GOLauncher 2: Fast, Flexible, and Dedicated Space Transportation for Nanosatellites

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ABSTRACT

Generation Orbit Launch Services, Inc. (GO) is currently developing GOLauncher 2, a dedicated nanosatellite launch system capable of providing responsive and affordable space transportation services to the emerging marketplace of government, commercial, and academic nanosatellite developers. GOLauncher 2 is designed around a novel air-launch approach, utilizing an existing business jet carrier aircraft and a set of expendable rocket stages to place up to 100 pounds of payload into Low Earth Orbit. As a systems integrator, GO has built a best-in-class team of partners and suppliers to provide major components of the system including aircraft modifications, propulsion, and avionics, all while leveraging ongoing technology development efforts to reduce development costs and development schedules. Additionally, GO has reached an agreement with Cecil Spaceport in Jacksonville, FL for initial operations of GOLauncher 2 under an FAA launch license. System development is currently on schedule to meet demand for government and commercial launch services starting in 2016. NASA has booked the first flight of GOLauncher 2 under the NASA Launch Services Enabling eXploration and Technology (NEXT) initiative for launch of three 3U CubeSats in late 2016. This work provides an overview of the GOLauncher 2 system, including key features, performance parameters, and concept of operations. Specific focus is also paid to discussion of payload-centric system elements including payload requirements, mechanical and electrical interfaces, launch vehicle integration, launch environments, and on-orbit operations capabilities.

INTRODUCTION

The GOLauncher concept has evolved into the current baseline, shown in Figure 1, through a set trade studies and design iterations. System design revolved around the mission of delivering a commercially viable, highly responsive, mission flexible, dedicated launch service for nanosatellites by 2016. This mission statement has driven the mission requirements for the system. These driving requirements are defined as follows in Table 1.

Figure 1. GOLauncher 2 Nanosat Launch Vehicle

Air launch is a key enabler of a system that meets these requirements to provide fast, flexible, dedicated launch for nanosatellites satellites. When compared to more traditional launch approaches, air launch utilizes an aircraft as both a reusable first stage and a launch pad, thus reducing the amount of expendable hardware used during each mission, increasing launch availability, and allowing for more flexible launch operations. Key features of air launch that make it an attractive part of a nanosatellite launch system include:

- Booster performance is improved by launching from altitude. Nozzle expansion ratio can be increased without incurring additional pressure losses, while drag losses are reduced due to decreased atmospheric density at altitude. Air launch opens the trade space to low-thrust and lower-cost liquid propulsion systems that would otherwise require systems too large or too expensive for ground launch. Cost can also be reduced if aircraft operating costs are lower than additional booster costs required to match system performance from the ground.
- Common mechanical (MIL-R-38957C) and electrical (MIL-STD-1760) interfaces are available for application of launch vehicles to multiple carrier aircraft. Standard military ejector racks are installed on a wide range of aircraft capable of launching large external stores.
- Opportunities exist for lean and flexible launch operations by operating out of small airfields with standardized ground support equipment for both aircraft and launch vehicle systems.

Table 1. GOLauncher 2 Mission Requirements

ID	Requirement
0-1	The system shall have a payload capability greater than 30 kg to a 425 km x 425 km x 30° orbit.
0-2	The system shall achieve first orbital flight by no later than December 31, 2016.
0-3	The system shall have a loss of payload reliability of less than 1 in 25 by the 16th flight.
0-4	The system shall have the capability for launch to inclinations less than or equal to 100°.
0-5	The system shall be capable of delivering payloads to altitudes greater than or equal to 740 km.
0-6	The system shall launch than six months after contract signature once mature operations are reached.
0-7	The system shall be capable of operating from a commercially-licensed spaceport within the United States.
0-8	The system shall be operated under a commercial FAA launch license.
0-9	The system shall be commercially available at a price consistent with those of CubeSat secondary launch options.

Additionally, the requirement to complete development by the end of 2016 drove the selection of existing and high Technology Readiness Level (TRL) technologies for application to vehicle subsystems. This further enables reduced development costs while maintaining low recurring costs. The combination of an existing, widely available aircraft with a small two stage expendable rocket with existing propulsion elements yields a launch system that can affordably provide dedicated small satellite launch.

