REAL TIME CLOUD COMPOSITION PROFILES WITH AN OPTOFLUIDIC INSTRUMENT.

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Closing Key Knowledge Gaps: VOLTR (Venus Optofluidic Liquid TRap) seeks to identify unknown UV absorbers, characterize the atmospheric constituents, and assess habitability or detect traces of life in potential habitable zones in Venus' clouds (~50 km, 1 atm and 60°C). VOLTR does this by collecting cloud aerosols, acquiring ultrafast (<1s) surface-enhanced Raman (SERS) and laser-induced breakdown (LIBS) spectra, and interpreting spectral data in real time during descent through the clouds of Venus.

VOLTR Innovations: VOLTR is a scientific payload that takes advantage of [1] the unique ability of Raman spectroscopy to qualitatively determine molecular composition and structure and organic functional groups; [2] SERS technology pioneered by our team that enables (at least) ppb-level quantitative analysis; [3] sub-ppm LIBS elemental quatitation; and [4] at-the-edge computing technologies also developed by our team for onboard lossless spectral data processing and compression.

Under the hood, VOLTR integrates an aerosol trap that passively captures atmospheric aerosols during descent. The trap is made of plasmonic materials that enable SERS and LIBS measurements immediately as aerosols adhere to the trap, without the need for sample manipulation. VOLTR utilizes a customized 515 nm pulsed laser for these measurements whose characteristics (adjustable rep. rate and a pulse energy) enable self-cleaning of the trap, a necessary innovation for repeated sampling-measurement cycles replacing resource-intensive mechanical systems for sample holder management.

VOLTR Performance: The optical trap is developed specifically to collect pristine aerosol samples in the size-range predicted for Venus's atmosphere (0.3 to 8.0 µm mean diameter). The physical properties of the trap enable particle capture while retaining the nanotexturing necessary to provide strong Raman signal enhancement. Based on preliminary tests, VOLTR is capable of ppb-level detection of organic functional groups, elements, and other trace compounds with a recycling capability enabling at least three reuses of the SERS-active surface, sufficient for a pathfinder-type dive-in mission to characterize the chemical composition of Venus' cloud deck.

Significance: VOLTR addresses the need for high sensitivity compositional analysis of Venus' atmosphere and answers a key astrobiology question: what is the mysterious UV absorber? VOLTR is a low-SWaP subsystem that can be configured for a variety of mission architectures to enhance the sensitivity of Raman instrumentation to trace compounds, organics, and biosignatures during aerosol capture on Venus and Titan or plume sampling in other Ocean Worlds.

