Science Motivations for a Modernized Global Fabry-Perot Interferometer Network

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Summary

The advances in Fabry-Perot interferometer (FPI) technology have been extensive and multi-
faceted over the past decade. Improvements in sensitivity are now feasible by one or two orders of magnitude. Stability of the FPI instrument is sufficient to make possible the measurements of vertical winds within the atmosphere with 1-2 m$^{-1}$ accuracy. The measurements of thermospheric winds from such FPI observatories are quite valuable for ingestion into Space Weather models for the purpose of forecasting ionospheric variability. However, the current state of FPI networking falls way short of what is feasible with current optical technology combined with broadband Internet access.
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1 Introduction

The motivation for a FPI network of observatories is three-fold. First, to assess the evolution of atmospheric dynamics for the mesosphere and thermosphere regions over physical dimensions ranging from small-scale, i.e., a few hundred meters, to large-scale, i.e., many thousands of km. Second, to provide the missing link in ion-neutral coupling that is represented by neutral dynamics in physical mechanisms. Third, to provide via real-time transfer of reduced observations of thermospheric dynamics to a central depository crucial results that may be ingested into models that are applied to generate Space Weather predictions thus mitigating the effects of ionospheric variability that degrade the accuracy of such predictions.

2 Motivation

The first aim described in the Introduction is based upon the new science regarding large scale structure for low-latitude or the polar region that the application of a global FPI network would study. For high latitude an example would be the twin cellular pattern of the polar neutral dynamics forced by ion convection. For low latitudes, an example would be the phenomenon of the convergence of tidal winds into the midnight sector generating the effects of the pressure bulge, the ”midnight collapse”, the midnight temperature maximum, and the ”brightness wave”. At the other extreme of the physical scale would be the microphysics involving ion-neutral coupling that can be studied with the combination of the AMISR radar and a network of several FPI instruments that would observe three line-of-sight components of the neutral wind vector in a common volume a few kms in size. Thus, such a network of the one or the other would represent the extension of CEDAR science studies to issues that were never before considered.

The second objective requires a bit more explanation and elaboration. As demonstrated in Figure 1 and Figure 2, the F-region ionosphere demonstrates a high degree of spatial and temporal variability from day to day on both local and global scales. It has been the aim of Space Weather models to predict and forecast these ”ionospheric weather” variations. It cannot be overstated the importance of such a capability as the ionosphere has a significant effect upon radio communications, navigation systems, surveillance systems, and power grids. The ionosphere is a strongly forced system with many agents acting at once: solar EUV illumination, the N₂/O composition ratios, the extent of auroral activity that governs the production of thermospheric gravity waves, auroral particle precipitation, and Lastly but not least, the direction and speed of the thermospheric neutral wind.

Figure 1: Global observations of changes in the total electron content determined from GPS ground-based observations. (from JPL web page).

All of these parameters are highly variable complicating the task of understanding and predicting the occurrences of these variations a great deal. We point out that it is the neutral wind parameter that has lacked attention in regard to the many issues pertaining to the fore-
casting of ionospheric weather. There is a vast amount of data pertaining to GPS observations of ionospheric densities that are being assimilated into Space Weather forecasting models. However, the role that thermospheric dynamics has in influencing the ionosphere is so great that even a little amount of data inputs from a sparse network of FPI observatories would go a long way toward obtaining significant improvements in these forecast results.

Figure 3 demonstrates quite vividly how the variability in the meridional component of the neutral wind would lead to changes in the F-region O\(^+\) density. Not only does the height of the ionosphere but also the magnitude of the topside electron density is linked closely to the direction and speed of the meridional component of the thermospheric neutral wind. Figure 4 illustrates an example of how a change in the meridional wind speed over the range of -100 m/s to 100 m/s can change the O\(^+\) ion density by nearly an order of magnitude for the topside region. Clearly, the thermospheric wind is an important parameter. Also, what is very clearly seen in this exercise is that the HWM representation of the winds as a function of the behavior of solar flux and magnetic activity is not nearly good enough to be a useful proxy for this parameter. The accuracy of Space Weather modeling would be much improved if it were possible to rely upon the ingestion of observations from a network of FPI observatories.

