Next Step
Space Weather Benchmarks

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SPACE WEATHER PHASE 1 BENCHMARKS

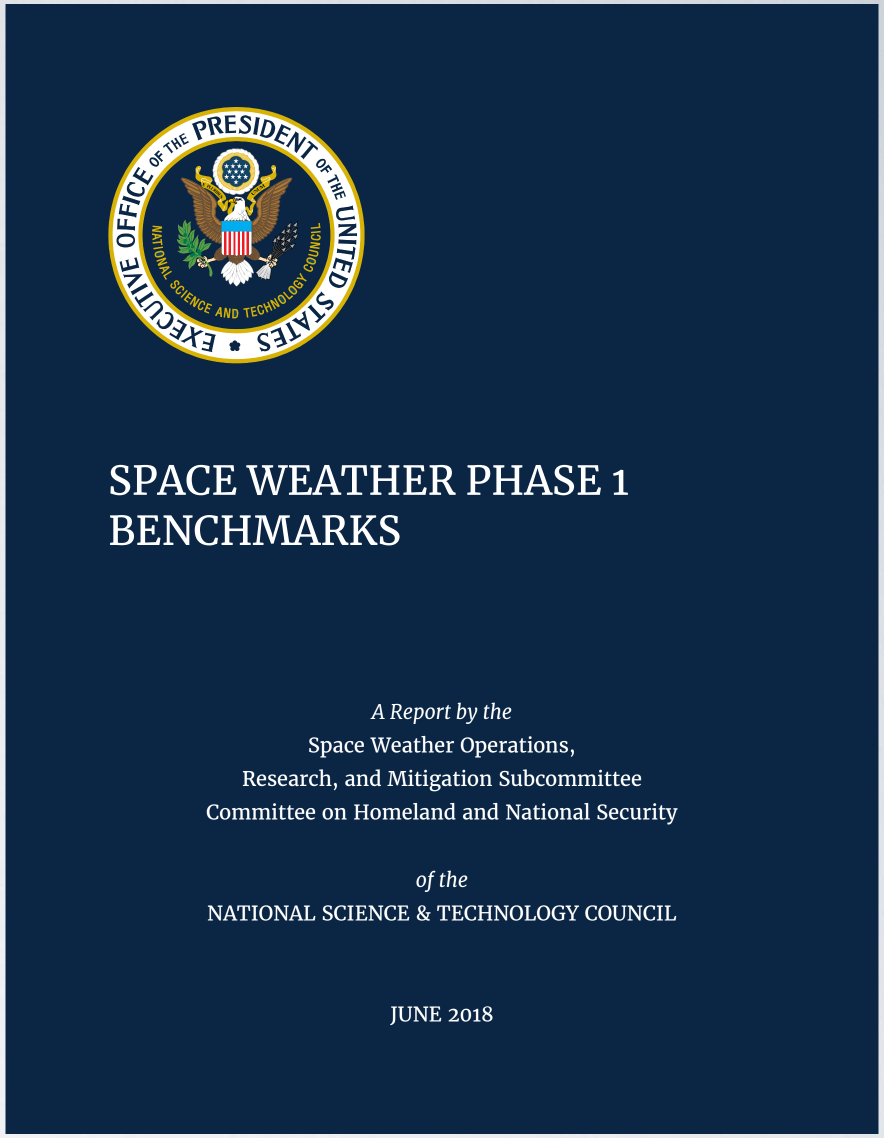
A Report by the
Space Weather Operations,
Research, and Mitigation Subcommittee
Committee on Homeland and National Security

of the
NATIONAL SCIENCE & TECHNOLOGY COUNCIL

JUNE 2018

Phase 1 Study

- Begun in 2017
- Published in 2018
- Conducted by the Space Weather Operations, Research, and Mitigation (SWORM) subcommittee
- Under the Department of Homeland Security
- Involved >25 federal departments and agencies



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Working Toward Phase 2

- Phase 1 was fairly rapid turn-around with little input from the scientific and operator communities
- The 'Next Steps' process is currently soliciting broad community participation to provide input to Phase 2
- Phase 2 envisions more "scientifically and statistically rigorous benchmarks"
- The SWx Action Plan calls for re-examining benchmarks every 5 years

What are benchmarks?

