Cubesat
Literature Survey Report

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September 26, 2013

Contents

List of Figures

List of Tables

1 Introduction

In a world where lack of space is becoming an increasingly problematic issue to deal with, miniaturization is becoming more of a necessity rather than an option. With sensors and actuators reaching small scales, it is now possible to actually design pico and nano satellites to meet certain required scientific goals. In this report, we are primarily concerned with nano satellites or CubeSats with sizes ranging from 1U(10cm x 10cm x 10cm) to 6U(60cm x 10cm x 10cm). Since CubeSats are small, it is possible to launch multiple CubeSats with a single scientific mission. Thus, using formation flying CubeSats, it is possible to perform missions which, earlier, were either too difficult to do or required much bigger satellites.

The objective of this literature survey is three-fold:

1. To uncover and understand the existing single, as well as multiple, satellite missions and some proposed concepts.

2. To enumerate the various actuators and sensors that are available today or will be available in the near future (with an acceptable Technology Readiness Level) and to analyse if they would satisfy our mission requirements.

3. To propose new missions based on formation flying of CubeSats.

These missions have been categorized into five different classes as Planetary Science, Earth Science, Astrophysics, Heliophysics and Technology demonstrations. There is also two charts presented at the end of these five sections, which give an idea of the various concepts, distributed across all these categories, that can be realized along with their scientific requirements.

Before explaining each of the missions individually, a graph, showing all the missions that have been mentioned in this report, has been plotted in Figure 1. The vertical axis has the number of satellites that are required to perform that particular mission. The horizontal axis has been split according to whether it can be performed using a single spacecraft or whether formation flying or constellations are required to perform the same. They have also been colour coded according to the mission class, i.e., into the five categories that were specified above.

Even though there are exceptions, it can be seen from Figure 1 that most of the existing missions are clustered towards the origin, i.e., they are missions which can mostly be done by single satellites. Thus there is a need for multiple satellite missions which can perform different missions or an existing mission more efficiently. Also, formation flying satellites have an advantage over constellations in many missions. Hence, most of our mission proposals have been aimed towards the formation flying region of the plot with 4-10 satellites.

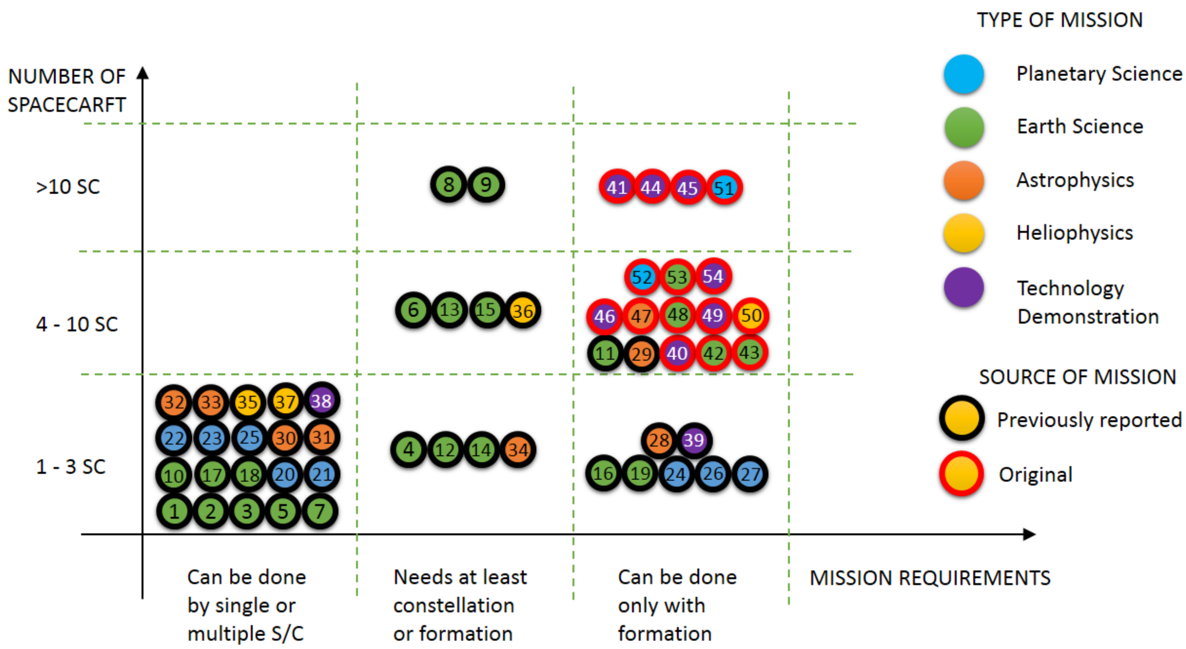

Figure 1: Mission Categorization

Key:

