Tunable Spatial Heterodyne Spectroscopy (SHS) for High Resolution Observations of Extended Targets in Visible and UV Wavelengths

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Summary

In the study of faint, extended sources at high resolving power in visible and UV ranges, a Spatial Heterodyne Spectrometer (SHS) offers significant étendue advantages relative to conventional dispersive grating spectrometers and other interferometric techniques. A SHS is a compact two beam interferometer that produces 2-D Fizeau fringe pattern from which the input spectrum can be obtained via a Fourier transform. Because of the unique concept in the basic SHS design, it can provide a resolving power (R) ~ 10^5 over a ~0.5º field of view (FOV) at visible and UV wavelengths. The primary limitation comes from its narrow resolvable bandpass that is defined by the highest spatial frequency that can be sampled by the detector (typically ~ 50Å). This limitation has made these instruments useful primarily for studies of single emission line features or molecular bands. However we are working on a Tunable Spatial Heterodyne Spectrometer (TSHS) design that enables slewing the acceptance band over a much broader spectral range. We describe here continuing progress toward development of an all-reflective TSHS at a fixed focal plane shared by the 0.6m Coude auxiliary telescope and the 3m Shane telescope on Mt. Hamilton. Our present effort involves a full description of building and setting up the first field version of TSHS in Mt. Hamilton in which we address technical design and alignment, instrument characteristics and setup, data reduction pipeline and preliminary observations.

Instrument Justification

The range of targets in planetary science is highly diverse, including small bodies, planets, moons, their atmospheres and space environments, and the interplanetary medium in which all are embedded. Size scales and perspectives also vary dramatically, with opportunities for both Earth based and in situ studies. Many characteristics of these targets, such as atmospheric dynamics, outflow/escape, radiative transfer, and isotopic ratios, are best addressed with high resolving power studies that integrate a large FOV.

SHS: High resolving power spectroscopy at wide FOV

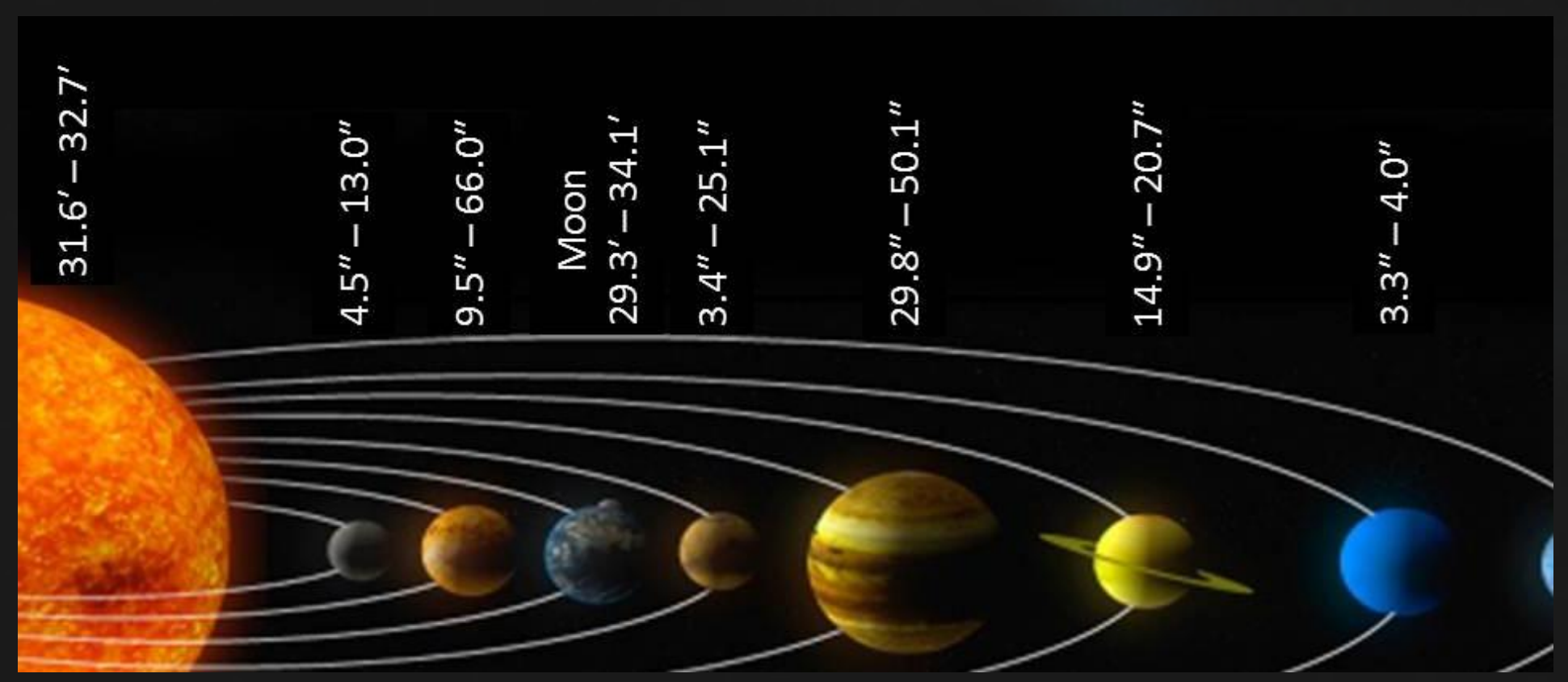
Solar system observations and remote sensing, in many cases, depends on measurement of fine spectral features from targets covering relatively large angular areas on the sky. For that reason there is a critical need for instruments that can study extended astronomical sources (wide FOV) at high resolving powers. An emerging technique that promises to fulfill this need is the all-reflective Special Heterodyne Spectrometer (SHS).

