Spatial Heterodyne Spectroscopy: An Emerging Optical Technique for Heliophysics and Beyond

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Abstract

At the end of the 1980s, an innovative optical technique called Spatial Heterodyne Spectroscopy (SHS) has become practical for scientific research applications with the availability of imaging detectors and more capable and affordable computers. SHS is similar to a conventional Fourier Transform Spectrometer since it also uses a Michelson type interferometer, but it samples the entire interferogram simultaneously in the spatial domain without the need for moving parts. In the past two decades, SHS has been used for laboratory spectroscopy, sounding rocket instruments, and space-borne experiments. The SHS concept has now reached a level of maturity that allows the serious consideration for NASA missions. Applications in the field of heliophysics include the measurement of upper atmospheric composition, winds and temperatures. Currently, observations of thermospheric winds present a major gap and their future availability will facilitate significant improvements in space weather prediction and our understanding of the atmosphere-iononsphere-magnetosphere interactions, including the effects of variable solar forcing from co-rotating interaction regions or coronal mass ejections. In addition to heliophysics applications, SHS is also a promising candidate for planetary applications, like the measurement of methane on Mars, or earth-science applications like the measurement of tropospheric winds. Continued development and application of this still novel technique will strengthen the position of SHS as a mature optical technique that is available for NASA missions. The unique properties of SHS have a strong potential to improve and enable future measurements, while minimizing resource requirements on the respective platforms.

1. This is how SHS works

1.1. The Basic SHS Concept is a Fourier Transform Spectrometer without Moving Parts

SHS is a method of Fourier transform spectroscopy based on a Michelson interferometer modified by replacing the mirrors in each arm with fixed diffraction gratings as shown in Figure 1 [*Harlander et al., 1992, 2003, 2004*]. For each wavelength in the wave front entering the interferometer, two wave fronts with a wavelength dependent crossing angle between them exit the interferometer (see Fig. 1). The resulting superposition of Fizeau fringes with wavelength dependent spatial frequencies is localized near the gratings and imaged by exit optics on a position-sensitive detector. Since each spectral element at the input is modulated by a unique spatial frequency at the output, the fringe image is a constant plus the Fourier transform of the input spectrum about the heterodyne wavelength (the wavelength producing parallel output wave fronts). The Fourier transform of the fringe image produces the spectrum within a limited spectral range, with the zero of the transform corresponding to the heterodyne wavelength.

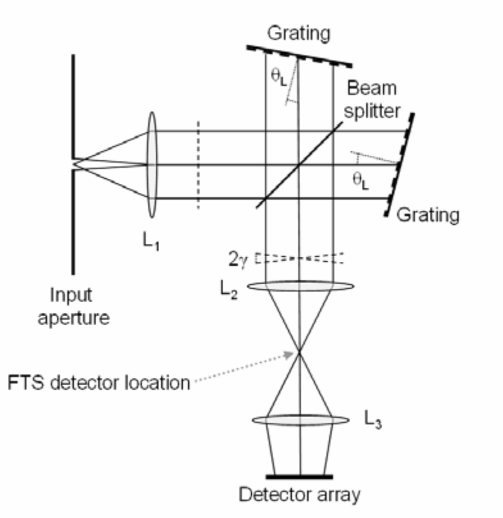

Figure 1*: Schematic diagram of the basic SHS configuration. For each wavelength in the incident wave front, two wave fronts with a wavelength-dependent crossing angle between them exit the interferometer. The resulting superposition of Fizeau fringes with wavelength-dependent spatial frequencies is localized near the gratings and imaged by exit optics on a position-sensitive detector. The image is the Fourier transform of the input spectrum about the heterodyne wavelength (the wavelength producing parallel output wave fronts). The arrow indicates the typical location of the detector for FTS and Fabry-Pérot spectrometry. From this position the interferometer elements are completely out of focus.*

With SHS, high spectral resolution can be achieved with only modest requirements on the spatial resolution of the detector. If the fringe pattern is imaged by N pixels in the dimension parallel to Fig. 1, N/2 spectral elements can be obtained without aliasing. An interference filter can be used to eliminate aliasing and multiplex noise from out-of-band light. SHS achieves a maximum resolving power equal to the theoretical resolving power of a dispersive (grating and prism) system; at the same time, its field of view is characteristic of interferometric spectrometers. When expressed as a solid angle, the field of view of a non-fieldwidened SHS is approximately 100 times larger than that of a conventional grating spectrometer of the same resolution.