SYSTEM OVERVIEW

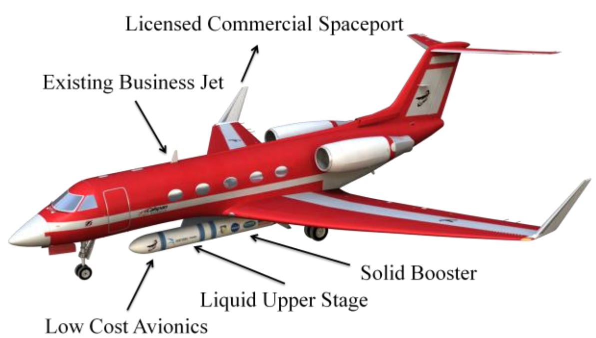


Figure 2. GOLauncher 2 Walk-Around Chart

The GOLauncher 2 consists of two major system elements: the Carrier Aircraft Platform (CAP) and the Rocket Vehicle (GO2-RV). The "walk around" chart given in Figure 2 depicts the fully integrated launch vehicle configuration. The baseline carrier aircraft is a Gulfstream IV-SP, structurally modified for external carriage of a large, releasable store. The GO2-RV is a 26 ft long, two-stage rocket vehicle weighing 8,500 lbm. The booster stage consists of a solid rocket motor, while the upper stage is powered by a liquid propulsion system. Modified commercial off-the-shelf avionics are used for guidance, navigation, and control, as well as tracking, telemetry, communications, and power. A full affinity diagram demonstrating the key subsystem interfaces is given in Figure 3. Finally, the system is operated out of a commercially licensed spaceport within the United States.

The development plan for the GOLauncher 2 is spread over the next 3 years. System Requirements Review was completed in January 2014, with Preliminary Design Review slated for late 2014. Additional tasks in 2014 include flight software development, CAP acquisition and modification, launch license preparation, and component flight testing. Critical Design Review will follow in 2015, along with propulsion qualification testing for both stages, integrated captive carry flight testing, and store separation wind tunnel testing. Final integration, assembly and checkout of the initial flight vehicle will take place in early 2016 while inert drop testing is conducted with inert test articles simulating the GO2-RV. Qualification flight operations are scheduled for 2016 from Cecil Spaceport in Jacksonville, FL, with follow-on commercial operations beginning later in the year.

Carrier Aircraft Platform

While the original tradespace covered a wide range of aircraft options including military fighters, bombers, and civil transport aircraft, a business jet was ultimately selected based on its performance in a number of key figures of merit including carriage capacity, availability, and cost. A detailed analysis of alternatives between a fighter jet and business jet is given in Table 2.

Table 2. Aircraft Selection Comparison

Characteristic	Fighter Jet	Business Jet
Capacity	5,000 lbm	10,000 lbm
Modification Experience	Some	Broad
Commercial Availability	Very Low	High
Ops Cost	High (>$50k/hr)	Low (<$10k/hr)
Acquisition Cost	High	Low
Maintenance Cost	High	Average
Operational Footprint	Large	Small
Commercial Supply Chain	Small	Extensive

