# Doppler Asymmetric Spatial Heterodyne Spectroscopy (DASH): An innovative concept for measuring winds in planetary atmospheres

Christoph R. Englert[a], John M. Harlander[b], David D. Babcock[c],
Michael H. Stevens[a], David E. Siskind[a]

[a] E. O. Hulburt Center for Space Research, Naval Research Laboratory, Code 7641,
4555 Overlook Ave, SW, Washington DC, 20375, USA
[b] St. Cloud State University, Department of Physics, Astronomy and Engineering Science,
720 4th Avenue South MS-315, St. Cloud, Minnesota 56301, USA
[c] Artep, Inc., 2922 Excelsior Springs Ct., Ellicott City, MD 21042, USA

Keywords: Wind, atmospheric dynamics, Doppler imaging, Spatial Heterodyne Spectroscopy, Michelson Interferometer, planetary atmospheres

## ABSTRACT

We introduce an innovative concept for inferring altitude profiles of horizontal wind in planetary atmospheres by measuring the Doppler shift of multiple emission lines versus altitude. Instruments using this approach will be especially well suited for interplanetary missions because they will be compact, rugged, and lightweight while minimizing power consumption and maximizing sensitivity, all without moving parts.

## 1. INTRODUCTION

Atmospheric wind measurements are common and routine in the Earth's troposphere. However, in the higher altitudes of the Earth's atmosphere and especially in the atmospheres of other planets, wind measurements are much harder to obtain and not commonly available. The need for higher altitude atmospheric wind measurements on Earth is typically derived from the desire to understand the atmospheric dynamics and energetics with the ultimate goal to improve weather forecasts and constrain global scale models[1]. As for planetary atmospheres, Mars is now a high priority for the National Aeronautics and Space Administration's (NASA).[2] Mars wind measurements will, for example, be important to plan aerobreaking and aerocapture maneuvers, as well as the safe entry, descent and landing (EDL) of spacecraft.[3]

A proven way of measuring horizontal atmospheric winds is to observe the Doppler shift of atmospheric emission lines from a satellite using a limb viewing geometry.[4,5,6] In order to measure wind speeds with useful precision (10m/s or better), the challenge is to measure the position of one or more Doppler shifted lines within 1/30,000,000 of their wavelength or better.

To date, very few instruments have been built and launched to measure horizontal atmospheric winds in the Earth's middle and upper atmosphere using a Doppler technique. Examples are: The Wind Imaging Interferometer[4] (WINDII) a stepped Michelson Interferometer, the High Resolution Doppler Imager[5] (HRDI), and the TIMED Doppler Interferometer[6] (TIDI) both using Fabry-Perot interferometers. No Doppler wind instrument has ever been part of an interplanetary mission.

In this paper, we introduce an innovative concept for inferring horizontal wind profiles from orbit, also using the Doppler shift of emission lines versus altitude. This new concept is especially well suited for interplanetary missions because it allows compact, rugged, and lightweight instrument designs maximizing sensitivity, all without moving parts. In the following we present the heritage of space borne wind instrumentation and the basic concept of the Doppler Asymmetric Spatial Heterodyne (DASH) technique. We subsequently discuss the challenge of instrumental drifts (zero wind reference), and report the results of a simple laboratory demonstration of the DASH concept.

Atmospheric Optical Modeling, Measurement, and Simulation II, edited by Stephen M. Hammel,
Anton Kohnle, Proc. of SPIE Vol. 6303, 63030T, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.681704

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| | | |
|---|---|---|
| 1. REPORT DATE<br>**2006** | 2. REPORT TYPE | 3. DATES COVERED<br>**00-00-2006 to 00-00-2006** |
| 4. TITLE AND SUBTITLE<br>**Doppler Asymmetric Spatial Heterodyne Spectroscopy (DASH): An innovative concept for measuring winds in planetary atmospheres** | | 5a. CONTRACT NUMBER<br>5b. GRANT NUMBER<br>5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | | 5d. PROJECT NUMBER<br>5e. TASK NUMBER<br>5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**Naval Research Laboratory,E. O. Hulburt Center for Space Research,4555 Overlook Avenue SW,Washington,DC,20375** | | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | | 10. SPONSOR/MONITOR'S ACRONYM(S)<br>11. SPONSOR/MONITOR'S REPORT NUMBER(S) |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT<br>**Approved for public release; distribution unlimited** | | |
| 13. SUPPLEMENTARY NOTES | | |
| 14. ABSTRACT<br>**see report** | | |
| 15. SUBJECT TERMS | | |

