Flight Tests Of XCOR's EZ-Rocket and Progress Toward a Microgravity and Microspacecraft Launcher

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Abstract. The first flight of the EZ-Rocket, a rocket-powered airplane built by XCOR Aerospace, occurred on July 21, 2001. The EZ-Rocket is based on a retrofitted Long-EZ homebuilt airframe; its engines and propulsion system, which utilize non-toxic, easy-to-handle propellants, were developed in-house from clean paper to manned flight operations in fewer than ten months, and for less than $500,000. The aircraft has taught the XCOR team rocket flight operations, and demonstrated that non-toxic propellants are reliable and inexpensive. Based on this demonstration vehicle, XCOR is ready to start the next incremental development in airframe and rocket engine capability, the Xerus vehicle. The Xerus will be able to fly a suborbital trajectory and deploy an expendable upper stage that will put 10 kg microsatellites into low Earth orbit. Without the upper stage, the Xerus could carry 250 kg for four minutes of high-quality microgravity flight. This paper will describe the current status and lessons learned in the precursor vehicle test program and engine development program, and discuss technical and business scenarios and likely timetables for extremely low cost flights of payloads of interest to the small satellite and microgravity research communities.

Introduction

In July, 2001, XCOR Aerospace (www.xcor.com) started flying a rocket-powered airplane, the EZ-Rocket, based on a reused Long-EZ homebuilt airframe with its original Continental piston engine and wooden propeller removed. The EZ-Rocket engines and propulsion system were developed in-house from clean paper to manned flight operations in less than one year, and for less than $500,000. Figure 1 shows the vehicle with both engines running over Mojave, CA.

Figure 1. The EZ-Rocket Flying Over Mojave, CA.

Note the rocket exhaust plumes from the twin 1.7 kN engines are almost invisible and leave no smoke trail. Through July 30, 2002, the plane has made 15 flights at a recurring cost of about $1,000 per flight. The vehicle is now in semi-retirement because it has finished its flight test program and XCOR is moving on to other programs. The plane has demonstrated routine, reliable, and low cost rocket flight operations using non-toxic propellants.

In July 2002, the United States' Federal Aviation Administration (FAA) certificated the EZ-Rocket to fly in front of a large crowd at the Experimental Aviation Association's annual air show in Oshkosh, Wisconsin. This is the first time a rocket-powered aircraft has been cleared for flight in public by the FAA. This required temporarily relicensing the craft as Experimental Exhibition. Since then, the vehicle has been restored to its Experimental Research and Development airworthiness certificate. Lt Col Rutan (USAF Ret.) was chosen to be XCOR's test pilot because he was the original factory test pilot for the Long-EZ, and because he has more time in this type of aircraft than anyone else in the world. In 1997, he flew his personal Long-EZ around the world. All flights except #8 have had Lt Col Rutan at the controls. That flight was piloted by Mike Melvill.

Figure 2 shows XCOR pilot USAF Lt Col (ret) Dick Rutan with the craft following one of the Mojave test flights.

Figure 2. Pilot Lt Col Rutan (USAF Ret.).

In this photo, the number one engine has had its Kevlar blast shield removed and the number two engine is covered. The engines are in the lower center of the photo.

EZ-Rocket Construction

The EZ-Rocket airframe started life as an amateur-built Long-EZ with a Continental O-200 piston engine and wooden propeller. It was flown 540 hours in this configuration before being acquired by XCOR for the purpose of serving as a rocket engine test vehicle. We chose this airframe because of its pusher configuration (engine mounted in the rear), its strength, and because of its known flying qualities. It was big enough to carry the additional propellants needed for rocket flights, but not so big that it would have stretched our resources unacceptably.