The combination of small spectrum features and variations across the planetary science targets presents a challenge towards the techniques that are used to study the planetary science targets at high resolving powers at wide FOV.

The current instruments that have been commonly used to study the extended targets at high resolving powers are mostly grating spectrometers :

- bounded to large telescopes: limited access time and space compatibility
- relatively small FOVs: limited by the time scales of the deviations in the target such as airglow, aurora, etc. Otherwise the mapping technique is limited by the telescope access time.
- low tradeoff stage between their R and FOV levels, e.g., the FOV of Keck-HIRES reduces to an aperture of less than 1arcsec while reaching to R~50,000.

We report here on progress toward building the first field version of SHS, a tunable instrument at Mt. Hamilton: *Khayyam*.



Most planetary science targets present wide FOVs which has not been addressed by the current high resolving power spectrometers.

Instrument Concept

TSHS instrument is a form of a Fourier Transform Spectrometer. A desired 'heterodyne' wavelength (λ_0) circulates the optical path with both interfering beams exiting the instrument following the same path. Other wavelengths disperse to different angles that are translated into a vector separation in the output, with the size of the angle between the beam propagation depending on the wavelength separation from the heterodyne configuration. A 2-D Fourier transform of the 2-D pattern recovers the input power spectrum.

At the small angel approximation:

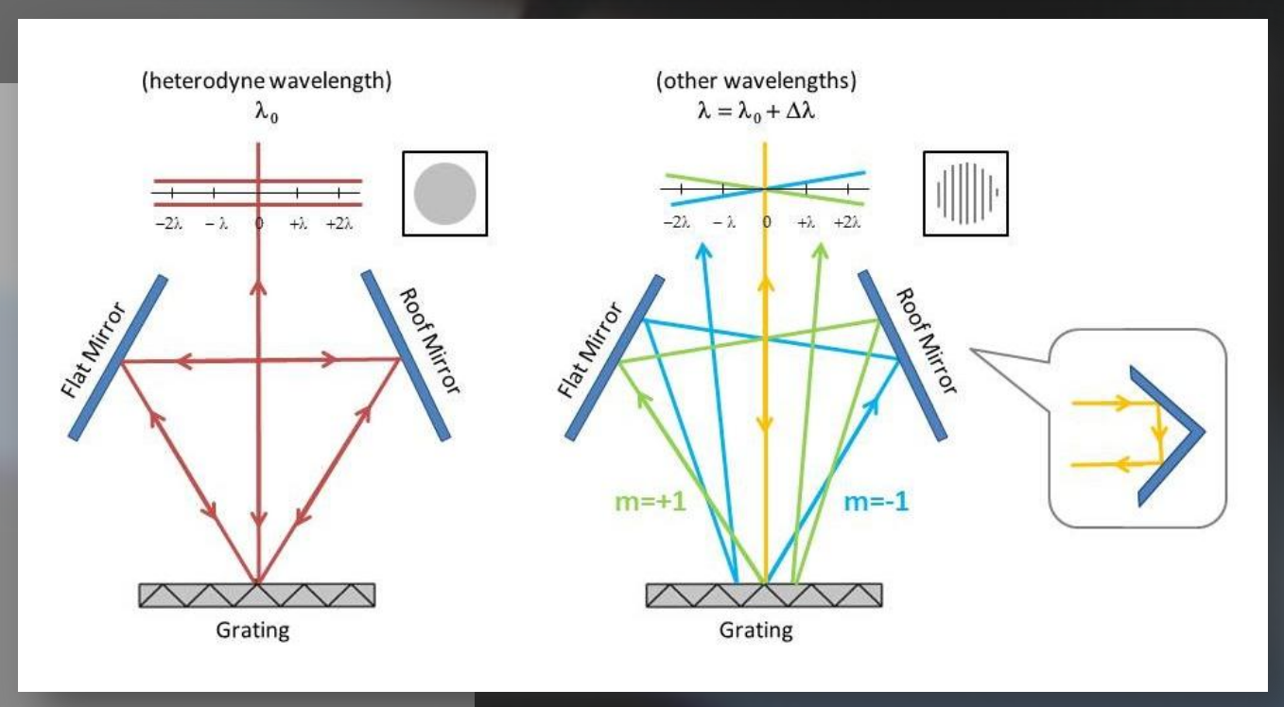
Resolving power: $$R = \frac{\lambda_0}{\Delta\lambda} = 4mWG$$

