AERACEPT (AEROSOL RAPID ANALYSIS COMBINED ENTRY PROBE/SONDE TECHNOLOGY): ENABLING IN SITU AEROSOL SCIENCE FOR SMALL SPACECRAFT MISSIONS

D. M. Gentry[1], A. Borner[2], C. Dang[3], C. Espinoza[1], J. B. E. Meurisse[2], C. Naughton[2], J. Park[1], A. Cassell[1], S. Dhaniyala[5], L. Iraci[1], A. Mattioda[1], P. Sobron[4], E. Venkatapathy[1], and A. Davila[1] , [1]NASA Ames Research Center, California, USA (diana.gentry@nasa.gov) , [2]Analytical Mechanics Associates, Inc. at NASA Ames Research Center , [3]Bay Area Environmental Research Institute at NASA Ames Research Center , [4]Impossible Sensing, Missouri, USA , [5]Clarkson University, New York, USA

Brief Author Biography: Diana Gentry is an early-career astrobiologist and bioengineer at NASA Ames Research Center, where she is the director of the Ames Aerobiology Laboratory and co-director of the Bioengineering and Instrumentation Group Laboratory.

Background: Aerosols, which include clouds, hazes, and dusts, are a key part of how energy and material are transported around planets, and thus key drivers of phenomena from weather and climate to long-term planetary evolution. As “Earthlike” planets (rocky with water) are also the most likely to have water/ice clouds, understanding aerosol impacts is also important for predicting short- and long-term habitability, e.g., the dramatic divergence between Earth’s and Venus’s planetary histories.

However, aerosols are both difficult to study remotely and highly dynamic in time and space. Large flagship missions with sondes capable of aerosol sampling, such as Huygens (Cassini) [1], are not frequent enough; upcoming descent probe concepts such as DAVINCI [2] or Venera-D [3] target overall atmospheric measurements but not particles directly. The ability to fit aerosol sampling and analysis in a small spacecraft mission envelope would enable the data coverage needed to characterize these planetary dynamics for the first time.

Overview: AERACEPT is an early-stage technology combining an entry vehicle and descent probe in a single aeroshell instrumented for aerosol particle sampling (Fig. 1). This approach combines previous technology demonstrations of sampling through an aeroshell body [4] and well-established particle sampling techniques from airborne science [5] with modern advances in thermal protection materials such as 3D woven carbon-carbon and HEEET. It is designed to be compatible with robust, fast cadence, low power, small footprint analysis instruments such as LIBS, SERS, and UV fluorescence. It is particularly well suited to a Venus mission, as the particles of interest will be in the subsonic regime of a passive descent, and is included as part of the Nephele Venus small spacecraft mission concept.

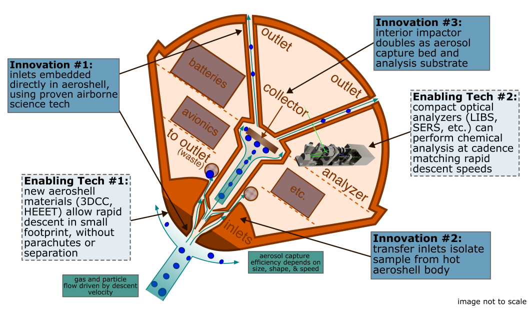

Figure 1. Concept diagram of AERACEPT in a Pioneer Venus style aeroshell, with VOLTR dual spectrometer as notional payload.

AERACEPT presents unusual dependencies between trajectory parameters, thermal protection requirements, fluid dynamics spanning the hypersonic to subsonic regimes, and particle capture efficiency. The three main technical questions are: (1) how will thermal degradation of aerosol samples, from the hot aeroshell body and high capture velocity, limit achievable science? (2) can the reduced footprint capture enough (and not too much!) sample for science? and (3) how will the cadence of current analysis limit the sample resolution of a faster descent? Although many of the subsystems involved in AERACEPT, such as the aeroshell body, inlet design, and particle capture approach, are at a high TRL, their integration for this application is unique. Developing appropriate thermal and flow models (including particle tracking) to address these questions, and experimentally validating the models, will move AERACEPT to TRL 4.