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **Same as Report (SAR)** | **8** | |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

## 2. HERITAGE

Atmospheric wind observations with optical remote sensing techniques that measure Doppler shift have a long heritage. To date, space based optical measurements of winds in the Earth's atmosphere have been performed using either Fabry-Perot interferometers or Michelson interferometers. Both instrument types use a limb viewing geometry to detect the Doppler shift of discrete atmospheric emission lines caused by the bulk velocity along the line of sight at the tangent layer. The horizontal wind vector is determined by combining two measurements of the same air mass with orthogonal look direction, typically taken several minutes apart, 45° and 135° from the ram of the satellite.

### 2.1. Fabry-Perot heritage

HRDI on NASA's Upper Atmospheric Research Satellite (UARS) and TIDI on NASA's Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) mission utilize a triple and a single Fabry-Perot interferometer, respectively, to measure emissions between 550-900 nm.[5,6] HRDI uses a single gimbaled telescope for elevation scanning and to provide for the orthogonal viewing directions. TIDI uses four elevation scanning telescopes.

The Fabry-Perot instruments utilize one or multiple etalons in series to isolate and spectrally resolve the emission line(s) of interest.[5,6] The spectrum over a narrow wavelength range is obtained directly by imaging the ring pattern produced by the interferometer on a position sensitive detector. Once the spectrum is obtained, the wind speed can be derived from the line position. The temperature can be determined from either the line width or a line ratio. The biggest technical challenge for the Fabry-Perots lies in achieving the required etalon alignment tolerances (better than ~λ/20) and maintaining this alignment during flight. Although many resolution elements are measured in parallel, the solid angle Ω for a single resolution element is determined by the resolving power R (i.e. $\Omega = 2\pi/R$) which can be small at the resolution required for Doppler measurements. Since the high resolving power necessitates a small solid angle, a large interferometer aperture may be required to obtain adequate signal on faint emissions. This results in a larger, heavier instrument.

### 2.2. Phase stepped Michelson heritage

The Wind Imaging Interferometer (WINDII) on UARS uses an all-glass, field widened, chromatically, and thermally compensated, phase-stepped Michelson interferometer.[4] The instrument simultaneously images the entire altitude range of two orthogonal fields of view using two fixed telescopes, thus avoiding a telescope scanning mechanism. Several other versions of phase-stepped interferometers have been built or proposed for the measurement of telluric winds[7,8] and winds on Mars.[9]

The basic principle behind all phase stepped Michelson interferometers is to measure a minimum of three, but typically four, interferogram points of a single isolated atmospheric emission line. The phase points are spaced by ~λ/4 (90°) about a step (or offset) in optical path difference (OPD) that is large enough to be sufficiently sensitive to both wind speed, which results in a phase shift at high OPD, and temperature, which results in a variation in modulation depth. This principle is illustrated in Figure 1. It shows a schematic interferogram as it would be recorded by a conventional scanning Michelson interferometer viewing an isolated, single Gaussian (temperature broadened) emission line. Zero path difference is at the center of the plot with maximum path difference at the edges. The carrier frequency of the fringe pattern is determined by the central wavenumber of the emission which is Doppler shifted by the wind speed. For a predominantly temperature broadened line, the width of the interferogram envelope is a measure of the temperature, with a higher temperature corresponding to a narrower envelope. The thick line in Figure 1 illustrates the residual obtained by taking the difference between two interferograms each corresponding to a different wind speed, which causes them to have slightly different carrier frequencies. The maximum response of the measurement to wind speed is at path difference $P_{OPT}$ where the amplitude of the signal difference is maximal. Assuming a temperature broadened, Gaussian line profile with width $\sigma_D$:

$$\sigma_D = \sigma_0 \sqrt{\frac{kT}{mc^2}} \tag{1}$$

the optimum path difference is:

$$P_{OPT} = \frac{1}{2\pi\sigma_D} \quad (2)$$

where $\sigma_0$ is the wavenumber of the line center, k is Boltzmann's constant, m is the molecular or atomic mass of the emission source, T is the temperature, and c is the speed of light.