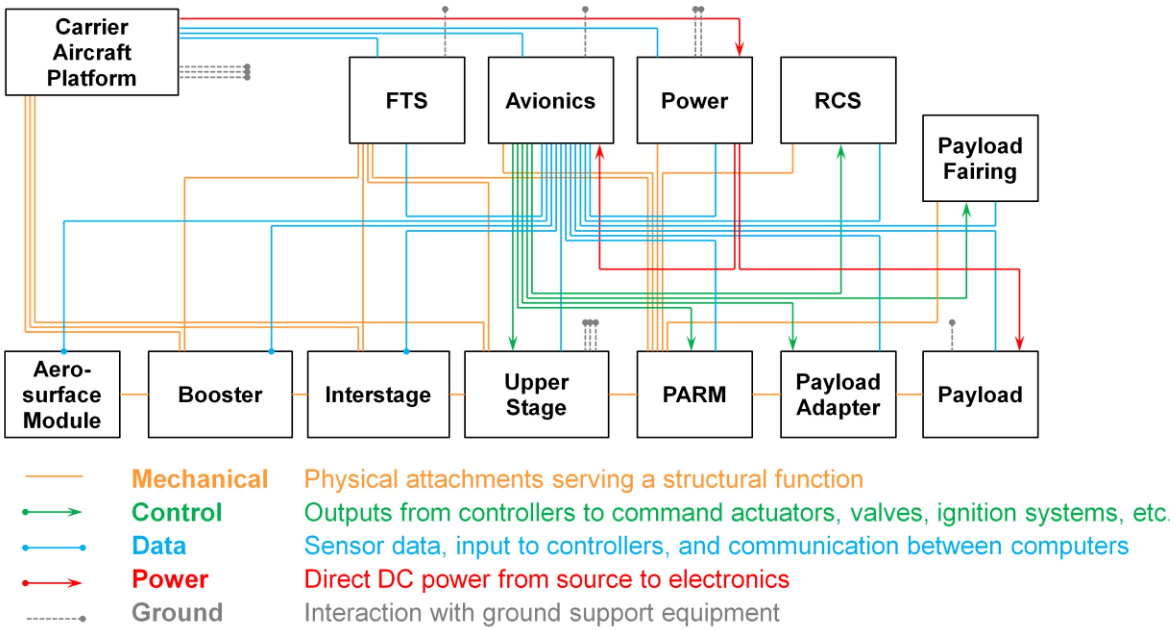


Figure 3. GOLauncher 2 Affinity Diagram

The CAP G-IV-SP will be capable of carrying an external store of up to 8,500 lbm, the gross weight limit for GOLauncher 2 Rocket Vehicle (GO2-RV). The CAP provides all electrical and mechanical interfaces necessary to carry and release the GO2-RV. In the event of an aborted launch, the CAP will be capable of both returning to base and landing with the GO2-RV still mated, or jettisoning the GO2-RV if necessary.

GO2 Rocket Vehicle Details

The GO2-RV is a two-stage vehicle utilizing a mature solid rocket motor first stage and a new upper stage using liquid oxygen (LOX) / rocket grade kerosene (RP-1) propellants. Control systems include TVC on both stages, plus a reaction control system for roll control and exoatmospheric attitude control during coast phases. The following sections detail the vehicle subsystems. An exploded view of the GO2-RV is given in Figure 4.

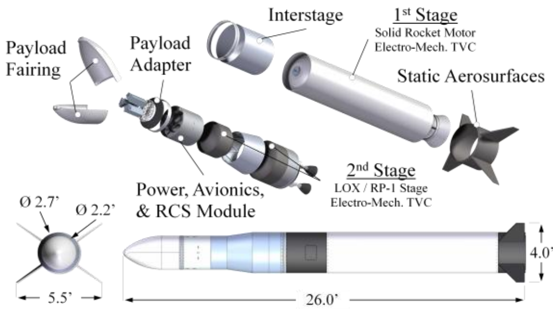


Figure 4. GO2-RV Exploded View

Booster Stage

The first stage motor is a commercial variant of a solid rocket booster motor stage produced by Aerojet Rocketdyne for missile applications. The motor design includes advanced materials such as a composite case, widely utilized Class 1.3 solid rocket propellant, and a flight-qualified electromechanical thrust vector control system. Motor production will take advantage of methods implemented on tactical missile production lines to reduce unit cost and improve reliability.

Upper Stage

The GO2-RV second stage is powered by two low-cost, high performance LOX / RP-1 rocket engines from Ventions, LLC. Leveraging several years of development efforts under NASA and DARPA programs, the upper stage will utilize two electric pump-fed, regeneratively-cooled engines and several other technology components already being developed and tested under separate government programs. The engines are fabricated in a low-cost, batch process to allow for realization of complex engine geometries. Electric pumps significantly reduce the complexity of the engine cycle, allowing for significant improvements in stage propellant mass fraction for a small-scale system. Mass production of engines, pumps, controllers, tanks and secondary structures will also follow both tactical missile and automotive manufacturing paradigms, aiming for realization of economies of scale to reduce recurring vehicle costs. The upper stage pressurization system consists of a set of high-pressure titanium tanks storing Helium pressurant gas for a variety of purposes including purge, valve actuation, and pressurization of the main propellant tanks to a nominal 30-50psi. It will also include other associated components such as regulators, manifolds, fill / drain and vent valves, and quick disconnects to the He fill system.

Additional structure for the upper stage will include an intertank structure, a payload interface, first stage and fairing interface structures, internal mechanisms to mount various components, and a thrust adapter / skirt for the engines.

