Mesospheric and Lower Thermospheric (MLT) Tide Studies Using the Ground Based Fabry-Perot Interferometer (FPI) and other passive optical instruments

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1. Overview

The goal of this part of the report is to briefly review current understanding of the MLT tides and to evaluate past passive optical observations of the MLT tides in winds and temperature and to examine how these measurements (mainly by FPIs) can contribute to the future understanding of MLT dynamics. These tides are the most prominent dynamical feature of the region. They are global scale waves with periods of integral fractions of a day (24, 12, 8, 6 hours etc.). Understanding of MLT tides is the key to the insight of energetics and dynamics of the region. These understandings will in turn provide insight into the influences of the troposphere and stratosphere from below and the magnetosphere and ionosphere from above. The mesosphere is also the link between the troposphere and stratosphere to atmosphere to the space. It is the least explored region of the Earth’s atmosphere. Furthermore, it is important because changes in the mesosphere may be the precursor or indicator of profound changes in the troposphere and stratosphere.

Because of the long history of the observational and modeling studies in the stratosphere and mesosphere, much progress has been made in understanding MLT tides [Forbes and Garrett, 1979; Vial, 1989, Vial and Forbes, 1989; Forbes, 1995; Hagan, 2000]. Yet, the fact remains that our knowledge of the MLT dynamics is still very limited. Tidal wave observations often fall short of providing a comprehensive view of the tides due to waves’ global and fast varying nature. This has been one of the reasons hampering further progress in this important area of research. Among the various instruments used to study tides, Fabry-Perot interferometer (FPI) and other passive optical instruments have provided important neutral wind and temperature measurements. While satellite based FPIs have often been in the spotlight (e.g. UARS HRDI and TIMED TIDI), it was the ground based FPI instruments that lay the technical and scientific foundation. With new advances in detector, computer, and network technologies, we see great potential for a future ground based global network of FPI and other passive optical instruments to address many of the pressing issues in the MLT dynamics. To understand how such a passive optical instrument network can contribute to the study of tides, it is helpful to highlight our current understandings of tides in the context of past FPI and other optical observational results. We emphasize the US funded projects and studies involving US scientists. We should point out that similar projects have also been carried out in other countries.
2. Migrating and Non-migrating Tides

Tides can be divided into two major categories: migrating and non-migrating tides. The migrating tides, often the strongest, are forced by the absorption of the solar UV radiation by the stratospheric ozone and the absorption of solar IR radiation by lower atmospheric water vapor. Consequently, they are sun-synchronous and propagate in a westward direction. In other words, the migrating tides are dependent on local time and independent of longitude and universal time. When tides propagate vertically, energy transferred from the lower atmosphere to the upper atmosphere, while the phase of tides progresses downward. It should be pointed out that there are also in-situ tidal sources in the upper atmosphere, although they are very weak.

Non-migrating tides include any tides that are not sun-synchronous, so they can propagate either eastward or westward with a variety of phase speeds (zonal wavenumbers). They can also be zonally symmetric. The sources for the non-migrating tides are less well understood than those of the migrating tides. Latent heat release and non-linear interaction between the migrating tides and planetary waves are among the possible causes for non-migrating tides. The presence of non-migrating tides introduces longitudinal and temporal variations other than those related to the local time. To separate migrating and non-migrating tides, measurements at multiple longitudes are needed. Current observational programs lack such capabilities.

3. Tide interactions with gravity waves and planetary waves

The sources of tides are in the stratosphere or troposphere. In order to conserve energy as tides propagate upward to the MLT, their amplitudes grow as the air density decreases. However, such growth will not go on indefinitely. In the lower thermosphere, tides are dissipated by molecular viscosity and ion drag. Tides can also dissipate in the middle atmosphere and observed tidal amplitudes are determined by both forcing and dissipation. While the solar forcing changes slowly with the season, there are many other factors related to the tidal dissipation, some of them may vary quickly. Gravity waves play an important role. Modeling the effects of the gravity waves continues to be a challenge. No global model has the spatial resolution to describe gravity wave induced variations. Hence, parameterization is used in all models. In some gravity wave parameterization scheme [Lindzen, 1981], gravity wave activity can interrupt the propagation of tides and damp the tidal amplitude, whereas in other schemes [Hines, 1997a; 1997b], gravity waves appear to enhance tidal activity. Thus, the question of how gravity waves affect tides is still unanswered.

