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MISSION ARCHITECTURE AND TECHNOLOGY OPTIONS FOR A FLAGSHIP CLASS VENUS IN SITU MISSION

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ABSTRACT

Venus, as part of the inner triad with Earth and Mars, represents an important exploration target if we want to learn more about solar system formation and evolution. Comparative planetology could also elucidate the differences between the past, present, and future of these three planets, and can help with the characterization of potential habitable zones in our solar system and, by extension, extra–solar systems. A long–lived *in situ* Venus mission concept, called the Venus Mobile Explorer, was prominently featured in NASA's 2006 SSE Roadmap and supported in the community White Paper by the Venus Exploration Analysis Group (VEXAG). Long-lived *in situ* missions are expected to belong to the largest (Flagship) mission class, which would require both enabling and enhancing technologies beside mission architecture options. Furthermore, extreme environment mitigation technologies for Venus are considered long lead development items and are expected to require technology development through a dedicated program. To better understand programmatic and technology needs and the motivating science behind them, in this fiscal year (FY08) NASA is funding a Venus Flaghip class mission study, based on key science and technology drivers identified by a NASA appointed Venus Science and Technology Definition Team (STDT). These mission drivers are then assembled around a suitable mission architecture to further refine technology and cost elements. In this paper we will discuss the connection between the final mission architecture and the connected technology drivers from this NASA funded study, which — if funded — could enable a future Flagship class Venus mission and potentially drive a proposed Venus technology development program.

INTRODUCTION

As discussed in the Solar System Exploration Decadal Survey [1] by the National Research Council (NRC) of the National Academies, Venus represents an important exploration target, which can help us to learn more about the formation and evolution of our solar system, and by extension, other extra–solar systems. Comparative planetology between Venus, Earth, and Mars could also elucidate the differences between the history and evolution of these planets, thus, for example, help constraining our models of potential habitable zones and the greenhouse effect. In response to these goals, both NASA's 2006 Solar System Exploration (SSE) Roadmap [2] and the community White Paper by the Venus Exploration Analysis Group (VEXAG) [3], prominently featured a long–lived Venus *in situ* mission concept, called the Venus Mobile Explorer (VME).

Due to its complexity and projected cost, VME belongs to the Flagship (largest) mission class for solar system exploration. Strategic Flagship class missions are usually directed by NASA and larger in their scope, with a projected cost cap between ∼\$1.5B and \$3B. Smaller Discovery and (Mars) Scout class, and medium class New Frontiers missions — capped at ∼\$425M–\$475M for the former (with launch vehicle), and ∼\$650M (without L/V) for the latter, respectively — are competitively selected through periodic NASA Announcements of Opportunity (AO).

Technology planning for Flagship class missions is reasonably well defined and constrained within mission development phases, and the mission impacts are well understood. (In comparison, Discovery and New Frontiers missions are typically planned an opportunity ahead and with a significantly lower cost cap, which may introduce limitations to technology development.) Relevant technologies for extreme environment mitigation were assessed and reported in [4]. In addition, the Science Mission Directorate (SMD) Science Plan [5] also identified technologies for extreme environments, as high–priority systems technologies needed to enable exploration of the outer solar system and Venus.

Since long–lived Venus *in situ* missions are significantly affected by the extreme environment of Venus, and the development of relevant technologies may take longer than for missions to other planetary targets, in FY'08 NASA initiated a mission study with an explicit goal of identifying and assessing a science driven Flagship mission architecture and its technology drivers. As a deliverable, the NASA appointed Venus Science and Technology Definition Team (STDT) was tasked to deliver a final report on a recommended point design and to derive a related technology plan, which could lead to technology investment over the next decade, and consequently enable a potential Venus flagship mission in the 2020–2025 timeframe.

Although the study is still ongoing, this paper addresses relevant Flagship class mission architecture concepts and related technologies for an *in situ* mission to the extreme environments of Venus.

EXTREME ENVIRONMENTS

Proposed *in situ* missions to Venus could encounter some of the most hostile environments in our solar system. Environments are considered "extreme," if they present extremes in pressure, temperature, radiation, and chemical or physical corrosion. In addition, certain planned missions would experience extremes in heat flux and deceleration, leading to their inclusion as missions in need of technologies for extreme environments.

At Venus, the super rotating atmosphere consists mainly of carbon dioxide (CO_2 ~96.5%) and nitrogen (N_2 ~3.5%), with small amounts of noble gases (e.g., He, Ne, Ar, Kr, Xe) and small amounts of reactive trace gases (e.g., SO_2, H_2O, CO, OCS, H_2S, HCl, SO, HF). The cloud layer is composed of aqueous sulphuric acid droplets between the altitudes of ~45 km and ~65 km. The zonal winds near the surface are ~1 m/s, increasing up to ~120 m/s at an altitude of ~65 km. Due to the greenhouse effect, the surface temperature reaches ~460°C to 480°C. The average surface pressure can be as high as ~92 bars. (Pressure, temperature and wind conditions as a function of altitude are illustrated in Figure 1.) At these conditions near the surface, the CO_2 becomes supercritical, which could further complicate missions planned to explore this region. Furthermore, the dense atmosphere is expected to introduce significant entry heating and potentially high g–loads for the aeroshell and for the *in situ* elements it carries.