Note that the fringe frequency in Figure 1 has been greatly reduced for illustrative purposes. A real interferogram taken with a Michelson interferometer for a near infrared (NIR) emission line would produce ~$10^5$ fringes between path differences 0 and $P_{OPT}$ under typical atmospheric conditions.

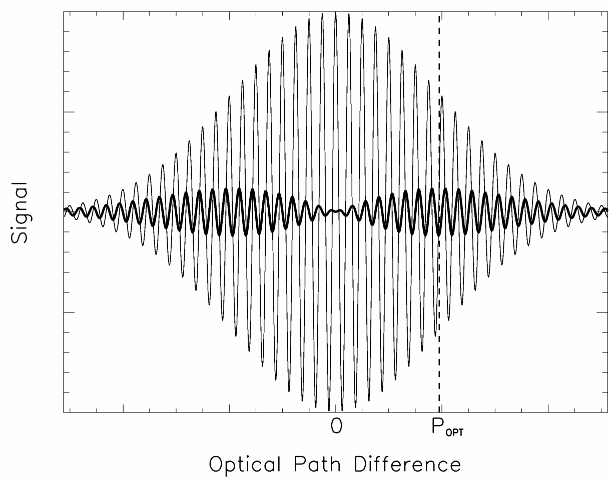


Figure 1: Schematic interferogram for an isolated Gaussian emission line. The thin curve shows the intensity vs. optical path difference for a Gaussian emission line as it would be recorded by a scanning Michelson interferometer scanned over the entire modulated path difference. Zero path difference is at the center of the plot where the visibility of the fringes is maximal. The thick curve illustrates the difference between two such interferograms corresponding to different wind speeds.

Determining Doppler shifts with a phase-stepped Michelson requires the isolation of a single emission line with a pre-filter. A fit of the interferogram phase at the four measured samples is then possible, which can subsequently be used to determine the Doppler frequency shift. If the line is close to other emissions in the spectrum, the pre-filter has to be extremely narrow, which can be achieved by an additional Fabry-Perot etalon prefilter, with all of its attendant difficulties and the resulting reduction in throughput.[8,9] Using an a priori line shape assumption (e.g. Gaussian or Voigt), the line width can be determined from the interferogram modulation, which yields the temperature for a predominantly temperature broadened line.

The optimal path difference step to measure wind speeds, $P_{OPT}$, can be tens of centimeters, depending on the emitter, temperature, and line position (e.g. in the near infrared). However, the desire to build a small, low mass, rugged, temperature stabilized payload for a Mars mission demands as small a step as possible. Note that the response to wind (envelope of thick curve in Figure 1) decreases slowly with path difference from $P_{OPT}$ towards zero path so that a smaller offset in optical path does not severely compromise the achievable precision. The optical path difference step around which the four phase points are measured is generally chosen as a tradeoff between: (1) visibility of the interferogram fringes, (2) phase shift of the fringe caused by the Doppler shift, and (3) optical and mechanical design issues such as size, chromatic and thermal compensation.

Several techniques have been used to measure the four phase points. The WINDII instrument uses piezoelectric actuators to move one mirror of the interferometer.[4] The MIMI (Mesospheric Imaging Michelson Interferometer) instrument uses a segmented mirror with four sections at different OPD, which avoids moving the mirror.[7] The WAMI (Waves Michelson Interferometer) version, designed for the Earth's atmosphere, proposes a moving, segmented mirror, allowing the simultaneous measurement of two emission lines with a two step mirror scan.[8] A phase-stepped Michelson interferometer has also been proposed for Mars[9] using a non-segmented, mirror moved by piezo actuators.