Without degrading the resolving power, fixed field-widening prisms can be placed in the arms of the interferometer to increase the solid angle field of view by another factor of ~100. The prism angle is chosen so that the gratings – when viewed from the exit of the interferometer – appear, from a geometrical optics standpoint, to be coincident to and perpendicular to the optical axis. Depending on the detector and optics before the interferometer, zero, one, or two dimensions of spatial information can be recorded. Compared to scanning Fourier Transform Spectrometers (FTS) and Fabry-Pérot spectrometers (FPS), SHS instruments have greatly relaxed alignment and surface figure tolerances. This is because in SHS, the elements of the interferometer are nearly imaged on the detector. As a result, each detector pixel integrates only over a small area in the interferometer and misalignments of a few wavelengths shift the heterodyne wavelength but do not reduce the fringe contrast. As long as the optical quality of the elements is good over the small area sampled by a detector pixel, flatness errors on the gratings, prisms and beamsplitter, or index of refraction inhomogeneities, distort the Fizeau fringe pattern but do not reduce its contrast. The measured response to monochromatic light sources provides a measure of the phase errors that can be used in software to correct broadband interferograms with minimal impact on the signal-to-noise ratio in the recovered spectrum [*Englert et al., 2004*]. The typical location for the detector in a FPS and FTS is indicated in Fig. 1. At this location, the interferometer elements are completely out of focus and optical misalignments and/or flatness errors of more than a fraction of a wavelength reduce the detected fringe contrast and the signal-to-noise ratio of the spectrum.

Figure 1 shows an SHS implementation that includes transmissive elements, like the beamsplitter. If only reflective, rather than transmissive optical elements are preferred for a specific application, for example because transparent, homogeneous materials are not available for a specific wavelength region, SHS can also be implemented in an all reflective configuration. Measurements in the far ultraviolet are an example for which an all reflective SHS might be a good choice [*Harlander et al., 1992*].

1.2. The Basic SHS Concept Can be Modified to Meet Specific Performance Requirements

The basic SHS configuration lends itself to modifications in order to meet challenging measurement requirements. The bandpass of SHS can, for example, be increased by using echelle gratings, rather than first order gratings [*Lawler et al., 2008*]. Another example is a tunable, all reflection SHS, which allows the rapid change of the spectrometer's passband [*Dawson and Harris, 2009*]. A third type of modified SHS is a concept that is optimized for measuring Doppler shifts for remote sensing measurements of atmospheric winds. Since most of the high spectral resolution information about the line center of an atmospheric emission line is contained in a part of the interferogram that is offset form the zero path position (center of the detector array in Fig. 1), one can save mass, size, and power resources of the experiment by measuring this part of the interferogram only. The modification to the basic SHS concept necessary to accomplish that is to simply lengthen one interferometer arm with respect to the other. This technique is called Doppler Asymmetric Spatial Heterodyne (DASH) spectroscopy [*Englert et al., 2007*]. It is very similar to the stepped Michelson technique which was applied very successfully by the WINDII experiment on the NASA UARS satellite [*Shepherd et al., 1993*]. Some advantages over the stepped Michelson are that DASH has no need for moving parts, it provides many more interferogram samples which are measured simultaneously, and it can observe several emission lines simultaneously.

2. Past SHS applications provide technical readiness for future missions

SHS was first utilized for high spectral resolution measurements of diffuse sources in the ultraviolet [*Harlander et al., 1992, 1994*]. For these applications, when compared to other conventional spectroscopic techniques, the main advantages of SHS are the high interferometric throughput, high spectral resolution, the compact, rugged package, and the relaxed alignment and fabrication tolerances. SHS instruments for the UV were also flown on sounding rockets [*Watchhorn et al, 2003, Stephan et al., 2001*] and the Space Shuttle [*Cardon et al., 2003*] taking advantage of their sensitivity, ruggedness and lack of moving parts. The fact that the SHS measurements are performed in the spatial domain rather than the temporal domain, which makes them insensitive to unwanted effects from changing scenes, was a main driver to develop an SHS instrument for atmospheric remote sensing in the thermal infrared [*Englert et al., 2009*].