From a technology point of view it is also important to point out that Jupiter and Saturn Deep Entry Probes at a 100 bars pressure elevation would experience similar coupled high pressure and temperature conditions, as those for Venus *in situ* missions near the surface.

Therefore, mission architectures and related technologies must address ways to mitigate these environmental conditions.

STUDY OBJECTIVES

At the beginning of this fiscal year (FY'08) NASA HQ formed the Venus STDT and tasked it to address six objectives for a Venus Flagship class mission study, with support provided by JPL. Specifically:

1. To develop and prioritize science goals, investigations and measurements, which are consistent with the recommendations of the NRC Decadal Survey [1], and the VEXAG community White Paper [3];

2. To identify suitable mission architectures and related instrument capabilities, through assessing their performance, cost, risk drivers and technology readiness;

3. To identify technology investment areas and maturation schedule required to support potential mission architectures in the 2020–2025 timeframe;

4. To assess and identify potential precursor observations and technology validation experiments that could be implemented on a prior medium class New Frontiers Venus mission, that could enable or enhance a future Flagship class mission;

5. To chart a path from proposed New Frontiers and Flagship class missions to a potential Venus Surface Sample Return Mission; and

6. To document the findings in a final study report and in a technology development plan that NASA HQ could utilize for potentially developing a Venus Technology Program.

ASSUMPTIONS

The mission architecture trade–space for this Flagship class mission study was constrained by NASA HQ by a number of given assumptions, as described below. The launch period was assumed between 2020 and 2025. The life cycle mission cost range — or cost cap — was set between \$3B and \$4B (in FY'08 dollars). The launch vehicle (L/V) for a single launch option was limited to a Delta IV-H L/V or smaller, and for a dual launch option to two Atlas V-551 or smaller. For telecommunications it was assumed that the Deep Space Network (DSN) would be available to support the mission with a 34 m antenna, and including Ka band. In addition, the impact of optical communication on the mission performance could be also considered. Regarding technology maturation, the instruments and systems would have to be at least at a Technology Readiness Lever (TRL) of 6. While in this particular study international collaboration is not considered, it is likely that by the time this mission becomes reality it could morph into an international mission, in the same fashion as Cassini–Huygens and the proposed Outer Planet Flagship Mission (OPFM) targeting either Titan or Europa are.

METHODOLOGY

In this section we describe the methodology used by the Venus STDT and the JPL Study Team to derive a final mission architecture for a point design [6]. The assessment process is further illustrated in Figure 2.

Science Figure of Merit Process

Since NASA's missions are predominantly science driven, the science members of the STDT took the VEXAG community White Paper [3] as a starting point for a list of science goals, objectives and measurements. The STDT then regrouped these investigations to eliminate duplications, and updated their prioritizations. The science measurements were also assigned to mission architecture elements (which are defined later). Then, a simple Figure of Merit (FOM) was constructed for each investigation and platform combination, using the formula of

$$FOM_s = 5 - P \times G$$

where P is the priority; and G is goodness. The priority ranking represented the scientific ranking of a given investigation and was assigned a numerical value between 1 and 4. If the investigation was considered essential, it was given priority (1), while highly desirable; desirable; and very good to have; were assigned (2), (3), and (4), respectively. The goodness value, summed for each instrument or measurement technique, yielded a science value against a given mission science goal. The assigned values scaled upwards from 0 to 3. For these instrument and platform goodness scores (0) was assigned if an investigation was not addressed; (1) was given for minor contribution or supporting observation; (2) for major contribution; and (3) for directly answering an investigation. Summing up these FOM values for each platform provided an overall FOM for that platform. Higher FOM represented higher science return.

Technology Figure of Merit Process

In parallel to the science FOM, a technology FOM was also constructed by the technology members of the STDT for each mission architecture element, using the formula of

$$FOM_t = \frac{C}{M}$$

where C is technology criticality and M is technology maturity. For criticality the ranking from 0 to 3 meant: not needed; useful; desirable; and must have. Similarly, maturity was defined on the basis of Technology Readiness Levels (TRL), and ranked from 0 to 3, representing TRL ranges from TRL 1–2 for (0); TRL 3–4 for (1); TRL 5–6 for (2); and TRL 7–9 for (3). Criticality was assessed by the mission architecture team based on mission impact, while maturity values were assigned by the STDT technology subgroup. Higher FOM meant higher technology development requirements. While the technology FOM did not impact the science driven selection of mission architectures, it gave an indication about how much technology needs to be developed to achieve them.

Mission Architecture Elements

As discussed above, the STDT established science and technology FOMs and mapped them against 13 mission architecture elements, which are listed and defined in Table 1. (The table also shows the corresponding science and technology FOMs, discussed above, and the estimated mission architecture element costs, discussed below.) These mission architecture elements included an orbiter or flyby spacecraft and a set of *in situ* platforms from which science measurements could be taken. *In situ* mission element complexities varied from a simple descent probe to a highly complex near surface mobile aerial platform with long traverse and periodic access to the surface. The STDT also differentiated between a single element and multiple elements of the same kind, since the latter could significantly enhance science by performing synergistic measurement at different locations. Mission lifetime — short or long — was an important differentiator. On one hand long lifetime enabled a long observation platform, on the other it introduced significant technology challenges, thus increasing mission cost and complexity.