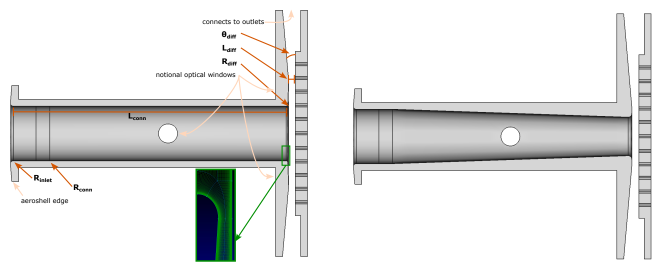

Figure 2. (l) Straight-inlet geometry showing parameters used for sensitivity tests; inset shows equivalent Pointwise grid. (r) Tapered geometry.

Status: A few different basic geometries for the internal flow path have been explored to understand the trade space between thermal constraints, achievable sample volume, and other science goal compatibility. The first (“open”) assumes the system is open and flow is unrestricted through the entire descent; otherwise, we assume that a valve or plug is used prior to entering the science operations regime (“closed”). In the closed case, options modeled include a straight inlet, a converging/diverging section at the inlet, a series of secondary inlets to bleed off boundary flow, a tapered inlet, and the inclusion of a diffuser at the exit from the collection plate to improve pressure recovery (Fig. 2).

Table 1. Examples of modeled inlet geometry parameters (definitions in Fig. 2).

R_{inlet} mm	θ_c °	R_{throat} mm	θ_d °	L_{throat} mm	R_{conn} mm	L_{conn} mm	θ_{diff} °	R_{diff} mm	L_{diff} mm
1	5	8	22	8.4	11.0	50	4	3.67	4.13
1	5	8	22	8.4	20.0	50	4	6.67	7.50
1	5	12	22	8.4	11.0	50	4	3.67	4.13
1	0	1	0	20.0	1.0	80	4	0.33	0.38
1	0	1	0	20.0	0.5	80	4	0.17	0.19

The Nephele mission concept descent trajectory was used to model the aeroshell thermal protection material (TPM) response in PATO, with the wall and kinetic heating in OpenFOAM. No crosstalk is predicted between the possible outgassing from the inlet/nose (3D CC) and Venus target analytes (Table 2.) Recession is predicted to be 1.1 mm after convective heating at 88 s. Peak temperature of the TPM is predicted at 3700 K, declining to 1300 K at the start of science operations. This results in a predicted inernal sample temperature delta $< 30\,\mathrm{K}$ to $60\,\mathrm{K}$, under which most analytes will be preserved (H_2O will be affected). These internal conditions are compatible with further laboratory benchtop testing.

We linked a compressible flow solver (rhoPimpleFoam) and a particle tracking solver (denseParticleFoam) to allow prediction of particle capture efficiency binned by size. This extended flow model tool was used to predict total accumulated sample number and volume for the Nephele Venus sonde, using the straight inlet with diffuser flow design (Fig. 3). The expected total sample volume for a 63 km to 39 km science operations ranges between $2\,\mu\mathrm{L}$ to $18\,\mu\mathrm{L}$ depending on the inlet taper. The equivalent capture efficiency is reasonable for particle diameters $> 1\,\mu\mathrm{m}$, leading to mid-size particles dominating the accumulated sample by number. However, the long tail of large particles means the sample volume is dominated by them ($99\,\% \geq 5\,\mu\mathrm{m}$).

Table 2. High-priority Venus aerosol constituent analytes.

type	target analyte
elemental	S, C, H, P, Cl, N, O, Fe
molecular	H_2O, H_2SO_4, SO_x, PO_x, NO_x, NH_x, CH_x
specific	organic moieties (C=C, C=O, C≡N, ...)

To understand the trade space of required sample analysis cadence, sensitivity, and limits of detection for the faster descent and smaller sample sizes generated by AERACEPT, a series of tests using Venus aerosol analogs spanning the high-priority analytes in Table 2 are underway. These tests cover techniques representing potential optical flight instruments: Raman spectroscopy, with or without surface-enhancement (SERS); laser-induced breakdown spectroscopy (LIBS); and UV/VIS absorbance and fluoresence spectroscopy. Preliminary results from the Raman and UV/VIS spectroscopy can be found in [6]. Material compatibility has been a significant challenge for SERS substrates, although silicon, PTFE, and graphene survived initial exposure tests.