Field of View: $$FOV \cong \frac{2\pi}{R}$$

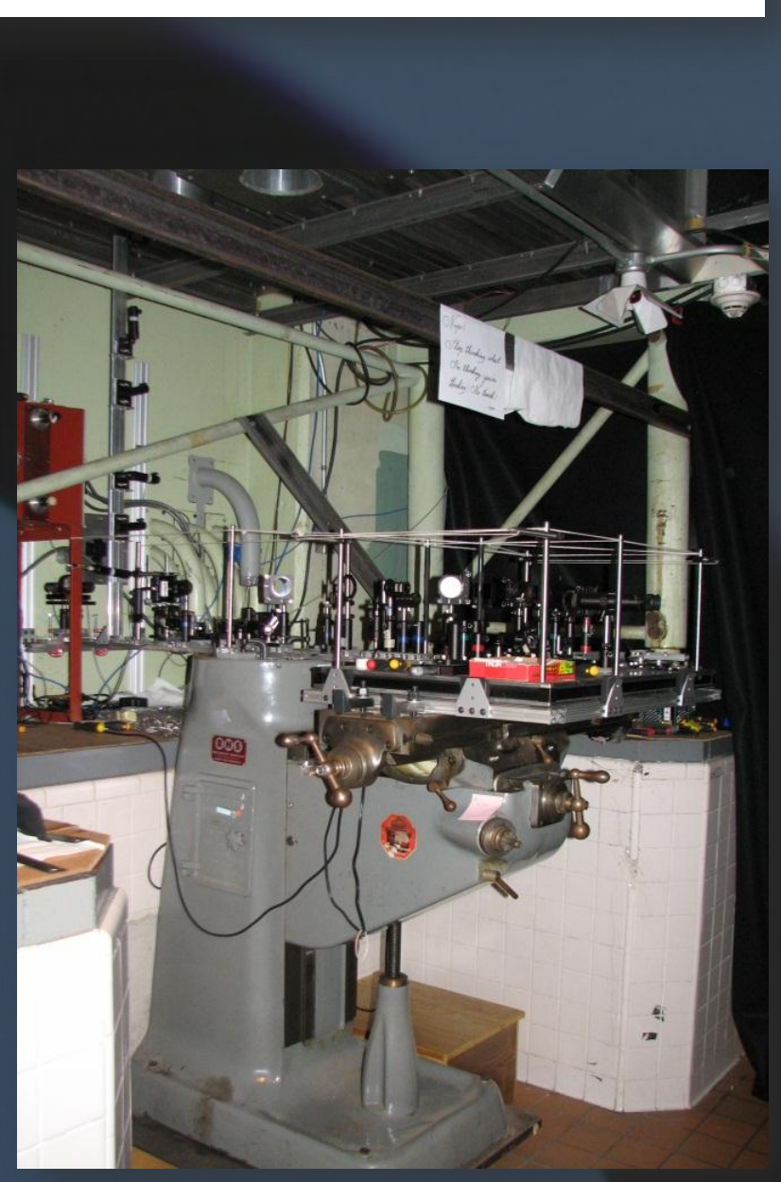
where m is the diffraction order, W is the beam width on the grating, and G is the groove density.

And Bandpass: $$\Delta\lambda_B = \frac{\lambda_0}{\frac{Rk}{N} - 1}$$

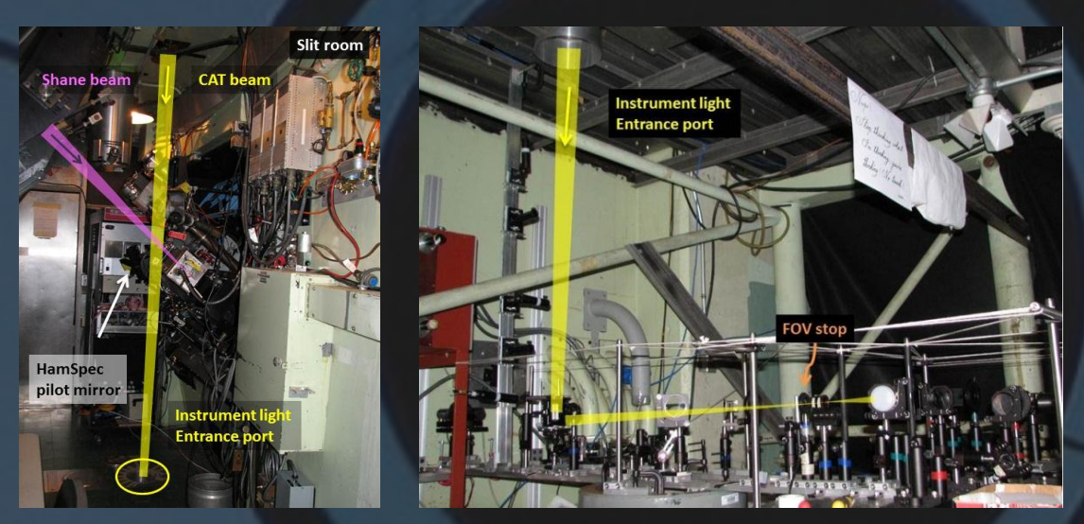
Where $\Delta\lambda_B$ is the half bandpass, R is the resolving power, k is the minimum number of pixels required to resolve one fringe (for the Nyquist limit: k=2), and N is the total number of pixels along the detector.



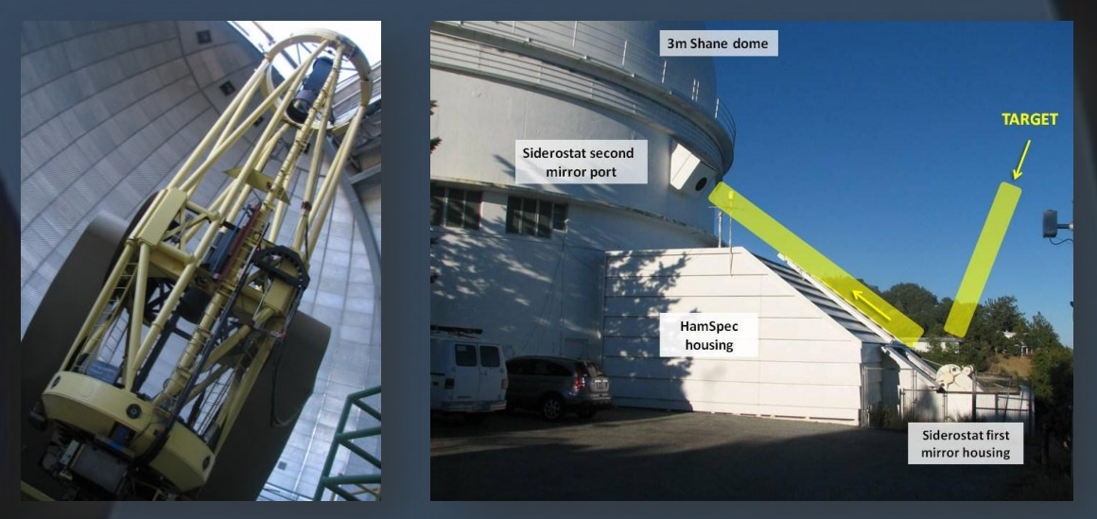
Khayyam



The integrated instrument, *Khayyam,* has been installed semi-permanently at the fixed location below the shared focal plane of the Coudé Auxiliary Telescope (CAT) and the Shane telescope coudé configuration at Mt. Hamilton. The instrument is setup on the lower half of a Bridgeport milling machine located on a concrete slab.

