Jet Propulsion Laboratory
California Institute of Technology

Next generation of miniaturized high spectral resolution spectrometers

Sona Hosseini
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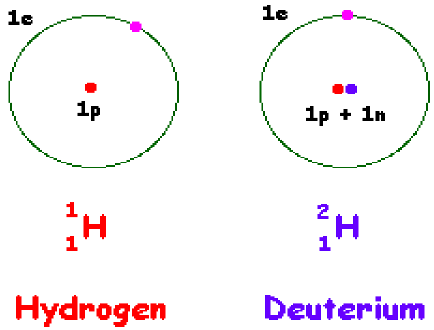
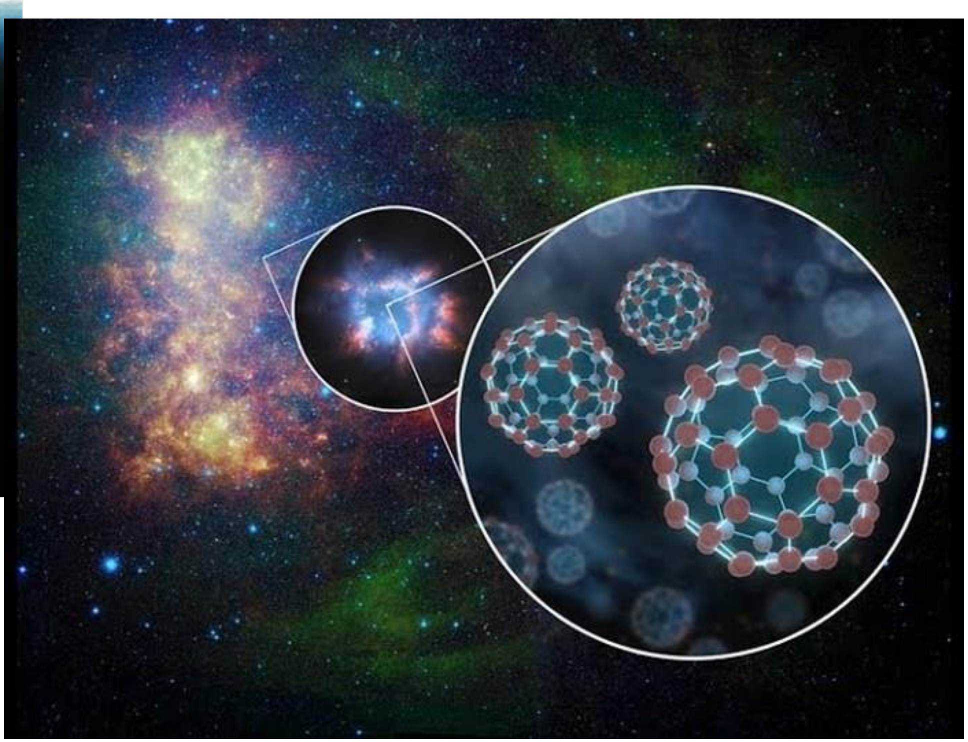
Tracing the source of Earth’s water is surprisingly complex

Follow the heavy water!

“There are numerous debates and models about the source of water and organic compounds on Earth and other terrestrial planets without converging to an agreement.”

- Kathrin Altwegg

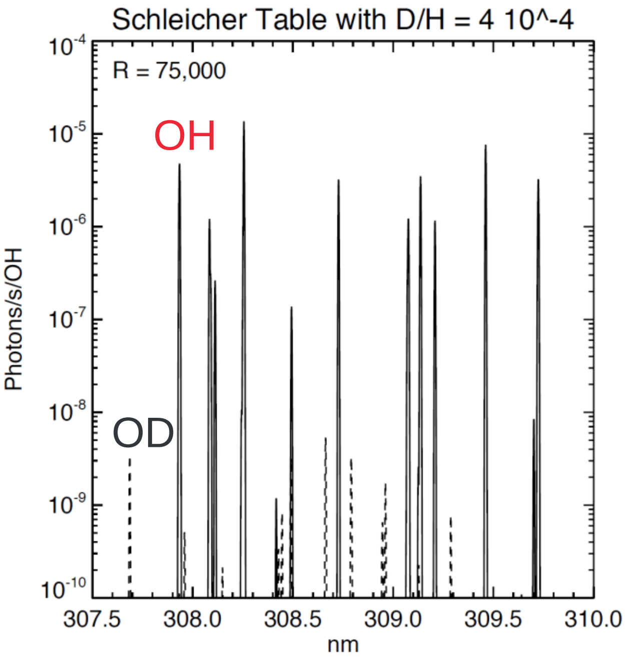




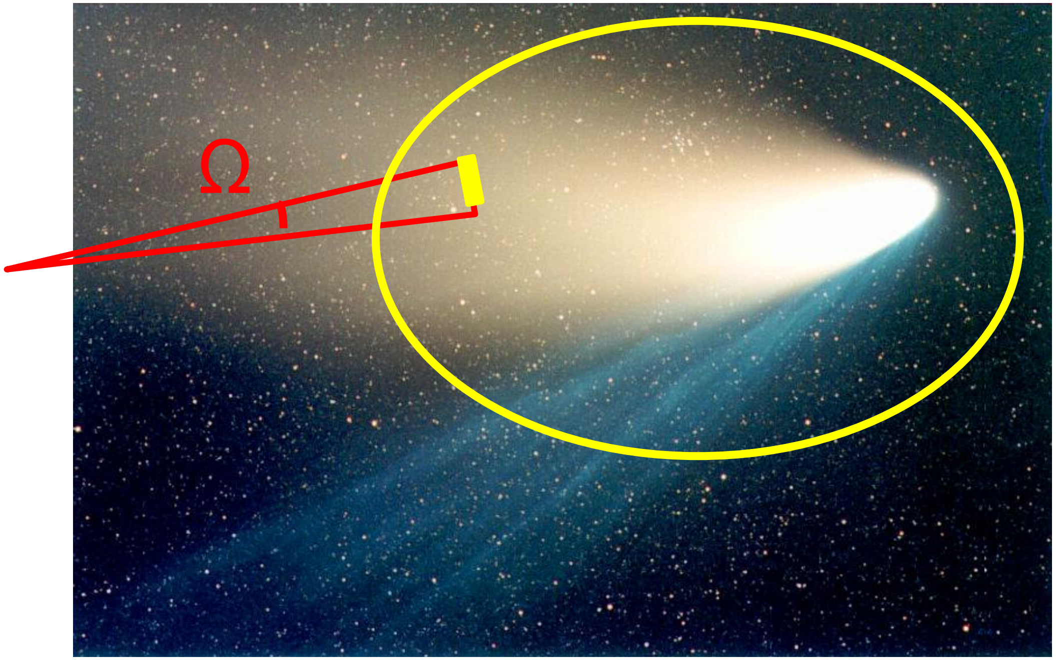
The origins of life, as we know, is tied to the origins of water on the Earth.

High Spectral Resolution Spectroscopy

High spectral resolution is needed for fine relative motions, multiple sources, isotope ratios, temperature, turbulence, currents, and etc.



Simulated spectra from OH and OD molecules.



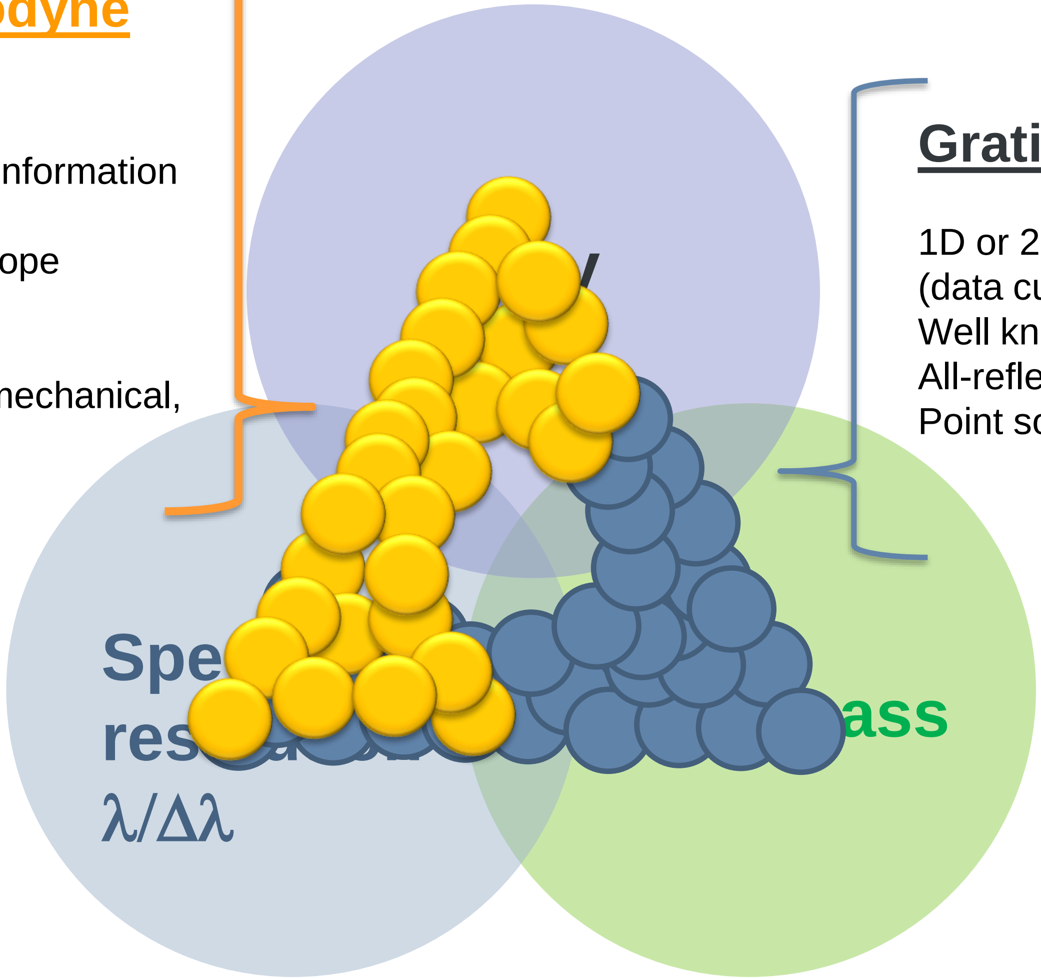
Comet Hale-Bopp

Spectrometry’s Trade Triangle

What do I *really* need for my science?