Tides also interact with planetary waves producing secondary waves including non-migrating tides. The secondary waves have periods slightly off the tidal periods depending on the period of the planetary wave involved. If the planetary wave is a stationary wave, then the secondary wave still has a period of the tide, only the zonal wavenumber is altered and the resulting wave is a non-migrating tide [Forbes et al., 1995].
4. Classical Tidal Theory

Although, far from the state of the art, the classical tidal theory explains some of the basic features of MLT tides with isothermal and zero zonal wind assumptions. In the classical tidal theory, the tidal motion equations are simplified by describing temporal and longitudinal variations with known tidal frequency and zonal wavenumber and separating temporal, vertical, and longitudinal dependences. The latitudinal variation is then governed by the Laplace tidal equation. The solution to the Laplace equation can be decomposed into a complete orthogonal eigen set of latitudinal Hough modes [Chapman and Lindzen, 1970]. The Hough mode eigen values (Lamb’s parameter) are dependent on the zonal wavenumber and wave frequency. They are also directly linked to the vertical wavelengths through the vertical equation parameter: the equivalent depth. Not all Hough modes can propagate. Often those gravest modes (with fewer nodes in the latitude) are the dominant modes. Longuet-Higgins [1968] has tabulated various modes in great detail.

The Laplace equation has singular points, which can affect its solution profoundly. For the diurnal tide, there is a singular point near 30° latitude. Consequently, most of the diurnal tide modes are limited to latitudes between 30°N and 30°S. Other well-known singular points for many modes are the poles. Hence, many migrating tide modes have zero value at the poles. For vector parameters, like neutral wind, only the zonal wavenumber one mode has non-zero values at the pole. For scalar parameters like temperature, only the zonal wavenumber zero mode has non zero value near the pole. These modes are mostly non-migrating tides. Hence, at high latitudes, the migrating tides are suppressed by the polar singular point and non-migrating tides with special zonal wavenumbers become significant.

5. Numerical Tidal Models

Contemporary modelers all use various numerical tidal models to study tides [e.g., Hagan and Forbes, 2002; 2003]. Recent work in this field is summarized in a review paper by Hagan [2000]. The most recent numerical tidal model: the Global Scale Wave Model 2002 (GSWM02) [Hagan and Forbes, 2002; 2003] has include many important features. The model is 2-dimentional, linearized, steady-state model extending from the ground to the thermosphere. The model solves the linearized and extended Navier-Stokes equations for the perturbation fields with a set of zonal wavenumbers and frequencies. The model includes the mean zonal field from the UARS HRDI measurements and also uses a zonal mean background atmosphere from the MSIS90 model. More importantly, the latest model also includes the forcing due to latent heat release associated with deep tropospheric convection. The model uses 13 components in the zonal wavenumber field to provide migrating and non-migrating tidal amplitudes and phases. The large number of combined migrating and non-migrating tide component outputs poses a challenge to observational programs that are trying to verify these results. A brief review of the past FPI observational results in the following sections will help to access future needs.
6. Low Latitude Tide Observations
Most of the US funded FPI systems at lower latitudes (less than 20 degree), such as these from Arecibo and South America, are used for equatorial upper thermosphere and ionosphere studies. Thus, unfortunately, there are no MLT tide results from these ground based FPI instruments in this important region.

7. Mid-Latitude Tide Observations
There have been several mid-latitude FPI observations of semi-diurnal tides. Hernandez et al. [1995] used combined two-emission (OH and O 5577Å) ground-based FPI and satellite airglow observation to determine the vertical wavelength of the 12-hour wave at Mount John (44° S). They were able to examine the seasonal variation of the vertical wavelength of the 12-hour wave in the mesosphere and found large vertical wavelength in the winter and fall seasons. Using Fritz Peak (40° N) FPI 5577 Å emission measurements from the east and west pointing directions (separated by 6 degrees in longitude), Hernandez [1995] estimated the zonal wavenumber of the 12-hour wave and was able to determine that wave was westward propagating and with zonal wavenumber around 2 meaning that the wave is a migrating semi-diurnal tide. He, however, was not able to exclude the zonal wavenumber 3. Because of the small separation between the two sampling points, there is a large uncertainty in the result.

