Snow and Water Imaging Spectrometer (SWIS): development of a CubeSat-compatible instrument

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ABSTRACT

The Snow and Water Imaging Spectrometer (SWIS) is a fast, high-uniformity, low-polarization sensitivity imaging spectrometer and telescope system designed for integration on a 6U CubeSat platform. Operating in the 350-1700 nm spectral region with 5.7 nm sampling, SWIS is capable of simultaneously addressing the demanding needs of coastal ocean science and snow and ice monitoring. New key technologies that facilitate the development of this instrument include a linear variable anti-reflection (LVAR) detector coating for stray light management, and a single drive on-board calibration mechanism utilizing a transmissive diffuser for solar calibration. We provide an overview of the SWIS instrument design, spacecraft configuration design, and potential science missions.

Keywords: imaging spectroscopy, Dyson spectrometer, CubeSat, snow cover, coastal ocean

1. INTRODUCTION

Imaging spectroscopy is a powerful remote sensing technique that provides insight into a variety of geologic processes. It has been demonstrated on airborne platforms (AVIRIS[1], HyDICE[2], MaRS[3], NGIS[4], PRISM[5]), and at both the moon (M3)[6] and Mars (CRISM).[7] While airborne campaigns can provide data on demand, they normally provide limited area coverage and can become expensive or infeasible if frequent repeated sampling of an area is required. Large flagship missions on the other hand can provide global coverage and frequent repeat albeit at the expense of resolution.

CubeSats can offer a relatively low-cost alternative that can achieve intermediate to high resolution relative to global missions, and more frequent or more regular sampling relative to airborne campaigns. These qualities are particularly attractive in the areas of coastal ocean zones and snow or ice covered mountains, which have the potential to be particularly well-served with a CubeSat platform. The CubeSat-compatible Snow and Water Imaging Spectrometer (SWIS) instrument can therefore occupy a useful niche and provide complementary functions, if it can be shown that high-quality, science-grade data can be obtained from such a platform.

SWIS operates with a spectral range of 350-1700 nm and 5.7 nm sampling. This satisfies both coastal ocean targets, where spectral signatures exist mainly below 0.9 µm[8], and snow and ice targets, which contain critical features from the visible into the near- and shortwave-infrared.[9,10] The telescope and spectrometer operate at F/1.8 and provide the high throughput necessary for sufficient signal from low-reflectivity (< 1%) water surfaces, while a fast readout rate avoids saturation over bright snow (reflectivity > 90%). At a 100 mm focal length, the telescope provides 160 m resolution from an orbit of 500 km and is the highest resolution form able to fit in the 6U CubeSat frame (approximately 10 x 20 x 30 cm) without deployable mirrors. The improvement over heritage sensors (typically having greater than 500 m resolution) is of great importance given the high spatial variability of coastal ocean and snow targets.[8-10]

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2. SWIS SCIENCE MISSION CONCEPTS

A conceptualized image of the SWIS 6U CubeSat spacecraft is shown in Figure 1. The field of view is 10° with 600 cross-track pixels. Pointing capability of ±20° provides a 50° field of regard. By utilizing six such SWIS CubeSat spacecraft, evenly spaced 60° apart at a 500 km orbit (Fig. 2), we achieve the flexibility to access any point on the globe at least once on a given day. In this configuration, sample targets of interest such as the Tuolumne River Basin (snow cover) and the Long Island Sound (coastal ocean), can be accessed more than 500 times per year (Fig. 3).