These platforms were then used to assemble a broad range of multi–element Flagship class mission architectures within the assumed cost range, while carrying out science investigations at a significantly higher scope than achievable by smaller New Frontiers or Discovery class missions.

Rapid Cost Assessment Process

Approximate mission costs were estimated by the mission architecture team at JPL, using a rapid cost assessment method, which was customized for Venus missions. This approach was successfully used during NASA's SSE Roadmap [2] process, and documented in [7].

For each Venus mission architecture concept, a set of *cost drivers* were established, identifying key capabilities that a mission would require to achieve its objectives. The three identified primary cost driver categories included (1) launch operations; (2) flight systems; and (3) mission operations. Additional categories accounted for (a) the operating environment; (b) technologies; (c) flight heritage from past missions; and (d) technology feed forward to future missions. These categories were set to divide potential missions into distinct categories and non–overlapping and comprehensive cost contributors. This ensured a detailed accounting of the various mission cost contributors, while eliminating potential double counting of these factors.

Each applicable cost driver was then associated with a *cost driver index*, acting as a measure for the overall magnitude of the perceived complexity. Cost driver indices were allocated based on an arbitrary five level exponential scale, where Levels 1 to 5 were assigned points from $2^1(= 2)$ to $2^5(= 32)$.

Using these definitions, the rapid cost assessment process consisted of four steps:

1. *Establishing a Reference Mission Set*: which included (a) identifying historic reference missions (e.g., MER, Stardust, Viking, Galileo, Cassini-Huygens); (b) assigning cost indices to each cost driver; (c) summing the cost indices; (d) plotting them against historic mission costs; and (d) calculating the slope of the curve fit over the data set.

2. *Calculating cost indices* for each of the 13 Venus mission architecture element (see Table 1).

3. *Identifying new Venus Flagship class architectures*, by combining multiple mission architecture elements until the target cost cap (between \$3B and \$4B) is reached. This assumed cost cap also included 10% allocation for science payload.

4. *Estimating costs for these mission architectures*, from the slope of the reference missions multiplied by the cost indices.

It was found that this approach could predict relative mission costs between the various architectures when the missions are still in their preliminary study phase and not yet fully defined. However, this method should be used for scoping only and not to replace higher fidelity methods, such as parametric costing or a grass root method. The estimated accuracy of the rapid cost assessment is ~10%–20% for relative costs, and ~30%–40% for absolute costs. Therefore, a more accurate cost estimation is still required at a later phase of the study.

MISSON ARCHITECTURES

In this section we provide an overview of typical Venus mission architectures, followed by a discussion on the STDT recommended mission architecture, which will serve as the basis for a detailed point design that will be performed by the JPL Study Team.

Selecting the most optimal mission architecture is a multi–disciplinary effort, because it has to account for targeted science investigations by selecting a suitable payload; it has to employ appropriate technologies which are relevant to the operating environments and measurement requirements; and it has to address programmatic considerations, including cost caps, mission development phases, and phasing between missions.

To date, a significant number of Venus missions were either flown or proposed, including mission architectures from orbiters to probes, balloons and landers, as shown in Table 3. While the mission architecture elements on these missions are found to be similar to potential future missions, the main differences will be accounted for through the payloads in support of the science questions they will target to answer. Therefore, these example architectures are not expected to cover the full mission architecture trades space, instead, they try to demonstrate the flexibility of how future mission concepts can be formulated in support of science.

Potential future missions can also vary in size and scope as well, from Discovery to Flagship class missions for NASA, although this study focuses on Flagship class architectures only. Other space agencies are also proposing missions to explore Venus. Under ESA's Cosmic Vision Program [8] an ESA lead team proposed a multi–element international mission, called the European Venus Explorer, or EVE [9]. Although it was not selected, it received high ranking from the selection committee and will likely be re–proposed for a potential launch after 2020. The mission concept for EVE included a European orbiter and cloud level balloon, a Russian short lived lander, and potentially a mid–level balloon under the cloud deck by the Japanese Aerospace Exploration Agency. JAXA is also planning to launch an orbiter in 2010, called Planet–C or Venus Climate Orbiter (VCO). [10]

Returning to the current study, the STDT and the JPL Study Team identified 17 multi–element mission architectures that would fit within the assumed cost cap of the a Venus Flagship mission. Among these architectures, three were recommended by the STDT science subgroups, one each, and a forth one which was jointly proposed by the STDT. The science and technology FOMs and estimated costs for these four architectures are shown in Table 2. The STDT also found that single element architectures, such as a near surface mobility platform alone, cannot answer all of the key science questions for Venus, and thus were not selected for this year's study.

Recommended Mission Architecture

It is evident from Table 2 that the STDT recommended multi–element mission architecture has the highest science FOM, and provides flexibility for payload accommodation on the various mission architecture elements. This allows for scalability in response to mission cost cap changes, and could lend itself to international collaboration in the future. In addition, this architecture supports synergies between measurements and science, therefore, further increasing the science return from the mission.

