A Mars Ascent Vehicle for Potential Mars Sample Return

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Abstract— This paper will cover the conceptual design of a Mars Ascent Vehicle (MAV) and efforts underway to raise the TRL at both the component and system levels. A system down select was executed resulting in a Hybrid Propulsion based Single Stage To Orbit (SSTO) MAV baseline architecture. This paper covers the Point of Departure design, as well as results of hardware developments that will be tested in several upcoming flight opportunities.

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1. MARS SAMPLE RETURN

Mars Sample Return (MSR) is highly desired by planetary scientists as a way to bring the full scientific capacity of Earth to bear on the evaluation of Martian samples to determine if life ever arose on the planet, or per chance may even exist today. Given the cost and challenge of putting significant mass on the surface of Mars, plus the necessity of tele-operating robotic systems and instruments remotely, it will likely be over a century before comparable scientific power will be available in-situ at Mars. More readily achievable is the approach of bringing some of Mars back to Earth to study. In fact, this ability has been studied for at least 20 years.

Today, the Mars 2020 mission is under development based on the highly successful MSL rover currently operating at Mars. (**Figure** 1) Mars 2020 brings with it a new powerful suite of instruments, plus a sample collection and caching system that will allow it to core drill targeted samples, carefully chosen by scientists exploiting the new instruments, and place them into hermetically sealed containers (tubes) which could potentially be returned by future missions. This capability would demonstrate the first leg of a potential MSR effort[1].

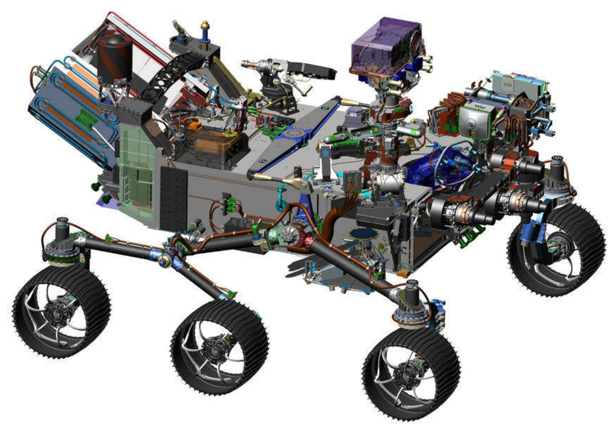

Figure 1 : Mars 2020 Rover with sample coring and caching system.

The exact approach for getting the samples back to Earth is not yet established, but the current reference architecture being used as a guide for mission studies is shown below[2]. In this architecture, the next mission in the quest to return samples would be an orbiter with the capability of collecting an Orbiting Sample (OS) and preparing it for return to Earth. In fact, the Mars Program is currently developing an orbiter mission concept called the Next Mars Orbiter (NeMO) whose prime mission would be to replace aging telecommunications and reconnaissance assets there [3]. The Mars Program is also evaluating bringing a technology demonstration payload that would demonstrate on orbit the capabilities needed to rendezvous, capture, perform the necessary Planetary Protection isolation encapsulation, and prepare an OS for return.

