System Science from Above and Below: Past, Present, Future

Anthea J. Coster,
the entire Haystack staff past and present,
the many, many people
I have collaborated with,
and all the GNSS signals
System-Science Model of Plasma Redistribution

1. Solar EUV and Joule heating drives storm enhanced plasma densities at low latitudes.

2. The magnetospheric ring current connects to the ionosphere, generating electric fields that funnel the low-latitude plasma towards higher latitudes.

3. Massive amounts of ionospheric plasma is supplied to the cusp, where it flows out into the magnetosphere.

4. Heavy ionospheric plasma reaches the plasma sheet, where it affects reconnection rates impacting substorm activity.

5. Ionospheric plasma is energized by storm convection and substorm, enhancing plasma pressure, which drives the ring current system that connects through the ionosphere.

6. Storm-time electric fields lead to transport and loss of plasmaspheric ions through magnetopause affects dayside reconnection rates.
Outline

History – mine

System Science
  Past (pre and post-GPS)
  Current
  Future
Space Age – First satellite launched 1957

4,550 satellites in orbit, as of Sept. 1, 2021

SPUTNIK
But why, some say, the Moon? Why choose this as our goal? And they may well ask, why climb the highest mountain? Why, 35 years ago, fly the Atlantic? Why does Rice play Texas?

We choose to go to the Moon! ... We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard; because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one we intend to win ...
Calculators cost approximately 3 mos. of room and board. Computer programs all done on punch cards.
The Ionosphere

The Ionosphere is divided into several regions:

- **D-region**: Lowest altitude region, typically between 50 and 100 km.
- **E-region**: Next highest region, typically between 100 and 300 km.
- **F-region**: Highest altitude region, typically between 300 and 1000 km.

The IRI-95 models describe electron and ion species density as a function of altitude. The diagrams illustrate the distribution of these species across the different regions of the ionosphere.

- **Topside**: The region where the electron density is highest, typically at the top of the F-region.

The ionosphere plays a crucial role in the propagation of electromagnetic waves, particularly for AM radio transmission.
Experience with different radars

9-track tapes, Calcomp plotters, no personal computers, no word processors

Yes those are cows
Outline

History – mine

System Science
Past (pre GPS)
Current
Future
Data Collected at Sagamore Hill, MA using a Faraday Rotation Technique

14 May 1969
Electron density variation at middle and subauroral latitudes: Trough

Data from DE 2 satellite in N. hem. 9 Dec 1981 at 7.6 UT (6 pm local).

Prolss, Ionospheric Storms at Mid-Latitudes: A Short Review
Early Storm Enhanced Density Measurement, 1986 and 1990

Outline

History – mine

System Science

Past
Current
Future

GPS era
$150,000 with the MIT discount in 1985.

Could only track 4 satellites at a time.
Satellites transmit/receive radio wave signals that propagate through the atmosphere.
Refraction and Dispersion

\[ n = \frac{c}{v_p}. \]
Appleton-Hartree Equation

\[ n^2 = 1 - \frac{X}{1 - iZ - \frac{1}{2} Y^2 \sin^2 \theta \pm \frac{1}{1 - X - iZ} \left( \frac{1}{4} Y^4 \sin^4 \theta + Y^2 \cos^2 \theta (1 - X - iZ)^2 \right)^{1/2}} \]

or, alternatively[^4]:

\[ n^2 = 1 - \frac{X (1 - X)}{1 - X - \frac{1}{2} Y^2 \sin^2 \theta \pm \left( \left( \frac{1}{2} Y^2 \sin^2 \theta \right)^2 + (1 - X)^2 Y^2 \cos^2 \theta \right)^{1/2}} \]

\[ n = \text{complex refractive index} \]
\[ i = \sqrt{-1} \]
\[ X = \frac{\omega_0^2}{\omega^2} \]
\[ Y = \frac{\omega_H}{\omega} \]
\[ Z = \frac{\nu}{\omega} \]
\[ \varepsilon_0 = \text{permittivity of free space} \]
\[ \mu_0 = \text{permeability of free space} \]
\[ B_0 = \text{ambient magnetic field strength} \]
\[ e = \text{electron charge} \]
\[ m = \text{electron mass} \]
\[ \theta = \text{angle between the ambient magnetic field vector and the wave vector} \]

[^4]: For a full description of the terms, see [reference].
Definition:

\[ \text{TEC} = \text{Total Electron Content} \quad (10^{16} \times \text{el/m}^2) \]

\[ \Delta R_{\text{ion}} (\text{meters}) = \frac{40.3}{f^2} \quad \text{TEC} \]
GPS Background

