Miniaturized Monolithic Hollow-Waveguide Spectrometer for CubeSat-Based Remote Mid-Infrared Sensing

G. Smalling[1*], B. Pearce[1], F. Luca[1], P. Russell[1], T. Hewagama[2,3], S. Aslam[3], J. Allen,Jr.[1,3]

[1]Appalachian State University (* at the meeting), [2]University of Maryland-Baltimore County, [3]NASA's Goddard Space Flight Center

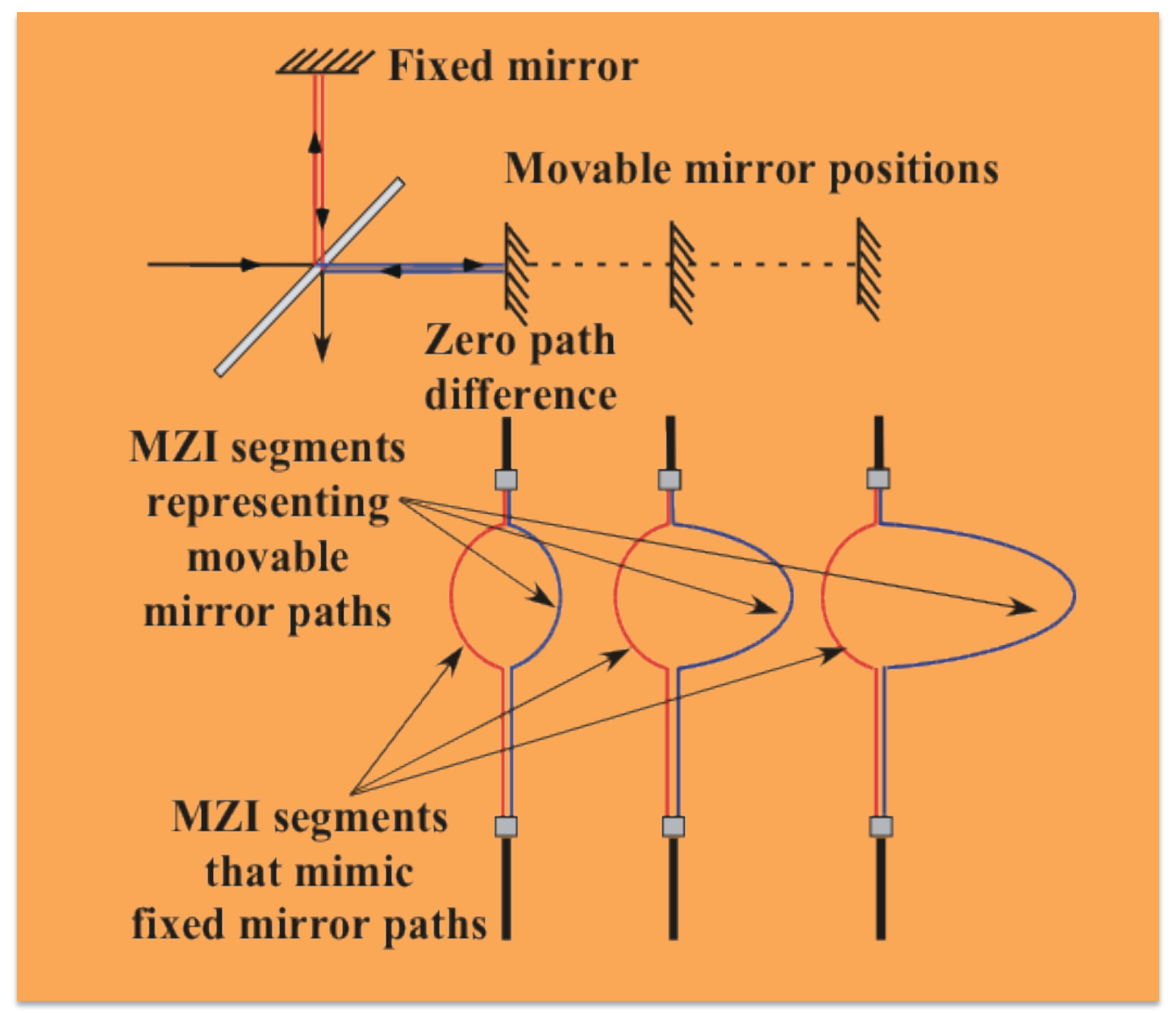
Abstract

Miniaturized monolithic waveguide devices have been designed as part of an ongoing project to develop a mini Fourier-Transform Spectrometer (micro-FTS) on a chip for remote sensing applications. One application of the micro-FTS waveguide device is remote atmospheric sensing via a CubeSat, providing a compact, lightweight platform for low-cost missions. Hollow-waveguide devices have been fabricated using photolithography and deep reactive ion etching (DRIE) techniques on silicon wafers. The devices were characterized using Scanning Electron Microscopy (SEM) and processed with a Focused Ion Beam (FIB) to remove debris produced by the manufacturing process. SEM analysis showed both silicon shards and over-deposition of gold within the waveguide channels as defects. Alternative manufacturing methods are being investigated to minimize defects and maintain the transmission integrity of the hollow waveguides.

