3 MHz</u>

<u>>9.5±3.3 dB at 20 MHz</u>

Ionospheric Modeling

- IRAP plasmasphere-ionosphere model (IPIM) (Marchaudon & Blelly, 2015)
  - A web service is available at http://transplanet.cdpp.eu/
  - Solves 1D (field aligned or vertical) transport eqs.
  - Fluid thermal e & i <-coupling-> kinetic suprathermal e
  - The kinetic module solves the steady state transport equation of the distribution function, accounting for primary and secondary collisions with the neutrals and excitation and ionization processes either by solar radiation illumination or electron impact
- Mars version
  - Uses the Mars Climate Database (MCD) (version 5.3) as input for neutral atmospheric conditions (e.g., Forget et al., 1999; Millour et al., 2015)
  - Includes the six major ion species (O2+, NO+, O+, CO2+, N2+, and H+) in the Martian ionosphere
  - Considers no magnetic field (Blelly et al., 2019)
- <u>Nightside</u> condition at 23:00:00 UT on 10 September 2017
- A flux of downward precipitating electrons (>20 keV) at 500 km was included in the model as a source of ionization

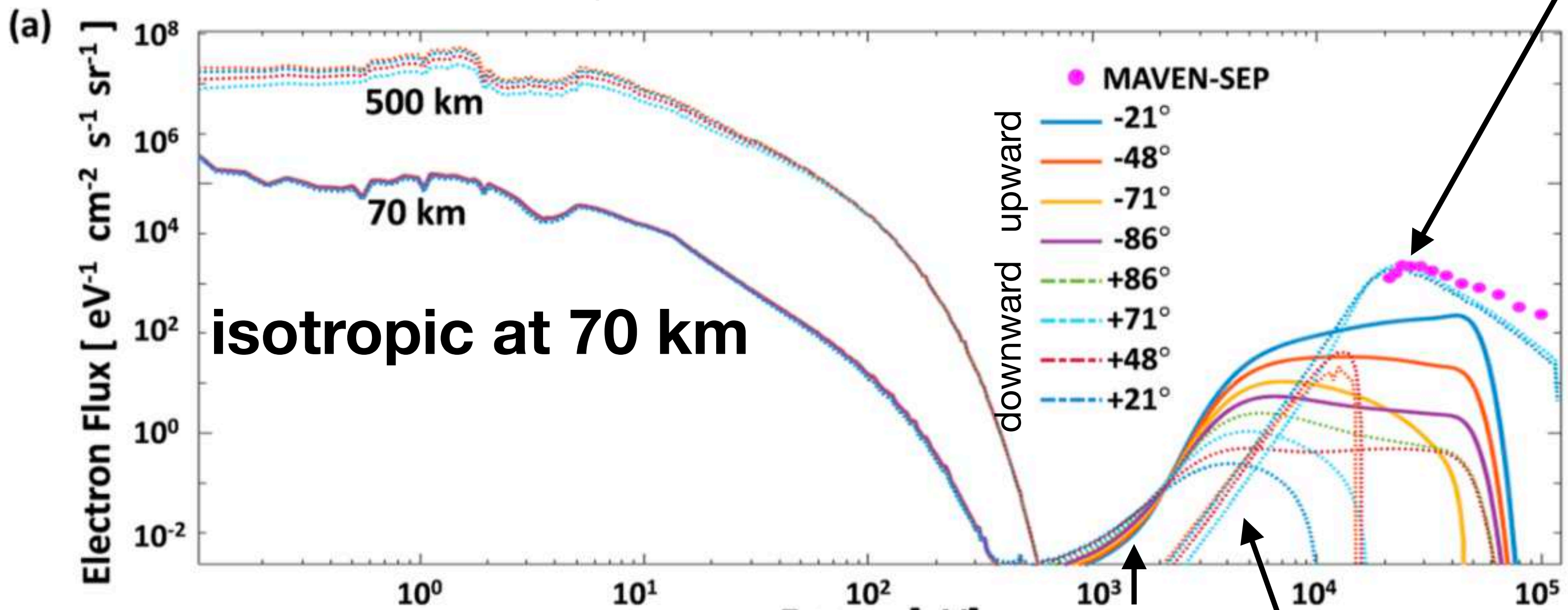
Synopsis of IPIM ionosphere model
(Blelly et al., 2019; http://transplanet.cdpp.eu/)



