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ICON Ionospheric Connection Explorer

Signature of atmospheric gravity waves in nighttime 135.6 nm OI emission line observed by ICON/FUV instrument: a simulation approach

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Background

Classical medium-scale traveling ionospheric disturbances (MSTIDs), characterized by horizontal wavelengths less than 1000 km, are the ionospheric signature of atmospheric gravity waves (AGWs). In low-latitude regions, AGWs could be the triggering phenomenon seeding instabilities in the evening sector that eventually produce equatorial plasma bubbles, generating scintillation in global navigation satellite system (GNSS) signals.

The upcoming NASA-ICON mission will remotely sense the ion and electron density, velocity and temperature at low latitudes from the bottom of the ionosphere up to the altitude of the spacecraft and perform in-situ measurements of the ion plasma drift velocity. In particular, the Far UltraViolet (FUV) instrument will image the ionospheric limb in the OI emission at 135.6 nm.

This work investigates how MSTIDs may be detected and characterized in the nighttime FUV emission, based on simulations only.

1. MSTIDs and ICON/FUV instrument

Medium-Scale Traveling Ionospheric Disturbances (MSTIDs)

- MSTIDS are wave-like fluctuations of neutral/ion/electron density in the ionosphere
- They play an important role in vertical transport of momentum and energy from the lower atmosphere up to the thermosphere
- Horizontal wavelength: 100 – 1000 km
- Period: 12 min – 1h
- Horizontal phase velocity: 50 – 300 m/s
- Classical MSTIDs: the density variations are due to the passage of an Atmospheric Gravity Wave (AGW) (>< non-classical MSTIDs for which density variations are due to electrodynamic coupling between Es and F layers), generally propagating upward

Mathematical formulation of classical MSTIDs

- AGW dispersion relation:

$$\omega^4 - \omega^2 c_0^2 (K_x^2 + K_{zr}^2 - K_{zi}^2) + \gamma g K_{zi}\omega^2 + (\gamma - 1) g^2 K_x^2 - i\omega^2 K_{zr}(\gamma g + 2c_0^2 K_{zi}) = 0$$

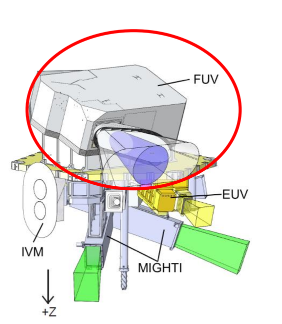
with ω the TID pulsation, c_0 the sound speed at a reference altitude, $\gamma = 5/3$, g the gravity acceleration, K_x, K_{zr} and K_{zi} the horizontal and vertical real and imaginary components of the TID wave vector, with $K_{zi} = \frac{1}{2H_0}$, H_0 being the atmospheric scale height

- Ne perturbation ΔN_e due to the TID (Hooke 1968):

$$\Delta N_e = \mathrm{i} N_{eo} u_b \omega^{-1}\left[\left(\frac{1}{N_{eo}}\frac{\partial N_{eo}}{\partial z} + K_{zi}\right)\sin I - iK_{br}\right]$$

with N_{eo} the electron density background, u_b the TID neutral wind oscillation parallel to the geomagnetic field, I the inclination of the geomagnetic field and K_{br} the real part of the projection of the wave vector on the geomagnetic field

The ICON mission

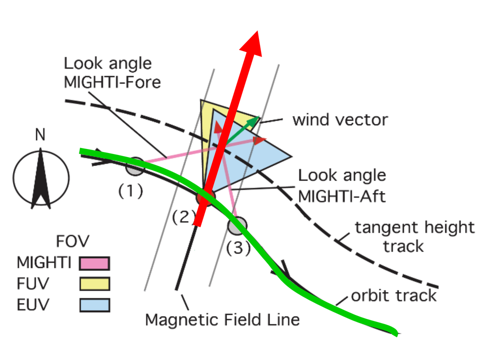


Credits : Immel et al. (2012)

- ICON = Ionospheric CONection Explorer
- Goal : understand the ionospheric variability by studying the connection between ionosphere and weather / space-weather
- Circular orbit, 27° inclination at 575 km altitude
- Four instruments, two of them in UV: EUV and FUV are co-aligned with a vertical field of view of 24°

The ICON/FUV instrument

- Two detectors at 135.6 and 155 nm for OI and N_2 LBH-band respectively
- Measure O^+ altitude profile (nighttime)
- Measure $[O]/[N_2]$ altitude profile (daytime)
- Time resolution: 12 s
- Horizontal/Vertical FOV : 18°/24°, northward directed
- Downward inclination of the FOV: 20°
- Level-1 science products nighttime: line-of-sight (LoS) integrated brightness in two observing modes: six stripes (vertical profiles) and full limb/sub-limb images