Spatial Heterodyne Spectromter

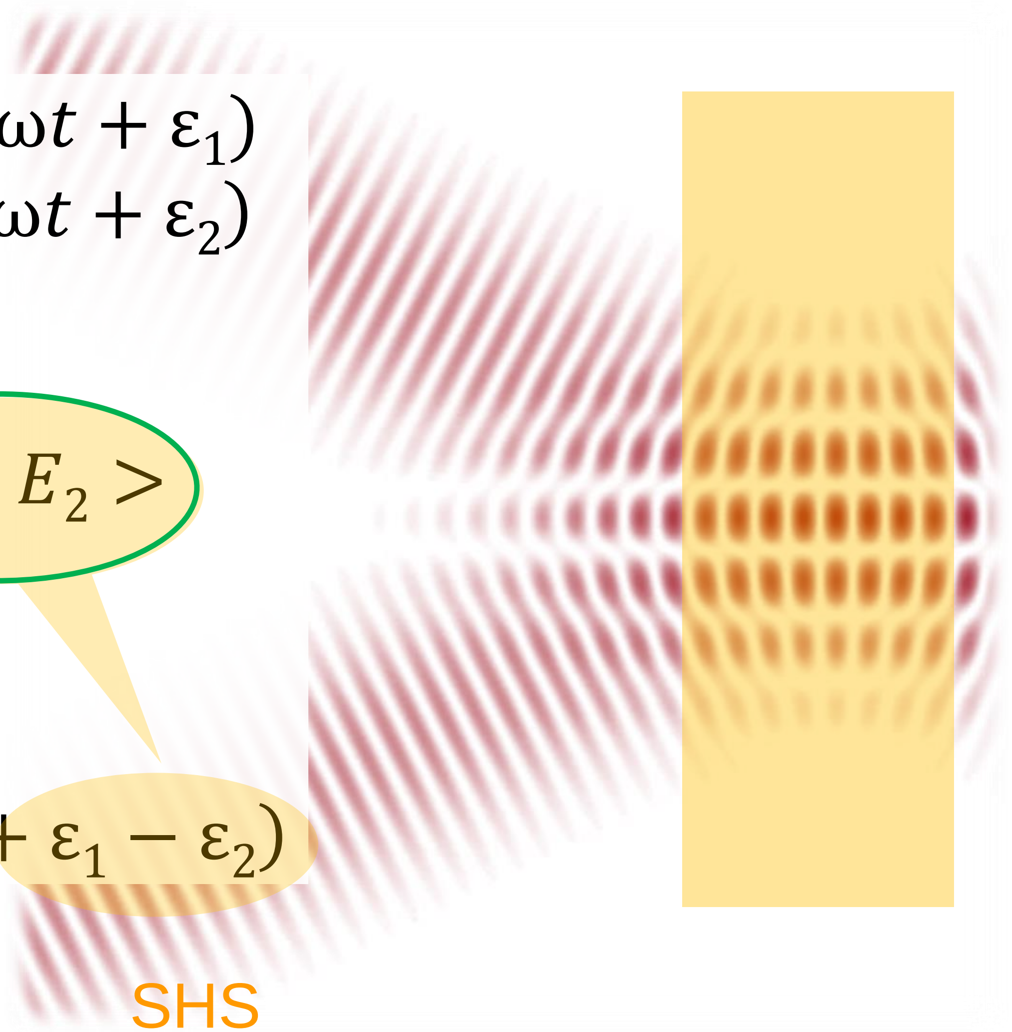
No, 1D or 2D spatial information
Compact/miniature
Small aperture telescope
Low data volume
All-reflective design
High tolerance (optomechanical, temperature)



Grating spectrometer

1D or 2D spatial information (data cube capability)
Well known concept/heritage
All-reflective design
Point sources (narrow FOV)

Two factors create an interference pattern



$$E_1\,(r,t) = E_{01}\cos(k_1.r - \omega t + \varepsilon_1)$$
$$E_2\,(r,t) = E_{02}\cos(k_2.r - \omega t + \varepsilon_2)$$

$$I = {E_1}^2 + {E_2}^2 + 2 < E_1.E_2 >$$

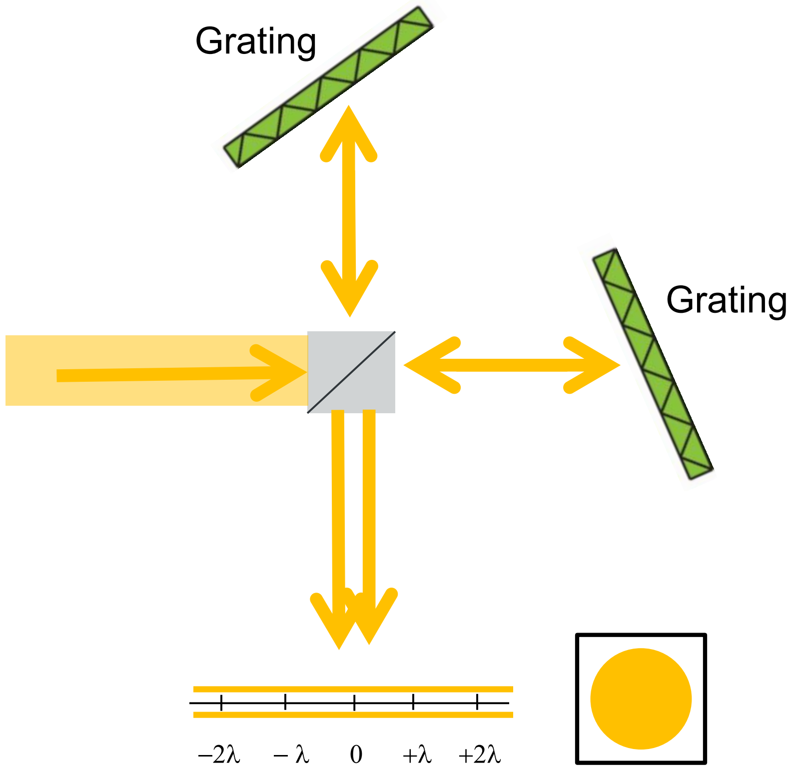
$$< E_1.E_2 > \\ = E_{01}\,.\,E_{02}\cos((k_1 - k_2).r + \varepsilon_1 - \varepsilon_2)$$

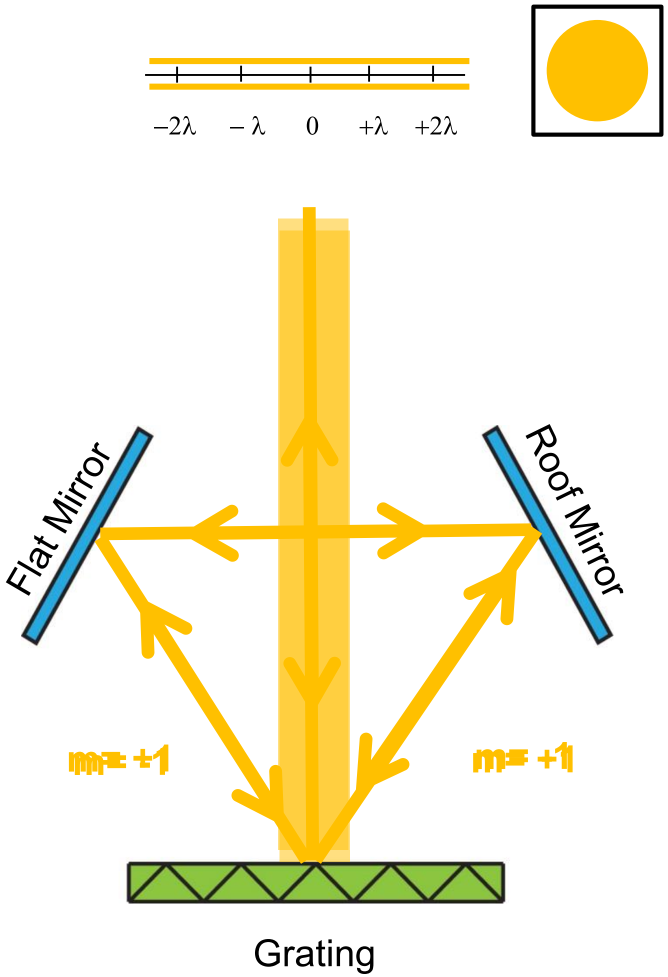
Conventional Interferometry

SHS

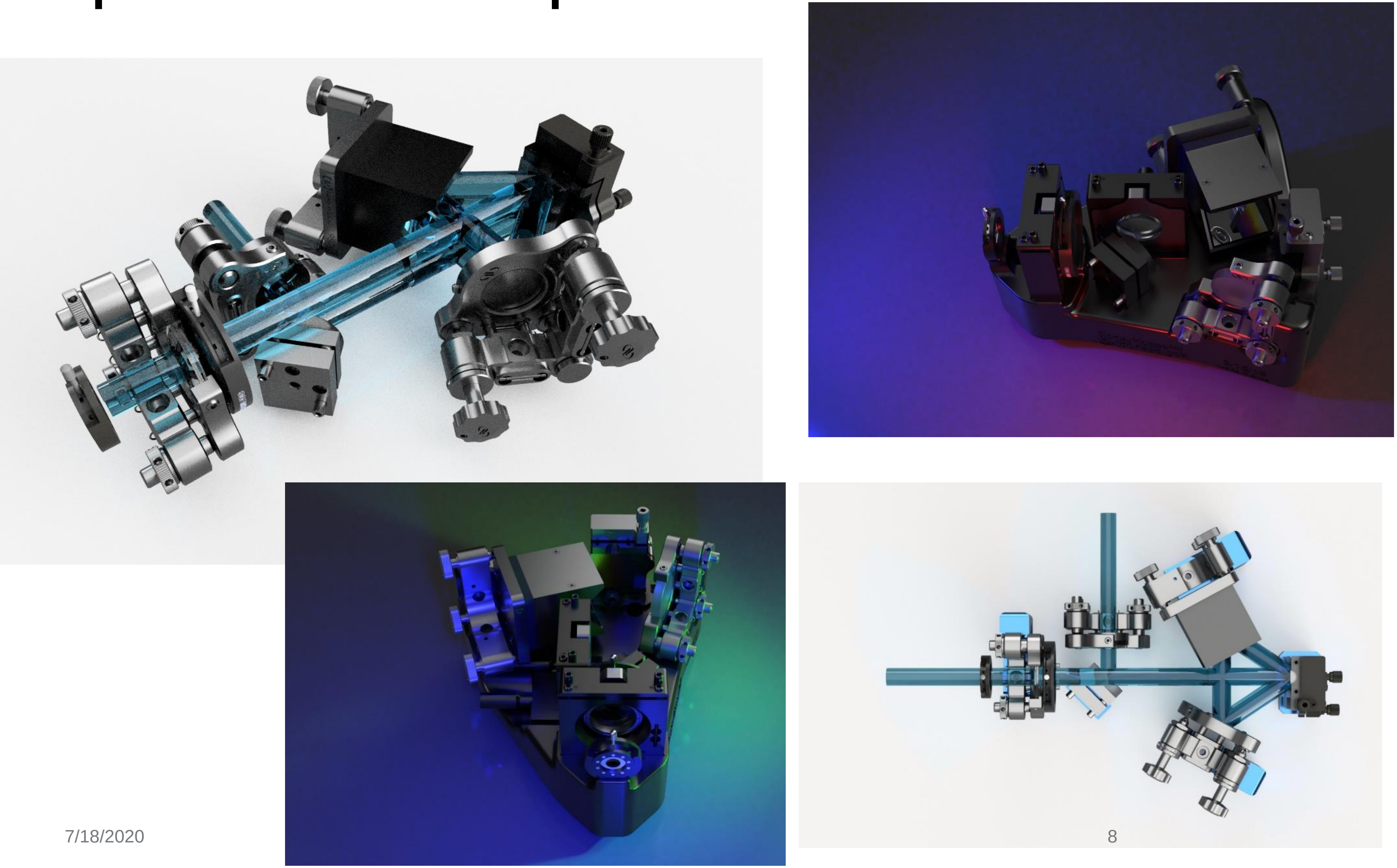
Hosseini, 2019

SHS is an interferometer with no moving parts





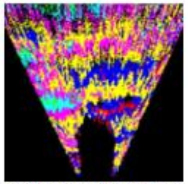
Developing the next generation of miniaturized high spectral resolution spectrometer



ROBOTICS

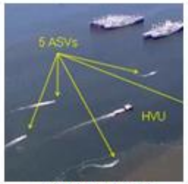
robots for everything!