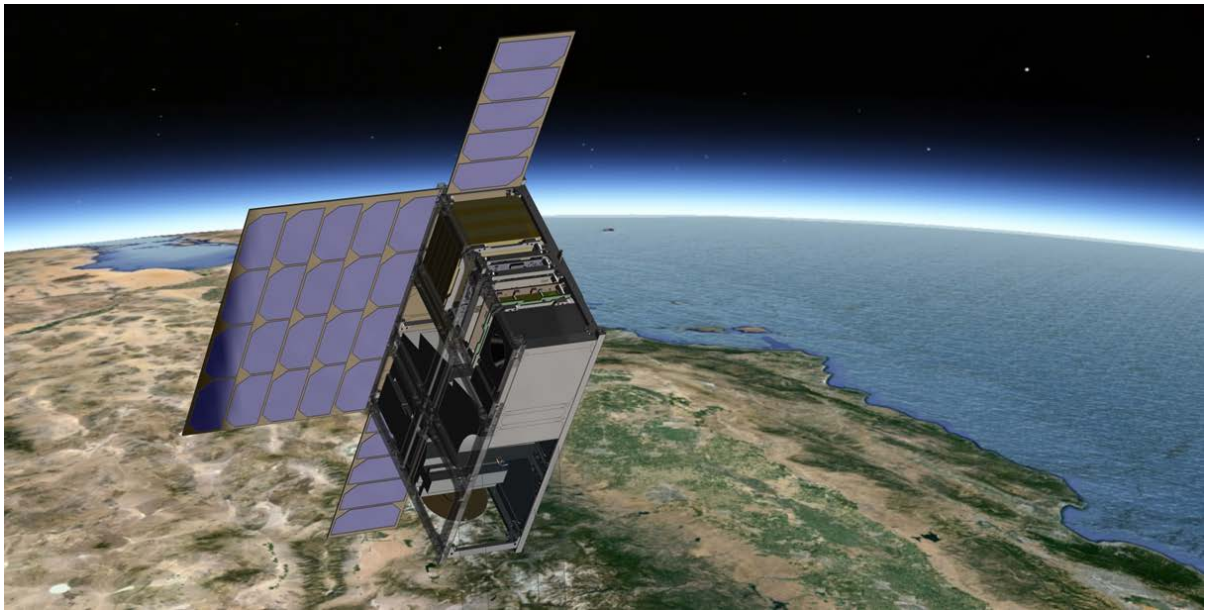

Fig 1: An artist's concept of the SWIS 6U CubeSat spacecraft, the spectrometer and telescope contained within the lower 4U

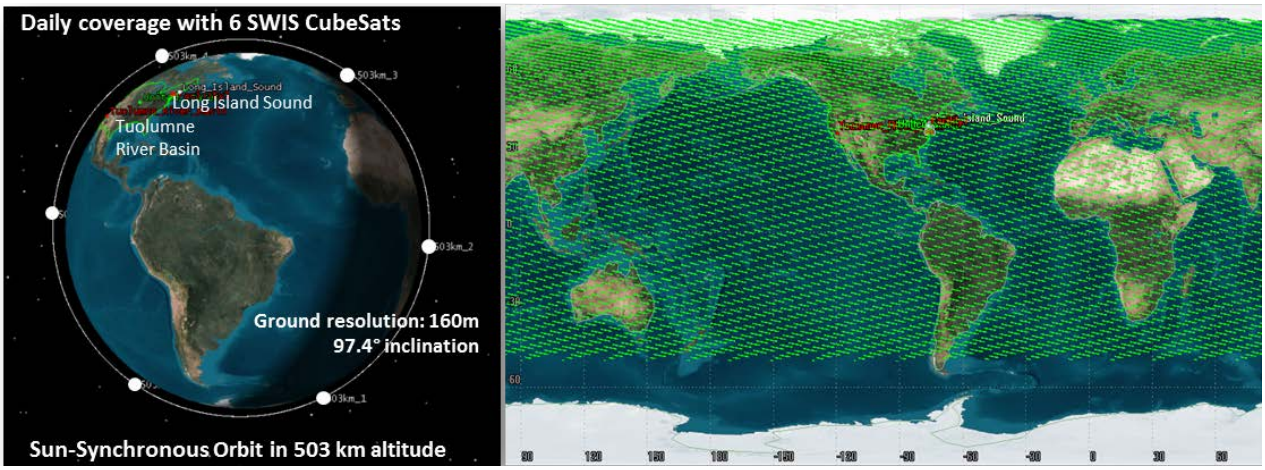

Fig 2: *Left:* One example of several possible configurations places 6 SWIS CubeSats evenly spaced at a 500 km orbit, each with a 50° field of regard, for flexibility to access any point on the globe on a given day. *Right:* Corresponding global coverage over one day with 6 CubeSats.

