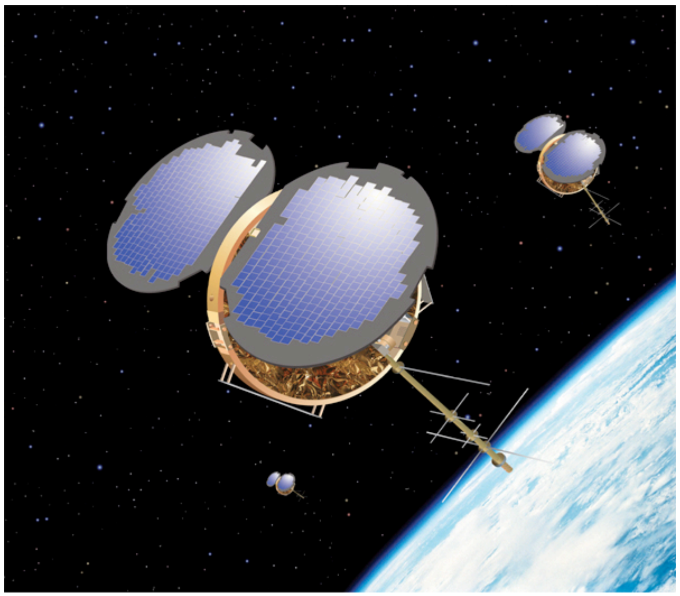


The Tiny Ionospheric Photometer: Science Applications

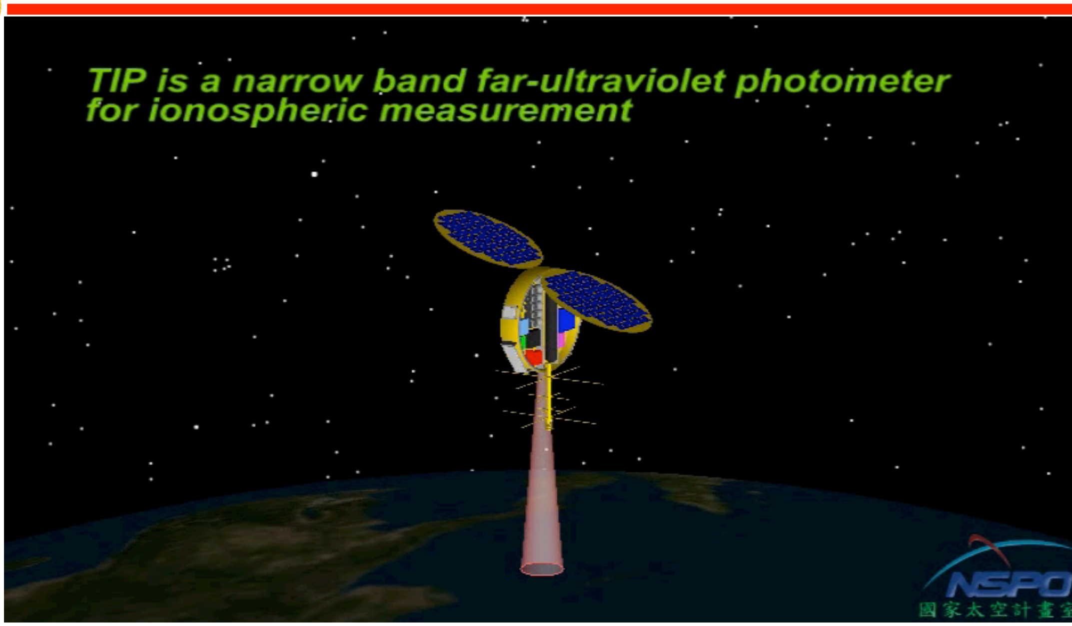
Scott Budzien, Ken Dymond, Stefan Thonnard
(Naval Research Laboratory, Washington, DC)
Ellen Bennert, and Clayton Coker
(Praxis, Inc., Alexandria, VA)

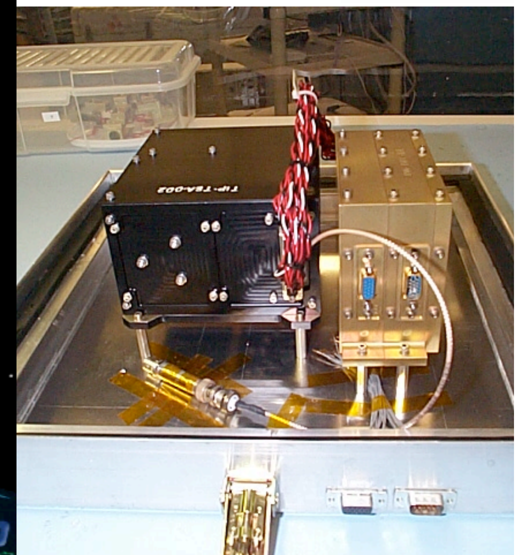
Outline

- The TIP Sensor on FORMOSAT-3/COSMIC
- UV ionospheric remote sensing
- How TIP works
- TIP data products
- Using TIP data
- Summary

The TIP Sensor on COSMIC/FORMOSAT-3

TIP on FORMOSAT-3/COSMIC

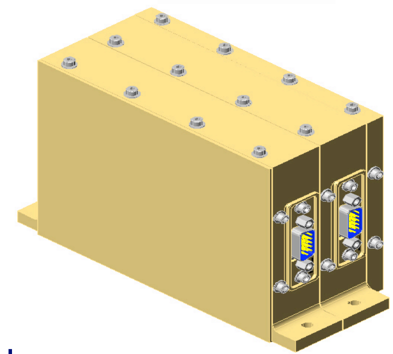




- What is the Tiny Ionospheric Photometer?
  - Small, lightweight, "smart" sensor
  - Topside airglow sounder
  - High sensitivity
- What does the Tiny Ionospheric Photometer measure?
  - UV remote sensing
  - OI 135.6 nm airglow emission
  - Other FUV airglow, aurora features
- How are the Tiny Ionospheric Photometer measurements used?
  - Ionospheric gradients
  - Ionosphere/Thermosphere morphology
  - Simple VEC estimates (vertical electron content)
  - GOX-TIP, TBB-TIP joint retrievals
  - Assimilative modeling
    - GAIM

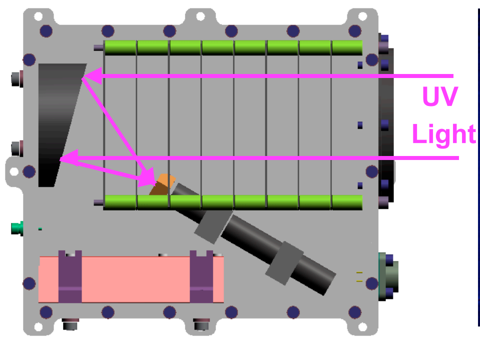
TIP Experiment Overview

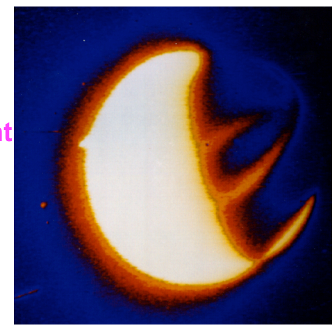
Electronics Module



Sensor Module:

- Photomultiplier tube observes UV light
- SrF_2 filter passes 131-160 nm emissions
- Very high sensitivity ~150 counts/s/Rayleigh



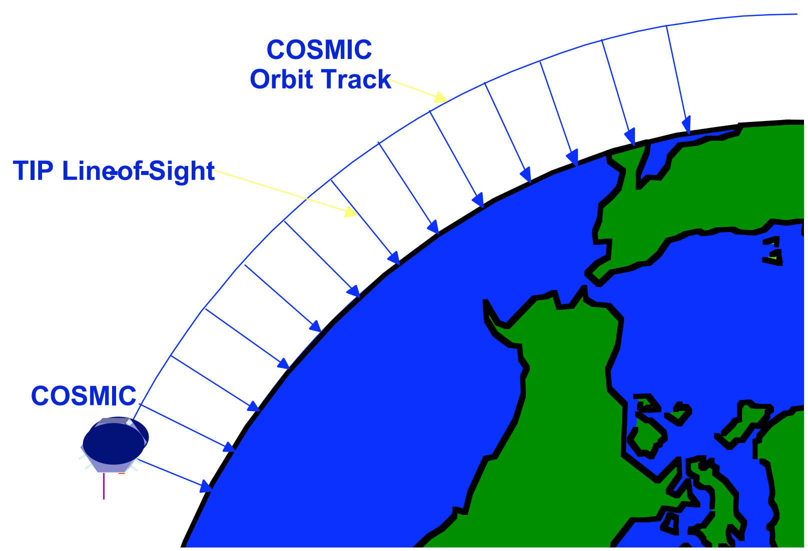


Measures intensity of naturally occurring 135.6-nm airglow, caused by the decay of the nighttime ionosphere.

Intensity is proportional to the vertical sum of the electron density-squared,

$$I \propto \int N_e^2$$

Nadir pointing 4^o circular field-of-view yields 30-km horizontal resolution from an altitude of 700 km.

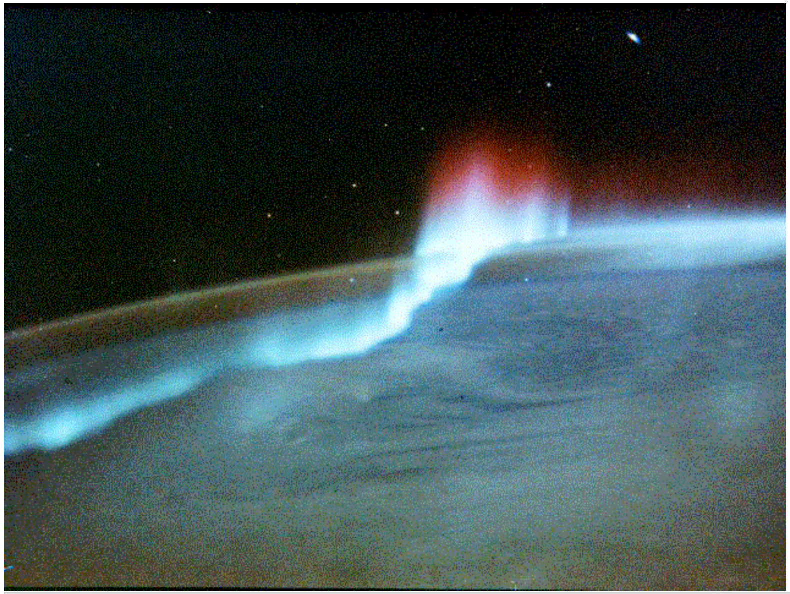


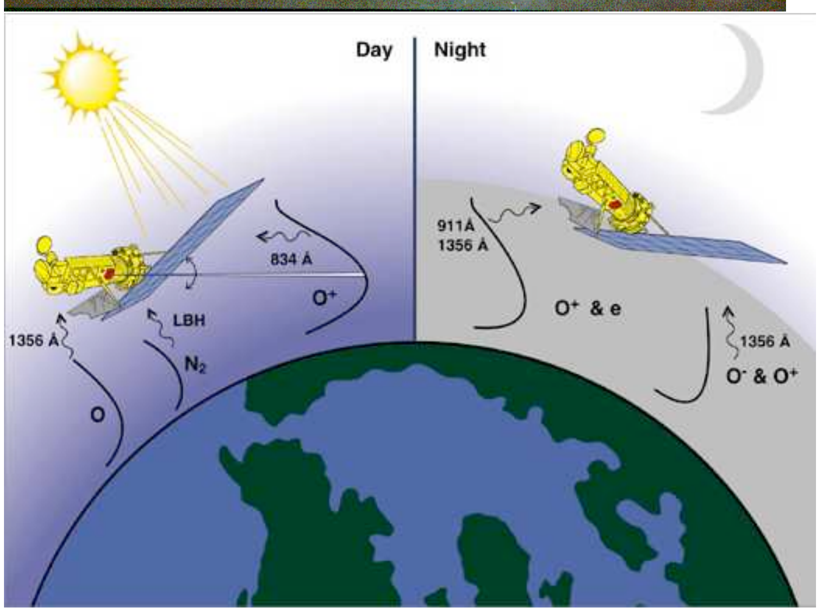
UV ionospheric remote sensing

UV radiation Overview

- EUV—Extreme Ultraviolet
  - E>12eV
  - λ<100 nm
  - Ionizing radiation
  - Requires vacuum in laboratory; Reflective optics only; Open Detectors
  - Doesn't penetrate below ~200 km; Earth as laboratory
- FUV—Far Ultraviolet
  - 12eV > E >6eV
  - λ<100 nm
  - Ionizes some Molecules; Dissociates Molecules
  - Requires vacuum in laboratory; Halide Filters; Windowed Detectors
  - Doesn't penetrate below ~100 km; Earth as laboratory
- MUV—Mid Ultraviolet (200-300 nm, UVC/UVB)
- NUV—Near Ultraviolet (300-400 nm, UVA)

Airglow





- Ionosphere & thermosphere glow day & night
  - EUV/FUV radiation produced
    fundamental electronic transitions
  - UV characterizes ionosphere
    - total brightness
    - altitude distribution
    - spectral distribution

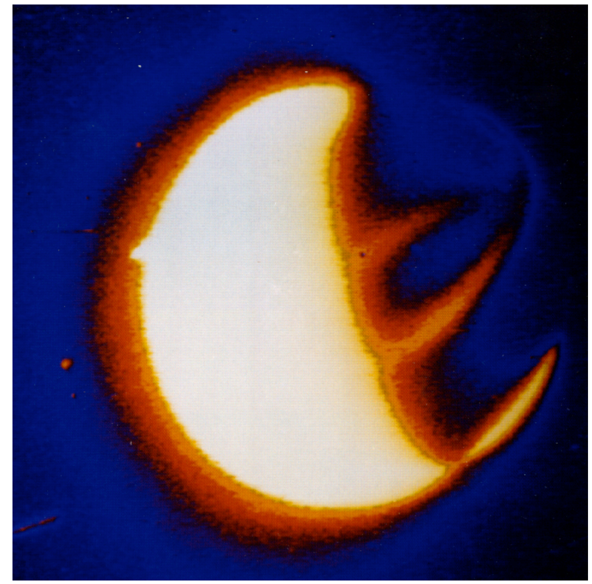
Simply view it...
  - Passive UV remote sensors

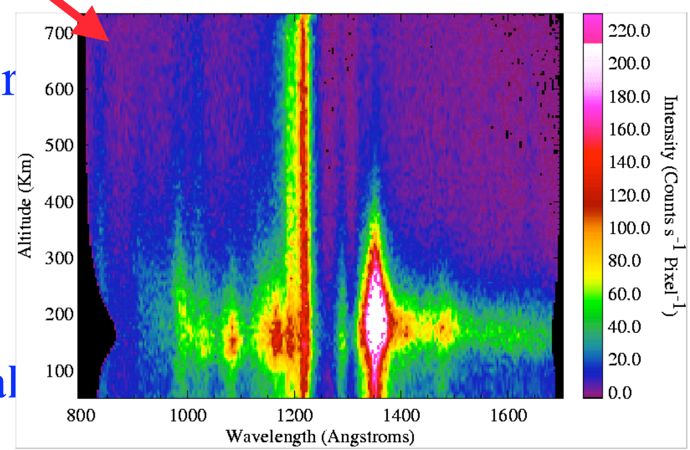
and interpret the glow
  - Physics-based data analysis

to characterize the upper atmosphere

What does the TIP measure?