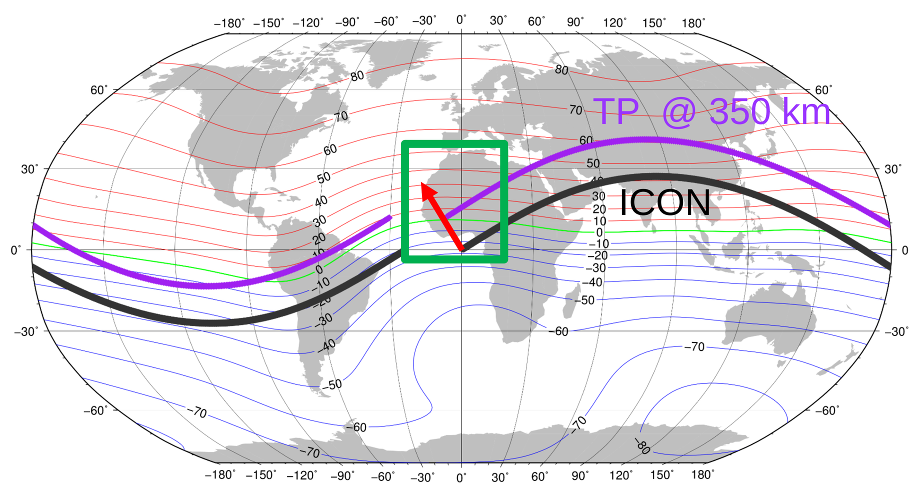
Credits : Immel et al. (2012)

? **Will ICON FUV be able to observe MSTIDs in the nighttime 135.6 nm emission** ?

2. Nighttime FUV simulations

Viewing geometry simulation

- Ionosphere (IRI-2016), geomagnetic field (IGRF12) and neutral atmosphere (NRLMSISE00) on a regular grid with a resolution of 0.5° x 0.5° x 4 km
- One ICON orbit, starting from 0°/0°; the area of interest crosses the two crests of the equatorial anomaly
- Computation of tangent points (TP) related a fictive stripe whose FOV is perpendicular to ICON's orbit track. No Level-1 image was simulated in this work.
- 12 s sampling rate
- For each scan: computation of intersections of the 256 lines-of-sight (LoS) with voxels
- Computation of the background conditions ($[O^+]$, Ne and $[O_2]$) and superimposition of an MSTID affecting ion and electron densities
- Nighttime conditions: 00h00 Local Time (LT)



ICON orbit track (black) and FUV tangent points at 350 km altitude (purple). The red arrow shows the FUV pointing direction. Geomagnetic field inclination is contoured in red and blue, for positive and negative values respectively. Dip equator is plotted in green. The area of interest corresponds to the green rectangle.

FUV nighttime level-1 product simulation

- The main production mechanism of nighttime OI 135.6 nm photons is the radiative recombination of O^+ ions:

$$O^+ + e \rightarrow O^* + h\nu$$

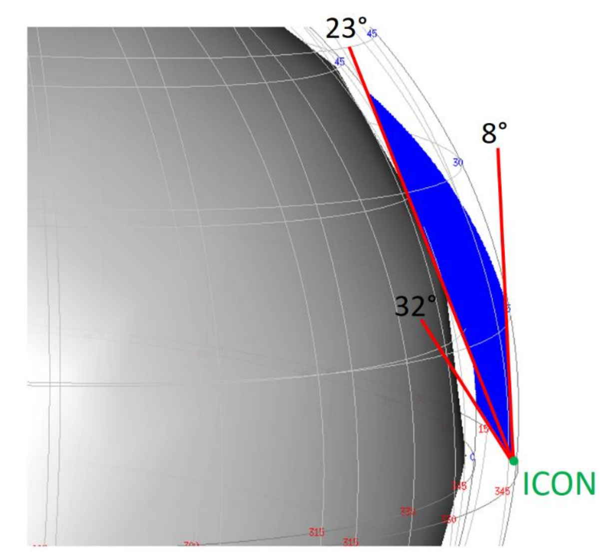
- The 135.6 nm emission results from the doublet ($^5S_2 \rightarrow {}^3P_1$) and ($^5S_2 \rightarrow {}^3P_2$)
- Computation of the Volume Emission Rate (VER) for each voxel:

$$\mathrm{VER} = \alpha_{1356}\, Ne\, [O^+]$$

with α_{1356} being the partial rate coefficient of the radiative recombination leading to 135.6 nm emission (7.3×10^{-13} $cm^3.s^{-1}$) and Ne the electron density.

