

Miniature Autonomous Rocket Recovery System (MARRS)

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This paper discusses the development and testing of the new-generation recovery system in high-powered rockets. It starts from the overall description of the rocket system, the requirements of the Miniature Autonomous Rocket Recovery System (MARRS) and is followed by a description of a flight tested MARRS. Next, simulation and results from the flight tests are given. This paper ends with conclusions and recommendations for follow-on testing.

Abbreviations

ADS	=	Aerial Delivery System
AGL	=	Above Ground Level
CEP	=	Circular Error Probable
ChIMU	=	Cheap Inertial Measurement Unit
GNC	=	Guidance, Navigation and Control
GPS	=	Global Positioning System
INS	=	Inertial Navigation System
MARRS	=	Miniature Autonomous Rocket Recovery System
MSL	=	Mean Sea Level
NASA	=	National Aeronautics and Space Administration
RDS	=	Rocket Dynamic Systems
SPL	=	Sound Pressure Level
TNT	=	Tactical Network Topology
UAV	=	Unmanned Air Vehicle
YPG	=	U.S. Army Yuma Proving Ground

I. Introduction

THESE days NASA conducts about two dozen research-related sounding rocket launches per year from several locations around the globe carrying different sized payloads to altitudes ranging from 100 to 1,000 kilometers and higher. Their payloads however are not always successfully recovered. Subsequently there is an interest in developing a capability to safely and accurately return both large and small scientific payloads back to some pre-determined location.¹ Other requirements to such a system include light weight and volume, low price and reusability, capability to survive high g-load factors during deployment and necessity to employ integrated GPS/INS navigation system rather than just GPS-based GNC system. This paper focuses on the development and testing of a prototype Miniature Autonomous Rocket Recovery System (MARRS), which is based on the autonomously guided parafoil technology. Recent developments in aerial payload delivery systems assure accurate delivery of the commercial payload within 100m from the target,² therefore there is a strong potential for meeting aforementioned requirements. Speaking of small payloads there are some proven technologies allowing delivering payloads even closer to the target.^{3,4} Specifically, this paper explores a capability to utilize an advanced GNC system developed for the Snowflake aerial delivery system (ADS).⁵ For this purpose, the GNC unit of this ADS was repackaged to fit a nose cone of a typical amateur solid-motor rocket and tested during several launches. The paper presents the concept and development of the MARRS prototype and is organized as follows. Section II presents the overall concept of MARRS followed by Section III providing a more detailed description of the two-stage solid-motor rocket system used to for the initial test of MARRS. Section IV addresses decelerators used in the test prototype including the

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Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE MAY 2011		2. REPORT TYPE		3. DATES COVERED 00-00-2011 to 00-00-2011	
4. TITLE AND SUBTITLE Miniature Autonomous Rocket Recovery System (MARRS)				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School, Department of Mechanical and Aerospace Engineering, Monterey, CA, 93943				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 12	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

MARRS prototype to be used in high-power small-diameter rockets like that described in Section III. Section IV presents the results of computer simulations and outcome of flight tests. The paper ends with conclusions and recommendations for the further development.

II. MARRS Concept and Description of Two-Stage Carrier Rocket

The overall goal of MARRS prototype development was to show that a guided ADS can be deployed from the rocket and that its GNC algorithm can be initialized correctly and assure an accurate delivery of rocket payload to an intended point of impact. With the MARRS prototype GNC algorithms developed and tested on a Snowflake ADS already^{4,5} the specific objective was to assure the deployment of the modified Snowflake (hereinafter referred to as Snowflake-R) somewhere upwind from the target at an altitude of at least 2,000' above ground level (AGL). To meet this objective a two-stage solid-motor rocket was chosen as a carrier to bring MARRS up to such an altitude. This section provides an overall description of a MARRS concept followed by introduction of a two-stage rocket intended to bring MARRS at a give altitude.

A. Concept of MARRS Prototype Deployment

The planned flight profile for the test two-stage rocket to deploy MARRS (Snowflake-R) is shown in Fig.1.

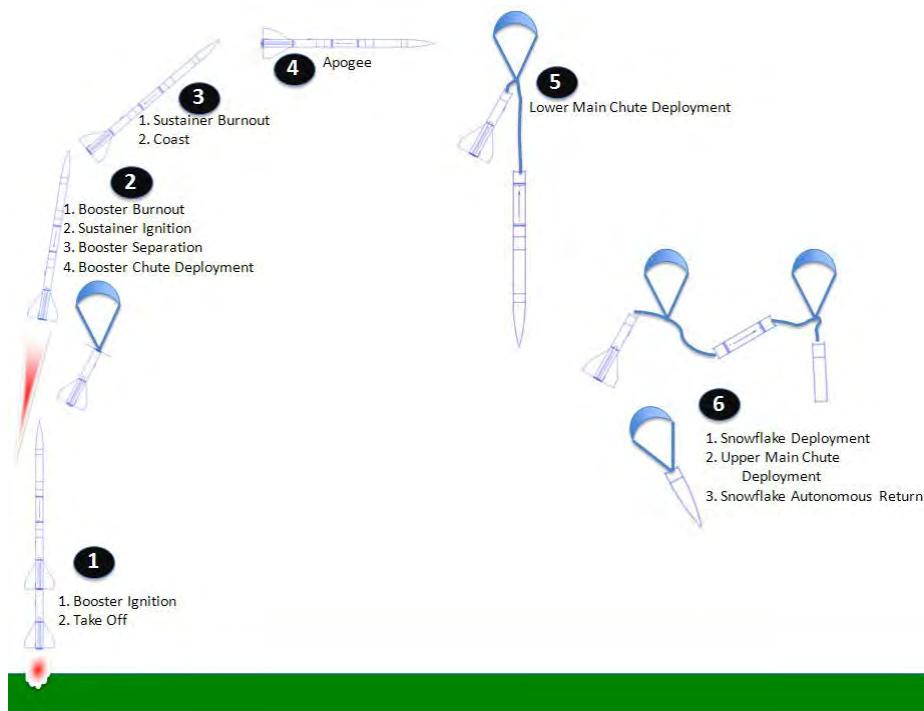


Figure 1. MARRS prototype deployment concept.