Figure 1. Image of an assembled micro-FTS chip containing multiple Mach-Zehnder waveguide pairs with a quarter shown for scale. Several chips could be stacked together to create a device capable of sampling a wider spectral range.

Introduction

- Typical FTS systems are massive, bulky, and require a large investment to place in orbit.
- FTS's traditionally require a moving mirror and beam splitter to divide the incoming light into different paths of varying lengths, resulting in a phase shift between light waves following different paths. Thus, mirror position modulates the phase shift.
- Interference between light from each path is used to produce an interferogram of intensity as a function of path length difference.
- The interferogram is processed mathematically using a fast Fourier transform (FFT) to yield the spectral form of intensity as a function of wavelength.
- The variation in path lengths of an FTS may be mimicked using a series of Mach-Zehnder interferometers (MZI). (See Fig. 3)
  - One path length of each pair is held constant and equal from pair to pair.
  - The other path is varied by increasing the length from pair to pair.
  - Florjanczyk (2009) and Okamoto (2010, 2012) have successfully demonstrated this in the near-infrared (NIR) using solid-core fiber optics [1-5].



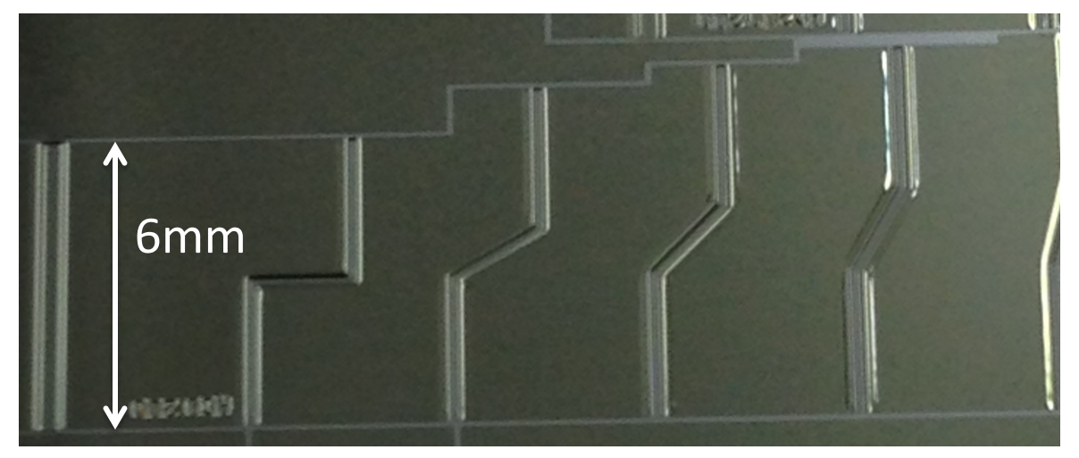


Figure 2 (above). Magnified image of a sample chip showing the geometry of the waveguide channels used in characterizing optical properties.