The Long-EZ is a fiberglass and foam composite airplane built with manual controls and hydraulic brakes. XCOR removed the electric heater, seat cushions, magnetic compass, engine instruments, and directional gyroscope from the cockpit. The piston engine, propeller, engine mount structure, engine cowling, and fuel feed system components behind the firewall were also removed. All else from the original amateur-built craft was retained. We then added the engine mount truss structure, propellant feed system, helium supply bottles, and pressurization system aft of the firewall on the same hardpoints to which the piston engine was attached. A three-piece composite cowling was fabricated to enclose all the above components. Mechanical Bourdon tube gauges were added to the instrument panel where the piston engine instruments had been. These indicate fuel and LOX tank pressures, and helium pressurant tank pressure. Engine chamber pressure gauges are electrically remote sensing with pressure transducers on each combustion chamber.

A pair of welded and heat-treated aluminum tanks were added to the passenger seat volume and covered with Styrofoam insulation for the liquid oxygen. Gasoline is normally carried in two strake tanks, but the high pressure alcohol could not be stored in those low pressure tanks. The alcohol tank was added as a strap-on cylindrical pressure vessel underneath the fuselage. It is much bigger and heavier than it needs to be, but was made from a standard size commercially available unit. Reuse of an off-the-shelf airframe meant the resulting propellant mass fraction is a relatively low .36, which is less than half the mass fraction achieved by our pilot's Voyager around-the-world airplane. Most flights are made at lower mass fraction because altitude performance is not a vehicle requirement.

EZ-Rocket Performance

The EZ-Rocket was built to be an operations demonstrator, not for high performance as measured in speed or maximum altitude. Its low mass fraction and the airframe's low never-exceed speed (Vne) of 97 m/sec indicated (190 kias) limited its flight performance. Our goal was to show safety, reliability, operability, and low flight cost using non-toxic propellants. Table 1, below, lists flight history.

Table 1. EZ-Rocket Flight History

Flight #	Date	Comments
1	7-21-01	1st single engine runway flight
2	9-10-01	2nd single engine runway flight
3	10-3-01	1st up & away, twin engine
4	11-09-01	Flight check for public demo
5	11-12-01	Public rollout, max altitude 9Kft
6	12-17-01	Proficiency flight
7	1-09-02	Televised flight for news TV
8	1-24-02	1st in-flight restart
9	2-01-02	Attempted touch & go
10	6-25-02	New engine, touch & go
11	6-27-02	Manual prevalve shutdown
12	7-11-02	2 low approaches, 2 relights each
13	7-11-02	2nd flight of the day
14	7-25-02	Oshkosh EAA air show
15	7-27-02	2nd flight for EAA air show

The first two flights were liftoff and landing without leaving the runway heading. All flights after the first two had a second engine installed. The final five flights were with engines serial numbers Three and Four installed. In addition to the pilot, the EZ-Rocket needs only three ground crew and two hours to recycle between flights. Marginal cost per flight is just under $1,000. Most of this is for technician's salaries, and the remainder is for consumables. Of the three consumables, helium is the most expensive. Therefore, a larger vehicle must have pump-fed engines to have low flight cost. This is because the helium is used to fill fuel and LOX tanks ullage gas volume. Figure 3 shows the EZ-Rocket loaded onto its road transport trailer for a cross country trip. Flying range of the vehicle is negligible.

Figure 3. The EZ-Rocket on the Road.

EZ-Rocket Engines

The XR-4A3 engines developed for the EZ-Rocket have been run 558 times to date for a total of 6,434 seconds, or 107 minutes of runtime. In all these test and operational runs, there has never been a hard start, engine explosion, or any mishap leading to personnel injuries. Each of the two engines develops 1.7 kN thrust and can be started and stopped repeatedly in flight. During flight #12, the engines were tested twice before flight and shut down and restarted six times during the flight. Fuel is 99% isopropyl alcohol and oxidizer is commercial grade liquid oxygen (LOX). The engines have machined copper alloy combustion chambers and are regeneratively cooled with the fuel.

