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Development of a Payload Module for the Phoenix-1C Hybrid Sounding Rocket

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The Phoenix-1C sounding rocket, developed under the Aerospace Systems Research Institute's Phoenix Hybrid Sounding Rocket programme, was flight tested for the first time in March 2023. The rocket featured a payload module specifically designed to accommodate three experimental payloads and to be recovered by parachute. This paper seeks to detail key aspects of the design, fabrication and testing of the payload module and its constituent subsystems, as well as report on its operation prior to and during the Phoenix-1C flight test.

I. Introduction

The Phoenix Hybrid Sounding Rocket programme is a flagship activity of the University of KwaZulu-Natal's Aerospace Systems Research Institute (ASRI). Its purpose is to generate human capital in aerospace engineering, primarily in order to lay the skills foundation for the establishment of a South African space launch capability. Since 2010, the programme has seen the development and flight testing of six low-altitude sounding rockets, namely the Phoenix-1A [1],1B Mk I [2], 1B Mk II [3], 1B Mk IIr, 1C and 1D, all propelled by hybrid rocket motors combusting paraffin wax and nitrous oxide, frequently with aluminium as an additive. Of these, five vehicles have enjoyed successful launches at South Africa's Denel Overberg Test Range (OTR), with the Phoenix-1B Mk IIr setting a new African hybrid rocket altitude record of 17.97 km in 2021.

The latest vehicle variants, Phoenix-1C and 1D, were launched during a flight test campaign at OTR in March 2023 [4]. While Phoenix-1D was designed to fly on a ballistic trajectory without recovery, Phoenix-1C featured a payload module designed to accommodate up to three 1U-sized experimental payloads and to be recovered by parachute with an ocean landing. During its flight, Phoenix-1C carried payloads for the South African National Space Agency, the Cape Peninsula University of Technology, and MaxIQ Space, a locally based space STEM company.

This paper serves to detail the design, fabrication and testing of the Phoenix-1C payload module and to report on the flight test of the Phoenix-1C rocket. Fig 1 shows a cross-sectional view of the Phoenix 1C hybrid rocket.

Fig 1 Phoenix 1C hybrid rocket [4].

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II. Payload Module Details

The Phoenix-1C payload module was designed to meet a variety of functional requirements. In particular, the payload module needed to:

1. Safely house up to three experimental payloads during flight, each having a volume not exceeding that of a 1U CubeSat and a mass not exceeding 1 kg.
2. Be mass- and cost-minimal.
3. Be recoverable by parachute.
4. Withstand an ocean landing without permitting seawater ingress and remaining buoyant thereafter.
5. Be locatable during flight and after landing.
6. Feature cameras for recording key video footage during flight.

The final payload module design, shown in CAD form in Fig. 2, comprised three subsystems, namely the:

1. Structures subsystem, consisting of the structural elements of the module, including the rocket's nosecone, an anchoring bulkhead, and the support structure onto which the payloads are mounted.
2. Recovery subsystem, consisting of the parachute, shock chords, and the deployment system responsible for ejecting the parachute at flight apogee.
3. Avionics subsystem, consisting of the flight computers used to initiate parachute ejection and transmit real-time vehicle position data, the batteries employed to provide power to electrical devices contained in the payload module, and the cameras used to record flight footage.

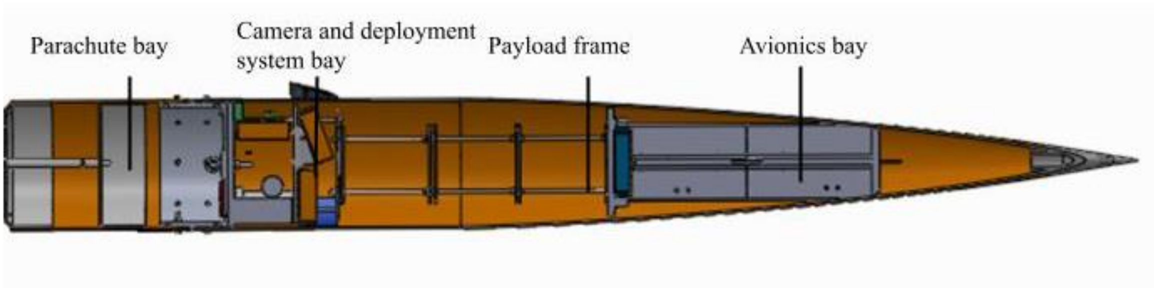

Fig. 2 Payload module CAD model.