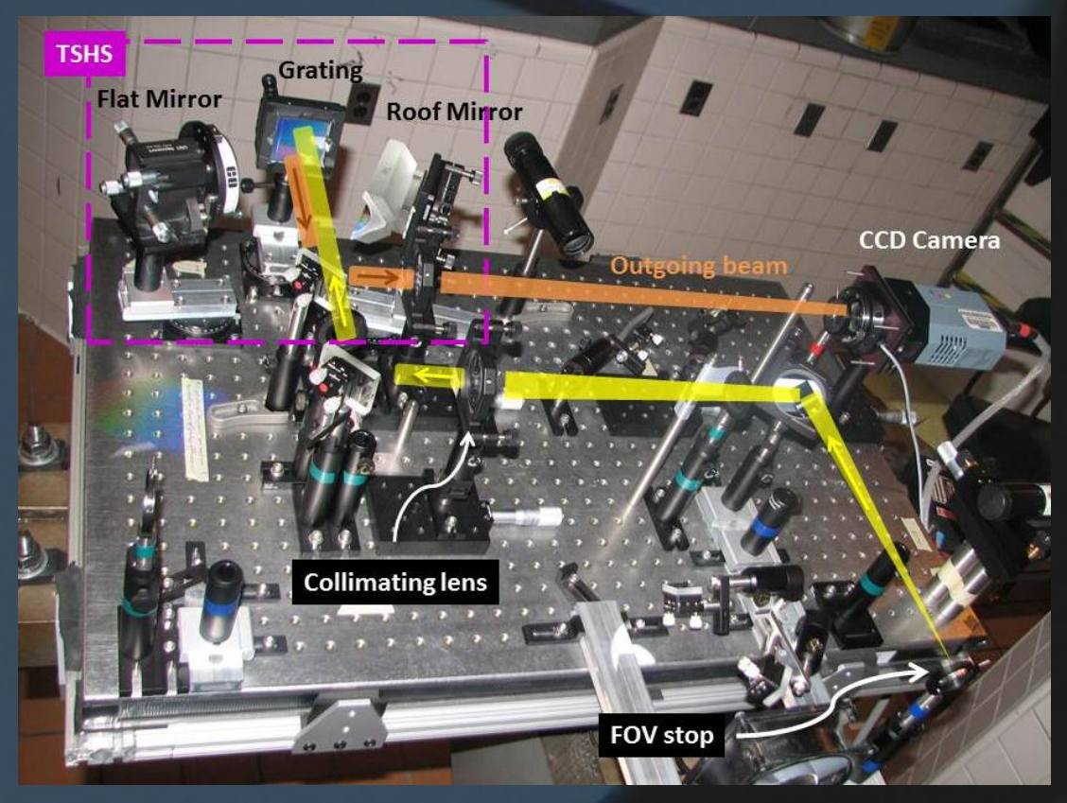


Light path from the CAT to HamSpec slit-room to Laser Pool, to FOV stop, to TSHS and to the camera.



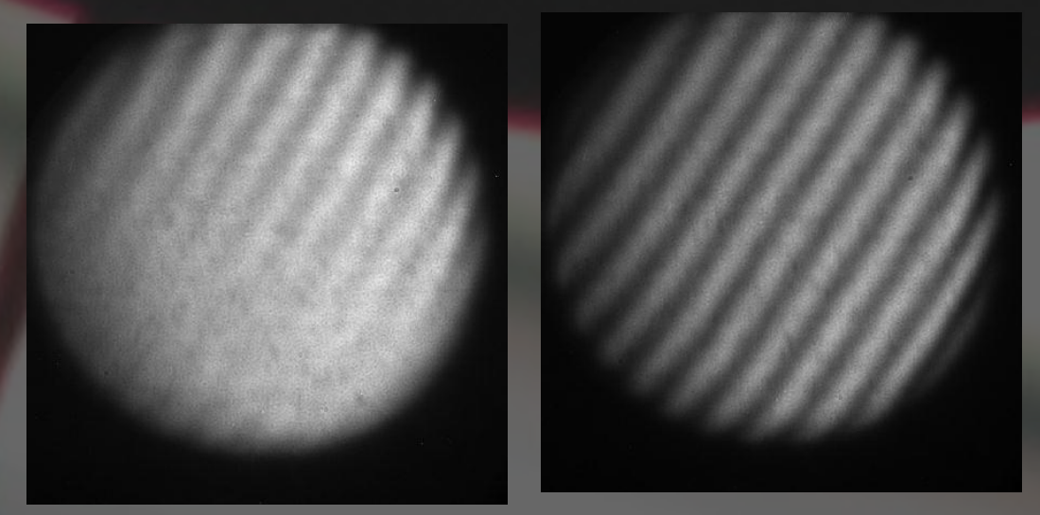
(left) 3m Shane telescope. (right) Light path through CAT outside the dome.