### 2.3. Spatial heterodyne spectroscopy heritage

SHS was conceived in the late 1980s and was mainly facilitated by the availability of array detectors.[10,11] The basic principle of SHS is that the path difference that is typically scanned by a Michelson interferometer is imaged onto a position-sensitive detector without moving parts. This is accomplished by replacing the return mirrors in a Michelson interferometer with Littrow diffraction gratings and imaging the gratings onto the detector. As a result, *SHS allows the design of compact, high throughput, high resolution spectrometers without moving parts.* To date, SHS has mainly been used in the UV and visible. The first orbital flight of an SHS was performed in 2002 with the proof of concept mission of SHIMMER (Spatial Heterodyne Imager for Mesospheric Radicals) on the Space Shuttle.[12,13,14] An improved version of SHIMMER, including a monolithic interferometer, shown in Figure 2, is scheduled to be placed in low-earth orbit on STPSat-1 in late 2006.[15]

The next section discusses details of the DASH approach and its advantages over the state of the art instrumentation.

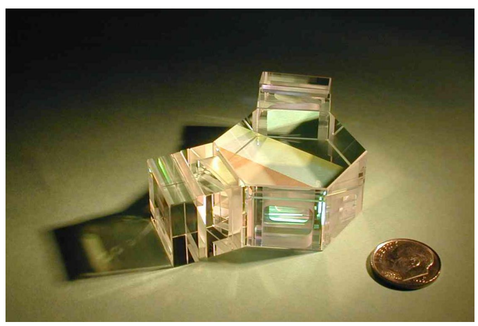

Figure 2: Monolithic SHS interferometer

## 3. THE DASH APPROACH AND ITS ADVANTAGES

We propose an approach that is a combination of the phase-stepped Michelson technique and Spatial Heterodyne Spectroscopy (SHS). Like the phase-stepped Michelson, the interferogram is sampled only at large optical path differences but the interferometer arms are terminated with fixed, tilted gratings, like in SHS. *This design allows us to measure not just four but hundreds of phase points of a heterodyned interferogram over a large path difference interval simultaneously without moving parts.*

The fundamental idea behind the DASH approach is (1) to overcome the extremely demanding fabrication tolerances and operating stability requirements imposed on Fabry-Perot instruments, (2) to avoid a scanning telescope usually used with Fabry-Perot instruments, and (3) to avoid the requirement of isolating a single emission line, while (4) conserving the high étendue (throughput) of a compact Michelson interferometer.

DASH is a slight variation (in fact a mere realignment) of the already proven basic SHS, taking advantage of the robustness, small size, and sensitivity of the SHS and extending its capability to a resolving power high enough to measure the Doppler shift caused by winds.

The primary difference between the basic SHS and DASH is that the range of sampled path differences is offset from zero path difference. In the basic SHS the centers of both gratings are the same distance from the beamsplitter producing a two-sided, heterodyned interferogram with zero path difference at the center, and maximum path difference at the edges of the recorded image. In the DASH concept (shown schematically in Figure 3) one of the gratings is placed further from the beamsplitter than the other, which makes the interferometer "asymmetric". The fringe pattern measured by DASH is a heterodyned interferogram obtained over a path difference *interval* (determined by the grating angle) centered on a large path difference *offset* or step (determined by the offset of one grating).

For the measurement of Doppler winds the instrument should have a large enough offset in path difference to enable the wind measurement and a large enough path difference interval to separate the multiple spectral components, i.e. emission lines in the passband. Like the basic SHS, the DASH concept allows field widening without moving parts by choosing prisms of the appropriate wedge angle and thickness for each arm.

