An Apochromatic Lens Based Fabry-Pérot Interferometer for Accurate Measurements of Lower Thermospheric Neutral Wind Velocity and Temperature

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ABSTRACT SA33B-3155

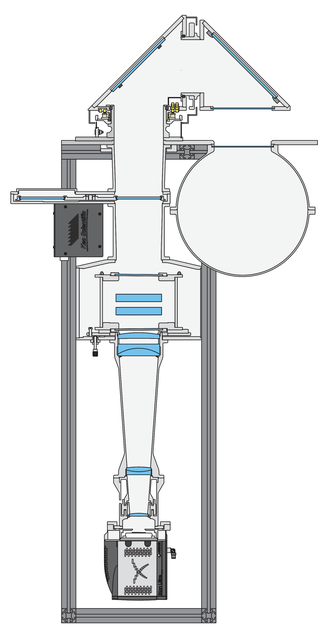
Fabry-Pérot interferometry is a well-established method of interrogating the lower thermosphere region of the Earth's atmosphere. Nighttime measurements of visible and infrared airglow in four cardinal directions and Zenith are inverted to yield wind speed and direction as well as temperature. A 300 mm focal length lens images ring patterns on a deep-cooled CCD achieving 11 full rings on the 13.3 mm square sensor in our instrument. The Fabry-Pérot Interferometer structure is based on a legacy design which passes emissions through a narrow-band filter, an etalon, and a focusing lens to image onto a CCD focal plane array, in contrast to traditional interferometers which often rely on telecentric filtering with complex optical arrangements prior to the light entering the etalon. The quality of the ring pattern greatly influences the residual error of processing the raw data into derived quantities. Our new instrument employs a novel apochromatic lens system developed at Keo Scientific that yields lower vignetting and sharper rings over an extended wavelength range, enabling higher quality measurements over the entire range of wavelengths. Examples of ring patterns and derived quantities from our first f/3, 100 mm diameter etalon instrument are presented here. The instrument was first deployed in July, 2019, by the Chinese Academy of Sciences Institute of Geology and Geophysics at their field-station in Mohe, Heilongjiang in Northern China.

FABRY-PÉROT INTERFEROMETRY AND AERONOMY

Fabry-Pérot interferometry for sensing Doppler winds and temperatures from thermospheric airglow is a well established technique. Wavelength shifts and spectral broadening of airglow emissions impart changes to the ring pattern produced by the Fabry-Pérot interferometer as recorded with a focal plane sensor. The image of the rings produced by the airglow emissions is compared to a calibration image, produced by diffuse 632.8 nm light from a local source, so that the shifts and broadening can be quantified relative to a known stable reference to determine velocities and temperatures. Narrow band filters, in a filter wheel, preceed the etalon to isolate the desired spectral feature to be measured. Airglow emission intensities are faint enough that long integrations of several minutes must be employed to gather enough signal to make reasonable measurements. Increasing the aperture of the instrument improves the temporal cadence of the derived velocities and temperature. As the aperture increases, the speed of the focusing lens must increase, which leads to an increase in aberrations. Our lens design replaces the traditional achromatic lens used in FPI instruments and provides an improvement of the quality of interference rings recorded by the sensor, leading to more accurate or higher-cadence derived quantities.

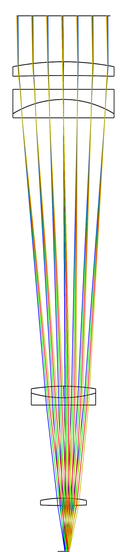
FPI DESIGN LEGACY AND CURRENT APPROACH

There are two legacy architectures of Fabry-Pérot interferometers for aeronomy research: a telecentric optics arrangement and a far field source arrangement. The telecentric designs focus the incoming fields normal to the filter. The light must be collimated again prior to passing through the etalon. In the far field source arrangement, the light from the source is passed through the filter assuming that the distance travelled from the source guarantees adequate collimation. Our optical design has a filter, etalon and lens. Since we do not use telecentric optics we have better overall throughput and uniformity, but our design requires a larger diameter filter than the telecentric type. An articulated mirror assembly is used to sample the four cardinal directions at 45° elevation, the zenith direction and the calibration source.



The FPI cross section shows how the components fit together. The major components are the sky scanner (top), calibration sphere, filter wheel, etalon, lens, and Andor EMCCD camera.