Niciejewski and Killeen [1995] examined the seasonal variation of the semi-diurnal tide amplitude and phase using two-emission (OH and O 5577Å) FPI observations at Peach Mountain (42° N). They noted large amplitudes during the spring and fall equinoxes. It should be noted that Wu and Killeen [1996] studied the seasonal variations of gravity wave occurrence at the same location and found that gravity wave activity peaks in the summer (when the semi-diurnal tide amplitude is smaller). Whether there is a connection between the gravity wave and semi-diurnal tide seasonal variations is a logical follow up question. There are so many possibilities. Gravity wave propagation can be affected by the tide. Gravity waves can also suppress or enhance the tide according to different GW parameterization schemes. The results seem to support notion the GW suppress the tide. Furthermore, seasonal changes of the tidal amplitude are dependent on solar forcing and many other factors. A single station observation probably will not tell us much. However, a multi-station network certainly can provide much information on this important issue. Moreover, multi-station measurements can provide much better estimate of the zonal wavenumber than what single station can do [Hernandez, 1995].

Mid latitude MLT region temperatures appear to show that the 8-hour oscillation is strongest during spring and fall seasons, [Taylor et al., 2001; Pendleton et al., 2000; Taylor et al., 1999]. Multi-station observations of temperature mapper and lidar appear to show the 8-hour is the migrating terdiurnal tide, however, the large uncertainty precluded a more definitive answer. [Taylor et al. 1999]. The 8-hour wave phase shifted 180 degree from spring to fall.
8. High Latitude Tide Observations

At high latitude, FPI observations have provided valuable information on mesospheric dynamics. Using an FPI at the South Pole, Hernandez et al. [1993] observed a 12 hour wave, which was considered the zonal wavenumber one non-migrating tide. Forbes et al. [1995] suggested that the non-migrating tide may be a result of non-linear interaction between the semi-diurnal migrating tide and a stationary planetary wave. At Resolute (75° N) the 12-hour wave was often observed in the OH emission neutral winds by an FPI [Fisher et al. 1999; Fisher et al., 2002; Wu et al., 2003]. Wu et al. [2003] used combined observations of two FPIs and an ISR from Eureka (80°N), Resolute (75°N), and Tromso (70°N), respectively, to examine the latitudinal variation of the 12-hour wave and found the amplitude of the 12-hour wave drops faster with latitude than models predict for a semi-diurnal migrating tide, which goes to zero the pole. The results appear to suggest that the 12-hour wave will go to zero well short of the pole. The uncertainty arises from the fact that at each latitude, there is only one station. If a non-migrating tide was involved then there is longitudinal variation in addition to the latitudinal variation. At 75° N, it unclear whether the 12-hour period wave is the semi-diurnal migrating tide or the non-migrating zonal wavenumber one wave. Without more multi-station observations further progress in the future will be difficult.

Won et al. [1999] used two FPIs at Thule Air Base (76.5° N) and Sondrestrom (67° N) to study the semi-diurnal tide in the O 5577Å emission winds. The greenline is more difficult than the OH emissions to analyze because of possible contamination from the higher thermospheric emission of the same line. Won et al. [1999] used the O 6300 Å measurement as a base to estimate the diurnal component of in the neutral wind, which is most likely from the upper thermosphere. They removed the diurnal component from the greenline emission neutral winds and thus removed the contribution from the upper thermosphere. The seasonal averaged semi-diurnal tidal amplitude and phase are, for most part, consistent with the Forbes and Vial [1989] model and ISR observations at Sondrestrom [Azeeem and Johnson, 1997]. While there is little inter-annual variability at Sondrestrom, such variability at Thule can be quite large. It is possible that the non-migrating tide may have contributed to the inter-annual variability.

