Significant Findings from the C/NOFS Satellite Mission

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Integrity ★ Service ★ Excellence
Overview

• Introduction
  • C/NOFS mission
  • Equatorial irregularities
• C/NOFS during Solar Min and Solar Max
  • Post midnight irregularities and large depletions
  • Climatology of irregularities
• Storm effects
• Discussion/Conclusion
  • More irregularities are observed over Africa than anywhere else on Earth
  • Lingering questions
C/NOFS: Equatorial satellite and ground stations to nowcast and forecast EDP and scintillation continuously

Mission Components:

- Satellite with 6 sensors in equatorial LEO orbit
  - 13 deg Inclination
  - 400 to 850 Km altitude
- Ground-based instruments
- Models (PBM0d)
- Data Center
Introduction
Equatorial Plasma Irregularities

- Plasma moves easily along field lines; upward plasma drift supports plasma against gravity \(\rightarrow\) unstable configuration
- E-region “shorts out” electrodynamic instability during day. At night, E-region conductivity too small to short-out E field
- Instability in plasma grows to form EPBs. Irregularities within EPBs affect radar systems and disrupt communication & navigation
C/NOFS Satellite Instruments

**GPS Receiver**
- C/NOFS Occultation Receiver for Ionospheric Sensing and Specification (CORISS)
- Developed by Aerospace (P. Straus, PI)
- Measures: Remote sensing of LoS TEC

**Electric Field Instrument**
- Vector Electric Field Instrument (VEFI)
- Developed by NASA/GSFC (R. Pfaff, PI)
- Measures: Vector AC and DC electric as well as magnetic fields
- Includes lightning detector

**Planar Langmuir Probe (PLP)**
- Developed by AFRL/RV BX (P. Roddy, PI)
- Measures: Ion Density, Ion Density Variations, Electron Temperature

**RF Beacon**
- Coherent EM Radio Tomography (CERTO)
- Developed by NRL (P. Bernhardt, PI)
- Measures: Remote sensing of RF scintillations and LoS TEC

**Ion Velocity Meter (IVM)**
- Developed by Univ. of Texas at Dallas (R. Heelis, PI)
- Measures: Vector Ion Velocity, Ion Density, Ion Temperature

**Neutral Wind Meter (NWM)**
- Developed by Univ. of Texas at Dallas (G. Earle, PI)
- Measures: Vector Neutral Wind Velocity
Irregularities Detected by PLP

Day 148, 28 May 2010 15:46:59 UT orbit 11464

**PLP in situ densities**
- 1 sec averages
- 1 min averages
- Altitude
- Spectrogram of PLP
- High Rate Data 10m – 20km

- Example of equatorial plasma bubbles (EPBs)
- During solar min, C/NOFS rarely saw irregularities at dusk -- when they were expected.
- However, irregularities were often present below the satellite, as deduced from ground-based scintillation measurements.
Solar Minimum
Large Depletions Seen at Dawn

Unexpected depletion in ambient density observed just before sunrise (~05:00 LT) occurs frequently in solar min, mostly during June-July.

From de La Beaujardièr et al., GRL, 2009
Modeling $N_e$ Depletions with PBMod

Measured $V_i$ from several orbits assimilated into PBMod model; simulation results match observed $N_e$ if VEFI data used, but not with empirical model used for $V_i$.

Assimilating actual wind might provide even better results than using empirical wind.

From Su et al., GRL, 09
Formation of Broad Plasma Depletions through Merging Process

*In situ* density and ion vertical drift for 4 consecutive C/NOFS orbits

(a) C/NOFS Orbit  
Orbit 803  
Orbit 804  
Orbit 805  
Orbit 806  

(b) Ion Density  
$\text{Ni (cm}^{-3}\text{)}$  
19:42-20:21 UT  
21:19-21:58 UT  
00:33-01:12 UT  

(c) Ion Vertical Velocity  
$V_{\text{vert}} \text{ (m/s)}$  

Large plasma depletions are due to multiple bubbles merging

*From Huang et al., JGR, 2011*
Formation of Broad Plasma Depletions through Merging Process

Example of bubble merging Detected by C/NOFS on 21 June 2008

From Huang et al., JGR, 2011
Equidistant EPBs

Orbits 730 & 731, Day 156, 04 June 2008

Orbit 731 shows almost equidistant EPBs separated by 8.5°
No wave apparent in the previous orbit (730) that could explain equidistant EPBs
Equidistant EPBs

Orbit 731, Day 156, 04 June 2008,
Upward ion velocity reaches 200 m/s in first EPB
Upward ion velocity (measured from VEFI) reaches 300 m/s in the set of almost equidistant EPBs, separated by ~ 1000 km (8.1°) in longitude. Waves were present on orbit 745 that could have triggered the EPBs, but they are longer (λ ~ 10.3°) and only 2 waves are apparent, thus the equidistant EPBs may not have been seeded by the wave observed on orbit 745.
Irregularity Climatology from DMSP Evening Sector -- Solar Max & Min

In Africa (Long ~ -20° to 52°) dusk irregs seen almost all year at solar max

Most topside depletions occur in Atlantic-Africa sector when the dusk terminator is aligned with magnetic field

Solar min climatology consistent

This solar min is the lowest yet!
Irregularity Climatology from DMSP Evening Sector -- Solar Max

**Plot of dn/n from DMSP -- similar to the plot above, although the parameter plotted is not exactly the same**

**In Africa (Long ~ -20° to 52°) dusk irregs seen almost all year at solar max**

*From Gentile et al., 2011*

*From Ober, pers. comm., 2012*
DMSP data confirm C/NOFS observations: during solar min, irregularities seen at dawn, rather than at dusk. In S. America & Africa, morning depletions seen May thru Sept, where they are most frequent.