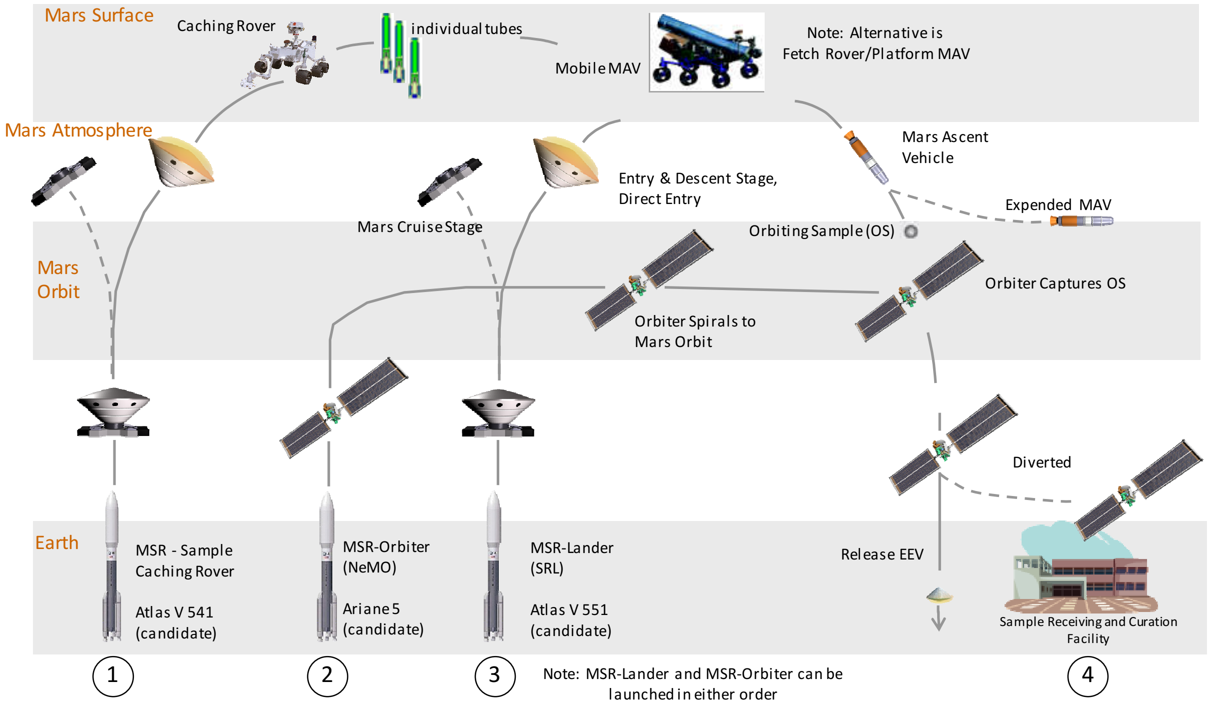

Figure 2: Current Reference Architecture for potential Mars Sample Return

Because of its telecommunications and reconnaissance functions, as well as its own science objectives, the NeMO orbiter, **Figure** 3**,** may choose to operate in a sun-synchronous orbit anywhere from 300-500 km altitude. This is important to a MAV from a design perspective as will be seen later. An open trade exists for the final journey home for the samples. In the simplest architecture (shown in **Figure 2),** the SRO would encapsulate the OS into an Earth Entry Vehicle (EEV) and start the return trip to Earth. Using solar electric propulsion, this would be performed by a slow spiral about Mars until finally exiting the Martian gravity well and following a heliocentric path back to Earth. Immediately prior to arrival at Earth, the EEV would be jettisoned by the SRO, and the SRO would perform a divert maneuver taking it off an intercept trajectory with Earth and leaving it forever in orbit about the sun. The EEV would enter the atmosphere ballistically, and land at a predetermined uninhabited location. Currently the Utah Test and Training Range (UTTR) is one likely candidate, but other locations are also under consideration. Alternative architectures also under consideration include an option to hand off the encapsulated OS to another orbiter at Mars, potentially provided by ESA as a contribution to the MSR effort. This would allow for the telecommunications and recon asset to remain at Mars for continued support to other missions. The ESA orbiter could follow a similar approach to the return leg. Another alternative is for the SRO (or ESA) orbiter to return to Earth, however instead of arriving on a ballistic trajectory for direct return, the orbiter would enter into a distant retrograde orbit about the Moon, and a crewed mission would be executed to rendezvous and collect the samples there, and return them safely to the Earth.

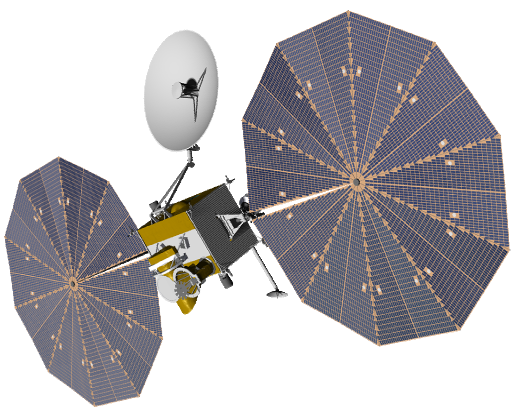

Figure 3: Conceptual Design for the Next Mars Orbiter (NeMO), including the demonstration ROCS payload seen here on the lower side of the Bus.

Following the Sample Return Orbiter (SRO) in the reference architecture **(Figure 2**), would be a Sample Return Lander (**Figure 4**). Currently, this lander concept would include the capability to drive to the Mars 2020 sample drop off locations, collect the samples, insert them into the return canister, and eventually launch the entire collection into orbit for retrieval. A number of candidate architectures are under consideration for this, but the simplest is shown in the reference architecture (**Figure 2**) where a Mars 2020-class rover includes the MAV as a payload and performs the traverses necessary to collect the samples. After collecting the final sample to return, it launches the MAV from its final location. Alternatives under consideration include a cooperative approach where a platform like lander (similar to Phoenix or InSight) hosts both the MAV and a smaller MER-class rover. The smaller rover could be provided by a partner (eg: ESA) which would traverse to the sample location points, then return to the lander base and load the samples into the MAV for launch. Launch would occur where the platform landed. This Fetch Rover approach requires much longer surface duration in order to perform a round trip to the samples and back, and this provides another driving requirement on the MAV, namely to survive a full Mars year (2 Earth years) on the surface. The uncertainty in the arrival date and actual duration for surface operations also dictate that the MAV be able to launch at any time of the Mars year.

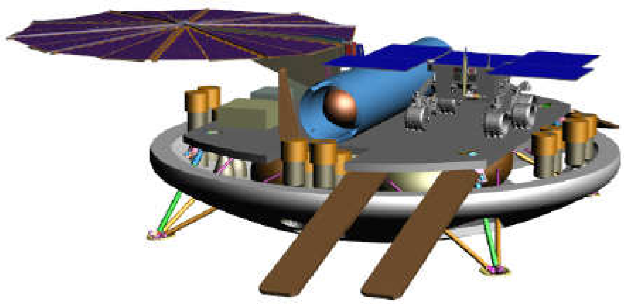

Figure 4: Conceptual Design of a solar powered platform style lander for SRL with Fetch rover and MAV

The final details of any MAV host will be unknown for many years, so in order to continue the advancement of the technologies necessary, the MAV concept being studied is designed to accommodate a large range of potential host constraints. Foremost is size, mass and power requirements. In agreement with the Mars Program Office, the driving constraint for packaging would result from a **Figure 5** skycrane-like delivery system (aka MSL and Mars 2020), although due to the higher landed mass required for an SRL, this would be delivered by a 4.7m aeroshell, an increase over the former 4.5m aeroshells. Similarly, while no precise delivery mass capability is yet known, the MAV system is being developed to minimize total landed mass to the extent possible. Similarly, it is unknown whether an RTG would be selected for a future lander. A platform lander may never use one. As such, a solar powered option solution must be maintained, and this also drives a MAV system to require a minimal amount of energy for survival. This is achieved through a combination of propulsion system selection and launch system design with good thermal control capability.

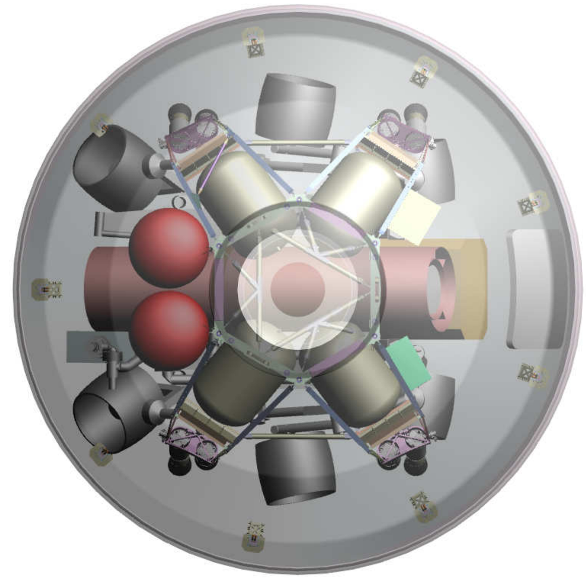

Figure 5: Packaging of a skycrane descent system in a 4.7m aeroshell to establish packaging constraints for a MAV

2. HYBRID SSTO MAV

In January 2016, after briefing the Mars Program Director on the results of the 2015 studies and the results of the End Of Year review, the decision was made to focus efforts on advancement of the hybrid Single Stage to Orbit (SSTO) MAV concept. While more than one option was considered viable, the hybrid approach appeared to have the most robust characteristics that satisfied the driving constraints of the other missions, as described earlier (size, mass, power). Given the limited Mars technology development funds available, focusing efforts on this approach improves the ability to advance the maturity level considerably. In this case, the hybrid was also the lowest TRL of the options considered.