Figure 3: Cartoon illustrating how the field-aligned direction of the neutral wind vector interacting with the F-region plasma will shift the plasma to higher or lower altitudes. (from Jee and Schunk CEDAR 2003 talk)

Figure 4: a) O\(^+\) density profiles calculated from ionospheric models with various winds. b) comparison of measured height hmax with computed height for various winds and the variation with local time. Data used in this study was obtained with the Arecibo and Millstone Hill ISR instruments. (from Jee and Schunk CEDAR 2003 talk).

3 Networking of FPI Observatories - Large Scale Mapping

There are ten CEDAR FPI observatories that have been operating over the past few
years: Peach Mountains, MI; Millstone Hill, MA; Sondre Stromfjord, Greenland; Resolute, Canada; Poker Flat, AK; Mt. John, New Zealand; South Pole, Antarctica; Carmen Altos, Chile; Arecibo, Peru; and Arecibo, PR. Figure 5 illustrates the distribution of these sites; also shown are the sites for all-sky imaging systems and Michelson interferometers. Several European FPIs (not shown) are located in the Scandinavian sector near Kiruna and Svalbard. The results from these observatories have contributed to numerous advances of our understanding of the mesospheric and thermospheric dynamics over the past three decades for the equatorial, mid-latitude, and polar regions. The technology of these instruments varies from that of pressure scanning (Arecibo) to imaging (Carmen Altos, Millstone Hill, Sonde Stromfjord), to that of piezoelectric scanning (Poker Flat, Mt. John, South Pole). While these observatories have been doing interesting science by combining these results with those of other instruments such as the Sondrestrom radar and all-sky imaging, there has been no systematic effort to organize and combine these measurements with the intent of providing a more comprehensive and large-scale coverage of mesospheric and thermospheric winds.

3.1 polar latitudes

An early effort led by Tim Killeen described by Killeen et al. [1986] showed a comparison of thermospheric winds observed from the Dynamic Explorer satellite DE-2 with the averaged results obtained by ground-based observations from 7 FPI observatories: Laurel Ridge, Fritz Peak, Calgary, Kiruna, Svalbard, Alaska (1972), and Ann Arbor. This comparison is shown in Figure 6. Figure 7 illustrates the comparison of these results to that of the predictions of the general circulation model of the day: namely, the NCAR TGCM model. It is important to note that these observations were not made simultaneously and were averaged over measurements made in other seasons and in other years. Nevertheless, it was possible to show that the observations from the individual FPI sites were reasonably consistent with those observed with the DE FPI instrument for passes that took place in December 1981.

Figure 6: Comparison of DE-2 satellite observations with averaged results from ground-based FPI observatories listed: Svalbard, Kiruna, Alaska (1972), Calgary, Fritz Peak, Ann Arbor, and Laurel Ridge for the month of December, 1981 (From Killeen et al. [1986]).

Another paper of interest that illustrates the usefulness of combining FPI observations is that of Killeen et al. [1995] who analyzed FPI
Figure 7: Comparison of DE-II FPI observations of thermospheric winds with results from ground-based FPI observations and with model predictions provided by the NCAR TGCM model (From Killeen et al. [1986]).

observations from Sondre Stromfjord ($\Lambda = 74$) and Thule ($\Lambda = 86$) that were obtained between 1985 and 1991. Figure 8 illustrate the results obtained in which the polar structure of the high latitude thermospheric winds can be discerned. One can see indications of the two-cell structure of the polar convective pattern may be readily observed even with just these two stations located in the polar cap and auroral regions.

These papers represent a pioneering effort to coordinate FPI observations on a global scale that could be compared with the NCAR general circulation model predictions for thermospheric dynamics. Unfortunately, this early vision had never been fully implemented to the degree that today Internet technology would allow. The vision that we have in regard to a global FPI network would be achieved when FPI observations are funneled in reduced form and in real time to a central depository where the results may be ingested as part of the data assimilation of numerous data sets to produce forecast predictions of the ionospheric state of the upper atmosphere. This is the vision that is represented by Schunk’s leadership in developing the GAIM data assimilation model (GAIM stands for Global Assimilation of Ionospheric Measurements), which is largely based upon the ingestion of data from the networks of ionosondes and GPS receivers. It is not feasible to rely upon models such as the Horizontal Wind Model of Hedin et al. [1991] as this model is not sufficiently accurate or realistic for the needs represented by the GAIM application to the forecasting of Space Weather.