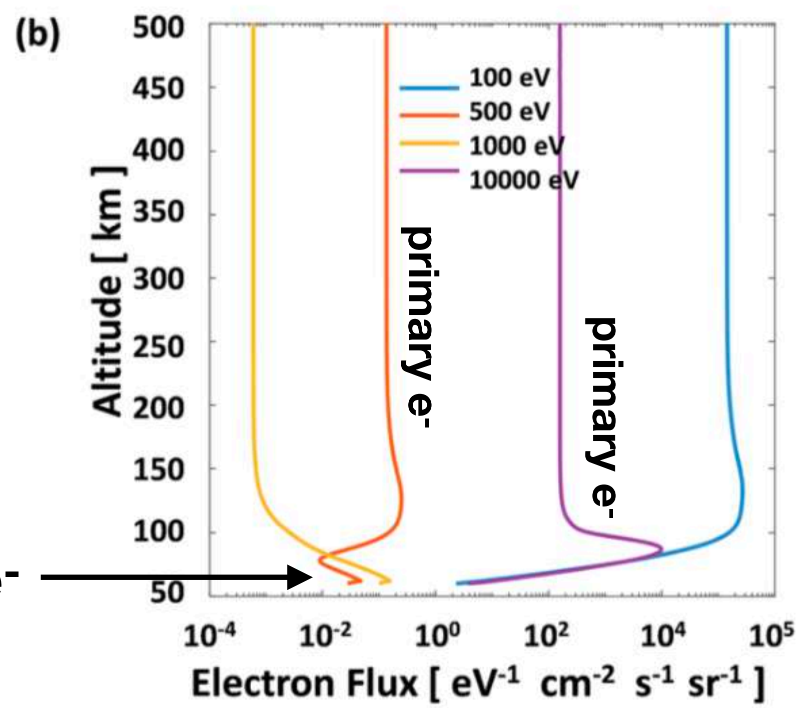
Model Results: Electron Flux

input e⁻ flux
fitted to SEP data at >20 keV
(*w/ what function???*)

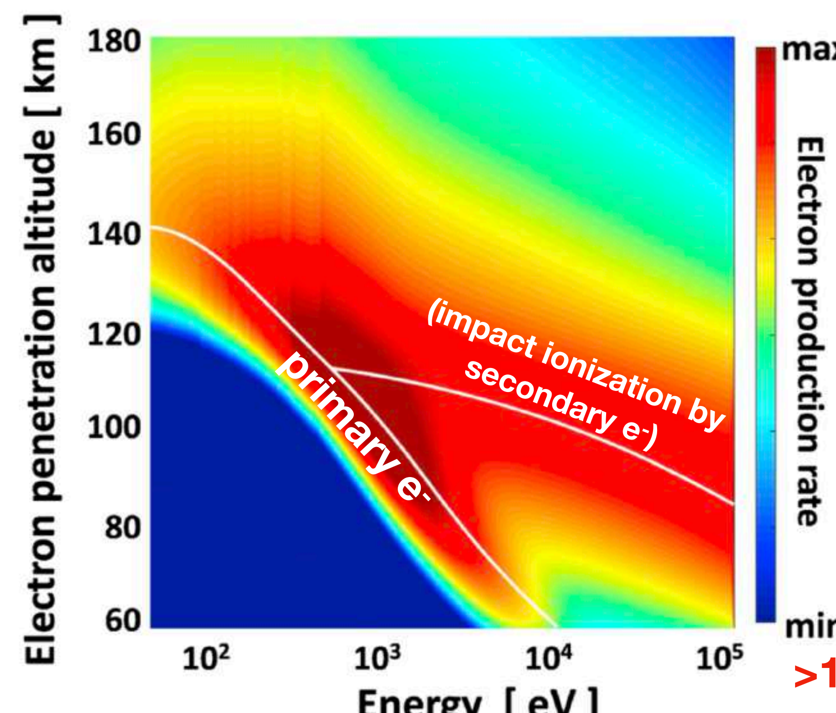
secondary e⁻



upward flux > downward flux at 70 km???



secondary e⁻



>10 keV e- は
高度60 km以下まで到達

Figure 6. Electron penetration depth versus energy. The while line indicates the altitude where the precipitating electrons are stopped. The upper white line at energy >500 eV is related to secondary electrons, while the lower one is related to the primary electrons.