1 - CADRE (Section 2.1)
2 - EXOCUBE (Section 2.2)
3 - Earthquake prediction using Ionospheric monitoring (Section 2.3.1)
4 - Ionosphere reaction to storms (Section 2.3.2)
5 - Atmospheric Plasma Depletion to predict GPS outages (Section 2.3.3)
6 - Earth imaging (Section 2.4)
7 - Gamma rays of thunderstorms (Section 2.5)
8 - Space-based ocean monitoring (Section 2.6)
9 - Map of Earth's electric field (Section 2.7)
10 - Raman spectroscopy (Section 2.8)
11 - Magnetosphere sampling (Section 2.9)
12 - Australian multi-spectral imagery (Section 2.10)
13 - Earth geodesy and astronomy (Section 2.11)
14 - Atmospheric temperature and humidity sounding (Section 2.12)
15 - EDSN (Section 2.13)
16 - Bi-directional reflectance distribution function (Section 2.14)
17 - Orbital debris mitigation (Section 2.15)
18 - Collapsible space telescope (Section 2.16)
19 - Fourier transform spectrometer (Section 2.17)
20 - Mineral mapping of asteroids (Section 3.1)
21 - Solar system escape (Section 3.2)

22 - Radio quite lunar CubeSat (Section 3.3)
23 - Tracking asteroids (Section 3.4)
24 - AeroCube - 4 (Section 3.5)
25 - Asteroid Prospector (Section 3.6)
26 - Real time Geolocation (Section 3.7)
27 - NASA's GRAIL (Section 3.8)
28 - Pinpointing gamma ray bursts (Section 4.1)
29 - Interferometry and SAR (Section 4.2)
30 - Studying sub-dwarf stars (Section 4.3)
31 - Space based low frequency radio telescope (Section 4.4)
32 - PanelSAR (Section 4.5)
33 - Deployable mirror for enhanced imagery (Section 4.6)
34 - AAReST (Section 4.7)
35 - Colorado student space weather experiment (Section 5.1)
36 - Solar polar imager (Section 5.2)
37 - Earth-Sun Sunward-of-L1 solar monitor (Section 5.3)
38 - Testing tether deployment (Section 6.1)
39 - CanX-4&5 (Section 6.2)
40 - Division of labor in satellite (Section 7.1)
41 - Space Advertising (Section 7.2)
42 - Orbiting marker in space (Section 7.3)
43 - Graveyard orbit transfer service (Section 7.4)
44 - Optical communication mission (Section 7.5)
45 - Satellite service in maintenance and repair (Section 7.6)
46 - 3D printing in space (Section 7.7)
47 - Tracking gamma ray bursts (Section 7.8)
48 - Ionospheric tomography (Section 7.9)
49 - Inflatable De-orbit device (Section 7.10)
50 - Variable range coronograph (Section 7.11)
51 - Tracking asteroid belts (Section 7.12)
52 - Sun Energy collector (Section 7.13)
53 - Space wake studies Section 7.14)
54 - Open source CubeSat testbed Section 7.15)

2 Earth Science Missions

2.1 CubeSat investigating Atmospheric Density Response to Extreme driving (CADRE)

This project's main instrument is a 3-Unit (3U) CubeSat which is named as CubeSat investigating Atmospheric Density Response to Extreme driving (CADRE). The major issue investigated is related to ion-neutral coupling, which includes neutral wind morphology and dynamics which are very important for understanding how the thermosphere reacts to energy input and the role this plays in magnetosphere-ionosphere coupling. This is currently being carried out by Aaron Ridley at University of Michigan. The link to the NSF award.