In stage 1 the booster engine is ignited from the ground. Once the rocket lifts off the ground an open break-wire arms the flight computer. Nominally, the avionics detect booster burnout by sensing when accelerations transition from positive to negative; a zero-g transition. As a backup, the developed system contains a time-delayed sustainer igniter. During stage 3, after sustainer burnout, the rocket coasts until apogee is reached. Shortly after apogee, at a predicted altitude of near 7,500' AGL, the lower main chute is to deploy. In stage 6 the avionics is to first deploy Snowflake-R (at about 3,000' AGL) and then the main chute (at about 1,500' AGL). This sequence is needed in order command Snowflake's release before the wiring between the payload bay and avionics bay is severed, as would occur when the upper main chute deployed. Once deployed, Snowflake-R brings the rocket cone down in a usual manner as described in Ref.5. Therefore, the recovery system of the developed MARRS test prototype was composed of three parachutes and an autonomously controlled parafoil.

B. System Components

The rocket chosen to test MARRS was a modified two-stage North-Star design by Rocket Dynamic Systems (RDS). Named Castor, this rocket had a takeoff weight of 42.6lbs and was approximately 15-feet tall with a

diameter of 5.5 inches. Figure 2a shows the rocket's component layout and Fig.2b – its launch on July 30th, 2010 at the Mohave Desert, CA.

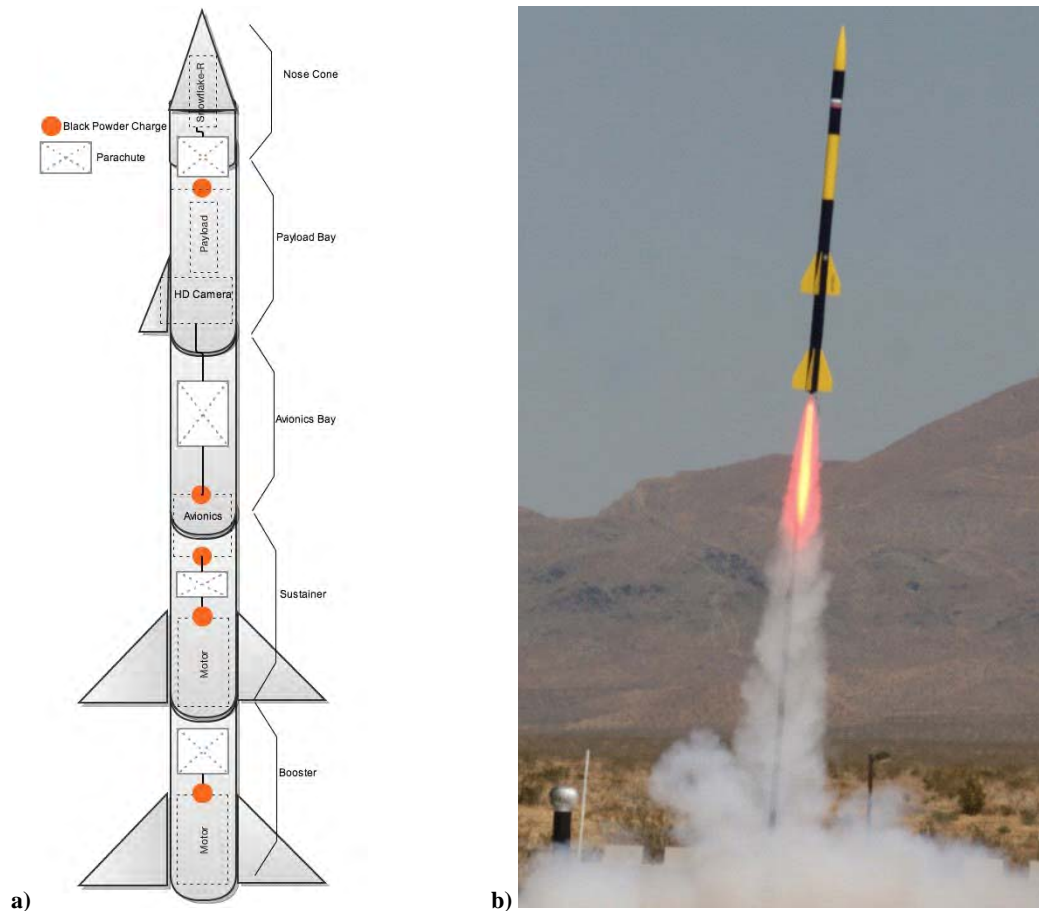


Figure 2. Castor component layout (a) and launch (b).

Starting from the top in Fig.2a, MARRS prototype, Snowflake-R, was primarily housed inside the rocket nosecone and, beyond autonomous return, is able to telemeter attitude and position data in real time. As mentioned above, the MARRS prototype utilizes a concept of a smart autonomously-guided parafoil system Snowflake developed and tested earlier.^{1,2} For the purpose of MARRS Snowflake's control unit was modified as shown in Fig.3a and tested (Fig.3b).

As shown in Fig.2a, approximately one third of Snowflake-R package continued into the payload section. The rest of the payload section housed a high definition camera that recorded video during the flight test. The avionics bay, contained the flight computers that controlled second stage ignition, chute deployment, payload release, and recorded acceleration, velocity, and pressure data on-board.

The primary on-board avionics was the G-Wiz HCX Flight computer shown in Fig.4. Using its onboard sensors, the this flight computer was able to determine many of the key events during a rocket flight; including launch, booster burn-out, sustainer ignition, sustainer burn-out, coast, apogee and low altitude. The HCX Flight computer swas also equipped with a break-wire detection to determine when the rocket was lifted away from the launch pad. Its microprocessor was used to control the firing sequence of the recovery system and the flight data was stored on a micro SD-card for post-flight processing.

The secondary avionics system was a Perfect Flight Mini-Alt/WD shown in Fig.5a. It served as a backup system for deploying the reserve parachutes. Both computers, assembled on a plywood card are shown in Fig.5b.