Ion & Electron Density Profile

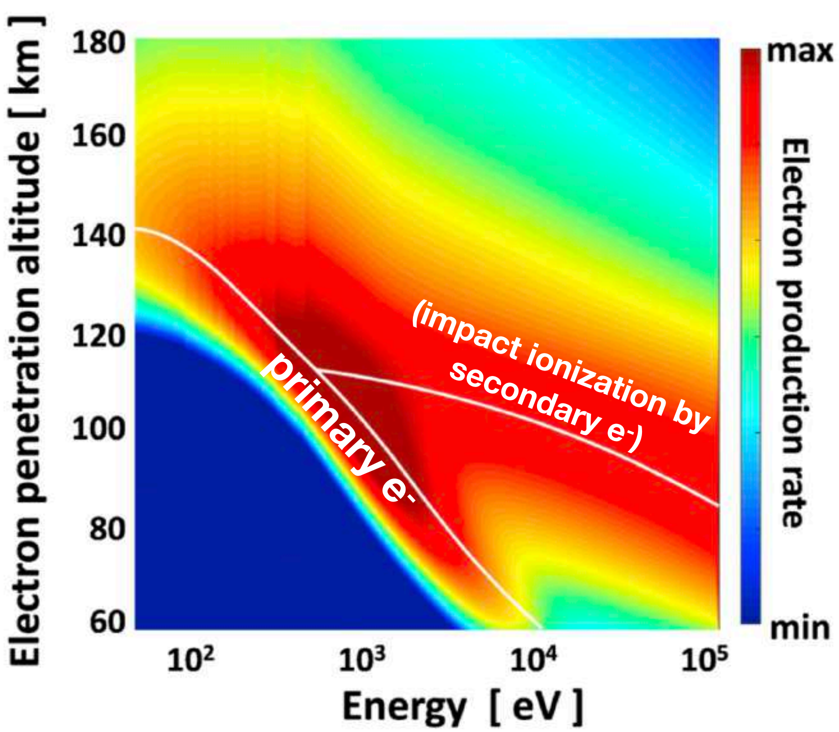
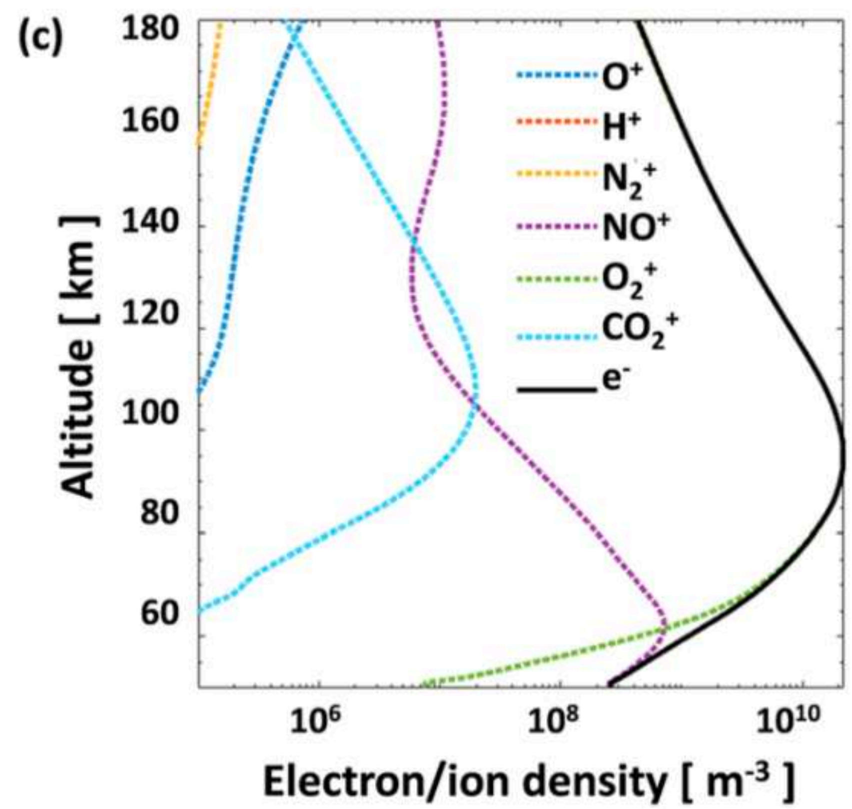


Figure 6. Electron penetration depth versus energy. The while line indicates the altitude where the precipitating electrons are stopped. The upper white line at energy >500 eV is related to secondary electrons, while the lower one is related to the primary electrons.