- Measures the Intensity of Naturally Occurring Airglow
  - Caused by Decay of Nighttime Ionosphere
  - Produces Light at 135.6 nm – Atomic Oxygen
- Why only at night?
  - Daytime signals are contaminated by other signatures
  - COSMIC requires a simple, very high sensitivity instrument
  - Simple – Low cost, low weight, low power
  - High sensitivity:
    - **Required to produce data of a quality comparable to GPS occultation measurements**
    - **Measure gradients when signals are weal**





Energy Deposition in the Upper Atmosphere

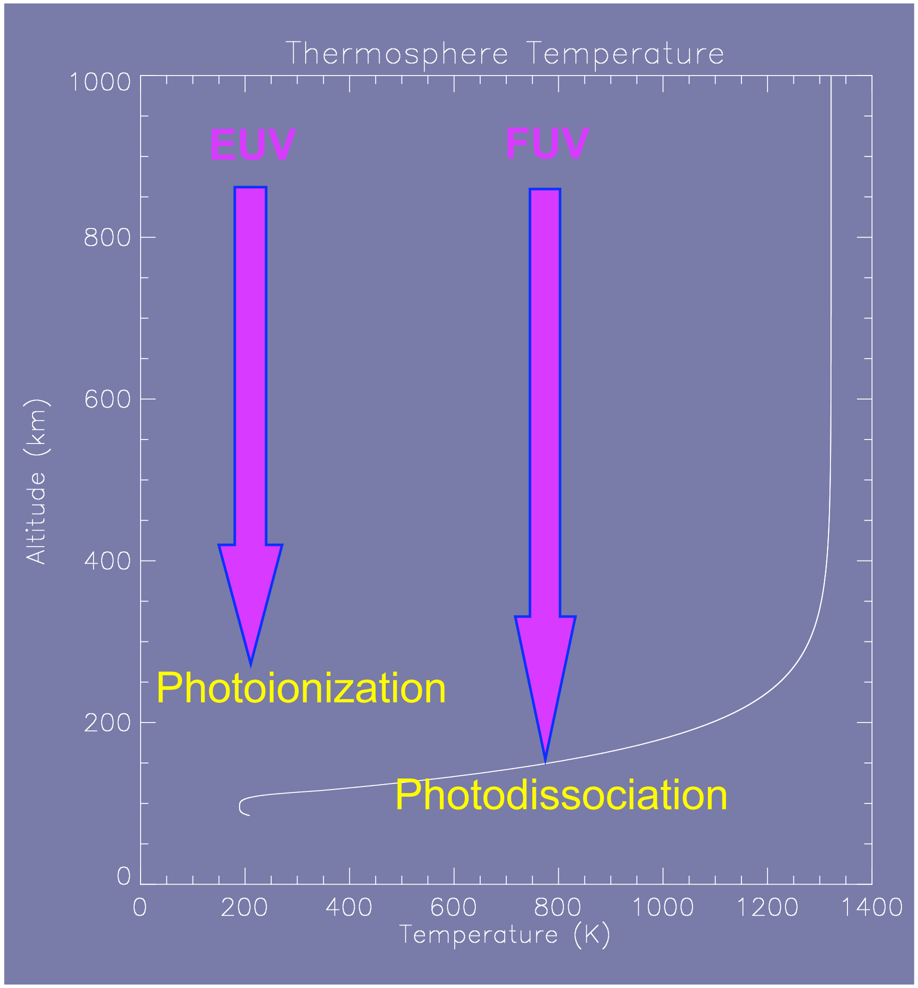
- (Above turbopause)
- Rapid temperature gradient indicates strong heating
- Extreme Ultraviolet (>12 eV)
  - Knock electrons free from atoms (generates Ionosphere)
  - Photoionization:

    $O + EUV \rightarrow O^+ + e^- + heat$

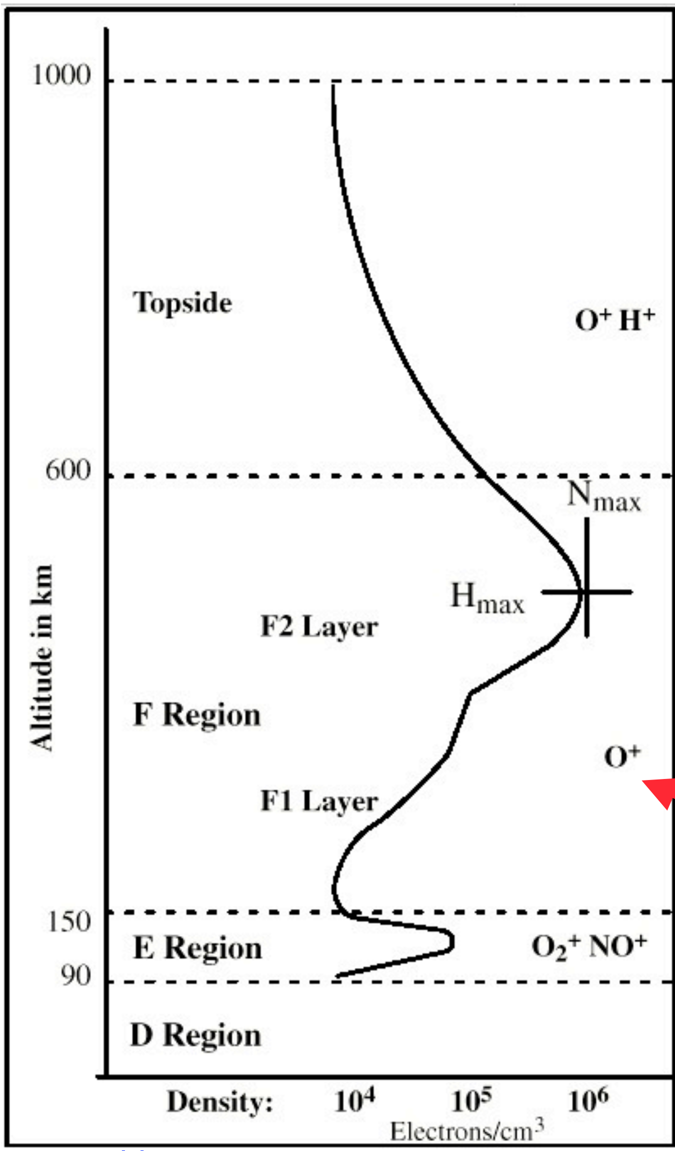
    $O_2 + EUV \rightarrow O_2^+ + e^- + heat$

    $N_2 + EUV \rightarrow N_2^+ + e^- + heat$
- Far Ultraviolet (6-12 eV)
  - Split molecules into atoms
  - Photodissociation:

    $O_2 + FUV \rightarrow O + O + heat$



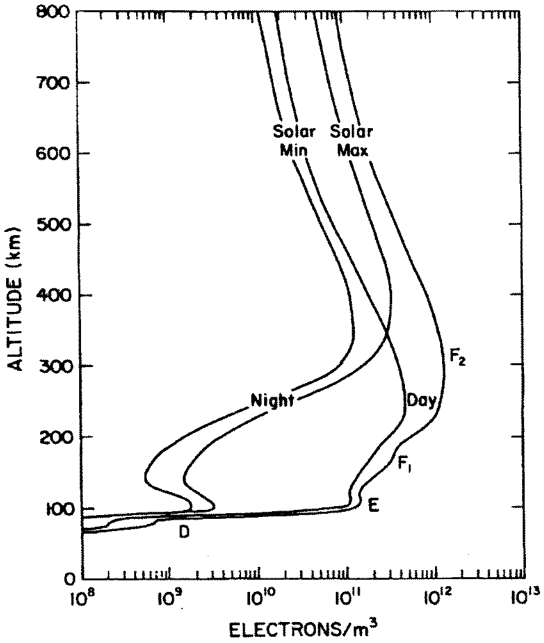
Ionosphere Structure and Composition



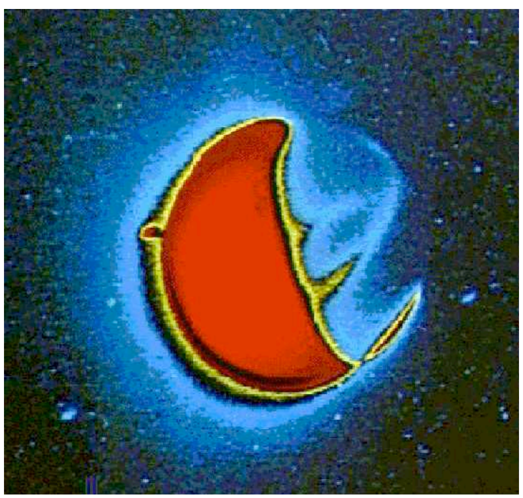
- Layers discovered by radar measurements
- D,E-region
  - Solar X-rays
- E-region
  - Solar X-rays
  - O_2, NO chemistry
- F-region
  - O ionization, recombination

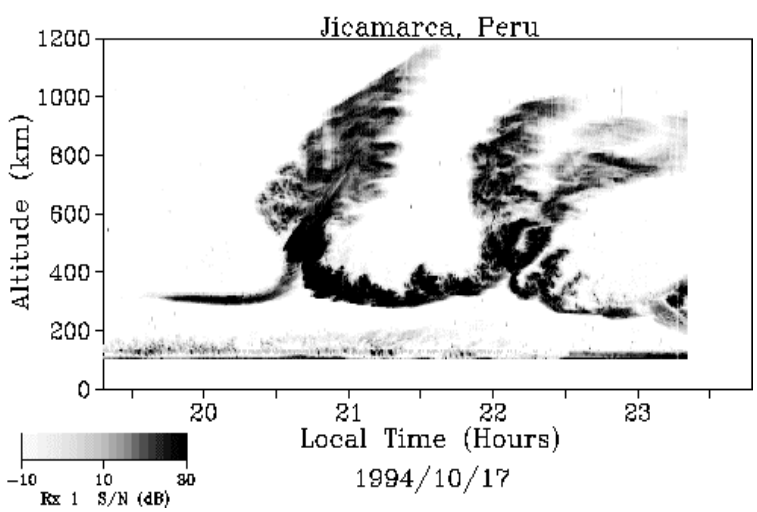
The key to how TIP works!

Ionosphere Variability

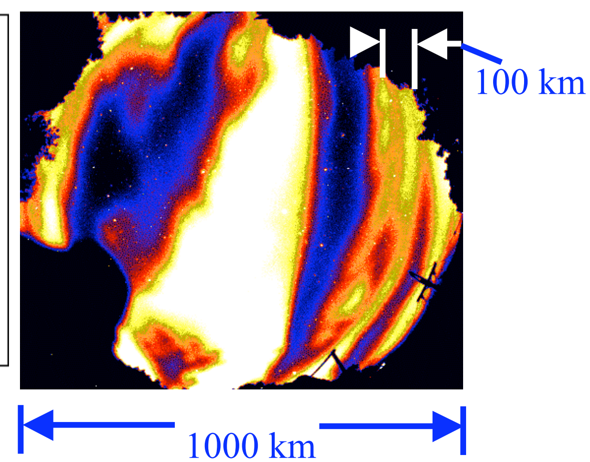


- Most Variable Component In The Atmosphere
  - Highest amplitude to solar (& other) forcing
  - Varies with local time ~10X
  - Varies with latitude ~10X
  - Varies with season & solar cycle ~10X
- Spatial variations
  - Global, Regional, Local

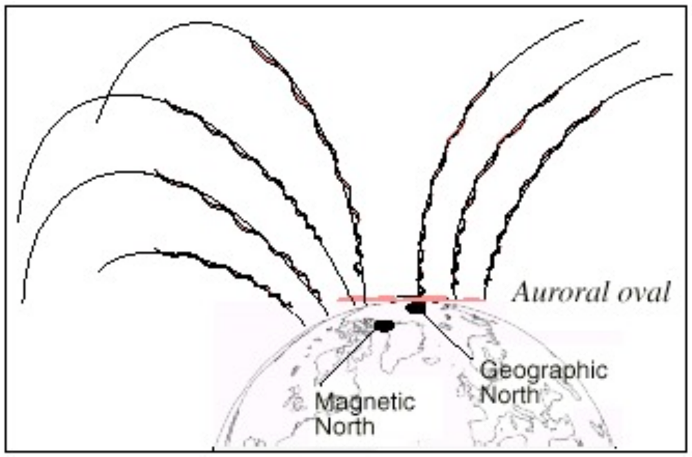


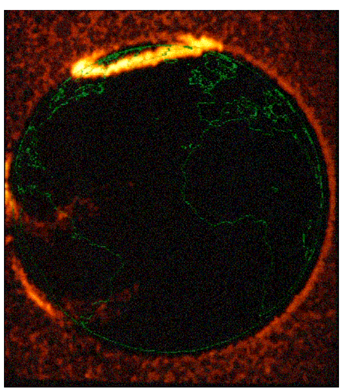


Arecibo, February 17, 1998



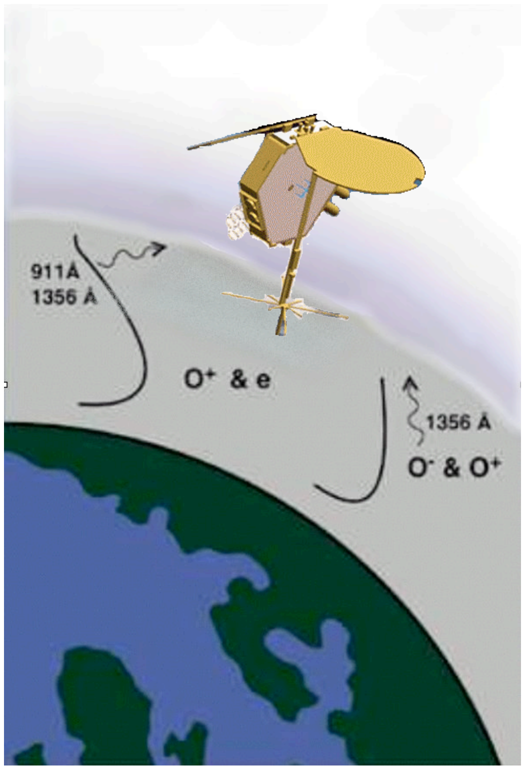
Polar Ionosphere and Thermosphere





- Solar radiation less intense in polar regions
- Earth's magnetic field directs solar wind particles to poles
- Auroral deposition
  - Ionization, day & night
  - Composition changes
  - Powerful currents
  - Major source of heating

TIP measurements



- TIP measures nighttime FUV emission of neutral atomic oxygen
- Radiative recombination: $O^{+}+e^{-} \rightarrow O+h\nu$
  - 135.6 nm produced by radiative recombination of O^{+} ions and electrons
  - O^{+} and e^{-} densities equal in the F-region
  - 135.6 emission intensity proportional to electron density squared
  - Simple algorithm relates electron density to 135.6 nm intensity measured by TIP
- Aurora: $O+e^{-} \rightarrow O+e^{-}+h\nu$
  - 135.6 nm produced in aurora through electron impact excitation
  - TIP can determine auroral boundaries

$$(Radio)\ TEC = \int n_e(s)ds$$

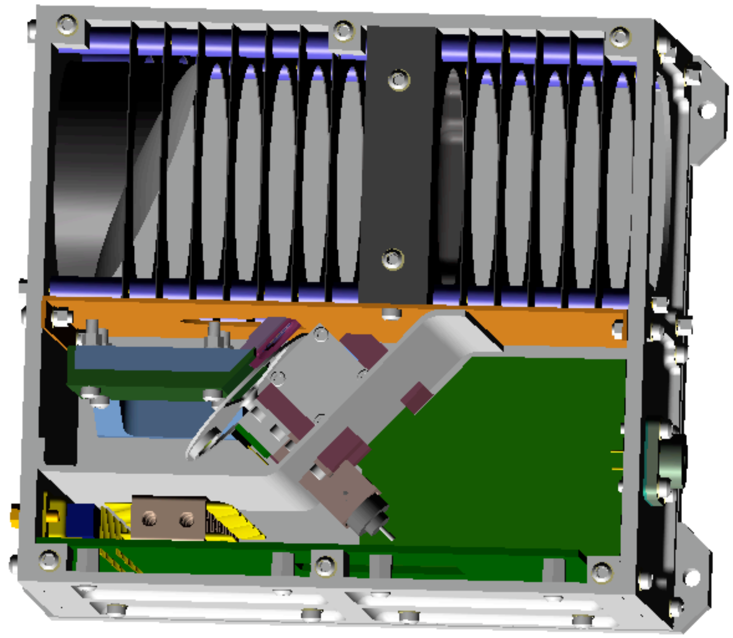
$$(Optical)\ Intensity \approx \alpha \int n_e^2(s)ds$$

where n_e is the electron density along the path s through the ionosphere and α is the radiative recombination rate

How TIP Works

What is the Tiny Ionospheric Photometer (TIP)?