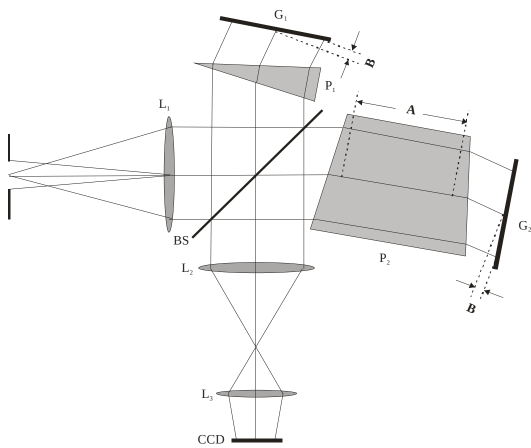


Figure 3: The field-widened DASH configuration. This field widened, asymmetric SHS consists of a Michelson interferometer with the return mirrors replaced by diffraction gratings $G_1$ and $G_2$. The gratings are imaged onto the array detector (e.g. a Charge-Coupled Device (CCD)) which records fringes of wavenumber-dependent spatial frequencies. Grating $G_2$ is further from the beamsplitter resulting in a step or offset in path difference. The path difference interval is determined by the grating angle. Field widening prisms $P_1$ and $P_2$ are chosen so the geometrical images of the gratings are coincident. (BS: Beamsplitter, $L_i$: Lenses schematically representing the telescope and exit optics, $P_i$: Field widening prisms, A&B: Geometric path differences relevant for the OPD offset and OPD interval)

The main differences between DASH and the phase-stepped Michelson are:

1) A much larger path difference interval is measured by the stepped SHS (several hundred wavelengths instead of one). Therefore, DASH *is not restricted to a single isolated Gaussian line*, rather multiple spectral lines can be measured simultaneously over the same field of view without an ultra-high resolution prefilter and its associated loss of étendue (throughput).

2) The SHS interferogram is effectively heterodyned by the Littrow wavenumber of the gratings producing low spatial frequencies at the detector. This means that the large path difference interval can be sampled by an imaging detector with a practical number of pixels. Furthermore, because the instrument measures a large path difference interval a DASH instrument can be designed so that each spectral element of interest produces a substantially different spatial frequency at the detector.

3) Many more phase points are sampled by DASH (determined by the number of detector pixels, typically a few hundred). When the spectrum consists of only of few primary emission lines as in the case considered here, the fringe pattern from each will be oversampled providing immunity to faint background features and instrumental effects like ghost fringes.

## 4. PHASE TRACKING AND INSTRUMENT DRIFT

Michelson-based instruments, including ones that use the DASH concept, depend on measuring the absolute phase of the fringe pattern to determine the Doppler wind velocity. As a result one of the most challenging aspects for these measurements is the calibration and tracking of instrument drifts that affect the phase measurement. The drifts can be minimized by appropriate thermal compensation within the interferometer. In addition, active thermal control is possible as well as periodic measurements of an on-board calibration source to determine the zero wind reference. All of these techniques have been implemented previously (e.g. on the WINDII instrument[4,16,17]) and can be readily adapted to DASH.

DASH offers an additional, powerful option to track instrument drifts. Since DASH allows for the observation of multiple emission lines, a well known line from an on-board calibration source can be superimposed onto the atmospheric signal so that the instrument drift can be determined simultaneously for every atmospheric measurement.

## 5. SIMPLE LABORATORY DEMONSTRATION OF A DASH MULTI-LINE PHASE MEASUREMENT

To demonstrate the basic principle of DASH, we performed a simple experiment using a visible/NIR breadboard SHS instrument (SHIM-Fire[18]) recently built at NRL for another project. SHIM-Fire is a conventional, non-fieldwidened SHS breadboard instrument with symmetric interferometer arms that measures double-sided interferograms. However, one of the gratings is mounted on a translation stage, so an offset in the optical path can easily be introduced by moving the grating away from the beamsplitter as indicated in Figure 4.

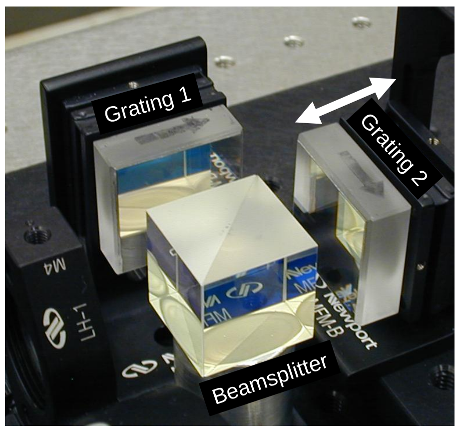


Figure 4: the SHIM-Fire interferometer is not field widened and built for ~800nm. Grating 2 can be translated to introduce a step in the optical path as indicated by the white arrow. The simultaneous phase measurements of two laser lines shown in Figure 5 were taken with this interferometer to demonstrate the basic DASH concept.