Figure 3 (left). Schematic of fiber optic MZI pairs used to simulate path differences between the fixed and moving mirrors of an FTS.

Miniaturizing the FTS System

- The project goal is to miniaturize the FTS by employing advances in photonics and materials-processing technologies to eliminate moving parts.
- The reduction in size and complexity of the mini-FTS makes the system attractive for use in CubeSat and Nanosatellite applications.
- The current devices have been designed for use in the mid-IR (MIR), specifically 8 to 12 μm range, however target range may be varied by adjusting path length.
- Hollow metal-wall waveguides were selected because few infrared transmissive materials in the desired wavelength range are available to fabricate dielectric waveguides.

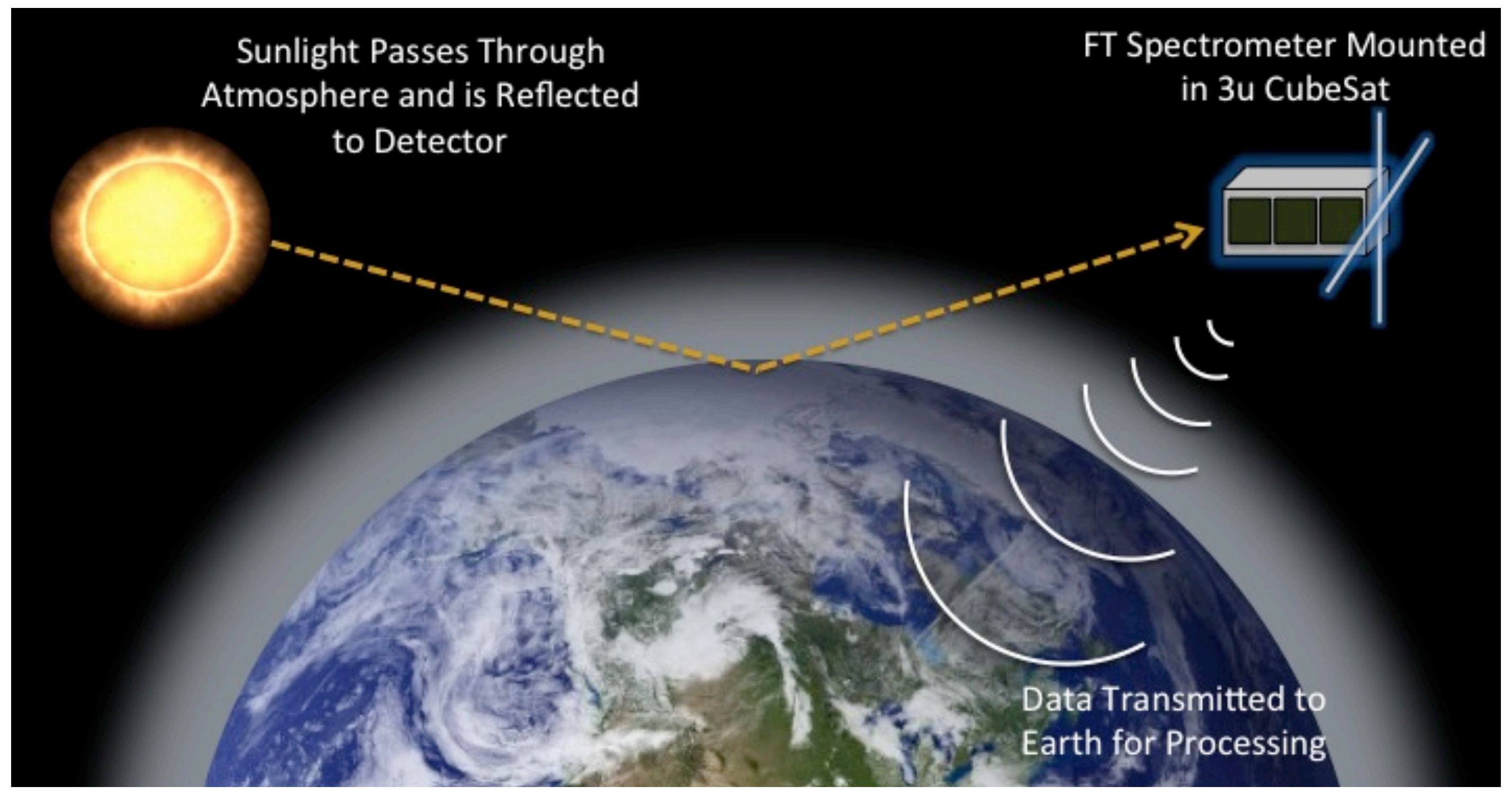


Figure 4. CubeSat for remote atmospheric sensing with onboard micro-FTS spectrometer. Data are transmitted back to earth for processing.

Imaging and Characterization

- Defects in the waveguides create scattering sites which reduce transmission, perturb the wave fronts of light propagating through the channels, and decrease the potential sensitivity of the device. Minimization of wall and entrance defects are therefore critical.
- Initial prototypes (process P1) were created using Deep Reactive Ion Etching (DRIE) techniques.
- Second round of prototypes (process P2) involved changes in the DRIE chemistry. The method of dicing was also changed to use DRIE to reduce fracturing at channel entrances and exits.
- Scanning Electron Microscopes (Hitachi S-570 with an Inca X-act model 51-ADD0017 x-ray detector and Hitachi S-4000 Field Emission) were used to image and characterize test chips produced by the different DRIE prescriptions.
- Multiple defects were found to be present within the waveguides on the chips:
  - **Type 1:** Small defects (< 10% of waveguide width) often attached to waveguide wall or extreme edge roughness
  - **Type 2:** Moderate (10% - 33% of waveguide width) typically debris produced in manufacturing process
  - **Type 3:** Major (33% - 100% of waveguide obstructed) clusters of debris or larger surface contaminants
- Primary sources of defects were determined to be silicon shards created in the manufacturing process, and over-deposition of gold in the waveguides (Fig. 5).