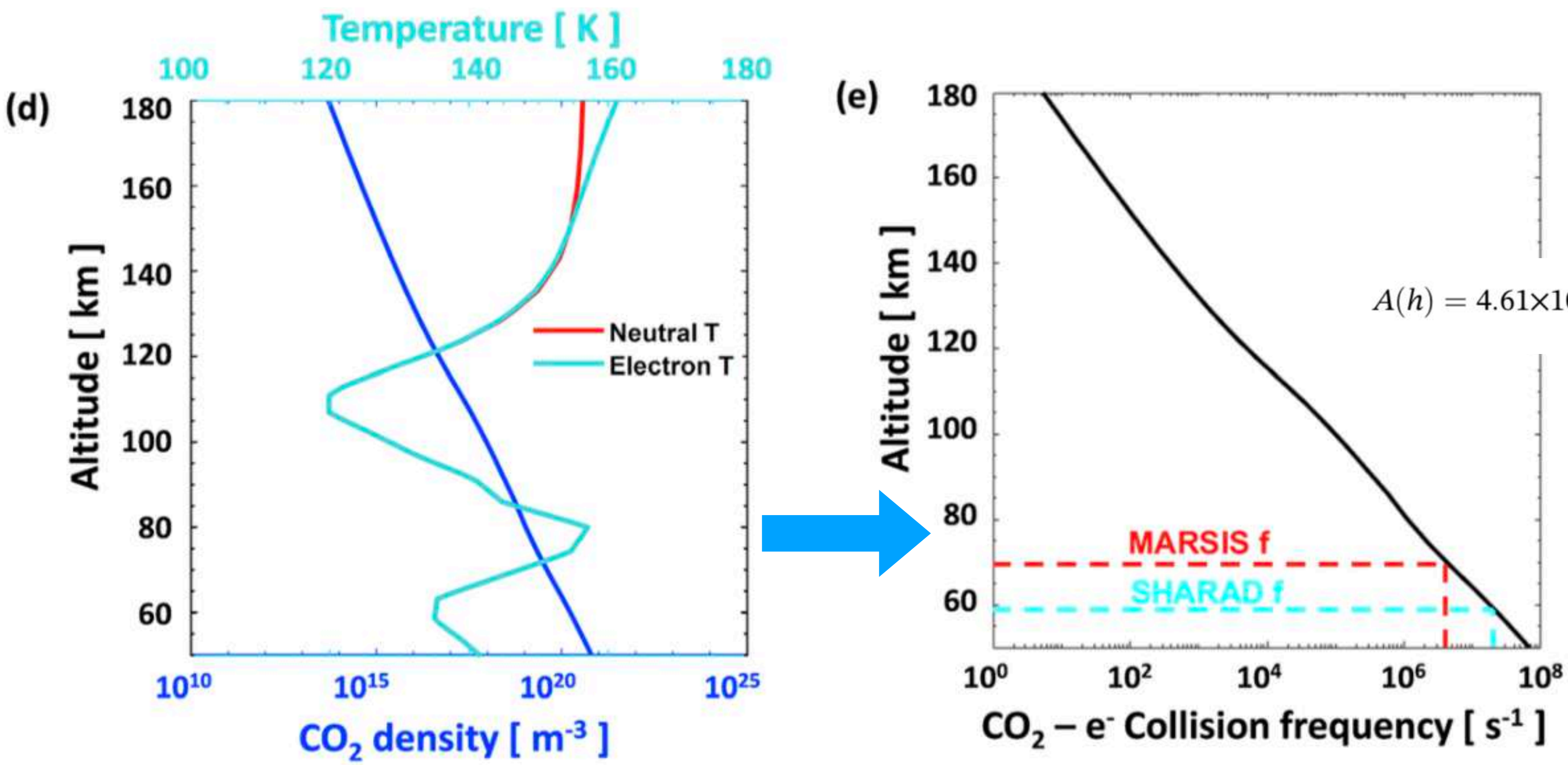


高度~90 kmに

ピーク密度~10^{10} m^{-3}の

O_2^+ 層が形成

en Collision Frequency



$$A(h) = 4.61\times10^7\ N_e(h)\ \frac{\nu(h)}{(2\,\pi\,f)^2 + \nu^2(h)}$$

電子１個あたりの

減衰率はω ~ vで最大

f ~ vとなる高度：

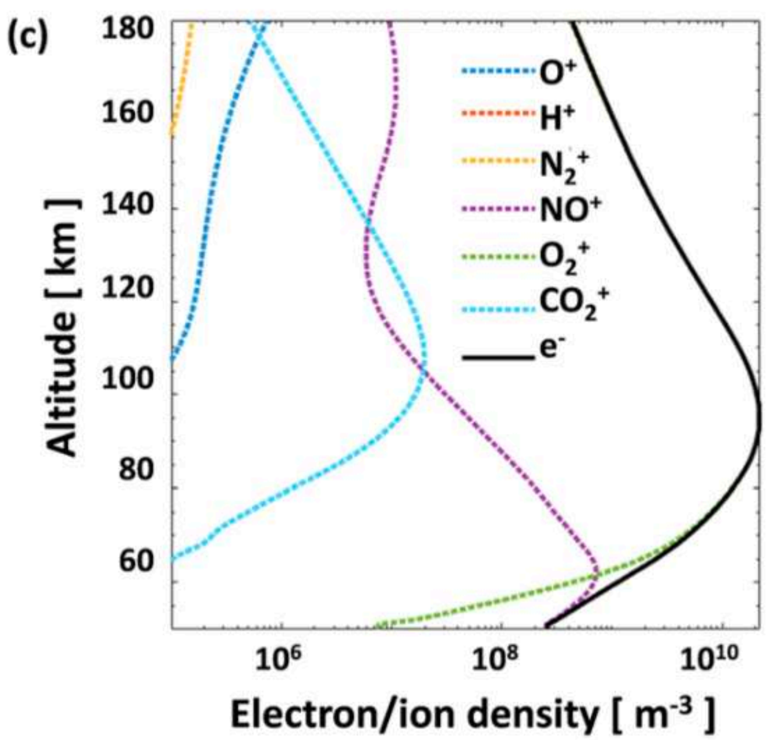
4 MHz -> 70 km

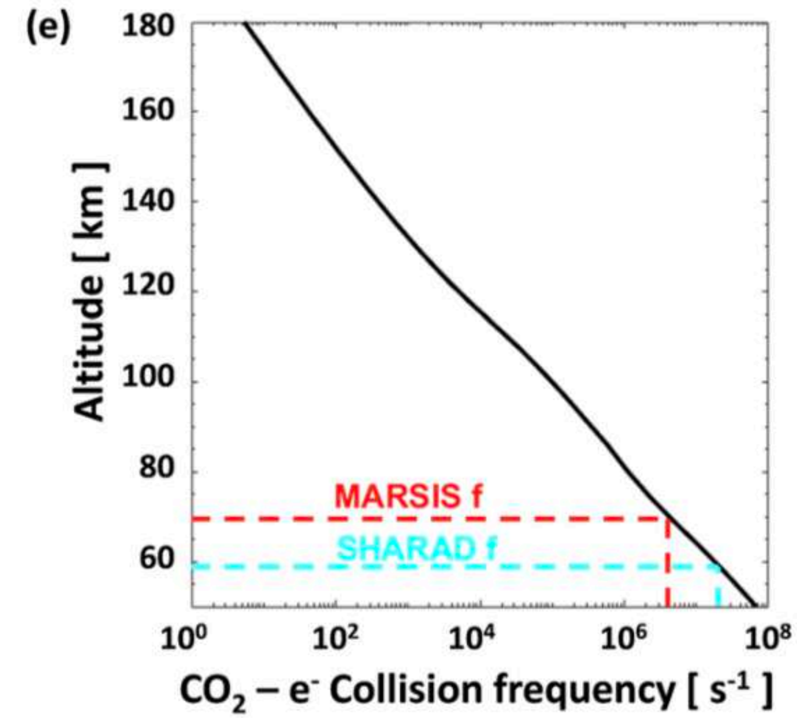
20 MHz -> 58 km

(なぜωでなくf???)