By shifting the CAT focus, we have eliminated most of the coupling optics and directly focused the beam on the FOV stop on the instrument which had improved the stability of the instrument

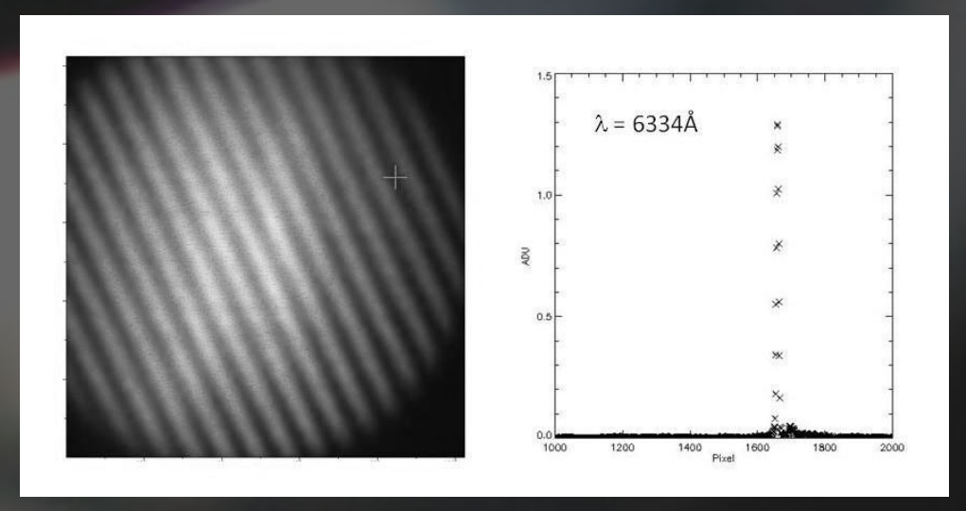


Preliminary results

The instrument alignment has been finalized and it can be tuned to different wavelengths. At the preliminary attempt, the SHS and the coupling system to the CAT has been aligned to several lines, e.g., HeNe laser wavelength at 6328 Å, Ne pen-ray lamp at 6402 Å, 6383 Å , 6334Å, and 6304 Å, Na double D lines at 588.9 Å and 589.5 Å

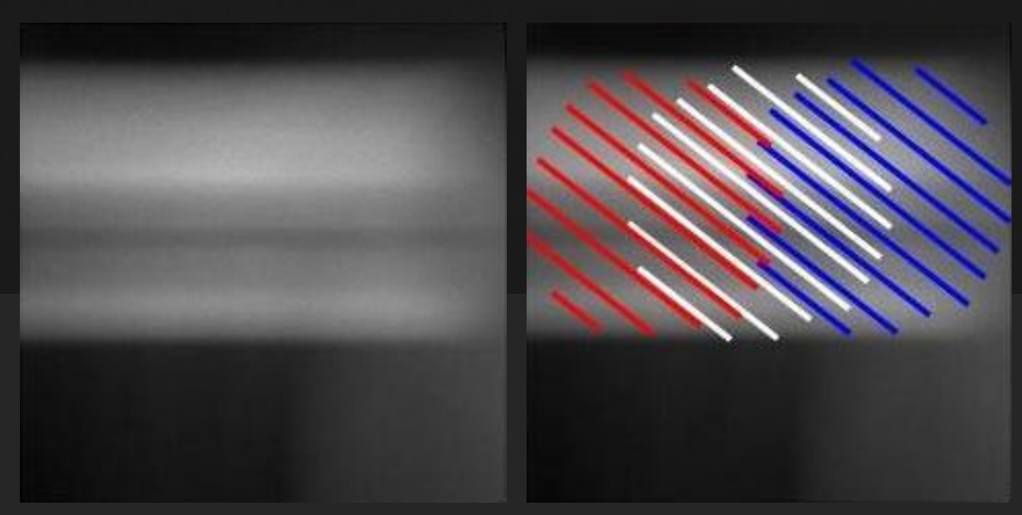


Environmental tests: Ne lamp data at 2500 seconds exposure time (left) taken with the original coupling system to the telescope. (Right) taken with the current coupling system to the telescope which clearly show the improvement.



The interference pattern from the Ne lamp at 6334Å wavelength. The plot shows the power spectra of the pattern using the preliminary data reduction code.

The first light was achieved during March 2012 from Jupiter and Mars which was taken with no filter.