Avionics

The avionics subsystem for the GO2-RV is based on an existing multi-functional systemboard product line in development by Tyvak Nano-satellite Systems, LLC. While initially designed and operated for CubeSat avionics applications, significant steps have been made to adapt the avionics framework for launch vehicle applications. Furthermore, existing development efforts are leveraged to retire system risks and provide assurance of the solution feasibility.

The heritage boards are currently in production and being used in a number of CubeSat projects. The system has successfully undergone environmental testing (vibration and thermal-vacuum) in the lab. The system provides a modular architecture that allows for scalability both internally and across multiple platforms. It is designed to handle the most common interfacing needs and it is able to handle evolutions of the launch vehicle as well as mission-specific needs (e.g. ground-based range to space-based range; traditional flight safety system to autonomous flight safety system). Stage-specific avionics and power subsystem components are included on both the booster and upper stage, interfacing directly with the core avionics package.

Flight Termination System

The GO2 will be equipped with a traditional flight termination system (FTS) designed to meet the requirements of the relevant range safety standards (RCC-319). The FTS utilizes a common set of small ordnance packages on both stages to terminate vehicle thrust in case of a violation of range safety rules during flight. The system uses two fully redundant strings for communication, power, and safe and arm devices. Although the baseline system uses a traditional command-destruct signal architecture, the avionics system is designed in such a way as to allow for evolution to an autonomous flight safety system in future versions of the vehicle. The full flight safety architecture will be developed to fly as a payload on precursor suborbital systems, affording opportunities for flight qualification and demonstration.

Subsystems

The GO2-RV features an integral, cylindrical cold gas Reaction Control System (RCS) module to provide 3-axis attitude control. Since the first two stages each provide TVC while burning, the module will only be used for roll control as needed during the stage burns, but will be used for full vehicle attitude control during all coast periods and payload deployment. The RCS features a set of high pressure GN2 tank, dual isolation valves, a fill/vent valve, pressure regulator, manifold ring, and eight dual-valve solenoid thrusters, as shown in Figure 5.

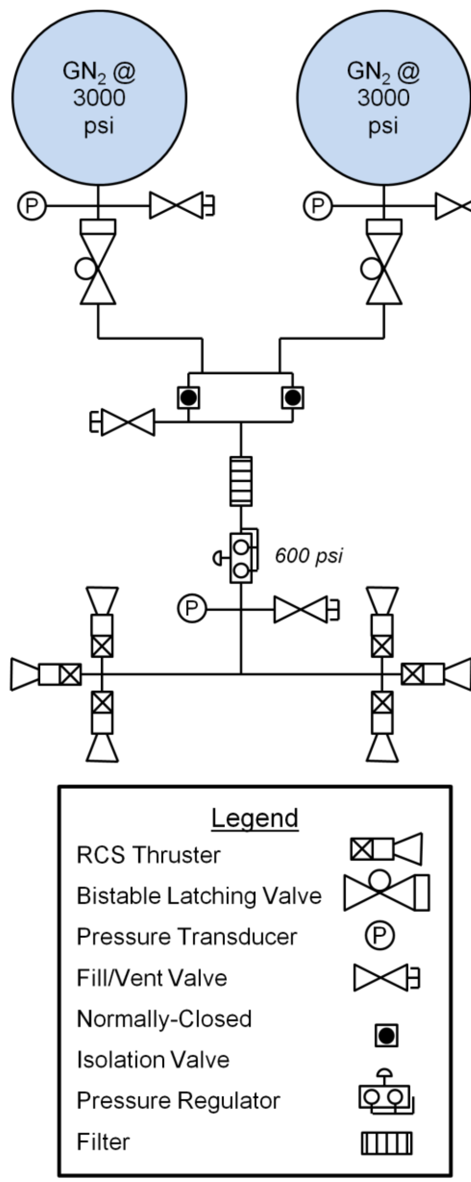


Figure 5. Reaction Control System Block Diagram

The power subsystem is a combination of stage-level and vehicle-level power supply, distribution and management. All power required by the vehicle will be provided via lithium-ion batteries. Electric pumps on the second stage propulsion system are a major component of the GO2 launch vehicle that requires significant power. This power demand will be handled by a power management and distribution system located near the second stage engines. Similarly, the power system and controllers required for the electro-mechanical TVC actuators on the first stage motor will be carried locally rather than with the core avionics, limiting wiring mass and upper stage battery mass. The remaining power supply (batteries), management (power switch board) and distribution (wiring) system will be located with the vehicle-level avionics system.