- TIP is a Narrow Band Far-Ultraviolet Photometer
  - Operates in the 131.0-160.0 nm Passband
  - High Sensitivity ~ 150 ct s^{-1} $Rayleigh^{-1}$ (design goal)
- Why Operate in the FUV?
  - There is no emission or light scattered from altitudes below ~100 km
    - No Earth's Surface Albedo to Worry About
    - No Terrestrial Sources to Consider
  - Strongest Nighttime Ionospheric Signature at 135.6 nm



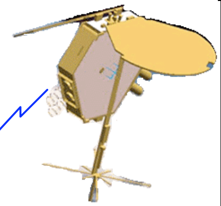
Mission Operations Concept

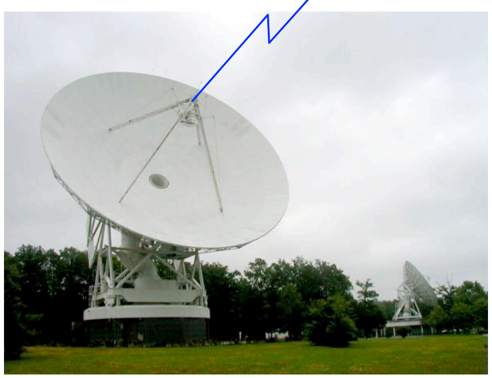
S/C sends 2 TIP command sequences during each orbit.

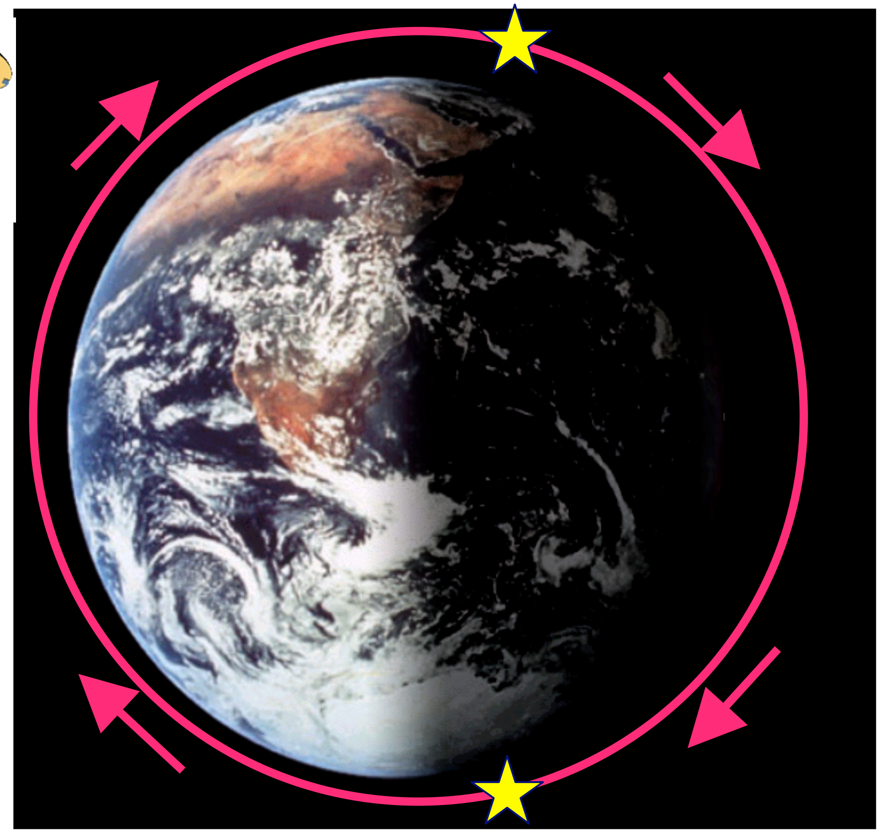
S/C Timed Command to TIP:
NIGHTSIDE OPERATIONAL

Daily or weekly upload of two TIP command sequences (for nightside and dayside) to S/C computer

2 buffers of 80 bytes each are required





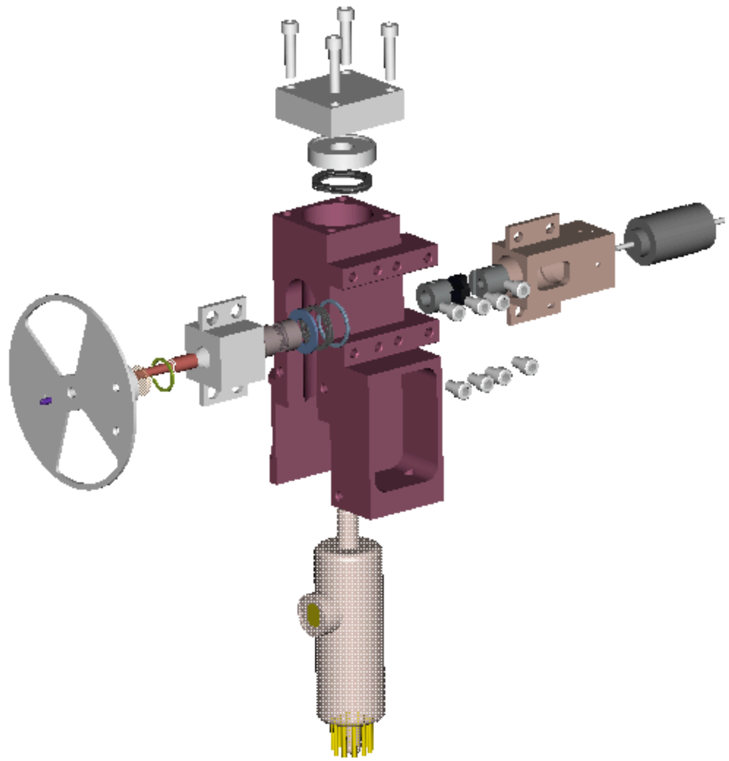


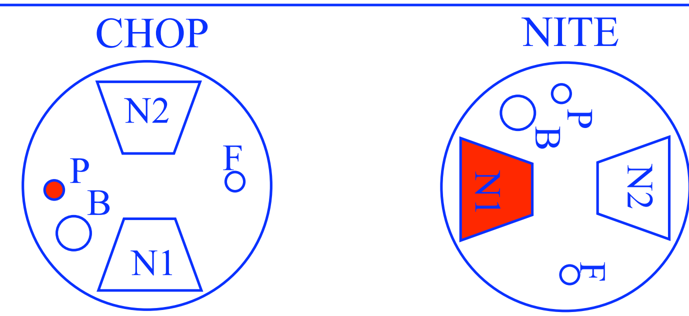
Command sequence normally a default byte pattern day in, day out, except for

- *on-orbit testing/troubleshooting*
- *possible observing campaigns*
- *adjusting for sensor degradation*

S/C Timed Command to TIP:
DAYSIDE STANDBY, CHOP, BAF2, or PINHOLE

TIP Filter Wheel and Operating Modes



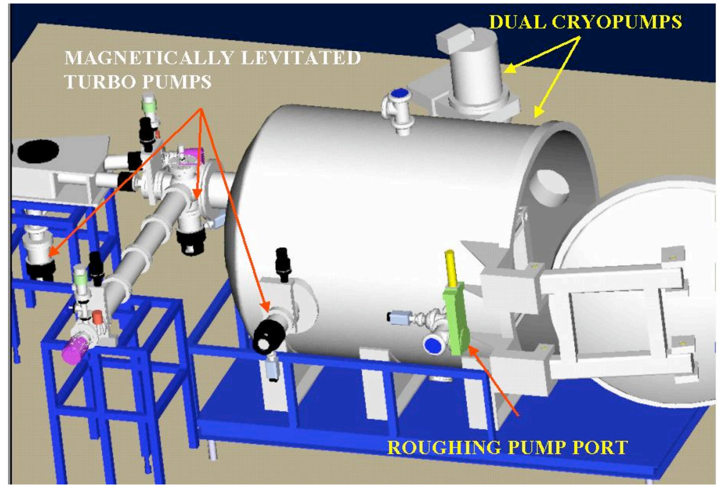


TIP Filter Wheel Modes

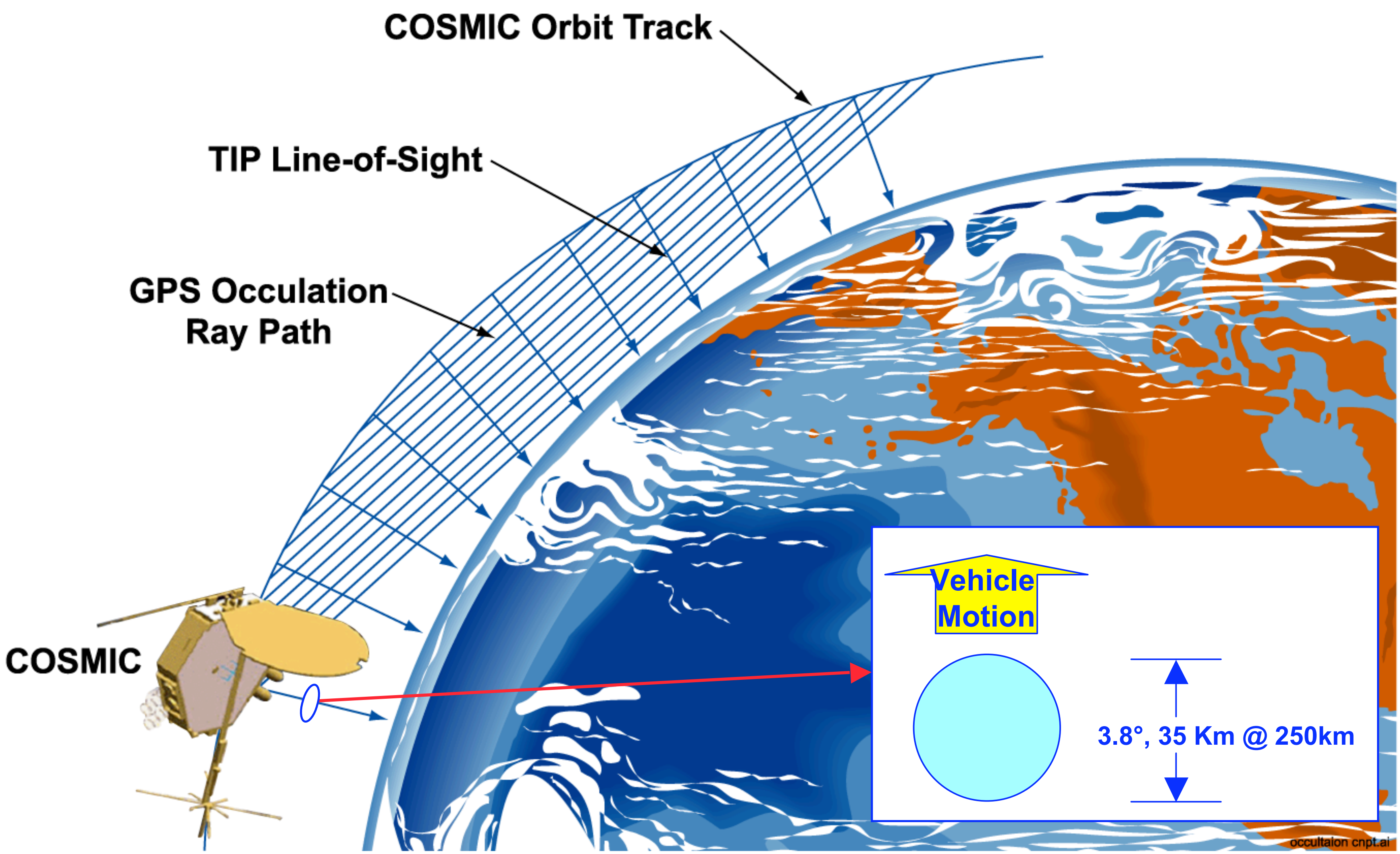
- TIP Modes
  - Standby
  - Nightside Operational
  - Dayside BaF2
  - Dayside Pinhole
  - Dayside Chop

Testing: Calibration Summary

- TIP calibrated in NRL UV Calibration Facility
  - Measured short-wavelength cut-off of filter as a function of temperature
  - Measured relative sensitivity as a function of wavelength
  - Measured absolute sensitivity at 1470 Å
  - Preliminary reduction completed
- Preliminary reduction of absolute sensitivity data for TIP006 yields for 1470 Å
  - SrF_2 filter sensitivity: 235 counts/s/Rayleigh
    - Goal: >150 ct/s/Rayleigh
    - Exceeded our design goal
  - BaF_2 filter sensitivity: 6 counts/s/Rayleigh
    - Goal: 1-2 ct/s/Rayleigh
    - Sensitivity is acceptable
  - Pinhole: 12 counts/s/Rayleigh
    - Goal: 1-2 ct/s/Rayleigh
    - Sensitivity is acceptable
- Other units' sensitivity 190-390 counts/s/Rayleigh
  - Variation in PMT QE
  - Variability in pulse discriminator settings
- On-orbit validation will allow periodic calibration monitoring