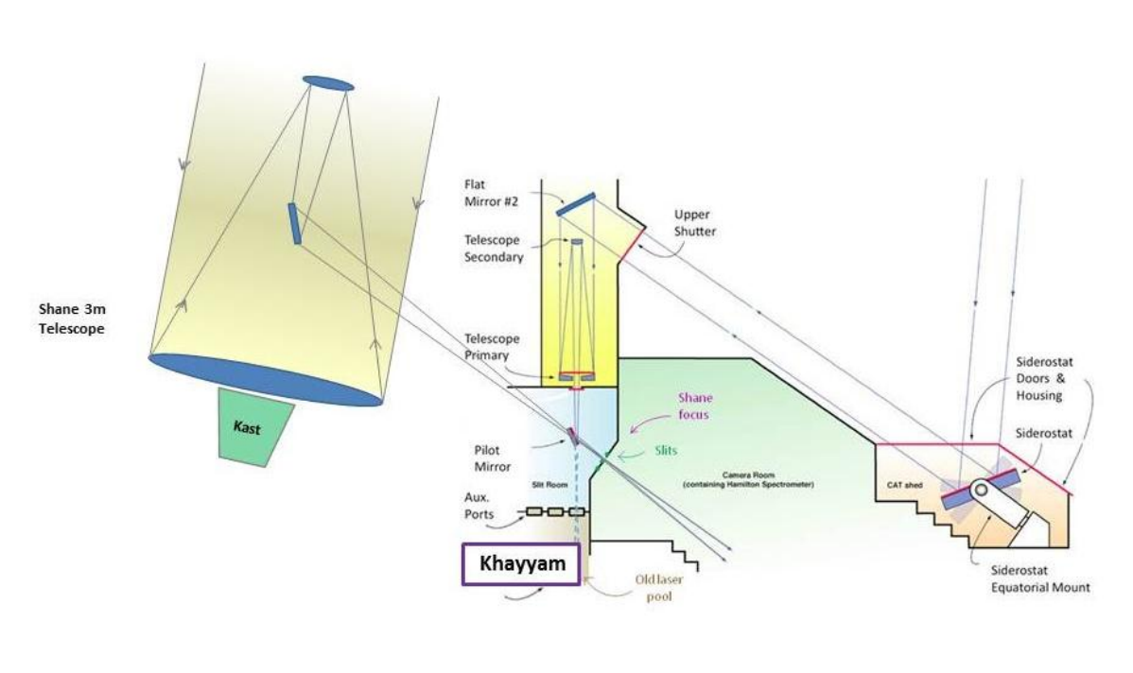


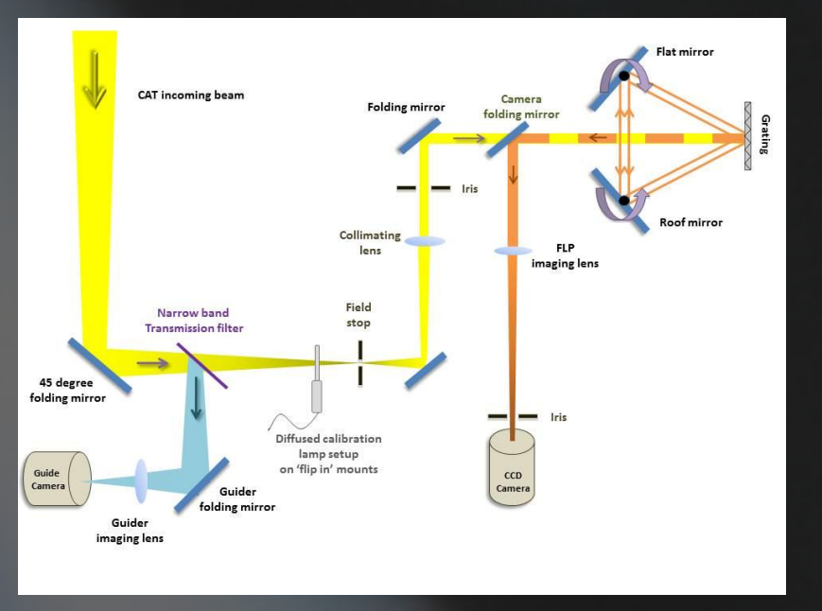
(left) Khayym's first light on March 8, 2012 from Jupiter when Khayyam was tuned to the 6383 Å Ne lamp emission line, without any filter. (right) schematically shows all the data from outer band wavelengths are overlapping.

The unique characteristic of Khayyam

SHS's raw throughput tracks telescope aperture with FOV linearly which is consistent with telescope size for extended targets. Therefore, although SHS don't necessarily need to couple to a telescope but they can be used with a telescope to reduce their FOV. This means for extended targets, small telescopes (<1 m) are as good as large telescopes.

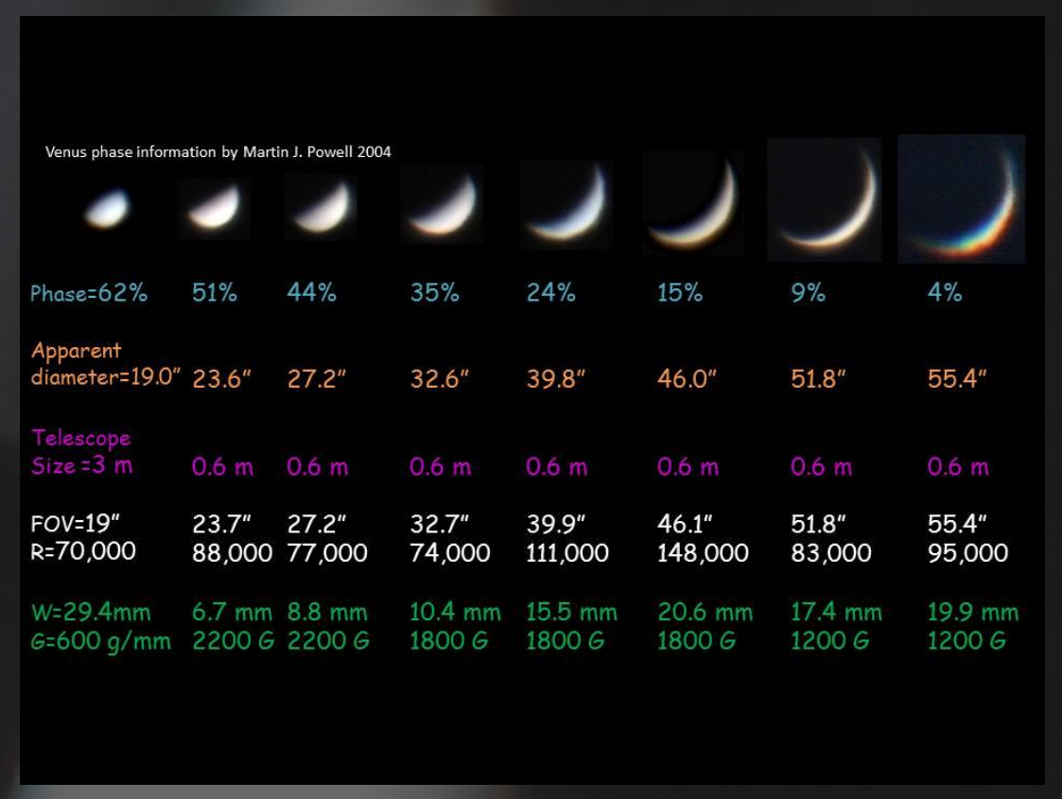
The potential of using both apertures would allow Khayyam to study different FOVs at same resolving power. This is particularly useful for following targets that tend to have changing sizes such as comets and following them to large heliocentric distances without sacrificing the resolving power.