Switching to Pump-fed Engines

XCOR's next generation of rocket engines will be pump-fed using in-house designed motor-pump assemblies. These are being developed under contract to a US government agency, and with matching private investment capital. They are reciprocating, rather than the more common turbine driven centrifugal pumps. XCOR chose the reciprocating piston pumps over turbopumps because of lower development cost and greater application flexibility in this small size. We chose piston pumps over pistonless pumps because they allow area ratio difference between motor and pump sections. Having an area ratio allows the pump outlet to be at a higher pressure than the motor drive gas. This in turn allows use with any of the three common rocket thermodynamic cycles: gas generator, expander, and staged combustion. Pump-fed engines are necessary to get the vehicle mass fraction required to fly acceptably high performance missions. Savings both in propellant tank mass and pressurization system mass are had with the pumps.

Based on lessons learned from the EZ-Rocket engine development and vehicle flight testing, XCOR is ready to take the next step. That will be an incremental development in airframe and rocket engine capability that will result in the ability to fly microspacecraft launch missions and microgravity experiments reliably and at university-level budgets. XCOR has designed, built, tested, and flown a cheap and reliable rocket powered vehicle with a restartable nontoxic propellant engine.

Xerus, the Next Step After the EZ-Rocket

While the EZ-Rocket used an existing airframe, the Xerus will have a new, purpose-designed airframe optimized for high speed and altitude, and for carrying propellants. The vehicle is small. Its dry weight is about twice that of the EZ-Rocket, or approximately 1,100 kg. Wingspan is a little less than the EZ-Rocket, because the aspect ratio of the high speed wing is less, and because takeoff and landing speeds are higher. Engine size goes from two each 1.7 kN on the EZ-Rocket to four each 13 kN on the Xerus. XCOR's team has experience designing, building, and testing engines up to 22 kN thrust. No technology breakthroughs are needed, just straightforward development. A preliminary solid model sketch of the Xerus is shown in Figure 4.

Figure 4. The Xerus Vehicle.

The vehicle will have the flying characteristics of an aircraft; it is not a new configuration with new flight behavior to learn. It is small enough that it can be flown without powered aerodynamic control surfaces, much as the Bell X-1 was. No novel computers or software need to be developed; no quad-redundant flight control avionics are required. The flight test program will be incremental, as is standard new aircraft practice. We expect at least 20, and likely 30 test flights before the first operational flight. Xerus is a small vehicle, and will cost less to build than a large one. Performance projections are based on preliminary design with margin, not on extrapolation from past vehicles that had different mission requirements.

Xerus Engines

XCOR is currently developing the rocket engines and their associated propellant pumps. Oxidizer will be liquid oxygen, as used in the EZ-Rocket, but we are switching to kerosene fuel. Kerosene has slightly higher specific impulse and lower cost than alcohol, and its density is a bit higher. First test hot fire of the engine in heat sink mode was done in March, 2003. Run duration in this mode is a maximum of 1.5 seconds, which is long enough for the engine to reach steady-state operation. This allows us to develop injector performance and to adjust combustion chamber stability techniques. Later, the regeneratively cooled combustion chamber will be added for long burntime capability. Figure 5 shows first fire of the larger engine intended for Xerus. Note the exhaust plume is much more dramatic than the EZ-Rocket's because of kerosene's characteristic yellow flame.