The nosecone was fabricated from filament-wound glass-epoxy composite owing to the material's radio transparency, while the anchoring bulkhead, responsible for connecting the payload module to the parachute shock chord, was machined from 6082 aluminium. Finite Element Analysis (FEA) performed on the bulkhead indicated a maximum Von Mises stress of 178.9 MPa and a total deformation of 0.489 mm using loading at a 10 g maximum acceleration of the vehicle. Fig. 3 shows the bulkhead Von Mises stresses and total deformation on the bulkhead.

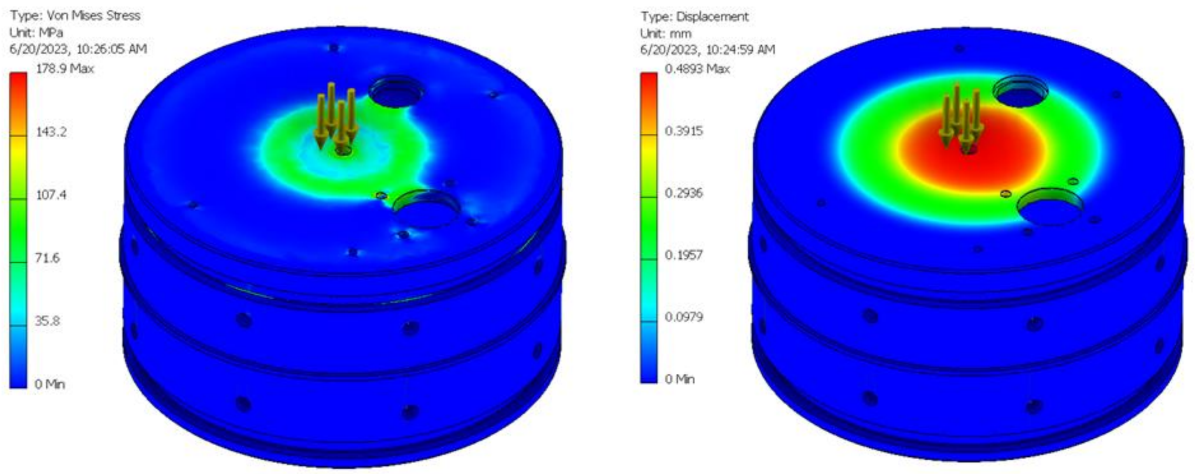

Fig. 3 Bulkhead Von Mises stress (left) and total deformation (right).

The stress on the bulkhead was indicated to be less than the 276 MPa yield strength of aluminium alloy 6082 and the deformation is far less than 1 mm. The payload mounting structure comprised an assembly of aluminium payload mounting plates and threaded brass rods; non-ferrous metals were selected due to the sensitivity of one of the payloads to magnetic interference. The arrangement of the payload mounting structure and respective payloads is displayed in Fig. 4.

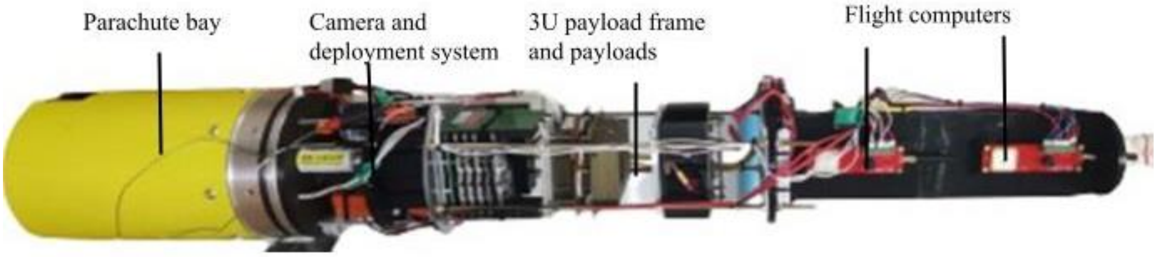

Fig. 4 Payload mounting structure assembly with payloads in place.