The payload fairing is of light-weight construction with a conventional composite face sheet over an aluminum honeycomb core. The cylindrical base section transitions to a blunted ogive nose, providing improved aerodynamic performance over a wide range of Mach numbers. The choice of composite is driven by the desire to reduce the overall fairing weight and therefore increase the vehicle's payload capability.

Multiple concepts have been considered for stage and fairing separation systems. However, the baseline system includes a circumferential tension band clamp released by non-pyrotechnic actuated separation nuts. Springs are used to passively impart adequate separation velocity to the upper stage and payload fairing. The non-pyrotechnic solution significantly reduces shock environments, below 50g's.

Payload Interface

Integration of payloads to the GO2 second stage will be accomplished through both standardized CubeSat form factor up to 12U, as well as through traditional low-shock payload separation systems. The standard vehicle configuration is defined up to a common composite payload adapter, on top of which is integrated an interchangeable metallic plate with mission-specific interface patterns. A view of the payload configuration is given in Figure 6, showing integration of three 3U P-PODs. The vehicle is capable of conducting 8 independent payload deployment maneuvers on a single flight.

In addition to standardizing physical and mechanical interfaces, effective support processes for CubeSat developers manifested on GO2 are being developed based on current practices with launch vehicle integration of secondary payloads. To facilitate this, a streamlined set of procedures for payload integration, designed with high levels of standardization to reduce recurring costs and integration time, is being developed as a critical component of achieving high short launch lead times and flight rates.

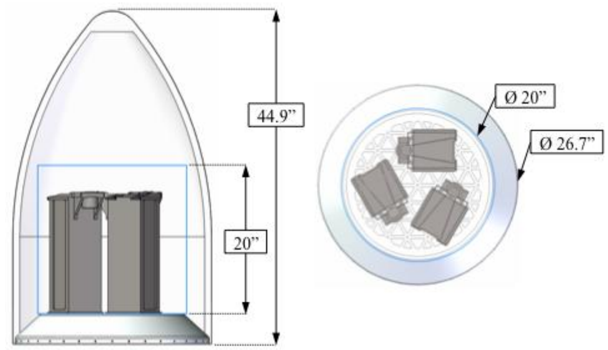


Figure 6. Sample Payload Configuration with Three 3U P-PODs

GROUND SEGMENT AND CONOPS DETAILS

Initial flights of GOLauncher 2 will be based from the Cecil Spaceport in Jacksonville, FL. Facilities at Cecil include a 12,500 ft runway, climate-controlled hangar space, mission operations control center, telemetry and tracking infrastructure, range safety protocols, propellant storage and loading, solid rocket motor storage, payload integration facilities, controlled airspace, and additional office space for payload and mission support personnel. Designated areas for fuel and oxidizer loading have been defined for both runways, while additional hangar facilities are proposed to be built along with an auxiliary taxiway to the east of Runway 18L-36R. GOLauncher 2 falls under the “Concept *Z*” portion of Cecil's FAA Spaceport Operator license (jet-powered aircraft carrying a rocket vehicle to altitude, releasing it, and returning to land under jet power) and will therefore not require modification of the license prior to operations. Future plans include expansion to other commercial spaceports around the United States and internationally.

Launch control facilities consist of ground-based, as well as airborne stations to facilitate air launch operations. Facilities onboard the CAP will include three consoles: two launch vehicle, one payload. In addition to the flight crew, the Launch Director, Flight Safety Officer , and Chief Engineer will be onboard the CAP during launch operations. All personnel on the CAP will be tied into voice and data communications with the ground-based team at the Launch Control Center (LCC).

Ground facilities will consist of six consoles in the LCC at Cecil Spaceport. These consoles include Launch Coordinator, Communications, GO2-RV Propulsion, Avionics/GNC, Structures/Dynamics, and

Flight Safety. Two additional stations will be available for customer personnel to monitor live telemetry and payload status. Cecil Spaceport is in the process of developing an advanced Air Traffic Control Tower facility, part of which includes assets for telemetry, communications, and optics for space launch activities. Mission operations will tie into this communications network to facilitate voice, data, and video communications with the CAP and GO2-RV.