For this demonstration an OPD offset of ~10 mm was chosen, corresponding to a 5 mm translation of the grating. A 10 mm offset was found to be large enough to demonstrate the DASH principle, yet small enough to maintain appropriate imaging of both gratings on the detector without fieldwidening. *The goal of this experiment was to show that even with multiple lines in the passband the phases of the interferogram contributions from those lines can be recovered simultaneously.*

We illuminated the interferometer with two diode lasers at ~772 nm and ~853 nm. To introduce a small wavelength change we changed their input voltage simultaneously. Just like in the atmospheric Doppler shift case, we expect the wavelengths of both spectral lines and therefore the phase at a given OPD offset to change simultaneously. A simple complex Fourier transform of the measured interferogram yields the real and imaginary Fourier components of the two superimposed fringe patterns. Their ratio ($\Im/\Re$) yields the tangent of the center phase of each line. The phases of the two monochromatic fringe patterns as a function of time (and laser voltage) are shown in Figure 5. The phases clearly show the response to the change in voltage which causes a slow change in temperature and wavelength of the lasers.

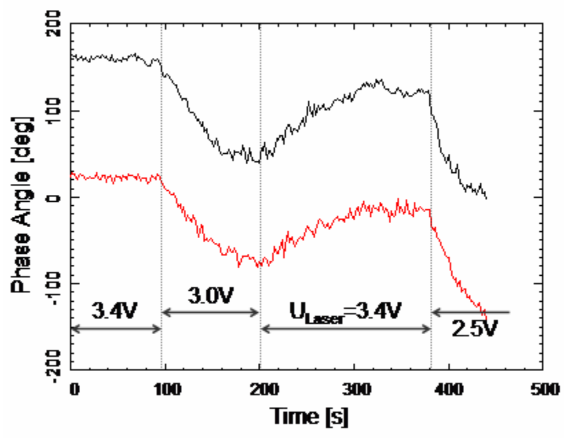


Figure 5: Interferogram phases of two laser lines at the center of the recorded interferogram (OPD ≈ 10 mm). The interferometer was viewing both lines simultaneously. Changing the input voltage of the diode lasers as indicated by the arrows causes slight changes in the temperature and the wavelength of the two diode lasers. These small wavelength changes are equivalent to the Doppler shifts in the proposed atmospheric application as they result in a phase shift of the superimposed fringe patterns. (Upper graph: center phase of 772 nm laser; lower graph: center phase of 853 nm laser)

## 6. SUMMARY

Following a brief review of the state of the art Doppler wind measurement techniques, we introduced the DASH (Doppler Asymmetric Spatial Heterodyne Spectroscopy) concept. This innovative concept is especially well suited for inferring vertical profiles of horizontal wind in planetary atmospheres by measuring the Doppler shift of multiple emission lines versus altitude. The DASH concept allows the design of compact, rugged, and lightweight satellite instruments with low power consumption and maximized sensitivity, all without moving parts.

## 7. ACKNOWLEDGEMENTS

This work was supported by the Office of Naval Research (ONR). We thank Ronen Feldman, John Moser, and Layne Marlin for their software, technical, and mechanical support.