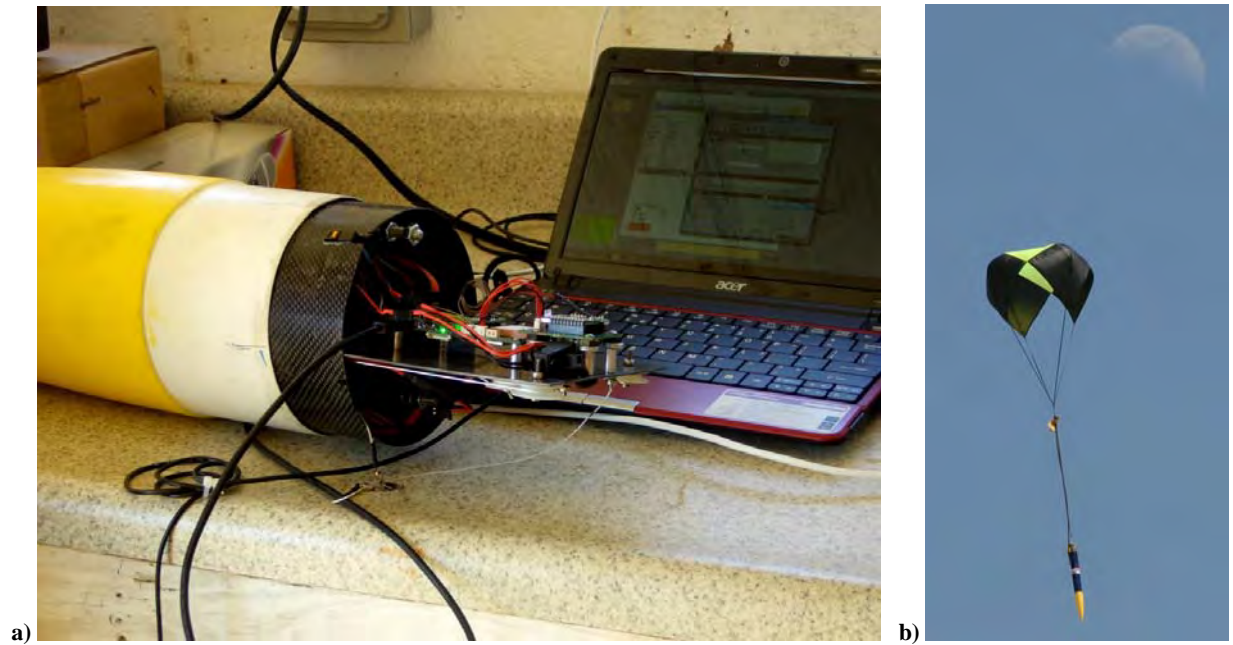


Figure 3. Snowflake-R preflight checkout (a) and testing (b).

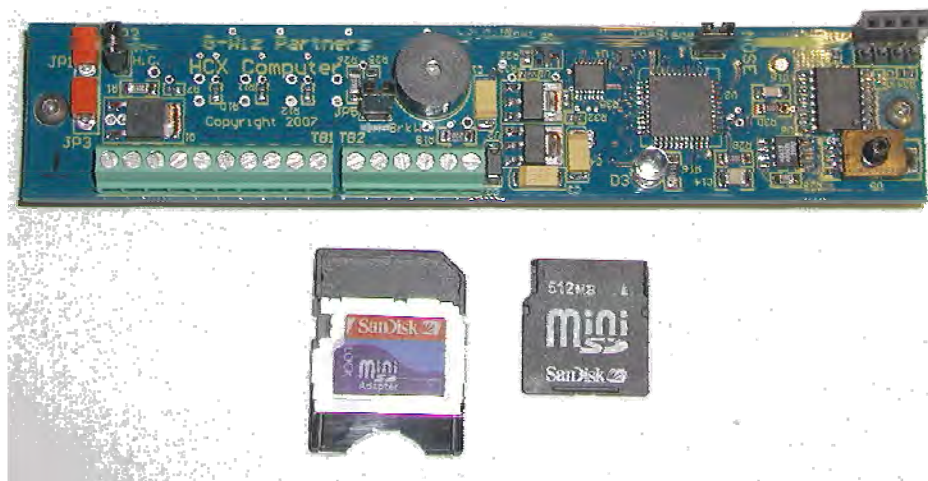


Figure 4. G-Wiz HCX flight computer.

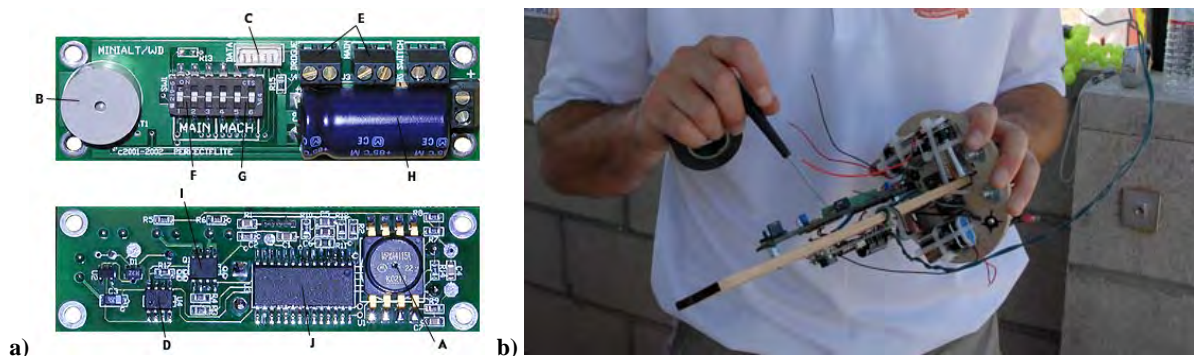


Figure 5. Perfect Flight computer (a) and assembly of primary and secondary avionics (b).

The third set of rocket avionics was the EFC-1K shown without its outer casing in Fig.6a. It proved to be a robust zero-g triggered igniter and was used to ignite the Black Powder Charges (BPCs). Figure 6b shows the EFC mounted on top of the booster motor with a BPC loaded in its nozzle.