- They are <u>not</u> metrics for model or prediction performance but <u>do</u> help set targets
- The benchmarks specify the **1-in-100 year** and **theoretical maximum** levels of space weather conditions that can affect critical infrastructure and the nation
- Benchmarks focus on <u>conditions</u> not <u>effects</u>

What is the purpose of benchmarks?

- Enhance awareness of threats among critical infrastructure owners and operators
- Provide input for engineering standards
- Provide input for vulnerability & risk assessments
- Help guide development of mitigation procedures
- Establish thresholds for action
- Set goals for academic and private sector innovation

Five Topic Areas - And the Chairs

- **Induced Geo-Electric Fields**
  Pete Riley, Predictive Science Inc.

- **Ionizing Radiation**
  Christina Cohen, Caltech

- **Ionospheric Disturbances**
  Susan Skone, University of Calgary

- **Solar Radio Bursts**
  Dale Gary, New Jersey Institute of Technology

- **Upper Atmospheric Expansion**
  David Jackson, UK Met Office

- Support from IDA (Tom Colvin, Seth Jonas, etc.)

Ionospheric Disturbances

- Susan Skone, chair
- Anthea Coster
- Keith Groves
- Jonathan Makela
- Ethan Miller
- Roger Varney

‘Next Steps’ will provide peer review of Phase 1 and input to Phase 2

- Are the current benchmark quantities (the variable, not its value) well-aligned with the objectives and use cases stated in the Phase 1 Document?
  - Are the benchmark values reasonable and up-to-date based on current understanding?
  - Assessment of Phase 1 benchmark values
  - Assessment of uncertainties on the benchmark values
  - Are there other studies that give different values that should be referenced?
- Is the methodology used to derive the benchmark values up-to-date, rigorous, and compelling?
  - Assessment of the methodology used.
  - Clarity of the description of the methodology.
  - Are there updates or alternatives?
- Recommendations for updates that could be done now or in the near term.
- Recommendations for longer-term studies or research that would improve the benchmark values, reduce their uncertainties, or improve their usability.

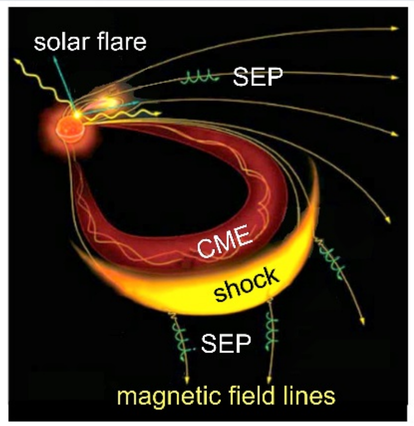
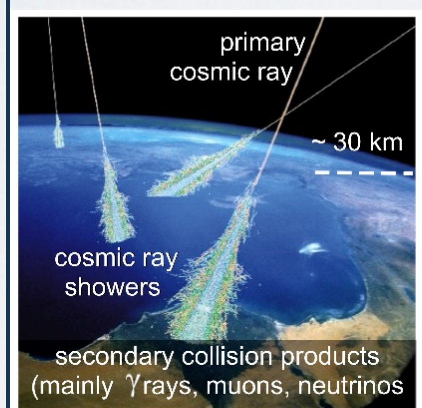
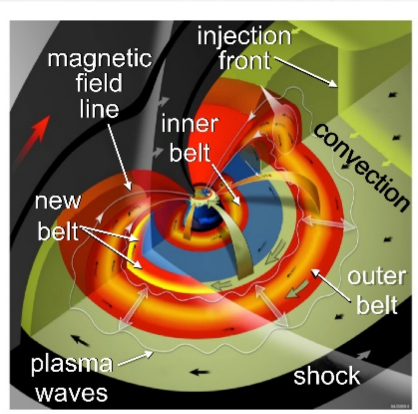
Elements of Each Topic Area