- LoS integration: the radiative transfer is quite simple as, during nighttime conditions, only molecular oxygen O_2 absorption is taken into account. The brightness for a given LoS, expressed in Rayleigh, is computed as follows:

$$\mathrm{B1356} = \sum_{i=1}^{n} \mathrm{VER}_i \,.\, d_i \,.\, e^{-\sigma_{O_2}.col_{O_2,i}}$$

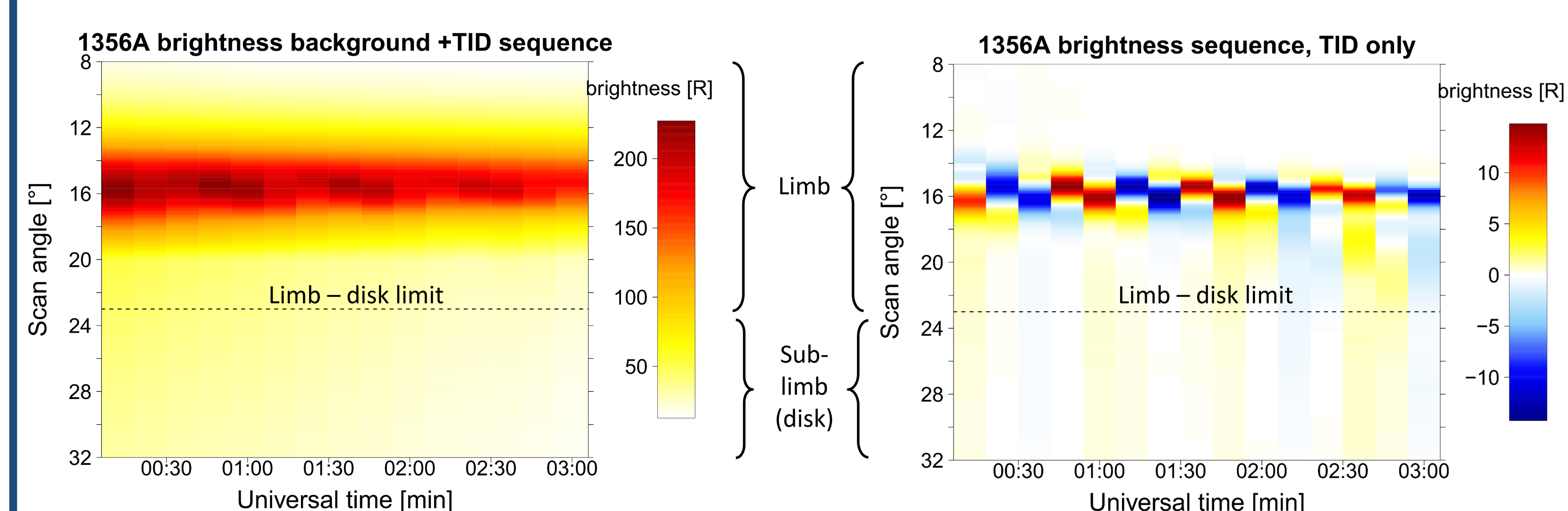


Cross-sectional view of the viewing geometry. Lines of sight with angles from 8 to 23° downwards are viewing the ionospheric limb while angles from 23 to 32° downwards are looking at the disk (sub-limb) region.

with n being the number of voxels crossed by the LoS, d_i the distance traveled by the LoS in the voxel i, σ_{O_2} the absorption cross-section of O_2 (7.13×10^{-18} cm^2) and $col_{O_2,i}$ the column of O_2 related to the voxel i.