2.2 Collaborative Research: CubeSat–Composition Variations in the Exosphere, Thermosphere, and Topside Ionosphere (EXOCUBE)

This project measures the densities of all significant neutral and ionized species in the upper atmosphere on a global scale. It is a 3U CubeSat. The main objective of this project is to provide the first in-situ global neutral density data in more than 25 years, which includes using the mass spectrometer technique to directly measure hydrogen densities. This missions also provides observational constraints for physical models of the upper atmosphere. Also, newly developed experimental techniques which are used to obtain neutral and ionized composition and densities from radar and optical observations can be tested and validated using the measurements from this mission. This is currently being done by John Noto at Scientific Solutions Incorporated. The link to the NSF award.

2.3 Ionosphere Monitoring (Concept)

2.3.1 Predicting Earthquakes through Ionosphere Monitoring

Early earthquake detection could help one third of the world's population. Precursors to the earthquake can be detected through variations in the ionosphere. The proposed satellite will have a RAS topside sounder and be used to monitor the areas of the Earth that have high seismic activity to predict earthquakes and prove that the prediction method is valid and accurate. The data could also help to improve GPS navigation models and study the reaction of the ionosphere to magnetic events. The formation may help to mitigate measurement errors [3]. A similar mission is scheduled to be launched by the Chinese Space Agency in 2014, though that one is not a formation[4].

2.3.2 Studying the Reaction of the Ionosphere to Storms

Magnetic storms can cause changes and bulges in the ionosphere. Understanding these bulges can help us to understand the magnetic storm that causes them as well. The DICE mission has studied this using 2 satellites equipped with langmuir and electric field probes to measure the plasma density and field strength [5, 6]. The ionospheric measurements can also track thunderstorms and cyclones if positioned near the oxygen absorption line (~500 km) at a near-equatorial orbit using a microwave spectrometer. [7]

2.3.3 Monitoring Atmospheric Plasma Depletion to Predict Outages in GPS and Communications

Depletion in ionospheric plasma can disrupt signal transferrance, and little is known about the depletion zones. The formation would study how the depletions change and propagate so that scientists can create a model and further their understanding of the phenomenon. The satellites would be in 360 km orbits at an inclination of 52 degrees [8][9]. These measurements can also help to show the interactions between the thermosphere and ionosphere [10].

2.4 Earth Imaging for Science Applications in Emerging Countries

A satellite imaging cluster would give less advanced parts of the world access to scientific data on things like resource consumption, pollution, and climate. The formation could do the imaging with each satellite operating a different camera type. The placement can range from 400-720 km, but the effects of the high drag environment make control much more difficult[11] [12] [13][14][15]. For example, the Nigerian government is launching a satellite of this type to monitor environmental issues within the country, provide high volume mapping data, and highly accurate image targeting and geolocation[16].

2.5 Observing Gamma Rays Emitted by Thunderstorms

The satellites will look for gamma rays emitted by thunderstorms in visual and radio frequencies. NASA's Fermi telescope has observed the phenomenon, but some more analysis of this phenomenon can help NASA and this analysis happen in conjunction with the GRB monitoring.[17] [18]

2.6 Space-Based Ocean Monitoring

The health of Earth's bodies of water can be monitored through multi-spectral imaging with high spatial and temporal resolution. This will help scientists to better understand the effects of tides on ocean color, as well as the evolution of ecosystems. One study proposes using 115 nanosats for global coverage, but this is extremely ambitious, the formation would be much much smaller. [19].

2.7 Completing the Map of the Earth's Electric Field

This project would use a system of small satellites to observe the Earth's electric field with radar measurements. A proposed project uses a constellation of 48 satellites. [20]. However, unless we want to create a 3D map this mission is not appropriate as it is designed for a constellation rather than for a formation. It would appear that other systems already make these measurements, but there are still areas of poor coverage that could be addressed [21].

2.8 Raman Spectroscopy to investigate the atmosphere

Create a more in-depth model of the upper atmosphere using Raman Spectroscopy from multiple sources in a formation to achieve a 3D (or at least more comprehensive) map of planetary mineral and chemical abundances. The same technique could be used to study other planets as well [22]. The main obstacle in this mission would be finding a detector array that would fit in our size constraints.