Driving
Flying
Landing
Small Body Orbiting
Subsurface Access
Instrument Placement
Sampling
Onboard Science

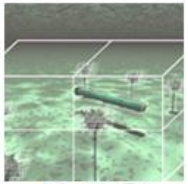

Autonomy Algorithms for Navigation in High Sea States in Support of ACTUV

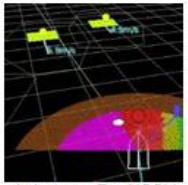

Autonomy and Perception for Uncrewed Sea Surface Vehicles


Autonomy and Situational Awareness for UMS



Autonomy and Situational Awareness for UMS


Autonomy For Unmanned Underwater Vehicles


Autonomy For USSV For Littoral Combat Ship Missions


Autonomy Integration For The US Navy Griffin Demonstration


AWIMR: Autonomous Walking Inspection and Maintenance Robot


Axel Rovers for Exploring Extreme Terrains


BiBlade Sampler for Small Body Sample Return

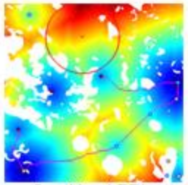

Biosleeve: Multi-electrode EMG Sleeve Human-Machine Interface

Browser-based Exoplanet Visualization for Education, Public Outreach and Engineering


Cave Robot

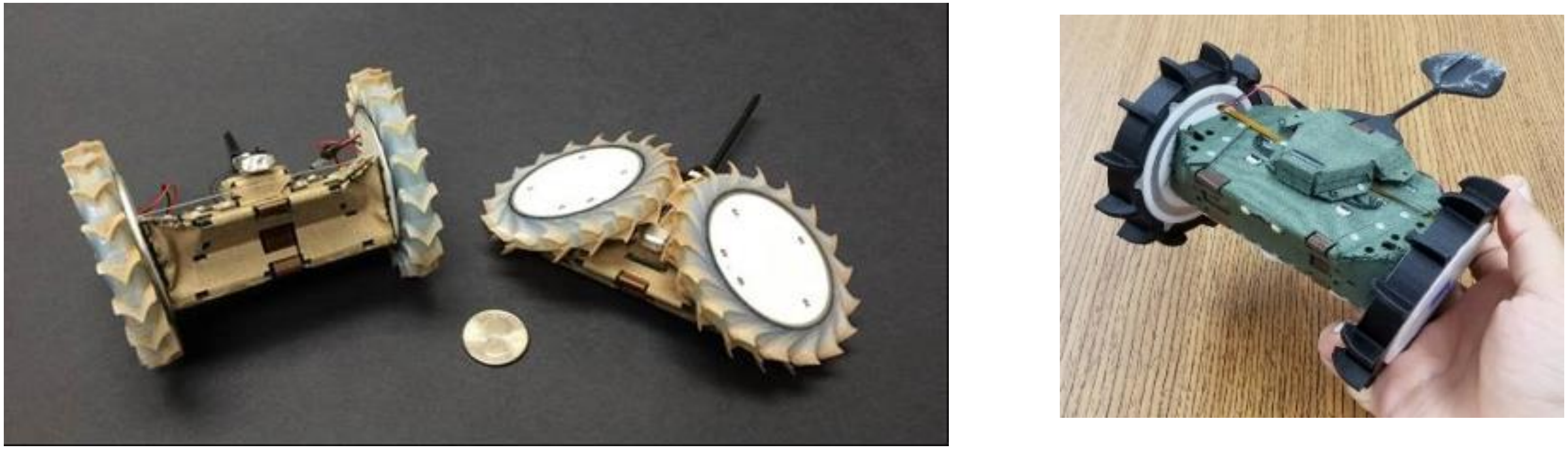

Cluster-Based Large Scale Surface Rover Simulations


CODE - Collaborative Ops in Denied Environment


Combined EDL-Mobility Analysis Trade Study Tool (CEMAT)

https://robotics.jpl.nasa.gov/

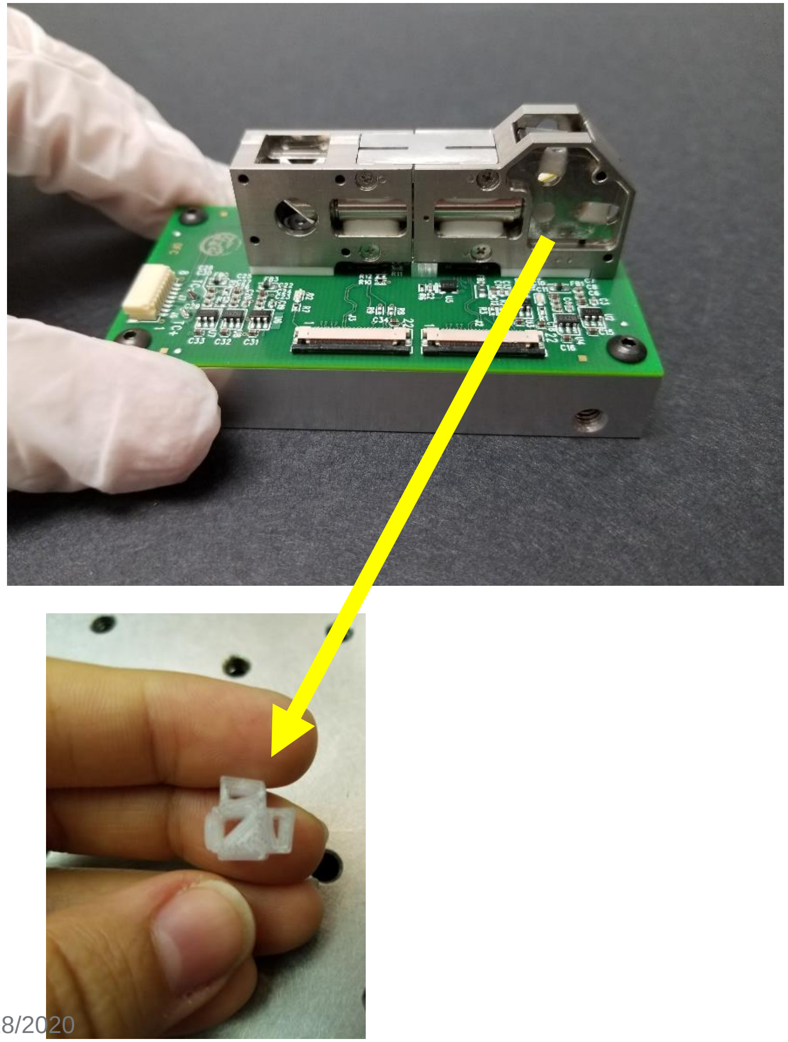
PUFFER will explore the moon, and other planetary surfaces

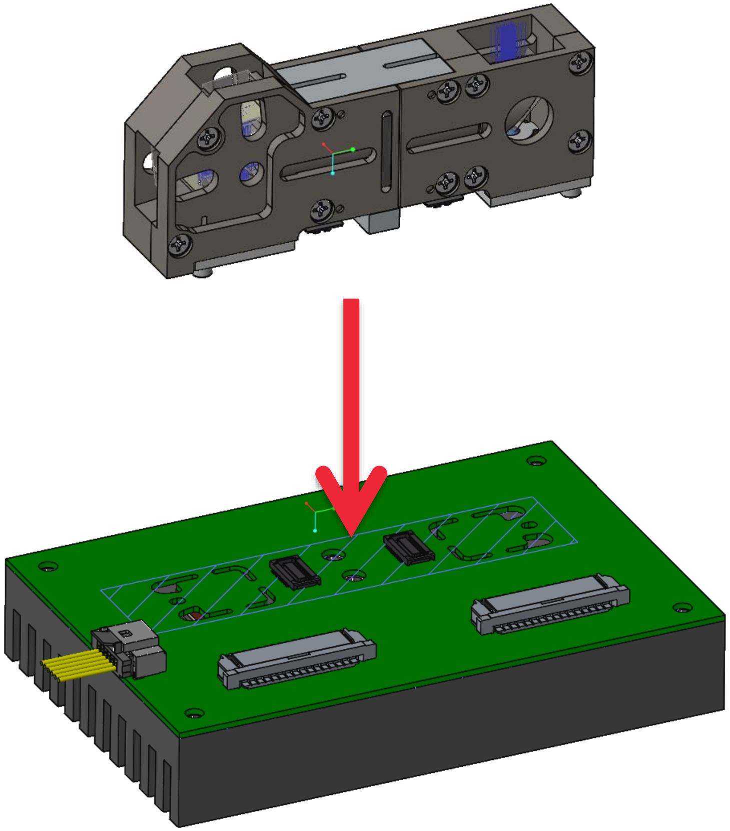


PUFFER (Pop-Up Flat-Folding Explorer Robot) is an origami-inspired robot that was developed to provide future NASA missions with simple, low-cost access to new high-value, higher-risk extreme terrains.

This project will also focus on developing “multi-agent” autonomy that enables multiple PUFFERs to leverage cooperative mobility, communication, and sensing to operate in ways that are not possible with a single rover.

