Nephele: An Entry Probe & Sonde Concept for a Venus Ride-Along or Small Spacecraft Mission

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Introduction: Nephele is a Venus atmospheric descent probe concept designed to analyze cloud, haze, and dust particles. It combines a unique set of technologies (Figure 1): recently developed thermal protection materials (3D-CC and HEEET), aerosol sampling technologies with heritage in both planetary and airborne science (high-speed inlets and particle separation), and rapid, robust optical analysis instruments (such as the VOLTR dual spectrometer). Nephele is designed to be complentary to other efforts such as DAVINCI [1] and Venera-D [2], which target Venus atmospheric gas analysis, by specifically targeting cloud and haze particles.

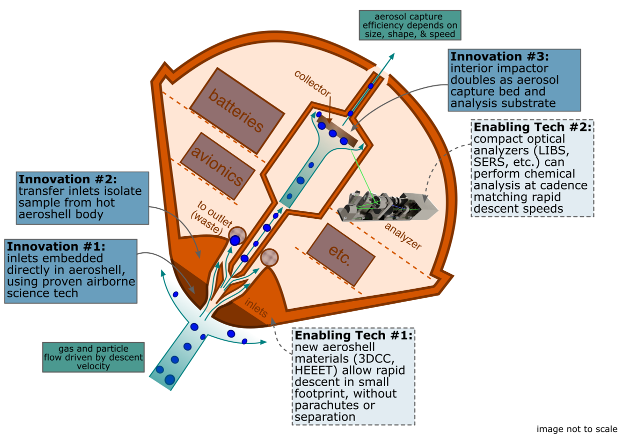

Figure 1. **Nephele descent probe concept**. It consists of a single-body aeroshell, aerosol particle capture system, and notional analysis payload, represented here by a simple impactor and the VOLTR dual LIBS/SERS spectrometer. This particular geometry is modeled on the Pioneer Venus Large Probe.

Nephele builds on the AERACEPT (AErosol Rapid Analysis Combined Entry Probe/sonde Technology) concept of a single aeroshell body that acts as both an entry vehicle and aerosol sampler, by embedding a series of inlets directly in the aeroshell nose. AERACEPT is designed to substantially reduce the mass, volume, and complexity required for aerosol sampling by removing the need for heat shield separation, deployable parachutes, and other means of descent control. AERACEPT uses the vehicle's own velocity – in this case, that of a passive descent trajectory – to drive aerosol capture and separation. AERACEPT is well suited for a Venus mission, where the particles of greatest interest will be in the subsonic portion of the trajectory, but could be adapted for other targets such as Titan, Triton, or the gas and ice giants.

Heritage: Flow-through inlet and particle capture designs are well established in larger probe mission contexts, including the Galileo descent probe, Huygens descent probe, Venera and VeGa sondes, and some ice giant sampling concepts like Nepture Odyssey. Self-contained small aeroshell sondes have flown for gas sampling before, including the Pioneer Venus probes and Mars Deep Space 2, but have not been designed analyze particulates beyond simple nephelometry (which does not require particle separation). Particle sampling has been demonstrated from a proof-of-concept aeroshell on Earth in a 1973 test [3], but thermal and material concerns at the time limited its potential mission benefit. Recent advances in entry system materials, such as the advanced carbon-carbon + HEEET design evaluated for the Cupid's Arrow flyby concept [4], make the technology mission-relevant now.

In addition to planetary flight missions, passive aerosol sampling has extensive airborne science heritage, both tropospheric and stratospheric. As the principles of adapting fluid dynamics designs for other atmospheres are well understood – the Mach, Reynolds, and Stokes numbers are the key parameters – Nephele's flow geometry also takes inspiration from recent advances in airborne science [5], particularly the secondary inlets used to protect the sample from material and thermal contamination.

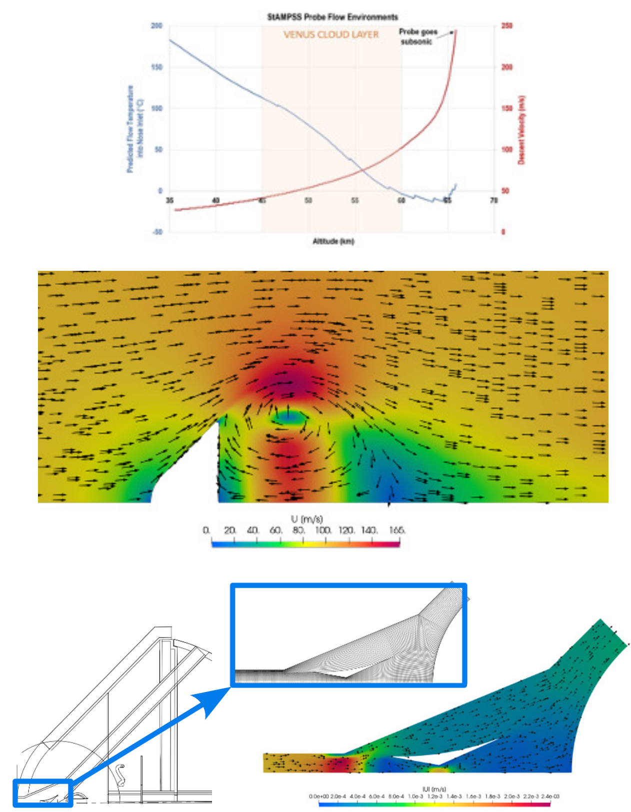

Figure 2. **Preliminary trajectory and flow modeling**. (t) Notional entry trajectory, showing the subsonic transition well above science operations. (m) Flow velocity around a simplified probe body at 60 km. (b) Magnified detail of the inlet system and particle tracking tool validation.