The hybrid MAV has several advantages over the other architectures considered. First, the propellant combination of wax-based solid fuel and MON-30 oxidizer allows the MAV survival temperature to go as low as -75C. The limit is the oxidizer that freezes at ~ -82-83C[4]. The paraffin-based fuel with specially chosen additives has been successfully tested to -105C. The next closest option was the bipropellant MAV which would use a combination of MonoMethylhydrazine (MMH) and MON-25 which could operate down to ~-44C (MMH freezes at -52C). Solid propellants are generally qualified to -40C. This substantially lower survival temperature for a hybrid provides for a much lower survival energy demand from the host.

Another key advantage is the high specific impulse of the hybrid. With a theoretical Isp of ~ 335 s, and a practical Isp ~314-320 s, the hybrid is the highest performing propulsion system and can therefor absorb dry mass increases more readily than other systems with less impact to GLOM. This impulse is achieved without metallicizing the fuel and therefore also reduces the erosion experienced on the nozzle throat preserving the high performance throughout the burns. The hybrid can be restarted as many times as is needed, and can also be throttled if that provided any performance or mass savings. Given the uncertainties today of some of the final details in ~ 2022 when an SRL mission might start up, flexibility and design robustness is important.

A hybrid MAV operates at lower chamber pressure than its cousin the solid, and thus over sizing the chamber slightly to accommodate increased total impulse (in the event of mass growth for instance) is not as costly. Similarly, the diameter of the system can be varied to buy back length as the oxidizer tank is scaled. Injection errors are also significantly less with a hybrid (or biprop) that can terminate thrust on command once the target impulse is provided, compared to a solid solution. The System-level benefits of a hybrid made this a clear choice for technology investment. While it is not a guarantee that a future SRL mission would choose to maintain this solution once it is initiated as a real project, it is expected that for all these reasons it is a strong contender. The goal of the Mars Program at this juncture is to raise the TRL of both the components and the System over the next few years to this end.

The Point Of Departure Review (PODR) version of the hybrid SSTO MAV[5] is shown in **Figure 6,** both with details and stowed within its launch tube. This is the condition it would be in when mated to a host platform. In addition to the launch tube, clearly visible is also the canister loading system that is required to insert the collected tubes into the OS prior to launch. This loading system is enclosed in a sealed system to protect the MAV and the OS from thermal and dust exposure while on the surface.

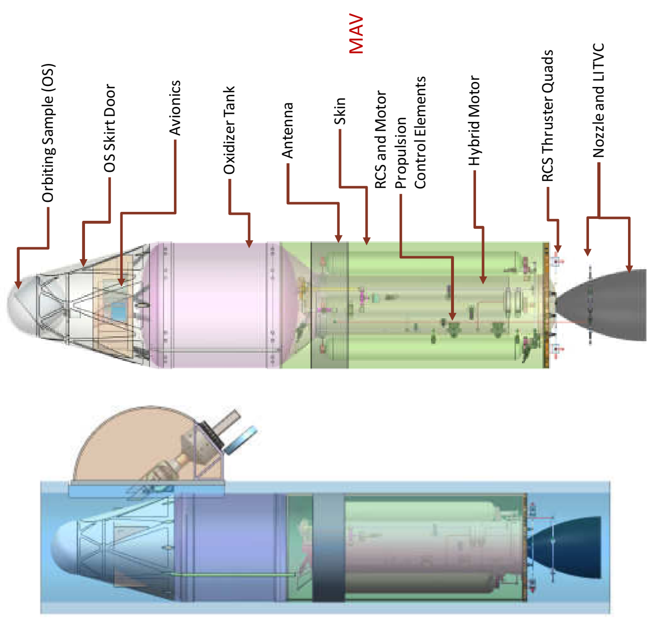

Figure 6: Current hybrid SSTO Mars MAV design configuration

3. Hybrid Design Trades

To arrive at the current design, several trades were performed. The first was in how to perform thrust vectoring during main engine burns. Thrust Vector Control (TVC) is critical to controlled flight of a vehicle like this, as Reaction Control Systems (RCS) would be unmanageably large if required to operate in this capacity. The vehicle is dynamically unstable and must remain under positive control at all times. There are many options for TVC. For liquid engines, it is most common to simply gimbal the whole engine with linear actuators and flexible propellant lines. In solid rocket motors, the common approach is to gimbal the nozzle itself. This is performed by linear actuators pushing the nozzle in the desired direction.

The thrust chamber continuity is maintained either through a spherical ball type friction interface (trapped ball) or through flexible materials (flex seal). The interface between the nozzle and the thrust chamber is extremely challenging and poses the most risk in this approach. Further, with the expected temperatures it would see on Mars, the flex seal designs were ruled out as the soft goods often become brittle at cold temps. The trapped ball nozzle approach is one option for a hybrid motor as well, as they share a similar geometry to solids in this area.