HOLMS (Heterodyne OH Lunar Miniature Spectrometer)





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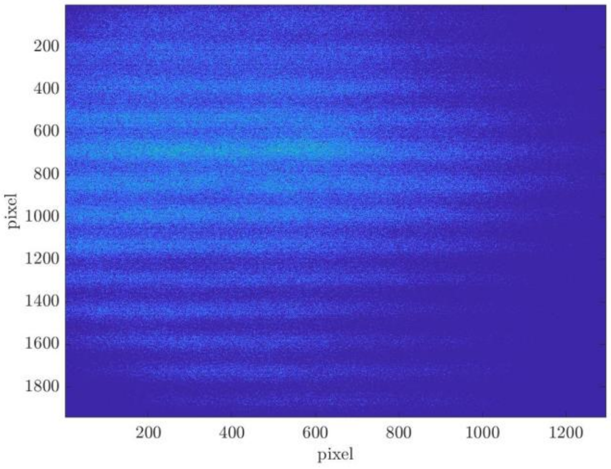
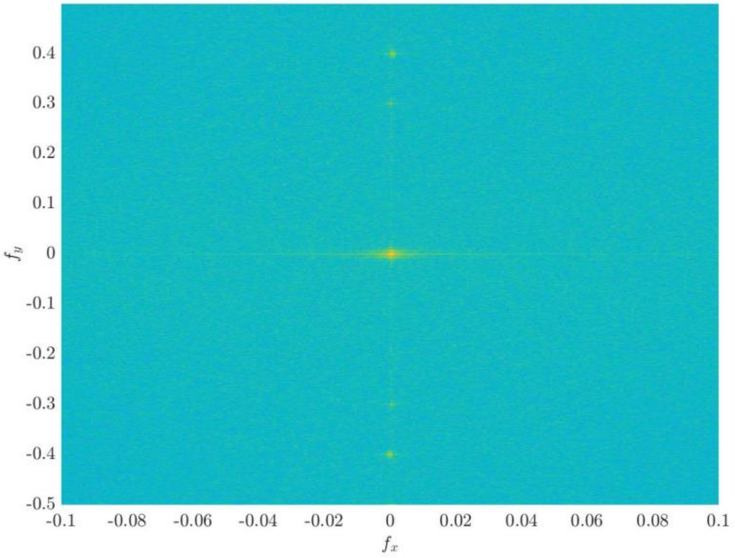
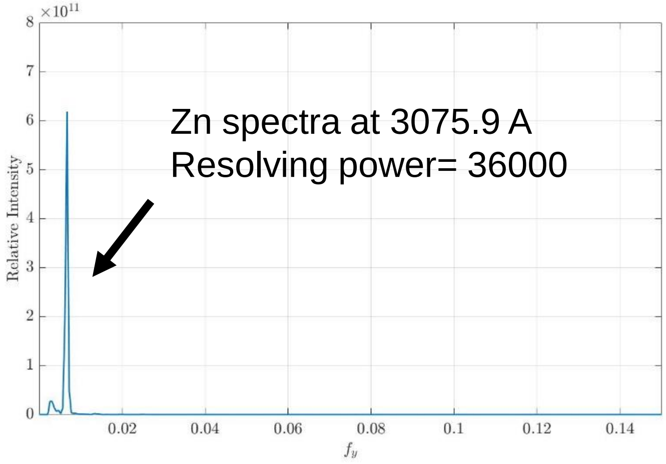
Zn lamp data analysis



Raw data from Zn hollow cathode lamp at 3075.9 A

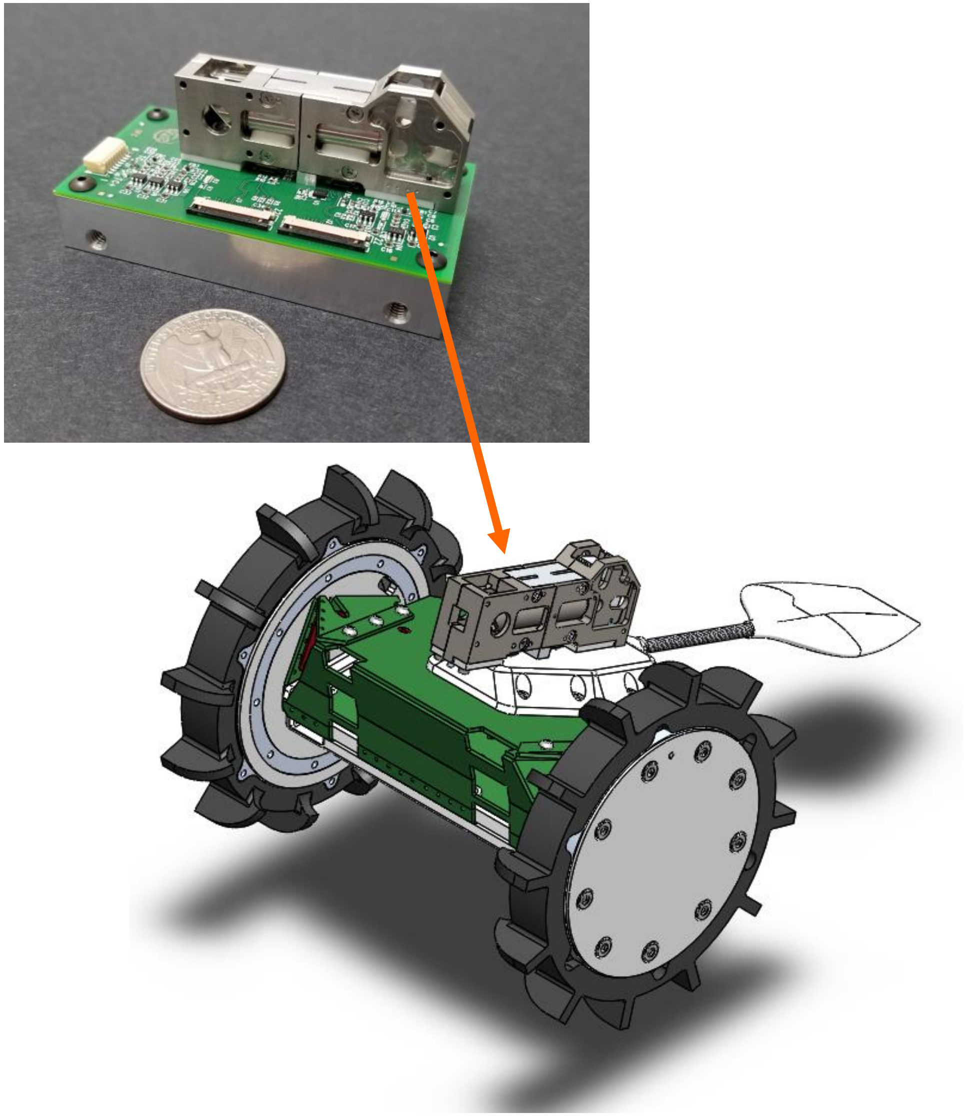
2-D FFT





Zn spectra at 3075.9 A
Resolving power= 36000

Hosseini, *et.al.*
under submission



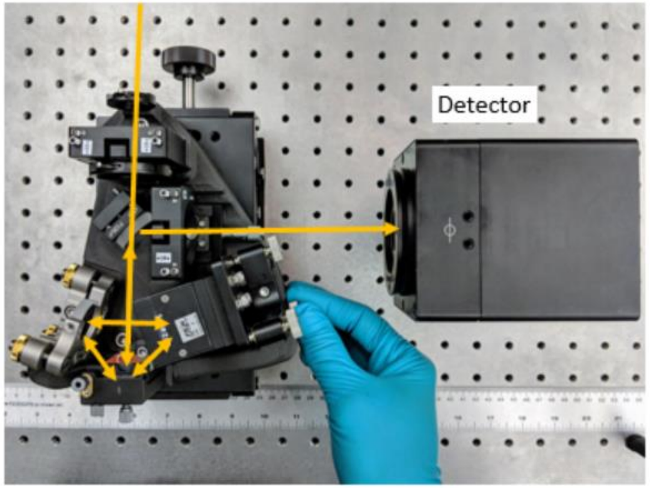
Heterodyne Wavelength	307.3 nm
Wavelengths of interest	OH: 308.6 Å OD: 307.9 Å
Calibration lines	Zn: 3075.9 A Al: 3093 A
Sensor (TRL4 solution) (TBD)	Sensor size: 2592 x 1144 Pixel size: 1.4 micron
Resolving power	~33600
Resolution	~0.09 Å
Bandpass	~3047.6–3118.3 Å (detector dependent)
FOV (field widen SHS) (TBD)	~4 x 4 degrees

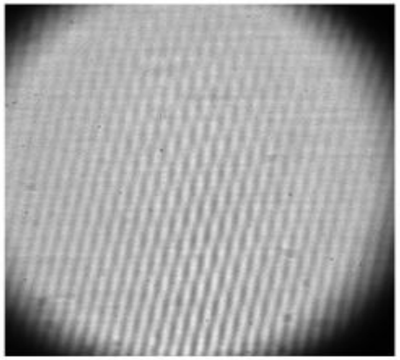
Specs / Resources	
Mass	~100 gm/channel
Power	~ 6 W
Volume	~20 cm x 10 cm x 3 cm per channel
Processing	Onboard FFT (TBD)
Precision/Accuracy	2 deg. pointing

Each HOLMS unite can observe a narrow bandpass at very high spectral resolution.