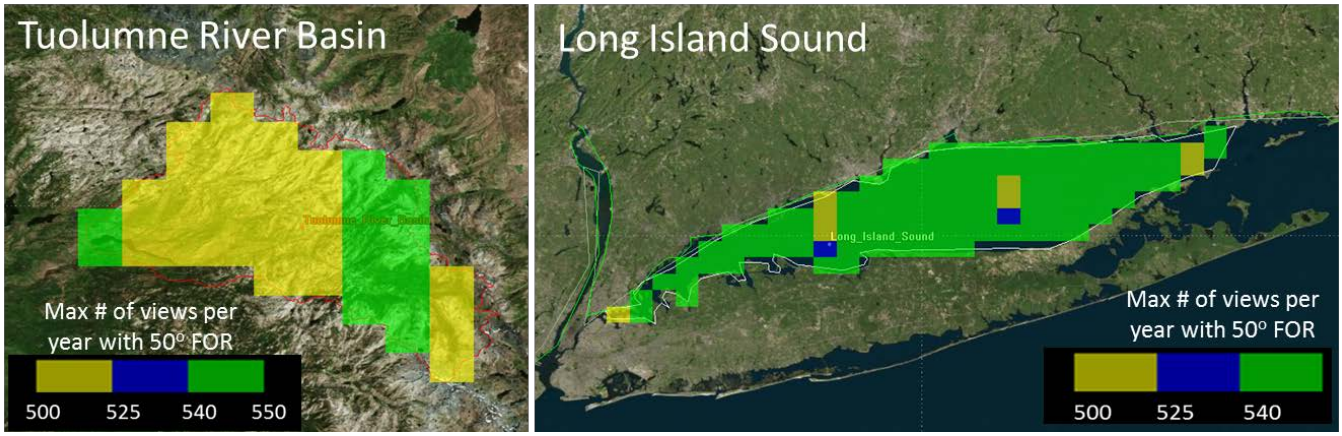

Fig 3: More than 500 views possible per year with a 6-CubeSat configuration over both the Tuolumne River Basin *(left)* and the Long Island Sound *(right)*.

Designed to meet requirements for both coastal ocean and snow cover, SWIS is particularly well-suited for studying glacier melt and its impacts on the aquatic ecosystem. Gradients from dry snow, to melting snow and ice, to melt-fed open-ocean span the most critical zones of climate change-impacted regions. In such regions, the SWIS spectrometer could simultaneously map the controlling processes of melt and the response of ocean biology to melt fluxes and nutrient loading.

Even without a fleet, a single SWIS CubeSat could provide adequate coverage for meaningful science over these targeted areas of interest (Fig. 4). Operating in a sun-synchronous orbit at 574km with a 50° field of regard, the single SWIS spacecraft could provide 40 revisits over six months to each of two such targets: the Jakobshavn Glacier in Greenland from April to September, and the Anverse Island Glacier in Antarctia from October to March (Fig. 5).