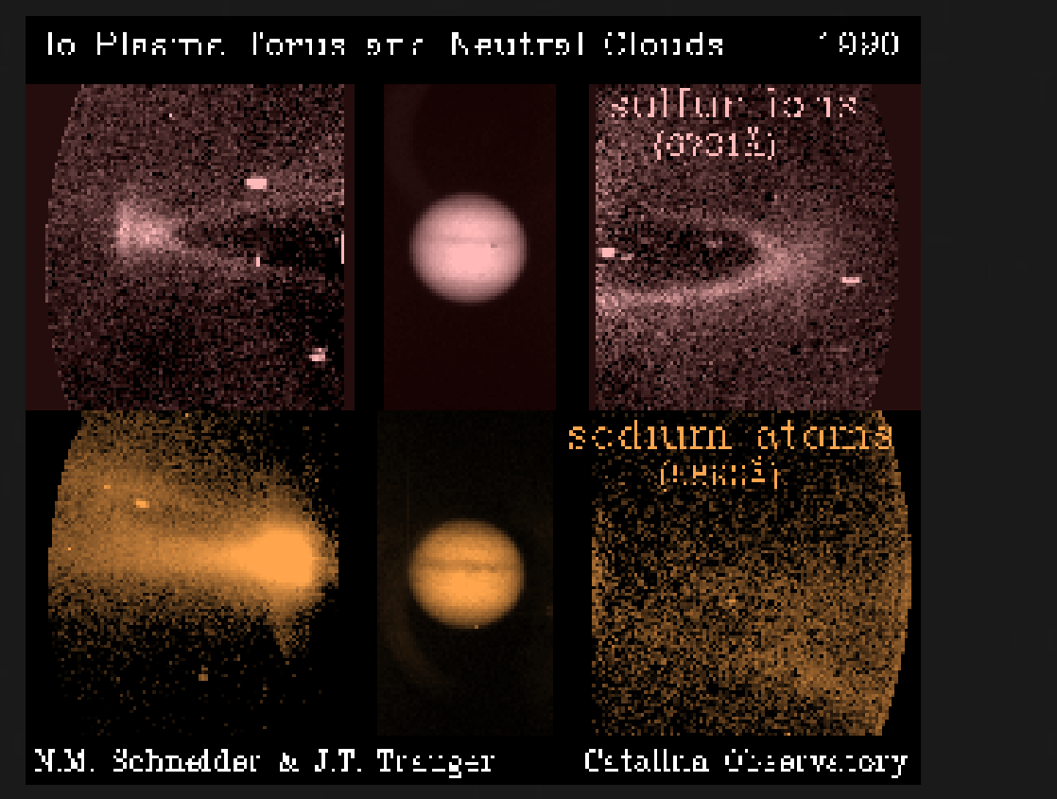
W (mm)	G (grooves/mm)	R	Total bandpass (Å)	SHS input acceptance angle	SHS-CAT FOV	SHS-Shane FOV
5	1200	24000	275.8	55′ 37″	27″	5″
10	1200	48000	136.4	39′ 19″	39″	7″
20	1200	96000	67.8	27′ 48″	55″	11″
5	600	12000	564.06	1˚ 18′ 39″	39″	7″
10	600	24000	275.8	55′ 37″	55″	11″
20	600	48000	136.4	39′ 19″	1′ 18″	15″

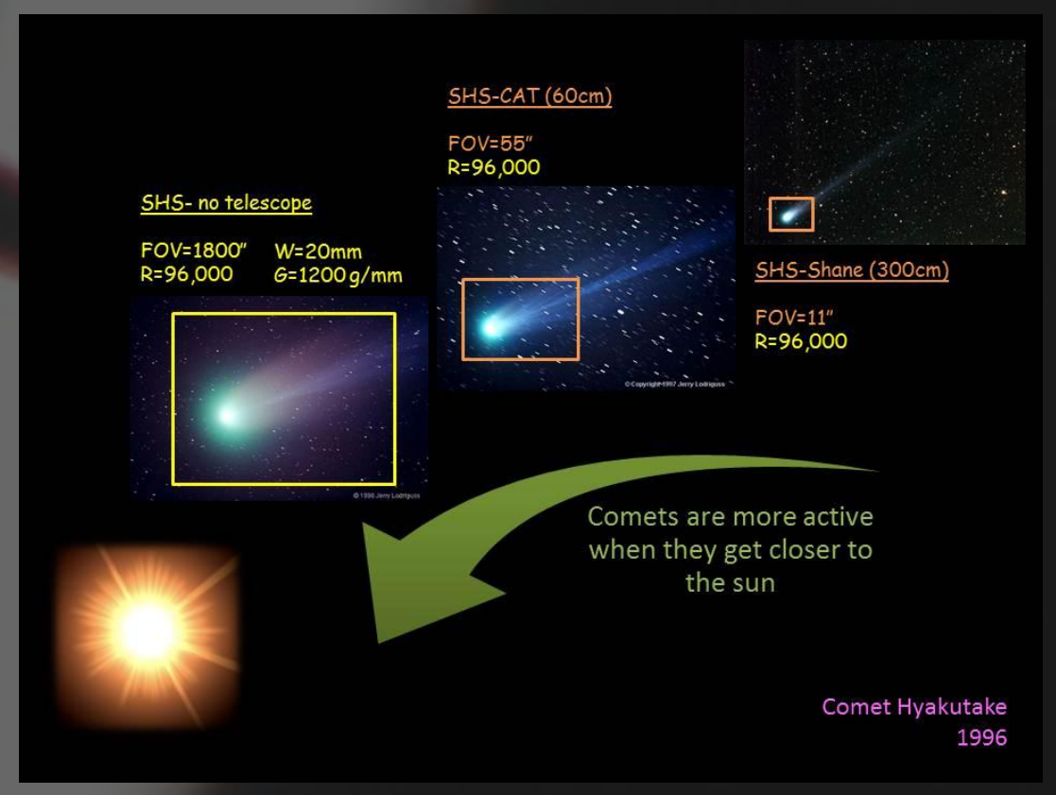
These numbers are for when the instrument is tuned to the HeNe laser wavelength at λ0=6328 Å