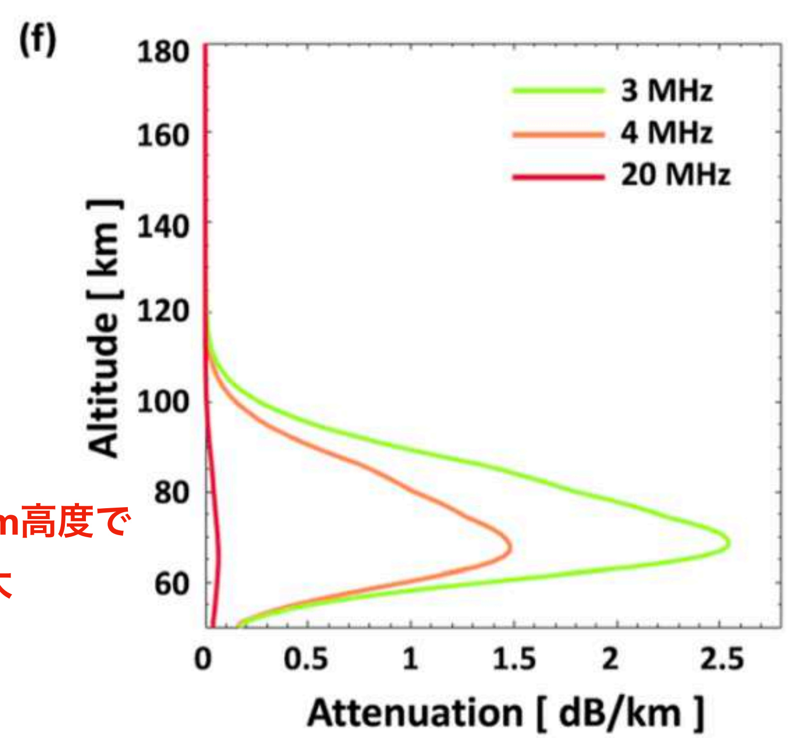
$$\nu\,(e^- - CO_2) = 3.68\times10^{-8}\ n\ \left(1 + 4.1\times10^{-11}\ |4500 - T_e|^{2.93}\right) \quad (4)$$

