Introduction to Suborbital Refueling

G. Flanagan, Alna Space Program
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Basic Concept

One of the basic cost drivers for a using a rocket to orbit is the small mass fraction that makes it into orbit. Take for example a single-stage rocket with a specific impulse of 350 sec. The ΔV needed to reach low-earth orbit is around 10,000 m/sec (counting aerodynamic and gravity losses). From the basic rocket equation, the ratio of the final mass to initial mass of the rocket is

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Exp[-10000 / (350 * 9.81)]
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0.0543408
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This 5% includes not only the payload, but the mass for empty tanks, propulsion, and other systems. The final payload value is so small that single-stage to orbit is a huge challenge that has yet to be achieved. Now imagine if a rocket could somehow be refueled at the halfway point in accelerating to orbital velocity. The mass ratio would then be

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Exp[-5000 / (350 * 9.81)]
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0.233111
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There have been proposals to refuel a rocket in mid-flight. These have typically taken the form of refueling in the atmosphere at low (subsonic) speed in order to “top-off” a winged spacecraft. The concept being proposed here is to dock with a fuel module outside the atmosphere during a ballistic trajectory at a substantial fraction of orbital velocity. There would not be time to transfer propellant. Instead, the docked combination of modules would immediately continue powering into orbit.

There would be no obvious cost advantage to simply using another rocket to carry fuel. Instead this is an opportunity to make use of a ground-based accelerator (or gun) to launch a fuel module that would then intercept a conventionally launched rocket. The fuel and systems in the gun-launched module could be designed to tolerant a high-G launch, while the payload in the rocket-launched module would experience only a low-G environment. One of the arguments against building a gun system is that in the early days of space industrialization there would be two few suitable payloads to justify the initial cost of the gun. Using a gun as part of a suborbital refueling system could greatly increase the utility of the gun system. Another argument against a gun system is that the gun can only insert payloads into a single orbital inclination. After docking, the combined modules can use the rocket boost to change the orbit plane, again increasing the utility of the gun.

The comments in this study will assume a gun launched propellant module. However, a more exotic possibility is to use propellant derived from an atmospheric harvesting system. In this case the propellant would initially be in orbit and employ aerodynamic deceleration to slow down to match trajectory with the up-coming rocket. In this case, the propellant module would only be carrying oxygen and the up-coming rocket would have to have sufficient fuel for the entire flight. This would be less efficient, but for most rocket propellant combinations the mass of oxygen far exceeds the fuel mass.

The following schematics show possible combinations of systems. The schematics are intended to show what equipment is included in each vehicle. They are not to scale. In Figure 1 the gun-launched module includes only propellant tanks and a docking mechanism. The rocket-launched module drops empty tanks after the first-stage burnout. The two modules dock and the original propulsion module relights to continue the boost. The docking mechanism must include means for quickly connecting propellant lines. The approach in Figure 1 has the advantage of minimizing the systems that have to survive the high-G gun launch. In Figure 2 the gun-launched module carries both propellant and a second stage rocket engine. This approach has the advantage of avoiding connecting propellant lines during docking, and the rocket engines can be optimized for in-atmosphere and vacuum conditions. The figures show the modules docking longitudinally, but tandem docking would also be suitable. Another alternative is to avoid dropping anything from the rocket-module. Not dropping empty tanks would be less mass efficient but may be desirable to avoid a complex event during the brief docking window or to allow for re usability.