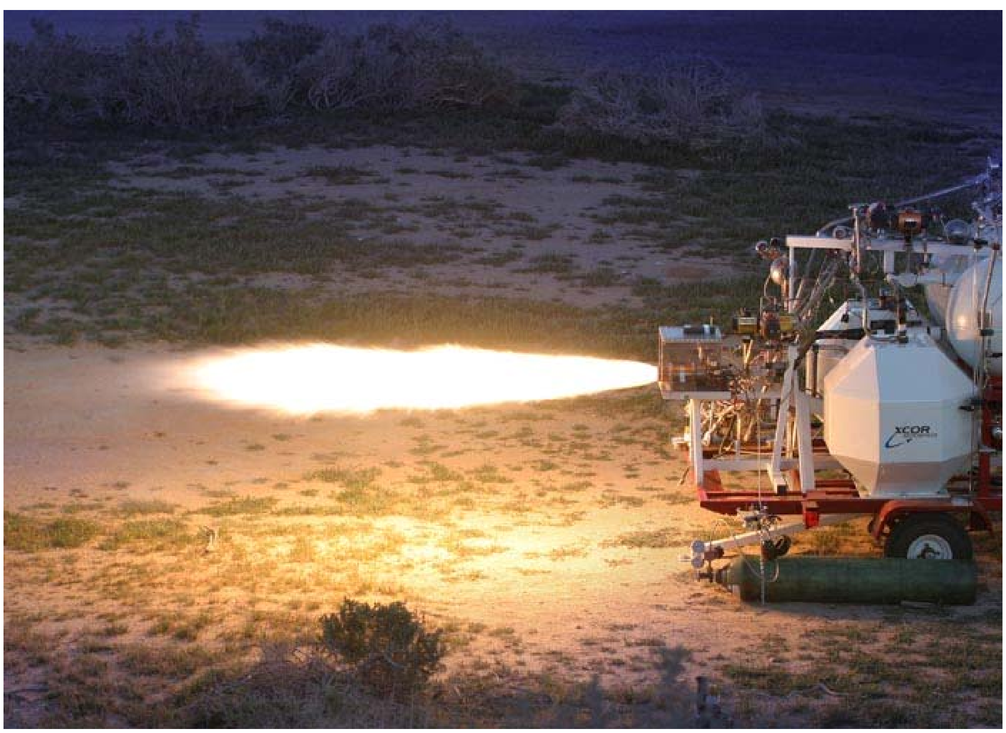

Figure 5. First Fire of Xerus Engine

Chamber pressure is 2.5 times higher than the pressure-fed EZ-Rocket engine, so the engine size is only 30% bigger to get 4.5 times the thrust. The photo also shows XCOR's mobile rocket engine test stand at our remote site on the east side of the Mojave, CA, airport. All work on the engines and test stand is done in our shops on the airport flight line. When we are ready to run, we move the mobile stand to its remote operations location.

The Xerus vehicle will fly a suborbital trajectory that leaves the atmosphere. It will be either an experiment carrier, or it will be capable of deploying an expendable upper stage to put a 10 kg microsatellite into low Earth orbit. XCOR believes that the number of micro-satellites will significantly increase if low launch cost and dedicated launch capability become a reality.

Xerus for the Microgravity Market

First market for the Xerus vehicle will be to fly experiment packages on a trajectory similar to what is now flown by sounding rockets. Experiment payload capability will be 250 kg. Vehicle electrical power will be available to the experimenter. Part of that 250 kg can be the investigator himself or herself. Because the Xerus is a piloted, reusable craft, this greatly expands the types of experiment that can be performed. Table 2 shows the major events during a typical sounding rocket trajectory.

Table2. Xerus Flight Profile

Time	Altitude	Event
Sec	Km	
0	.86	Engine start
12	.87	Takeoff from runway
80	11.7	Mach 1
167	68.2	Engine cutoff
182	85.6	10E-4 g begins (10E-5 m/sec)
316	171	Peak altitude
430	110	10E-4 g ends
496	23	Max 6 g pullout starts
1100	.86	Landing

Minimum acceleration will be less than the 10E-5 m/sec shown in the table, but the exact number will not be known until we measure it in actual flight. Maximum acceleration on reentry will last for about 20 seconds. The low acceleration levels in the table assume the experiment is directly mounted to the vehicle frame, using the maximum payload volume and mass available.

The initial altitude is not zero because the flight is assumed to take place from Mojave where field elevation is .86 km. The observant reader will have noted that the low acceleration time is 20 sec longer during coast up than during coast down. This is because the vehicle's angle-of-attack (AOA) is low on the way up, therefore lift forces are low. During reentry, the AOA is high so that deceleration and pullout can start as soon as possible. Thus, lift forces dominate vehicle acceleration during the times adjacent to the low acceleration experiment period. Because aerodynamic effects dominate the low acceleration environment, the onset of low-G is gradual and can be used to the experimenter's best advantage, such as for sample heating and cooling.