2.9 Formation Flying to Sample Volume of Magnetosphere

Use a formation of CubeSats to create a more detailed 3D model of the magnetosphere, adding detailed dynamic measurements. However, NASA launched twin satellites in Fall 2012 which perform a similar mission. Also several earlier missions have achieved similar results without using formations[23]. Hence the need for a formation is not established here. In one proposed mission, a master satellite ejects several picosats which take 2-axis magnetometer data and relay it to the master. Relative position and attitude control are not necessary as long as the positions and attitudes can be discerned.[24]

2.10 Satisfying Australia's Future Need for Multi-Spectral Imagery

Geosciences Australia studied the need for satellite images of the Australian geography. As a result, the company created a document titled "Continuity of Earth Observation Data for Australia - Operational Requirements to 2015 for Lands, Coasts and Oceans." which contains their conclusions. The most relevant idea is that there is a need to image the Australian landmass daily which will not be covered with the launch of the newest public satellites. To satisfy the imaging requirements of Australia the paper proposes a 6U CubeSat with commercial software to help the bigger satellites and obtain medium spatial resolution and high temporal resolution. [25]

2.11 Small Satellite Constellations for Earth Geodesy and Aeronomy(Concept)

Drag-free nanosatellites consist of an external shielding that contains a free-floating mass. By measuring the movement of the free-floating mass with respect to the shielding, this satellites are able to precisely compute the drag and therefore determine their orbital position with more accuracy. Consequently, this kind of satellites can improve the accuracy and sensitivity of the aeronomy and geodesy measurements, specially if they cooperate with other satellites to make those measurements. This characteristic can be used to map the Earth's mass distribution with high precision, compute high-order harmonics or even try to detect gravitational waves.[26]

2.12 A 6U CubeSat Constellation for Atmospheric Temperature and Humidity Sounding

This paper describes the development and implementation of a 118 GHz temperature sensor and a 183 GHz humidity sensor which are suitable for a 6U CubeSat. In addition, the appropriate design of a 10 cm antenna provides a sufficient footprint of approximately 25 km. The paper takes advantage of the technology developed for the High Altitude Microwave Scanning Radiometer (HAMSR) by JPL. [27]

2.13 Simultaneous Multi-Point Space Weather Measurements using the Low Cost EDSN CubeSat Constellation

The Edison Demonstration of Smallsat Networks (EDSN) mission consists of eight CubeSats that will be launched to a low-Earth orbit. These CubeSats are intended to monitor spatial and temporal variations in the radiation levels by cooperating in loose formation at approximately 500 km above the Earth's surface. This will allow a better understanding of the space weather that could lead to an improvement of the current space weather models. EDSN mission will carry the Energetic Particle Integrating Space Environment Monitor (EPISEM) that will determine the radiation environment by taking measurements over a dispersed area of energetic charged particles. The expected launch date for this mission is late 2013 as a secondary payload on a DoD mission.[28][29]

2.14 Design of Nano-satellite Cluster Formations for Bi-Directional Reflectance Distribution Function (BRDF) Estimations

The Bidirectional Reflectance Distribution Function (BRDF) evaluates the variation of reflectivity in terms of direction and spectrum over the surface of the Earth. This function is essential to determine various parameters such as albedo which is currently estimated using a wide 3D angular range of illumination and direction sensors in the visible and near infrared wavelengths. This paper proposes a nano-satellite cluster to improve the computation of BRDF. The project is presented as an additional help for current BRDF systems.[30]

2.15 Design and Analysis of a Nanosatellite Platform for Orbital Debris Mitigation through Launch of Space Tether in Low Earth Orbits

This paper proposes a nano-satellite platform, with commercial of the shelf components, to tether space debris by instantly solving Lambert's problem. The nano-satellite platform will contain a tether launching system with two Terminator Tape tethers built by the company Tethers Unlimited. Space debris will be spotted by the nano-satellite in cooperation with the ground stations. Once the space debris is targeted, the nano-satellite will predict the trajectory of the debris and perform the proper launching maneuvers, determined from by solving the Lambert's problem, for the Terminator Tape to grab the space debris.[31]

2.16 Collapsible Space Telescope (CST) for Nanosatellite Imaging and Observation

A low-cost collapsible Cassegrain telescope that can fit in a 4U portion of a 6U CubeSat is being developed by NASA Ames Research Center. The intention of this mission is to obtain high-resolution imaging of Earth and space observations when coupled with an appropriate imaging sensor. The implementation of this kind of telescope in a small satellite sets the path to swarm missions with distributed apertures.[32]