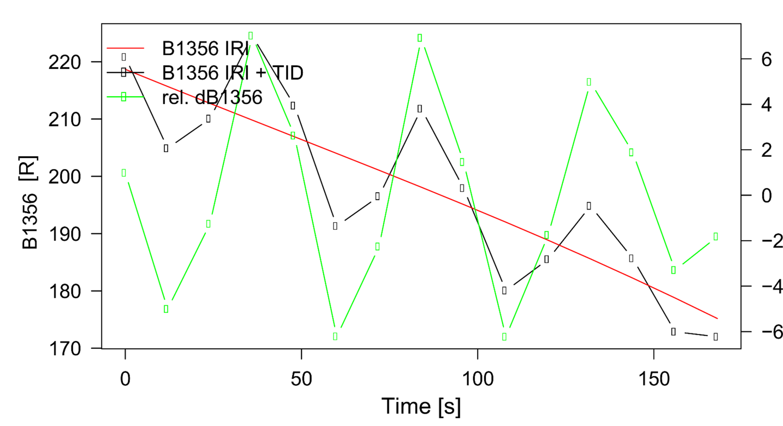
Example

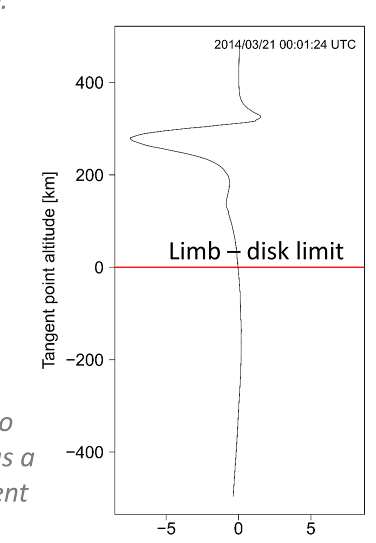
- Period: 25 min
- HZ/V wavelength: 300/165 km
- Azimuth: 63°
- Upward propagation
- HZ/V phase velocity: 46/84 $m.s^{-1}$
- MSTID amplitude of maximum 15% of the $[O^+]$ background



Time series (keograms) of the stripe brightness in the 135.6 nm emission (B1356) during the passage of a classical MSTID. Left: Brightness due to both background (IRI) and MSTID contributions. Right: Brightness due to the MSTID only.

B1356 time series for the LoS that observed the maximum brightness due to the TID (tangent point altitude of 304 km). Crest-to-crest relative variations of more than 10% are observed.





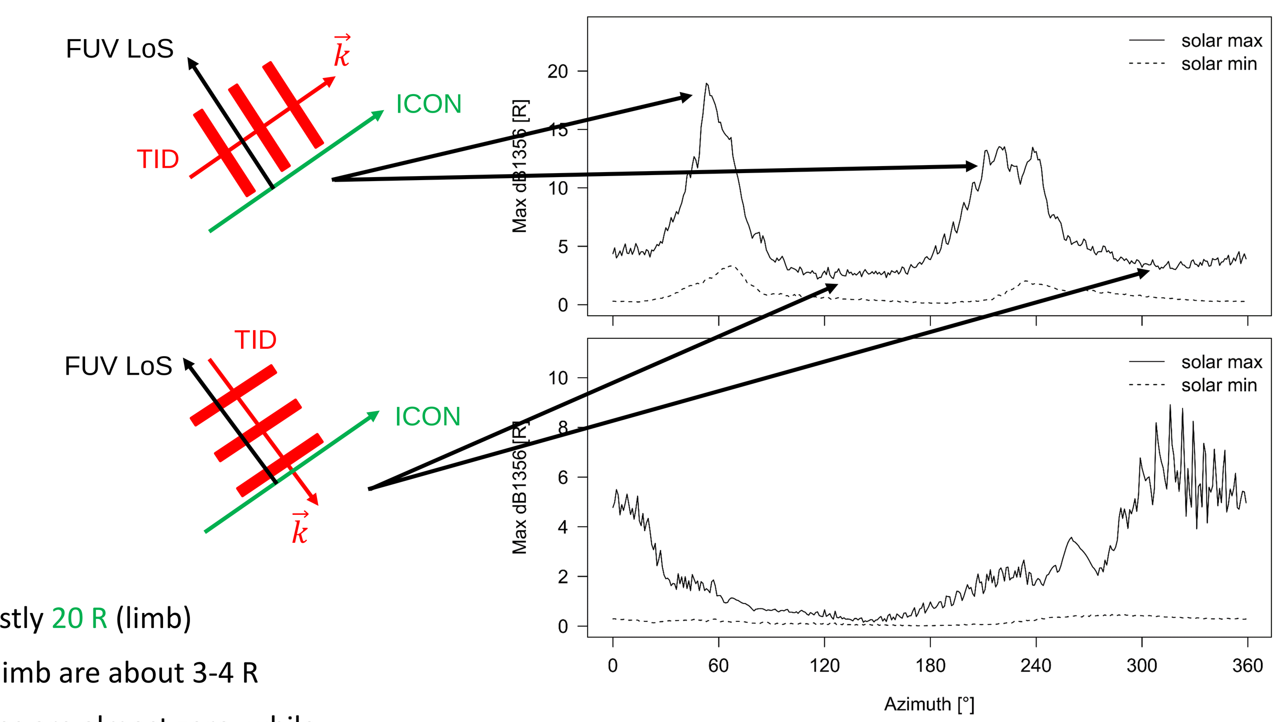
Relative B1356 due to the MSTID only [%] as a function of the tangent altitude

3. Results

Influence of MSTID azimuth

Analysis of the influence of the relative orientation of the MSTID and the FUV line of sight on the brightness signature of the MSTID