The recovery subsystem was designed according to the deployment of one parachute in a single event just after a vehicle apogee of 11 000 m above sea level as predicted by the baseline flight trajectory simulation. for nominal launch parameters. The parachute was sized to minimize wind drift during descent while ensuring a survivable descent rate upon landing. and parachute deployment force calculations were used to determine shock chord strength requirements. A CO_2 deployment system was used to pressurize the parachute bay, separate the payload module from the rocket, and, in doing so, eject the parachute. Successful separation of the payload module and, thus parachute deployment of the parachute was verified via ground testing. In this regard, Fig 5 and Fig 6 show the payload module before and after separation.

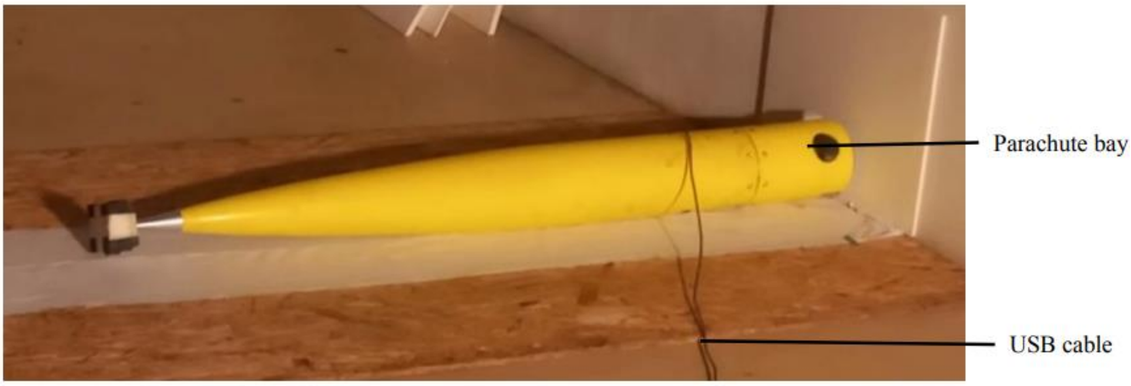

Fig. 5 Payload module deployment setup.

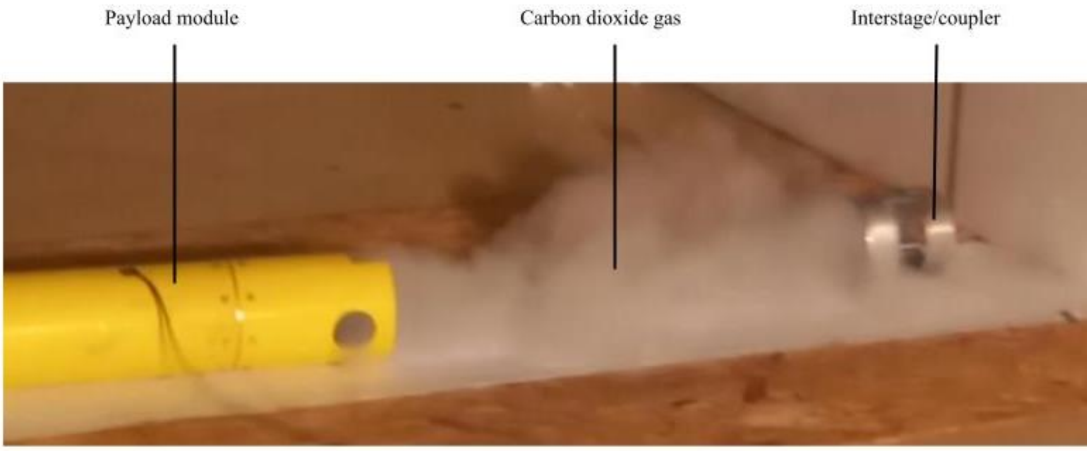

Fig. 6 Payload module after separation.