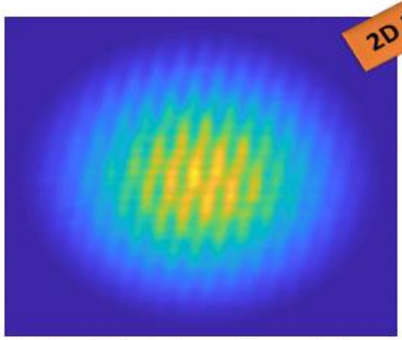
Hosseini,
under submission

Spatial Heterodyne Spectrometer

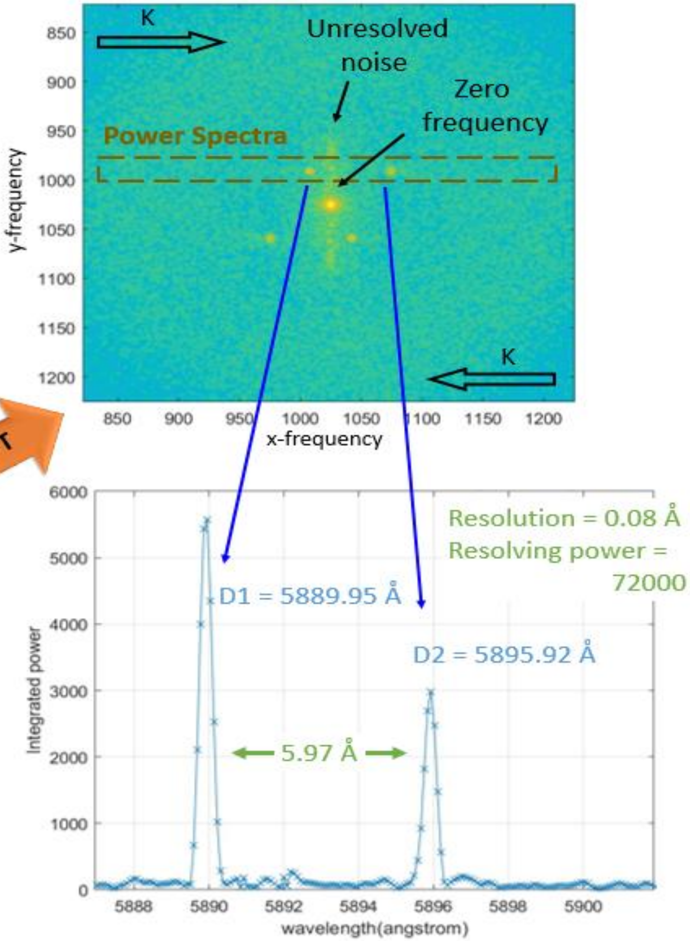




Raw fringes from Na doublet at 5889 Å and 5895 Å



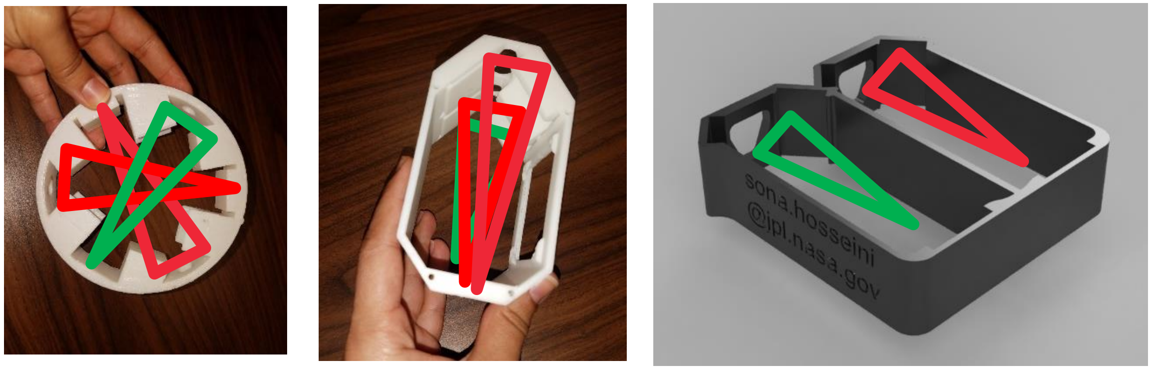
Before FFT, a Hanning window is applied to the data after reduction of dark, read noise and flat fielding.



Hosseini, under submission

Multi-unit SHS covering multiple species with no moving mechanism

Multi-units

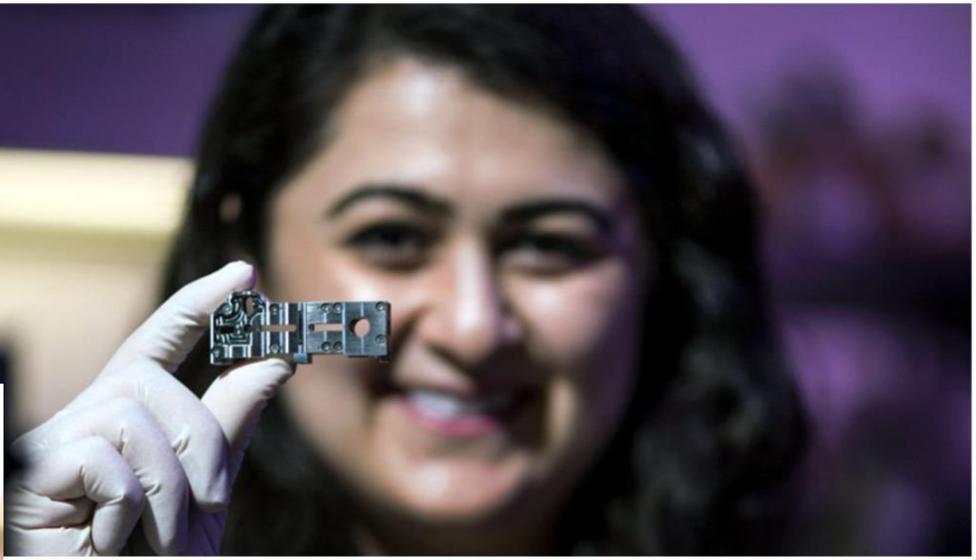


Isotope ratios	
OD/OH	308 Å separated by ~6 Å
$^{18}O/^{16}O$	^{16}OH and ^{18}OH at 3121 Å separated by < 0.3Å
$^{15}N/^{14}N$	N^{2+} at 3914 Å
Abundance ratios	
C_2/CN and CN/OH	C_2 at 5165 Å (^{13}CC at 5120-5170Å), CN at 3883Å
CO/OH and CO_2/OH	CO at 1510 Å, CO+ at 3954 Å, CO_2^+ at 3509 Å, OH at 3090 Å.

Sona Hosseini: The 2020 SPIE Early Career Achievement Award – Government/Industry Focus

The SPIE Early Career Achievement Award recognizes significant and innovative technical contributions in the engineering or scientific fields of relevance to SPIE

13 November 2019 Community



POWER TO THE PUNY

LITTLE GOES A LONG WAY

how we understand the shape and nature of our universe, just like Galileo's, are coming from ultraviolet, infrared, X-ray, and other wavelengths of light.

Technologists have developed a spectrometer to leverage these technology trends in optical sciences. Many of NASA's future key scientific goals will become achievable with the benefits of the next generation of miniature high-resolution spectrometers. The JPL mini high-res spectrometer is about the size of a thumb, obtains high spectral resolution with no moving parts, and requires very small input optics. It can observe weak targeted atomic and molecular spectral lines at these high resolutions thanks to a novel interferometric capability known as a spatial heterodyne spectrometer.

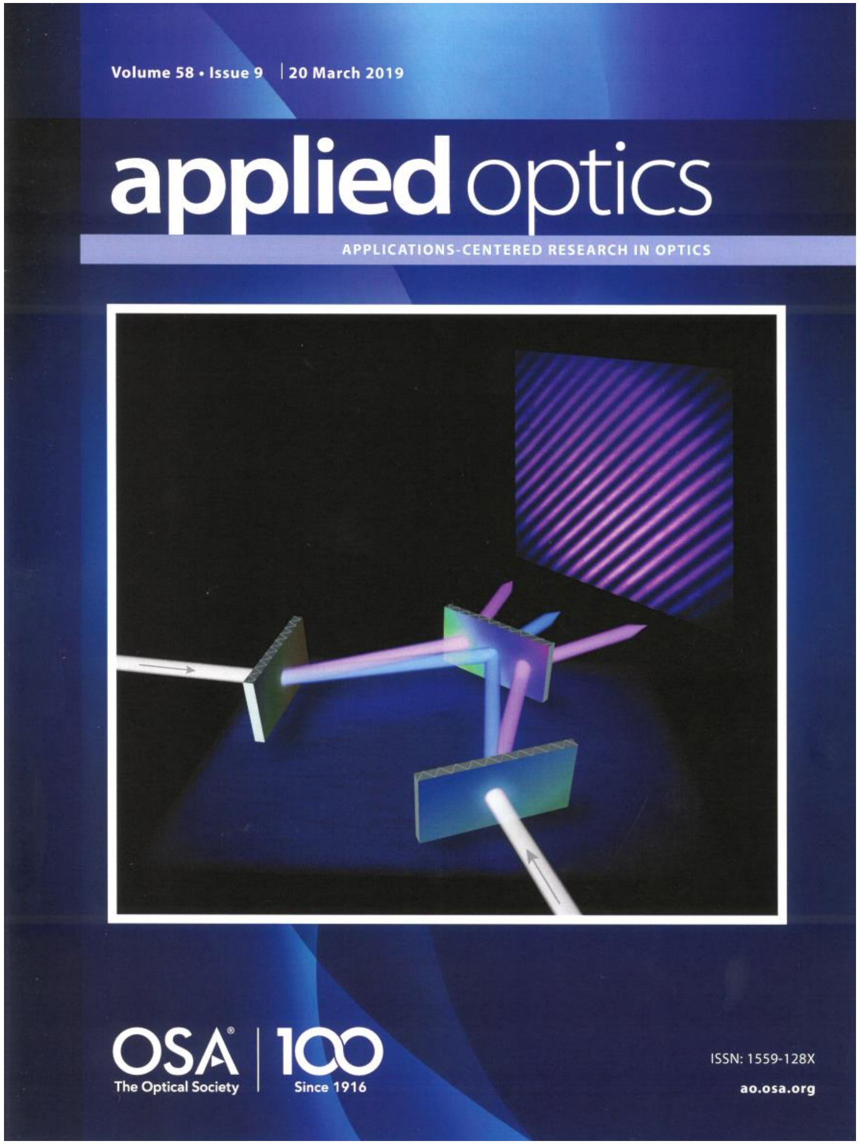
Employing this technology, future platforms will see fainter signals with higher sensitivity to detect and analyze important volatiles such as water in a comet, lunar environment, or anywhere else. Having the capability to detect isotopic ratios in the water tell us about its source, and ultimately where the water on Earth came from. High-sensitivity miniature sensors

time monitoring of anesthetic and respiratory gas mixtures in combat fields or during medical surgeries. The technology also opens the door to personalized medicine, like scanning eyes or blood. And thanks to the spectrometer's small size, all these capabilities could be accessed from a small, hand-held device, like a phone.

USING A NEW CAPABILITY, SPATIAL HETERODYNE SPECTROMETERS, FAR SMALLER—AND IN MANY WAYS MORE CAPABLE—SENSORS ARE NOW AVAILABLE FOR USE IN SPACE, WITH MYRIAD APPLICATIONS HERE ON EARTH

BIG THINGS COME IN SMALL PACKAGES

This miniaturized system could lead to unprecedented amounts of science return on mission investment, whether by freeing up mass in one system, or enabling a distributed network of small sensors.



Volume 58 • Issue 9 | 20 March 2019

applied optics

APPLICATIONS-CENTERED RESEARCH IN OPTICS

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ISSN: 1559-128X

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Research Article Vol. 58, No. 9 / 20 March 2019 / Applied Optics 2311

applied optics

Characterization of cyclical spatial heterodyne spectrometers for astrophysical and planetary studies

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Received 15 October 2018; revised 11 January 2019; accepted 13 January 2019; posted 14 January 2019 (Doc. ID 348409); published 18 March 2019

High-resolution spectroscopy can make key science measurements for a variety of astrophysics and planetary targets, including solar system planetary atmospheres, comets, solar wind charge exchange emission, and interstellar and interplanetary medium. With the ability to record adjacent spectral lines simultaneously key isotopic ratios such as D/H, $^{12}C/^{13}C$, $^{16}O/^{18}O$, etc., can be measured precisely. Traditional high spectral resolution spectrometers usually must couple to large optics to compensate for their low throughput, which prohibits achieving compactness, in particular in space and remote field applications. Also, the high cost of construction and maintenance limit their quantity and usage for the long duration temporal measurement of the sources. Spatial heterodyne spectrometers (SHS) are increasingly used in scientific observations and industry. To date, SHS instruments come in two major architectures: Michelson design and cyclical design. Cyclical SHS, also known as reflective SHS, can offer significant advantages over traditional spectrometers in obtaining high-resolution spectra in shorter wavelengths. Although cyclical SHSs have been introduced before, there has been no mathematical or performance characterization of their technique. This paper presents a comprehensive mathematical design and performance expectations of the cyclical tunable SHS technique to enable and expand its usage in a variety of platforms and applications, in the industry and astronomical observations from ground and space telescopes.

https://doi.org/10.1364/AO.58.002311

1. INTRODUCTION

Spatial heterodyne spectrometers (SHSs) are an emerging class of remote sensing instruments that fill the gap for providing the combination of high spectral resolving power (R, ~20,000–200,000) over a large field of view (FOV, ~0.5–10 deg) in a compact format coupled to a small aperture (<0.5 m diameter) telescope. SHS produces a wavenumber-dependent 2D-Fizeau fringe pattern from which the input spectrum is obtained via a Fourier transform. SHS spectrometers provide a modern, inexpensive, and accessible method for a compact high-throughput, high-resolution, wide FOV instrument suitable for studies of extended sources observed from ground and space platforms. High-resolution spectroscopy can reveal additional information about the physical characteristics of the source, such as velocity, temperature, pressure, composition, and the amount of energy entering or leaving a system. Especially, the high spectral resolution and high-throughput capability of SHS allows adjacent spectral line collection and separation for accurate measurements of isotopic ratios such as OD/OH, $^{3}He/^{4}He$, $^{14}N/^{15}N$, $^{12}C/^{13}C$, $^{16}O/^{18}O$, etc., in extended faint gases such as cometary coma.