SPACE WEATHER PHASE 1 BENCHMARKS

Benchmarks for Ionospheric Disturbances	
Environmental parameter	The ionosphere is highly variable and is driven externally by solar extreme ultraviolet (EUV) and X-ray irradiance, geomagnetic storms, and the neutral atmosphere. These drivers can affect the total electron content (TEC), highest affected frequency (HAF), maximum usable frequency (MUF), height of the F_2 layer (hmF_2), peak density of the F_2 layer (NmF_2), and the phase and amplitude scintillation indices Sigma-Phi and S4. Ionospheric variability affects radio signal propagation by changing the reflection, refraction, absorption, and delay of the radio signal.
Methodology for determining benchmarks	The extreme impacts of ionospheric disturbances on communication, navigation, and positioning systems would be fully described by global maps of a number of parameters, including the TEC, HAF, MUF, hmF_2, NmF_2, and the phase and amplitude scintillation indices Sigma-Phi and S4.
1-in-100-year benchmarks	Not feasible to compute benchmark. Complexities in modeling ionospheric disturbances prevented setting useful benchmarks with reasonable uncertainty.
Theoretical maximum benchmarks	Not feasible to compute benchmarks. Advances in scientific understanding of the entire magnetosphere-ionosphere-thermosphere (MIT) system and its response to extreme geomagnetic storms would improve the ability to quantify benchmarks for ionospheric disturbances. While benchmarks were not developed, values were measured during the intense 2003 Halloween event for ionospheric disturbances. These include a vertical TEC of 250 TECu (where 1 TECu = 1×10^{16} electrons m^{-2}) with an associated error of approximately 3 TECu, a TEC spatial range gradient of 40 cm/km, and a TEC temporal range gradient of 15 cm/s.[d, e, f] These conditions could last up to several days.[g]

Includes deeper textual explanations

Types & Sources of Ionizing Radiation

<table>
<tr><td rowspan="3">Solar Energetic Particles (SEPs)
</td><td>Type</td><td><u>Ions</u>: 1 megaelectron volts (MeV) to 20 gigaelectron volt (GeV) hydrogen (H), helium (He), and heavy ions
<u>Electrons</u>: Smaller fluxes with particle energies up to 10 MeV</td></tr>
<tr><td>Source</td><td>Accelerated in flares, at shocks in the corona, and at interplanetary shocks, in particular those ahead of fast coronal mass ejections</td></tr>
<tr><td>Hazard</td><td><u>Ions:</u>
> 500 MeV: penetrate to ground level
> 100 MeV: radiation hazard for airplane crews and passengers
>30 MeV hazard for space tourism
<u>Electrons</u>
Penetrate into polar cap region. Reach the moon and the Lagrangian points where space missions reside.</td></tr>
<tr><td rowspan="3">Cosmic Rays
</td><td>Type</td><td>Near-constant isotropic flux. Nuclei of all natural elements in the Periodic Table: 90% H. 9% He, 1% heavier elements
Energy Range: 1MeV–1 billion MeV</td></tr>
<tr><td>Source</td><td>Not fully understood. Thought to originate in the large, expanding shells of supernovas. A small portion are accelerated at neutron stars or black holes.</td></tr>
<tr><td>Hazard</td><td>Radiation hazard for astronauts and airplane crews. Effects of the primary cosmic rays scale with the square of the atomic number. Small percentages of heavy ions have large effects. Generate particle showers passing through thin mechanical shielding or the atmosphere. The atmosphere absorbs most of the cosmic ray energy before reaching the surface. However, protection from cosmic rays in space is the most difficult of all ionizing radiation.</td></tr>
<tr><td rowspan="3">Radiation Belts
</td><td>Type</td><td><u>Inner belt</u> (1.2-3 Earth radii): > 1 MeV H^+ (proton), <MeV electrons
<u>Outer belt</u> (3-10 Earth radii): 0.1–10 MeV electrons, < 1 MeV H^+ (proton)</td></tr>
<tr><td>Source</td><td>Intensity determined by the balance among radial diffusion, wave-particle interactions, non-adiabatic processes and (inner belt) neutrino decay. Outer electron belt drops out & reforms in response to space weather. New belts rapidly formed in response to interplanetary shocks/SEPs</td></tr>
<tr><td>Hazard</td><td><u>Inner belt</u>: Greatest hazard is > 30 MeV protons that can penetrate space suits & spacecraft walls. An expanded inner belt may encompass the International Space Station and low Earth orbit (LEO) satellites.
<u>Outer belt:</u> 0.1–10 MeV electrons cause surface charging, arcing & phantom commands on satellites</td></tr>
</table>