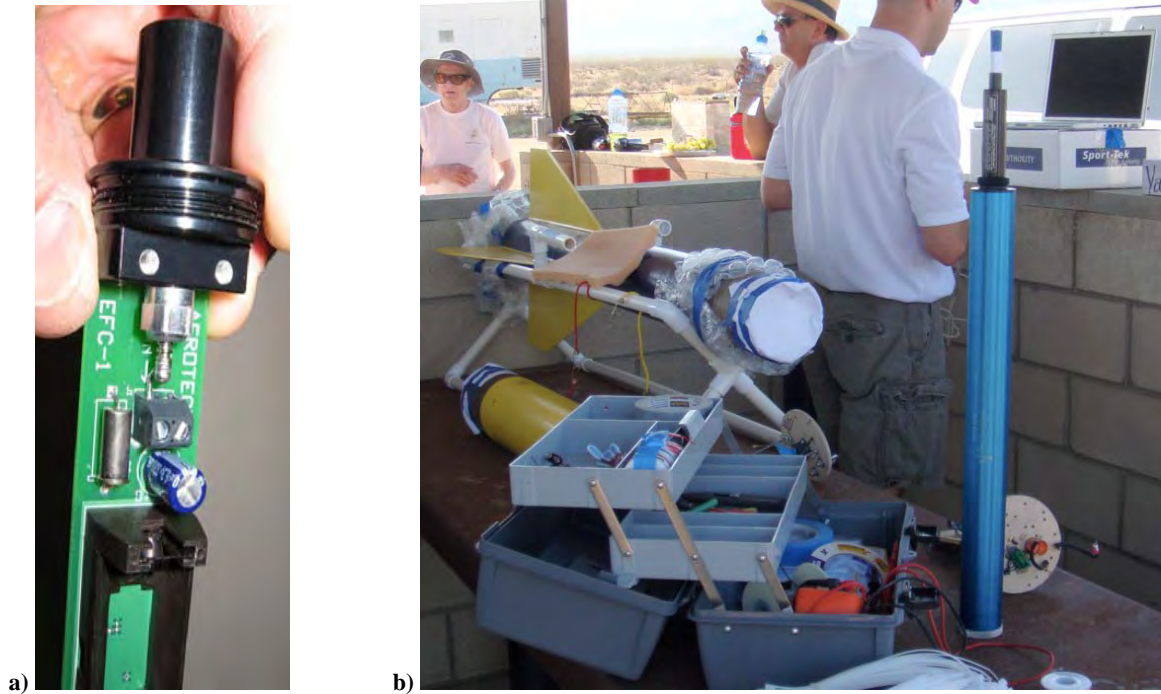


Figure 6. G-Triggered igniters (a) and loaded booster motor and igniter (b).

The last two (bottom) sections of the rocket as shown in Fig.2a are the upper and lower stages, commonly referred to as the sustainer and the booster, respectively. The booster used Aerotech K1275 rocket propellant for faster initial acceleration while the sustainer used Aerotech K828FJ propellant for longer burn time. Their thrust and propellant mass loss curves are shown in Fig.7. These thrust curves were used to develop performance predictions as will be discussed later.

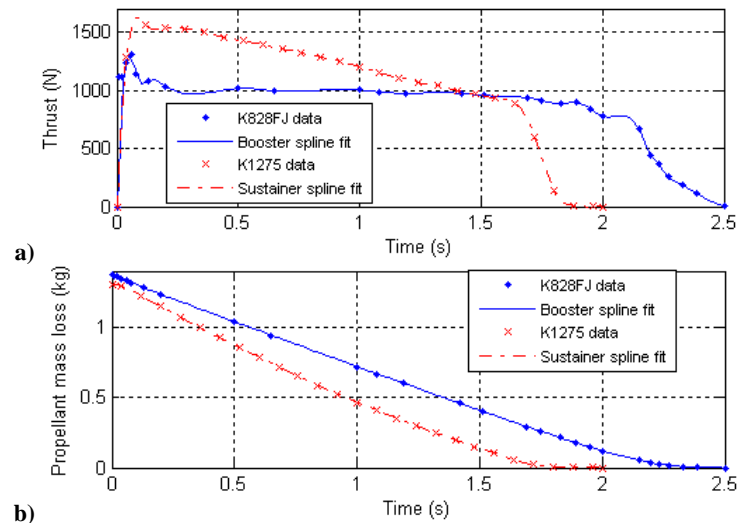


Figure 7. Booster and sustainer thrust (a) and propellant mass loss (b).

The black powder charges depicted in Fig.2a as the dark circles were used to separate stages one from another and were composed of approximately 4 to 6 cubic centimeters of FFFF black powder.

C. Rocket System Structure

The rocket body was an epoxy-laden phenolic-cardboard composite. Four fins were attached to each booster stage. The wooden fins were bolted to the integrating polycarbonate bulkheads (left-most image in Fig.8), which were then resin epoxied and riveted to both the rocket motor and the rocket body.



Figure 8. Rocket booster assembly.

A jig was used to ensure that the fins were positioned precisely 90° from each other during the cure cycle. These manufacturing steps are shown in Figs.8.

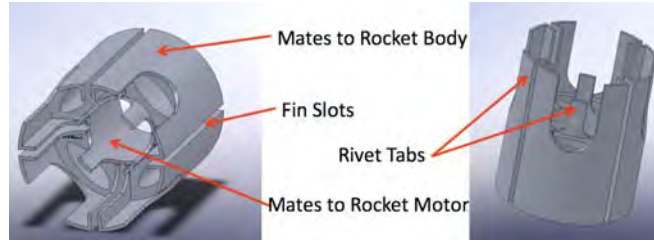


Figure 9. Rocket bulkhead 3D print model.

The solidworks model used to 3D-print the bulkhead is shown in Fig.9. The 3D printer was able to create the bulkhead with an internal honeycomb structure that was both strong and lightweight. It was also able to meet precise 2-milimeter tolerances on the complex geometry.

III. Rocket Recovery System and MARRS Prototype

This section discusses test prototype recovery system relied on three uncontrolled parachute systems, and one controlled parafoil (Snowflake-R).