Modeled Attenuation

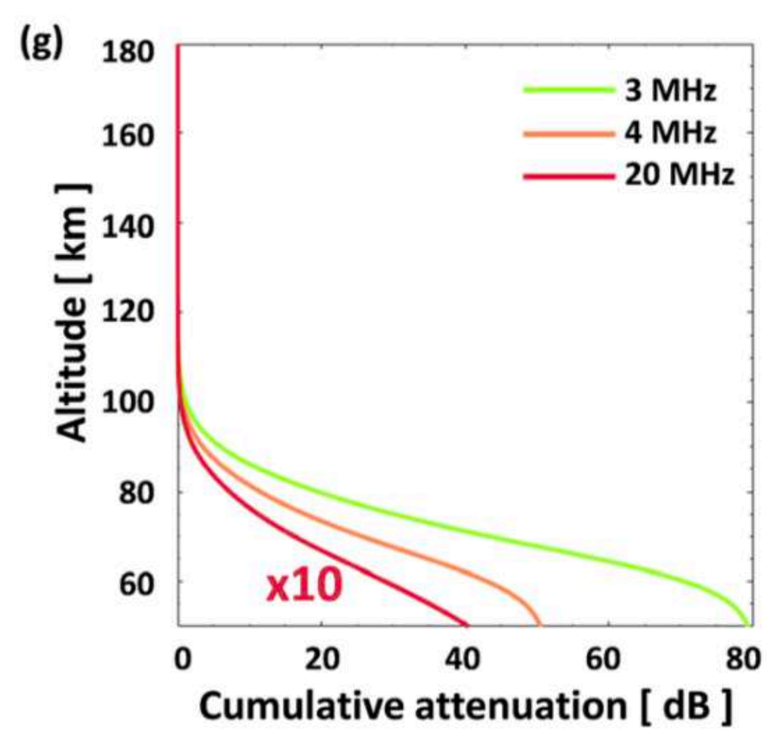




$$A(h) = 4.61\times10^{7}\, N_e(h)\, \frac{\nu(h)}{(2\,\pi\, f)^2 + \nu^2(h)}$$



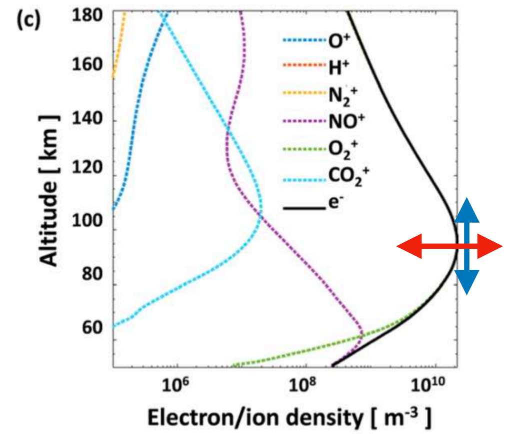
どの周波数も~70 km高度で
減衰率が最大



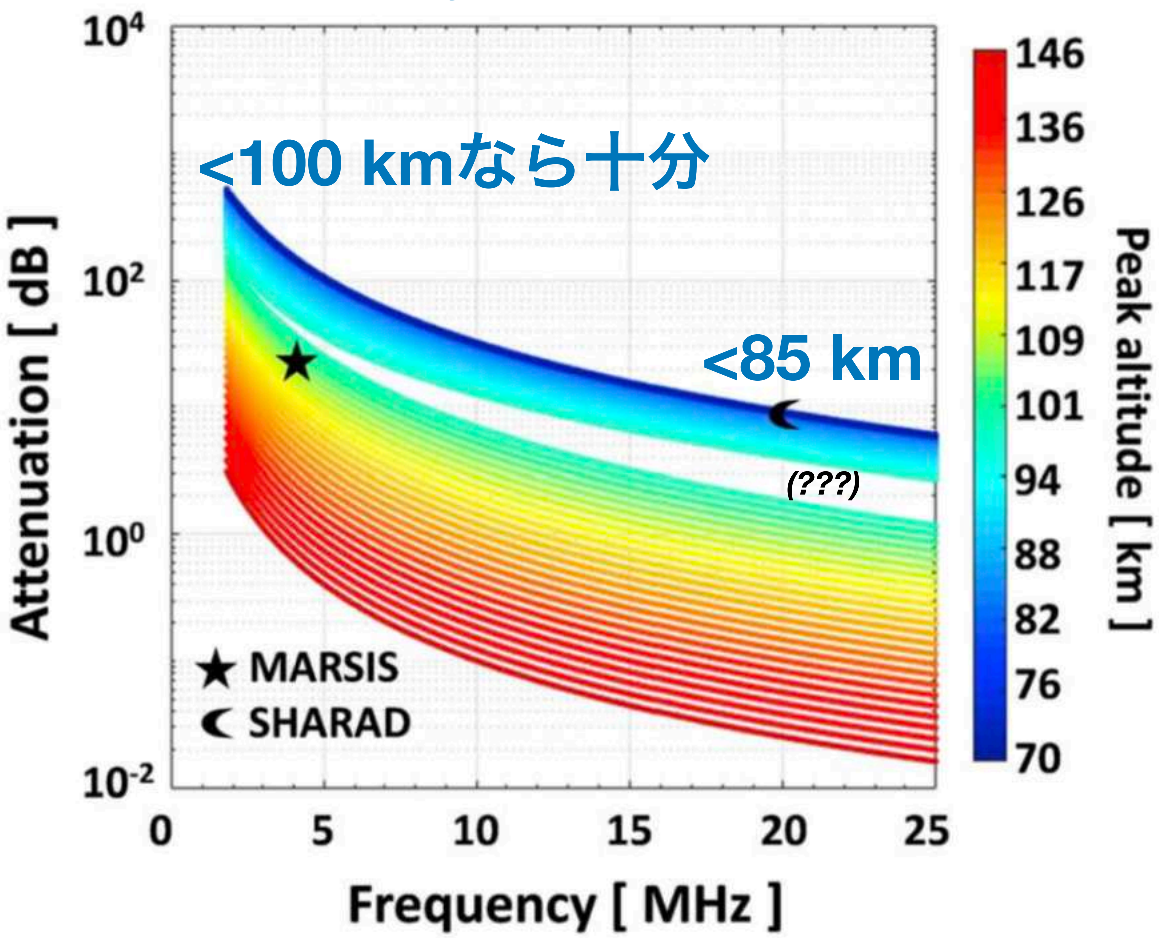
Model:
79, 50, and 4 dB
for 3, 4, and 20 MHz

MARSIS:
>17 dB at 3 MHz
>18 dB at 4 MHz
SHARAD:
>9.5 dB at 20 MHz

Ne Profiles Required for Blackout



Same shape, same peak Ne
w/ varying peak alt.