Example: Atmospheric Expansion Benchmarks

- Some benchmarks include multiple scenarios
- Ideally benchmarks are quantitive with uncertainties
- Some are specific and well-documented. Some are 'educated guesses'
- Identifies areas where benchmarks are not currently possible

1-in-100-year benchmarks	Cause of Upper Atmosphere Expansion	Altitude (km)	Benchmark (percent neutral density increase)[m]	Associated Uncertainty
	Solar Extreme Ultraviolet and Far Ultraviolet Radiation	250	50%	± 30%
		400	100%	± 30%
		850	200%	± 30%
	Solar EUV Radiation Enhancement during Solar Flares	400	75%	factor of 2
	Coronal Mass Ejections Driving Geomagnetic Storms	400	400%	± 100%
Theoretical maximum benchmarks	Solar Extreme Ultraviolet and Far Ultraviolet Radiation	250	100%	factor of 2
		400	160%	factor of 2
		850	300%	factor of 2
	Solar EUV Radiation Enhancement during Solar Flares	400	135%	factor of 2
	Coronal Mass Ejections Driving Geomagnetic Storms	400	Not feasible to compute benchmarks	± 100%

Benchmarks for Ionospheric Disturbances Space Weather Action Plan 1.3.1

"benchmarks and associated confidence levels will define at least the following:"

- Ionospheric radio absorption and duration as a function of frequency
- Total electron content (slant, vertical, and rate of change)
- Ionospheric refractive index
- Peak ionospheric densities and the height of the peak [of the layer].