An exercise that was carried out by one of Schunk’s students, Mr. G. Jee, is rather interesting. The results shown in Figure 9 illustrate how much variability that might occur from changes in the thermospheric zonal wind component for several different longitudinal components. Before, we had emphasized how
changes in the meridional wind might affect the distribution of plasma in the F-region. Thus, this work also demonstrates that the zonal variability of thermospheric winds would also play a role in determining how the plasma is distributed in the F-region. This dependency upon the zonal thermospheric wind component complicates the problem of interpreting the results obtained from GPS determination of total electron content (TEC) and the LOFAR observations of plasma content that are expected to emerge in the latter part of this decade. It is clear from the consideration of GAIM results that even a limited contribution of the ingestion of FPI observations from a few FPI stations would be beneficial toward improving the accuracy of Space Weather forecasting of ionospheric weather. It should also be noted that additional FPI stations exist that are supported by international institutions. These stations are located in Norway, Svalbard, Brazil, and Japan. It should be quite feasible to include these FPI stations as part of the FPI network that we are projecting for the future.

Figure 9: Comparison of O+ profiles for different selections of HWM zonal wind speed for three different mid-latitude locations (from Jee and Schunk’s CEDAR 2003 talk).

3.2 low latitude - Midnight Temperature Maximum

The convergence of thermospheric winds at low latitudes at night produces an interesting phenomenon called the midnight temperature maximum (MTM), in which the temperatures at midnight exhibit a small peak, ~3-10% in amplitude. Its linkage with the simultaneous reversal of the thermospheric nighttime meridional wind near 01 LT was an important discovery that emerged from the analysis of incoherent scatter radar observations at Arecibo, Puerto Rico (18.6 °N, 75 °W) [Harper, 1973; Behnke and Harper, 1973]. Since this early work, the MTM phenomenon has been the focus of considerable experimental and theoretical research over the past three decades.

The technique of mapping the MTM neutral dynamics was first applied in the pioneering MTM work of Burnside et al. [1981] and Friedman and Herrera [1982], Figure 10 and Figure 11 present Fabry-Perot interferometer (FPI) observations that illustrate the dynamics and the localized heating of the MTM phenomenon. Figure 10 shows two examples of the meridional wind reversal together with the vertical wind inferred from the observed meridional wind gradient. Figure 11 (bottom) illustrates the MTM temperature increase observed with the Arecipua FPI at a low latitude site. The zonal wind variation shown in Figure 11 (top) presents also the MTM ‘camel hump’ structure discussed by Herrero et al. [1993] in which the MTM causes the abatement of the zonal wind as the MTM feature passes over the station. We note that the advent of the use of CCD detectors has improved the sensitivity of the FPI by nearly two orders of magnitude so that much more accurate measurements of these parameters can be obtained with this instrument.

There remains much to be learned about the MTM morphology and the tidal forcing mechanism believed to be the source of this feature, especially if a chain of FPI observatories could be applied to map the MTM wind, temperature, and airglow intensity disturbances as the tidal disturbance propagates in latitude from the geographic equator toward the poles. Motivation to renew research on the MTM comes from the realization that it provides a beautiful example of the importance of ion-neutral cou-
Figure 10: a) Two nights in 1980 showing the MTM meridional wind reversal observed with the Arecibo FPI. The mapping pattern used was a set of 8 azimuthal directions with typical measurement error of 25 to 35 m s\(^{-1}\) per direction after three minutes of integration. Negative values are southward. b) Calculated vertical winds based upon the measured meridional wind gradients shown in a). (From Burnside et al. [1981]).

Sampling at low latitudes, a region that is not at all well understood. None of the current physics-based numerical models reproduces the MTM phenomenon in which the interplay of the neutral dynamics with the background ionosphere is crucial. Clearly, the MTM represents an excellent test of current physics-based models and how well they simulate the low latitude ionosphere, a region of prime interest for Space Weather.