Current Development: Validation of the Nephele concept centers on three key questions: (1) Can it capture enough (and not too much!) aerosol sample in such a small footprint? (2) How will thermal degradation of aerosol samples, from the hot aeroshell body and high capture velocity, limit the achievable science? (3) Can current optical technology perform elemental and molecular analyses quickly enough to keep up with a faster descent?

For a given descent trajectory, the trade space for aerosol capture with AERACEPT is generally governed by the available pressure drop (which depends on the aeroshell and flow path geometry) and the aperture diameter of the primary inlet. Together, these determine the lower size cutoff for particles that can be effectively captured. This geometry can be further specialized to target a specific particle size range if desired, at the cost of sacrificing representative (isokinetic) sampling across particle sizes. Total transect resolution, or the number of samples taken across a given altitude range, can also be adjusted to support a specific science investigation. Nephele has completed preliminary flow modeling of a simplified system geometry (Figure 2). Nephele currently targets a single isokinetic sample of particles larger than 1 μm within 60 km to 47 km, spanning the middle and lower Venus cloud layers.

Material contamination concerns are primarily outgassing from the thermal protection materials making direct contact with the sample flow path, particularly compounds that might cross-talk with target science analytes (Table 1). The choice of 3D-CC for the Nephele aeroshell nose, a non-ablative material, eliminates the majority of concerns present with traditional designs. Thermal contamination of the sample, which could cause loss of volatiles from the sample as well as chemical changes, comes from two sources, heat transfer from the still-hot aeroshell material and kinetic heating from the change in relative flow speed as the ambient atmosphere is ingested. Modeling is still underway to capture these effects for Nephele.

Table 1. **Potential science targets.** Some suggested elemental and molecular targets for constraining Venus aerosol composition.

type	target analyte
elemental	S, H, 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, ...)

Lastly, a significant limitation of previous descent probes targeting aerosols has been the relatively slow analysis cadence of the science payload; for example, mass spectrometry, especially for volatiles and at higher mass numbers. For Venus, where the expected operational time after descent is extremely limited, analysis cadence sharply limits the possible transect resolution. Recent developments in optical analysis instruments, as represented in examples such as Impossible Sensing's Venus Optofluidic Liquid TRap (VOLTR) instrument [6], offer the possibility of high analysis cadence with much less sacrifice of analytical capability. VOLTR is capable of both laser-induced breakdown spectroscopy, or LIBS (which provides information on elemental abundance) and surface-enhanced Raman spectroscopy, or SERS (which provides information on molecular bonds), and can be built and packaged without moving parts. As part of investigating the science trade space available to AERACEPT, preliminary material compatibility and sensitivity tests have been done on SERS substrates (Figure 3).

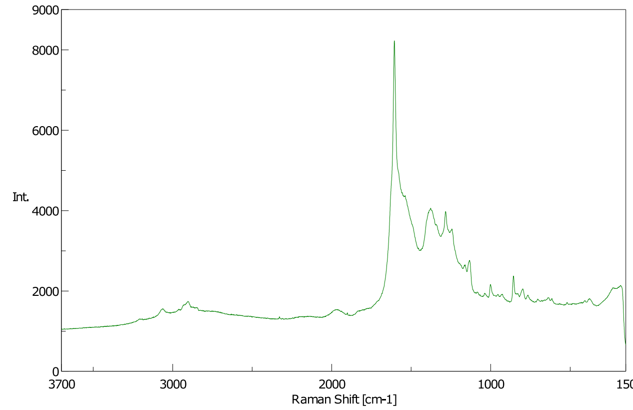

Figure 3. **Surface-enhanced Raman (SERS) demonstration**. Results from a simple test substrate, consisting of 500 nm evaporation-deposited silver on a silicon substrate, with a trace organics mixture. The signals at $>3000\,\mathrm{cm}^{-1}$ are aromatic C−H stretch; $2800\,\mathrm{cm}^{-1}$ to $3000\,\mathrm{cm}^{-1}$, aliphatic C−H; $\sim 1600\,\mathrm{cm}^{-1}$, aromatic C=C; $\sim 1350\,\mathrm{cm}^{-1}$ to $1400\,\mathrm{cm}^{-1}$, aliphatic C bonds.

Future Work: Active development efforts on AERACEPT are primarily focused on refining and optimizing the flow geometry. The flow model will be validated and refined with a wind tunnel scale test. The thermal material response model will be validated with an empirical plasma jet scale test at University of Illinois Urbana-Champaign's CHESS facility; this will also help address concerns about the predicted material response and reactivity, including the stability of the sampling inlet shape during entry.

The Nephele mission concept is being developed in parallel. A science traceability matrix is being drafted with a particular focus on the achievable sample size, number, and limits of detection for different possible combinations of instruments, including LIBS, SERS, UV fluorescence, and nephelometry. Laboratory testing is underway to validate some of these tradeoffs, in particular the particle size range and sampling altitude range, using Venus cloud particle analogs.

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References:

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

[2] 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.

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

[4] Rabinovitch J. et al. (2019) Cupid's Arrow: Hypervelocity Noble Gas Sampling in the Upper Atmosphere of Venus.Tech. rep., Jet Propulsion Laboratory, Pasadena, USA.

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

[6] Simon K. et al. (2021) In *19th VEXAG Meeting 2021*, 8063. Lunar and Planetary Institute, (Virtual).