Ionospheric Disturbances Sources & Environmental Effects

Table 8. Effect of extreme events on the ionosphere

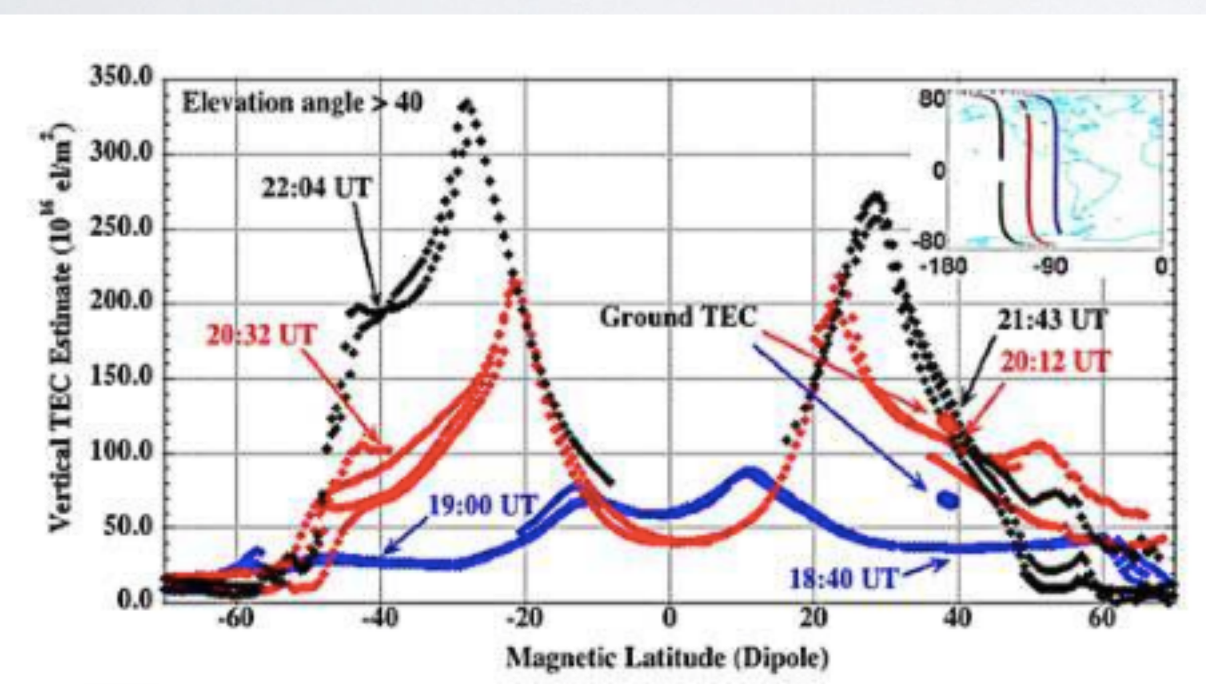
Phenomenon	Event	Location	Environmental Effect
Flare	D Region Enhancement	Sunlit side of Earth	Absorbs RF signals from HF to VHF in the lower ionosphere
Energetic Protons	D Region Enhancement	High and mid-latitudes	Absorbs RF signals from HF to VHF in the lower ionosphere
Geomagnetic Storms	Polar Cap and Aurora	High and mid-latitudes	Patches, plasma structures, and ionospheric gradients refract radio waves.
	Traveling Ionospheric Disturbances and Storm-Enhanced Densities	Mid-latitude region on the dayside of Earth	Creates large TEC enhancements (up to 200 TEC units) and strong gradients in TEC
	Equatorial Scintillation	Latitudes ±20 degrees of geomagnetic equator	Large-scale plasma depletions and associated small-scale ionospheric structures observed just after sunset and generally up to midnight. Scintillation of transmitted radio signals.

Ionospheric Disturbance Benchmarks

Because of the complexities in modeling ionospheric disturbances, **no quantitative benchmarks were set for this section.** Although much is known about the local characteristics of the ionosphere that change in response to geomagnetic storm conditions, it is still difficult to quantify the global response to an extreme storm. Earth's ionosphere is a dynamic system, and is strongly coupled to both the magnetosphere and the neutral atmosphere. A better understanding of the entire MIT system and its response to extreme geomagnetic storms would help inform this benchmark. Providing benchmark estimates of various extremes in the ionospheric parameters with uncertainties approaching 100% could potentially be misleading and may lead to severe under or over estimation of disturbances to the ionosphere. Phase 2 of the benchmarks effort (NSWAP 1.3.3) will seek to refine the benchmark values and uncertainties.