To date, there are two major architectures based on the SHS technique, the Michelson design and the cyclical design. The majority of the SHS instruments are the Michelson SHS design where a grating in Littrow angle replaces the mirror in each interferometer arm. The first SHS was reported by Dohi and Suzuki [1] and thoroughly developed later for high spectral resolution applications [2–7] and Raman spectroscopy [8–10]. In the cyclical SHS design, a symmetric grating is used to both disperse and split the incoming beam. The $m = \pm 1$ orders of the grating rotate inside the interferometer and interfere with each other after exiting the interferometer. Although the cyclical SHS design can come with refractive optics [11], to date, the majority of the cyclical SHSs have an all-reflective design and hence are sometimes referred to as "reflective SHS" or "all-reflective SHS" design. A variety of reflective cyclical SHSs was reported by Harlander [2] and later developed by Chakrabarti *et al.* [12], Harlander *et al.* [13], Harris *et al.* [14], Dawson and Harris [15], Corliss *et al.* [16], and Hosseini *et al.* [17]. One of the beneficiary compensations of the cyclical SHS design is that the beam from both interferometer arms incidences the same optical surfaces in a common-path architecture. Because any

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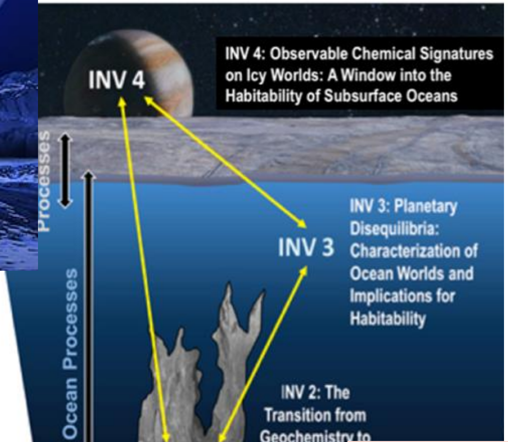
Icy, Ocean, (fill the blank), WORLD



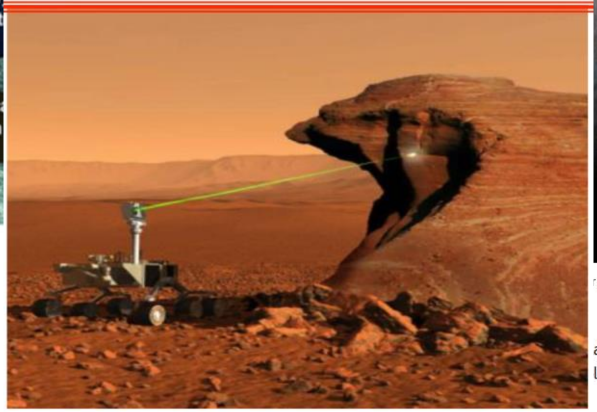
Bold new plan announced to explore alien ocean worlds

By Paul Scott Anderson in SPACE | November 2, 2018

Earth is not the only ocean world in the solar system. In fact, there are several. A new paper just published in Astrobiology seeks to plan out the best ways to explore these alien oceans.

system – apart from Earth of course. Image via

ace in the solar system with liquid
ld. But now, thanks to various spacecraft



It takes a village

It takes time

It needs $$

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Astrophysics
Interstellar Medium
Lyman-alpha mapping
Galaxies
Solar wind interface

Planetary Science
Mars atmosphere
Cometary Coma
Io Plasma Torus
Venus night airglow
Lunar sodium tail
Planetary plums

Earth Science
Wind and Temperature profiles
OH and Ozone Measurements

Jet Propulsion Laboratory
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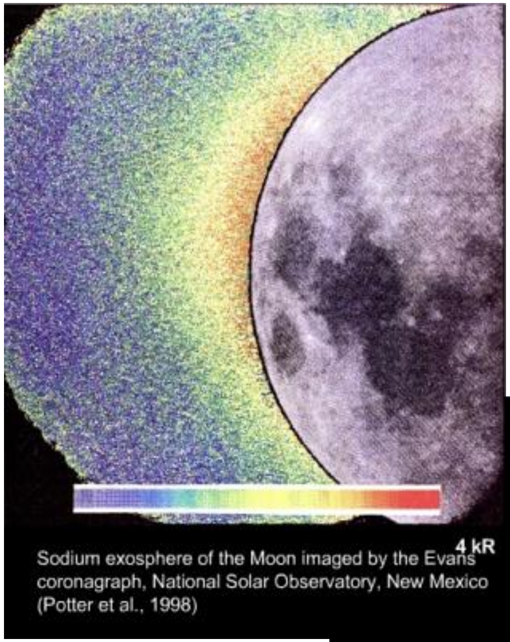
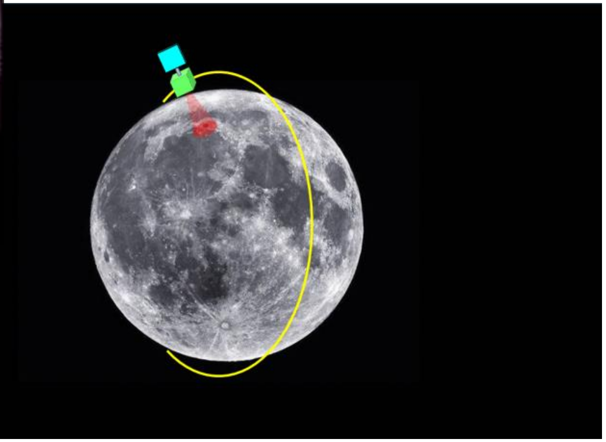
Backup

Little is know about the Lunar exosphere



Sodium exosphere of the Moon imaged by the Evans coronagraph, National Solar Observatory, New Mexico (Potter et al., 1998)



Characterize the existence of a lunar volatiles, i.e., OH
Potential detection of the full extent of the lunar OH tail
Acquire seasonal lunar limb observations

Spatial resolution: 1.7 km

Spectral resolution- Band 307.3 nm

- Resolving power R = 72,000
- Resolution: $\Delta\lambda \sim 0.1$ Å

Exposure time: 7sec

No mechanisms or moving parts

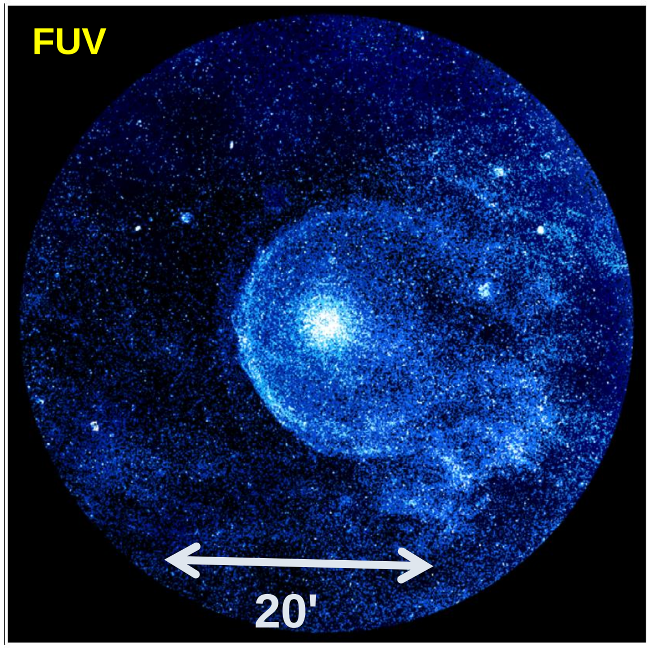
Detector temperature: -20 C

Passive cooling for detector

<u>The goal is to measure OH intensity in 308nm vs.</u>
Solar photons, Solar Energetic Particles, Solar wind, Meteoric influx, Large impacts