Same shape, same peak alt.
w/ varying peak Ne

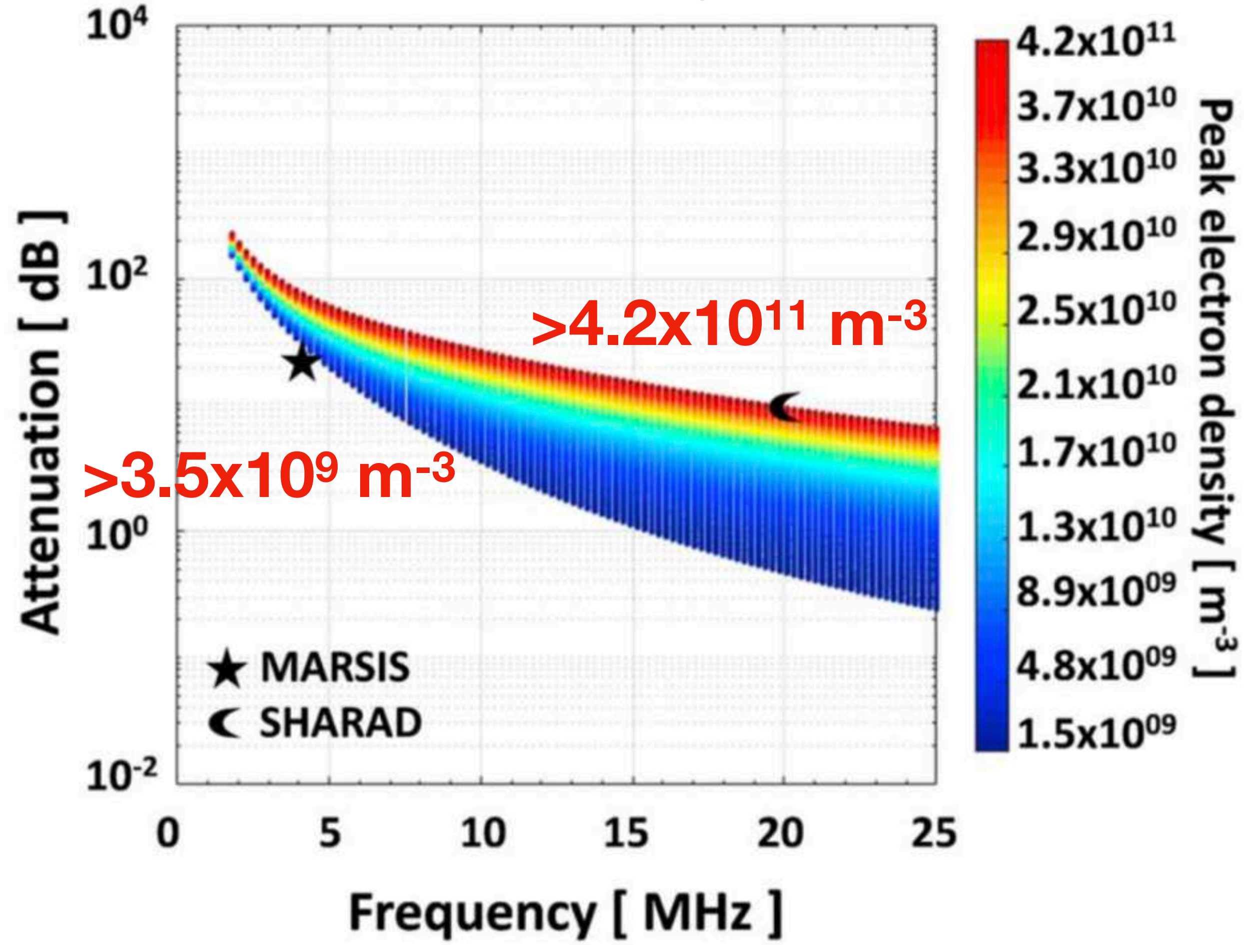


Figure 7. (left panel) Total attenuation versus radar frequency for the electron density profile of Figure 5c at different altitudes. (right panel) Total attenuation versus radar frequency for different electron density peak values of profile of Figure 5c. A star indicates the estimated lower bound on MARSIS attenuation, and the crescent marks the attenuation measured for SHARAD.

Discussion: Ionizing Agent

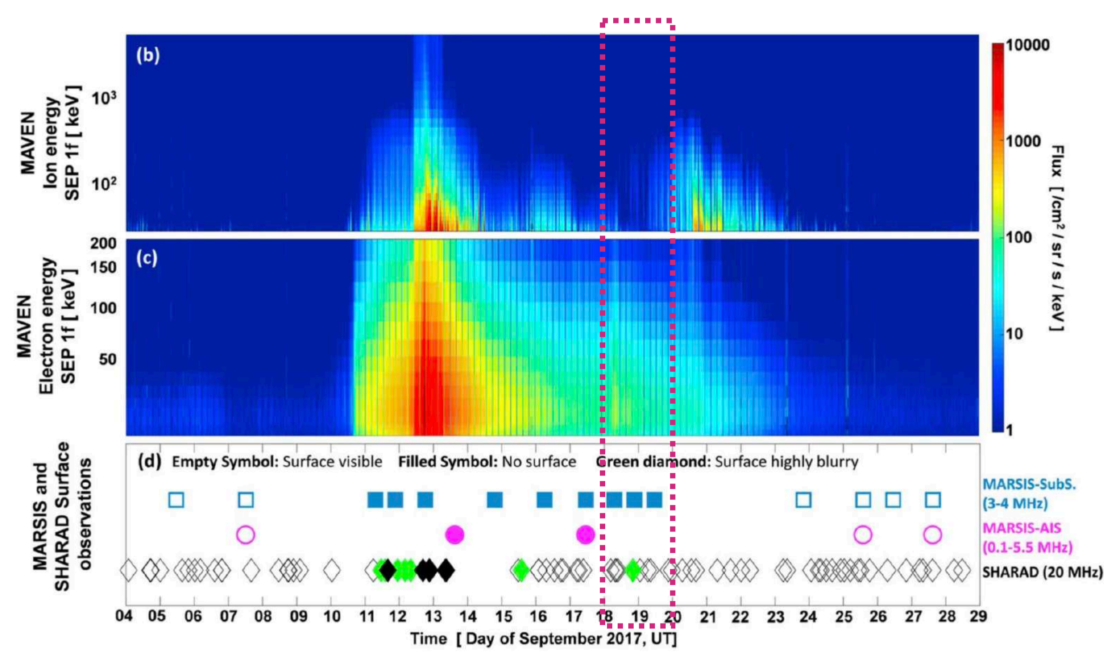
- SEPイベント中に火星夜側電離圏の電子密度が増大し、レーダーエコーが消失することはよく知られている
- 電離源は？
  - SEPプロトン：Morgan et al. (2006); Němec et al. (2015); Sheel et al. (2012)など、ほとんどの先行研究
  - SEP電子：Ulusen et al. (2012)
- O_2^+のlifetimeは数分程度(Bones et al., 2015) 、寿命の長い金属イオンでは説明できない（イベント中に特に増えていない）