methodology

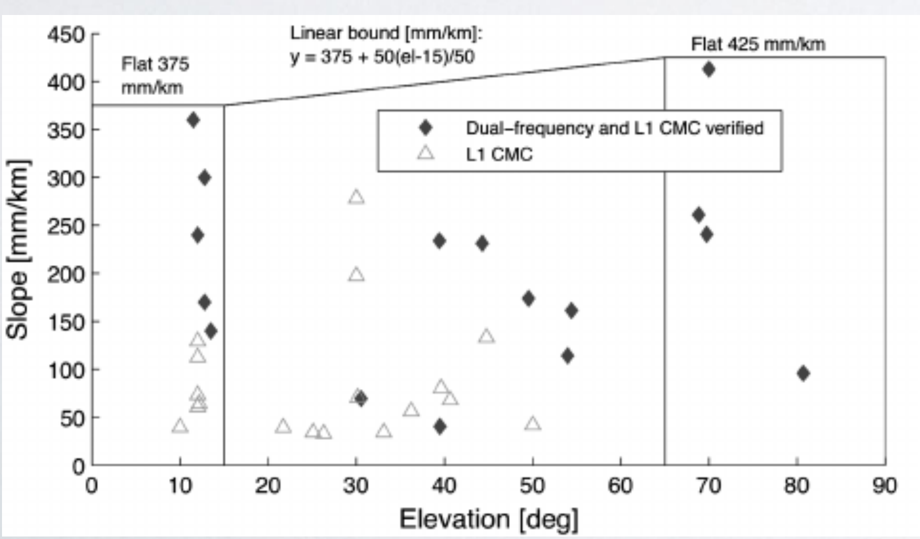
Type	Value/ duration/ extent	Extreme Event	Drivers	Model/ theory	Data/ observations/ stats	Gaps/ Limitations	Recommendations (short and long term)
VTEC	350 TEC units with duration several hours **[NEW]**	Equatorial anomaly Storm enhanced density	Model extreme inputs include F10.7 (400 sfu) and vertical drift (200 m/s).	Ionosphere-plasmasphere model with high upper boundary (above 600 km).	Extreme value analysis using ionosonde and GPS/GNSS data (focus on CONUS first and then extend out globally). Review IGY data.	Larger magnitude observations of the phenomena are available and should be considered. Limited efforts to attempt modeling approaches.	Values provided in Phase 1 could be multiplied by a factor as suggested by UK group but with justification from the modeling efforts. Solar experts could provide consistent values (EUV and F10.7) to all WG modeling approaches. Consider recent review papers by Jakowski and Hoque (2019) on spatial/gradient indices. More thorough literature review may be useful for refined benchmarks.

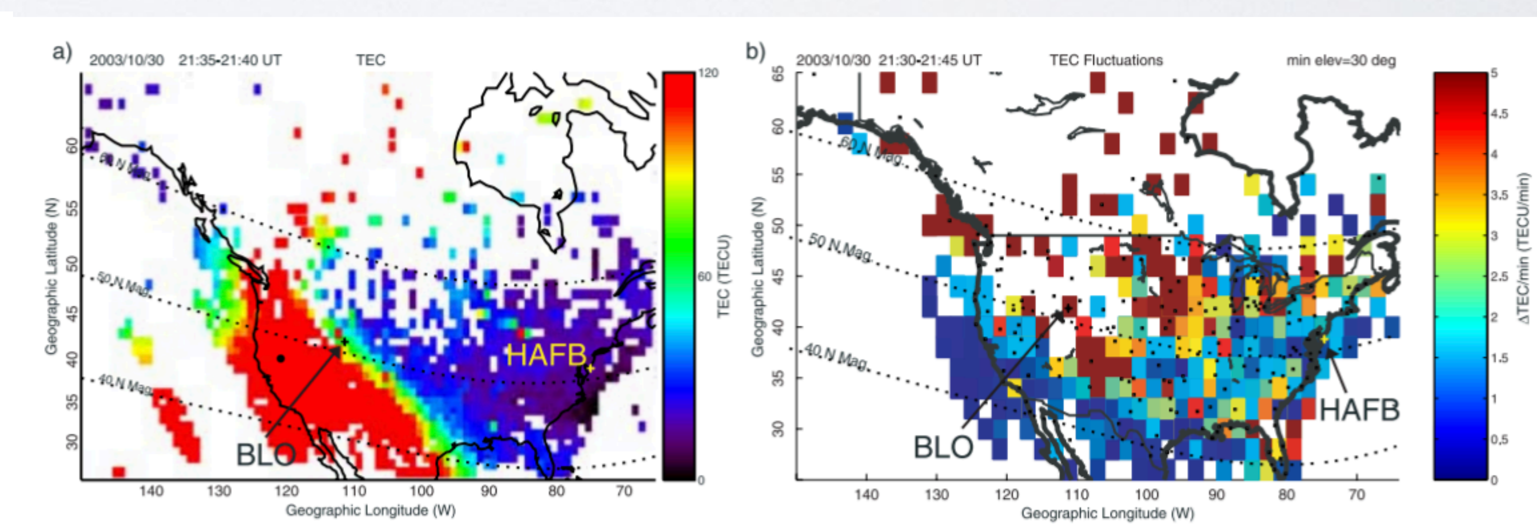


TEC Spatial/Temporal Gradients

Phase 1 benchmark of TEC spatial range gradient of 40 cm/km, and a TEC temporal range gradient of 15 cm/s.