For redundancy, the avionics subsystem featured two separate AIM Xtra flight computers manufactured by South African company, Entacore. These issued electrical current to the CO_2 deployment system immediately after apogee was detected by means of inertial measurement in combination with GPS positioning. Fig. 7 shows the avionics system architecture.

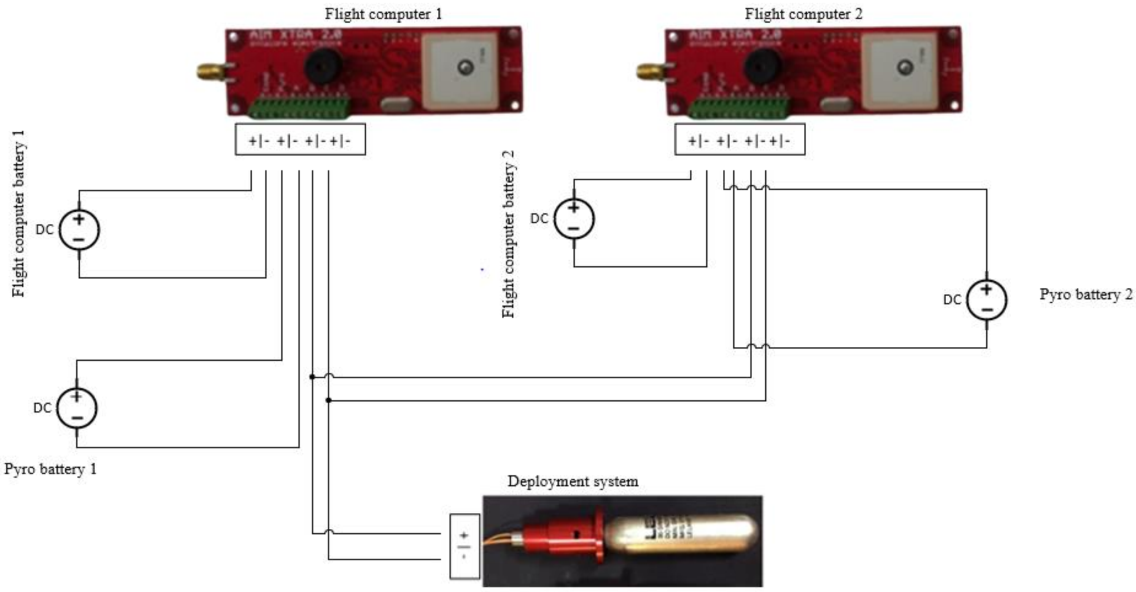

Fig. 7 Avionics system architecture.

The flight computers also transmitted key data during and after flight, which was received by a base station. Two Runcam 2 cameras were used to record HD footage during flight, with one camera positioned to face radially outward and the other to face downwards into the parachute bay in order to capture footage of the separation and parachute ejection events.

III. Phoenix-1C Flight Test

The flight test of the Phoenix-1C rocket took place on the afternoon of Thursday, 23 March 2023. Unfortunately, substantial variations in upper-air wind speed and direction raised the risk of an excursion of the payload module beyond the safety footprint during its return descent to an intolerable level, even after a reduction in launch elevation angle (from 80° to 75°) and nitrous oxide loading (from 25 kg to 15 kg). In order to permit the launch to proceed ahead of the expected arrival of inclement weather, the decision was made to fuse the payload module to the rocket to prevent inadvertent payload module separation and parachute deployment during flight. Recovery of the payload module could, therefore, not be attempted, although an outside possibility existed that the rocket could enter a flat spin after apogee and impact the ocean at a speed low enough for the payload module to remain intact.