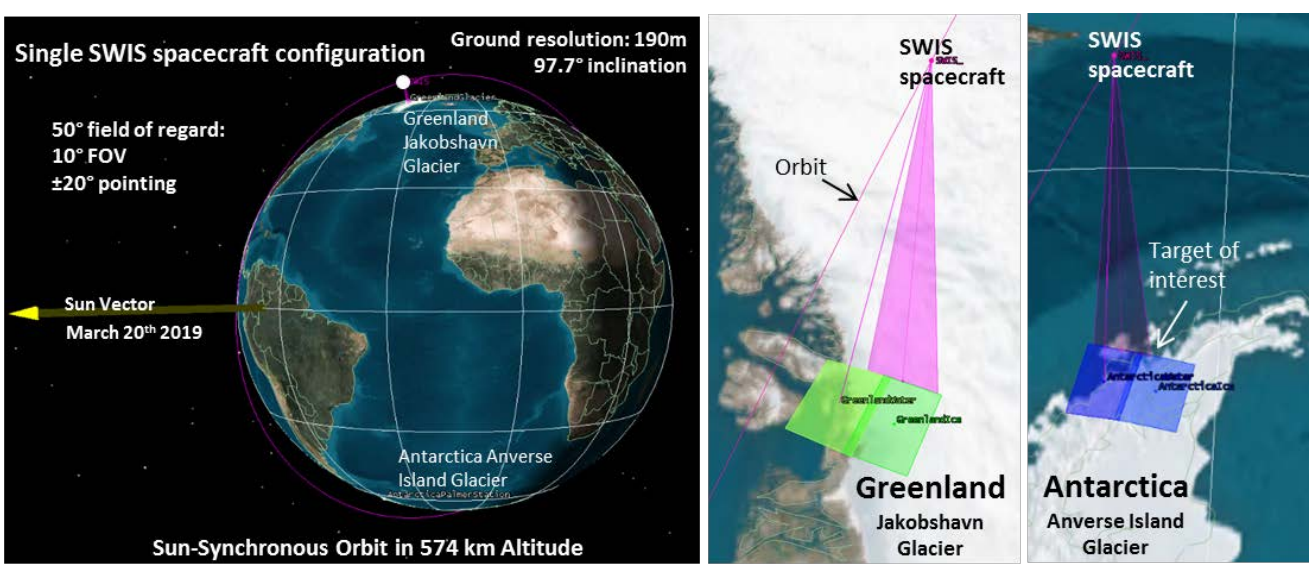

Fig. 4: A configuration involving a single SWIS CubeSat instrument can provide adequate coverage for targeted areas of interest. *Left:* Orbit simulation for single CubeSat in sun-synchronous orbit at 574km provides 190m ground resolution. *Right:* Area of detail over Greenland Jakobshavn Glacier, a target of interest for studying glacier melting processes.

