Ionosphere Mitigation through Species Characterization and Stratification

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1. Abstract

Total Electron Count (TEC), the main component in characterization of the ionosphere, is not everything and does not completely describe the contents or the dynamics of the ionosphere. Current understanding of the ionosphere is based on reflection of Radio Frequency energy. The amount of return is highly dependent on the TEC and as such is used to describe its status for uses in satellite communication or GPS beacon performance. However, TEC based measurements are highly limiting in not only mapping out the full ionosphere layer but can also exhibit shadowing when returns from different layers of the Ionosphere are not received. For a full understanding of the dynamics of the ionosphere it is preferable to consider the whole gamut of contributors. Contributors such as ionospheric composition and dynamics requires determination of factors beyond TEC such as atomic and molecular species concentration, ion-based contributions and how they interact and correlate with the radiation belts, and even solar events.

Atomic and molecular species concentration requires a study of specific abundance measurements in each layer as a function of altitude and geographical distribution. Similarly, ion-based contributions require a study of concentrations associated with relevant species as a function of altitude and geographical distribution. We study the available concentration of these contributors to further understand their interactions within the ionosphere. The desired outcome of this study is to drive the field to generate a new set of requirements to attain better space situational awareness and understanding.

2. Laser Induced Fluorescence for Detection and Ranging

We introduce a new concept for measuring the content on the ionosphere using laser induced fluorescence. Laser (or light) induced fluorescence is a method commonly used to probe the characteristics of plasmas (both sparse and dense). For an atomic or molecular species of interest, an initial wavelength, λ_0 is chosen based on the available excitable energy states of the valence electrons (e.g., see O^+ in Figure 1). A laser tuned to this wavelength is used to excite the valence electrons to this energy state. Based on the probability to de-excite, the electrons will transition to lower energy states releasing a photon of longer wavelengths than λ_0. In essence, the atomic or molecular species has been fluoresced by the tuned laser. Using a detector tune to at least two of the fluorescence wavelengths, an estimate of the number density of the atomic species in each de-exited energy state can be estimated from the Boltzmann equation based on the comparison of the flux at each wavelength. Similarly, an estimation of the number density of a species in the neutral and first ionization state can be estimated by the Saha-Boltzmann equation. A consequence of this equation also gives the electron number density.

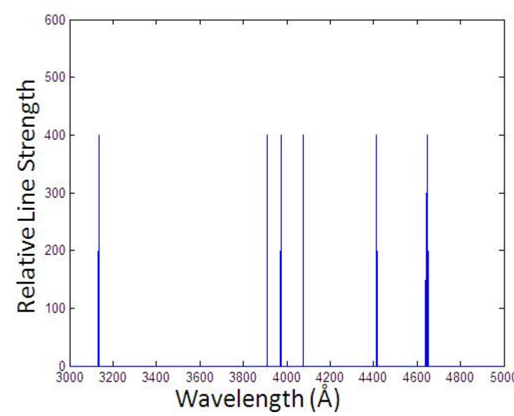

Fig. 1. Prominent singly ionized oxygen emission lines from the 3000 - 5000 $\mathring{A}$ wavelength region.

This process is basically selective active spectroscopy of gases and plasmas. Light Detection and Ranging (LIDAR) systems have been used for this purpose in both mesospheric and ionospheric studies of the Earths atmosphere studying heavier neutral and ion metal number densities for species such as Fe and Fe^+ (e.g., see Alpers et al. 1990), Ca^+ (e.g., see Granier et al. 1985, 1989), K^+ (Eska et al. 1999), etc. These number densities are then tied into the altitude of the target via Rayleigh scattering measurements to calibrate the time of arrival of the photons. These studies integrate for 10 minutes or longer, but do not track the sky during this period of time. Since the densities of these species are so sparse (e.g. 3000 cm-3 for Fe) scanning the sky for shorter periods of integration are not possible with the current optics. The LIDAR system simply probes the sky directly above the detector.

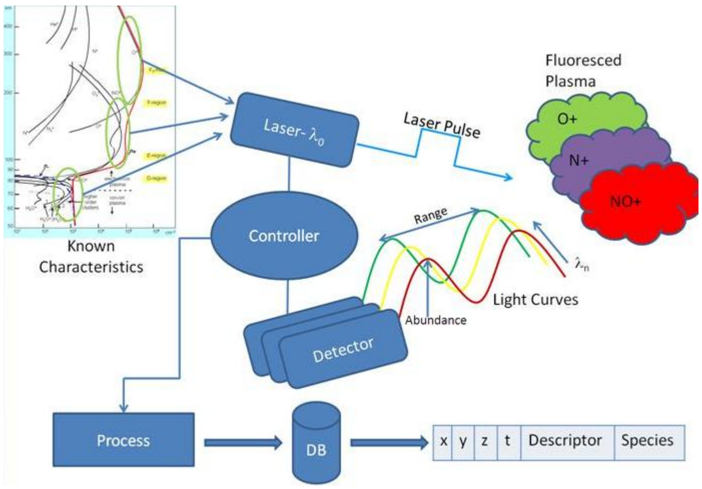

FIG. 2. The light induced fluorescence for detection and ranging (LIFDAR) illustrated concept.