TIP / GPS Occultation Concept

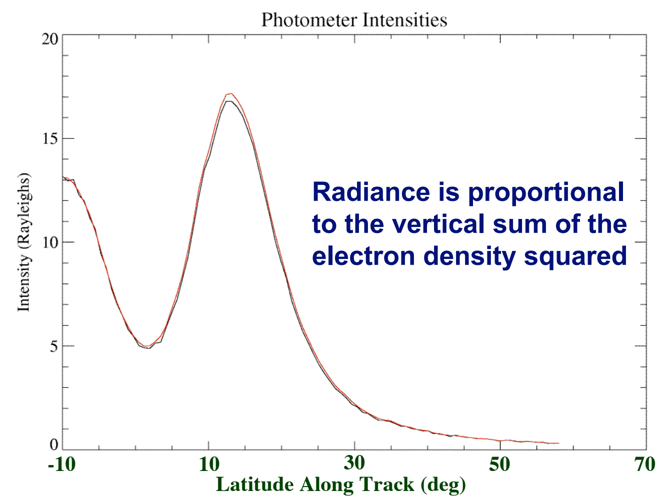


TIP Data Products

TIP Products

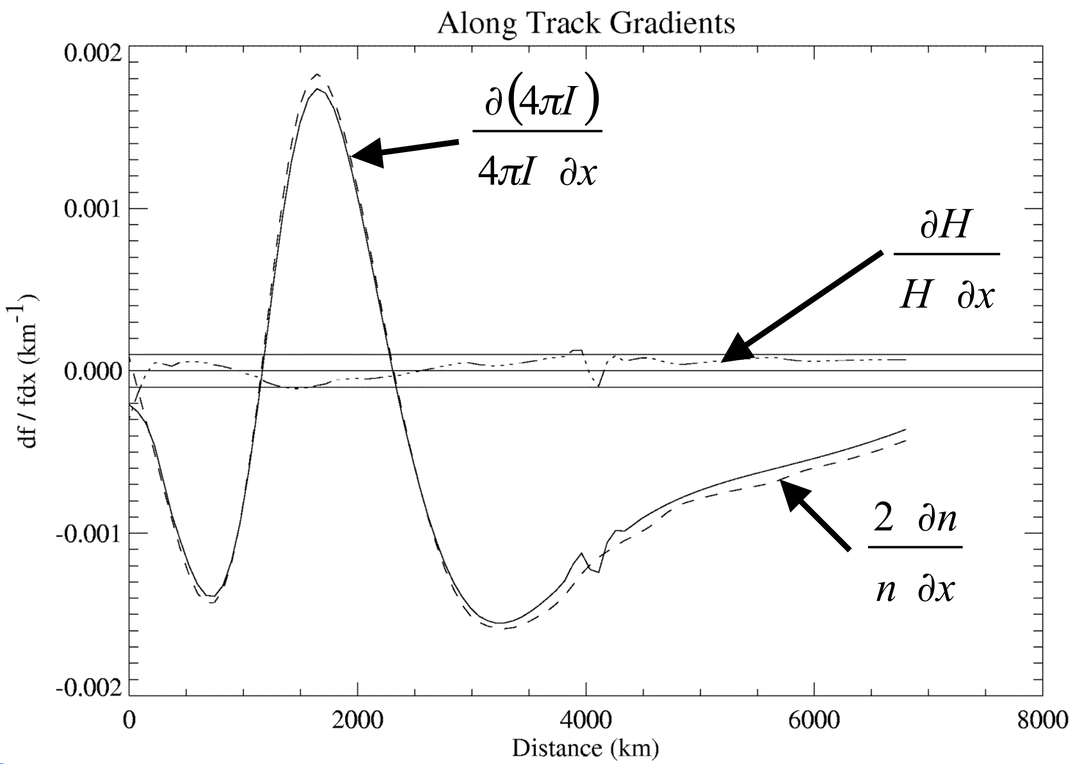
- Level 0 Products
  - Nighttime Count Rate – SrF_2 Filter (Photons/s)
  - Daytime Count Rate – SrF_2 Filter (Photons/s)
  - Daytime Chopped Count Rate – SrF_2 & BAF_2 Filters (Photons/s)
  - Dark Count (Counts/s) – Used for Data Quality Control
- Level 1 Products
  - Nighttime Along-Track Radiance at 135.6 nm
  - Daytime Along-Track Radiance at 135.6 nm
  - Daytime Along-Track LBH Radiance

Level 1 Product Nadir Radiance



Level 2 Products (Primary)

- Level 2 Primary Products (Nighttime)
  - Vertically Integrated Square of Electron Density
  - N_{max} (Peak Electron Density) Gradient Along Track



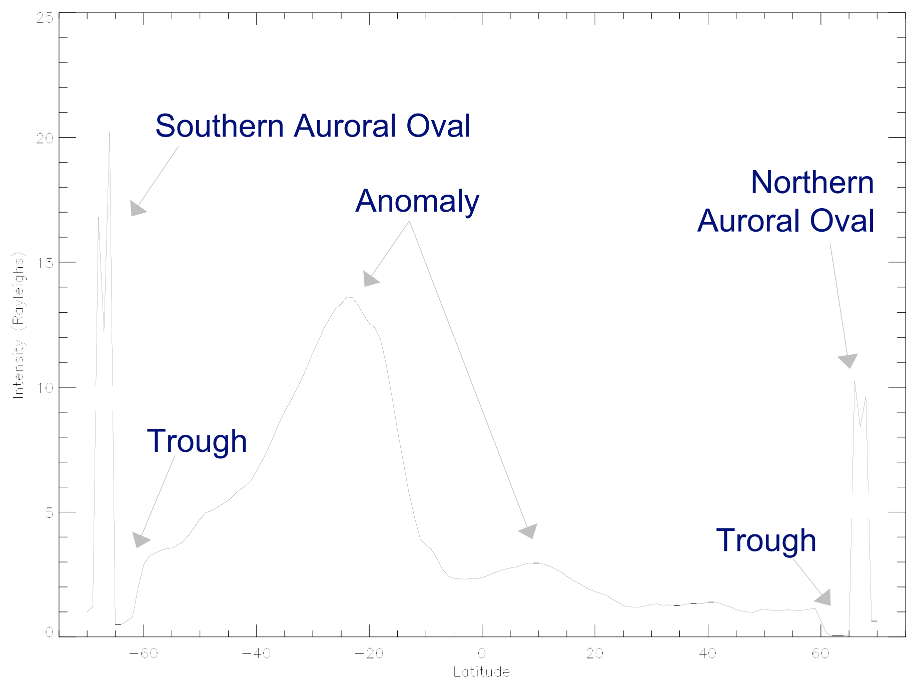
Percent Change in Peak Electron Density Per km Along Track of SV (Logarithmic Derivative)

$$\frac{\partial(4\pi I)}{4\pi I\ \partial x} \approx \frac{2\ \partial n}{n\ \partial x} + \frac{\partial H}{H\ \partial x}$$

Level 2 Products (Secondary)

- Location of auroral oval (Night)
- Location and magnitude of Anomaly crests and trough
- Location and depth of F-region plumes
- Location, width and depth of mid-latitude trough
- Location, width and depth of mid-latitude depletions
- Peak electron density N_{max} along track using MSIS/IRI-90
- Location and magnitude of dusk anomaly peaks (Terminator)
- O/N_2 Column Ratio Along Track Using Emission Model (Day)
- Peak Electron Density N_{max} Along Track Using MSIS/IRI-90

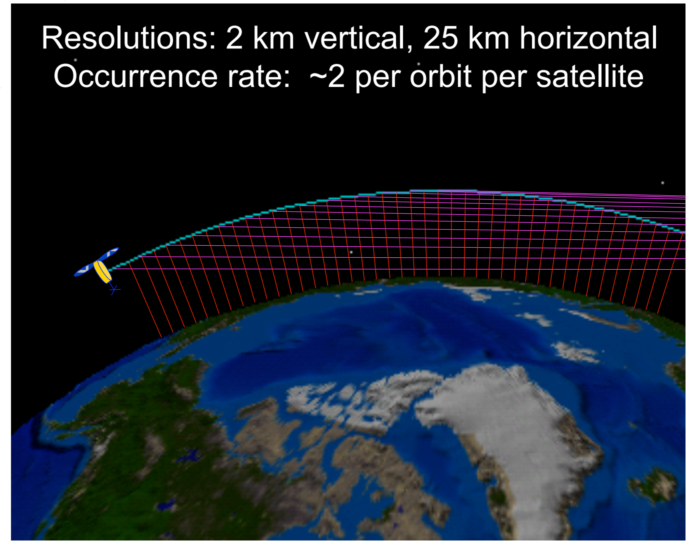
Level 2 Products



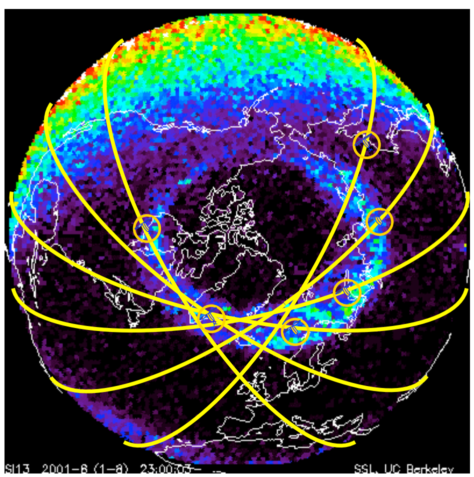
Level 3 Products

- High resolution electron density along track, tomographically derived from GPS occultations and TIP nadir observations
- Global nighttime feature map – Appleton peaks, instability regions, trough, N_{max} gradient, 90-min updates, derived from multiple SVs
- Auroral boundary map – global nighttime, 90-min updates, derived from multiple SVs

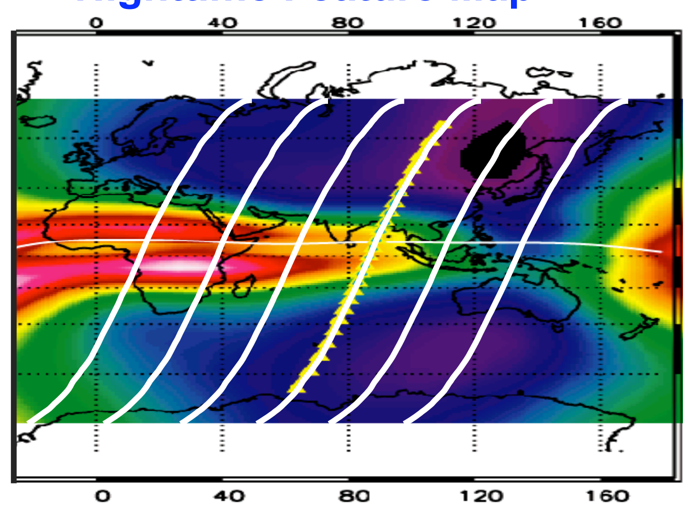
High Resolution Electron Density



Auroral Boundary Map



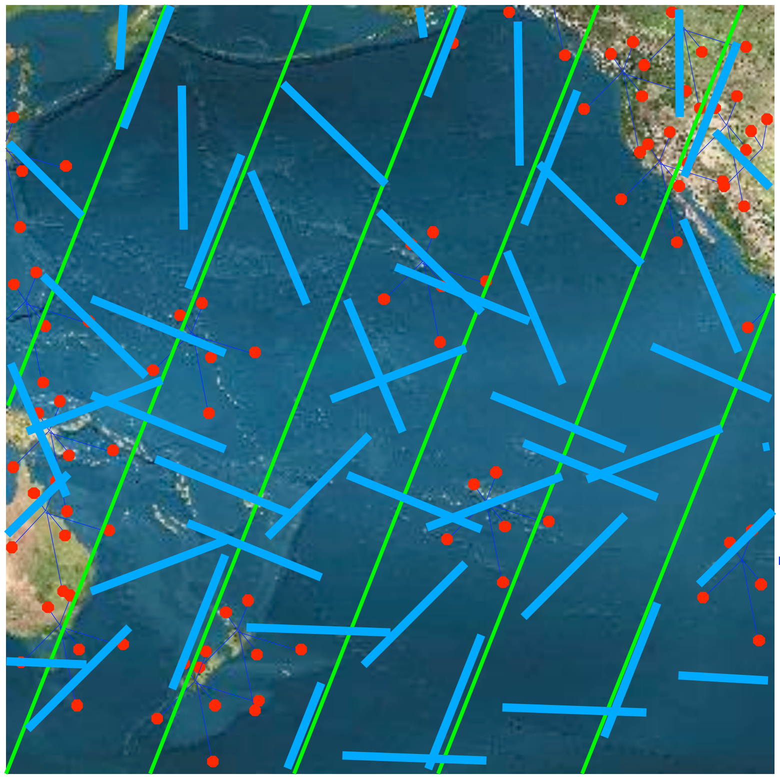
Nighttime Feature Map



Level 4 Product

- Level 4 Product
  - Electron density nighttime map v. altitude, latitude and longitude, derived from multiple SVs and GPS occultation data using assimilative model

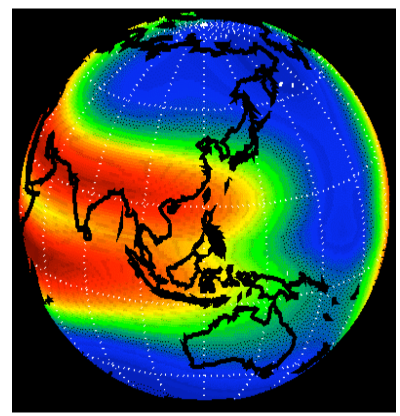
Nighttime 90-min Data Coverage



- Vertical Information from Occultations
- Horizontal Information from TIP
- Temporal Information from GPS Stations

Assimilative Model

Global N_e



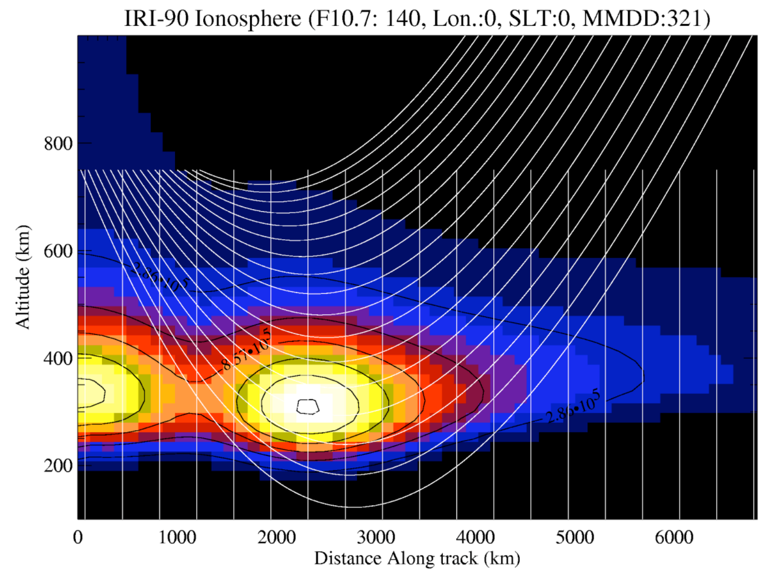
Using TIP Data

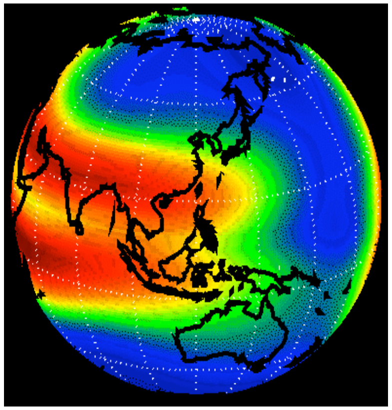
Motivation

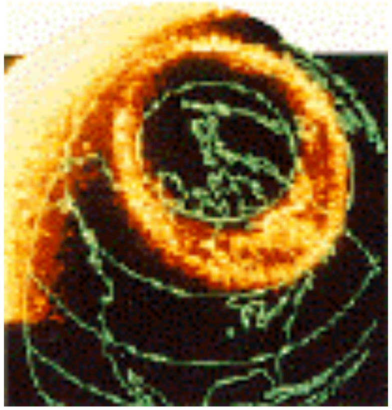
- Proliferation of satellite-based ionospheric measurement systems
  - Optical and Radio-based
- Optical techniques
  - UV limb scanning
  - UV disk scanning
  - UV disk imaging
- Radio techniques
  - Radio Occultation
  - Beacon tomography
  - Radar altimetry
- Coincident and orthogonal measurements
- Assimilative models – continuous, medium-resolution 3D volume
- Inversion techniques – temporal, high-resolution 2D image