After the necessary vehicle and launch gantry adjustments were made, the launch proceeded, with the vehicle following a very clean ballistic trajectory. Analysis of the flight data transmitted by the onboard Aim Xtra flight computers indicated that the rocket reached an apogee altitude of 7.985 km, corresponding to 41 seconds in Fig. 8., which shows vehicle altitude vs time. The high-precision radar tracking equipment at OTR measured a vehicle apogee altitude of 7.954 km, at 41 seconds, as shown in Fig.8. The strong correlation between the OTR ground measurements and the data transmitted from the Aim Xtra flight computers confirms the fidelity of the transmitted flight computer measurements. The maximum altitude measured by the Aim Xtra and OTR tracking hardware surpasses the nominal value predicted by an in-house 6-DOF flight dynamics simulation code. The nominal trajectory shown in Fig.8 was generated by the code for the case of a 15 kg oxidizer load.

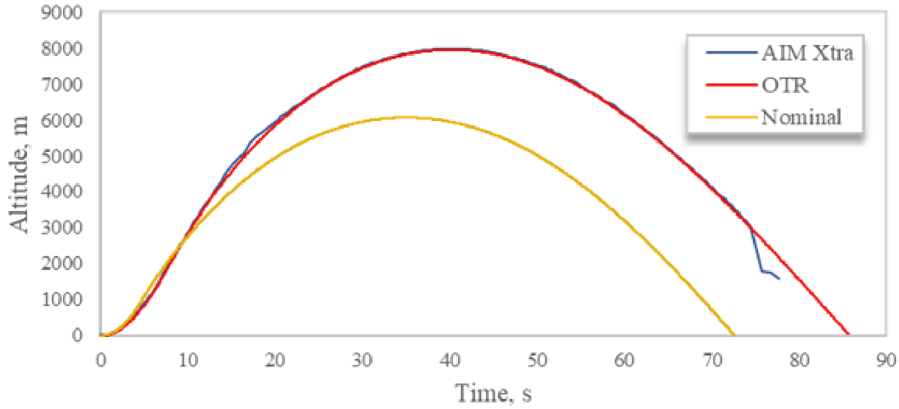

Fig. 8 Vehicle altitude vs time [4].

The vehicle reached a maximum axial velocity of 476 m/s and an apogee axial velocity of 47 m/s corresponding to 41 seconds, as shown in Fig. 9, which represents the vehicle's axial velocity as a function of time. This value suggests that the payload module may have been at risk of failing if it had been deployed at the flight's apogee, as the associated dynamic pressure would have exceeded the parachute design limit. The dynamic pressure that would have been encountered at the design point is considerably lower as a result of reduced air density. The is a strong correlation between the axial velocity data recorded by the OTR infrastructure and the Aim Xtra flight computer as well as the nominal flight velocity.

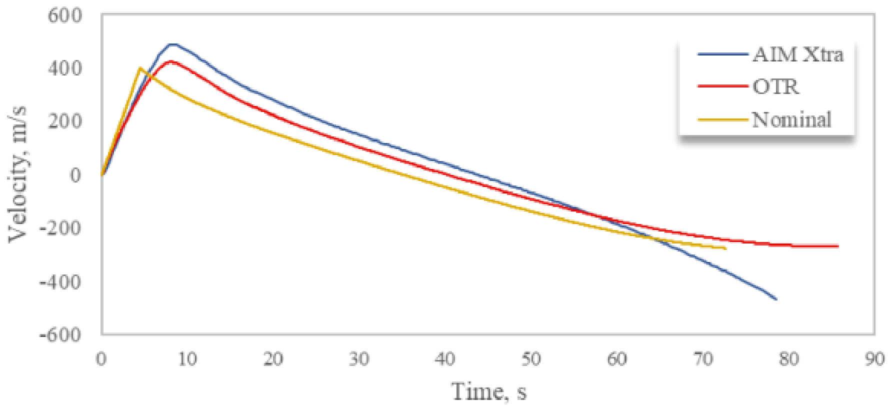

Fig. 9 Vehicle axial velocity vs time [4].