Specifically, the recommended architecture includes a highly capable orbiter with a design lifetime of ∼4 years; two cloud level super–pressure balloons floating at a constant altitude between 52 and 70 km with a design lifetime of 1 month; and two landers which would also perform science measurements during atmospheric descent. The baseline architecture called for short lived landers, because most of the landed science could be carried out during the expected 5–10 hours period. However, two instruments — a seismometer and a meteorology station — operating for up to ∼243 days (i.e., Venus' sidereal rotation period, or length of day), could significantly enhance the science return. Therefore, the feasibility of long lived elements on the short lived landers will be assessed as part of the study. This, however, should be evaluated in the framework of its full mission impact, including not only science, but also mission cost, technology development requirements, complexity and risk.

The proposed mission architecture would include two launches. The study baselined launches in 2021, ∼6 months apart, although backup launch options are available in every 19 months (in 2022 and 2024) due to orbital phasing between Venus and Earth. Each of the two Atlas V–551 launch vehicles could deliver up to ∼5500 kg mass to Venus. The carrier spacecraft with two Venus entry systems, each accommodating a balloon and a lander, would be launched in late April, 2021, on a Type IV trajectory, and arrive at Venus after a 456–days cruise in late July, 2022. The two aeroshells would be released from the carrier 20 and 10 days before arrival, targeting their predetermined entry and landing sites on the day side of Venus. This was required by science, in order to allow for imaging during descent and after landing. During the flyby, the carrier spacecraft could be equipped to provide backup telecom support from the landers and balloons, and confirmation that the entry was successful. The orbiter would be launched in late October, 2021, on a Type II trajectory, and would arrive to Venus in early April, 2022, following a 159–days cruise. This earlier arrival would provide sufficient time for the orbiter to set up a 300 km $\times$ 40000 km elliptic orbit, with the apoapse optimized for up to ∼5–6 hours of continuous visibility of the *in situ* elements (as a function of their landing location).

Following atmospheric entry, the entry, separation, then the descent and inflation for the balloon, and the descent and landing for the lander, would follow similar steps and timelines as those of the historic Russian VeGa missions. The balloons could deploy in about 15–20 minutes and start operating. The landers would take ∼1–1.5 to descend, while performing descent science. This would be followed by surface operations, while communicating the data to the orbiter. After completing *in situ* science support, the obiter would circularize its orbit at ∼300 km, and begin its own long science phase.

A preliminary payloads for these platforms were recommended by the STDT, based on the highest priority science objectives and measurements. Notional payloads for the three mission architecture elements (orbiter, balloons and landers) are provided in Table 3.

Because the study is still ongoing, this paper only addressed generic features of the concept. Full details on the proposed mission architecture, operating scenarios, and data rates and volumes for the point design will be provided in the final report.

TECHNOLOGIES

Preliminary results indicate that the proposed science driven mission architecture has a low technology FOM, which means that the baseline configuration may not introduce significant technology challenges. It is also expected that for this configuration all instruments could be brought to at least TRL 6 before 2015 (i.e., 5 years before the earliest assumed launch date).

In the second phase of the study, the STDT will address enabling and enhancing technologies for instruments, components, and subsystems, based on the point design, and document the findings in a technology development plan.

Technologies can be divided into two major subgroups, such as,

- *Technologies for science measurements*: including instrument operation; sample processing; data acquisition; etc., and
- *Technologies for operations and survivability*: of subsystems on architecture elements, including thermal mitigation; power; telecom; command and data handling; mobility; etc.,

Specifically, technologies for science measurements address aspects of instrument designs to operate in extreme environments, and operational constraints to perform a desired science measurement. For example, silicon based electronics can't operate at Venus surface temperatures and should be protected in a thermal enclosure, while certain imagers may require active cooling of the focal plane to perform their measurements.

Technologies for operations and survivability are typically coupled with suitable system architecture approaches.

System architecture approaches could include:

- *Full tolerance*: where components are designed to survive the extreme environments. Full tolerance might not be technically feasible, since some of the component can't be developed to operate at 460 °C and 92 bars.
- *Full protection*: where components would be placed inside a protective environment (e.g., to mitigate pressure and temperature). Full protection could be prohibitively expensive to develop, and might not be practical either, since the mission architecture requires components, such as sensors, sample acquisition systems, to be placed outside of the thermally controlled pressure vessel.
- *Hybrid system*: is where some of the components would be protected and some would be tolerant. For the Venus landers of this study a hybrid system approach is recommended as it combines the benefits from the other two approaches.

In general, it is expected that any lander configuration would require technology development for pressure and temperature mitigation and sample acquisition and handling.

While the landers in the baseline mission architecture could utilize passive thermal management, the long lived elements would likely require active thermal control (cooling) coupled with a Venus specific Radioisotope Power System (RPS). If implemented, it could increase the lifetime of the landers or parts of the landed elements from several hours to weeks or months, therefore, it could significantly increase the science return. However, due to the low TRL of this technology, the full mission impact should be carefully assessed.

Beside the landers, the recommended architecture also includes cloud level balloons. Other mission architectures could use aerial mobility platforms at lower altitudes and near the surface. Since extreme environment conditions and the technology difficulty to mitigate them increase with the decrease of altitude and the increase of mission lifetime, these aerial platforms should be specifically designed to address these specific conditions, as discussed in [11].

A general overview of Venus related extreme environment technologies is given in [4] and [12].