During a 10 second period just after leaving the atmosphere, the Xerus reorients itself for the proper AOA for reentry. The payload volume is about 2.0 m ahead of the vehicle center of gravity, and this reorientation will be a rotation about the CG at a maximum of 5 degrees/sec.

The flight will be a lifting trajectory, although thrust will be greater than lift for most of the powered duration. Maximum altitude will not be determined by propulsion system performance. The 170 km altitude is relatively easy to achieve with the vehicle having a mass fraction of .68. Peak altitude is determined by two aspects of reentry. One is the maximum pullout acceleration requirement, and the narrow window of allowable pitch and yaw angle to achieve pullout. The other altitude limiting feature of the reentry is vehicle skin heating limitations.

For smaller experiments needing a better-quality microgravity environment, the payload can be free-floated within the payload compartment. Current XCOR models predict that this will reduce the sensed acceleration to 10^{-6} to 10^{-7} m/sec^2 within a roughly 40 cm diameter sphere. Keeping the acceleration this low will require a non-contact interface to the experiment package and will require an additional launch lock mechanism to be added for these flights only. The actual acceleration achieved will depend on design quality of the free-float package and will include air currents, power or data transmission methods, and handoff forces. XCOR plans to have the experiment isolation package developed by a partner organization as a drop-in capability. The module would simply bolt to an interface on the vehicle for customers who need three to four minutes of true microgravity.

Ground turnaround time between flights will be approximately two hours, up to four flights a day per vehicle. Price per flight would be approximately $50,000 for the full payload bay. Of course, there will be opportunities for smaller experiments to share the ride and cost. We expect a university or commercial partner to handle this ride-sharing service.

The Xerus as a Microsatellite Launcher

Xerus will also be capable of launching a microsatellite with an expendable upper stage. Maximum launch performance is used for this mission because reentry is less of a problem, as the trajectory is flattened compared to a maximum altitude flight. Reentry of a winged vehicle is easier with more horizontal velocity because the pullout to horizontal flight is easier. A typical satellite launch scenario would start from a runway takeoff and powered climb lasting less than four minutes. Engine cutoff occurs at Mach 4.1 at 61 km altitude. Second stage separation and ignition happen within the next 10 seconds. The Xerus then coasts for another minute up to an apogee of 110 km before reentering and gliding back to the takeoff runway. Payload size is whatever fits into a .6 m diameter by .7 m long ogive.

Because no solid fuel rocket motors are employed, payload shock and vibration environment will be relatively benign without the need for payload isolation. Maximum acceleration at upper stage burnout is about 8 g. It is a smooth 8 g, unlike the high-vibration traditional solid rocket motor that shakes and vibrates. These numbers assume the spent upper stage is left attached to the satellite. Leaving the stage attached will be desirable to most payload owners since the stage will have a three-axis stabilized guidance, navigation, and control system, and some residual propellants for pointing.

Ground support facilities will be minimal compared to other launch vehicles. No toxic or explosive chemicals, no pyrotechnic devices and no solid rocket propellants will be used. Both Xerus and its upper stage will need nothing more than liquid oxygen, kerosene, and helium. Liquid oxygen is now routinely and safely handled at large hospitals, cement plants and many other industrial plants.

The vehicle will need a hangar for servicing, and a crane to attach the upper stage. Processing for experiments and payloads will require a clean facility inside the hangar, similar to current sounding rocket support facilities at White Sands or Wallops instead of the massive infrastructure at the major US satellite launch ranges at Cape Kennedy, Cape Canaveral or Vandenberg Air Force Base. Facilities will be adequate at any temperate or tropical latitude airport with a runway of at least 1,800 m. Liquid oxygen will be supplied commercially by commercial commodity providers. The facility will have to be FAA approved as a launch site, because Xerus will be licensed as a Reusable Launch Vehicle, rather than as an experimental aircraft. A significant fraction of XCOR's development effort is spent working with the FAA to reduce the regulatory risk.