Besides the 12-hour wave, a 10-hour wave was also observed in both the southern and northern polar region by FPIs [Hernandez et al, 1992; Hernandez et al., 1996; Wu et al., 2002]. Hernandez et al. [1992] suggested that it may be a Lamb wave based on its large vertical wavelength, whereas Wu et al. [2002] believed that the wave maybe a result of a non-linear interaction between the semi-diurnal migrating tide and quasi-two day wave. They made this determination on the basis of apparent high zonal wavenumber (~5) and short vertical wavelength of the wave in their observations. Based on a numerical model, Mayr et al. [2003] suggest the 10-hour wave maybe a planetary-scale inertio gravity wave with zonal wavenumber 4. The observation by Wu et al. [2002] was not accurate enough to differentiate between zonal wavenumber 5 and 4. Thus, this issue
requires further study with more accurate measurements from a longitudinal and latitudinal chain in the high latitudes.

Past observations also show high occurrences of 8-hour, 6-hour, and 4-hour waves in MLT temperatures at high latitudes [Won et al., 2003; Oznovich et al., 1995; Oznovich et al. 1997a; 1997b; Walterscheid and Sivjee, 1996; Sivjee and Walterscheid, 1994; Walterscheid and Sivjee, 2001]. Most of these waves are likely to be the zonally symmetric non-migrating tides. Using two-station observations, Won et al. [2003] were able to provide strong evidence to support the notion that the 4-hour wave was a zonally symmetric oscillation.

Early studies on the 8-hour oscillation eta value appear to show inconsistent results. Model calculations [Schubert and Walterscheid, 1991; Walterscheid and Schubert, 1995] showed that phase of the eta value should be positive for the terdiurnal tide, whereas various early observations summarized by Taylor et al. [2001] all showed negative phase for the 8-hour oscillation. This is still an unsolved issue.

9. Future Network

The common problem in the previous mentioned observational results is the lack of a coordinated observational effort. Measurements from a few stations are used to address what is a multifaceted global scale phenomenon resulting in many uncertainties. Tides are global scale waves with complex vertical, latitudinal, longitudinal structure, and short-term, medium-term, and long-term variations. A comprehensive understanding of tides requires long-term detailed observation and study of their various aspects. To examine the vertical structure such as the vertical wavelength and damping, measurements at multiple altitudes are needed. To resolve various tidal modes, data from many latitudes are required. To separate the migrating and non-migrating tides, a longitudinal chain is called for.

Of course ground-based FPI and other passive optical instruments are not the only kind of the instrument can provide measurements in the MLT region. How does the ground based FPI compare to other ground based active instruments and space borne FPIs?

Ground Based Fabry-Perot Interferometer Pros and Cons in comparison with other type of instruments:

Pro:
1. Relatively inexpensive,
2. High automation level,
3. Longer nighttime observation (compared to LIDAR),
4. Less power consumption than LIDARs and radars,
5. Multi-height observations,
6. Good local time coverage compare to satellite based instruments,
7. Simple data analysis procedures with fewer assumptions (compared to radars)
8. Easy estimation of measurement uncertainty,
9. Measurement accuracy can be improved by upgrading the instrument (larger etalon, high detector QE, high filter transmittance) unlike the meteor radar, which is limited by the number of meteor echoes.

10. Easily deployable.

Cons:
1. Uncertainties to the airglow peak height,
2. Most of the system works only during nighttime and under good weather.
3. Cannot provide high resolution wind and temperature profiles.

Compared to a LIDAR or an incoherent scatter radar, the information that can be obtained by an FPI or other passive optical instruments is limited. For example, a state of art sodium LIDAR can provide day-night high resolution wind and temperature profiles. An FPI, for example, can only provide mostly nighttime winds and temperatures at a few heights. However, for the cost of one LIDAR, one may build and operate many FPIs to provide much more extended latitudinal or longitudinal coverage for resolving the horizontal structure of the tide. Moreover, an FPI usually has will have a better time coverage because it will be turned on every night automatically. These advantages make FPI an ideal instrument for forming a network. Overall there is a need for a balanced approach: using LIDAR to obtain detailed atmospheric profiles at a few important geographic locations, while deploying many FPIs and other passive instruments to provide a global or large regional coverage at a few altitudes. This approach will allow us not only see the whole forest but also have a detailed view of trees in the forest.