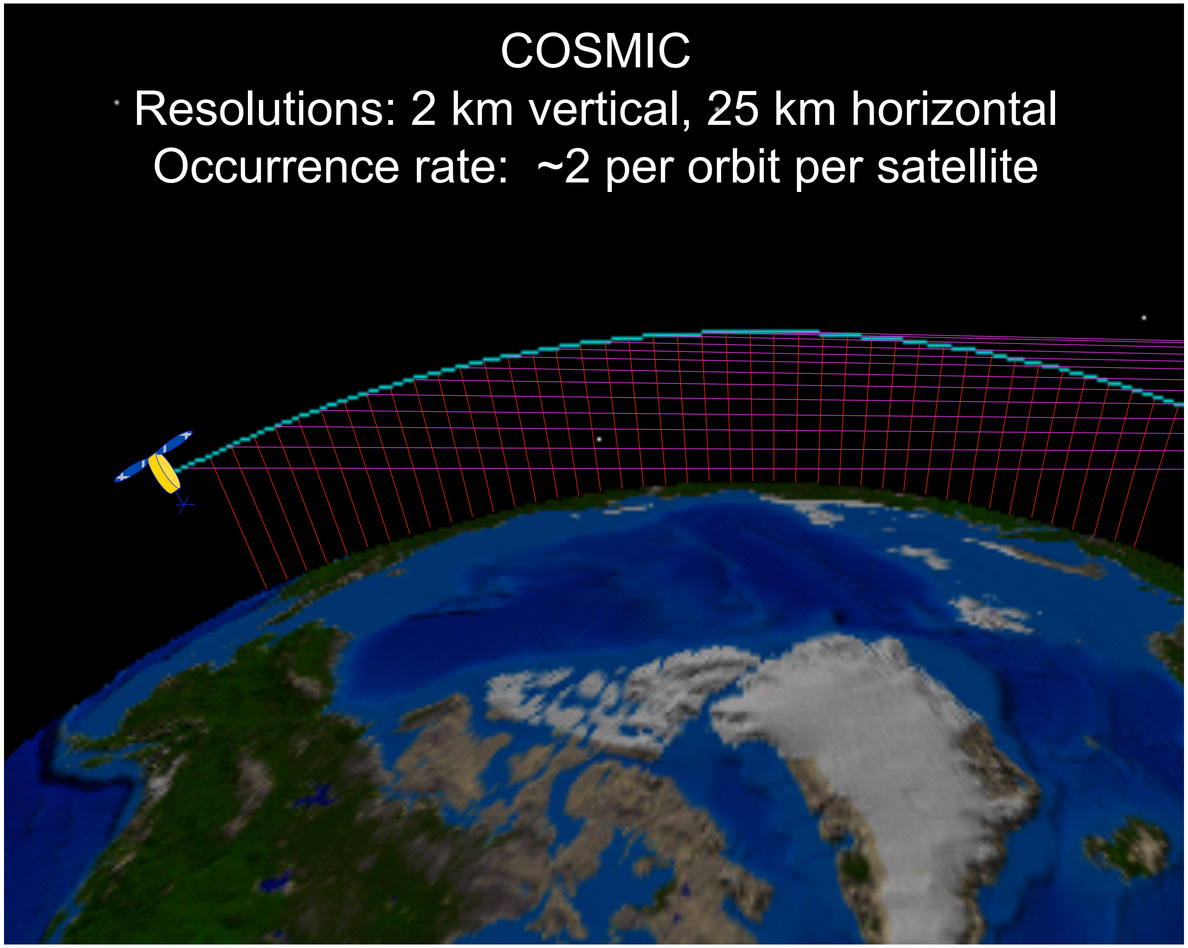
How Will the Tiny Ionospheric Photometer Measurements Be Used?

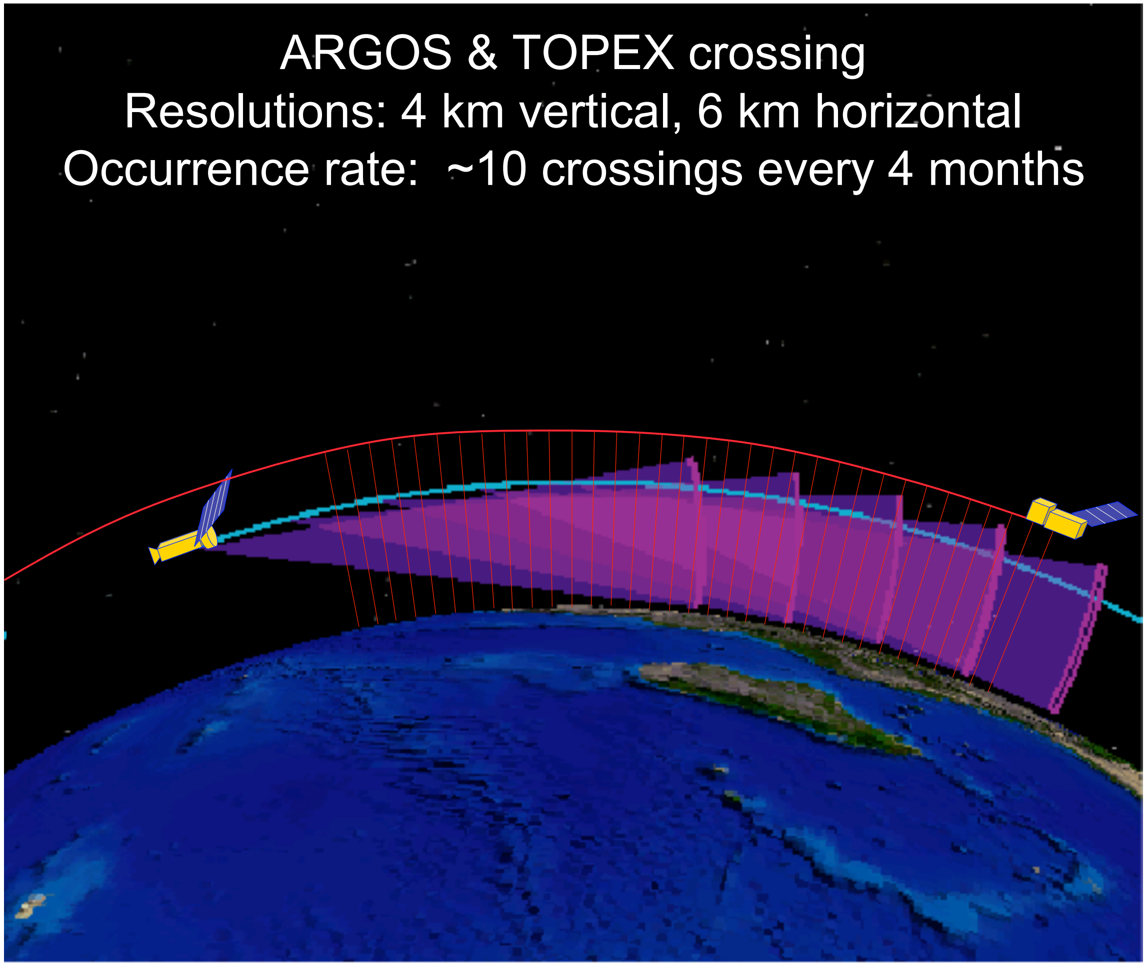
- Primary Goal: Provide Accurate Characterization of Ionospheric Electron Density Gradients
  - Inaccuracies in GPS occultation measurements of electron density due to gradients
  - TIP measurements will be used to correct for gradients
- Secondary Goals:
  - Location of auroral oval – TIP measured 135.6 nm emission produced by aurorae
  - Location of Appleton peaks – infer ionospheric dynamics
  - Detection of F-region plumes – specify instability conditions
  - Add to Ionospheric & Thermospheric Climatology Databases



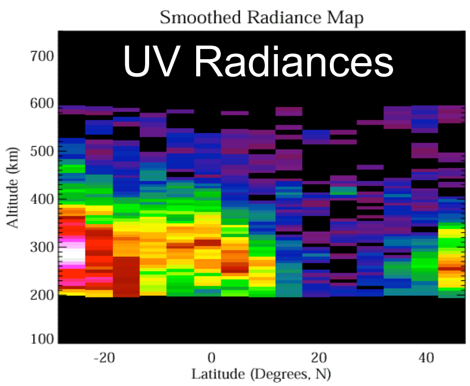


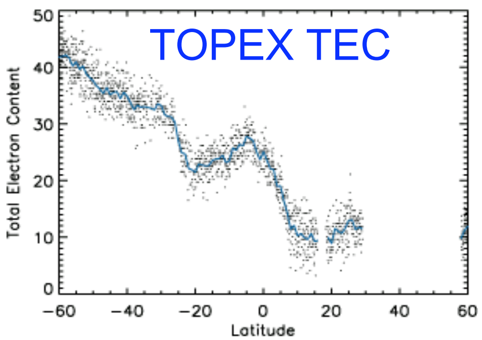



COSMIC
Resolutions: 2 km vertical, 25 km horizontal
Occurrence rate: ~2 per orbit per satellite


ARGOS & TOPEX crossing
Resolutions: 4 km vertical, 6 km horizontal
Occurrence rate: ~10 crossings every 4 months

Inversion Algorithm





Input Data, y_j

Estimate Parameters, m^i_k

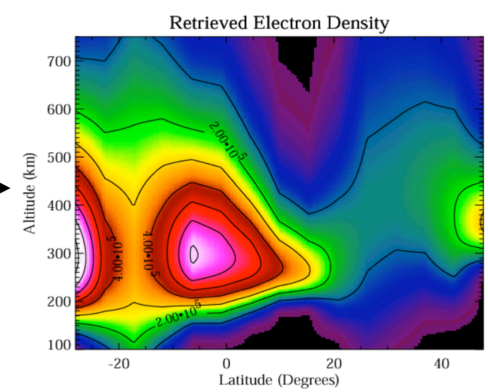
Model Data, d^i_j

Compare Input & Model Data

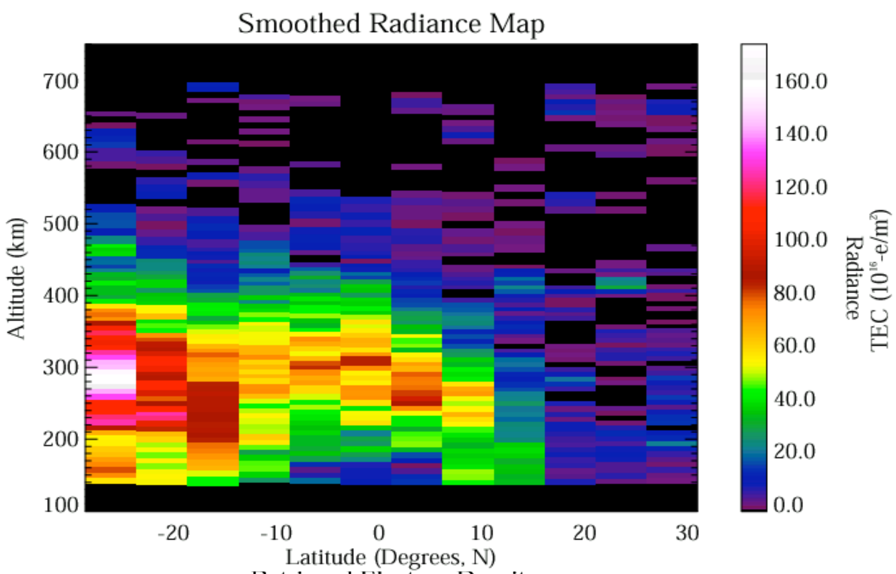
$$X^2 = \sum_j \left((y_j - d^i_j)/\sigma_j \right)^2 + W^2 \sum_k L^2(m^i_k)$$

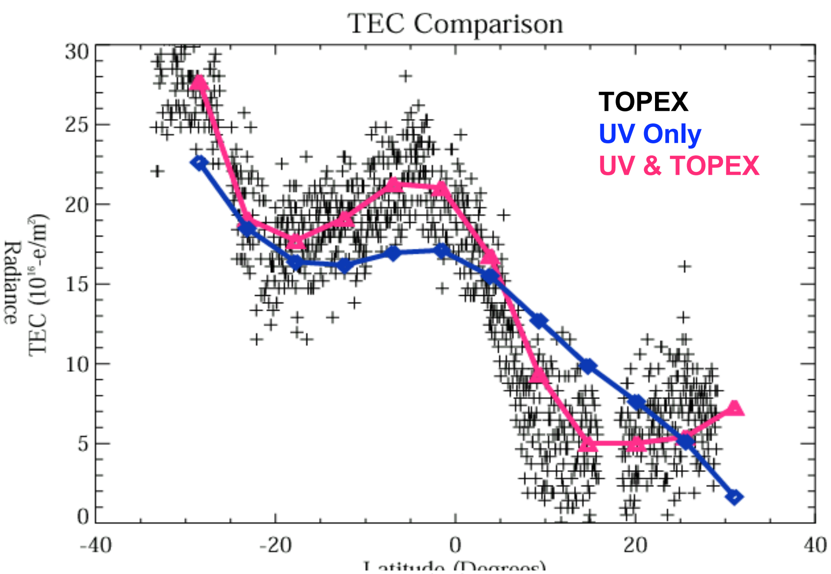
Evaluate Changes to Parameters , δm^i_k

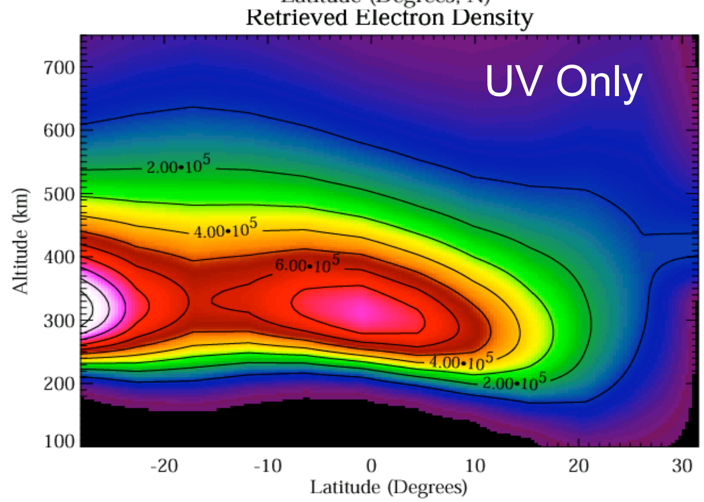
2D Electron Density

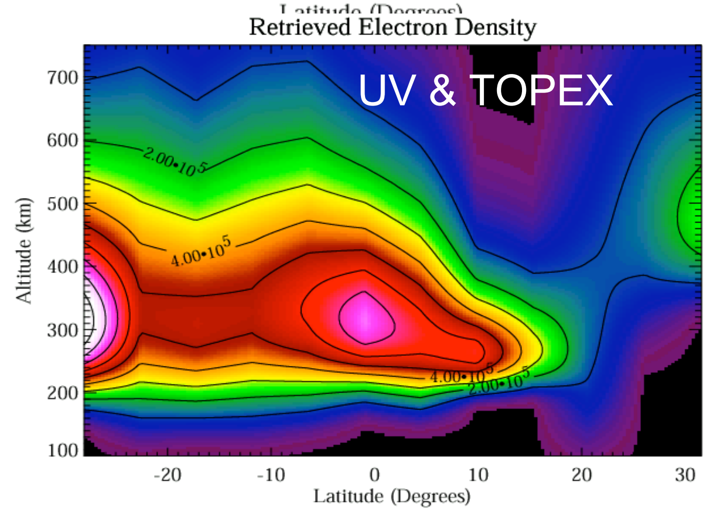


How Good Is It?

