A Navigation Test Flight for a Lunar CubeSat

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A CubeSat is a payload package having dimensions 10cm x 10cm x 10cm and a mass that cannot exceed 1.33 kg. They can also be made in double and triple length (10cm x 10cm x 30cm and 4 kg). Although a number of CubeSats have previously been developed and launched into Earth orbit, none have accomplished missions involving interplanetary navigation. A version of NASA's GPS Enhanced Onboard Navigation System (GEONS) rewritten in Ada/SPARK for enhanced reliability, will use a sophisticated space tested GPS system and a star / near body tracking camera for navigation components. The non-standard low energy transfer strategy through a Lissajous orbit at the Earth-Moon L1 Lagrange point to achieve Lunar orbit insertion and a safe decent to the Lunar surface require sophisticated navigation systems. The triple CubeSat would get a ride with a communications satellite launch to the geosynchronous transfer orbit (GTO). The CubeSat would then travel under its own power to the Moon. Two variations are being studied, and the Vermont Lunar CubeSat project will use high-energy mono-propellant and/or a long duration ion thruster for propulsion to the Moon.

The chemically propelled mission would have a double CubeSat as a booster carrying the single CubeSat as payload from the GTO to Lunar orbit insertion. The chemically propelled single CubeSat would then descend to a soft landing on the Moon.

The xenon ion drive triple CubeSat would travel to the Moon and enter orbit for observations with its instrument payload. It would use the low energy transfer ala the ESA SMART-1 spacecraft.

We have been selected by NASA for the ELaNa IV launch on an Orbital Sciences Minotaur 1 to a 500 km orbit in July, 2013. This single CubeSat would test the navigation software and hardware, sending celestial, GPS and GEONS information to our ground station.

I. Introduction

A CubeSat is a payload package having dimensions 10cm x 10cm x 10cm and a mass that cannot exceed 1.33 kg. They can also be made in double and triple length (10cm x 10cm x 30cm and 4 kg). Beginning in 1999, California Polytechnic State University (Cal Poly) and Stanford University developed the CubeSat specifications to help universities worldwide to perform space science and exploration.[1] Following the success of a number of academic missions, commercial and government space organizations have started to use CubeSats for a variety of relatively low cost missions. CubeSats have been launched as secondary payloads on launch vehicles such as Falcons 1& 9, Dnepr, Taurus XL, Atlas V, Vega and the Space Shuttle. They are almost always deployed from a Poly Picosatellite Orbital Deployer (P-POD), developed at Cal Poly. The P-POD can contain three single CubeSats, a single and a double, two one and one-half CubeSats, or a triple. Particularly with triple CubeSats, very sophisticated missions can be contemplated. There are currently CubeSats in development to search for extra solar planets, an x-ray cosmic background telescope, a "spy satellite" with 3 m ground resolution and a thunderstorm gamma ray flash detector. Single CubeSats have done many somewhat less sophisticated measurements, many flying with GPS and/or cameras. There have been CubeSats with passive magnetic, active magnetic and momentum wheel attitude control. Several have had limited propulsion (chemical, cold gas and electric) capabilities.

All have radios, most with up and downlink capabilities. There are a number of companies that make off the shelf boards with the various subsystems used in CubeSats. There are electrical power system boards for controlling the photovoltaic charging of batteries and generating several bus voltages, star trackers, cameras, GPS, deployable

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antenna systems, CPU boards and several deorbiting methods (inflatable balloons and electro-magnetic) and structures.

Although a number of CubeSats have previously been developed and launched into Earth orbit, none have accomplished missions involving interplanetary navigation. This would require both a substantial means of propulsion and a sophisticated navigation system. The CubeSat we are currently developing will test the navigation component we would use on a self-propelled triple CubeSat to go to the Moon or Mars. The triple would have one of two propulsion schemes depending on the particular mission if going to the Moon. A chemical propulsion system would be used for a Hohmann transfer to the Moon, with a landing on the Moon. This would be a single linked to a double. An ion drive system would be used for a mission with the CubeSat orbiting the Moon with appropriate instruments for Lunar data collection.

During the initial investigation of our Lunar CubeSat prototyping grant (a NASA Consortium Development Grant) there was an announcement of the new Education Launch of Nano-satellites (ELaNa) initiative, to which we applied and were selected for a launch. This was critical, as the original $20-30,000 launch costs for the first CubeSats has been bid up in recent years to $75-100,000. The initial launch cost associated with the ELaNa program was announced at $30,000. It was later changed to a free launch. This program, was initiated by Garrett Skrobot, Launch Services Program at Kennedy Space Center. Since NASA was funding CubeSat projects at universities, and the launch costs were becoming prohibitive, NASA funded launches seemed like an ideal location for secondary payload CubeSats.

This seemed like an ideal opportunity for testing a critical part of a Lunar mission, our navigation system during an actual space flight. A version of NASA Goddard’s GPS Enhanced Onboard Navigation System (GEONS) software rewritten in SPARK/Ada for enhanced reliability, will use a sophisticated space tested GPS system and a star / near body tracking camera for navigation components. The GEONS software does very sophisticated GPS signal processing for much longer range use of GPS satellite signals, and very good orbit propagation calculations to keep track of spacecraft position during GPS signal loss. The software can also do celestial navigation when there is no GPS signal. The GEONS system, which was derived from several prior programs (at least one written in Ada), was developed in the C language for increased portability. In using SPARK/Ada, we are using a language and toolset which has about 1% of the error rate of C. We have already found several errors in the NASA program while translating the first 25% of GEONS.