For example, if Xerus were to launch operationally from the Hawaiian Islands, payloads could be placed in orbital inclinations from 15 to 30 degrees, to a circular 400 km altitude orbit. Going to 500 km instead of 400 km would lower the payload mass by about 1 kg. The payload to any inclination between 15 and 30 degrees is within 1 kg. The vehicle is still in preliminary design and XCOR is studying how much it would change to make the payload 10 kg to polar orbit. Polar orbit capability will require the vehicle to be bigger than that shown in the illustration, and we are still in the process of making that decision. Unlike previous attempts to launch vehicles from places other than federal ranges which have met with significant local opposition, this vehicle uses nontoxic propellants and will not require disfiguring infrastructure much beyond that of a normal operating airport. In the case of Hawaiian launch, sonic booms would be offshore. For other locales, trajectories would need to be designed to minimize noise impact, and will be part of the facility spaceport license.

Technology Roadmap

XCOR's key design philosophy is, while maintaining safety, to make every design decision to optimize cost and operational simplicity (which is, ultimately, also cost) rather than performance. Reliability, operability, and low maintenance all come before high performance. The key milestones on XCOR's technology roadmap will each now be discussed in turn.

Airframe

XCOR has designed, built, tested, and flown a cheap and reliable rocket powered vehicle. The proposed Xerus is a reasonable incremental step from the current vehicle, with several milestones to verify progress. New airframe technologies are being developed and these are proceeding in parallel.

One of the developing technologies is a new composite material for the LOX tank. XCOR owns the intellectual property rights to the Rotary Rocket LOX tank development, and we are pushing that further with private funding. This is currently proceeding along two parallel paths, only one of which needs to succeed for Xerus to be successful as shown. Xerus performance as a manned sounding rocket is assured with current technology, but the satellite launch mission needs for one of the parallel efforts to succeed.

Xerus wing design is straightforward, and unlike an airplane, does not have to be optimized to get good cruise range on minimum fuel. Even in an emergency, landing weight is less than half of takeoff weight, which simplifies wing and gear design. Wing design is also simplified by the decision to allow takeoff speed to be much greater than landing speed. Thus, wing area for takeoff is not larger than wing area needed for landing. Xerus is a small vehicle, which is inherently cheaper to build than a large one.

Systems

The Xerus is small enough that it can be flown without powered aerodynamic control surfaces, which means minimal software to develop, and requires no quad-redundant flight control avionics. Compared to an airplane that cruises supersonically, operational requirements are far easier to meet. Unlike a typical supersonic fighter plane, Xerus needs no weapons stores, has no necessity for dogfight maneuvers, no need to fly after sustaining battle damage, and no air inlets. A large fraction of conventional aircraft CFD and wind tunnel design goes to develop the air inlet performance as a function of Mach, indicated airspeed, and angle-of-attack.

Systems that do need to be developed include the navigational instruments and their pilot displays. Xerus will have three redundant, independent, different design methods of presenting pitch and yaw information to the pilot in order to reduce the hazard of improper attitude during reentry. These designs are new developments of proven technology, but will be implemented in a novel fashion.

Engines

XCOR is currently working, supported both with company money and a small DARPA contract, to develop a low cost propellant pump in the appropriate size for Xerus. XCOR has already developed a rocket engine injector design with demonstrated low fabrication costs. Traditionally, the engine injector and turbopumps are the expensive parts. We expect engine development to proceed to first long duration hot-fire by the second quarter of 2004. The only new technology in the engine is in the piston pumps, and they are proceeding early in order to reduce technical risk. All else has been done previously; it is only the configuration that is new.