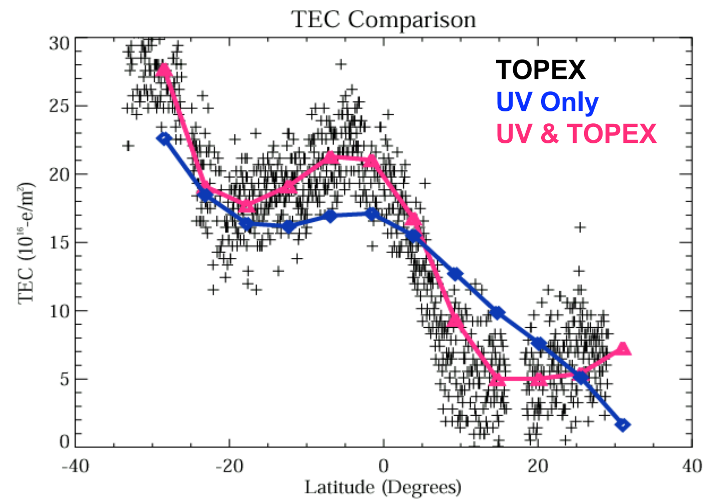


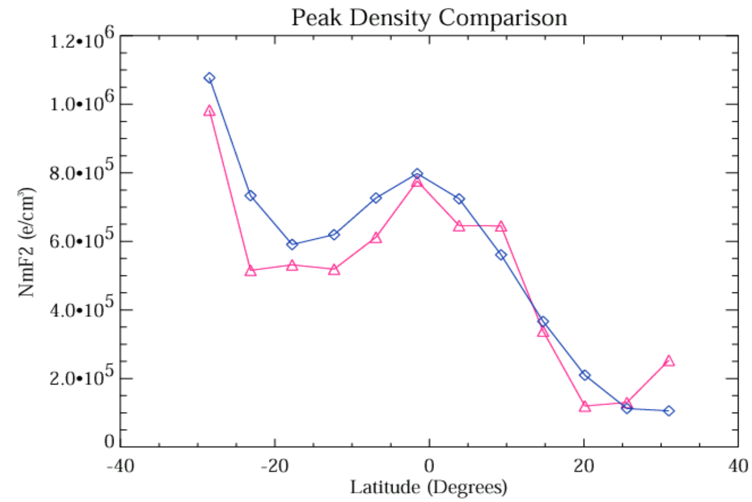


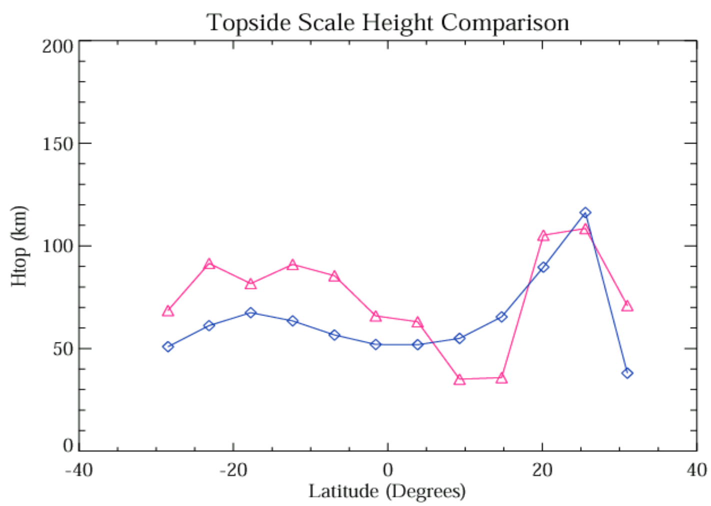


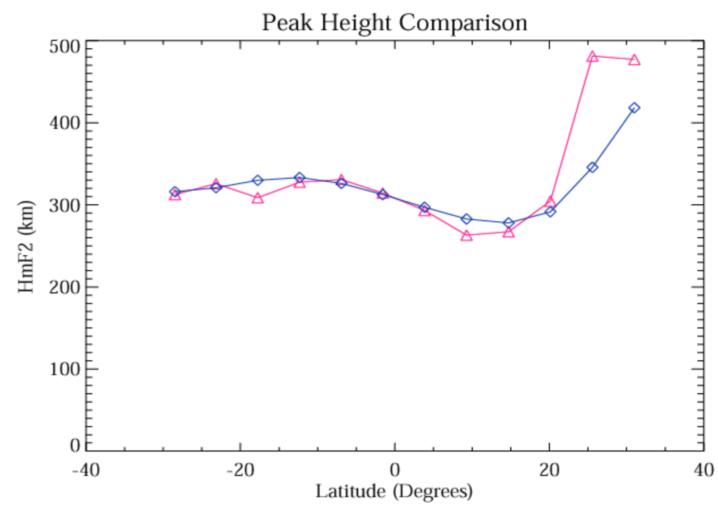


Density Profile Refinements

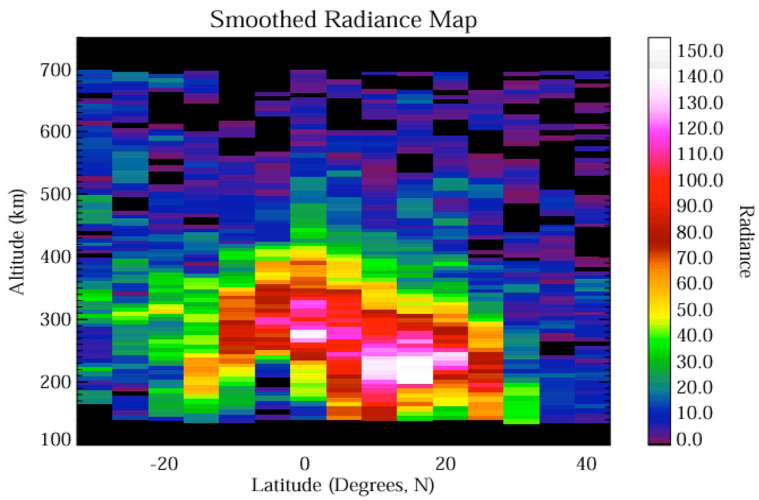


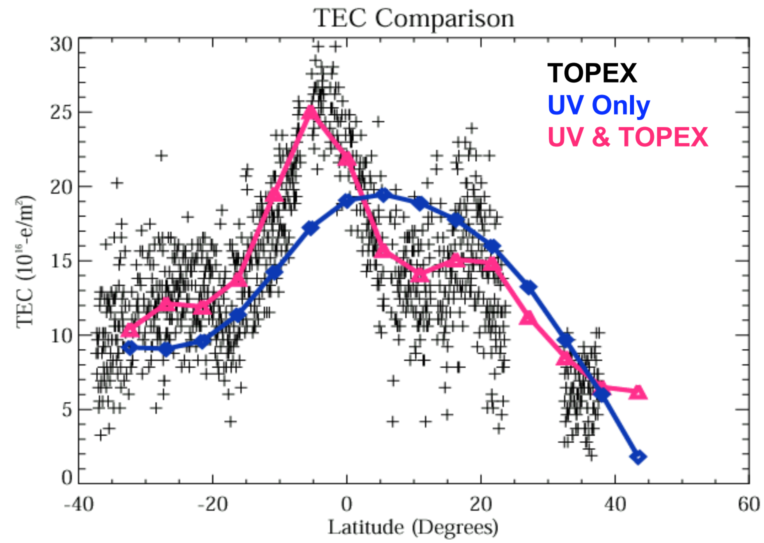


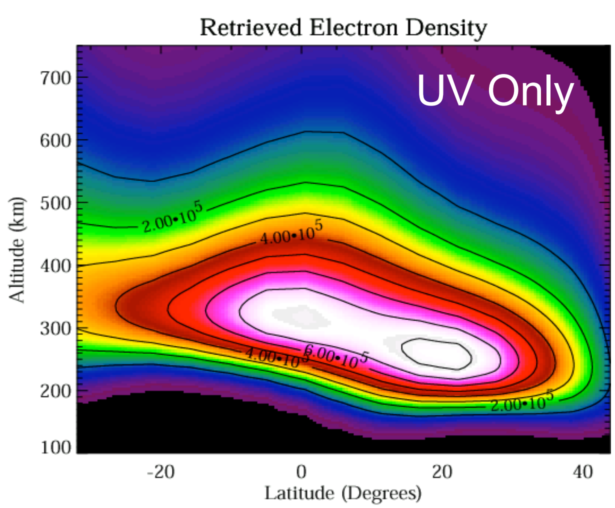


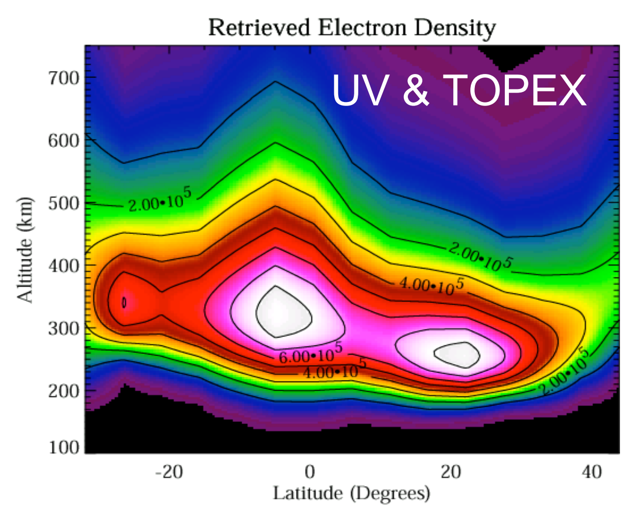


Case 2

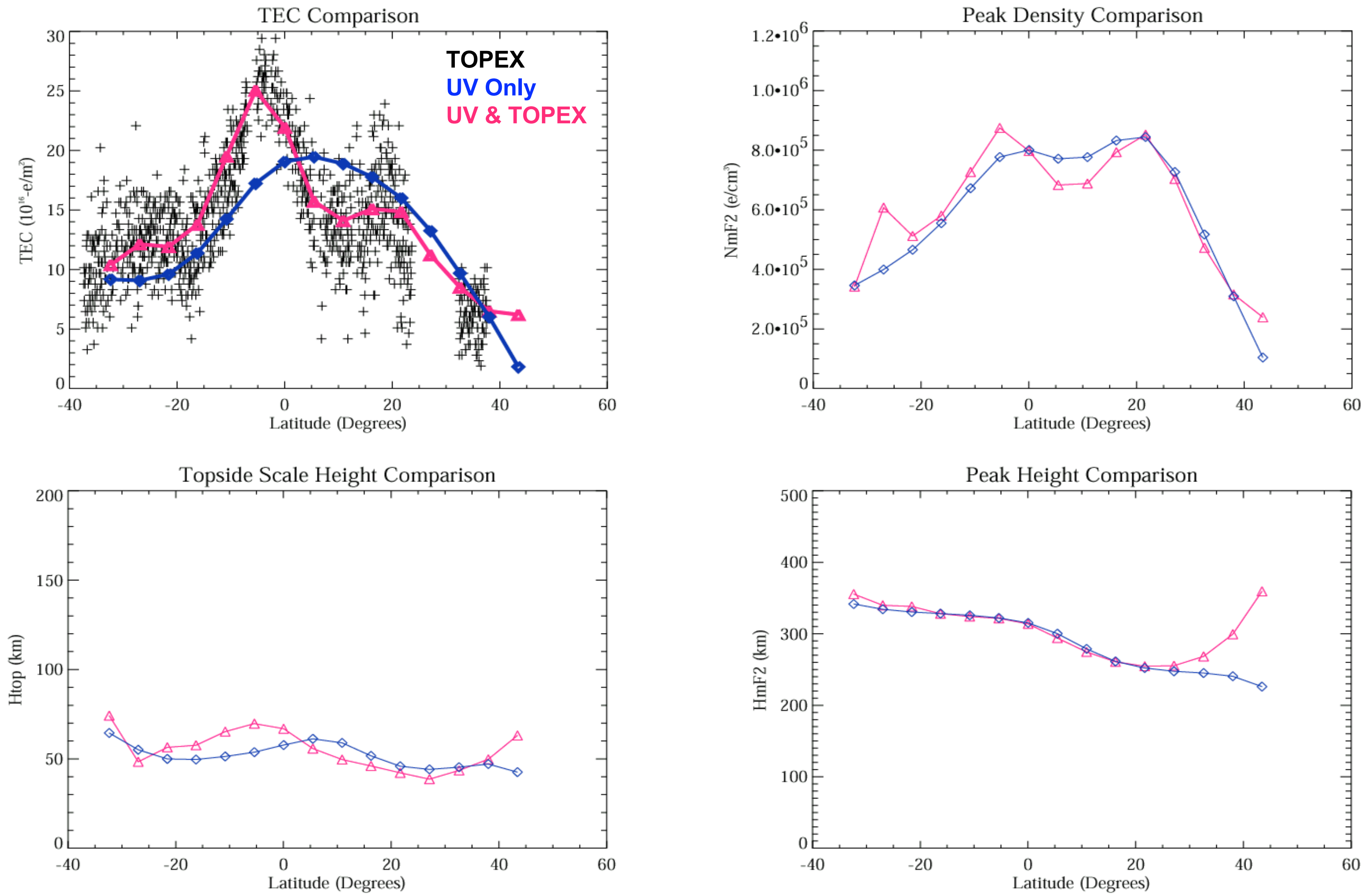

Smoothed Radiance Map
Altitude (km)
Latitude (Degrees, N)
Radiance
100
200
300
400
500
600
700
-20
0
20
40
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0


TEC Comparison
TOPEX
UV Only
UV & TOPEX
TEC (10^{16}-e/m^2)
Latitude (Degrees)
0
5
10
15
20
25
30
-40
-20
0
20
40
60

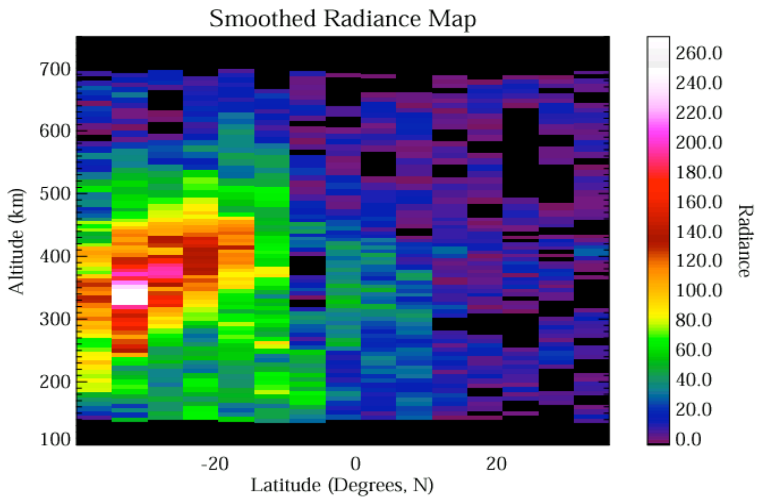

Retrieved Electron Density
UV Only
Altitude (km)
Latitude (Degrees)
$2.00\cdot10^5$
$4.00\cdot10^5$
$6.00\cdot10^5$
100
200
300
400
500
600
700
-20
0
20
40

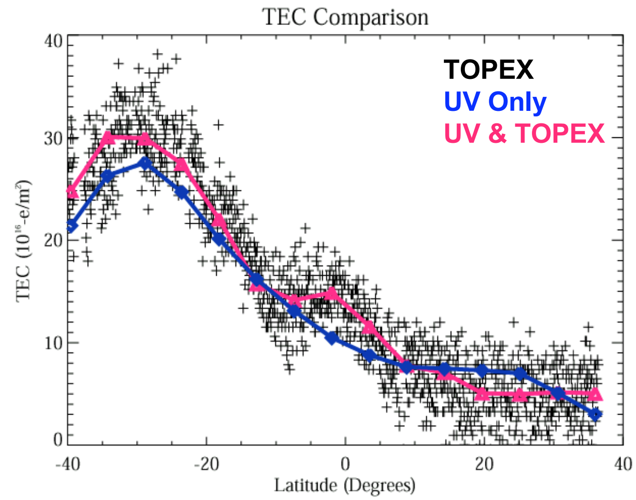

Retrieved Electron Density
UV & TOPEX
Altitude (km)
Latitude (Degrees)
$2.00\cdot10^5$
$4.00\cdot10^5$
$6.00\cdot10^5$
100
200
300
400
500
600
700
-20
0
20
40