Payload and CAP Integration

The GO2 rocket is transported by truck from the integration facility to Cecil Field Spaceport, fully integrated and checked out. Transportation may eventually be conducted with the CAP, but this is not the baseline concept of operations. A dolly horizontally supports the vehicle for payload integration and final checkout, removing the need for large overhead lifts. Upon acceptance at the GO hangar, a team of six technicians is prepared to conduct final integration, testing, and checkout of the GOLauncher system. A notional depiction of the hangar facilities is given in Figure 7. Initial functional checkout of the GO2 rocket is conducted prior to payload integration. When the payload is received at the hangar, it is transported to a clean room for checkout and integration. The payload will first be mechanically and electrically mated to the payload adapter, fueled and charged, then encapsulated in the launch vehicle fairing. The encapsulated payload is finally mated to the GO2 rocket with ground support equipment (GSE) umbilicals for airflow, power, and data uplink installed.

Figure 7. Notional Final Vehicle Integration at Cecil Spaceport

The CAP arrives at the hangar facility at least six days ahead of launch. Store attachment and jettison hardware is already integrated to the centerline of the aircraft prior to its ferry to the launch site. Further, all aircraft-based checkout procedures for airborne support equipment (ASE) are also completed prior to arrival at the launch site. Final launch vehicle testing is conducted prior to mating the GO2-RV to the CAP to verify operability of power systems, communications, thrust vector control, and live ordnance. This includes full flight simulation with avionics hardware in-the-loop during the launch mission dress rehearsal. The onboard flight termination software system is tested in an open-loop fashion while sequestered from the onboard destruct hardware. With integration and testing completed, the GO2-RV is mated rocket to the CAP.

Day-of-Launch Operations

Day-of-flight operations begin with transfer of umbilicals from GSE to airborne support equipment (ASE). The GO2-RV is powered-up approximately 2.5 hours prior to booster ignition. All powered-up preflight checks are conducted on the runway prior to fueling of the GO2-RV. The upper stage is fueled with RP-1 at the staging location. The CAP is then taxied by pushback tractor to the designated oxidizer loading area where LOX is loaded on the upper stage from a small mobile tanker. The CAP engine startup sequence then commences followed by final hold pending ATC clearance for takeoff. Care is taken to minimize the time between oxidizer top-off and booster ignition in order to limit propellant boil off. This delay is expected to be on the order of 90 minutes.

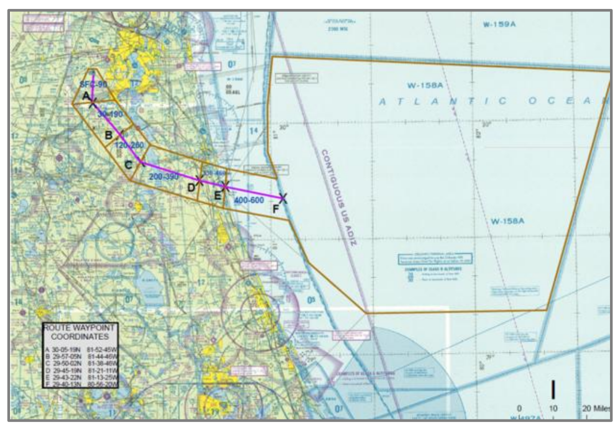


Figure 8. Warning Area W158-A and Flight Corridor from Cecil Spaceport

Upon departure from Cecil Spaceport, the CAP will follow the flight path to the restricted airspace off the east coast of Florida and north of the Eastern Test Range. The US Navy controls the this airspace, known as W-158A Warning Area, depicted in Figure 8. Its availability and clearing is coordinated through the Jacksonville Aviation Authority. Expenditure of live ordnance is commonly conducted in this operating area. Once offshore, the CAP will align with the mission-specific launch azimuth and conduct the release maneuver. Downrange range clearing is coordinated with the FAA.