▸ 数日に渡るレーダーエコー消失を説明するためには、太陽粒子降り込みによる電離は連続的でなければならない

- 今回のイベントでは、SEP電子は連続的に観測されているが、SEPイオンはblackout中にほぼ検出されていない期間がある

▸ <u>SEP電子降り込みが原因</u>

- 夜側大気へのSEP電子の降り込みは、IUVSのオーロラ観測とも整合的



AISモード観測との比較

- Harada et al. (2018): ~120 km高度に~1-2x10^{10} m^{-3}程度の電子密度ピーク

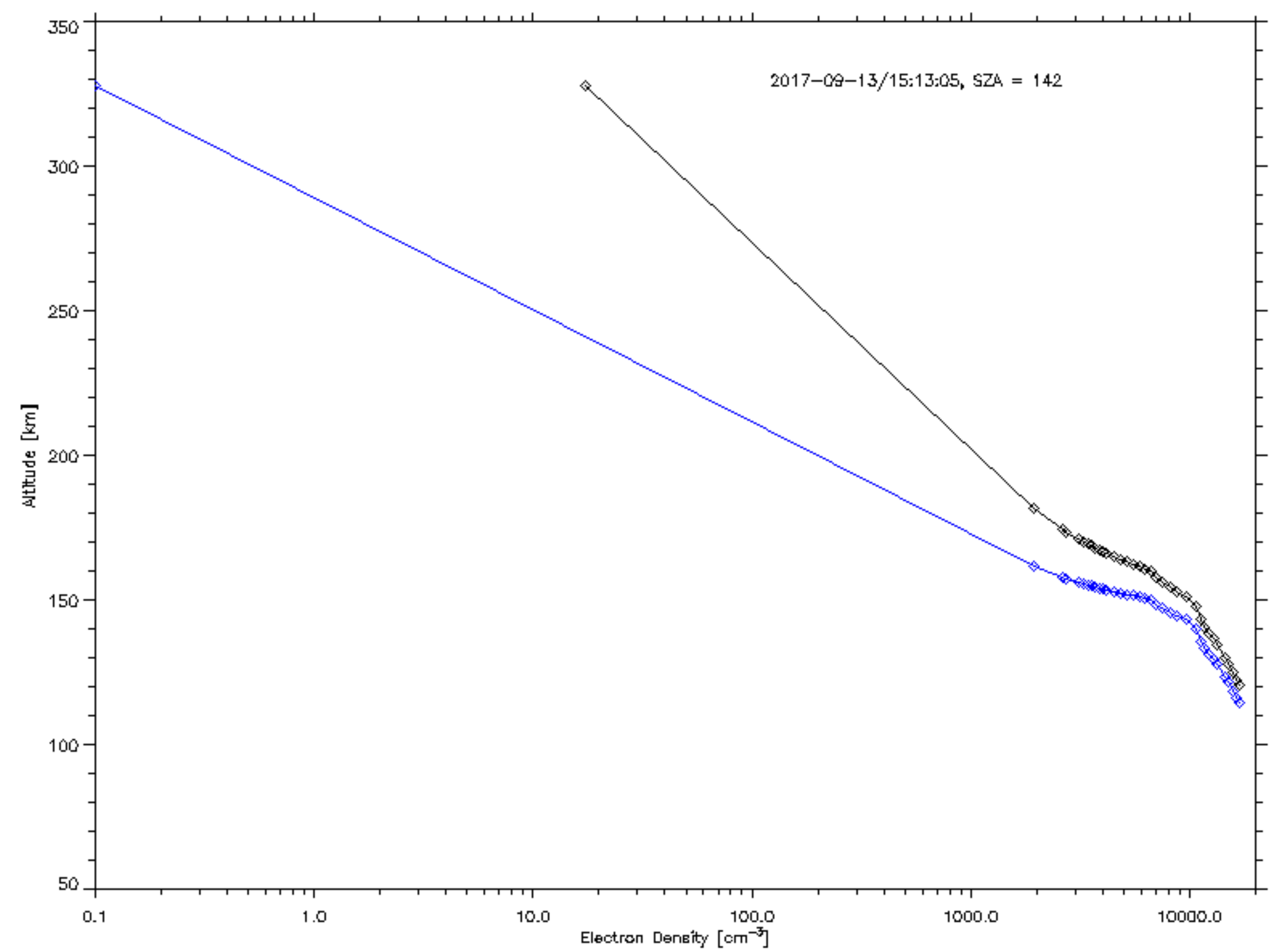
- 今回のシミュレーション結果と比べて、ピーク密度は同程度だが、ピーク高度（90 km）に差がある

1. 20 keV以下の電子降り込みとその結果生じる二次電子による電離（主に>100 km高度）が含まれていないため？

2. 見かけ高度の補正処理（特にローカル電子密度の導出）に不定性？ *(-> Next slide)*

Wait Wait...Local Ne?

- Even with an extremely low local Ne of 0.1 cm^{-3}, the dispersion-corrected peak altitude is still above 110 km
- Uncertainty in local Ne *cannot* explain the difference between the observed and modeled peak altitudes



結論

- 2017年9月の宇宙天気イベント中に、火星軌道で稼働中のレーダー、MARSISおよびSHARADが取得したデータにおいて、火星表面からのエコーが消失した。
- モデル計算から、（プロトンではなく）太陽高エネルギー電子の降り込みによって、90 km高度に10^{10} m^{-3}程度のピークを持つO_2^+層が生成され、電波吸収を引き起し得ることが示された。
- HF帯のレーダーや無線通信は火星周辺の宇宙天気の影響を強く受ける。