A. Recovery System

The drawing in Fig.10 shows the planned recovery process broken out into an upper and lower system. In the upper recovery system Snowflake-R is shown deployed and using the 11 square-foot parafoil to control itself back home. The payload and avionics bays were connected via a 20 foot long Nylon strap that housed a shock-cord with a maximum extended length of 20 feet. Approximately 10 feet off the line the upper main parachute a TAC-9-B from Giant Leap Rocketry, was attached. As shown in the lower recovery system, the other end of the avionics bay was connected to the sustainer via 24 foot long Kevlar line upon which was the lower main parachute; a 50" Rocket Rage Parachute. The booster had a 70" Rocket Rage parachute.

In order to protect the parachutes from burns, the parachutes were wrapped in protective Kevlar cloth and a layer of flame-retardant cellulose was packed in between the BPC and parachute.

The dimensions of these three uncontrolled parachutes are summarized in Table 1. Based on these dimensions parachute performance was estimated using the following simple formulas:

$$S = \pi (r_o - r_i)^2 = \pi (1.778m - 0.127m)^2 = 8.6m^2$$

$$V = \sqrt{\frac{2mg}{\rho C_D S}} = \sqrt{\frac{2 \cdot 13.61kg \cdot 9.81 \frac{m}{s^2}}{1.22 \frac{kg}{m^3} \cdot 1.2 \cdot 8.6m^2}} = 4.6 \frac{m}{s} (15.1fps)$$

Here m is the mass of a component, g - acceleration due to gravity, ρ - air density, C_D - drag coefficient, S - canopy's area, V - descent rate.

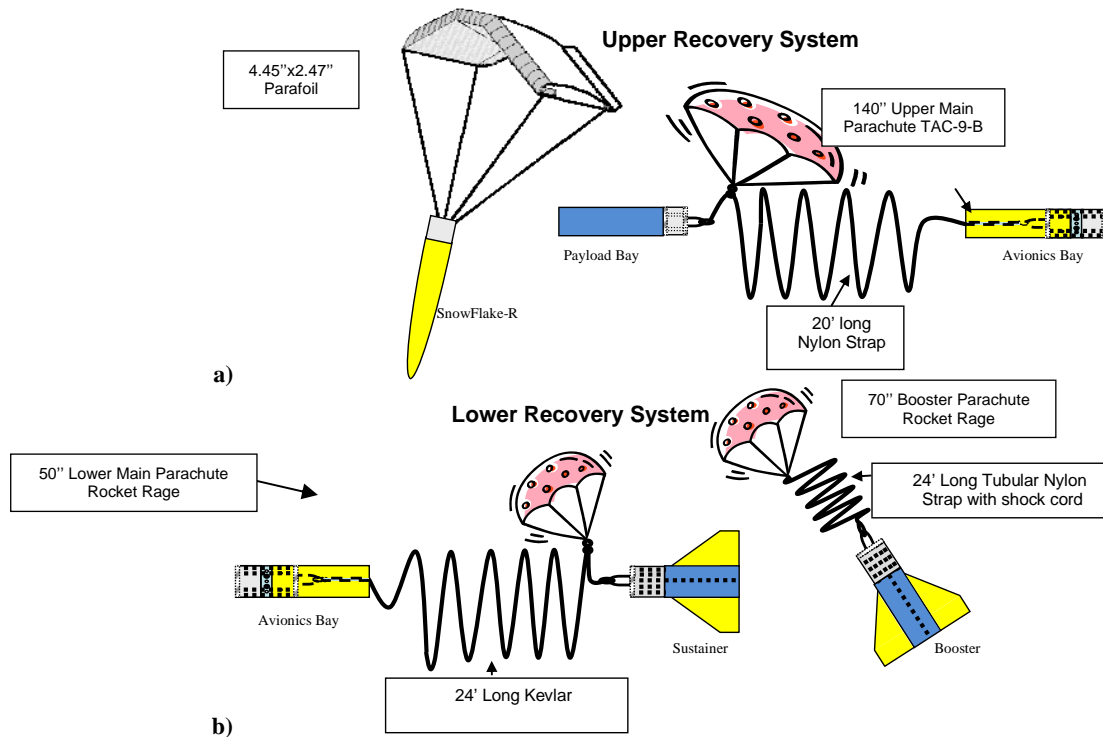


Figure 10. Upper (a) and lower (b) recover systems.

Table 1. Recovery system components and descent rates.

Component	Model	Diameter				Approximate		Decent Rate			Notes	
		Outer		Inner		S*	Mass**	Expected	Actual			
		in	m	in	m							
Upper Main Chute	TAC-9-B	140	3.556	10	0.254	8.56	13.61	4.62	15.14	14.90	See Section IV	
Lower Main Chute	White Rocket Rage	50	1.27	3	0.0762	1.12	-	-	-	-	Negative Deployment	
Booster Chute	Orange Rocket Rage	70	1.778	5	0.127	2.14	4.10	5.07	16.62	-	No data recorded	
Avionics		Free Fall									41.36	Free Fall
Parafoil	-	L(in)	L(m)	W(in)	W(m)	1.02	2.00	5.12	16.81	-	Negative Deployment	
		53.4	1.356	29.64	0.7529							

* Surface Area

** Dry Mass of Supported Rocket Components

III. MARRS Prototype

A MARRS must be able to operate during extreme conditions. Rocket launches can see accelerations as high as 10+ g's, during which the MARRS needs to accomplish attitude determination at a minimum. Electronic components must also be functioning inside of intense vibroacoustic environments; approximately 70db+ Sound Pressure Level (SPL).

Snowflake, the MARRS prototype selected for this flight test, is an existing system with the demonstrated ability to return itself to a predetermined landing site up to 10-20 meters of accuracy. Snowflake uses a Global Positioning System (GPS) receiver and an INS (Inertial Navigation System) to determine its location, speed, and winds aloft. Along with a pre-determined landing site and spiral way-points, Snowflake uses this information to determine its required trajectory and to control the parafoil to keep itself on course. The parafoil is controlled by two lines connecting the parafoil's trailing edge corners to two servos. Snowflake's GNC sends commands to each servo to either pull or release on the lines. By doing so, Snowflake can control the direction of flight and to a small extent, the descent rate. Although the employment concept of Snowflake remained unchanged, the system needed to be modified for use as a MARRS. First of all, the system was redesigned to fit inside 5.5-inch diameter body as shown in Fig.11. Second of all, Snowflake-R uses a commercially available hardware from Ryan Mechatronics, which includes a Monkey navigation board and a Cheap Inertial Measurement Unit (CHIMU) Micro Attitude Heading

Reference System (AHRS) as shown in Fig.12. The ChIMU seats into the module plug in on the Monkey to provide quaternion attitude estimation. More detailed layout of the Monkey navigation board is shown in Fig.13.