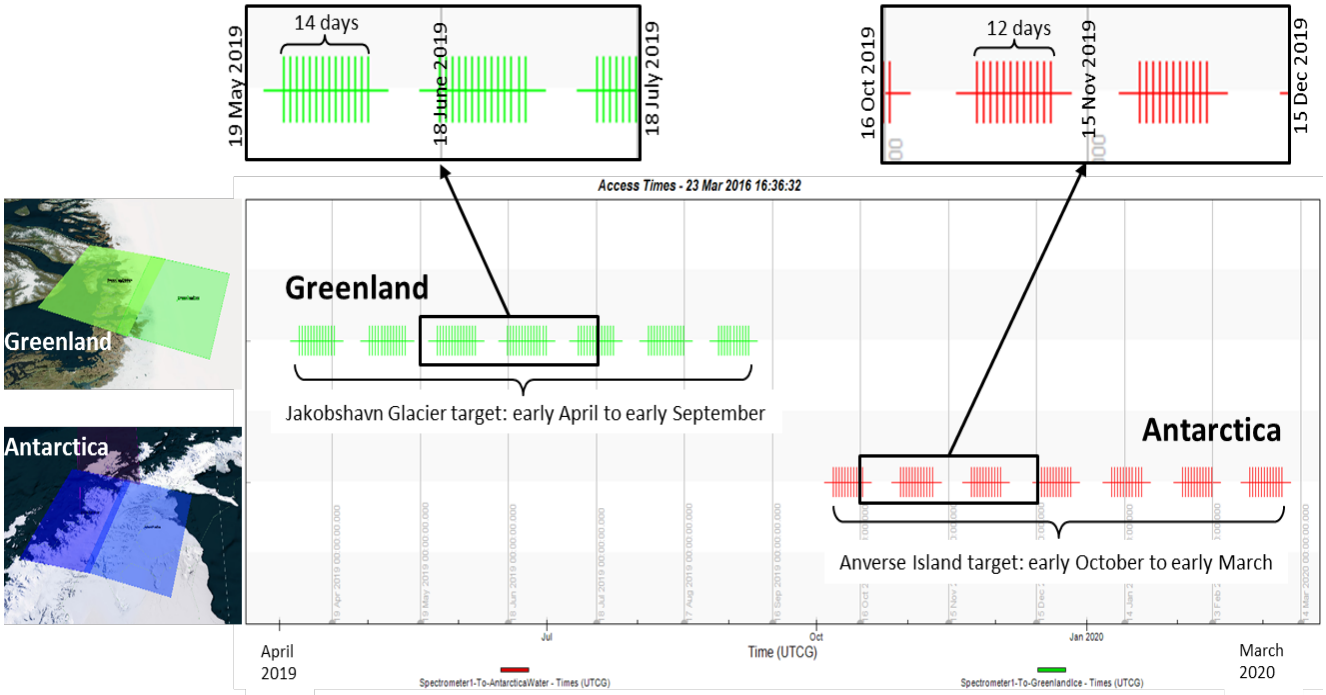

Fig 5: Simulation of a single SWIS CubeSat at a 574 km altitude sun-synchronous orbit, with 97.7° inclination and 50° field of regard. Each band indicates one collection opportunity at two glacier melt targets of interest: Jakobshavn Glacier, Greenland (green) and Anverse Island, Antarctica (red). Over a period of 6 months (April to September for Greenland; October to March for Antarctica), the CubeSat achieves 7 visits to each site, each time providing 12-14 days of consecutive-day access. Full target area coverage is possible by alternating between two adjacent patches on consecutive days, providing each site with approximately 40 visits over a 6 month period.

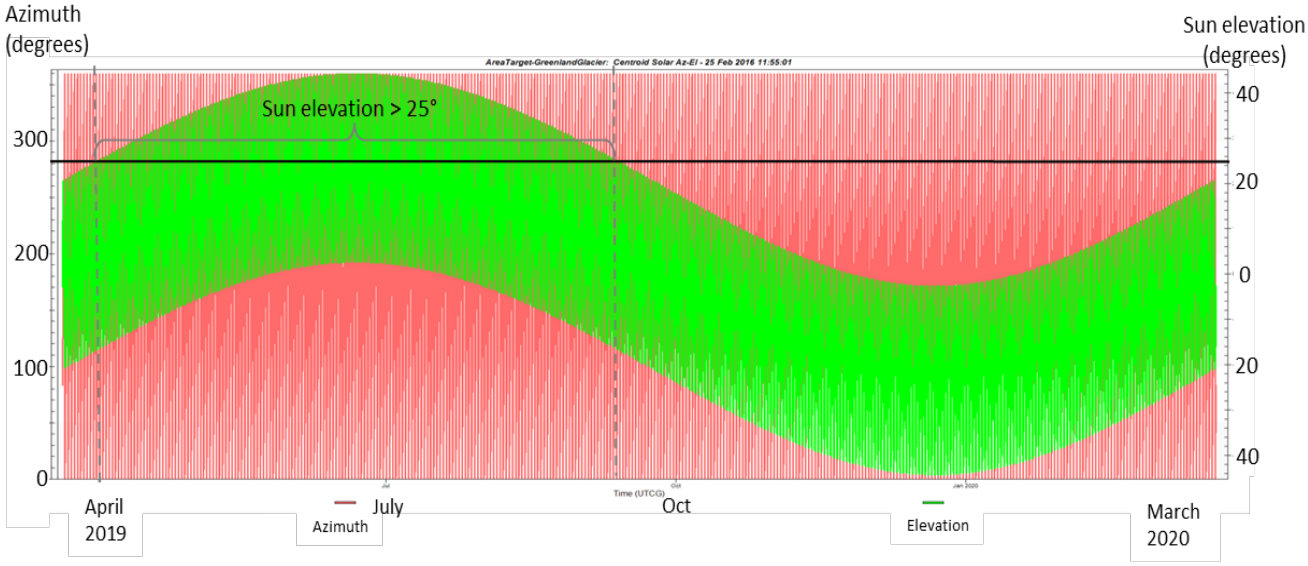

Fig 6: Sun elevation in green over 1 year at Greenland Jakobshavn Glacier target. Only between April and September is the sun elevation greater than 25°, as required for data collection.

3. SWIS DESIGN

3.1 Optical design and specifications

The SWIS optical design consists of a three-mirror anastigmat (TMA) telescope and Dyson form spectrometer. A raytrace is shown in Fig. 7, and system specifications are given in Table 1. SWIS smile and keystone are negligible at less than 1% of a 30 µm pixel, with expected response function FWHM variation at 10% or better. Ref. 11 contains a further discussion on the optical design and stray light considerations.