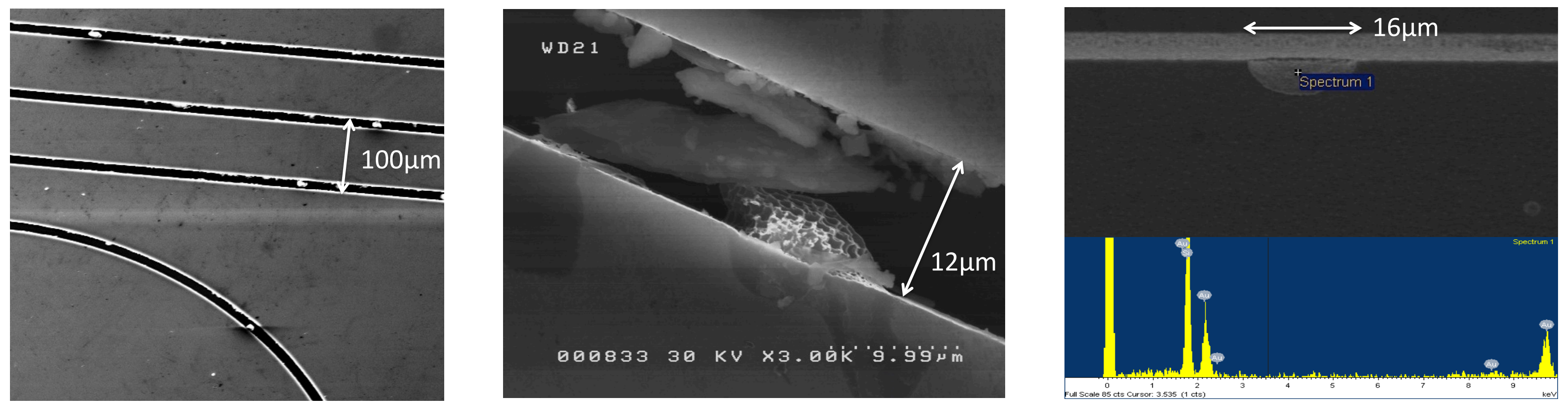


Figure 5. SEM images (left, center) of defects and debris in waveguide channels produced by process P1, and image (right) with spectrum showing over-deposition of gold along waveguide wall.

Defects per Linear mm of Waveguide Length

	Waveguide Width < 100 μm			Waveguide Width > 100 μm		
	Mean	Standard Deviation	St. Dev. of the Mean	**Mean**	Standard Deviation	St. Dev. of the Mean
Chips Produced via Process P1						
Type 1 Defects	**6.3**	3.1	1.8	**1.2**	1.1	0.5
Type 2 Defects	**1.3**	1.0	0.6	**1.0**	0.7	0.3
Type 3 Defects	**0.11**	0.07	0.04	**0.04**	0.09	0.04
Chips Produced via Process P2						
Type 1 Defects	**2.1**	1.3	0.4	**0.77**	0.83	0.27
Type 2 Defects	**0.81**	0.73	0.19	**0.22**	0.30	0.10
Type 3 Defects	**0.28**	0.28	0.08	**0.02**	0.05	0.02
Percent Improvement in Defect Count After Cleaning With Air Burst (Both Methods)						
Type 1 Defects	**35%**	29%	9%	**50%**	33%	10%
Type 2 Defects	**57%**	56%	17%	**61%**	35%	11%
Type 3 Defects	**81%**	24%	8%	**100%**[1]	~	~

[1]. Total Number of observed type 3 defects on waveguides > 100 um was 2. Both were removed by air burst.

Table 1. Defects per linear mm of waveguide length sorted by production method and waveguide width. Prototype chips produced via process P2 have significantly reduced numbers of defects per mm, especially for Type 1 defects in narrow waveguides. Defect reduction after cleaning with air burst is also shown, and is effective at reducing counts per mm, especially of type 2 and 3 defects (commonly loose debris from chip manufacturing).

Cleaning and Defect Correction

- Fewer defects per mm were observed on chips produced using P2 DRIE methods, especially for narrow waveguides (< 100μm width).
- Cleaning chips using an air burst (3s burst from each direction) was effective at reducing number of defects per mm, particularly loose debris (Types 2 & 3).
- Air burst was not as effective at reducing number of Type 1 defects, or in cleaning small waveguides.
- Hitachi FB 2100 Focused Ion Beam (FIB) Microscope was used to clean defects along waveguide walls.
- FIB effective for localized defects, but not viable for machining entire waveguide.