Strong longitudinal dependency probably related to 4 wave pattern from lower atmosphere tides.

Dotted lines mark the times when the dawn terminator is aligned with the magnetic field.
Irregularity Climatology from C/NOFS

- Statistical study of PLP density depletions
  - Longitude dependence of nighttime $\Delta N/N$ from May 2008 to October 2009
  - As with DMSP dawn sector, 4-wave pattern apparent
  - Similar average patterns seen in ion drifts and neutrals

From Dao et al., 2011
C/NOFS Plasma Densities during Solar Minimum at 500 km

Periodic structures apparent in averages of detrended plasma densities. Climatology (strongest in June-September, weakest in December) agrees with DE-3 tidal climatology (from Huang, 2012)
Irregularity Climatology
DMSP Dusk & Dawn Depletion Rates vs F10.7

Distribution rates of evening sector depletions for 1989 – 2009 (left) correlate well with F10.7; correlation coefficient = 0.94.

Dawn sector rates (right) show the reverse: rates anticorrelated with F10.7

\[ DR = -10.66 + 0.147 <F_{10.7}> \]
\[ R = 0.94 \]

\[ DR = 31.3 - 0.36 <F_{10.7}> \]
\[ R = 0.77 \]

Gentile et al., 2011
2011 Ground-based SCINDA

- Data from Nairobi ground-based scintillation receiver
- Lat = -1°, Long = 37°
- Each night is one vertical line
- Time = 0 at sunset
- Data gap from day~215 (Aug 3)
Nairobi ground-based scintillation receiver

- 31-day running average
- Data indicate that from May to the Aug data gap, scintillation starts after midnight on most days (still solar min behavior)
- Rest of the year, solar max behavior
- SCINDA data show Africa has maximum probability of observing scintillation
C/NOFS Signature of Equatorial Anomaly Peak

Day 154, 03 June 2011, 23:54:33 UT, Orbit 16990

Equatorial peak seen at ~-10° MLat appears sharp and narrow
• Magnetic storm on Aug 5, 2011

• B-total reaches 30 nT

• Solar wind speed 400 to 600 km/s

• Dst max at 19:16 UT
Storm Effects:

Strong Irregularities Form Immediately

- Virtually no irregularities in PLP during orbit 17925 before storm (1916 UT)
- Next orbit (17926), at 2013 UT, strong EPBs seen, even though C/NOFS flies at high L values, indicating almost immediate ionospheric reaction
Storm Effects:
Ionosphere Blown Away

• Large bite-out observed during orbit 17930
• Ionosphere blown away at 01:30 UT Aug 6, ~6 hours after storm started
• Bite-out lasts for 7 hours, until solar illumination replenishes F region
• Plasma irregularities seen ~9 hours after storm started
Discussion/Conclusion

• During solar min, irregularities do not occur after dusk
  – Prereversal enhancement not seen except during storm main phase
  – 4-wave pattern evident in irregularities, plasma drift, neutral density

• Probability of observing irregularities
  – At dusk increases with F10.7
  – At dawn decreases with F10.7
  – Plasma irregularities are more frequent in Africa than anywhere else

• Example of very narrow equatorial anomaly peak

• Storm effects
  – Minutes after storm sudden commencement, irregularities are formed
  – During storm, nightside ionosphere blown away due to large upward field
  – Strom effects last many hours (~ 9 hrs in the case of Aug 5, 2011 storm)

• Unresolved questions
  – Origins of almost equidistant irregularities, ~1000 km apart
  – Causes of day-to-day variability
  – Role of penetration E-field and disturbance dynamo in irregularity formation
Extras
Why Do We Care About the Ionosphere?

Ionosphere formed by solar EUV/UV radiation

Subject to Raleigh-Taylor instability during day to night transition

Reflects, refracts, diffracts & scatters radio waves

Leads to highly variable reflection/refraction = “SCINTILLATION”

Scintillated GPS Signal

Unclassified, Unlimited Distribution
Estimate Scintillation Far from C/NOFS Using PLP and AC E-field

Scintillation is often present below the satellite
Planned product: Estimate scintillation using PLP data at the Fresnel scale and E and B data from VEFI
(from Burke et al., 2011; Gentile et al., 2011; Dao et al., 2011)
Connecting C/NOFS Satellite and Ground Observations 13 January 2010

Power spectral densities 3 - 8,000 Hz measured by VEFI in two components of the ambient electric field show power at the Fresnel scale $F_S$.

Significant spectral power measured by PLP at Fresnel (~1 km) scale size suggests C/NOFS was magnetically conjugate to bottomside irregularities similar to those responsible for observed scintillations.
Appleton Anomaly Seen from Space

- Image of the Earth seen from the GUVI instrument on the TIMED satellite
- Green line is magnetic equator
- Integrated emission proportional to $N_e^2$
- Images are all obtained at the same local time
- Black streaks are Equatorial Plasma Bubbles (EPBs), seen on most satellite passes
- 135.6 nm emission from $O^+$ radiative recombination
VEFI magnetometer recorded geomagnetic storm of 24 October 2011; largest storm observed by C/NOFS to date!
C/NOFS Plasma Densities during Solar Minimum at 500 km vs IRI Model

PLP plasma density variations (blue) and IRI model (red) vs longitude June 2008

Clear 4-wave structure on the dayside shows evidence of tidal forcing from the troposphere.

From Huang et al., AGU, 2010