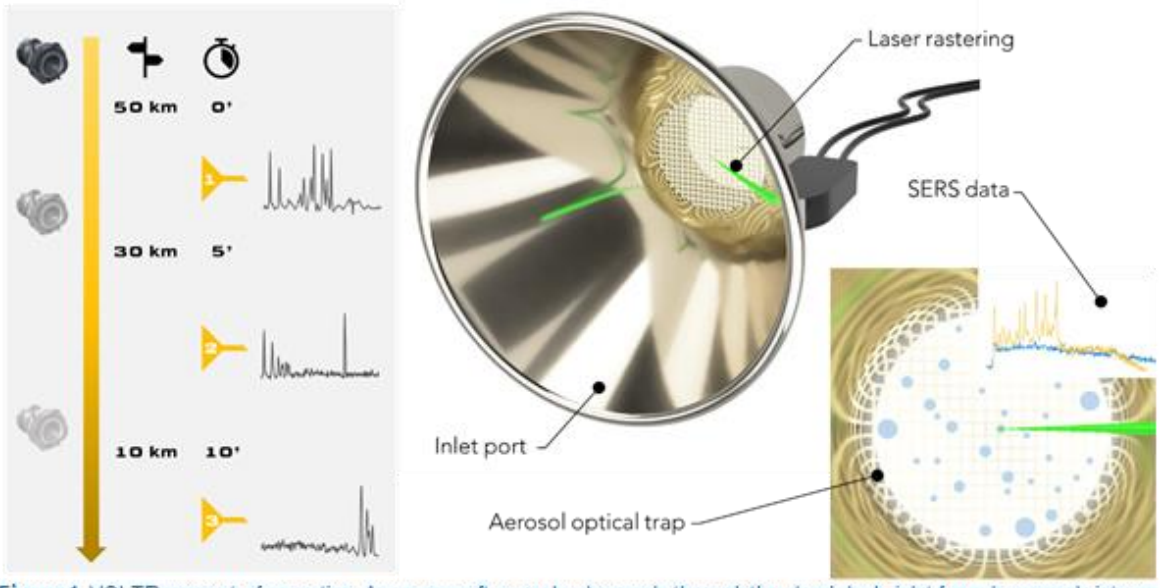

Figure 1. VOLTR concept of operation. As spacecraft or probe descends through the cloud deck, inlet funnels aerosols into an optical aerosol trap (< 10 mm diameter). The laser rasters the trap and conducts SERS measurements continuously throughout the duration of the mission. An in-situ cleaning method makes the trap reusable, enabling at least three discrete sampling and subsequent measurement events. SERS measurements enable high sensitivity (sub-ppm) detection and identification, through Raman spectral fingerprinting, of molecular functional groups and specific molecular identities.

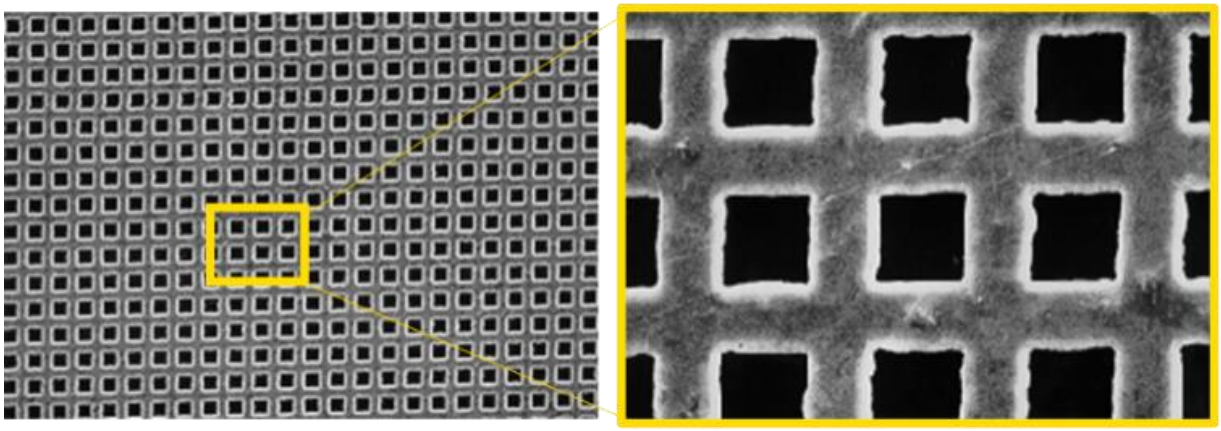

Figure 2. SERS meshes with uniform pore sizes ranging from 8-234 µm. Larger pores less restrictive to airflow through the mesh but reduce particle capture efficiency.

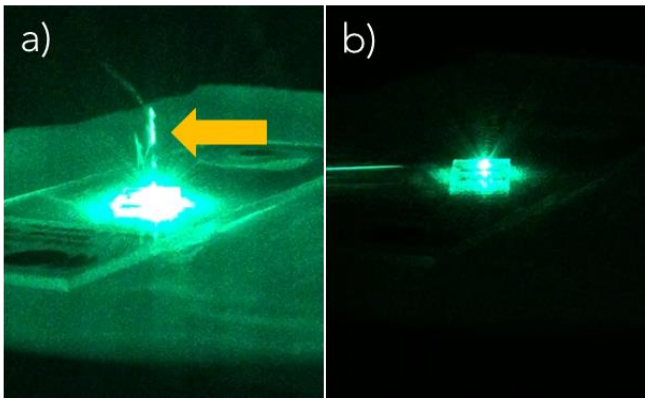

Figure 3. Example of Coherent Flare NX pulsed laser performing measurements and cleaning on commercial SERS substrate. Cleaning of the substrate at high rep rates (a) compared to low rep. rates where SERS measurement was performed (b). Yellow arrow indicates analyte removal due to ablation.