- These are GPS L1 specific values based on Datta-Barua (2010).
- **Recommendation**: Benchmark should be technological system agnostic. Values of TECu/km and TECu/s are more general (2.5 TECu/km, 1 TECu/s)
- **Recommendation**: Additional statistical analysis of existing TEC data will better elucidate these values.





How do you get involved?

- **Read and review the Phase 1 report!**
  google "space weather benchmarks"
- An RFI was published and advertised but with little response
  https://idalink.org/SWxBenchmarks
- Community Input Workshop was held in Denver April 23
- Input welcome in any form at any time. Contact me or any focus area member
- Town Hall and release of draft report for stakeholder feedback, September, Washington, DC
- Final Report and Space Weather Benchmark Session at Fall AGU

Contact any of the following committee members

- Susan Skone, chair
- Anthea Coster
- Keith Groves
- Jonathan Makela
- Ethan Miller
- Roger Varney

NmF2 and hmF2 → MUF

Ionospheric Disturbances WG

Estimating Maxima: NmF2

- Maximum observed GPS-TEC was 350 TECu (*Mannucci, et al*, 2005) during the Halloween Storm 2003; data source: CHAMP POD-TEC.
- Following *Gerzen, et al*, (2013):

$$N_{mF_2} = \frac{\mathrm{vTEC}}{\tau} = 1.24 \times 10^{10} \left(f_{oF_2}\right)^2$$

- Values of tau are in (270,420). For a nominal value of tau of 300, NmF2 is 1E13 m^{-3}. This corresponds to a plasma frequency (foF2) of 28.4 MHz or a MUF of 145 MHz.
- Informally, our group knows of reported foF2 values around 22 MHz (6E12 m^{-3}) and and MUF of 140 MHz during quiet conditions. Further study indicated.

Estimating Minima: NmF2

- Turning “off” production and transport in the continuity equation leads to NmF2 → 0.

$$\frac{dn_e}{dt} = \mathrm{Production} - \mathrm{Loss} + \mathrm{Transport}$$

- This condition is nearly met at solar minimum, under quiet conditions, in the winter (dark) polar cap. The duration of this may be many days, although in practice, convection transports some plasma into the polar cap on a diurnal basis.

Estimating Maxima: hmF2

- Sustained high equatorial vertical drift (favorable **E** x **B** transport geometry).
- 120 m/s vertical drift observed by Kelley, et al (2010) during November 2004 storm.
- hmF2 rose to 850 km.
- *Ionospheric profile is expected to be highly distorted (concept of hmF2 may be meaningless) and cause other "interesting" phenomena for HF users under these conditions.*

Recommendations: Extreme Events Next Steps

- Revisit the ionogram database at both high and low latitudes
  - IGY 1957-1958 corresponds to highest solar activity levels in ~400 years.
  - 2008-2009 corresponds to lowest solar activity levels since systematic ionospheric soundings.
  - Conduct extreme value analyses for NmF2.
- Run physics-based models with high and low solar flux (EUV, F10.7) inputs for NmF2. Coordinate with solar, ionizing radiation, thermosphere WGs.
- Run physics-based models with prompt penetration electric fields consistent with 200 m/s vertical drifts for hmF2.
- Coordinate/investigate with TEC maxima/minima.
- Consider spatial and temporal evolution of these values.

Recommendations: General

- To the extent practical and valid, harmonize benchmarks and recommendations with the existing engineering tools for HF propagation:
  - VOACAP (Voice of America Coverage Area Prediction) parameters
  - ITU-R P.533-13 ‘Method for the prediction of the performance of HF circuits’
  - ITU-R P.534-5 ‘Method for calculating sporadic-E field strength’
  - ITU-R P.581-2 ‘The concept of "worst month”’
- Some of the ITU-R recommendations include complex and detailed descriptions of the ionosphere and its variability. We encourage development of *future benchmarks that reflect that attention to detail already encoded in the engineering standards*.