The need for a scanning LIDAR system that uses active fluorescence spectroscopy for more abundant species (e.g. NO^+, O^+, N^+, etc.) is apparent for ionosphere awareness. Figure 2 shows a generalized description of a Laser Induced Fluorescence for Detection and Ranging (LIFDAR) system that scans the sky with the motion of the Earth's rotation. Species of interest are selected based on the known major contributors to the electron plasma (e.g. NO^+, O^+, and N^+) according to the plot on the left of Figure 2. The tuned laser wavelength used in the LIFDAR system is selected based on these species to excite their valence electrons to known higher available energy states. The photons that return are at longer wavelengths caused by the fluorescence of that species and are captured by multiple detectors tuned to wavelengths with high probabilities of energy state transitions from the excited energy state. Fluxes from these detectors are processed according to the Saha-Boltzmann equations and the amount of Rayleigh scattering from λ_0 for range calibration and number density calculations of the ion species and electron number densities. In order to scan the sky integration times need to be on the order of minutes. The associated optics for measuring the fluorescence needs to be on the order of 2 meter diameters (i.e. small telescopes). After processing the fluorescence fluxes, a database of the x, y, z, t, and density for a species of interest can be stored in a database for further analysis or visualization. An example operational view is given in Figure 3 for one particular LIFDAR site.

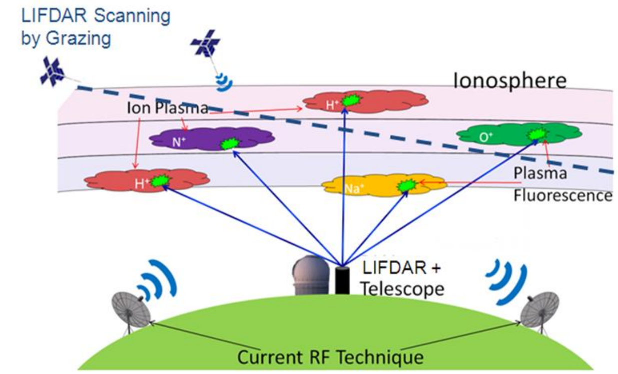

FIG. 3. The operational view of the LIFDAR concept from ground and space.

3. Better Ionosphere Awareness

Reliance on communication and GPS satellites for our daily activities is more dominant now than any time in recent history. Disruptions to these services from space weather events dramatically effect our daily activities as a consequence. The changes in the ionosphere due to increased solar activity that interacts with the Earth's magnetosphere cause most of the disruption seen in communications and GPS satellite services. An example of how GPS effects our daily lives is depicted in Figure 4 (courtesy of the December 2010 American Meteorological Society Space Weather GPS workshop final report). GPS is not only used for giving position accuracy on the Earth, but it is integrated into the vital services of the power, finance, and communication industries.

Many ongoing efforts endeavor to be aware of the current status of the electron plasma density and attempt to forecast future perturbations within the electron and ion plasmas within the ionosphere. Much of these efforts are based on the very physical concept that causes the disruption of the communication disruption: the plasma or critical frequency of the electron plasma in the ionosphere. As the plasma frequency increases, all communication and GPS signals that have RF frequencies less than or equal to the plasma frequency reflect off the ionosphere. Frequencies that are greater than the plasma frequency are subject to scintillation effects causing signal degradation and pointing errors. RF ground and space ionosondes and radiosondes use this reflection to their advantage by calculating the time it takes to bounce RF frequencies off the ionosphere to give an estimate of the plasma frequency, and ultimately the electron plasma density or total electron count (TEC). This method, however, can only be used to crudely identify altitudes of the cutoff frequency. Much of the ionosphere is then characterized by models that use this new data. The result often is represented like Figure 5. Notice that regions of high activity are large blobs overlaid on a global map.