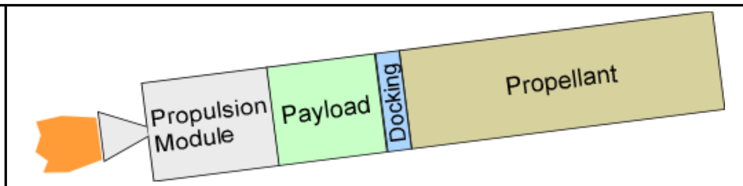
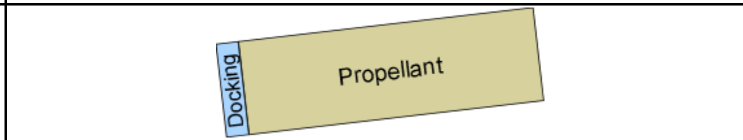
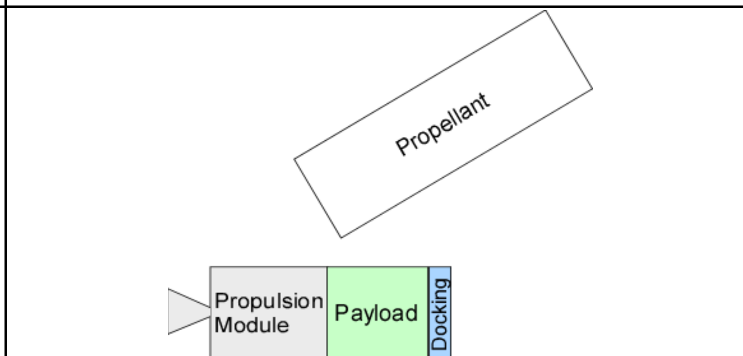
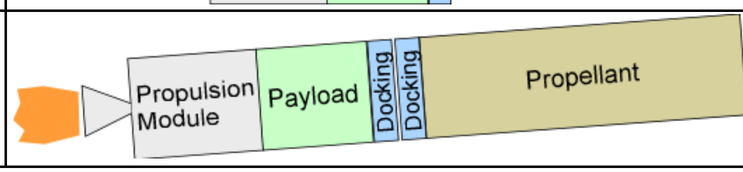
Low – G Rocket Launch Module	
High – G Gun Launch Module	
Rocket Module Transition	
Docked. Boost to orbit	

Figure 1. Refueling system with gun-launch module carrying only propellant

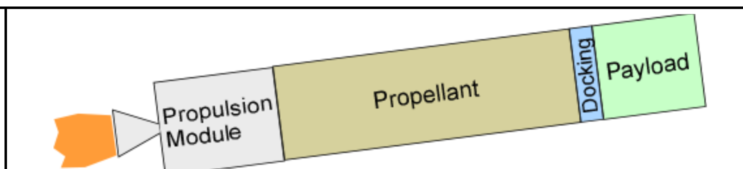
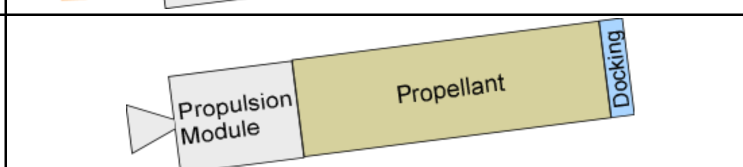
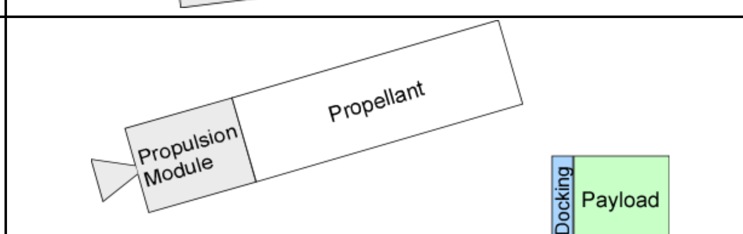
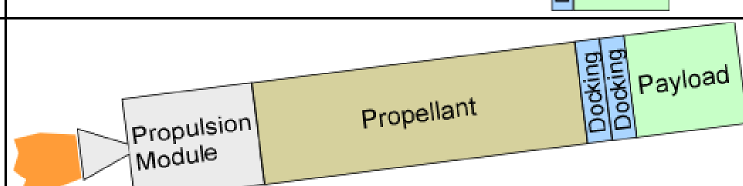
Low – G Rocket Launch Module	
High – G Gun Launch Module	
Rocket Module Transition	
Docked. Boost to orbit	

Figure 2. Refueling system with gun-launch module carrying propellant and second stage propulsion system.

Time Available for Docking

Examples

Consider a ballistic trajectory that has a tangential velocity at it’s peak of 4000 m/sec, and a peak altitude of 1000 km. Figure 3 shows this trajectory relative to the earth’s surface.