Parameter	Baseline	Alternatives	Outcome
Measurement Types	SERS	LIDAR, fluorescence, LIBS	High TRL VOLTR instrument design for performing the measurements necessary for precise characterization of Venus atmosphere in descending probe or fly-through application.
SERS type	Au, Ni, Cu	Ag-based, TiO_2 composite	
Substrate type	Metal mesh	Fiber mesh w/ embedded nanoparticles, other	
Cleaning Method	Pulsed laser	High voltage, UV, flush, plasma	
Instrument Capabilities	Grid mapping	Point, complex mapping geometry	
Instrument Application	Venus probe	Ocean Worlds plume analysis	

Figure 4. VOLTR design conderations

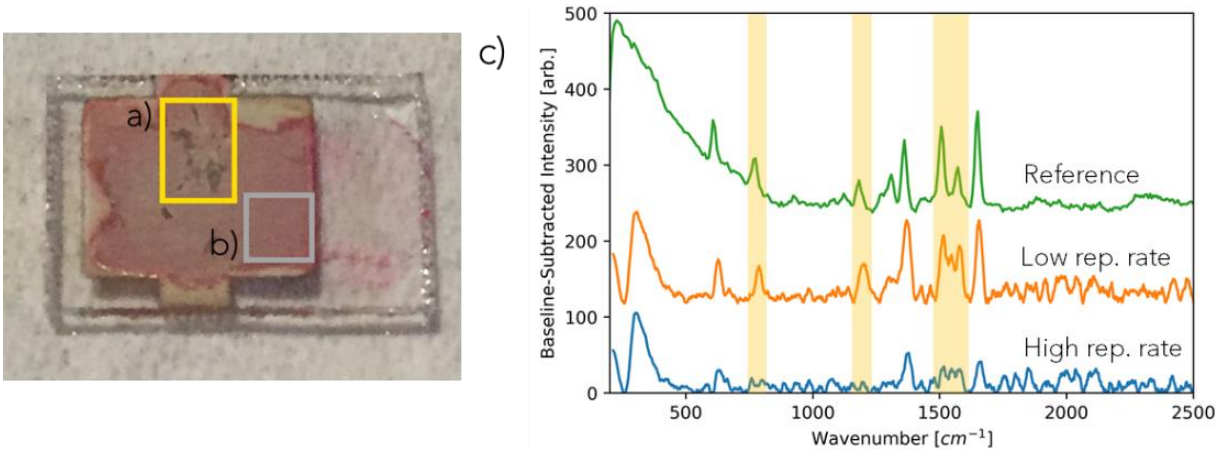

Figure 5. SERS measurement and substrate cleaning demonstration using 515 nm pulsed laser. Cleaning resulting from high rep. rate (a) compared to area where SERS measurement was successfully performed at low rep. rate (b). Comparison of R6G SERS data (c) collected using 515 nm pulsed laser at 500 Hz (blue) and 50 Hz (orange) compared to 532 nm CW laser (green). Yellow bands indicate assortment of key peaks that are lost in noise in high rep. rate spectrum due to vaporization of analyte from surface.

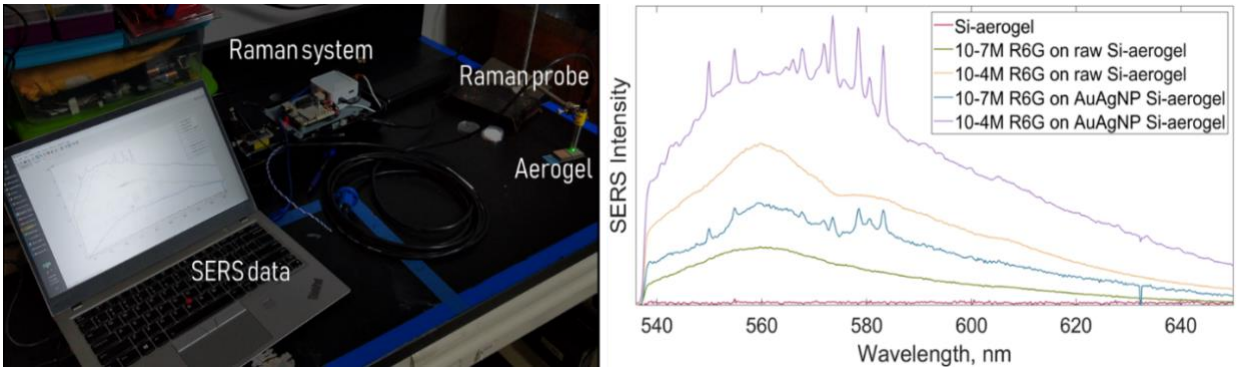

Figure 6. Our plasmonic nanoparticles provide extreme signal enhancements that enable detection down to 10-7 (48 ppb w/w). VOLTR detection limit is lower with our original condensation and filtration design.