Figure 11. Snowflake-R (a) and its assembly (b).

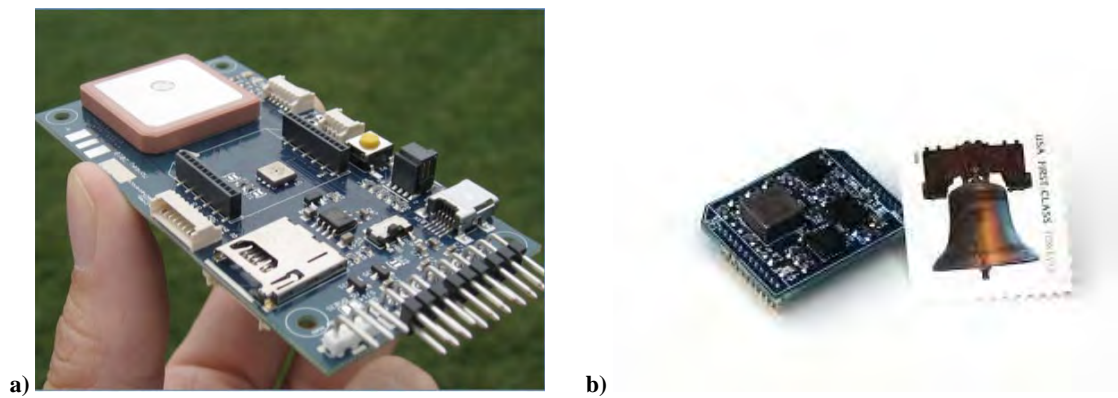


Figure 12. Monkey board (a) and CHIMU Micro AHRS (b).

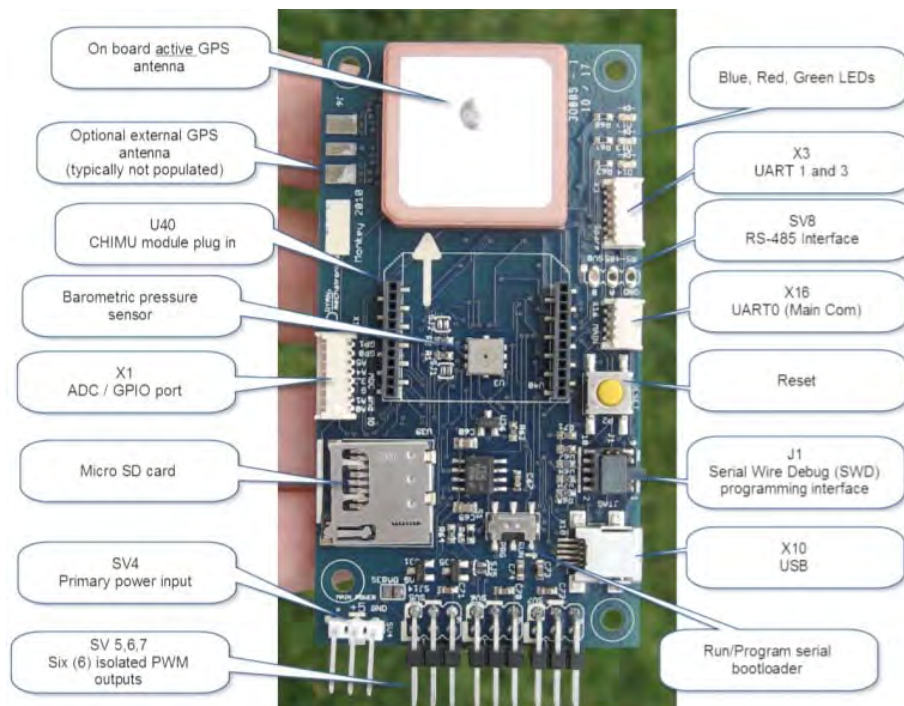


Figure 13. Monkey navigation board components.

Wireless communication is accomplished using the Maxstream 1mW Xbee transceiver module shown in Fig.14.

IV. Rocket Computer Simulation and Flight Test Results

This section presents computer simulations and predictions of rocket performance, compares them to those obtained in flight test and discusses the results of three deployments of MARSS prototype fulfilled on July 30th and October 16th of 2010.

A. Predicted Performance

Rocket predictions were generated in the MATLAB development environment. To this end, mass properties of the rocket were carefully weighed and entered into the program for components in both the upper and lower stages. Static stability was then determined by finding the Center of gravity (CG) and the Center of Pressure (CP) locations on the rocket. The rocket was considered stable if the CG was ahead of the CP inbetween one to three calibers (rocket body diameters). Figure 15 depicts how the lifting force of the rocket's surfaces, like the fins, are a restoring force when the CG is ahead of the CP and a divergent force otherwise for a given protobation of angle alpha.



Figure 14. Xbee Transceiver.