The payload module was subjected to a maximum axial acceleration of 9.98 g during flight. Fig. 10 shows the vehicle axial acceleration vs time (flight computer). The acceleration vs time graph recorded by the flight computer indicated that the payload module subsystems were subjected to an acceleration less than the design acceleration of 10 g.

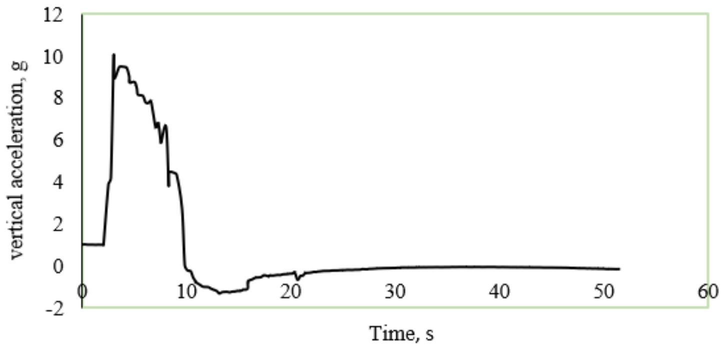

Fig. 10 Vehicle axial acceleration vs time.

The Aim base ground station tracked the payload module during the flight test. At lift-off, a maximum signal strength of -51 dBm changing to -108 dBm upon ocean landing. The radio frequency communication between the ground station and the onboard flight computer verified the acceptable radio frequency transparency of the payload module. The GPS coordinates of the vehicle obtained using the Aim base ground station were used to provide vehicle flight trajectory overlay in Google Earth as shown in Fig. 11.

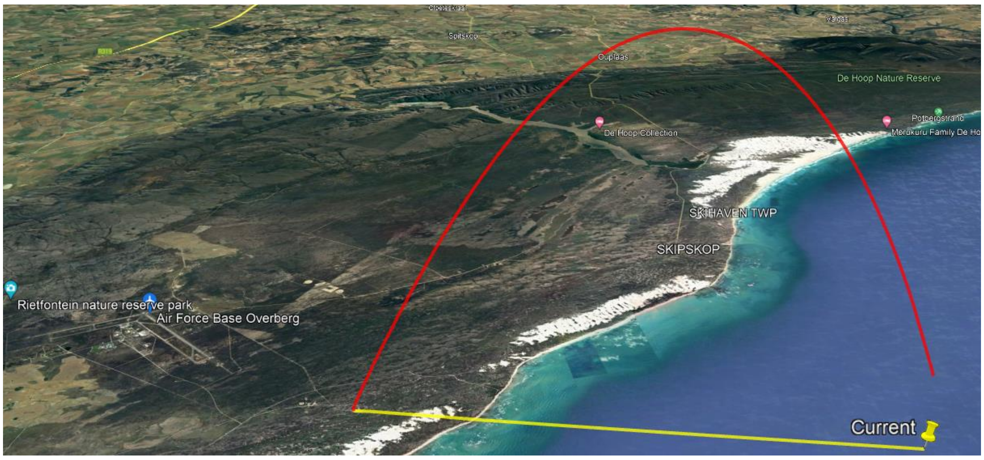

Fig. 11 Vehicle flight trajectory and GPS data (flight computer).

IV. Conclusion

Since its inception in 2010, the Phoenix Hybrid Sounding Rocket programme has fulfilled a very effective role in the Aerospace Systems Research Institute's efforts to develop skilled human capital in aerospace engineering. It has also led to the development of six low-altitude sounding rockets and facilitated a variety of research studies relating to hybrid rocket propulsion technology. The latest rocket launched in the Phoenix series, the Phoenix-1C, featured a recoverable payload module specifically developed to carry up to three 1U-sized payloads. This paper has detailed key aspects of the design, fabrication and testing of the payload module and its constituent subsystems, as well as report on its operation prior to and during the Phoenix-1C flight test. The vehicle flight data was successfully transmitted from lift-off to ocean landing through radio frequency communication between the flight computer and the ground station. The recovery system was not enabled during flight, however ground tests indicated that the design is suitable for use in future Phoenix rockets.

Acknowledgements

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