Ionosphere: Past, Present and Future Problems

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Outline

• Ionospheric Environment
• Status
• High Latitudes
• Middle Latitudes
• Low Latitudes
• Summary
Ionospheric Environment
F-Region

\[ \text{O} + \text{hv} \rightarrow \text{O}^+ + \text{e}^* \]

\[ \text{O}^+ + \text{N}_2 \rightarrow \text{NO}^+ + \text{N} \]

\[ \text{O}^+ + \text{O}_2 \rightarrow \text{O}_2^+ + \text{O} \]

Topside

\[ \text{O}^+ + \text{H} \Leftrightarrow \text{H}^+ + \text{O} \]
Diffusion and Wind-Induced Flow Along B
Sojka and Schunk (1979)
Ionospheric Variations

- Altitude
- Latitude
- Longitude
- Universal Time
- Season
- Solar Cycle
- Geomagnetic Activity
Status

• Ionosphere has both a Background State (Climatology) and a Disturbed State (Weather)
• Climatology is Basically Understood
• Weather Involves Storms, Substorms, Plasma Structures, Wave Activity, and Plasma Instabilities
• Main Research Focus is on Weather
High Latitudes
Lyons (1992)
Polar Wind

F-Region Convection

E-Region Currents

ALITUDE (km)

$u_\perp = 2 \text{ km s}^{-1}$
$u_{\parallel} = 6 \text{ km s}^{-1}$

$u_e$

Schunk (1983)
Volland Model

2-cell Pattern, $\Delta \Phi = 40$ kV, No Corotation
Sojka et al. (1979)
Geographic Inertial Frame

Sojka et al. (1979)
High Latitude Climatology

Brinton et al., 1978
Storms and Substorms

- **Ionosphere**
  - Increased Convection Speeds
  - Increased Joule and Particle Heating
  - \( O^+ \rightarrow NO^+ \)
  - \( T_i \rightarrow T_{i\parallel}, T_{i\perp} \)

- **Thermosphere**
  - Gravity Waves
  - O/N\(_2\) Changes
  - Enhanced Winds
  - Supersonic Winds
  - Anisotropic \( T_n \)
Satellite Images

- Ground Photograph by Jan Curtis.
- FUV Image from the IMAGE Satellite.
Satellite Images


- Bastille Day Storm
- July 14-15, 2000
- Snapshots During a 1-Hour Period
Ionosphere Forecast Model

NmF2  UT 0700

Storm
12 MLT

No Storm
12 MLT

4.44 6.4 8.5 0.5 2.5 4.5 6.5 8.6 0.0
Ionosphere Forecast Model

O+/Ne 300 km  UT 0700

Storm

No Storm

12 MLT

18

60

70

80

50

0

0.0  0.2  0.4  0.6  0.8  1.0

0.0  0.2  0.4  0.6  0.8  1.0
Neutral Gas Expansion

Cusp Heating

Expansion due to Auroral Heating

Midnight Surge
Ion Polar Wind

- Cusp Electrons
- Photoelectrons
- Energized Ions
- Polar Wind

$J_{||}$
O\(^+\)  6 UT

Demars and Schunk (2003)
$H^+ \quad 6 \text{ UT}$

Demars and Schunk (2003)
Neutral Polar Wind

Neutral Polar Wind

Noon-Midnight Meridian Flux 6:10 UT

\[ H^+ \]

\[ H_s \]

\[ O^+ \]

\[ O_s \]
Causes of Plasma Structures

- Changes in the Solar Wind Drivers
- Structured Electric Fields
- Structured Particle Precipitation
- Time Variations in E-fields and Precipitation
- Time Delays and Feedback Mechanisms in the M-I-T System
- Plasma Instabilities
$-1 < B_y < +1; B_z < -1$
Greenland

100-300 km by
1000-3000 km

Valladares et al (1994)
Mesoscale Ionospheric Structures

- Propagating Plasma Patches
- Propagating Atmospheric Hole
- Propagating Polar Wind Jets
- Propagating Neutral Streams
- Sun-Aligned Polar Cap Arcs
- Theta Aurora
- Boundary and Auroral Blobs
- Stationary Polar Wind Jets
- Neutral Polar Wind Streams
- Sub-Auroral Ion Drift Events (SAID)
- Storm Enhanced Densities (SED) Ridges
The near-Earth domain composed of the magnetosphere, polar wind, ionosphere and neutral atmosphere. Shown are propagating, supersonic, polar wind jets and propagating atmospheric holes.
Propagating Plasma Patches

- Mesoscale Regions of Enhanced Plasma Density
- Created in or Equatorward of Noon Auroral Zone
- Antisunward Convection with Background Plasma
- Horizontal Extent of 200 - 1000 km
- Circular or Cigar-Shaped
- Single or Multiple Patches
- Density Enhancement of Few % to Factor 100
- Enhancement Extends Along B
Single, Circular, Propagating Plasma Patch

- Gaussian Patch Distribution - 1000 km
- Peak $N_e$ Factor 5 Above Background
- $F_{10.7} = 150$, Winter Polar Region
- Quiet Conditions, then Southward IMF & 100 kV at Time Plasma Patch Imposed
  - Collisional Snowplow
  - $N_n$ Depletion in and Behind Patch, Enhancement in Front
  - Increased $U_n$ in Patch
  - Neutral Gas Upwelling and O/N$_2$ Changes
  - Disturbance Moves Along with Patch
$t = 0$