CONCLUSIONS

In the first phase of the Venus Flagship study the NASA HQ appointed Venus Science and Technology Definition Team assessed science goals, objectives and measurements, potential technology needs, and the relevant Figures of Merits for both science and technology. These factors, cross referenced with estimated mission costs, pointed to a mission architecture that included an orbiter, two cloud level balloons and two landers. This recommended mission architecture provided the highest science FOM, with a relatively modest technology requirement, and thus, the basis for a point design in the second phase of the study. The orbiter and the two balloons were baselined for operational lifetimes of 4 years and 1 month, respectively. The two landers were baselined to operate for about 5 to 10 hours on the surface, but an option was also identified where a long lived element could operate for up to ~243 days, while performing seismometry and meteorology observations.

FUTURE WORK

In the second phase of this still ongoing Venus Flagship study the JPL Study Team will carry out a point design on the STDT recommended mission architecture. Beside documenting the findings, the STDT will also recommend a technology development plan to enable such a flagship mission. The technology plan is expected to reach beyond the point design, in order to provide sufficient flexibility for enabling a future flagship architecture, which might be different from the architecture recommended here. While this architecture represents the current best estimate for a flagship mission concept, future architecture changes could reflect possible shifts in science focus, for example, in response to potential precursor Discovery and/or New Frontiers missions, or to NRC recommendations from a soon to be updated Decadal Survey. Furthermore, findings from this study may point to a follow up study next year, where additional flagship architectures could be addressed to broaden our understanding of potential science returns from various configurations, and to augment the technology development plan. The final study report could also provide an important input to the next Decadal Survey.

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REFERENCES

[1] NRC. New Frontiers in the Solar System, an integrated exploration strategy. Technical report, Space Studies Board, National Research Council, Washington, D.C., 2003.

[2] SSE Roadmap Team. Solar System Exploration – This is the Solar System Exploration Roadmap for NASA's Science Mission Directorate. Technical Report JPL D-35618, National Aeronautics and Space Administration, Washington, D.C., August 2006.

[3] VEXAG. Venus Exploration Analysis Group. http://www.lpi.usra.edu/vexag/, August 2008.

[4] E.A. Kolawa, T.S. Balint, G. Birur, E. Brandon, L. Del Castillo, J.L. Hall, M. Johnson, R. Kirschman, R. Manvi, M. Mojarradi, A. Moussessian, J. Patel, M. Pauken, C. Peterson, J. Whitacre, E. Martinez, E. Venkapathy, P. Newdeck, and Okajie R. Extreme Environment Technologies for Future Space Science Missions. Technical Report JPL D-32832, National Aeronautics and Space Administration, Washington, D.C., September 2007.

[5] NASA-SMD. Science Plan for NASA's Science Mission Directorate 2007–2016. Technical report, National Aeronautics and Space Administration, Washington, D.C., May 2007.

[6] M.A. Bullock, D. Senske, and J.H. Kwok. Venus Flagship Study — Interim Briefing. Presentation at NASA HQ, SMD–Planetary Science Division, May 2008.

[7] C. Peterson, J. Cutts, T. Balint, and J. Hall. Rapid Cost Assessment of Space Mission Concepts through application of Complexity–Based Cost Indices. In *IEEE Aerospace Conference*, number IEEEAC paper #1632, Big Sky, Montana, March 2008.

[8] ESA. Cosmic Vision, Space Science for Europe 2015–2025. Technical Report ESA BR-247, October 2005.

[9] E. Chassefiere, O. Korablev, T. Imamura, K. H. Baines, C.F. Wilson, D.V. Titov, K.L. Aplin, T. Balint, J.E. Blamont, C.G. Cochrane, Cs. Ferencz, F. Ferri, M. Gerasimov, J.J. Leitner, J. Lopez-Moreno, B. Marty, M. Martynov, S. Pogrebenko, A. Rodin, J.A. Whiteway, L.V. Zasova, J. Michaud, R. Bertrand, J.-M. Charbonnier, D. Carbonne, P. Raizonville, and and the EVE team. European Venus Explorer (EVE): an in-situ mission to Venus. *Experimental Astronomy, ESA Cosmic Vision - CV07 special issue*, (ISSN 0922-6435 (Print) 1572-9508 (Online); DOI 10.1007/s10686-008-9093-x), 2008.

[10] M. Nakamura and Planet-C project team. Present status of Venus Climate Orbiter (Planet-C). In *37th COSPAR Scientific Assembly, Symposium C31: Planetary Atmospheres*, Montreal, Canada, July 2008.

[11] J.A. Cutts, T.S. Balint, J.L. Hall, V. Kerzhanovich, J. Jones, E.A. Kolawa, and J. Nott. Technology Challenges for Exploration of Planets with Aerial Platforms. In *37th COSPAR Scientific Assembly, Symposium B06: Scientific investigations from Planetary Probes and Aerial Platforms*, Montreal, Canada, July 2008.

[12] J.A. Cutts, T.S. Balint, E. Chassefiere, and E.A. Kolawa. *Chapman Monograph – Exploring Venus as a Terrestrial Planet*, chapter Chapter 13: Technology Perspectives in the Future Exploration of Venus. Books and Monographs. AGU, ISBN 978-0-87590-441-2 edition, 2007.

[13] T.S. Balint, J.A. Cutts, and J.H. Kwok. Overview of Flagship Class Venus Mission Architectures. In *6th International Planetary Probe Workshop (IPPW–6)*, Atlanta, GA, June 2008.