2.17 FTS CubeSat Constellation Providing 3D Winds

This paper describes the technological and scientific developments required for the implementation of a Fourier Transform Spectrometer (FTS) instrument. The FTS is intended to fit in a 6U CubeSat and would allow more precise tropospheric wind forecasts from space. To achieve that goal, the mission requires flight formation so the CubeSats know the inter-satellite distance and cooperate to provide measurements in different layers of the atmosphere. The measurements taken then can be overlapped to create 3D profiles of the atmospheric wind. This would mean a great improvement in current weather models and will allow longer-term weather forecasts. [33]

3 Planetary Science Missions

3.1 Mineral Mapping of Asteroids (Concept)

The proposed mission overview is a single 6U CubeSat launched on a GEO satellite or Mars-bound mission as a secondary payload. There is a solar sail to reach near Earth asteroids. The proposed science objectives is to map surface composition of 3 asteroids at 1-20 m spatial resolution.

Required instrumentation: spatial IFOV of 0.5 mrad, spatial sampling 0.5 m -10 m depending on the encounter range, Spectral sampling 10 nm, Imaging Spectrometer, 0.4 – 1.7 μm. This could perhaps extend to a 2.5 μm w/ HOT-BIRD or other advanced detector and achievable cooling. Link to presentation given by Robert Staehle

3.2 Solar system escape (Concept)

The plan is to use a large area, low mass spacecraft for a high speed trajectory with a low perihelion which would explore the interplanetary environment, heliosheath and perhaps heliopause. It is also aimed to test communications, power, pointing and miniaturized instrument technologies. Link to presentation given by Robert Staehle

The required instrumentation include instruments that measure plasma, solar wind, energetic particles and cosmic rays, a magnetometer and cameras to observe sail interaction with environment.

3.3 Radio Quiet Lunar CubeSat (Concept)

The aim is to assess radio quiet volume in shielded zone behind the Moon for future 21 cm cosmology missions. The proposed science mission is to find the usable volume behind the Moon for high sensitivity 21 cm cosmology observations which determines utility of lunar surface vs. orbiting missions. Link to presentation given by Robert Staehle

3.4 Tracking Asteroids and Satellite Debris

A formation of satellites would search for Earth-approaching asteroids and potentially hazardous debris satellites using a small imaging telescope [34]. One study suggests an orbit of 6000-40000 km [35]. Similarly, space debris of 1-10 cm is difficult to track using current methods and can be very dangerous to things like solar arrays and radiators [36]. One study suggests the use of optical and radar telescopes to track the small debris [37].

3.5 Operations, Orbit Determination, and Formation Control of the AeroCube-4 CubeSats

Aerospace Corporation built three AeroCube-4 satellites which were launched in 2012. Each of these satellites was able to estimate its position with 20m of accuracy by means of a GPS receiver installed in each spacecraft. In addition, each satellite was equipped with extendable wings that allowed variations in the cross-sectional area of the spacecraft. These two features, the high precision orbital positioning and the variable wings, allowed the measurement of the deliberate changes in the drag profile caused by the different configurations of the wing. The purpose of the project was to achieved formation flight via wing manipulation and indeed the team succeeded reordering the satellites over the course of several weeks.[38]

3.6 Asteroid Prospector

This mission contains the design of a small reusable spacecraft that is able to go to asteroids from LEO as long as they are closer than 1.3 AU from the sun. The study includes details on the several new technologies that are needed to make this mission possible such as: a 3 cm ion engine from Busek, the autonomous optical navigation system, the precision miniature reaction wheels, and high performance green propellant and Honeywell's new Dependable Multiprocessor.[39]

3.7 Real-Time Geolocation with a Satellite Formation

This study demonstrates that a group of two or three satellites in LEO is able to accurately position a source of electromagnetic pulses on the surface of the Earth. The position of the emitting source is computed using time differences of arriving signals. The study also talks about how this could be beneficial for other missions such as the Mars rover or a busy constellation of positioning satellites.[40]

3.8 NASA's GRAIL Spacecraft Formation Flight, End of Mission Results, and Small-Satellite Applications

This mission, the Gravity Recovery and Interior Laboratory (GRAIL), consists of two identical spacecraft designed to map the variations of the gravitational field of the Moon. To do so, it is of great importance that the spacecrafts measure the distance in between with high accuracy and also orbit in the same orbital plane and height over the Moon's surface.[41]

4 Astrophysical Missions

4.1 Pinpointing the Source of Gamma Ray Bursts (Concept)

The formation could be used to source GRBs through precise triangulation. If researchers could receive the measurements of inter-satellite distance and GRB incident time accurately enough, they could potentially increase the accuracy of GRB detection and positioning. [42]. This has since been proven unnecessary, there are sufficient satellites in orbit to do this, through the use of gamma ray detectors and UV detectors. The UV detectors can do the positioning that would have required a formation with only gamma ray detectors.