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subOrbitGraphic[4000, 1000]
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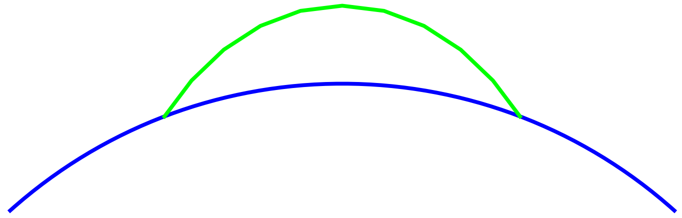

The time needed to reach the peak is

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subOrbitTime[4000, 1000]
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{278.215, 253.693}
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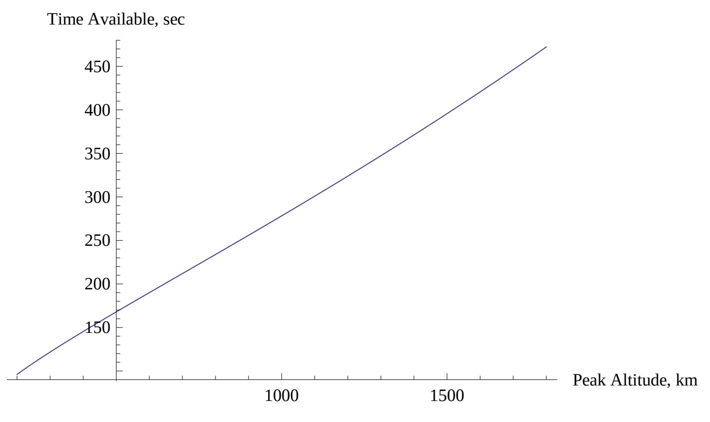
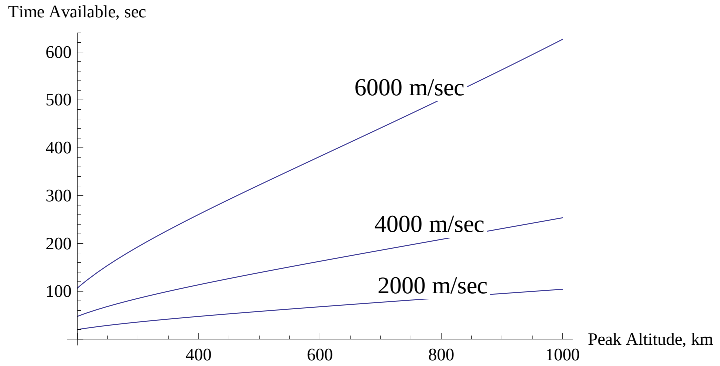
where the first number is from the earth’s surface, and the second number is from the top of the atmosphere (150 km). This is the time that the gun-launched module is in free-flight and available to dock. We assume that docking should occur before the peak of the trajectory, although starting the second-stage boost on the downside of the trajectory is also possible. At a constant 3G acceleration, the rocket module will require 135 seconds to reach 4000 m/sec. If the rocket follows that same path, then we should subtract 135 seconds from 278 to get a docking window of 143 seconds. This is not quite correct because the rocket will not follow a purely ballistic path during it’s powered flight phase. The window of 143 seconds is very short but may be feasible for a purely automated intercept and docking sequence. Figure 4 shows a plot of time from gun-launch to trajectory peak as a function of the assumed maximum altitude of the trajectory. A trade-off is that the rocket first-stage ΔV increases with peak altitude which lowers the burn-out mass fraction.



One could select a different docking velocity. Figure 5 shows the time to the peak for a series of assumed tangential velocities at the peak.



Gun Launch Angle

Another challenge of the proposed system is the required gun-launch angle relative to the earth's surface. For example, a trajectory with a tangential velocity of 4000 m/sec at a peak altitude of 500 km requires a launch angle of

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30.5505
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There are large advantages to building a horizontal or near horizontal gun track [1]. It is possible to change the gun projectile trajectory using aerodynamic lift [2]. Thirty degrees would be near the upper limit of angle change possible with lift. The system may require a combination of gun-track exit angle [3] and lift in order to reach the required trajectory.

References

1. G. Flanagan, Observations on Siting an Accelerator, June 2011.
2. G. Flanagan, Initial Trajectory and Atmospheric Effects, July 2011.
3. G. Flanagan, Adding curvature to accelerator path to change exit angle, July 2011