Operations

Consider the X-15 airplane, a US government experimental craft that flew during the 1960s but was discontinued in favor of the Shuttle and similar craft. Three X-15 vehicles flew 199 missions with airplane-style support. The entire program, including construction of the vehicles and engines, cost less than a single flight of the Space Shuttle. The rocket engine on the X-15 was not the highest performance attainable; it was designed for safety and operability. The program's purpose was to fly new aerodynamic profiles; the propulsion system was just there to provide a standard of performance. If the X-15 were built today and if it were just an operations demonstrator, it could incorporate many lessons learned since then, and use cheaper commercial technology. XCOR's cost models make sense if one thinks of the Xerus as a half scale X-15 built by a small, lean organization using composite structures and commercially available subsystem technologies.

Some people claim that it is inherently difficult and expensive to travel to space, and cite the examples of current space launch activities being large government and big contractor programs. But this has not always been true. Alan Shepard rode to space on a Redstone. A modified Redstone renamed Jupiter launched our first satellite in 1959. By today's standards, these were neither very complicated, nor expensive, nor big. Current EZ-Rocket engines already have higher specific impulse than Redstone did, and they are expected to improve another 10% with further development.

Best Practices

XCOR does not simultaneously need to develop the management team, engineering team, test facilities, engines, and the airframe. The team has studied the business and technical lessons learned by earlier ventures. An incremental program in management process and best practice development will be used similar to that used to develop other commercial technologies. The core team is in place with the management, design, fabrication, build, and test abilities needed for a small, fast paced development project.

Universities as Change Agents

Universities have for quite some time been unable to find an affordable or timely ride to space for student or even faculty-developed payloads. A Xerus vehicle is small enough, easy enough to operate, and inexpensive enough to be within the range of a major capital investment by a consortium of universities, funded by a combination of foundation, grant, and endowment monies. The scale of funding required is of the order of any other large scientific instrument, such as a major telescope or well-equipped biotech laboratory. The return on such an investment in prestige and access to a novel resource would be similar to that afforded by such traditional academic facility investment, particularly for the first group to put together such an arrangement.

In no field other than launch services are investigators given no opportunity to buy cheaper services or services that might better fit their timetables. They are simply handed whatever room happens to be left on vehicles designed for other purposes altogether, and primarily dedicated to payloads with different needs. Universities should be given money to purchase launch packages as part of grants to create instruments and payloads, not made to scrounge for secondary payload spaces when – and if – the odd one turns up. In the case of the Xerus, it will be the experimenter who determines flight dates, not the service provider. Customer based operations should be part of microgravity flights, just as they are for products and services.

Many universities have proven themselves effective administrators of complex research facilities, such as telescopes on remote mountaintops, deep ocean submersibles, and the like. They could in principle provide the experience and infrastructure to provide payload integration and operate a vehicle like the Xerus. It would be a service to the overall academic community to provide that community with reliable and responsive payload service to low Earth orbit, with paying customers from government clients on an additional, reimbursable basis. Innovation in aerospace has in some part been stalled because of an inability to launch small, experimental payloads on a timely basis. In addition, export controls make it very expensive and difficult for American universities to launch on foreign rockets, the only real options for university budgets at this time.

XCOR's partner organization Takeoff Technologies LLC has been exploring business models that involve a university or consortium of universities raising funds to own and operate a Xerus vehicle for the university community's use. Key issues and concerns for the most part center around liability and finding ways to retire technology risk as quickly as possible while keeping costs low.

The current major aerospace companies have no strong incentive to provide universities with cheaper access to space. Government projects include several technology development programs and a few large vehicle development programs that may lead to hardware in a decade. Today's aerospace industry leaders routinely propose greater sophistication, higher performance, and better materials as the path to lower costs. XCOR, on the other hand, believes that low cost design from clean paper, emphasis on operations, and use of non-toxic propellants should have priority over high performance as measured by thrust-to-weight ratio or specific impulse.

We encourage discussion within the various stakeholder communities of the merits of vehicle development and operations led by, and optimized for, the university community. The time has come for universities to stop waiting for secondary or tertiary payload opportunities that may never come, and to take matters into their own hands so that experiments and payloads reach space in a timely manner that complements student and academic career time scales.

Within three years of starting the Xerus program we expect to begin customer flights. We look forward to working in space with the university and small satellite community.