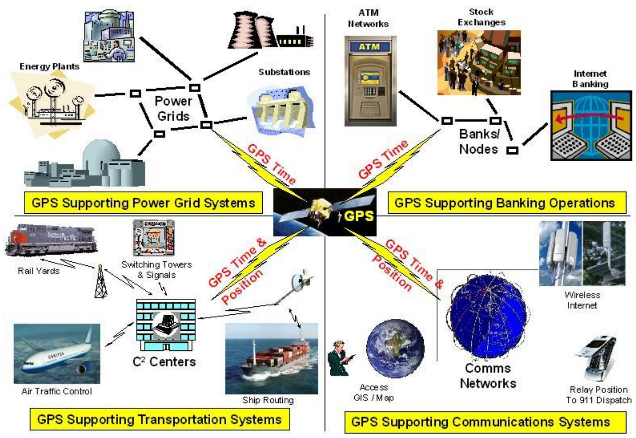

FIG. 4. An illustration demonstrating the dependence of GPS services on the power grid, banking, transportation, and communication systems courtesy of the December 2010 American Meteorological Society Space Weather GPS workshop final report.

In top panel of Figure 6 the same data is presented in 3D (via Google Earth). Notice that this interpretation has no texture or depth. On the bottom panel of Figure 6 is the electron density measured at Arecibo Observatory LIDAR facility during a 36 hour period for altitudes between 140 – 660 km. Notice that there is a lot of texture and depth in the bottom panel that is not seen in the top panel. Current RF sensing techniques of the ionosphere are missing information vital to the total situational awareness of the plasma environment. New LIDAR techniques (such as LIFDAR) are necessary for a better understanding of the status of the ionosphere.

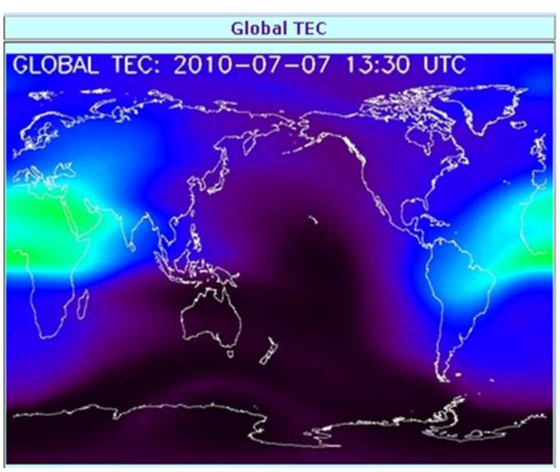

FIG. 5. The current total electron count (TEC) visualization map courtesy of Space Environment Technologies.

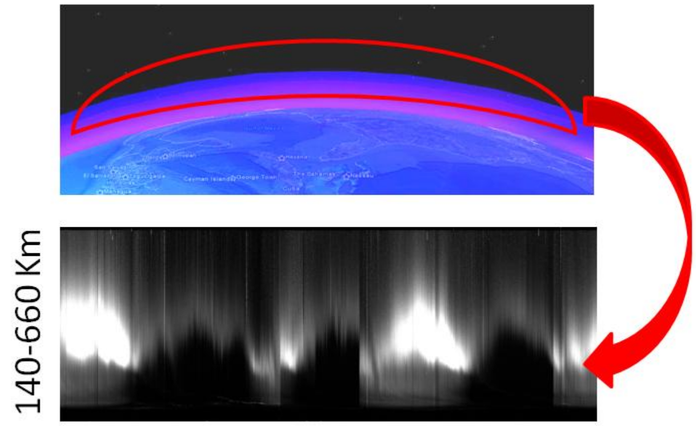

FIG. 6. The TEC of the Earth's ionosphere displayed on Google Earth using data from RF facilities (top), and the electron density courtesy of the Arecibo Observatory LIDAR database over a 36 hour period (bottom).

4. Conclusions

The LIFDAR concept will give unprecedented resolution of the Earth's ionosphere. By using laser induced fluorescence of ion species within the ionosphere plasma, 3D density maps of major contributing ion species plus electron densities will give a more in depth understanding and awareness during space weather events. Models that ingest this data will give better forecasts of hazardous events that cause disruptions to pointing, navigation, and timing applications (services such as communication, GPS, transportation, banking, etc.).

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REFERENCES

Alpers, M., J. Hoeffner, and U. von Zahn, 1990: Iron atom densities in the polar mesosphere from lidar observations. *Geophys. Res. Lett.*, **17**, 2345–2348.

Eska, V., U. von Zahn, and J. M. C. Plane, 1999: The terrestrial potassium layer (75-110 km) between 71 degrees s and 54 degrees n: Observations and modeling. *J. Geophys. Res.*, **104**, 17 173–17 186.

Granier, C., J. P. Jegou, and G. Megie, 1985: Resonant lidar detection of ca and ca(+) in the upper atmosphere. *Geophys. Res. Lett.*, **12**, 655–658.

Granier, C., J. P. Jegou, and G. Megie, 1989: Atomic and ionic calcium in the earth's upper atmosphere. *J. Geophys. Res.*, **94**, 9917–9924.