- At most 32 satellites
- 6 orbital planes
- 4~6 satellites per plane
- 55° inclination angle
- near circular orbit
- ~20000 km altitude
- ~12 hours round trip
  (11 hour 58 min 2.05 sec)
GPS Background

Each GPS spacecraft:

- Carries highly accurate clock
- Transmits its clock and position
- Signals are transmitted on 2 (or 3) frequencies
- First satellites launched in 1978
- Fully operational in 1995 (19 in 1991)
GPS Positioning

Error Sources:
- Ephemeris Error
- GPS Clock Error
- Receiver Noise
- Multipath
- Atmosphere:
  - Troposphere
  - Ionosphere

Measurements: Pseudoranges \( \{R_i\} \)

Given: Satellite Positions \( \{(x_i, y_i, z_i)\} \)

\[
R_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} - b,
\]

\(i = 1, 2, \ldots, N\)

Unknown: User Position \((x, y, z)\)
Receiver Clock Bias \(b\)
TEC from GPS is measured from the difference of the GPS pseudo-range measurement at two frequencies

\[ P_1 - P_2 = 40.3 \text{TEC} \left( \frac{1}{f_2^2} - \frac{1}{f_1^2} \right) \]

\[ \text{TEC} = \frac{1}{40.3} \left( \frac{f_1f_2}{f_1 - f_2} \right) (P_2 - P_1) \]

Where \( P_1 \) and \( P_2 \) are the pseudo-ranges measured by GPS at the two different frequencies, \( f_1 \) and \( f_2 \).
Illustration of GPS Phase and Group Delay TEC data. GPS Sv 6. 1 March 1989

Travelling Ionospheric Disturbances (TIDs)

Differential Ionospheric Errors greater than 34 cm (2 TEC units) are problematic.

• TIDS are short-term variations in the TEC, covering a large range of periods and amplitudes.
  Originate either:
  • in auroral regions (associated with geomagnetic disturbances (high Kp)).
  • Or not. These are generated by unknown sources, possibly:
    • atmospheric tides, tropospheric weather, volcanic explosions, earthquakes, rocket launches.
Historical GPS TID Data: 1991
(near solar maximum)

Anthea Coster and Patricia Doherty
TEC DATA measured from Five Sites

TEC Data from Five Sites, SVN 25

08 November 1998
4 May 1997: $K_p = 9$ (Geomagnetic Storm)

First Difference of Ionospheric Delay

GPS satellites are color-coded
In the 1990’s very few (if any) AGU/CEDAR scientists using GPS TEC data.

Starting in the mid-1990’s, we started organizing yearly sessions at URSI/USNC on “GPS and the ionosphere.”

It became a personal goal of mine to see that GPS data was more utilized by the atmospheric science community.
IGS: International GNSS Service

The creation of the IGS was **initiated in 1989** and became an **official International Association of Geodesy service** in 1994.

Early user of internet.

Stressed importance of standardized products, freely accessible on the internet.

The **IGS Central Bureau** is located in the USA at JPL. Today the IGS is an **interdisciplinary service in support of Earth Sciences and Society** committed to use of the data from all GNSS.
In 1992 the IGS was based on about 20 geodetic receivers, 400+ receivers are active and their data retrievable today

Based on this data JPL scientists first developed mapping of TEC across the US
Outline

History – mine

System Science
  Past (pre and post-GPS)
  Current (2000-now)
  Future
Solar Flare of 14 July 2000

SoHo – Solar Flare

SoHo – Coronal Mass Ejection

Biggest Solar Storm in Nine Years

Caused very large magnetic storm and ionospheric effects

Estimated Planetary K Index (3 hour data)
GPS Loss of Lock at Millstone Hill

Local Westward Ion Velocity at Millstone Hill

Zenith TEC Over Millstone Hill

Loss of Lock on GPS L2 signal
TEC Disturbances on 15 July 2000

UTC Time (Hours) starting at day 197

Florida site

TEC Units

POR4
WES2
NRC1
MHR3
GPS Total Electron Content Map

Illustration of Storm Enhanced Density

Coster, Foster, Erickson, Rideout, 2000
Distributed vs. single point measurements

Wide Area Distribution of 'Raw' Information

Distributed networks of sensors yield global physics unattainable with single-point measurements

Example: Global GPS-derived ionospheric mapping during geomagnetic disturbances
IMAGE Data of Plasmasphere

Foster, Coster, Erickson, Rideout, 2003
Nighttime MSTID Observations (TEC, Airglow) [Saito et al., 2001]
Solar Flare

A violent explosion in the Sun's atmosphere; energy equivalent of a hundred million hydrogen bombs. Giant bursts of X-rays and energy which travel at the speed of light

- Arrival: 8 min from Sun to Earth (149.6 million km)
- Duration: minutes to 3 hrs
- Daylight-side impact
Sept 6, 2017
Forces that act on the Ionosphere

These forces produce ionospheric changes: electric fields, electron density, temperature, composition,..