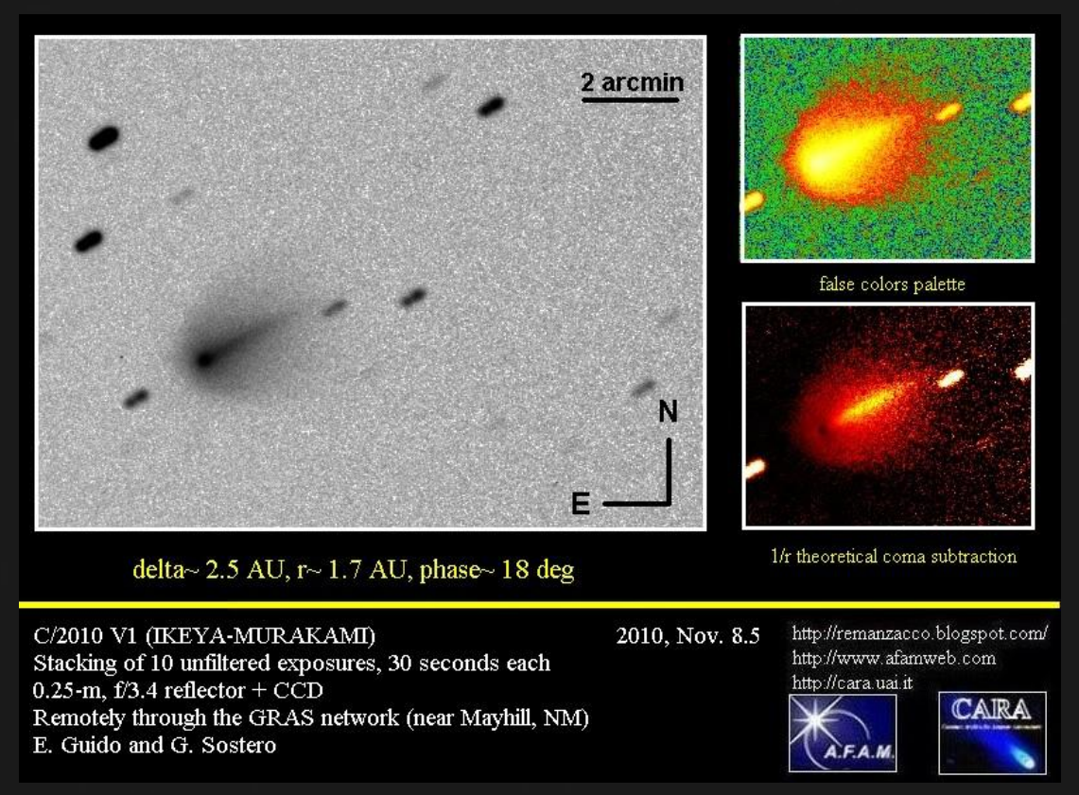


Venus phase information by Martin J. Powell 2004

Phase=62%	51%	44%	35%	24%	15%	9%	4%
Apparent diameter=19.0″	23.6″	27.2″	32.6″	39.8″	46.0″	51.8″	55.4″
Telescope Size =3 m	0.6 m	0.6 m	0.6 m	0.6 m	0.6 m	0.6 m	0.6 m
FOV=19″ R=70,000	23.7″ 88,000	27.2″ 77,000	32.7″ 74,000	39.9″ 111,000	46.1″ 148,000	51.8″ 83,000	55.4″ 95,000
W=29.4mm G=600 g/mm	6.7 mm 2200 G	8.8 mm 2200 G	10.4 mm 1800 G	15.5 mm 1800 G	20.6 mm 1800 G	17.4 mm 1200 G	19.9 mm 1200 G







C/2010 V1 (IKEYA-MURAKAMI)
Stacking of 10 unfiltered exposures, 30 seconds each
0.25-m, f/3.4 reflector + CCD
Remotely through the GRAS network (near Mayhill, NM)
E. Guido and G. Sostero

Ongoing development

- Data reduction pipeline: in order to perform a detailed environmental test, enhancing the instrument and reducing the data
- Spider Pattern signature: no SHS instruments have been used with spider structures before. A complete study is needed in order to eliminate the spider pattern using the code.
- Multiple grating: in order to tune to a different bandpass without moving the mirrors and changing the geometrical setup
- Automatic tuning feature: for faster and more accurate tuning

Acknowledgment

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