## REFERENCES

1. Lahoz W.A., R. Brugge, D.R. Jackson, S. Migliorini, R. Swinbank, D. Lary, and A. Lee, "An observing system simulation experiment to evaluate the scientific merit of the wind and ozone measurements from the future SWIFT instrument", *Q. J. R. Meteorol. Soc.*, **131**, 503-523, 2005.
2. NASA (National Aeronautics and Space Administration), "2006 NASA Strategic Plan", *http://www1.nasa.gov /pdf/142302main_2006_NASA_Strategic_Plan.pdf*, (accessed: July, 2006) 2006.
3. MEPAG (Mars Exploration Program Analysis Group), "Mars, Scientific Goals, Objectives, Investigations, and Priorities: 2006. Unpublished document, http://mepag.jpl.nasa.gov/reports/MEPAG%20Goals_2-10-2006.pdf, (accessed: July, 2006) 2006.
4. Shepherd G.G. et al., "WINDII, the Wind Imaging Interferometer on the Upper Atmosphere Research Satellite", *J. Geophys. Res.*, **98**, 10725-10750, 1993.
5. Hayes P.B. et al., "The High-Resolution Doppler Imager on the Upper Atmosphere Research Satellite", *J. Geophys. Res.*, **98**, 10713-10723, 1993.
6. Killeen T.L. et al., "TIMED Doppler Interferometer (TIDI), *Proc. SPIE*, **3756**, 289-315, 1999.
7. Babcock et al., "A Prototype Near-IR Mesospheric Imaging Michelson Interferometer (MIMI) for Atmospheric Wind Measurement," *Eos Trans. AGU*, 85(47), Fall Meet. Suppl., Abstract SA41A-1040, 2004.

8. Ward, W.E. et al., “The Waves Michelson Interferometer: A visible/near IR interferometer for observing middle atmosphere dynamics and constituents,” *Proc. SPIE Int. Soc. Opt. Eng.*, 4540, 100, 2001.
9. Ward, W.E. et al., “An imaging interferometer for satellite observation of wind and temperature on Mars, the Dynamics Atmosphere Mars Observer (DYNAMO),” *Proc. SPIE Int. Soc. Opt. Eng.*, 4833, 226, 2002.
10. Harlander J.M., R.J. Reynolds, and F.L. Roesler, “Spatial heterodyne spectroscopy for the exploration of diffuse interstellar emission lines at far ultraviolet wavelengths,” *Astrophys. J*., 396, 730-740, 1992.
11. Harlander J.M. et al., “Field-Widened Spatial Heterodyne Spectroscopy: Correcting for Optical Defects and New Vacuum Ultraviolet Performance Tests,” *Proc. SPIE Int. Soc. Opt. Eng*., 2280, 310, 1994.
12. Harlander J.M., F.L. Roesler, J.G. Cardon, C.R. Englert, and R.R. Conway, “SHIMMER: A Spatial Heterodyne Spectrometer for Remote Sensing of Earth's Middle Atmosphere,” *Appl. Opt.*, 41, 1343-1352, 2002.
13. Cardon J.G., C.R. Englert, J.M. Harlander, F.L. Roesler M.H. Stevens, “SHIMMER on STS-112: Development and Proof-of-Concept Flight, AIAA Space 2003 Conference & Exposition,” *AIAA Paper* 2003-6224, 2003.
14. Englert C.R., J.M. Harlander, J.G. Cardon, and F.L. Roesler, “Correction of phase distortion in spatial heterodyne spectroscopy,” *Appl. Opt.*, 43, 6680-6687, 2004.
15. Harlander J.M., F.L. Roesler, C.R. Englert, J.G. Cardon, R.R. Conway, C.M. Brown, J. Wimperis, “Robust monolithic ultraviolet interferometer for the SHIMMER instrument on STPSat-1,” *Applied Optics*, **42**, 2829-2834, 2003.
16. Thuillier G. and G.G. Shepherd, “Fully compensated Michelson interferometer of fixed path difference,” *Appl. Opt.*, 24, 1599, 1985.
17. Thuillier G. and M. Herse, “Thermally stable field compensated Michelson interferometer for measurements of temperature and wind in the planetary atmospheres,” *Appl. Opt.*, 30, 1210, 1991.
18. Englert, C.R., J.T. Bays, J.C. Owrutsky, J.M. Harlander, “SHIM-Fire Breadboard - Instrument Design, Integration, and First Measurements,” *NRL Memorandum Report*, NRL/MR/7640--05-8926, Nov. 23, 2005.