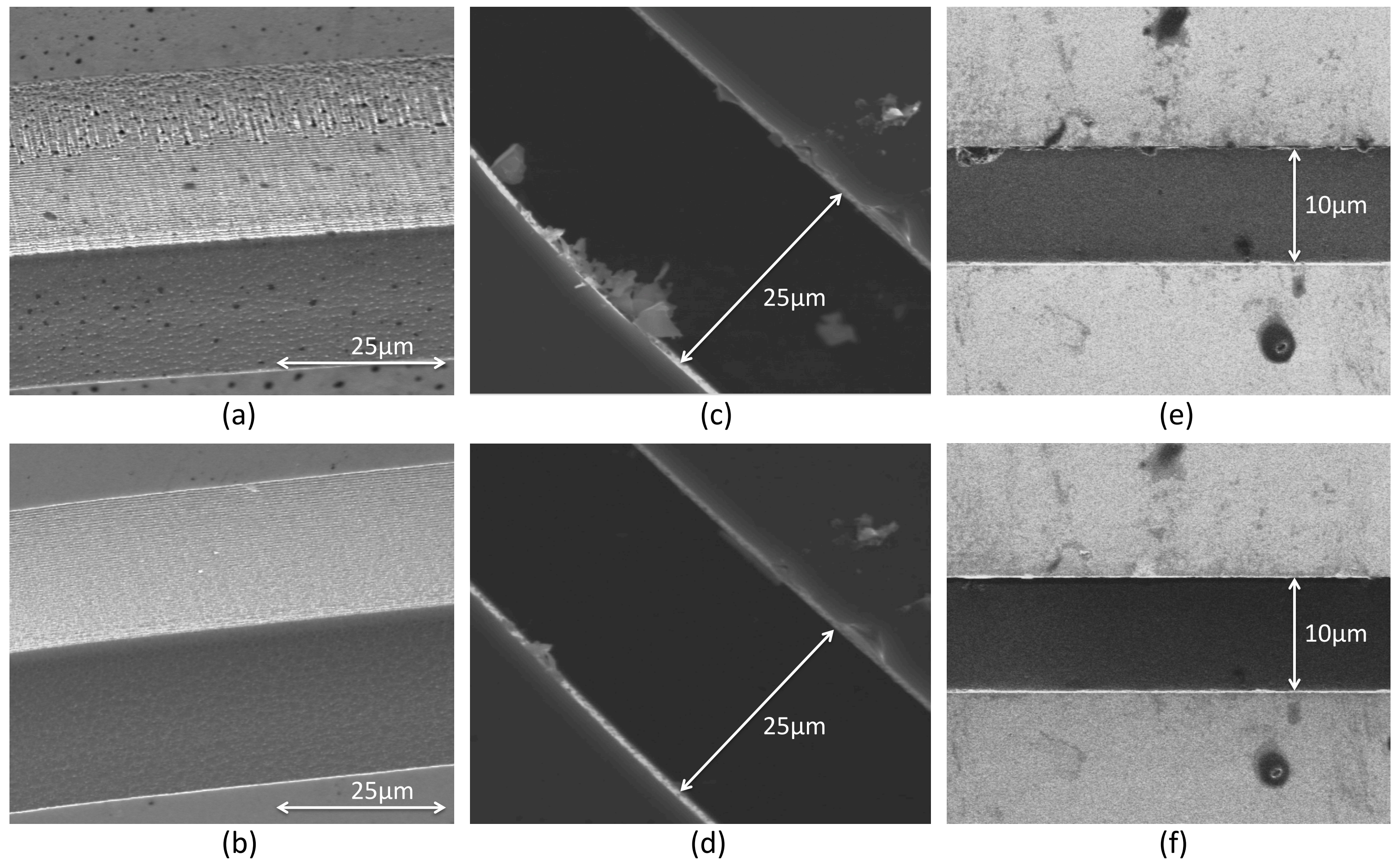


Figure 4. SEM images of waveguide channel walls produced by processes P1 (a) and P2 (b). Images of waveguide produced via P2 before (c) and after (d) cleaning with air burst. Images of waveguide produced by P1 before (e) and after (f) milling using FIB.

Conclusions and Future Applications

The ultimate goal of this project is the successful development of a fully functional FTS that can be used for Nanosatellite and CubeSat applications. Results suggest that careful tuning of DRIE chemistry and cleaving method is critical in device fabrication. Cleaning and defect correction are also necessary before coating the waveguides or assembling the chips. Further characterization using an Atomic Force Microscope to measure surface roughness inside the waveguides is underway. Testing of the spectrometer will be performed to quantify the effects of observed defects on device performance.