Compared to MF and Meteor radars, FPI wind can provide much more consistent winds at relatively high temporal resolution. MF and Meteor radar wind often require averaging over a long time period (~ hour). FPI can also provide temperatures without making too many assumptions. Wind errors are easily estimated. A high capacity FPI can measure wind variations at time scales on the orders of minutes not hours. Moreover FPI also can provide upper thermosphere winds. This is not to say that FPI is better in every aspects. Radars can provide wind profiles and daytime measurements. For long term variations radars are more suitable instrument. For fast variations, FPIs are more appropriate. New FPIs should be more portable than the radars.

### 10. Issues important to the MLT tidal studies

**Low Latitude region**

At lower latitude, in addition to tides, there are various other equatorial waves and long-term oscillations such as the SAO and QBO. It will be important to examine how these waves and long-term oscillations interact with tides. Non-migrating tides are also important topics. Since numerical models (e.g. GSWM02) have been improved to provide non-migrating tides, observational efforts should match the capabilities of the model in order to make further progress. Garcia [2000] examined the importance of various equatorial waves to the SAO and noted the need to understand waves with zonal wavenumber 4-25, which will require even more longitudinal samplings to observe.
Mid latitude region
Gravity wave and tidal interaction is an important issue. Past combined observations at Peach Mountain with an imager and an FPI are an effective way to examine the connection between GWs and tides. Gravity wave seasonal variations may not be same at all longitudes. All sky camera observations near Rocky Mountain region do not appear to show the same seasonal variability as near Peach Mountain [Private Communication B. P. Williams]. Long-term combined observations at different longitudes are needed to address the issue.

High latitude region
In the high latitude region, FPIs and other passive optical observations of tides are limited to a few stations. To determine the 12-hour is a non-migrating tide or migrating tide requires multiple stations at the same latitude and different longitudes. Moreover, it is still not clear how far the 12-hour non-migrating \( (s=1) \) tide extends from the pole. Longitudinal chains at several latitudes are needed.

11. Collaborations with TIMED, AMISR, and LIDAR

It is clear that ground-based optical instrument such as the FPI can do a great deal, but probably not enough to address many important issues of the MLT dynamics if used alone, collaborative studies with other instruments are crucial.

In tidal studies, satellite instrument like TIDI can provide global coverage at limited local times everyday that cannot be matched by ground-based instruments that are restricted by landmass distribution. Yet because the satellite coverage is limited to a few local times everyday, aliasing is major problem for tidal analysis. Often long time periods are needed to accumulate enough local time samplings to determine tidal amplitudes. Day-to-day tidal variability often caused great uncertainties. Ground-based instruments like FPI can provide invaluable local time coverage to shorten the time period needed to determine the tidal parameters. A latitudinal chain of ground-based instruments will be a great complement to satellite measurements.

Incoherent scatter radars such as AMISR are great instruments to study the upper atmosphere and ionosphere, particularly the magnetosphere and ionosphere coupling and ion-neutral coupling. ISR radars can provide altitude profiles of many important parameters including neutral winds to heights FPI cannot measure. And it has been and will be an important tool to analyze tidal propagation and dissipation. Combined FPI and ISR observations will be of great benefit to ionospheric, magnetospheric, thermospheric, and mesospheric studies. Upper thermospheric neutral winds from the FPI can be used to calculate the Joule heating in the high latitudes. A distributed FPI network can provide large regional coverage of tidal waves, while ISRs provide measurements over a great altitude range. Similar scheme should also work in collaboration with LIDAR instruments.
12. Summary
FPI and other optical observations have made great contributions to the understanding of MLT tides, along with other observations. The contribution can be even greater if a coordinated observational program consisting of the several latitudinal and longitudinal chains can be formed. From equatorial region to the polar region, such chains can address many important issue related to the MLT energetics and dynamics. More specifically, these chains should be able to separate migrating and non-migrating tides at several latitudes, to provide tidal amplitudes variations with shorter time periods, to have better latitudinal coverage (one sampling point, perhaps, every 10° latitude). New technologies in detectors should allow the FPI to be more compact and have even higher automation to provide better accuracy at even lower cost. We see great potential for such a coordinated observational program to advance our understanding of the MLT region dynamics.

Acknowledgements
Many helpful comments are provided by Dr. A. Burns and Dr. M. Hagan.

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