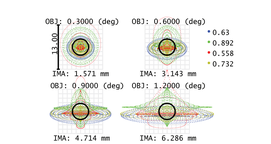
The ZEMAX raytrace of the apochromatic lens design shows the optical path starting beneath the etalon. This lens has 6 elements in 4 groups, with a focusing mechanism on the last lens before the sensor.



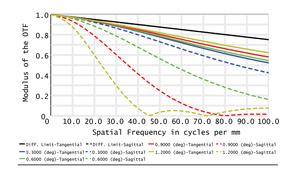
INNOVATION - IMPROVED CHROMATIC PERFORMANCE

The quality of the derived thermospheric velocity and temperature is related to the shape of the recorded ring pattern relative to the ideal Airy function shape. A single achromatic lens was used in a previous version of this instrument, but residual image curvature and axial chromatic aberration contributed performance degradations. An apochromatic lens, with 6 elements in 4 groups, provides a flat image plane with excellent chromatic aberration performance.

The distortion and lateral chromatic aberration of the lens are important to the raw data inversion, where calibration images are captured when the instrument is illuminated with diffuse 632.8 nm laser light. It is important that the calibration rings conform to the Airy function spacing, and this spacing conformity is necessary for all observation wavelengths since they are relative to only one calibration wavelength. This allows accurate data inversion at all observation wavelengths. The recorded lineshape from the calibration source is also used to remove systematic degradations introduced into the data from residual aberrations.

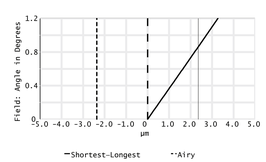


Spot Diagram

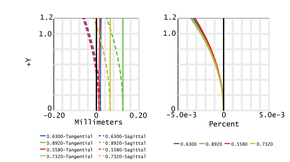


Diffraction MTF

The circles in the spot function diagrams and the black line in the MTF plot represent the diffraction limit at 630 nm. The optical system was optimized for tangential performance, to guarantee thin rings, since the spot radius along the rings will not adversely affect the data inversion to physical quantities.



Lateral Color

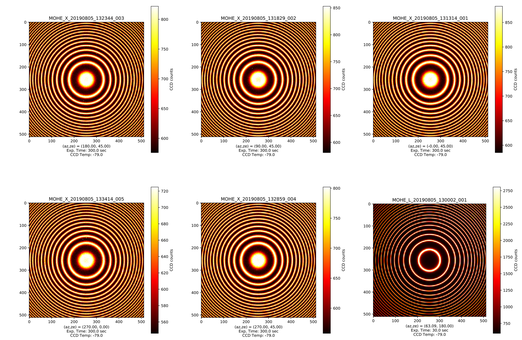


Field Curvature Distortion

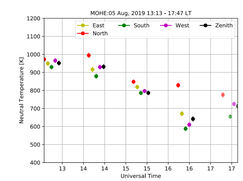
The residual lateral chromatic aberration is just over 3 µm from the center to the edge of the image over the 550 to 900 nm wavelength range. Residual distortion is approximately 0.0035% (~0.2 µm) from the center to the edge of the image. This error is equivalent to about 15% of one 2x2 binned pixel (26 µm).

DERIVED TEMPERATURE AND WIND VELOCITY

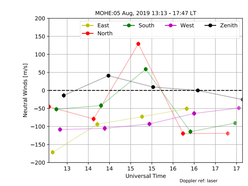
Shown below are a series of images acquired at the Mohe field site on August 5, 2019. The six images are five sky observations at 630 nm and one image of the calibration light. These images represent typical data collected by this instrument.



Temperatures and winds derived from the raw data above are shown in the following graphs.

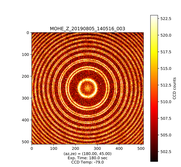


Neutral Temperature, OI 630 nm



Neutral Wind Velocity, OI 630 nm

The ring pattern to the right is from emission at 892 nm. Note the sharp resolution of the two lines of this doublet. An inversion algorithm for this wavelength has to account for both emission peaks in the ring pattern.



CONCLUSION

The FPI described in this poster was deployed in July 2019 at Mohe, China, where it has been operating and collecting data. The design of the optics has been described here and shows potential to improve the quality or cadence of the derived temperature and neutral wind velocity of the upper thermosphere. We will follow up with an analysis of the data quality and quantify the improvement in the coming year.