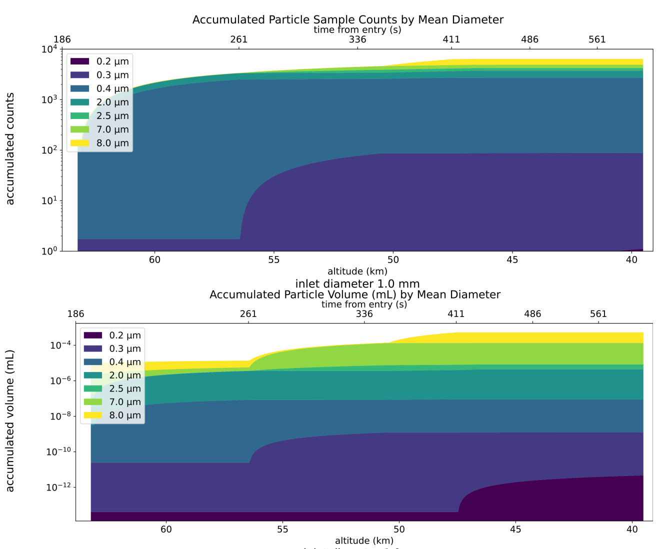

Figure 3. (t) Accumulated particle number and (b) volume sample predictions for 63 km to 39 km at Venus.

Future Work: The current "most favorable" geometry is the closed tapered case with diffuser. The open case significantly limits sample volume due to the narrow inlet and possible analytical techniques due to the difficult internal thermal environment. The taper significantly improves capture efficiency at the lower end of the particle diameter range ($< 1\,\mu\mathrm{m}$). Future optimization can include iteratively improving the specific parameters of the taper and diffuser (Table 1) to target a specific particle size or altitude range.

Particle separation is currently modeled as simple inertial impaction. Other approaches with significant heritage such as cyclone separation or liquid impingement compatible with a microfluidics interface could be used in a larger-footprint mission. However, because inertial impaction inherently provides some separation by particle density and size, another potential optimization to selectively analyze specific particle sizes can be to target the optical path towards a specific area of the collector plate.

Validation of the thermal material response model is planned at the University of Illinois Urbana Champaign Plasmatron facility, which allows for testing in CO_2 matching stagnation point heat load ($CH = 0.1696\,\mathrm{kg\,m^{-2}\,s^{-1}}$ by matching q_W with FIAT). Validation of the flow and particle tracking models is planned at the NASA Ames Fluid Mechanics Laboratory comparing ambient and captured aerosol particle distributions.

Although AERACEPT's early-stage development has used the Nephele Venus mission concept as a use case, it could be applied to other solar system exploration targets for whom small-footprint atmospheric sampling and analysis offers compelling science return. Validated thermal and flow models will allow basic predictions of performance at other target bodies of interest, such as Titan, Triton, or the ice and gas giants.

Acknowledgments: AERACEPT is funded through the NASA Early Career Initiative, NASA Ames Center Innovation Fund, NASA Ames Science Directorate Innovation Fund, & NASA Ames Entry Systems and Technology Division Innovation Fund. Additional thanks to Francesco Panerai, Eduardo Almeida, Amanda Brecht, and the NASA Ames Mission Design Center team.

References:

[1] Lebreton J.P. et al. (2005) *Nature*, 438(70697069):758–764.

[2] Garvin J.B. et al. (2022) *The Planetary Science Journal*, 3(5):117.

[3] Zasova L. (2019) Venera-D: Expanding Our Horizon of Terrestrial Planet Climate and Geology Through the Comprehensive Exploration of Venus. Tech. rep., Venera-D Joint Science Definition Team, Moscow, Russia.

[4] Seiff A. et al. (1973) *Icarus*, 18(4):525.

[5] Dhaniyala S. et al. (2003) *Aerosol Science and Technology*, 37(10):828.

[6] Dang C. et al. (2023) P31F–3150. American Geophysical Union, San Francisco, CA, USA.