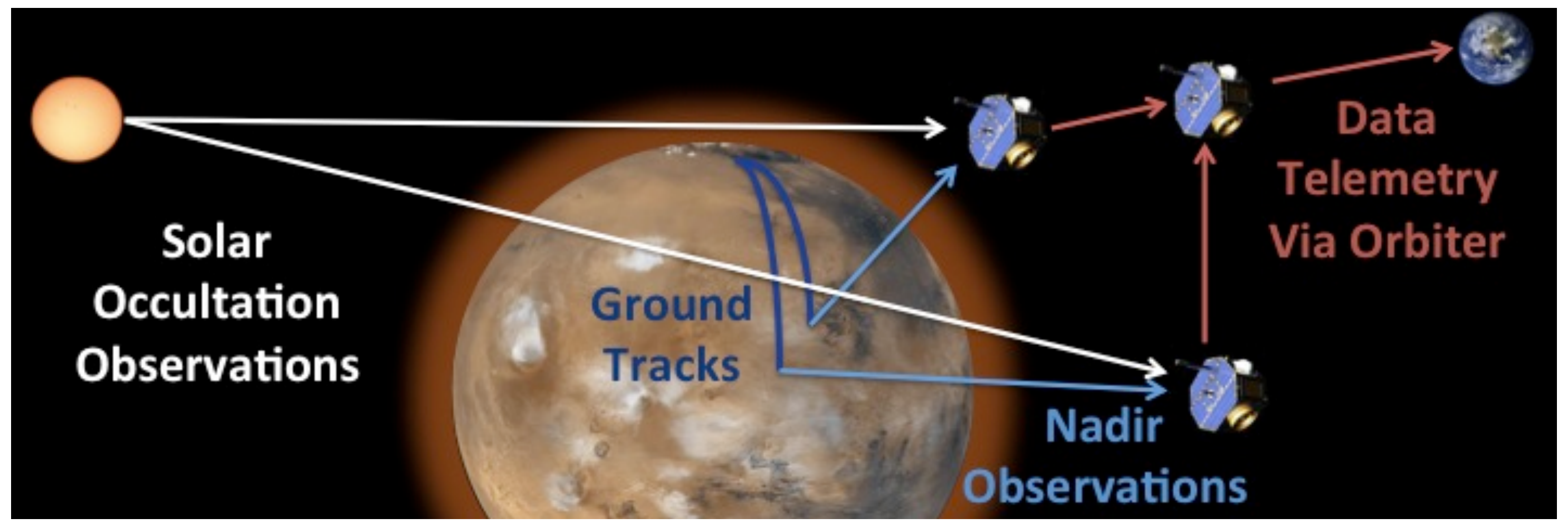


Figure 6. Displayed is a concept for remote sensing of planetary surfaces (nadir observations) and planetary atmospheres (solar occultations) using multiple micro-FTS spectrometers.

Acknowledgements

This project has been funded through NASA's SmallSat Technology Development Program and through a North Carolina Space Grant, and we would like to gratefully acknowledge their support. We would also like to thank P. Roman for fabricating the devices.

References

1. Florjańczyk, M., Alonso-Ramos, C., Bock, P., Bogdanov, A., Cheben, P., Molina-Fernández, I., Janz, S., Lamontagne, B., Ortega-Moñux, A., Scott, A., Sinclair, K., Solheim, B., Xu, D., 2012, Optical and Quantum Electronics, "Development of a Fourier-transform waveguide spectrometer for space applications", 44, 549-556.
2. Florjańczyk, M., Cheben, P., Janz, S., Lamontagne, B., Lapointe, J., Scott, A. Solheim, B. and Xu, D. X., 2009, Proc. SPIE 7356, 73560V.
3. Okamoto, K., 2012, Laser & Photonics Reviews, "Progress and technical challenge for planar waveguide devices: silica and silicon waveguides", 6, 14-23.
4. Okamoto, K., Aoyagi, H., and Takada, K., 2010, "Fabrication of Fourier-transform, integrated-optic spatial heterodyne spectrometer on silica-based planar waveguide", Optics Lett., 35, 2103.
5. Okamoto, K., 2010, "Planar Waveguide Devices for Communication and Sensing Applications", Journal of the Optical Society of Korea, 14, 290-297.