There are several methods for transfer to the Moon that use less energy than the standard Hohmann transfer. The non-standard low energy transfer strategy through a Lissajous orbit at the Earth-Moon L1 Lagrange point to achieve Lunar orbit insertion and a safe decent to the Lunar surface require sophisticated navigation systems, as do weak stability boundary and “shoot the Moon” ballistic capture trajectories. The triple CubeSat would get a ride with a communications satellite launch to the elliptical geosynchronous transfer orbit (GTO). This would be the starting point for any of the low energy transfers. The CubeSat would then travel under its own power to the Moon.

Two propulsion systems are being studied, and the Vermont Lunar CubeSat project will use either a high-energy mono-propellant, such as hydroxyl-ammonium nitrate (HAN) based and/or a long duration xenon ion thruster for propulsion during the journey to the Moon. The chemical propellant would be used for a rapid Hohmann transfer and orbital insertion at the Moon. This mission type would have a double CubeSat as a booster carrying the single CubeSat as payload from the GTO to Lunar orbit insertion. The chemically propelled single CubeSat would then descend to a soft landing on the Moon. We have studying the same basic mission profile as the Apollo missions, with a Lunar orbit of 100 km altitude, followed by an 8-10 minute descent to the Lunar surface. The lander would have very limited room for a very simple instrument. The HAN propellant system requires a heated catalyst in the rocket engine combustion chamber. This system was selected over a hypergolic bi-propellant system with the advice of the propulsion group at Goddard Space Flight Center.

The xenon ion drive triple CubeSat would travel to the Moon and enter orbit for observations with its instrument payload. The MiXI xenon thruster, developed at NASA’s Jet Propulsion Lab, would be exactly the right size for a triple CubeSat. With 0.5-0.75 kg of xenon at 150-200 atmospheres would supply a delta-v of 4,000 – 6,000 ms^{-1}. This would be adequate for either a Lunar or Martian mission. Low energy flight paths to the Moon, have been used before by larger spacecraft. In 1990-1, Ed Belbruno[i] of the Jet Propulsion Laboratory proposed using a low-energy (weak stability boundary) trajectory with a ballistic capture to enter lunar orbit using zero delta-v to save the 197 kg

Japanese Hiten mission which had a 50 ms^{-1} velocity deficit from its launch vehicle. Another path would use the low energy transfer ala the ESA SMART-1[ii] spacecraft in 2003-6. SMART-1 was a 367 kg spacecraft, as compared to our 4 kg xenon ion drive triple CubeSat. This was a launch to a GTO, with the xenon ion drive fired at perigee each time to gradually enlarge the ellipse over the course of about 12 months until the orbit reached the Lagrange point, L1. The orbit then switched to around the Moon, that highly elliptical orbit was reduced by a factor of about 10 over the next three months with the use of the ion drive. After 14 months of observations, the ion drive was used to deorbit the spacecraft for a Lunar impact.

We have been selected by NASA for the ELaNa IV launch on an Orbital Sciences Minotaur 1 rocket to a 500 km orbit in July, 2013. We are getting a piggy back ride on the Air Force ORS-3 launch. Our single CubeSat would test the navigation software and hardware, sending celestial, GPS and GEONS information to our ground station. We are using a Novatel OEMV-1 GPS board with the CoCom speed and altitude limits removed. We are also using their API to allow us to run the GEONS software on the ARM processor on the Novatel board. There is about 4 MB RAM and 4 MB ROM available on the OEMV-1 for our use. This gives us a lot of computer power for the navigation software compared to our control CPU (which comes with our CubeSat Kit structure), a Texas Instrument MSP430F2618 with 8 kB RAM and 116 kB of ROM. We are using an Astrodev Helium-100 radio with 2m uplink and 70 cm downlink, and an ISIS AntS deployable antenna system with crossed 2 m and 70 cm dipoles. Our power supply is a Clyde Space 1U EPS with a 10 Wh battery. Our camera board will also contain a Microstrain 3DM-GX3® -25 inertial measurement unit (IMU). We are using passive magnetic stabilization with Alnico-V magnets and HyMu-80 hysteresis rods. Our photovoltaic boards, covering the outside of the CubeSat are being made by LED Dynamics with flashing LEDs for observation of the CubeSat from the ground.

The orbital lifetime of a 1.33 kg single CubeSat at an altitude of 500 km is about 7 years with natural reentry due to atmospheric and solar drag. We hope to take data for a minimum of several months with possible extension if everything is working to several years. On a Lunar mission for our triple xenon ion drive CubeSat, we would need to navigate for at least one and one half years. The GEONS calculation results as well as the raw GPS position would be downloaded with simultaneous star tracker camera photos for further analysis on the ground. We have built a ground station at Vermont Technical College for that purpose. We would in addition be joining the GENSO network of university ground stations which allows remote operation of other ground stations when they are not otherwise occupied, allowing global coverage for CubeSat communications. The successful operation of our navigation system in this ELaNa IV LEO launch would give us much increased confidence of our navigational capabilities for our much more complex and expensive Lunar mission.

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Computer Software

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