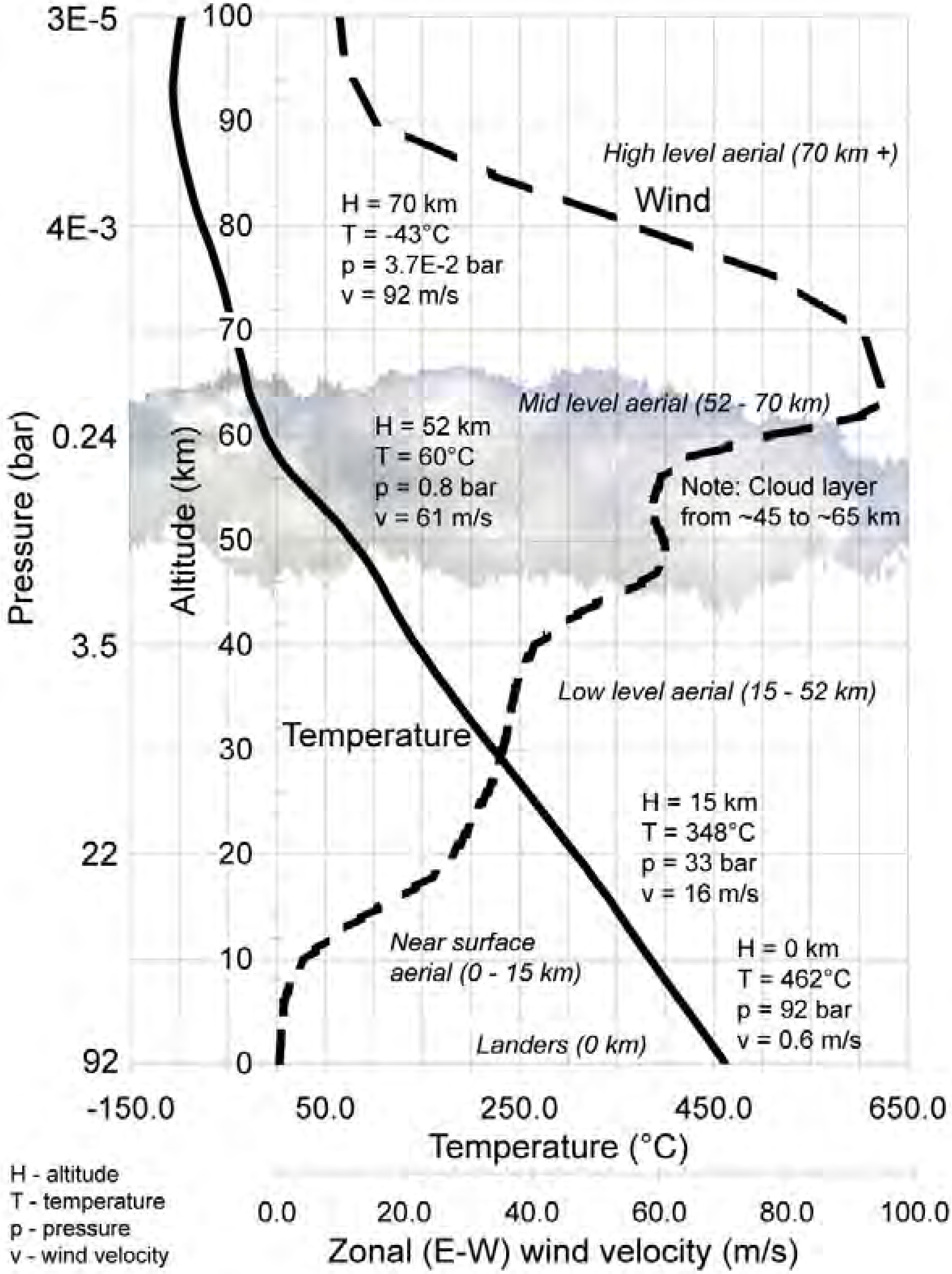

Figure 1: Pressure, temperature and wind conditions at Venus

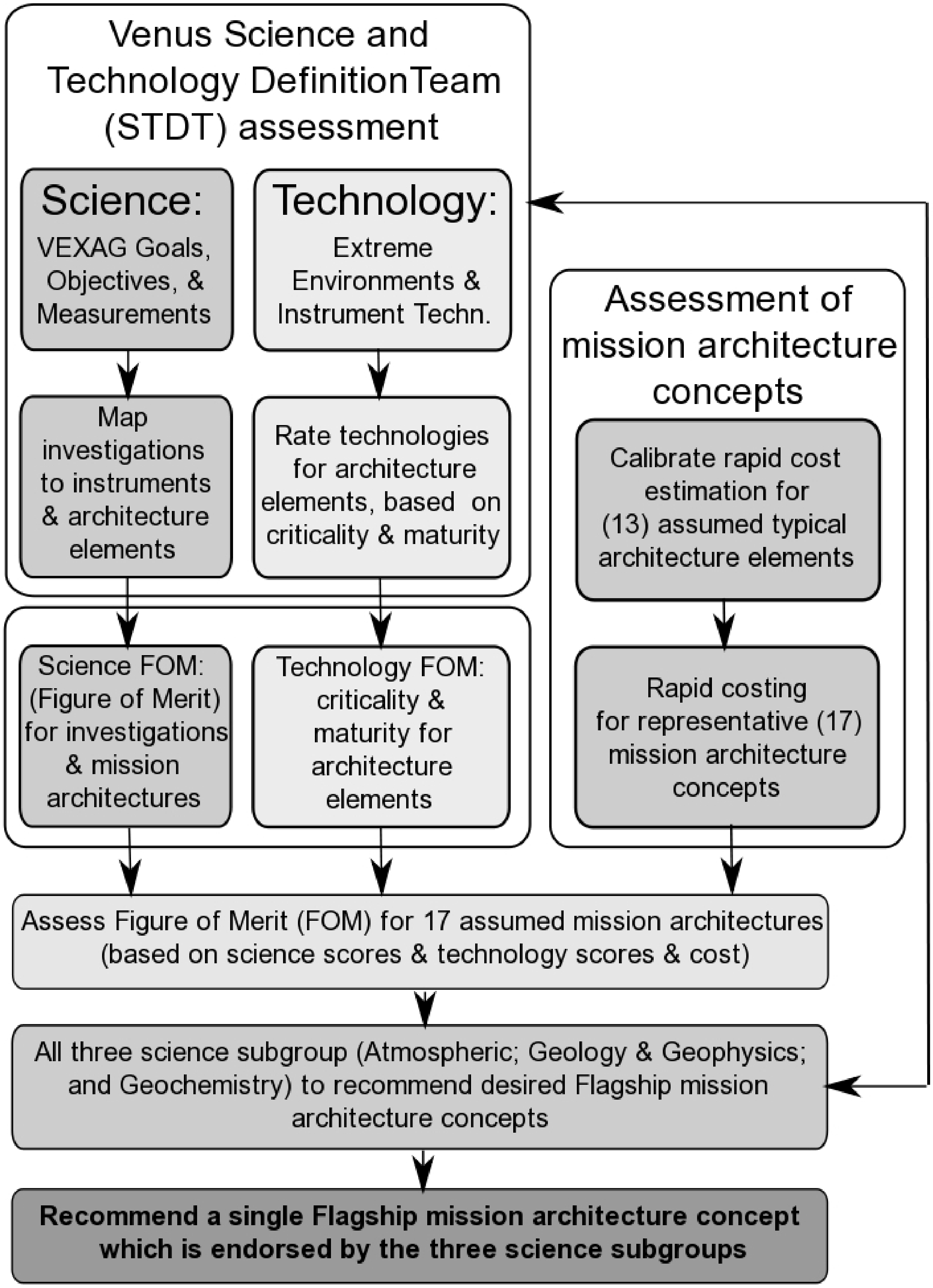

Figure 2: Flowchart for the Venus STDT Figure of Merit (FOM) process

Table 1: Mission architecture elements, FOMs, and cost estimates.

Architecture Element	Description	Science FOM	Tech. FOM	Cost est.
Orbiter	Self–evident, but can dip into the exosphere for *in situ* sampling	177	0	\$0.48B
High–Level Aerial	Altitude >70 km, above clouds	169	3	\$0.55B
Mid–Level Aerial	Altitude 52–70 km, in clouds (about the same altitude as the VeGa balloons)	191	3	\$0.91B
Low–Level Aerial	Altitude 15–52 km, below clouds, limited view of surface due to attenuation	176	14	\$1.4B
Near–Surface Aerial	Altitude 0–15 km, NIR imaging of surface is possible, no surface access	170	20	\$2.1B
Single Entry Probe	No surface access, descent science only	136	2	\$0.51B
Multiple Entry Probes	No surface access, descent science only	171	2	\$0.54B
Short–Lived Lander	Single lander, about 5–10 hours lifetime on surface, passive cooling	153	12	\$1.02B
Short–Lived Landers	Multiple landers, about 5–10 hours lifetime on surface, passive cooling	214	12	\$1.05B
Long–Lived Lander	Single lander, days to weeks lifetime, may require active cooling and RPS	223	21	\$2.3B
Long–Lived Landers	Multiple landers, days to weeks lifetime, may require active cooling and RPS, long lived network possible	264	21	\$2.33B
Surface System with Mobility	Active or passive cooling, mobility with surface access at multiple locations (e.g., rover with short traverse or metallic bellows with long traverse)	209	53	\$3.59B
Coordinated Atmospheric Platforms	Large number (e.g., swarm) of *in situ* elements, with simultaneous measurements	129	21	\$1.98B