- Maximum response is obtained at limb, when the TID wave vector is parallel or anti-parallel to ICON velocity vector
- Minimum response on the limb is observed when the TID wave vector is perpendicular to ICON velocity vector



- Maximum values are mostly 20 R (limb)
- Minimum values on the limb are about 3-4 R
- Sub-limb: minimum values are almost zero, while maximum can reach 6 to 8 R
- Solar maximum signal is several times larger than during solar minimum

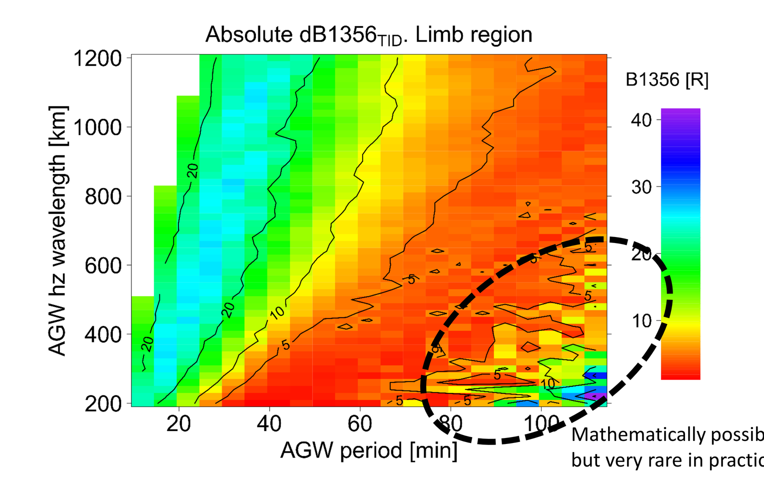
Influence of TID azimuth on its 135.6 nm emission, for limb (top) and sub-limb (bottom) regions. Solid lines plot solar maximum conditions (December 2013) while dotted line is related to deep solar minimum (December 2008).

Influence of MSTID period and horizontal wavelength

- Limb simulation
- Azimuth = 63°

} largest TID signal (see above)

- TID horizontal wavelength between 200 and 1200 km
- TID period between 12 and 112 minutes
- Results: ➢ Absolute values oscillate between 5 and approx. 30 R
  ➢ Larger values are observed for the function $\lambda_{HZ} \approx 20\ period$



Influence of TID horizontal wavelength and period on its 135.6 nm emission, limb region

FUV noise computation

- FUV 135.6 nm channel responsivity: 49 counts/kR/s/science pixel (Mende et al. 2017)
- The error is distributed following a Poisson's law → $error = \sqrt{n}$
- Example: With 12 s integration, a 135.6 nm brightness background of 200 R gives 117 counts, which leads to an error of about 11 counts
- The error is therefore the order of magnitude of the brightness enhancement due to a 15% amplitude TID that can be observed in the most favorable cases, *i.e.* solar maximum, optimal observation geometry, large ionospheric background, etc.
- The detection of MSTIDs, especially during solar minimum, would therefore need more signal, which means that we need to increase the integration time and/or to merge the six vertical stripes. Such methodology may induce a large smoothing of the MSTID characteristics due to their specific spatial and temporal variations.

Summary and future work

- The contribution of MSTIDs in the OI 135.6 nm emission is simulated during nighttime over the equatorial region
- MSTID detection strongly depends on the relative orientation between the TID and the FUV lines of sight
- MSTID detection also depends on its intrinsic propagation parameters (wavelength and period)
- With several dozens of Rayleighs in optimal conditions, the MSTID signal is the order of magnitude of the detector noise
- Ionospheric background densities twice larger induce a brightness four times larger (see the VER computation formula) and a detector noise twice larger → the more background, the better the MSTID detection
- Given the previous considerations, the following strategies could be set up to improve the signal-to-noise ratio:
  - Merge the six simultaneous vertical stripes into a single one, which will increase the FUV response by a factor 6
  - Time integration can be extended to 24 s to increase the FUV response by a factor 2. These two strategies will induce a large smoothing of the TID characteristics, which could make its detection more tricky
  - Considering local times for which $[O^+]$ and Ne are larger. For instance, considering 22h00 LT instead of 00h00 in December solstice in 2013 enhances the ionospheric background by about 45% → 135.6 nm brightness x 2 !
- Future work:
  - the study of non-classical MSTIDs using the same methodology
  - the study of daytime MSTIDs using N_2 LBH band and the OI 135.6 nm. This simulation will rely on VER computation by a photo-chemistry model, in addition to a thin line radiative transfer for LoS integration

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