Solar/Magnetospheric forcing, e.g., geomagnetic storms

Tropospheric/Stratospheric forcing, e.g., planetary waves

[adapted from Marchavilas, 2007]
GPS TEC change – no warming

- GPS TEC (Total Electron Content) data show large-scale picture of ionospheric behavior
- Before the warming, TEC change is 10-20% from mean and vertical drift is small
- The mean is Jan 1-14, 2009
GPS TEC during warming: morning sector

- During stratwarming, TEC increases in excess of 50-100% in the morning
- Large upward drift at Jicamarca
- The magnitude of increase is similar to effects of severe geomagnetic storms
SuperDarn Convection Patterns merged with DMSP and Global TEC
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Big Data: Example - Transition Region Explorer (TREx) sites
Development of a sensor web
MERGE DATA FROM DIFFERENT SENSORS

MACAWS and CHAIN networks with GNSS TEC and scintillation parameters combined with THEMIS All-sky imager data

- NSF MRI Collaborative: Development of Monitors for Alaskan and Canadian Auroral Weather in Space (MACAWS) plus Canadian High Arctic Ionospheric Network (CHAIN)
- World-wide network GNSS TEC receivers
- THEMIS All-sky imagers

MIT Haystack Observatory, U. Calgary, U of Alaska

University of New Brunswick
Merged All-sky imagers, GNSS Scintillation, and GNSS Total Electron Content (TEC) maps – March 1, 2017
April 15, 2022 02:00 UT
The ionosphere as Earth system sensor

Space-time variations in the ionospheric density field provide a projection of dynamics drivers above (left, magnetospheric substorm) and below (right, Tohoku earthquake).


MANGO ASI – Jonathan Makala, Asti Bhatt, Brian Harding

24 May 2022, 04:11 UT

GREEN LINE
EASTWARD WIND (M/S)

NORTHWARD WIND (M/S)
MANGO DATA compared to GNSS TID data
05/29/2017
This looping video shows a series of GOES-17 satellite images that caught an umbrella cloud generated by the underwater eruption of the Hunga Tonga-Hunga Ha'apai volcano on Jan. 15, 2022.

Crescent-shaped bow shock waves and numerous lighting strikes are also visible.

Initial waves had huge amplitudes and wavelengths (~ 2K km!)

Subsequent waves had 300-500 km wavelengths
Beidou and GPS data coverage for Tonga eruption study

Distance-Time plot to show eruption induced global TID propagation
Evident TID occurrence was based on the distance from the epic center;

TIDs reached 20K km distance 17 hrs after the eruption;

Shock fronts traveled at ~ 350 m/s

Regional disturbances lasted for 8-10 hrs
Big Data and Computational Reconstruction

Consecutive 5-minute images of three-dimensional ionospheric density patterns observed with the Poker Flat Incoherent Scatter Radar (PFISR) during a geomagnetically active period. (After Semeter et al., 09, 10)
Regional 3-D electron density specification with a new TEC-based Ionospheric Data Assimilation System (TIDAS)

Region: the continental U.S.; Data assimilation Method: En3DVAR; Background: NeQuick

1. Ground-based and Space-borne Datasets: GNSS TEC + COSMIC RO + JASON TEC + Millstone Hill ISR

2. Ensemble-based background error covariance

3. Three-Dimensional Variation (3DVAR) Approach

4. Sparse-Matrix Storage

MERGE DATA FROM DIFFERENT SENSORS
Regional 3-D electron density specification with a new TEC-based Ionospheric Data Assimilation System (TIDAS)

Resolution: $1^\circ$ (Latitude) x $1^\circ$ (Longitude) x 20 km (Altitude) x 5 min

- TIDAS data assimilation results provide a reasonable representation of the morphology and evolution of well known large-scale ionospheric characteristics, such as the equatorial ionization anomaly (EIA) at low latitudes, mid-latitude storm-enhanced density (SED) containing a remarkable density gradient, and the main ionospheric trough with TEC depletions at subauroral.
- In particular, TIDAS data assimilation product captures well the 3-D fine structures and dynamic evolution of SED.
HMONG Guide in North Vietnam has more sophisticated cell phone than Cornell-educated Mechanical Engineer.
West Texas 15 Sept 2000 near El Paso Texas
Aurora In West Texas Skies
Credit & Copyright: Chris Grohusko, Astronomy Picture of the Day

(from astronomy picture of the day)
Summary:
- Find easier ways to integrate different data sets; Standardize data formats
- Utilize all signals
- Improve visualization of data sets; Standardize data formats
- Modelers, data scientists, experimentalists: collaborate