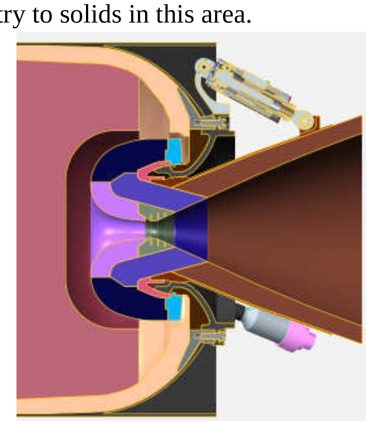

Figure 7: Example of trapped ball nozzle with linear actuators for Thrust Vector Control in solid rocket motors.

Another alternative to a moving nozzle that is afforded a hybrid rocket motor is to use a simply fixed nozzle, and inject either the oxidizer or pressurant into ports downstream of the throat in the nozzle itself. The injection of liquids or gases here create a shock wave and flow separation where the supersonic combustion gases travel down the wall of the nozzle. By injecting into various ports around the nozzle, the effective thrust vector can be diverted up to many degrees. This is called Liquid Injection Thrust Vector Control (LITVC)[6] and requires no complex moving parts. Simple solenoid valves are opened and closed tor result in the desired vectoring (shown in **Figure 8)**.

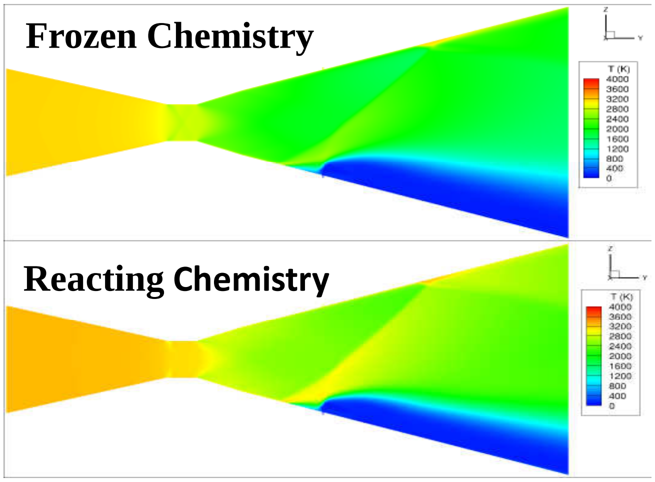

Figure 8: Simulations of Liquid Injection Thrust Vector Control including reactive and non-reactive species showing wall shock formations

Other TVC options were also considered, including Jet Vanes and nozzle tabs for instance, but LITVC appears to be the simplest, lightest and most robust approach. One major drawback in their use is the quantized response level they provide. Where a linearly gimbaled nozzle can be smoothly transitioned with fine resolution to a desired value, LITVC relies on pulses of injected fluid with discrete impulse levels and at constrained time intervals, dictated by the speed at which the valves operate.

Reaction Control Systems were also heavily studied. In a more global sense, both the type and sizing of the RCS systems had to be considered. In a purely delta-V minimized approach, the MAV terminates the first burn of its two burn sequence while still within the appreciable atmosphere and at very high velocity. Given the mass uncertainties in the CG and moments of inertia, plus the fact that the design is inherently unstable, we were finding that the RCS system needed thrust levels in the ~100lbf range to maintain vehicle stability after the main engine terminated (TVC provides ample control authority as long as the engine is running). Thrust at these levels requires substantial propulsion capability (ie: mass and complexity). We found that by tailoring the trajectory to enforce a minimum dynamic pressure at burnout below a certain value had minimal effect on the overall mass efficiency, and dropped the RCS sizing requirements down to under 7 lbf. These levels can be readily achieved by cold gas and similar types of approaches. Once the sizing was established, then the trades of minimum mass could be undertaken. Using a small hydrazine system would be relatively simple in this range, however due to the high freezing point of hydrazine (~ 2C) it would require significant heat to keep warm and defeat the low temperature benefit that the hybrids provided. Instead cold gas was elected as the best approach. GHe is generally the pressurant of choice for a liquid propulsion system to minimize mass. When used as a medium for cold gas purposes however its low density makes it a poor candidate for moderate impulse levels (Isp is high, but density is low, so equivalent impulse would require either 7X storage pressure or volume compared to GN2). A further trade was executed looking at the relative benefits of staying with the GHe pressurant that was already available, versus a completely separate GN2 system which is seen on larger systems. Based on the current predicted value for RCS consumption (very low), the current GHe system is the mass winner. GHe also does not suffer the potential to condensate at the low temperatures expected as the gas is expelled out of the tanks.

There are a few trades still open at the time of this paper writing. The first of which is a trade between motor casing material and propellant tank material. Under evaluation for both is composite versus titanium. In both applications, a composite structure is lower in mass. However, to affix the motor and tanks to other elements of the structure, special composite adapters must be glued and / or wrapped into the cases in order to provide attachment points and take substantial loads. These add-on structures are not as mass efficient as the rest of the composite structure as a whole, and the net mass of this approach is comparable to or potentially heavier than a custom constructed Ti alloy structure whose attachment points can be integrated seamlessly into the base structure. Mass is not the only factor in this trade, as Coefficient of Thermal Expansion (CTE) may also play a significant role, both in the diurnal and seasonal temps experienced while on the surface, plus the temperature extremes they will see during ascent. Due to CTE and current mass estimates, the reference baseline for MAV is to use Carbon Overwrapped Pressure vessels (COPV) for both the Oxidizer and GHe tanks. These would be moderately thin Al liners wrapped with a T1000 fiber. These would be compliant with the 1.5X factor of safety at their expected MEOPS during ground handling, and at least 1.25X at flight operating conditions. The motor casing will be filament wound over the insulation wrapped fuel grain. The nozzle would be integrated into the motor directly and wrapped as part of the overall assembly. Both the motor and the oxidizer tank are in the primary load path and will be attached via flanges integrated into them at the forward and aft ends.