Hosseini, Davidsson
under submission

We have no spectra from Astrospheres because they are faint



GALEX FUV image
Sahai & Chronopoulos 2010

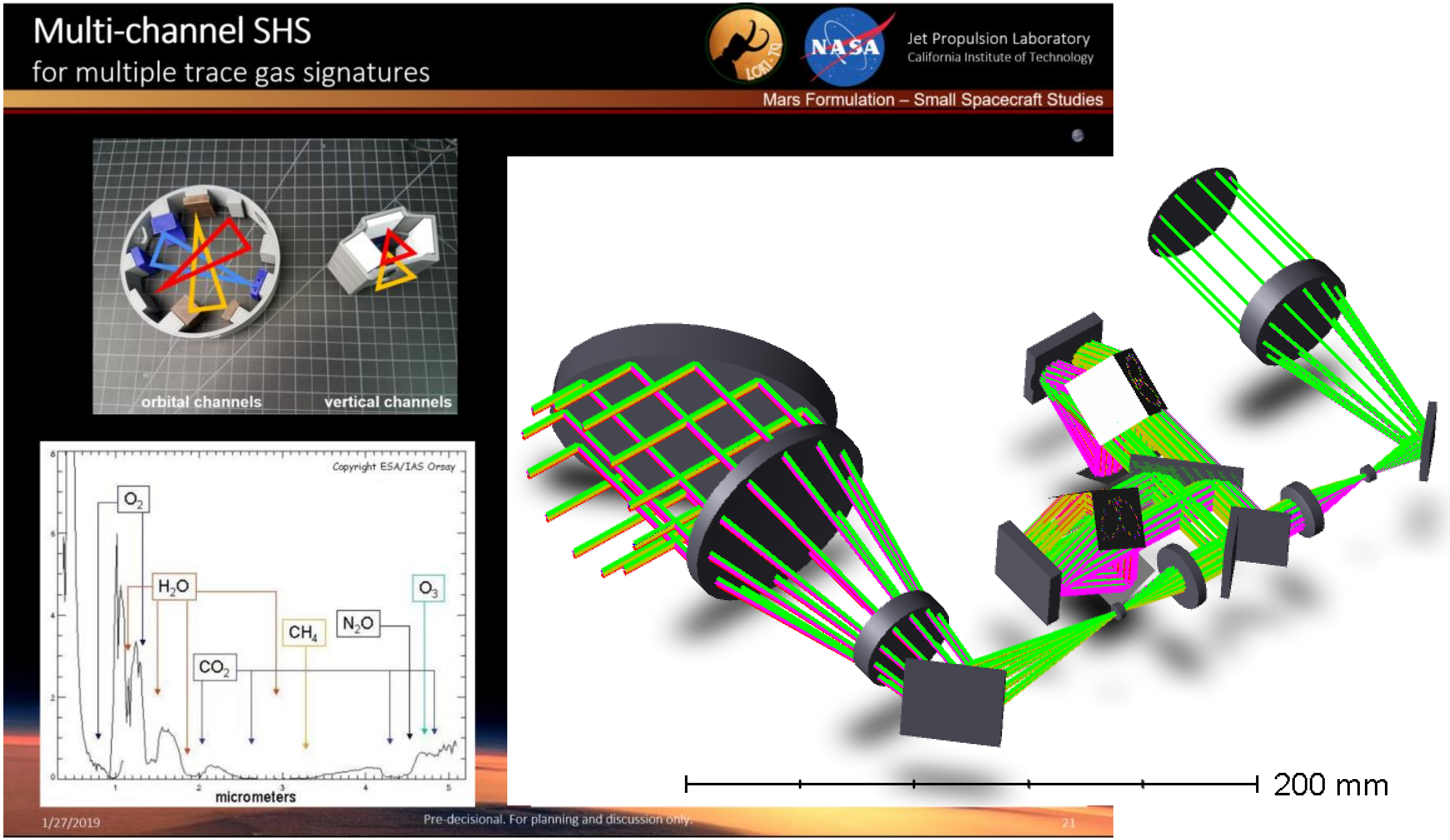
Deepest imaging study for the most well studied AGB star (Asymptotic Giant Branch Star), IRC+10216 detects the circumstellar envelope to a radius of ~200 arcsec,

GALEX FUV images detect envelope to 6x radius
Mass lost is > 1.4 M_{sun} over a period > 69,000 yr

FUV emission from astrospheres
likely due to line-emission in the Lyman-Werner emission band of H_2 collisionally excited by hot electrons in shocked gas (*from models of low-spectral-resolution GALEX grism spectra of one object*).

High-resolution spectroscopy at 1610 Å needed to confirm the nature of the emission, and determine the physical properties of the emitting region.

Hosseini, Sahai
under submission



Multi-channel SHS

for multiple trace gas signatures

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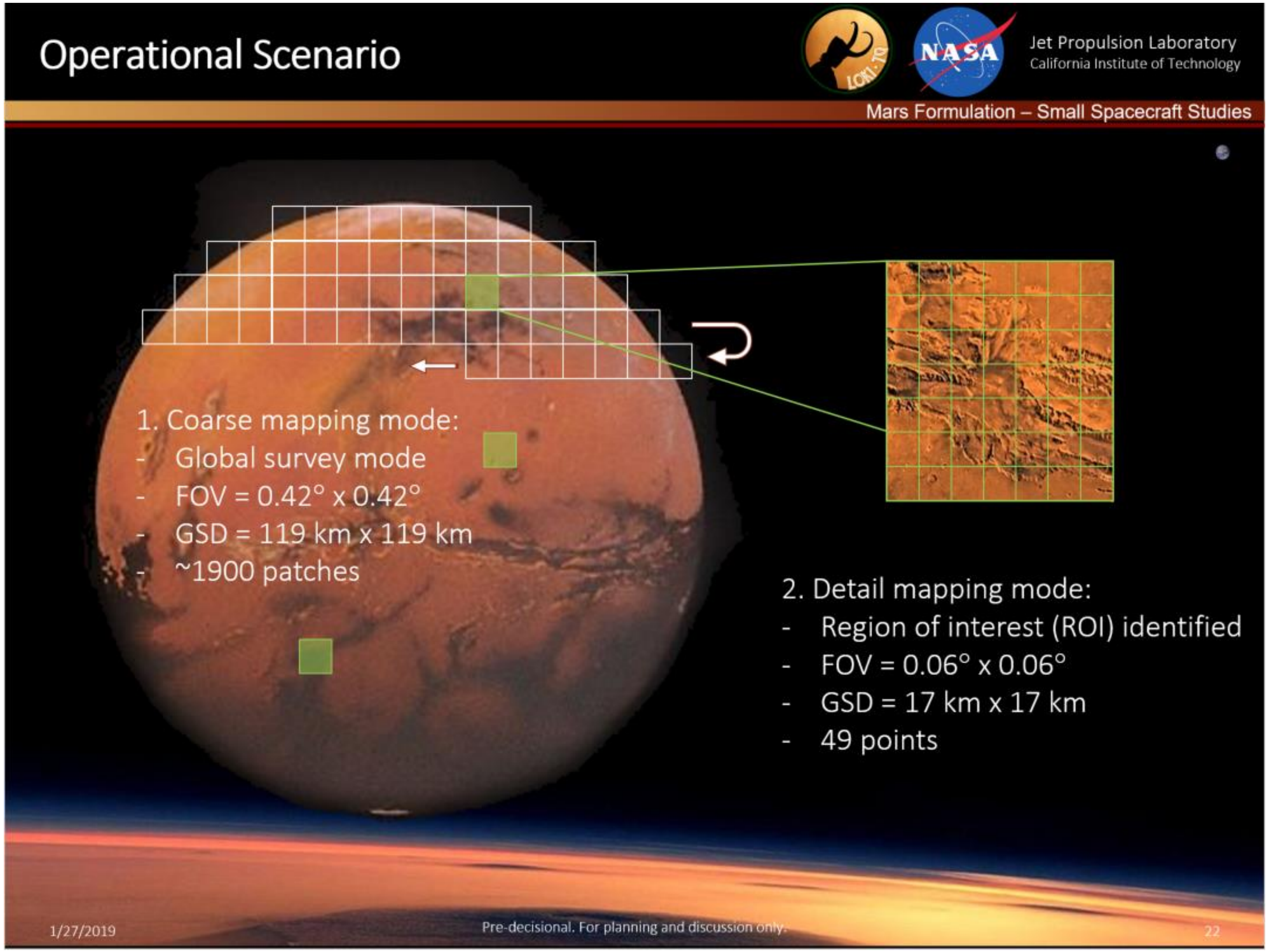
Mars Formulation – Small Spacecraft Studies

1/27/2019

Pre-decisional. For planning and discussion only.

21



Operational Scenario

Jet Propulsion Laboratory
California Institute of Technology

Mars Formulation – Small Spacecraft Studies

1. Coarse mapping mode:
- Global survey mode
- FOV = 0.42° x 0.42°
- GSD = 119 km x 119 km
- ~1900 patches

2. Detail mapping mode:
- Region of interest (ROI) identified
- FOV = 0.06° x 0.06°
- GSD = 17 km x 17 km
- 49 points

1/27/2019

Pre-decisional. For planning and discussion only.

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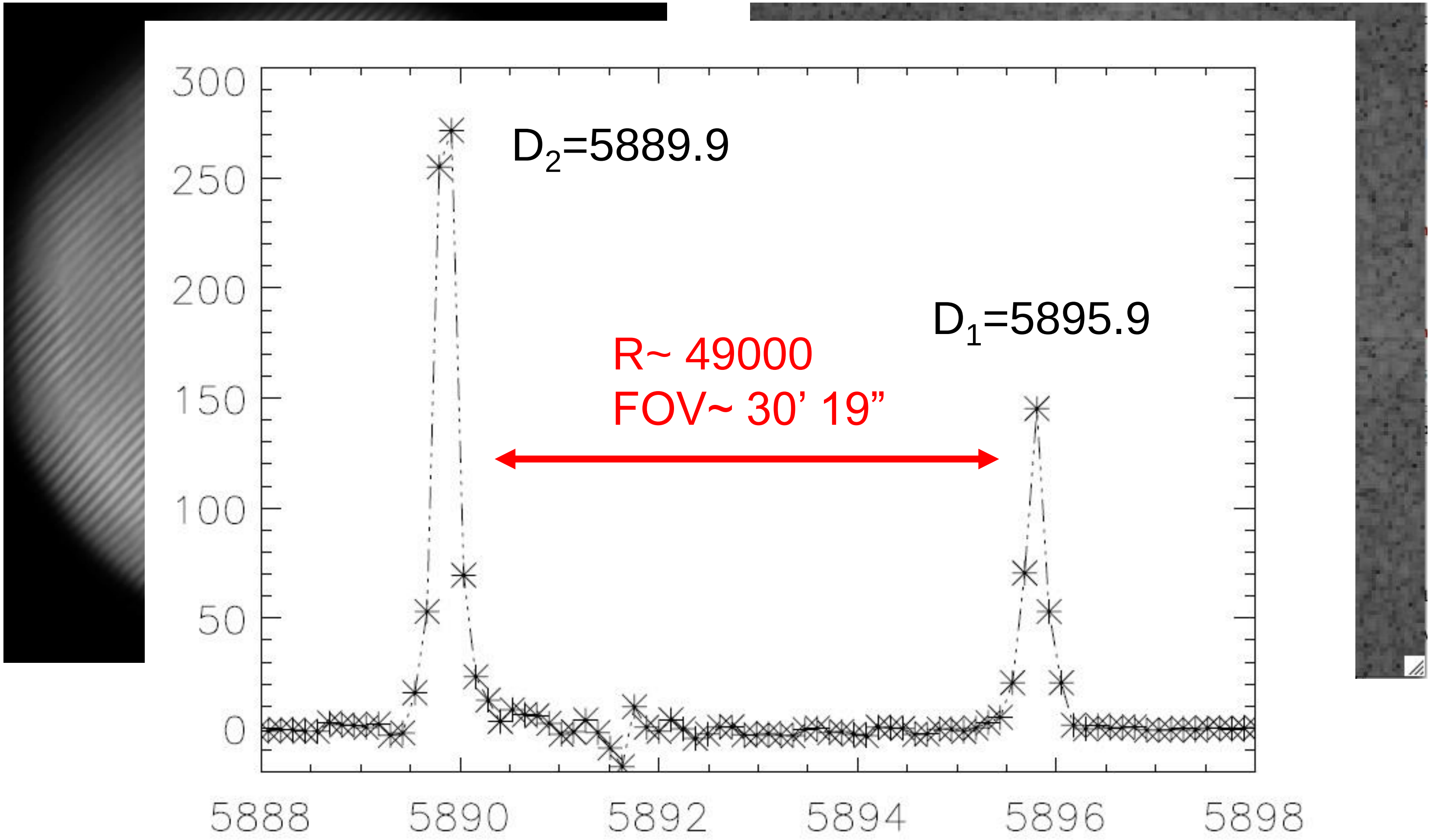
Miniaturization can maintain sensitivity