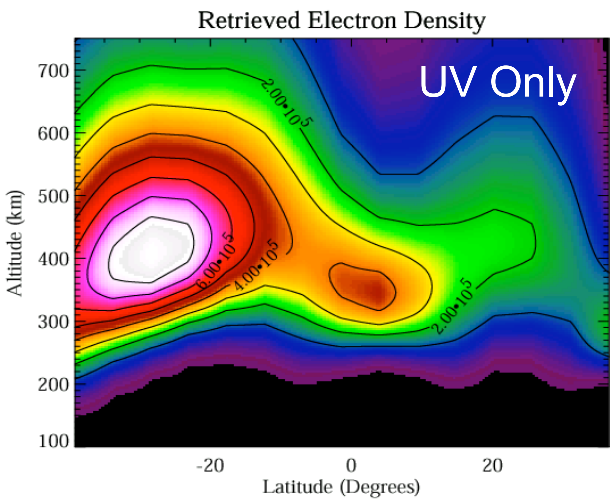
Case 2 Refinements

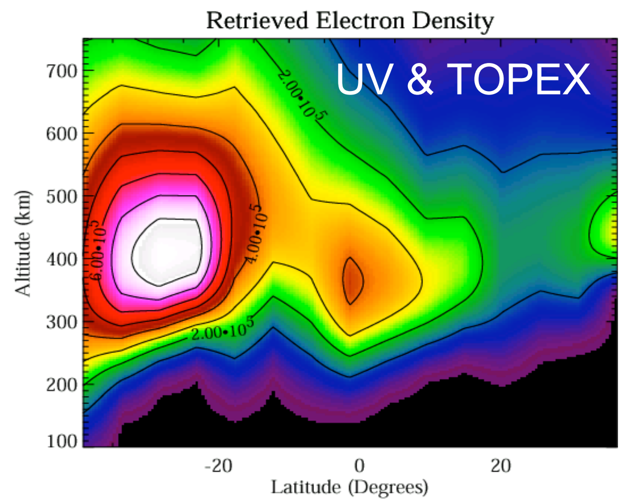


Case 3

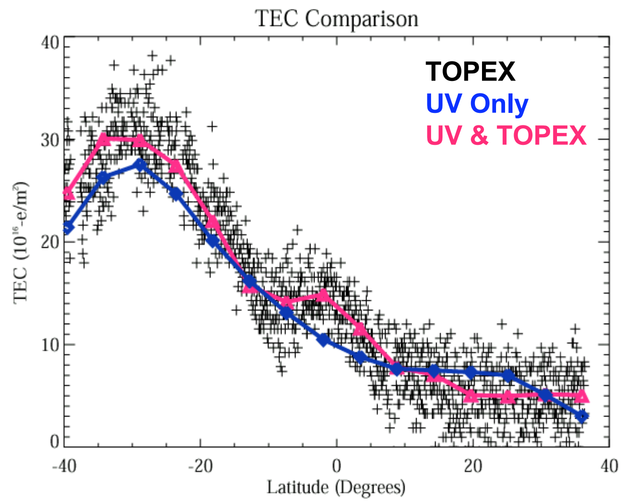

Smoothed Radiance Map
Altitude (km)
Latitude (Degrees, N)
Radiance
700
600
500
400
300
200
100
-20
0
20
260.0
240.0
220.0
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0

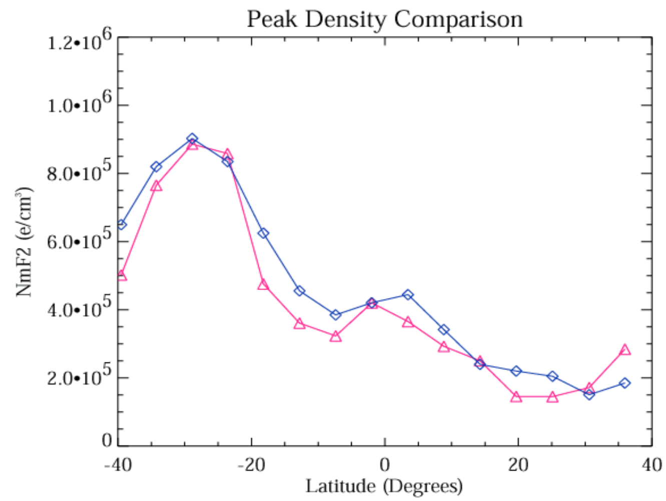

TEC Comparison
TOPEX
UV Only
UV & TOPEX
TEC (10^{16}-e/m^2)
Latitude (Degrees)
40
30
20
10
0
-40
-20
0
20
40

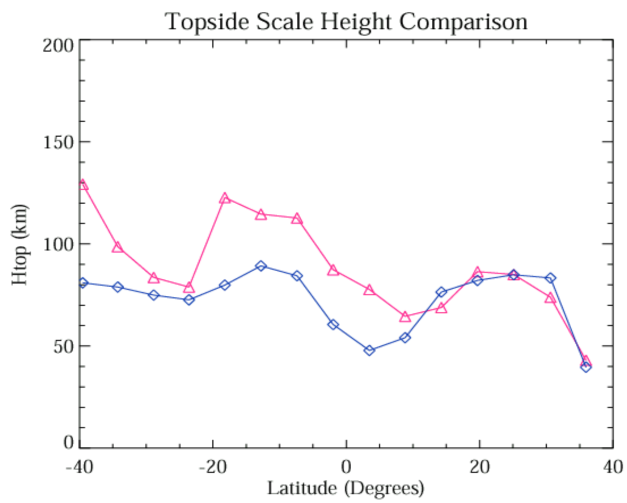

Retrieved Electron Density
UV Only
Altitude (km)
Latitude (Degrees)
700
600
500
400
300
200
100
-20
0
20

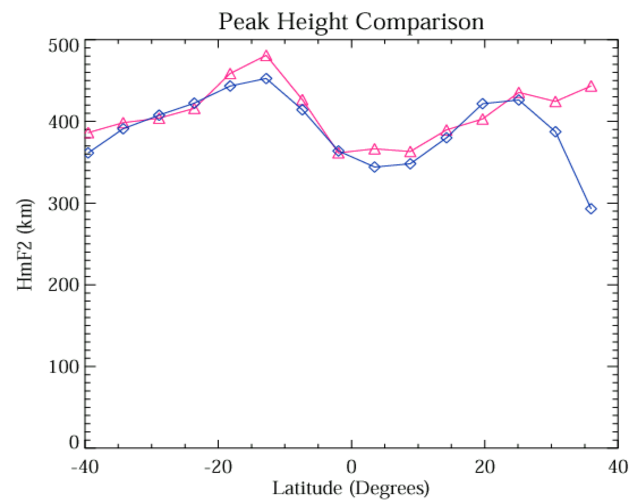

Retrieved Electron Density
UV & TOPEX
Altitude (km)
Latitude (Degrees)
700
600
500
400
300
200
100
-20
0
20

Case 3 Refinements

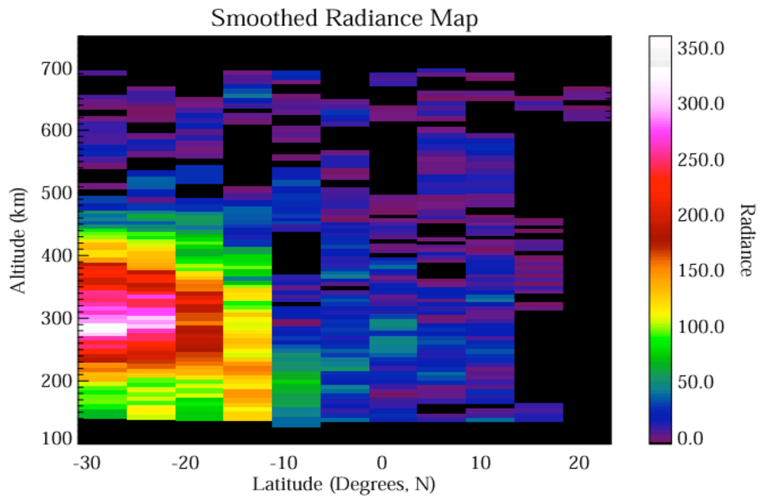




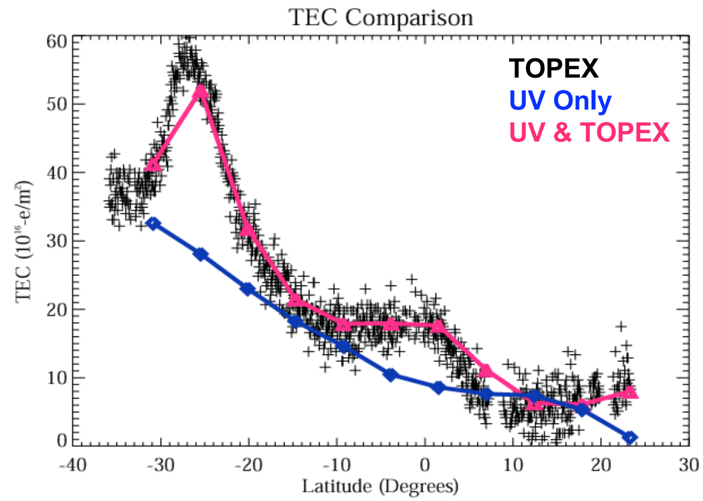




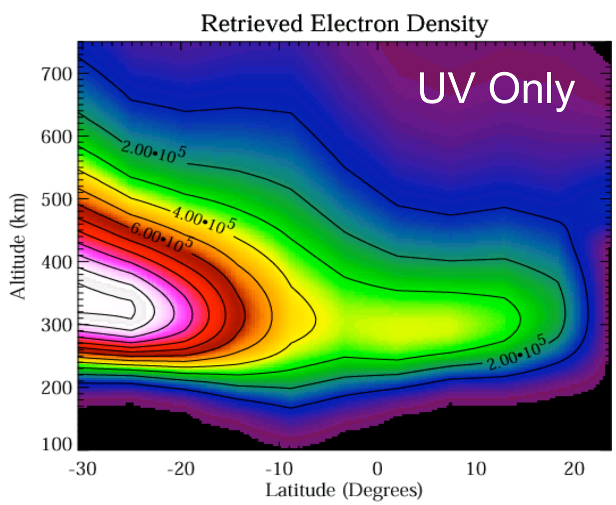
Case 4



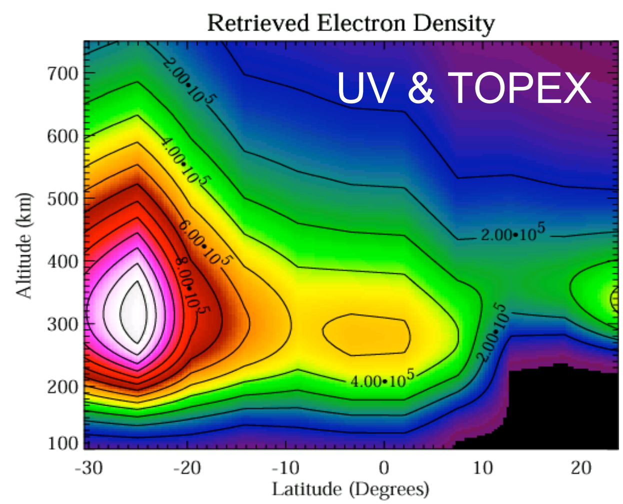
Smoothed Radiance Map
Altitude (km)
Latitude (Degrees, N)
Radiance
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0



TEC Comparison
TOPEX
UV Only
UV & TOPEX
TEC (10^{16}-e/m^2)
Latitude (Degrees)

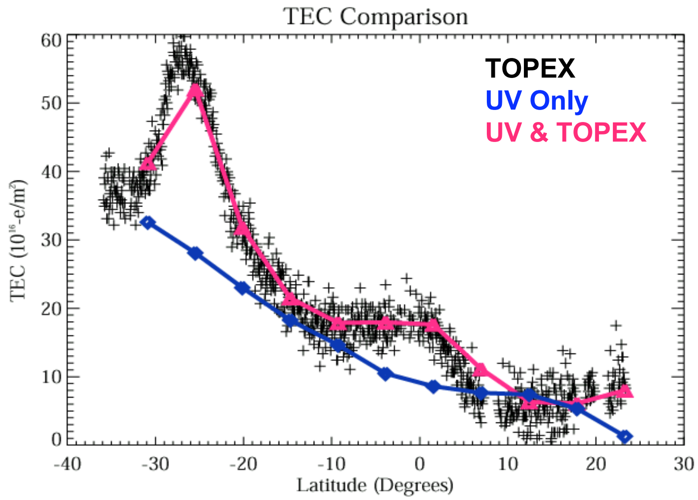


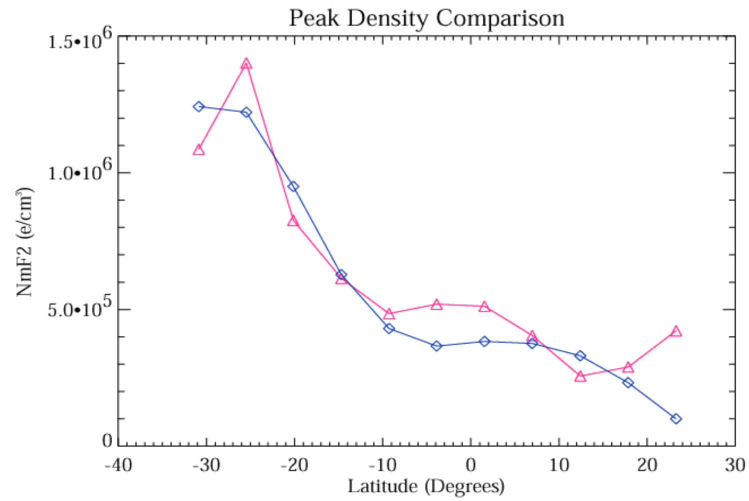
Retrieved Electron Density
UV Only
Altitude (km)
Latitude (Degrees)
2.00•10^5
4.00•10^5
6.00•10^5

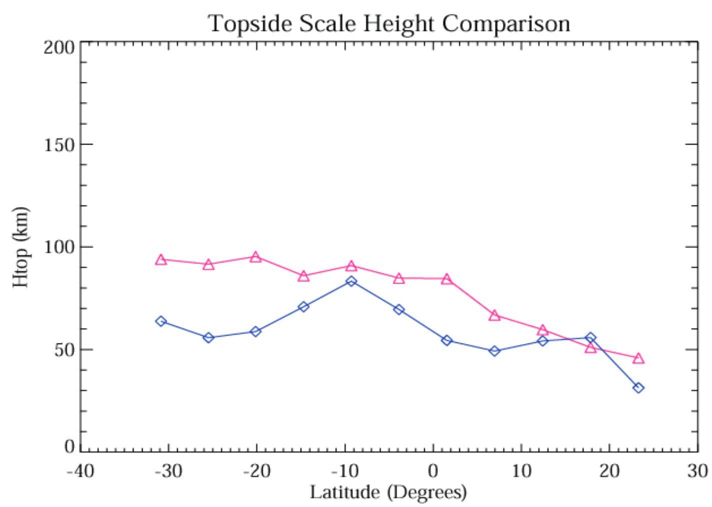


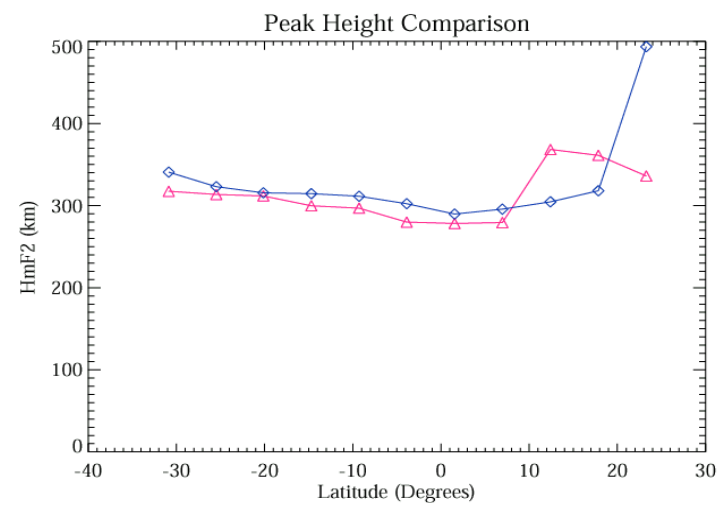
Retrieved Electron Density
UV & TOPEX
Altitude (km)
Latitude (Degrees)
2.00•10^5
4.00•10^5
6.00•10^5
8.00•10^5