Another open trade is the use of pyrotechnic or other ignition systems versus the inclusion of a hypergolic additive in the fuel. We have a couple of organizations investigating potential additives that react hypergolically with MON oxidizers[7]. It is not yet clear what percentage level these will need to be included at to ensure rapid ignition. It is also not yet understood what handling constraints, if any, this addition might impose on ground operations. Including the power and control circuitry on a MAV however to perform ignitions, as well as the ignitors themselves, adds considerable dry mass and will require more localized heating to keep them above qualification temperatures. If the development programs are successful, no additional mass will be required, and the motors will light spontaneously after the oxidizer flow has been initiated. If not, then in the worst case the MAV must carry ignitors, control HW, cabling and power to perform multiple restarts internally. For now, a compromise approach is being assumed where a pyrotechnically initiated ignitor is fired by the lander host for the first burn. This connection is made through the T-0 connection with the lander and uses the Pyro Initiation Unit (PIU) that already exists on the lander. The subsequent operations are initiated via hypergolic reaction. The fuel with the hypergolic additive resides within the core of the fuel and is only exposed after the first burn recedes the outer layers away. This precludes any ground handling exposure concerns. If the additives do not manifest as hoped, these may all become internally initiated events.

Figure 9: Example configuration of a hybrid fuel grain with embedded hypergolic additive for late burns

On the mission side, the MAV is currently being designed to envelope all of the potential sites on Mars between -30 and +30 deg latitude, as Mars 2020 has not yet picked a landing site, and is unlikely to do so prior to 2019. Further, as mentioned, it is assuming a worst case target orbit of a 500 km sun synchronous orbit where the NeMO orbiter may choose to go for science reasons. Combining these two issues MAV has established an equatorial launch from -2.5 km MOLA altitude as its reference launch site. The adoption of this high inclination orbit has resulted in ~ 30 kg of GLOM increase alone. The higher energy target orbit also increases the “gear ratio” of dry mass increases on the MAV. In the early versions of the hybrid MAV, the gear ratio was approximately 4.6:1. The design maturity and the Payload mass increase from 14 kg to 18 kg has increased this to 4.9:1. With the higher energy target orbit, the cost is now 5.6:1. The higher energy orbits are the dominant factor in GLOM. The current top Mars 2020 candidate sites[8] are shown in **Figure 10**. As soon as one is chosen, the MAV baseline design can take advantage of some potential mass savings. Similarly, once the NeMO orbiter identifies an actual target orbit, MAV may further be able to reduce its sized accordingly.

Launch site	*GLOM [kg]*
Equator, -2.5 km	*342.7*
SW Melas (12.2 N, -1.9 km)	*338.8*
Columbia Hills (-14.4 S, -1.9 km)	*337.9*
Jezero (18.5 N, -2.5 km)	*337.5*
NE Syrtis (17.8 N, -2.2 km)	*337.1*
Mawrth (24 N, -2.3 km)	*334.1*
Eberswalde (-23 S, -1.4 km)	*332.7*
Holden (-26.4 S, -2.1 km)	*332.3*
Nili Fossae (21 N, -0.6 km)	*332.1*

Figure 10: Current top Mars 2020 landing sites under consideration and potential MAV GLOM for each.

4. AHEAD OF ITS TIME

The MAV concept is being developed in advance of the host that would carry it. This is often the case with new technologies that require early investment, and MAV is not unique here. How then do we ensure that the work being done and assumptions being made get properly captured and documented for the benefit of the future teams that could ultimately be working on SRL and the MAV in the coming decade?

In addition to capturing a set of requirements for a MAV, and documenting the analysis and design work leading up to the Point of Departure Review (PODR), MAV is generating 4 Interface Control Documents (ICDs). The PODR will capture a snapshot of the MAV design that meets all of its external requirements and design constraints, as well as flowdown of those requirements to internal subsystems. It will capture a design that closes with respect to performance and can establish an anchor for subsequent technology maturation efforts. While not a formal project, the PODR is being treated from a design maturity level similar to a PDR.

The four ICDs under development capture four primary interfaces, two external and two internal. The two external interfaces are the MAV System to Host interface, and the MAV to Payload interface. The internal ICDs capture the details between the MAV itself and the launch system, and the launch system to the loading system. These are currently under separate direction (JPL for the MAV and loading system and MSFC for the launch system) but may also become separate contract items for a future SRL mission. The two external ICDs are being negotiated and agreed to by representatives of their respective study leads. In the case of the Host ICD, Erik Nilsen within the Mars Program Office runs the SRL studies and provides feedback and concurrence on details and assumptions that cross the host to MAV boundary. As these details mature, he incorporates them into his studies, and these would become accommodation requirements for a future SRL mission development. Similarly, Tom Komarek leads the Advanced Development Team (ADT) for the Mars Program Office and is in charge of the Payload definition (especially the OS). His team serves as the interface proxy to the Mars 2020 mission (producing the sample tubes), the MAV/SRL mission concept, and the SRO mission concept. The OS is central to all three. The detailed interfaces between the Payload system (which includes the OS) are iterated on between the parties and captured in the ICDs between them. The future SRL mission, like the MAV, would also be responsible for producing the Flight payload, and many of these details will be established prior to their existence as needed to support earlier efforts (such as the ROCS system on NeMO that could fly in 2022), hence it is critical these interface definitions get captured and well documented.

5. ADVANCING THE TRL LEVEL

With the establishment of a MAV design that adequately satisfies the needs of a future SRL mission, work can proceed to mature all the components and System that it represents. Bringing this System to a TRL 6 level is a key objective of the Mars Program as a method of risk reduction for the potential future SRL mission. The MAV itself is considered the key remaining risk to being able to successfully execute a Mars Sample Return mission in its entirety.

The MAV team intends to do this by implementing a development and test flight program over the next three years. MAV was funded through 2017 to initiate this effort and has already begun in earnest. For the hybrid propulsion system, two hybrid propulsion vendors are on contract to develop and test full scale Mars MAV motors in both ground and flight configurations. Two vendors were also funded in 2016, and successfully completed the first-ever full motor firings with MON 3 oxidizer in both 3” and 10” motor sizes. The knowledge they gained from this effort is leading to improvements in the motor design and performance and will be demonstrated through multiple full duration ground tests in 2017. In several of these tests, LITVC nozzles will also be employed in order to capture some of the basic functionality and evaluate potential erosion concerns with their use. The vendors will also demonstrate individually their respective approach to making flight weight motors, and will fire a full scale flight weight motor for a full duration burn. This series of tests will provide both an anchoring and TRL advancement for the Mars MAV motors, but the knowledge from these will inform the MAV team of the appropriate changes to make to define a terrestrial demonstration design which may have slightly different design requirements than a Mars version.