In the past decade, FPI technology has been revolutionized with the application of the imaging CCD detector. But there have been no MTM studies which incorporate the new FPI technology. To illustrate the expected improvement that the state-of-the-art instrument would provide, we expect that measurement errors would be reduced from \(~\pm 25\) m s\(^{-1}\) for horizontal wind speeds and \(~\pm 100\) K for temperatures [Burnside et al., 1981] to one tenth of this, i.e., \(~\pm 2-3\) m s\(^{-1}\) and \(~\pm 10\) K for a signal of \(~100\) Rayleighs and 3 minutes of integration. Moreover, these instruments would have the additional exceptional feature of portability enabling the support of campaign operations.

While the main scientific goal of a low latitude chain of FPI observatories is achieving a much better understanding of ion-neutral coupling, especially in how it relates to the MTM, there is an additional compelling objective. While abundant global datasets on plasma densities are being assembled from techniques.
such as tomographic inversion of GPS total electron content measurements, there is no equivalent set of measurements on the global distribution of thermospheric winds and temperatures, particularly those that can be collected and analyzed in real time. We further expect that the FPI measurements can be reduced and the results transmitted to a central depository in real time. The inputs from a network of such FPI observatories could be ingested into global thermospheric forecasting models to predict thermospheric/ionspheric "weather". Figure 12 illustrates the distribution of a meridional chain of FPI observatories located in South America that is expected to be operating by mid-2005, in support of the C/NOFS Air Force satellite that is designed to improve our study of low latitude plasma instabilities. The three FPI observatories planned for Talara, Huancayo, and Cerro Tololo are undergoing construction or testing, and deployment to these locations should be completed by June, 2005.

4 Networking of FPI observatories - Small Scale Structure

NSF will shortly be establishing one or more new incoherent scatter observatories, based on the AMISR concept. Briefly, AMISR will use phased-array radar technology that allows beam steering over the entire field of view within milliseconds. The key science issue that can be addressed by this agile pointing (the main strength of AMISR) is clearly the small-scale spatial structure and temporal evolution of the parameter fields measured by the radar.

There is tremendous synergy between the AMISR initiative and the new capabilities that all-sky imaging provides for Fabry-Perot instruments; the all-sky mode allows an FPI to map spatial structures in wind and temperature fields. Figure 13 below shows $\approx 3$ hours of all-sky images of the Doppler temperature field over Poker Flat, derived from 557.7-nm emission spectra. Prominent arcs of both elevated and depressed temperature correspond to auroral arcs of varying characteristic energy.
co-located AMISR radar could map the three-dimensional structure of the arcs that generate these signatures.

Figure 13: All-sky maps of 557.7 nm Doppler temperature above Poker Flat over a ≈3-hour period (from Mark Conde, private communication).

It is also possible to map vector winds based on all-sky observations of Doppler shifts as seen in Figure 14. However, a single station can only observe one component of what is, in reality, a three-component wind field. Inferring the two-dimensional horizontal vector wind involves gross assumptions regarding the underlying three-component velocity field. One such assumption is that the thermospheric wind field is relatively invariant to local time changes over a time period of 30 minutes. Such assumptions were necessary to generate Figure 14, but clearly, for times of vigorous activity, this assumption will not hold.

While these assumptions are often reasonable, the most interesting cases are when the atmosphere is highly disturbed and the assumptions break down. However, it is possible to map the actual three-component wind field above an AMISR radar site without any assumptions. This would require three all-sky Doppler mapping FPS instruments, located in a triangular array, with overlapping fields of view above the radar. It is now straightforward to make such instruments portable, so that they could follow the AMISR radar deployments. Alternatively, they could be fielded individually, at widely separated sites, in support of the global wind measurements discussed above.

Figure 14: Horizontal F-region vector wind field inferred from all-sky maps of 630.0-nm doppler shift. The background image shows the location of the aurora at this time, based on images from two ground-based all-sky cameras. (from Mark Conde, private communication, December, 2003).
References