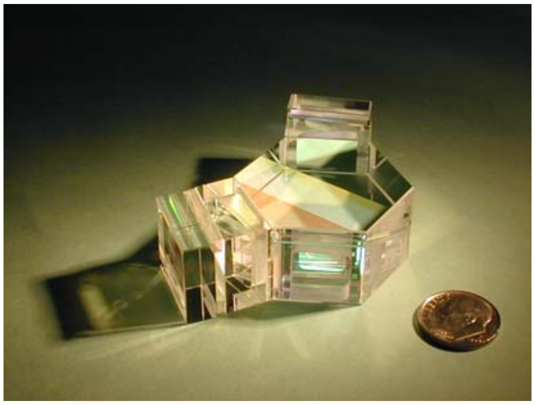

Figure 2: *Photograph of the monolithic SHS interferometer for the near ultraviolet flown on as part of the SHIMMER payload on STPSat-1 [Harlander at al., 2004, Englert et al., 2010a]*.

The single most significant advance of the SHS readiness for future space flights was achieved with the first monolithic SHS interferometer [*Harlander et al., 2004*], which as successfully flown on a free flying satellite in low-Earth-orbit for 2.5 years [*Englert et al., 2010a*]. The monolithic interferometer is shown in Figure 2. Since all optical elements of the interferometer are optically contacted, it is extremely robust, light, and compact. It was integrated in an instrument called SHIMMER (Spatial Heterodyne Imager for Mesospheric Radicals) which was the primary payload of the STPSat-1 spacecraft. SHIMMER was designed to measure mesospheric hydroxyl using solar resonance fluorescence in the near infrared. A similar measurement was made from the Space Shuttle in the 1990s using a conventional grating spectrograph [*Conway et al., 1999*]. However the SHS technique facilitated the reduction of size and power by about an order of magnitude. This allowed the SHS instrument to be integrated on a small satellite which led to about 2.5 years of data compared to two times two weeks from the Space Shuttle. The successful flight of SHIMMER demonstrated that SHS is suitable for long duration space flight applications and thus can be considered for future NASA missions.

For the DASH modification of SHS, the heritage is not only derived from SHIMMER on STPSat-1 [*Englert et al., 2010a*], but also from the WINDII instrument [*Shepherd et al., 1993*], which also used the interferogram phase at a finite optical path difference to determine wind speeds. Moreover, a monolithic DASH device was recently built, characterized and successfully used to measure thermospheric oxygen red line winds from the ground [*Harlander et al., 2010; Englert et al., 2010b*]. A photograph of the monolithic DASH interferometer is shown in Fig. 3.

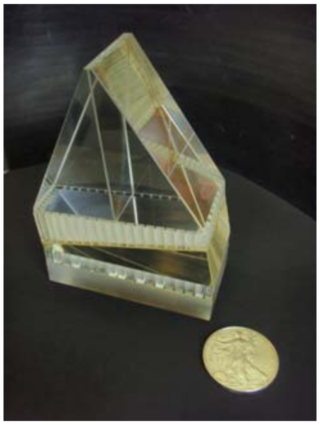

Figure 3: *Monolithic, temperature compensated DASH interferometer designed for measuring thermospheric winds using the oxygen red line (λ=630nm). This particular design uses a Kösters prism beam splitter, which makes the two interferometer arms parallel and allows the use of a single field widening prism and grating for both arms. The spacers between the beamsplitter, field widening prism, and grating are made up of individual posts ("Stonehenge Design") to minimize mechanical strain originating from the thermal expansion of the different glasses.*