Figure 11: Example of composite overwrapped flight weight hybrid rocket[9] motor similar to Mars MAV size.

Key objectives of the flight demonstration include

1) Performance of the hybrid propulsion system
2) Long coast and restart of the motor
3) Handoff between TVC and RCS control after MECO 1
4) LITVC performance
5) Closed loop guidance and control with the flight avionics and GNC HW
6) Anchoring of flight, aero and aerothermal models

The current thinking of a flight profile to achieve these objectives is to fire the motor initially to ensure a coast to exoatmospheric conditions comparable to Mars. Once there, restart the engine and perform several maneuvers with the LITVC system. Note that the LITVC system will not work at sea level due the flow in the nozzle not being fully developed at that back pressure level. As a result, the demo airframe will likely require fins for stabilization during the first part of flight. Upon completion of the LITVC maneuvers, the vehicle will re-enter and deploy its recovery system. The system will hopefully be successfully recovered in the ocean for forensic analysis. High rate data will be available via telecom throughout the flight, but additional data will be recorded on board that will be valuable to recover. A similar approach is being followed with the Peregrine flight test, and the team will have some experience with doing this.

Detailed flight design trades for the demo will commence shortly after the PODR in December of 2016. In addition to the surface launched concept described, the team will also assess an alternative option that launches a more Mars like MAV from a high altitude balloon at ~ 30km altitude mimicking very closely the same conditions expected at Mars. While this provides a more direct comparison and relationship to a MAV mission, it may also be out of reach for the current demonstration mission budget, and cut backs elsewhere may be required.

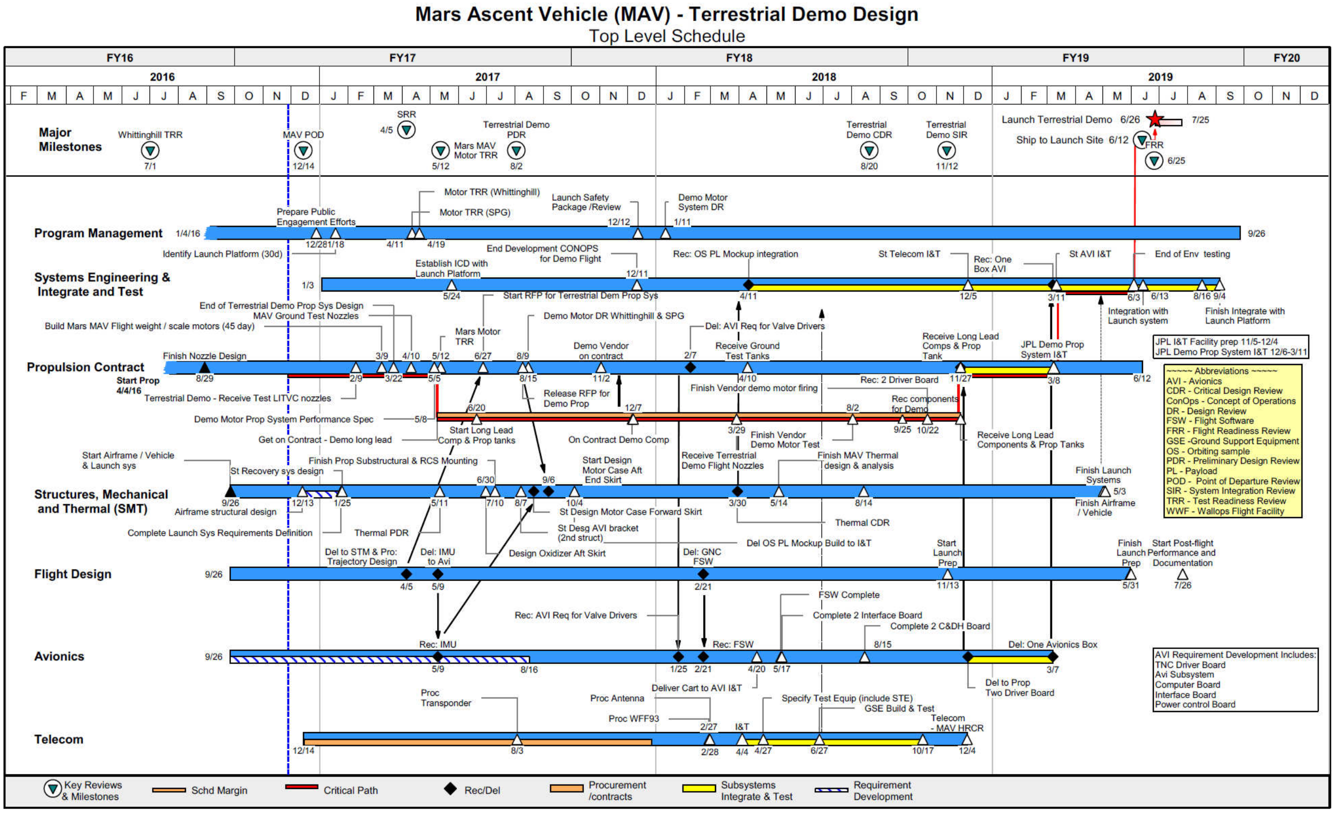

Figure 12: Top Level Schedule of the MAV flight demonstration mission development

On the path to a demo mission, the Project will follow a typical mission lifecycle, albeit slightly compressed from a normal flight mission development (shown in **Figure 12**).

The MAV Team will execute a Demo System PDR in August of 2017 based on all test data to date, plus the final objectives established for a terrestrial flight demonstration mission to launch in 2019. This demonstration mission will likely launch out of WFF and if successful, will demonstrate a System level TRL for the MAV concept at TRL 6. A competition will be held amongst the two competing vendors in 2017 to select which will be the provider of the terrestrial demo flight motors. The current plan is to use the vendor performance on the flight weight Mars MAV motor tests from mid-2017, plus the results of their design reviews for a terrestrial demo motor, plus their respective proposals as scoring criteria. After selection the chosen vendor will produce a set of test hardware to be fired over the full flight sequence prior to building the final demo Flight Hardware.