Table 1: SWIS system specifications

Property	**Value**
Spectral range	350-1700 nm
Spectral sampling	5.7 nm (/30 µm)
Cross track spatial elements	600 (+40 monitor)
Uniformity	95%
Resolution	0.3 mrad
Slit width	30 µm
Working F-number	1.8
Cross track FOV	10° (±20° pointing)

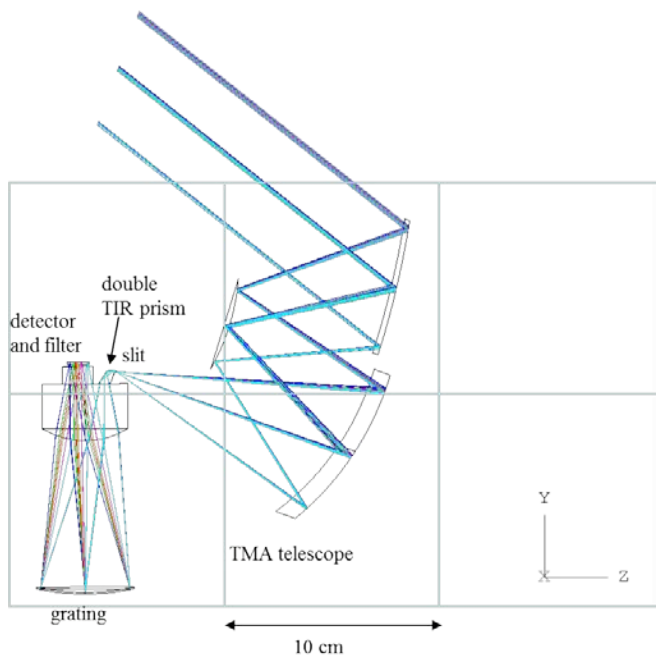

Figure 7: Spectrometer and telescope raytrace overlaid with a 20 cm x 30 cm rectangular footprint, approximating a 6U CubeSat frame. The frame extends 10 cm in the x-direction, and telescope mirror size is maximized within that available space. The folding arrangement is made possible by a small prism used in dual total internal reflection.

A critical component of the design is the diffraction grating, which is fabricated at JPL with a tailored broadband response. The polarization sensitivity of the entire system is estimated to be below 2% through the range 350-1000 nm using bare aluminum mirror coatings. This includes variation due to the grating, measured at < 1% over these wavelengths. Beyond 1000 nm, the polarization sensitivity is allowed to increase somewhat since the corresponding polarization variation of the stimulus due to the atmosphere is reduced. As with the PRISM instrument, proprietary processes allow the manufacturing of non-linear groove profiles that can simultaneously optimize diffraction efficiency through the band and also minimize polarization sensitivity.[5] Compared to PRISM, the present design is somewhat more challenging due to the smaller spectrometer and groove size. However, a satisfactory solution has been obtained based on a trilinear groove profile. Measurements results of the instrument grating are shown in Fig. 8.