	GALEX	HUBBLE - STIS	HUBBLE - COS	SHS
				
Spectroscopy Technique	Grism and bandpass filters	Dispersive grating	Dispersive grating	Interferometric
Telescope Aperture	0.5 m	2.4 m	2.4 m	0.3 m
Wavelength	FUV band = 1344–1786 Å	"140M" channel = 1140–1741 Å	"G160M" channel = 1405–1775 Å	1200–1700 Å
Spatial Resolution	4.3 arcsec (FUV), 5.3 arcsec (NUV)	0.2 arcsec	2.5 arcsec	45 arcsec
Spectral Resolving Power	250–300	10,000	20,000–24,000	144,000
Detector QE	MCP, 12%	CsI, 25% @ 1216 Å	MCP 32% @ 1216 Å	CCD, 40–50%

Na lamp D line separation demonstrative the high spectra resolution



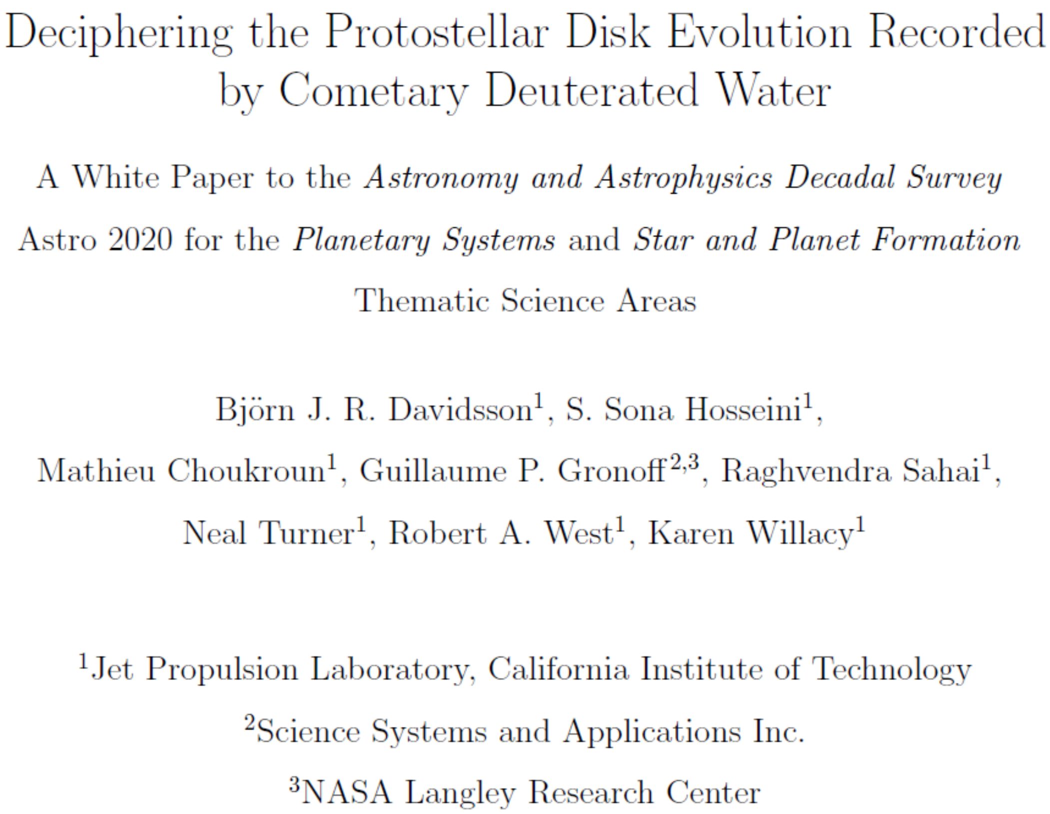
D_2=5889.9

D_1=5895.9

R~ 49000
FOV~ 30’ 19”

Hosseini, 2019

Astro2020 White paper



Deciphering the Protostellar Disk Evolution Recorded by Cometary Deuterated Water

A White Paper to the *Astronomy and Astrophysics Decadal Survey*

Astro 2020 for the *Planetary Systems* and *Star and Planet Formation*

Thematic Science Areas

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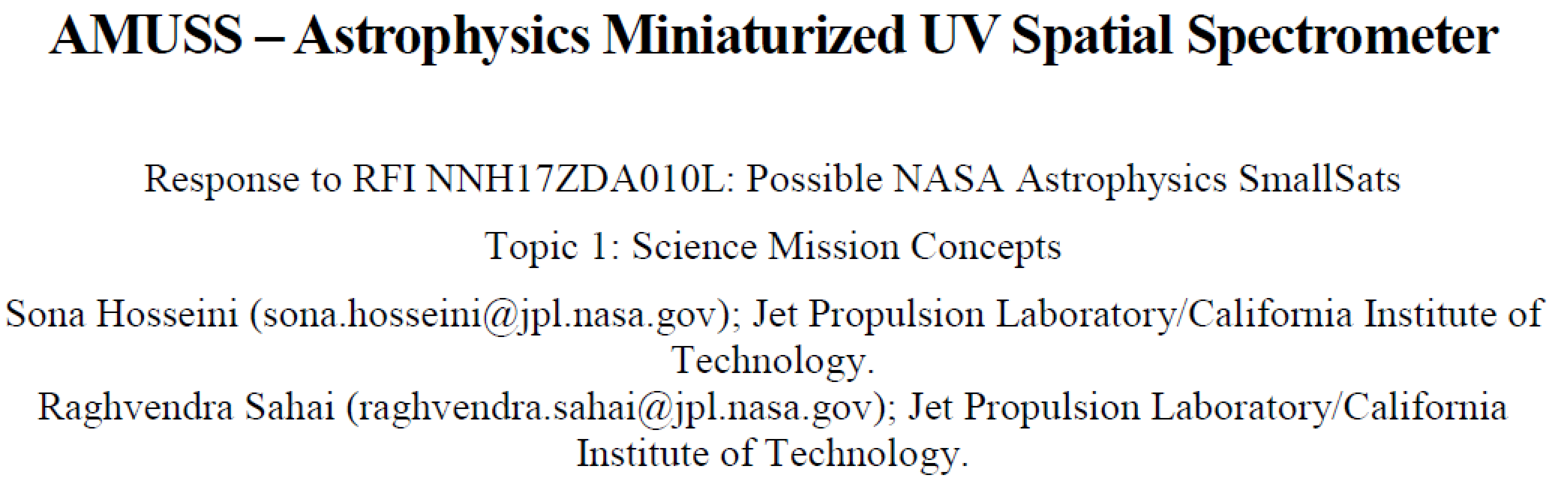
February 2019

Astrophysics RFI



AMUSS – Astrophysics Miniaturized UV Spatial Spectrometer

Response to RFI NNH17ZDA010L: Possible NASA Astrophysics SmallSats

Topic 1: Science Mission Concepts

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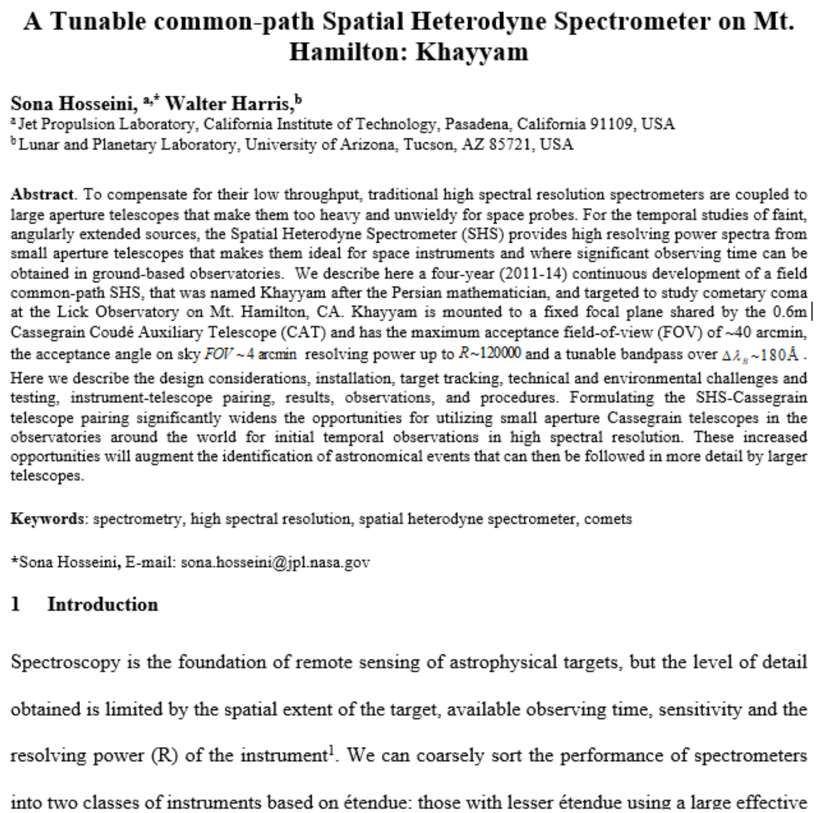
November 2017

Journal of Telescopes and Astronomical Instrum

Under final revision



A Tunable common-path Spatial Heterodyne Spectrometer on Mt. Hamilton: Khayyam

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Abstract. To compensate for their low throughput, traditional high spectral resolution spectrometers are coupled to large aperture telescopes that make them too heavy and unwieldy for space probes. For the temporal studies of faint, angularly extended sources, the Spatial Heterodyne Spectrometer (SHS) provides high resolving power spectra from small aperture telescopes that makes them ideal for space instruments and where significant observing time can be obtained in ground-based observatories. We describe here a four-year (2011-14) continuous development of a field common-path SHS, that was named Khayyam after the Persian mathematician, and targeted to study cometary coma at the Lick Observatory on Mt. Hamilton, CA. Khayyam is mounted to a fixed focal plane shared by the 0.6m Cassegrain Coudé Auxiliary Telescope (CAT) and has the maximum acceptance field-of-view (FOV) of ~40 arcmin, the acceptance angle on sky $FOV \sim 4$ arcmin resolving power up to $R \sim 120000$ and a tunable bandpass over $\Delta\lambda_B \sim 180\text{Å}$. Here we describe the design considerations, installation, target tracking, technical and environmental challenges and testing, instrument-telescope pairing, results, observations, and procedures. Formulating the SHS-Cassegrain telescope pairing significantly widens the opportunities for utilizing small aperture Cassegrain telescopes in the observatories around the world for initial temporal observations in high spectral resolution. These increased opportunities will augment the identification of astronomical events that can then be followed in more detail by larger telescopes.

Keywords: spectrometry, high spectral resolution, spatial heterodyne spectrometer, comets

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1 Introduction

Spectroscopy is the foundation of remote sensing of astrophysical targets, but the level of detail obtained is limited by the spatial extent of the target, available observing time, sensitivity and the resolving power (R) of the instrument[1]. We can coarsely sort the performance of spectrometers into two classes of instruments based on étendue: those with lesser étendue using a large effective

March 2019