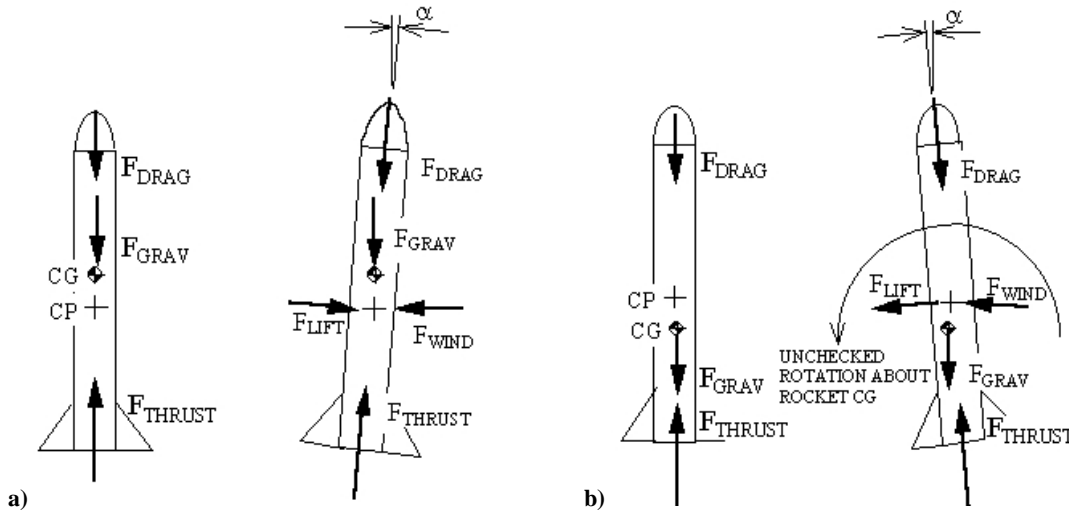


Figure 15. Static stability criteria for stable (a) and unstable (b) rockets.

Next, splines were used to fit the manufacturer data on thrust profiles and propellant mass loss as a function of time just after ignition as shown in Fig.7. Using these splines it was simply a matter of finding the resulting accelerations and integrating once for velocity and twice for position

$$\mathbf{F} = m\mathbf{a} \Rightarrow \mathbf{a} = \frac{\mathbf{F}}{m} \Rightarrow \mathbf{v} = \int \mathbf{a} dt \Rightarrow \mathbf{p} = \int \mathbf{v} dt \Rightarrow \mathbf{F}_D = -C_D A \frac{1}{2} \rho \|\mathbf{v}\|^2$$

The one caveat is that process needed to be iterated to account for drag. Previous iterations of velocity provided the estimates for drag until the solution converged to a solution where the initial drag and final drag estimates were nearly identical.

This process was repeated for stages 1 through 4 shown in Figure 1. Figure 16 shows how the drag estimate increased with every iteration and ultimately lowered performance. Figure 17 shows the final predicted acceleration, velocity, and altitude profile. For the same of comparison, the altitude plot also features a prediction obtained using another (open source) code.

The longitude-altitude profile was predicted using winds aloft profiles obtained from nearby airports (Fig.18 shows an example of such a profile, as recorded near General Wm J Fox Airfield, Lancaster, CA).

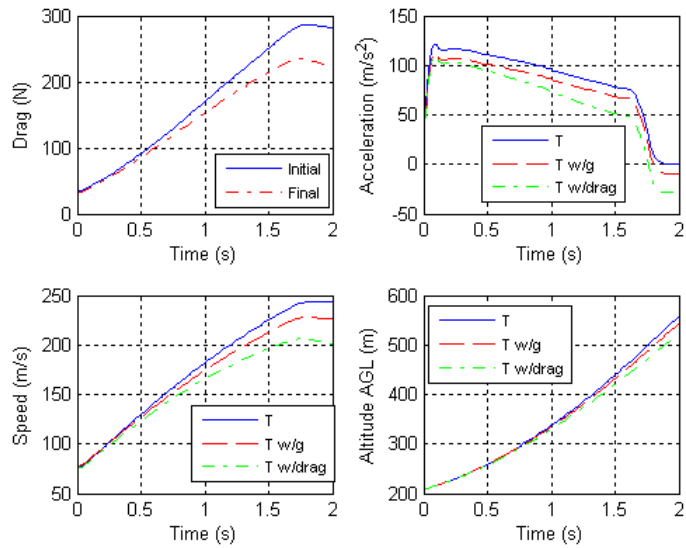


Figure 16. Drag affect on performance on sustainer

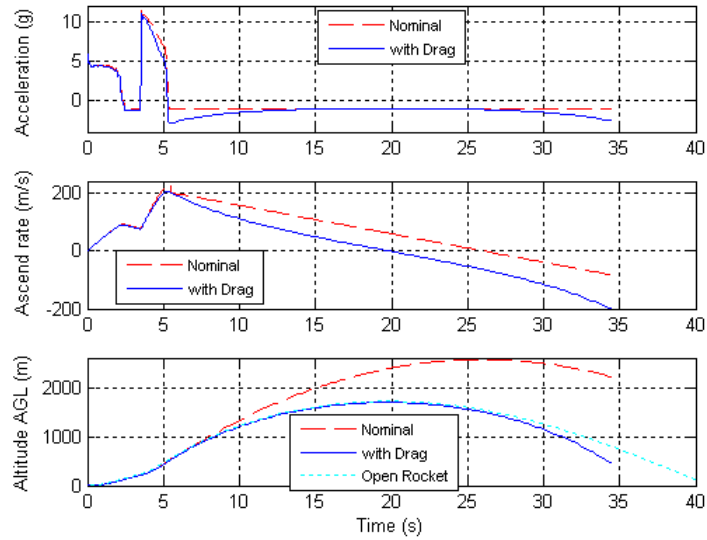


Figure 17. Predicted flight performance.

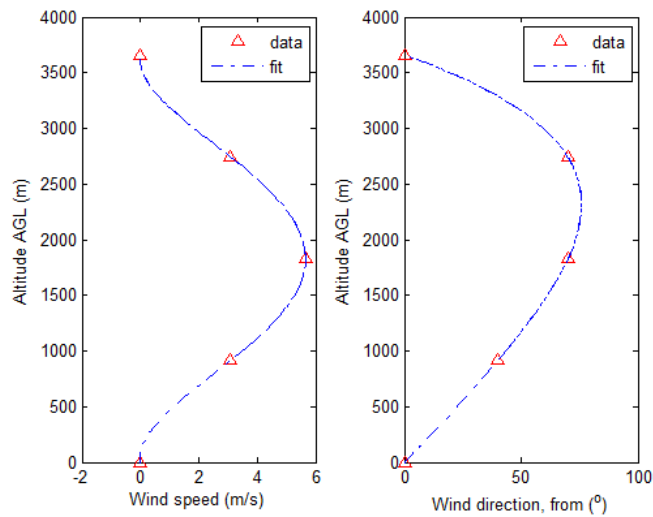


Figure 18. Example of a wind profile.