3. SHS can contribute significantly to future heliophysics missions

The advantages of SHS can make this approach the method of choice for of key heliophysics mission objectives. One example is the measurement of **thermospheric wind and temperature profiles**, which is absolutely necessary to address one of the priority objectives in the latest heliophysics roadmap [NASA, 2009]: “*Discover how winds and the composition of the upper atmosphere drive the electrical fields and chemical reactions that control the Earth’s iononsphere*.” Thermospheric wind measurements also have a long term societal impact, since they will facilitate significant improvements in the prediction of space weather effects that influence satellite operations, trajectory calculations (drag), and the propagation of electromagnetic waves through the ionosphere. Space weather has effects our daily life through GPS outages, power grid failures, or communication problems. Moreover, it is highly likely that commercial sub-orbital flights will become common in the near future [*Foust, 2010*]. These flights, with pilots, scientists, and tourists on board, will go to altitudes that are well within the thermosphere/ionosphere region and the providers will have a need for environmental data at all flight levels.

The above mentioned, modified SHS concept called **DASH is a prime candidate to measure thermospheric wind and temperature profiles** from low Earth orbit. The instrument would be **small and light enough** (<35kg) **to be included even in small missions**. For the thermosphere, typical measurements could be conducted **between 90-300km altitude with up to 5km altitude resolution** observing the oxygen red and green lines. With horizontal resolutions of a few hundred kilometers, one can achieve a wind speed **precision of less than 5m/s** and **temperature precision of less than 5K**, depending on the source brightness and altitude resolution. The **cost of such a thermospheric instrument is estimated to be in the $20M range**.

DASH is also a candidate for measuring mesospheric winds and temperatures using molecular emissions, since it is able to simultaneously observe several spectral lines. A primary candidate for a suitable emission is the molecular oxygen band around 1.27μm. This effort is also highly relevant to the NASA 2009 Heliophysics Roadmap [NASA, 2009] which lists as one of its science investigations: “What is responsible for the dramatic variability of the ionosphere-thermosphere-mesosphere (ITM) region?” and “How do coupled middle and upper atmospheres respond to external drivers and to each other?” One major aspect of these questions is to understand how gravity waves propagate through, and break within the mesosphere. Since gravity wave propagation is intimately linked with the background wind flow [*Holton, 1983*], knowledge of the mesospheric wind field will help to answer these questions.

SHS also has the potential to contribute to solar physics investigations. For example, SHS is likely a suitable method that can meet the spatial imaging and spectral resolution requirements necessary for the first observation of the magnetic field in solar flares [*Uri Feldman, private communication*]. The instrument would measure the Zeeman splitting of an infrared solar emission line [*Greenhouse et al., 1993; Feldman et al., 1984*] within a flare, which gives direct information on the local magnetic field.

4. SHS Applications are Cross Cutting Between Heliospheric Themes and Beyond

We have demonstrated above with some examples that instruments based on SHS can contribute at a minimum to the two themes: “Atmosphere Ionosphere-Magnetosphere Interactions” and “Solar and Heliospheric Physics”. Other NASA objectives in planetary research and Earth science also have the potential to benefit significantly from the SHS technique. Two examples are the measurement of methane, water vapor, and carbon dioxide in the Martian atmosphere

[*Englert et al., 2008*], and the use of a DASH interferometer as the back-end of a tropospheric wind LIDAR [*Englert and Siskind, 2010*].

The Mars application is a solar occultation observation with a very high resolution SHS spectrometer that measures CH_4, H_2O and CO_2 absorption lines in a narrow passband. Measuring CO_2 together with water vapor and methane is important so that the correct volume mixing ratios can be inferred in the presence of multi-scattering. The proposed, non field widened interferometer is no bigger than the case of a compact disk (CD), has a resolving power of 150,000 at 3.2μm, and uses immersion gratings.

DASH as a LIDAR back-end is a concept that was driven by the increasing need to acquire global tropospheric wind fields, which is a priority for the NASA Earth Science Division. The technology for this type of measurement is still under development in the US. The measurement of three-dimensional tropospheric winds is listed as a "Tier 3" class mission (i.e. "technology development underway") in the last Decadal Survey and the 2010 NASA Science Plan [*NASA, 2010*].

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