The demo mission CDR will be held in August of 2018 and will incorporate the details of all the test programs into a final flight system design. Systems integration will occur several months later, followed by an environmental test program, and launch processing at WFF. As might be expected, the critical path for the effort runs through propulsion, both for the motor developments themselves, as well as due to some long lead support items such as tanks and regulators.

In addition to propulsion, several other areas of development are also underway as part of an overall MAV system. The launch system will be prototyped and tested with surrogate motors to fully anchor launch models and environmental predicts. Of concern with a launch system are both the pressure and acoustic fields that result and impinge on the MAV itself, but also the dynamics of the launch system with respect to the MAV during takeoff. The design must preclude contact and also excessive tipoff torques on the MAV.

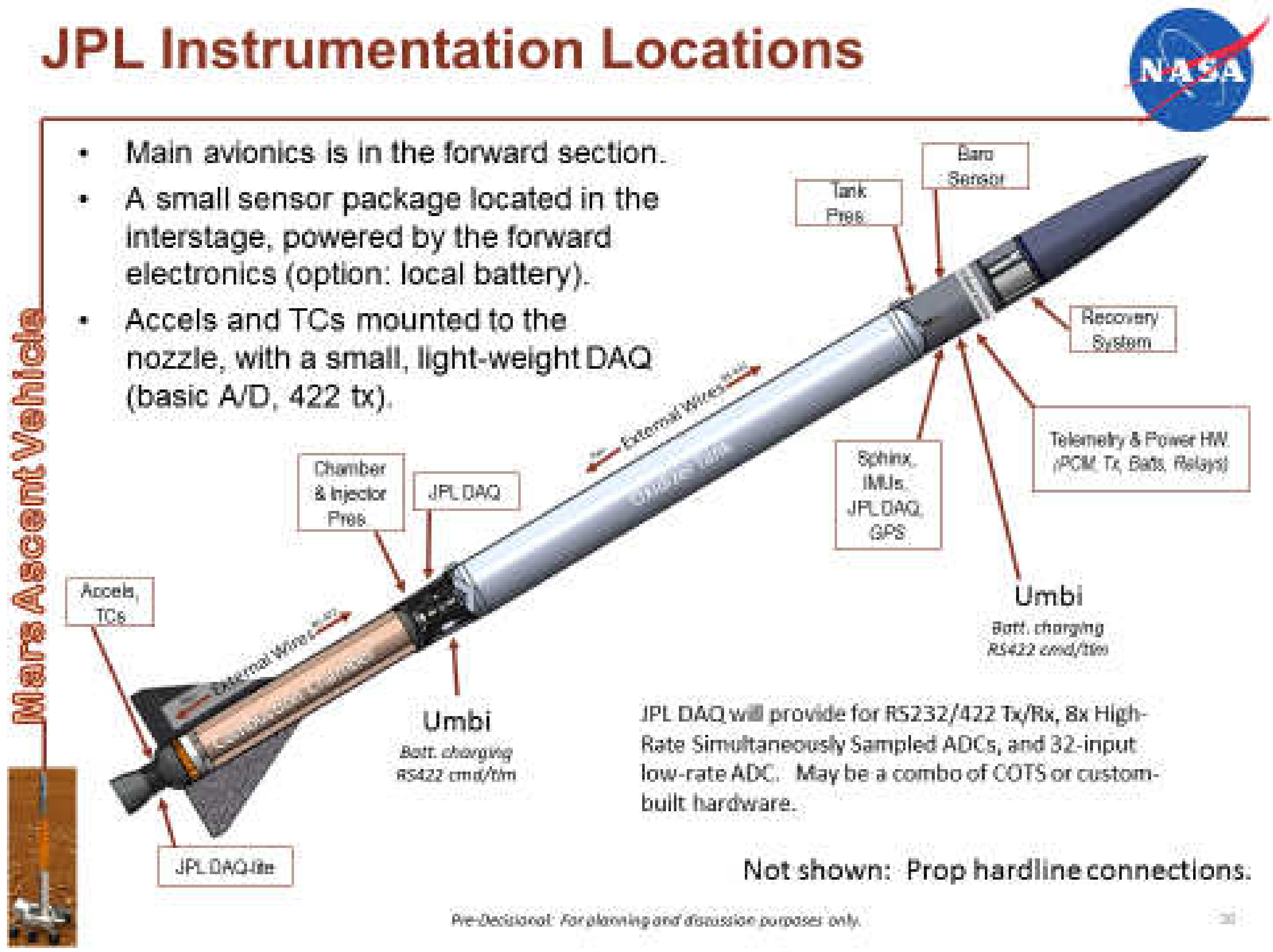

Figure 13: Instrumentation of the Ames Peregrine sounding rocket.

The avionics and GNC sensors must also operate as expected. The current baseline for MAV leverages the development of a new computing system developed at JPL for cubesats called Sphinx[10] (shown in **Figure 14Error! Reference source not found.**). This new compute element is extremely powerful and low power and will be used in several upcoming microsatellite missions. JPL has an opportunity in partnership with Ames Research Center (ARC) to fly this and two of the top MAV candidate IMUs on a sounding rocket flight in the spring of 2017. The Peregrine rocket (**Figure 13**) has been developed by ARC as a potential alternative to the running solid rocket motor systems used for sounding rocket experiments out of Wallops Flight Facility (WFF). This new Peregrine uses a similar paraffin-based hybrid rocket motor with N2O as the oxidizer. As such, JPL is also leveraging this opportunity to capture inflight environments and launch acoustics of a comparably sized paraffin based motor that can be used to develop the terrestrial demonstration mission hardware against.