Abort scenarios include several contingent courses of action. In the event of a no-go call once airborne, pressurized oxidizer will be vented to the atmosphere to inert the upper stage. While methods for airborne top-off of cryogenic propellants are currently being studied at GO, the baseline concept is to insulate the cryogenic tank on the second stage and vent boil off gases as necessary to maintain safe tank operating pressures during ground and captive carry operations. The CAP crew will safe the vehicle, including the flight termination system and return to base with the GO2 rocket remaining mated. In the event of a safety risk to either the CAP crew or the uninvolved public, the CAP will conduct a controlled jettison of the GO2 rocket within the designated warning area.

TRAJECTORY AND PERFORMANCE

A key advantage of the GO2 launch vehicle is the capability to place payloads into a variety of orbital destinations. The combination of an air-launch platform, with flexible basing options, allows selection of a variety of orbital inclinations, from equatorial orbits to sun-synchronous. Figure 10 lists the payload capability of the GO2 to various orbits. Launch vehicle performance was computed using the Program to Optimize Simulated Trajectories[1] with aerodynamic data generated in Missile DATCOM[2].

Shown in Figure 9, the launch sequence for the GO2 starts with the mated GO2-RV and CAP performing a conventional takeoff from a commercial spaceport. Once within the open water range, the CAP performs the launch flight release maneuver. This zoom-climb maneuver is designed to achieve a high altitude, high flight path angle release condition of the GO2-RV. Nominal release conditions are 40kft, Mach 0.7, with a flight path angle of 40 degrees. Flight simulation work has been completed to demonstrate that the G-IV-SP will have sufficient performance to place the GO2-RV at these release conditions.

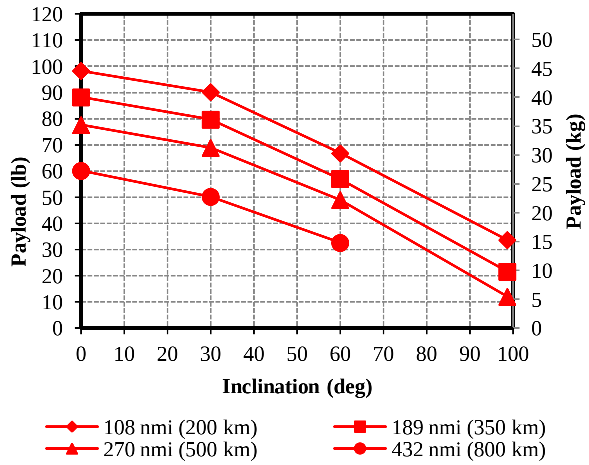


Figure 10. GOLauncher 2 Orbital Payload Performance

After dropping the rocket, the CAP performs a roll maneuver to distance the airplane from the GO2-RV. A nominal 5 second free fall is planned before first stage ignition to allow for separation between the aircraft and the launch vehicle. The aerosurfaces of the GO2-RV are designed to remain fixed and provide sufficient