B. Testing Results

The original test of the MARRS was performed on July 30th, 2010 at the Mohave Desert, CA (Fig.2b). The predicted apogee altitude was 1,695 meters or 5,560' AGL. At an elevation of 2,000', this would be 7,560' MSL. The actual maximum altitude as recorded by Snowflake-R (Fig.19) was about 40m (115') higher than that.

Unfortunately, due to miss-wiring, the upper main chute was deployed during stage 5, not the lower main chute as intended. (The EFC is ultimately what ignited the upper stage as the break wire failed to break at take-off. However, during sustainer ignition, the break wire was severed and the avionics became armed.) Consequently, the avionics were separated from Snowflake-R before deployment was commanded. Although Snowflake came down under the upper main parachute and connected to the payload bay, it did transmit data throughout the entire flight and did attempt servo commands simulating autonomous flight back to the launch pad. A 3D profile as recorded by Snowflake is shown in Fig.20.

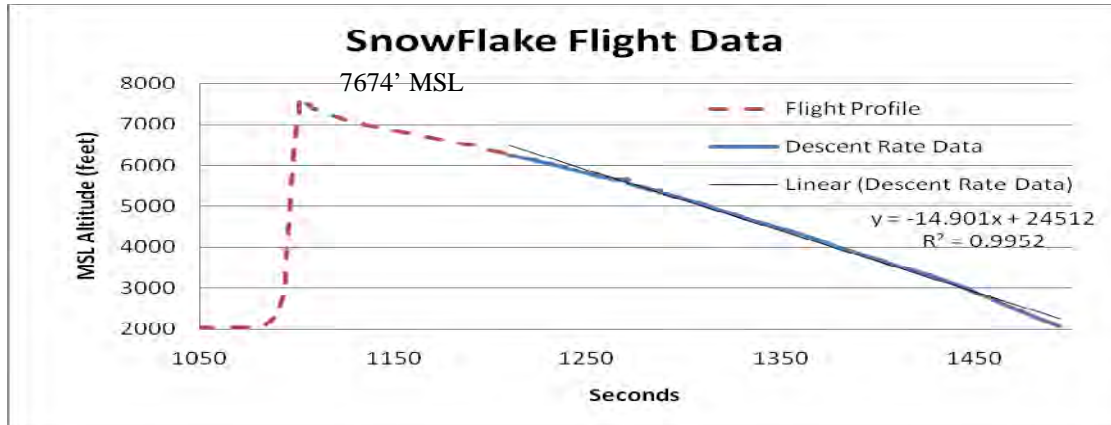


Figure 19. Altitude data profile.

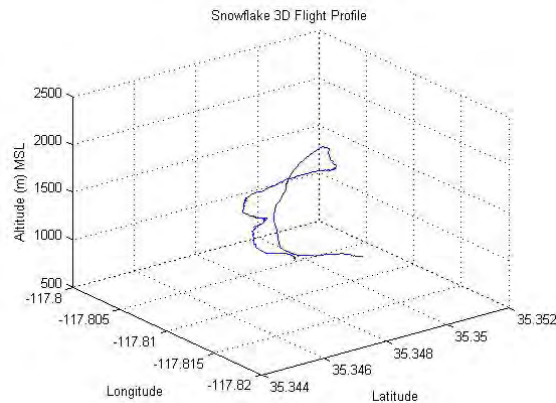


Figure 20. Rocket flight profile.

In October of 2010 follow-on testing was accomplished using Snowflake-R on two single-stage rockets named Bignuke and Magnum (Fig.21a depicts Magnum launch). Prior to launch the target coordinates were marked as shown in Fig.21b. For both launches Snowflake was deployed successfully, as planned, bringing MARRS prototype back to the launch site (Fig.22).

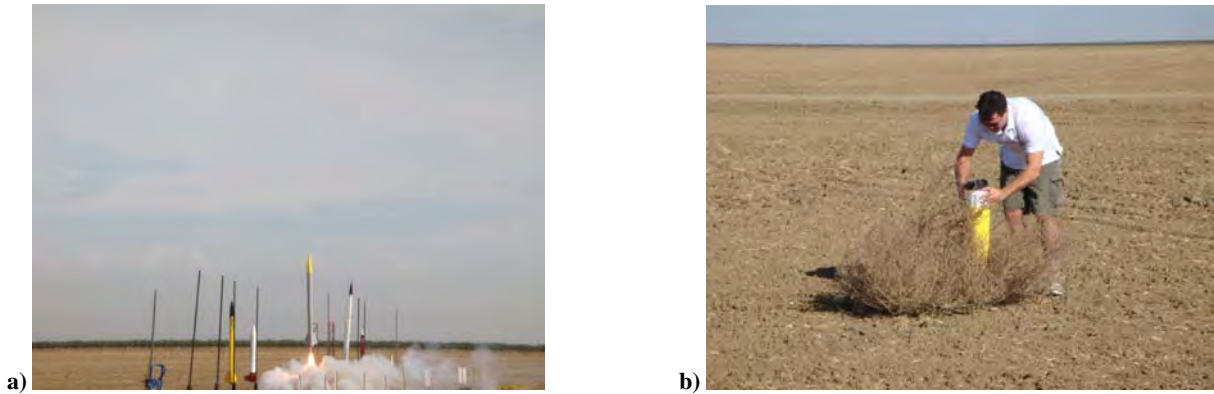


Figure 21. Magnum (a) launch and target marking (b).



Figure 22. MARRS delivers payload as planned.

Conclusions

MARRS prototype, Snowflake-R, showed its ability to operate during and survive through the extreme conditions of rocket flight. The challenges in deploying it from two-stage amateur rockets included launch environment (high g-load), stage separations, and black powder burn while deploying MARRS. In fact, it was the stage separation issue, which precluded MARRS to be deployed during an initial test. In two following tests Snowflake-R was deployed as intended, however it suffered from minor black powder burn during the second launch. Nevertheless, the system does appear to be suitable for use as a MARRS, so the continued testing is recommended to find the full extent of the system's capabilities and limitations.

Acknowledgements

The authors would like to thank the Point Lobos Section of AIAA for sponsoring the rocket launches and the Wright family for allowing them to use their one-stage rockets.

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