Case 4 Refinements



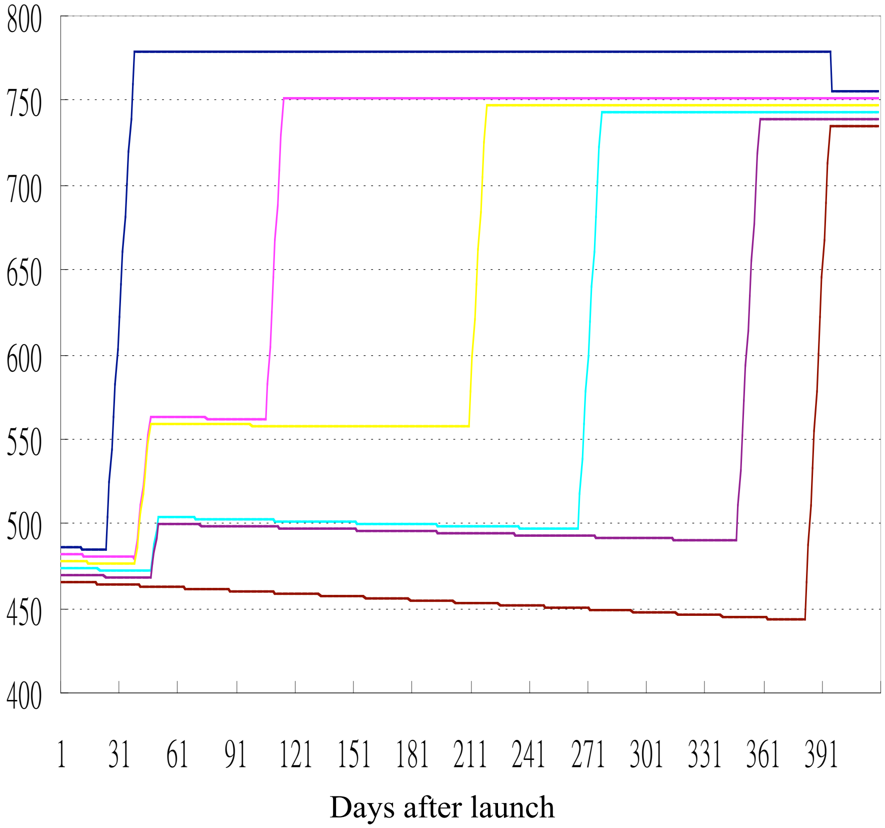






Constellation Rollout

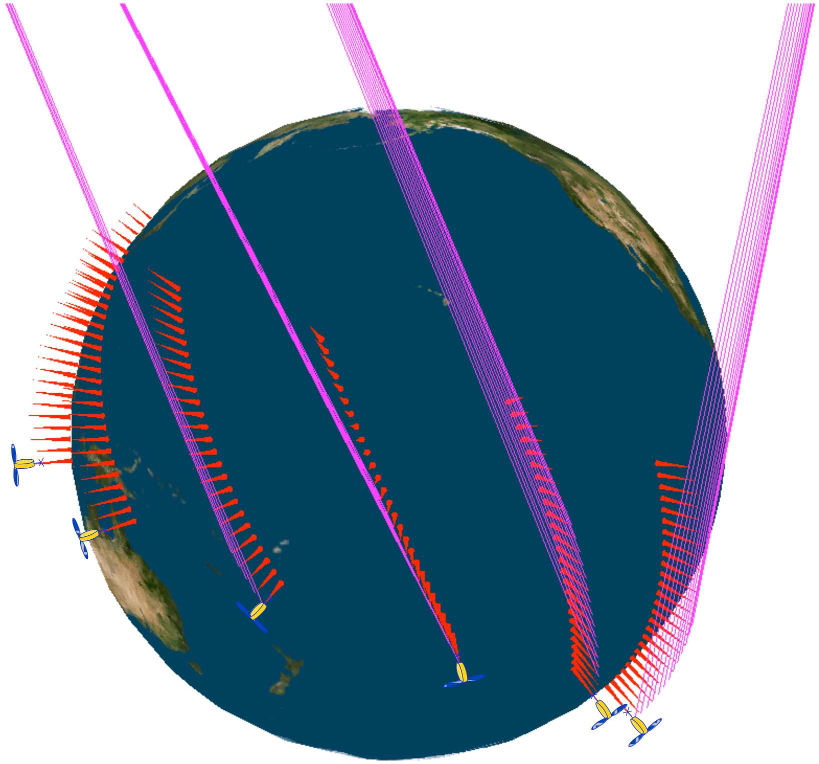
- Unique opportunities for low latitude/equatorial science during constellation rollout
- First Year
  - Highest horizontal resolution better than 10-km from 475-km orbit altitude
- Subsequent years
  - All sensors near 750-km altitude



Longitudinal Coverage

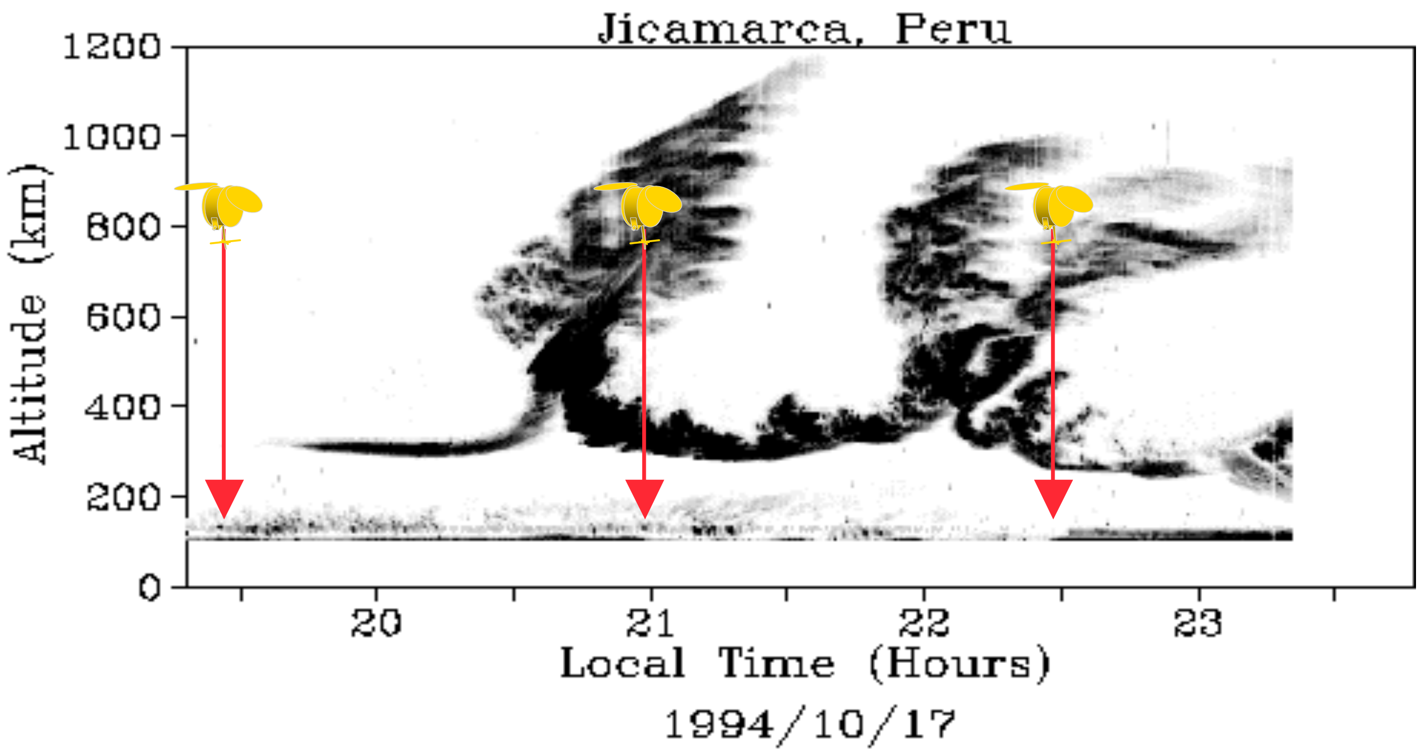
- Global coverage of low latitude/equatorial ionosphere
  - Specify Appleton anomaly
  - Significantly improve data assimilation models
  - Storm dynamics
  - Detect instabilities
  - Investigate precursor conditions

15-min coverage



Temporal Coverage

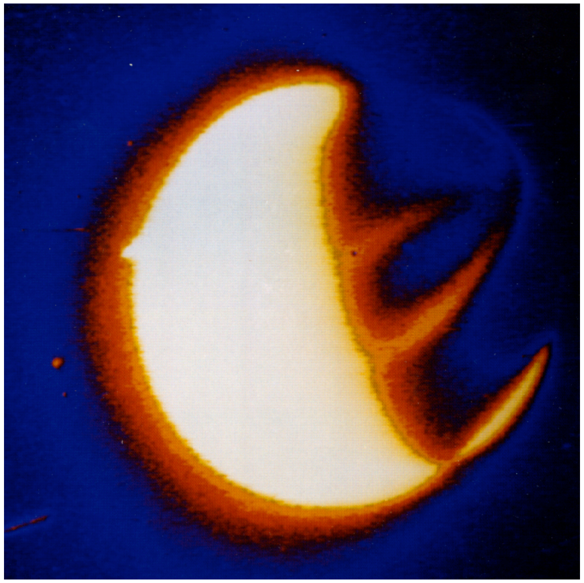
- Latitudinal snapshot over fixed site every ~90 min
- Precursor conditions (winds and electric field)
- Verify instability generation
- Investigate effect of drivers on instability generation
- Test against ground-based sensors

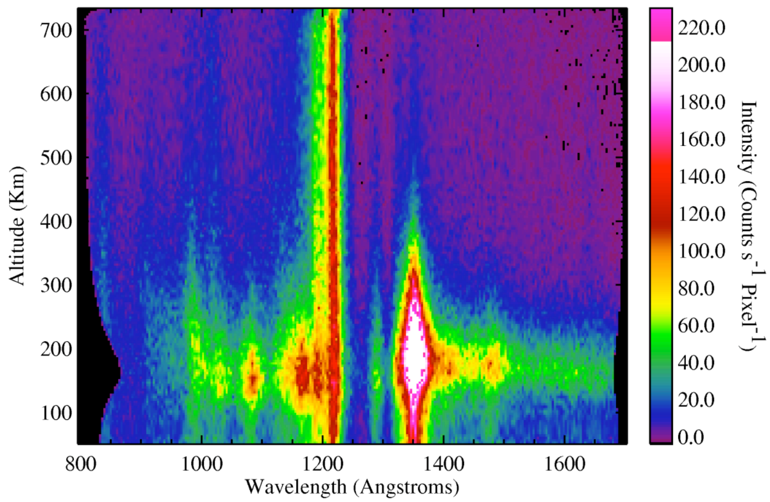


Summary

What TIP Measures

- Nighttime: Measures Intensity of Naturally Occurring Recombination Airglow
  - Caused by Decay of Nighttime Ionosphere
  - Produces Light at 135.6 nm – Atomic Oxygen
  - Ionospheric Diagnostic
- Daytime: Measures Intensity of Naturally Occurring Electron Impact Excited Airglow
  - Caused by Excitation of Oxygen and Nitrogen
  - Produces Light at 135.6 nm (Atomic Oxygen) and in Lyman-Birge-Hopfield Bands of Molecular Nitrogen
  - Thermospheric Diagnostic
    - May be Able to Infer Ionosphere
    - Should Observe Dynamical Effects in Twilight

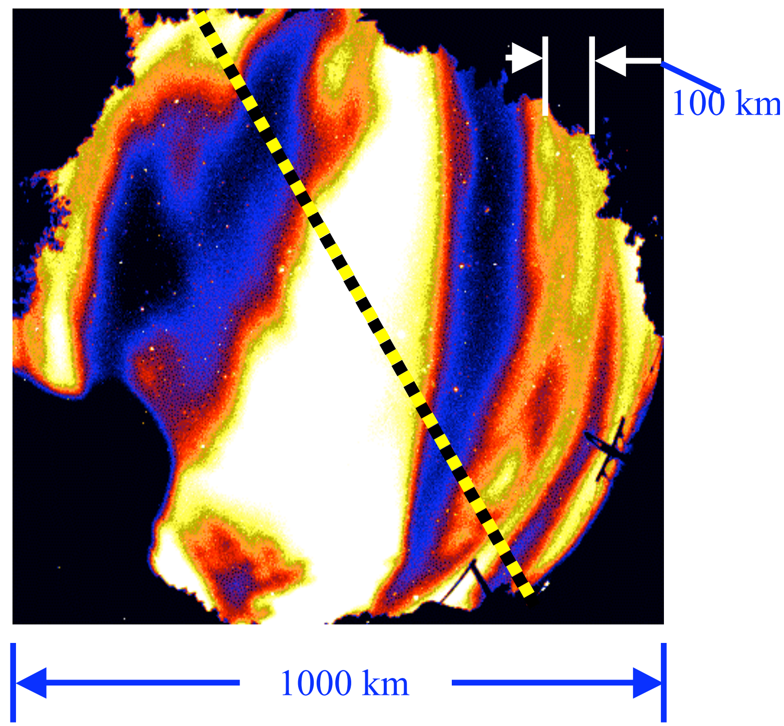




Sensitivity and Resolution

- High Sensitivity
  - 150 counts/s/Rayleigh
  - 2 orders of magnitude more sensitive than GUVI for equivalent pixel size
  - 3 orders of magnitude more sensitive than IMAGE
  - Details of anomaly crests, trough, and depletions
- High Resolution
  - 10-km horizontally during constellation rollout
  - 30-km horizontally from 750-km altitude
  - Similar to ground-based all-sky imager

Footprint of TIP sensor across all-sky image



TIP Product Summary

- No TIP products are produced and processed on-orbit
  - All are produced post-pass, on the ground
- Most products are produced by simple manipulation of the raw data
  - Examples
    - Multiplication by a scalar (Calibration to Radiance units)
    - Derivative of observed radiance
  - Level 0, 1, & Most Level 2 products easily produced at CDAAC
  - Some Level 2 and Higher Level products will require additional processing
    - Initially processed at NRL and transmitted to CDAAC
    - May eventually be accommodated at CDAAC
- We Have the Global Assimilating Ionospheric Model at NRL
  - Required to produce Level 4 products
  - On-going research and operational GAIM work