$N_e$

300 km

$\Delta T_n$

$\Delta U_n$

$\Delta N$

$t = 1 \text{ hr}$
Qaanaaq, Greenland, October 29, 1989

All-Sky Images (630 nm)

2 - Minute Interval
Neutral Density Perturbation
Neutral Gas Perturbations
300 km

- Single, Circular, Propagating Plasma Patch
  - $\rho_n \sim 30-35\%$
  - $T_n \sim 100 - 300$ K
  - $U_n \sim 100$ m/s

- Multiple, Cigar-Shaped, Propagating Plasma Patches
  - $\rho_n \sim 30\%$
  - $T_n \sim 100 - 400$ K
  - $U_n \sim 150$ m/s

- Comparable to Day-Night Change in the Thermosphere at Mid-Latitudes
MSIS Thermosphere

Noon-Midnight Variation at 300 km
Mid-Latitudes

• Solar Minimum, Winter Solstice
  $\rho_n \sim 40\%$
  $T_n \sim 45\ K$

• Solar Maximum, Summer Solstice
  $\rho_n \sim 50\%$
  $T_n \sim 250\ K$
Propagating Polar Wind Jet

- Cusp Electrons
- Photoelectrons
- Energized Ions
- Polar Wind
n(O+): 500 km, winter max
$n(H^+)$: 6:00 UT, win max

Mid-Latitudes
Interhemisphere Flow

Evans and Holt (1978)
Cluster Mission
Plasma Density Structures
Transverse Equatorial Size 20-5000 km

Gauss-Markov Kalman Filter Example

- November 16, 2003
- GPS Ground TEC measurements from more than 900 GPS Receivers (from SOPAC Data Archive)
- Includes Receivers from:
  - IGS
  - CORS
  - EUREF
  - and others
Climate

Kalman Filter

More than 3000 Slant TEC Measurements are assimilated every 15 minutes.
Gauss-Markov Kalman Filter Example
Regional Mode

- 3-D Ionospheric $N_e$ Reconstruction over North America
- Large Geomagnetic Storm on November 20-21, 2003
- GPS Ground TEC Measurements from more than 300 GPS Receivers (CORS GPS Network + other) over the continental US and Canada
- 2 Ionosondes at Dyess and Eglin
  → Observe large TEC Enhancements over the Great Lakes during November 20, 2003 @ 2000 UT.
Global Assimilation of Ionospheric Measurements
Utah State University, (435)797-2962, schunk@cc.usu.edu;
Universities of Colorado (Boulder), Texas (Dallas), and Washington

"Bringing the pieces together"

Climate

Kalman Filter

About 2000 Slant TEC Values are Assimilated every 15 min
Schunk et al. (2005)
Eastward Electric Field Uplifts Equatorial Ionosphere

Poleward SAPS Electric Field Strips Away Outer Layers of Plasmasphere

Low-Latitude Ionosphere

- Equatorial Anomaly
- $N_e$ Variability
- Spread-F/Plasma Bubbles
- Rayleigh-Taylor Instability
Snapshot of modeled electron densities at 300 km and 12 UT displayed in a geographic coordinate system. The electron densities were calculated from the Ionosphere-Plasmasphere Model (IPM) and are shown along geomagnetic field lines.
Effects of Diffusion, Electric Fields, and Winds on the Low-Latitude Ionosphere

F-region Ionization Transport Process With the Transequatorial Wind
Equatorial Fountain

Hanson and Moffett (1966)
Low Latitude Climatology

1998, Day 363, 1400 LT
- International Reference Ionosphere (IRI)
- $f_o F_2$ for solar Maximum, Equinox and UT=0

Bilitza et al. (1993)
GPS/MET Satellite

Equatorial Profiles

-5° ≤ θ ≤ 5°
1200 < local time < 1400

-5° ≤ θ ≤ 5°
2000 < local time < 2200
Equatorial Plasma Bubbles

- Vertically Elongated Wedges of Depleted Plasma
- Entire North - South Extent of B Depleted
- Up to Factor 1000 Depletion
- Bubble Apex Altitudes Between 500 - 1500 km
- Typical Bubbles: 100-500 m/s up
- Fast Bubbles: 500 m/s - 5 km/s up
  1 km/s horizontal
Spread F/Equatorial Bubbles

Argo and Kelley (1986)
Equatorial Spread-F and Bubbles

JULIA Coherent Scatter Radar

Hysell and Burcham (1998)
• DMSP F10 Satellite
• 234 E Longitude, 19.7 MLT, 117 SZA, 750 km Orbit
• Typical Bubbles: 100-500 m/s up
• Fast Bubbles: 500 m/s - 5 km/s up
  1 km/s horizontal
Neutral Density (top) and Temperature (bottom) Perturbations due to 4 Plasma Bubbles

300 km
Golden Age of Aeronomy

• Large Amount of Data Available
• Access via Virtual Observatories
• Data Assimilation Models
• Coupled Physics-Based Geospace Models
• Community Coordinated Modeling Center (CCMC)
• Elucidating Mass, Momentum, and Energy Coupling in the M-I-T System at Global, Regional, and Local Scales will be Possible
• Rigorous Inclusion of Instabilities in Global Models will be Possible