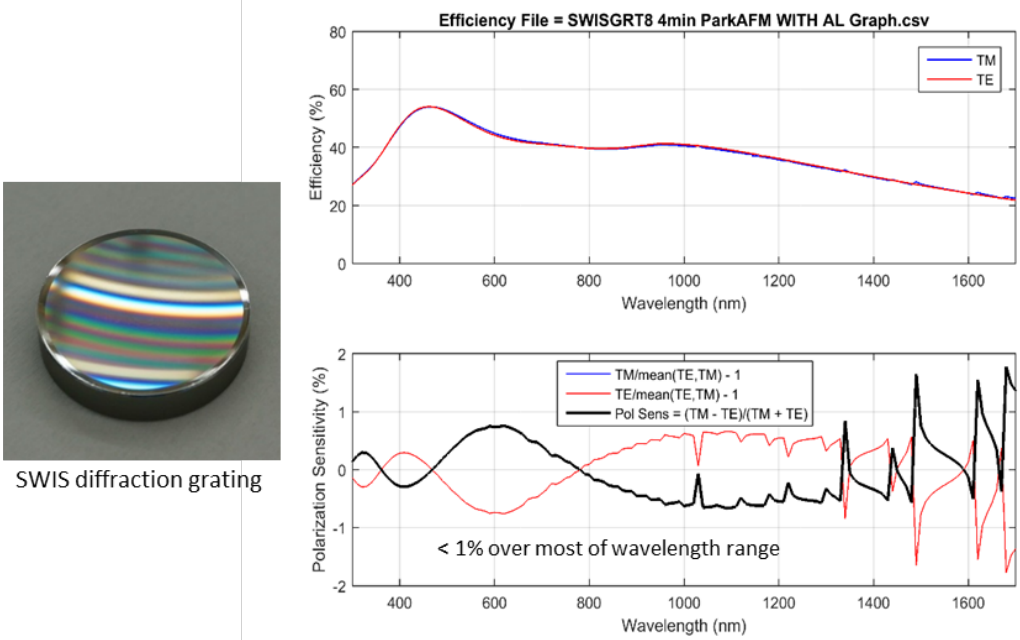

Figure 8: Left: Macro photo of SWIS diffraction grating. Right: Grating efficiency (top) and polarization sensitivity (bottom) is <1% over most of the wavelength range. The resonances seen in the second figure are typically smoothed out by the variation in the grating angle of incidence through the aperture.

3.2 Optomechanical Design

The SWIS optomechanical assembly fits within 4U (10 x 20 x 20 cm) of a 6U (10 x 20 x 30 cm) CubeSat frame (Fig. 5). Total combined mass of the optomechanical assembly is 1.84 kg, with 967 g attributed to the telescope, 679 g from the spectrometer, and 195 g for instrument interface bipods and fittings. To satisfy the stringent radiometric calibration accuracy required for imaging spectroscopy[12], we have developed a new single drive mechanism which performs the dual function of positioning the on-board calibrator (OBC) as well as providing a shutter for dark frames. Solar calibration is achieved using a transmissive diffuser material, Heraeus OM-100, which is Lambertian enough that we might achieve stable illumination without the need for highly accurate CubeSat pointing. A further discussion on the SWIS optomechanical design, structural analysis and solar calibration mechanism is provided in Ref. 13.

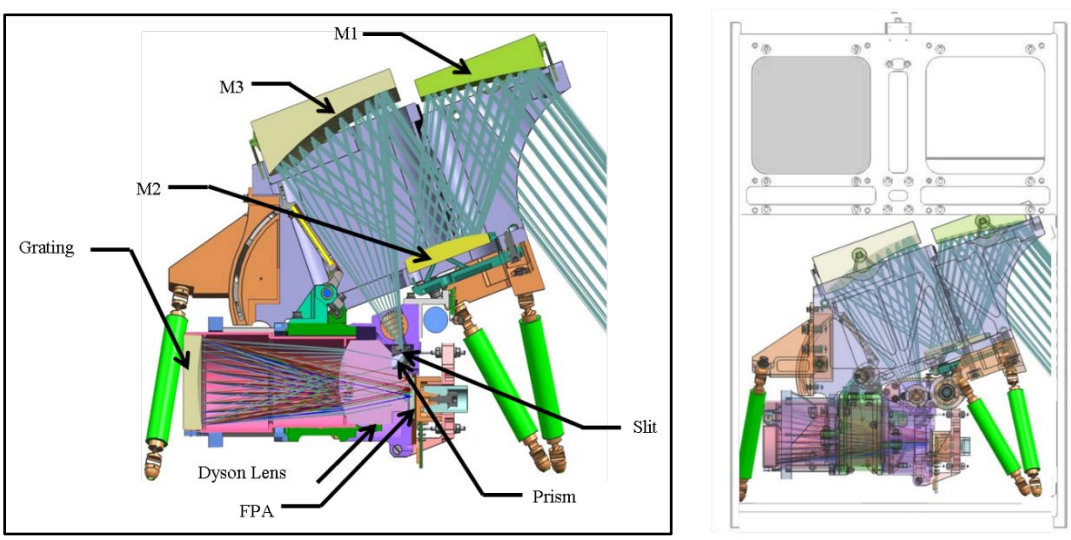

Figure 9: *Left:* SWIS optomechanical model section view showing optical elements; *Right:* Orientation in 6U CubeSat frame

3.3 Thermal design

The SWIS thermal design is discussed in greater detail in Ref. 13, but centers around three important thermal requirements. The first is to maintain all components within their operational and non-operational temperature limits. Most components have unremarkable temperature limits, but the focal plane array (FPA) must be held below 250 K. In addition there are two notable stability requirements: the FPA temperature must be stable to ±0.1 K, and the spectrometer temperature must be stable to ±1 K. A detailed modeling analysis under nominal conditions (beta angle 37°, altitude 500km) indicates that these requirements are met, with a potential for detector operating temperature down to 230 K. Testing of the detector material at the planned operational temperature of 250 K shows good response and dark current, providing 20K in margin. Other data indicate the rest of the spacecraft components have on-orbit temperatures within the component temperature limits.