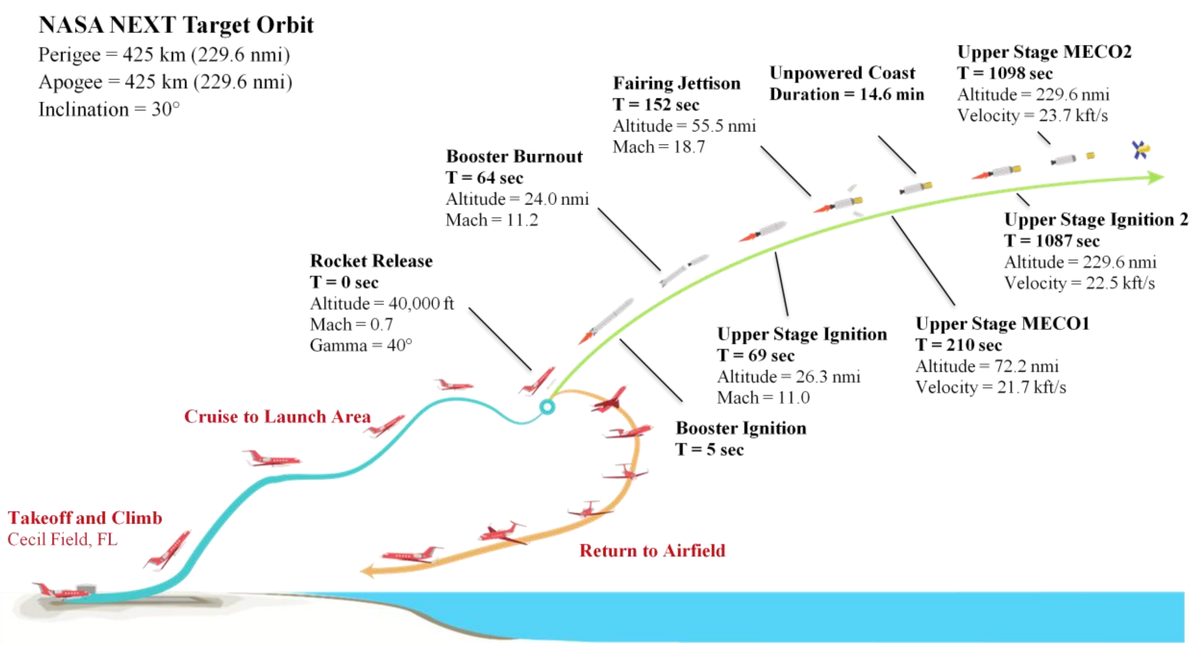


Figure 9. Nominal GOLauncher 2 Trajectory Overview

static margin allowing for adequate longitudinal, lateral, and directional stability of the launch vehicle during this free fall. After the free fall, first stage ignition occurs. During the first stage burn, pitch and yaw control are provided through gimbaling of the solid motor nozzle. Roll control is provided by the RCS module. The nominal first stage burn time is approximately 40 seconds.

Once first stage burnout is confirmed, the launch vehicle staging maneuver occurs. After a short coast period, the second stage burn occurs. For lower altitude orbits a single second stage burn is used to place the payload into the desired orbit. For higher altitude orbits the initial second stage burn is used to place the vehicle into an elliptical orbit. Following a coast up to apogee, the propellant is settled by the RCS and an additional second stage burn is performed to circularize the orbit. Payload fairing separation occurs during the second stage burn once aeroheating due to atmospheric drag becomes negligible (nominally below 1 W/m2) and dynamic pressure drops below 0.1 psf. During the second stage burns, pitch and yaw control are provided using TVC on the second stage. Roll control is again provided by the RCS module. The RCS is also used to provide vehicle stability and control during all coast phases to ensure successful stage separation and deployment of the payload.

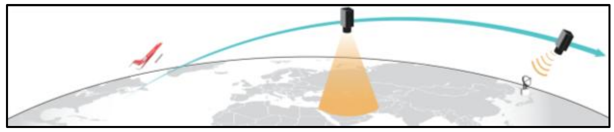
APPLICATIONS

With the availability of dedicated launch options, the utility of nanosatellites will increase dramatically. By removing the limitations of secondary launch including lack of schedule and orbital destination control and priority, along with spacecraft design constraints, numerous expanded and novel applications of nanosatellites become feasible, including rapid constellation deployment, low altitude reconnaissance, rapid technology development, and interplanetary missions.

CubeSat Constellation Deployment

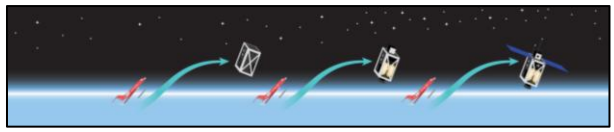
- Multiple orbital planes
- Phased launch schedules
- Fast transition from launch to operations

Low Altitude Reconnaissance



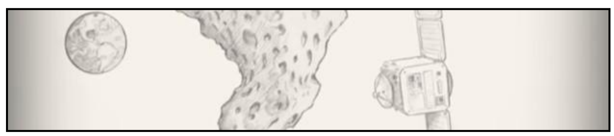
- Sub-meter resolution from a 3U CubeSat
- Any inclination
- Fast call up (8 to 24 hours)

Rapid Technology Development



- Short lead time for space qualification
- R&D turnaround in 3 months
- Multiple in-space iterations annually

Interplanetary CubeSat Missions



- Full mission cost at level of science cost budget for larger missions
- Propulsion capable of precise Earth escape
- Tailor launch schedule to target specific destination NEA and planetary opportunities

CONCLUSION

The GOLauncher 2 presents an excellent opportunity to expand the capabilities of nanosatellites far beyond technology development and experimentation, while also enhancing current applications. The flexibility of the air launch approach, coupled with the integration of existing technologies make GOLauncher 2 a near-term option for nanosatellite developers in need of affordable space access in the coming years.

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