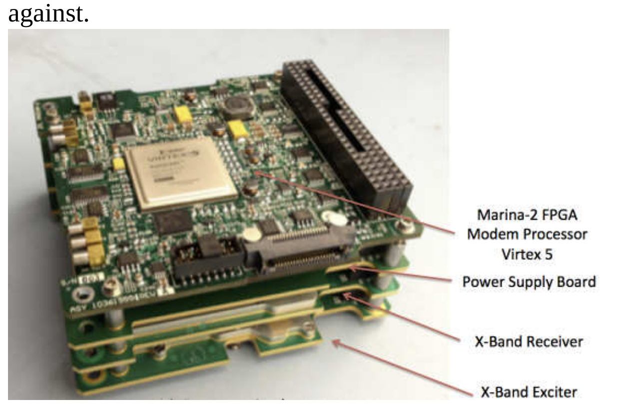

Figure 14: JPL Sphinx CubeSat flight avionics development for use on MAV

Finally, a separate contract may be awarded to one of the vendors (could be any of two runoff candidates) to upgrade their test facility for operation at -20C, the current Mars design point. The only remaining demonstration necessary to demonstrate full TRL 6 compliance for the MAV motors is operation at the design temperature with the design oxidizer (MON 30). For cost and availability reasons, MON 3 is used for all development and demonstration testing for operation at room temperature. MON 3 freezes if taken to -20C making it inappropriate for use at Mars. Conversely, MON30 at room temperature has a very high vapor pressure, and is hard to work with for normal development. To address this, in addition to all the data that will be acquired from MON-3 tests and flights, several motor firings will be performed with MON30 at full scale to eliminate the only remaining open question, once the MON-3 based developments are completed.

6. PEOPLE INVOLVED

This effort is comprised of many participants across many centers. Much of the System design work and external program interfacing is done at the Jet Propulsion Laboratory. JPL has led many of the architecture trades to date, and helped to get the demonstration mission funded and started. Flight and trajectory trades and sensitivity studies are being performed, as well as full 6-DOF monte carlo modeling. JPL also has several recent PhD hybrid propulsion engineers who are familiar with paraffin-based systems. Working closely with JPL has been the Marshall Space Flight Center (MSFC) who has led many propulsion development efforts for MAV, and also has some highly experienced hybrid propulsion experts who have been invaluable helping to provide analysis and guidance on the propulsion system development, including LITVC design and modeling. MSFC also leads the launch system development for MAV. The Langley Research Center (LaRC) has been supporting MAV for several years now providing computational fluid dynamics modeling (CFD) of MAV geometries, establishing the aero coefficients, assessing RCS and flow field interactions and performing aero heating analysis and predicts. Ames Research Center is flying a similar hybrid system as a sounding rocket, and MAV has teamed with them to leverage a flight opportunity for some hardware and some of its team. ARC is also advising on the use and sizing of thermal protection systems (TPS) that will be used on the Payload at Mars, and may be demonstrated for the Demo mission.

In addition to the NASA participants, members of three propulsion companies have been also supporting MAV. The Space Propulsion Group, Parabilis Space Technologies, and Whittinghill Aerospace are all experienced hybrid rocket companies and are rapidly advancing the systems required for a Mars Ascent Vehicle. Also supporting MAV technologies are members of the faculty and staff at Purdue and at Penn State, testing fuels with MON oxidizers, as well as hypergolic additives that might be used for hybrids.

An effort of this scope could not be done without a large number of people all working toward a common goal, and so far this group has demonstrated both the capability and enthusiasm to see it through. The coming years promise to be exciting times.

7. SUMMARY

The Mars Ascent Vehicle concept development effort has progressed beyond trade studies and parametric evaluations. It is now on a mission to advance the TRL level of all its constituent parts as well as the System itself, culminating in a terrestrial technology demonstration flight in 2019. Upon successfully performing that historic flight, a significant obstacle to the potential return of samples from Mars will have been vanquished!

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REFERENCES

[1] http://mars.nasa.gov/mars2020/

[2] JPL internal presentation

[3] https://en.wikipedia.org/wiki/Mars_2022_orbiter

[4] All propellant properties, especially Freezing points, can be found on Wikipedia

[5] Design Review, Dec 14, 2016 at the Jet Propulsion Laboratory

[6] “Studies on Thrust Vector Control using Secondary Injection Sonic and Supersonic Jets“, 2nd International Conference on Mechanical, Electronics and Mechatronics Engineering (ICMEME'2013) June 17-18, 2013

[7] Characterization of Ethylenediamine Bisborane as a Hypergolic Hybrid Rocket Fuel Additive, JOURNAL OF PROPULSION AND POWER Vol. 31, No. 1, January–February 2015

[8] http://marsnext.jpl.nasa.gov/

[9] Personal Blog, SpaceshipOne, http://www.airbum.com/pireps/PirepSS1.html

[10] CubeSat for Planetary Science and Exploration, Breaking New Grounds, *sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_167850.pdf*

BIOGRAPHY

Robert Shotwell received a B.S. in Aerospace Engineering (Magna Cum Laude) from Texas A&M University in 1995 and a MS in Astronautics (with Honors) from USC in 2003. He has been with JPL for more than 24 years. He is currently the Chief Engineer of the Astronomy and Physics Directorate at JPL. Prior to this role, he served as the Chief Engineer for the Mars Program, previously served as the Program Engineer for the Advanced Optical Systems Program Office at JPL, preceded by serving as the Project Systems Engineer for the Phoenix Lander. He has led numerous micro&small sat efforts at JPL, as well as served in the Propulsion (both chemical and EP groups) developing, delivering and testing FHW for Mars Pathfinder, Deep Space 1, SIRTF and TelStar 8. He spent two years serving as the facility manager for the EP labs, as well as performing technology development and hardware testing for both JPL and external customers.

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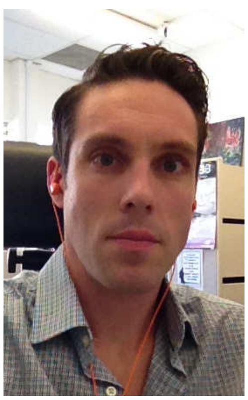

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APPENDIX A