3.4 Spacecraft configuration design

The current spacecraft configuration model (Fig. 10) is favorable for accommodation in a 6U CubeSat frame. Components have been identified and designed specifically to fit within a standard 6U satellite dispenser available from Planetary Systems Corporation.

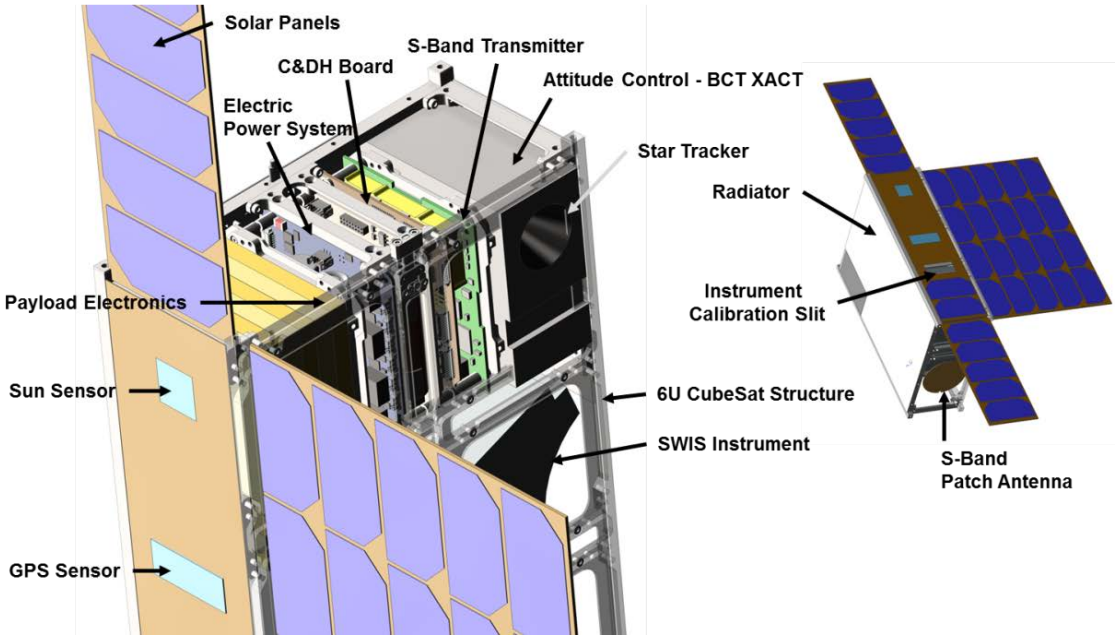

Figure 10: SWIS CubeSat configuration within a 6U structure. The optomechanical instrument fits within the lower 4U.

4. CURRENT STATUS

Assembly and alignment of the SWIS optomechanical system is underway. By early 2017, the system will undergo thermal and vibration testing in flight-like conditions. A CHROMA detector array, optimized for high temperature operation, is under development at Teledyne, with testing of the detector material showing good response and dark current at operating temperature. Detector electronics and flex cable have been fabricated, and a linear variable anti-reflection coating has been developed to enhance quantum efficiency and minimize backscatter. A complete system model is under study and is favorable for eventual accommodation in a 6U CubeSat.

5. CONCLUSIONS

We present a high-heritage, science-grade imaging spectrometer design suitable for CubeSat applications. The design advances the state of the art in compact sensors of this kind in terms of size and spectral coverage. New enabling technologies include a linear variable anti-reflection (LVAR) coating to provide a critical reduction in stray light, and a single drive on-board calibrator (OBC) for solar and dark calibration. The current spacecraft configuration is well-contained within a standard commercial 6U frame. Useful missions can be designed using the SWIS instrument to address targeted areas of the Earth's surface with high spatial and temporal resolution, and high throughput signal to noise. Potential science applications have been identified over coastal ocean and snow/ice covered mountain regions utilizing either a single CubeSat for targeted coverage or six CubeSats for global access.

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