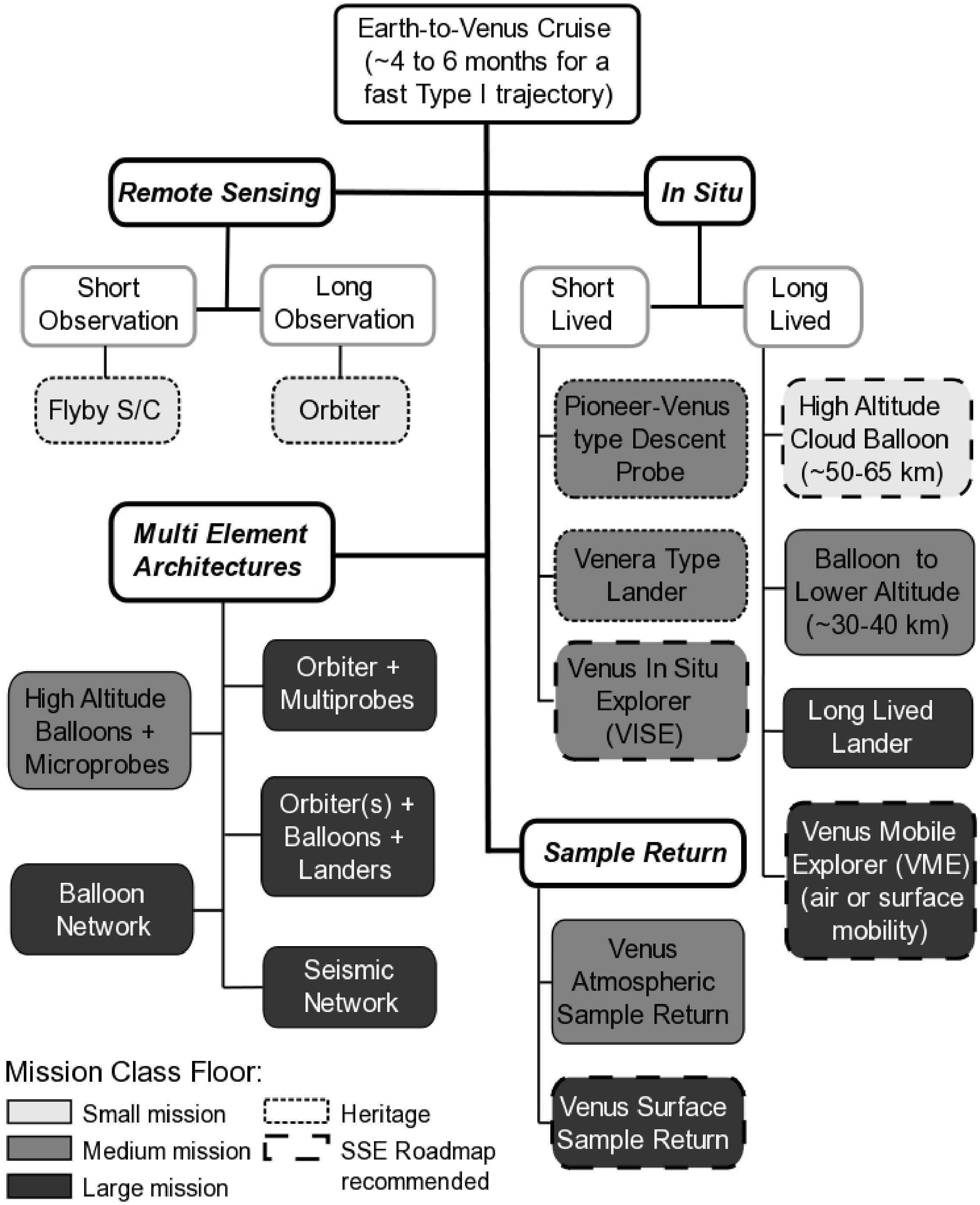

Figure 3: Venus mission architecture examples [13]

Table 2: Potential Flagship class mission architectures, FOMs, and cost estimates.

Recommended by	Mission architecture concept	Science FOM	Tech. FOM	Cost est.
Mission architecture choices by STDT Science Subgroups				
Geology Subgroup	Multi–element architecture with 1 orbiter; and 1 near surface aerial platform	347	20	\$3.2B
Atmospheric Subgroup	Multi–element architecture with 1 orbiter; 2 mid–level aerial platforms; and 2 entry probes	539	5	\$2.9B
Geochemistry Subgroup	Multi–element architecture with 1 flyby; and 1 short lived lander	214	12	\$2B
STDT recommended mission architecture for detailed Flagship study				
Full STDT	Multi–element architecture with 1 orbiter; 2 mid–level aerial platforms; and 2 short lived landers (could include long lived elements)	753	15	\$3.7B

Table 3: Notional payload for the orbiter, two balloons, and two landers (by the STDT).

Orbiter	**2 Balloons**	**2 Landers**		
Lifetime (∼4 years)	*(∼1 month)*	*Descent Phase (∼1–1.5 hour)*	*Landed Phase (∼5–10 hrs)*	*Long Lived Package (∼243 days)*
InSAR — Interferometric Synthetic Aperture Radar	ASI — Atmospheric Science Instrument (p; T; wind; acceleration)	ASI	Microscopic imager	*ASI (long life; not in baseline)*
Vis–NIR Imaging Spectrometer	GC/MS — Gas Chromatograph / Mass Spectrometer (long life)	Vis–NIR Cameras with spot spectrometry	XRD / XRF	*Seismometer (long life; not in baseline)*
Nutral Ion Mass Spectrometer	Nephelometer	GC / MS	Heat Flux Plate	
Sub–mm Sounder	Vis-NIR camera	Magnetometer	Passive Gamma Ray Detector	
Magnetometer	Magnetometer	*(Descent phase only)*	Sample acquisition, transfer, and preparation	
Langmuir Probe	Radio tracking	*(Net Flux Radiometer)*	Drill to ∼ 10 *cm*	
Radio Subsystem (USO — Ultra Stable Oscillator)		*(Nephelometer)*	*Seismometer (short life)*	