4.2 Interferometry and Synthetic Aperture Radar Formation Flying

A formation of >2 CubeSats will work together to create a digital terrain model or study surface deformation. A cross-track pendulum formation is easier to isolate the crosstrack and along-track components. A cartwheel formation, however, reduces the height errors [43]. The application is widely studied for formations.

4.3 Studying Sub-dwarf Stars Using a Small Telescope

A satellite-bourne telescope would be used to study distant sub-dwarf stars, to set the lower limit on the age of "metal-poor sub-dwarf" stars to help establish an age for the universe. The attitude control system would need to be accurate to within 30 arc-seconds [44]. Another possible mission would be imaging star fields [45]. To make the formation relevant, each satellite would need a different type of instrument to further the science.

4.4 Astronomical Antenna for a Space Based Low Frequency Radio Telescope

A great atmospheric interference occurs for low radio frequencies, specially bellow 30 MHz. For that reason low frequency radio telescopes are not feasible on the surface of the Earth. Therefore the only way to collect reliable data in that frequency is by placing the instruments in space. The Orbiting Low Frequency Antennas for Radio Astronomy (OLFAR) consists of a swarm of nano-satellites, each of them with three dipoles that satisfy the space restrictions in cubesats, intended to build a low-frequency distributed radio telescope in space. This paper describes the design, simulations, testing and measurements of a scale model of the system. [46]

4.5 PanelSAR: A Smallsat Radar Instrument

PanelSAR describes a solution to implement a low-cost and low power consuming synthetic aperture radar in a small satellite. The study states that a low power SAR, which has already been proved in aircraft, and several other features of the system, such as modularity, reliability and low mass are key to reach a low cost solution.[47]

4.6 Deployable Mirror for Enhanced Imagery Suitable for Small Satellite Applications

Small satellite volume restrictions are a clear drawback for large aperture monolithic mirrors for telescopes. Consequently, high spatial resolution can not be achieved with a single mirror. One solution to this problem is the development of deployable optical systems that could surpass the performance of monolithic mirrors and greatly improve the capabilities of small satellites. A passively aligned deployable mirror is under development by the Space Dynamics Laboratory (SDL) and they have built one of the "petals" that conform the deployable mirror. The spectrum they are interested in varies from short wave infrared to long wave infrared due to the image quality obtained.[48]

4.7 Autonomous Assembly of a Reconfigurable Space Telescope (AAReST) – A CubeSat/Microsatellite Based Technology Demonstrator

This study has been reported here because it remarks the disadvantages of formation flying satellites and proposes an alternative to formation flight, namely autonomous assembly. The paper states that autonomous assembly is cheaper and more efficient when building space telescopes with large apertures. In addition, the study claims that it is difficult to maintain a stable alignment among spacecrafts in flight formation. The mission developed in the study contains two 3U cubesats, each of them would operate an electrically actuated adaptive mirror. In addition, there would be a central 9U cubesat core, housing two fixed mirror, where the 3U cubesats could dock and un-dock.[49]

5 Heliophysical Missions

5.1 Colorado Student Space Weather Experiment

This is a three-year multi-disciplinary team effort and the aim is to and operate a CubeSat. This 3U Cubesat carries an energetic particle sensor which will address fundamental space weather science questions regarding topics like relationship between solar flares, energetic particles and geomagnetic storms in the near Earth space environment. The particle instrument is the Relativistic Electron and Proton Telescope integrated little experiment (REPTile). REPTile is designed to measure directional differential flux of energetic protons, 10-40 MeV, and electrons, 0.5 to $>$ 3 MeV. The major science objectives of this project are to investigate the relationships between solar energetic particles, flares, and coronal mass ejections, and also to characterize the variations of the Earth's radiation belt electrons. This is currently being carried out by Xinlin Li at University of Colorado at Boulder. The link to the NSF award.

5.2 Solar Polar Imager CubeSat Constellation (Concept)

This mission is a concept of 6 spacecraft in a constellation of highly inclined orbits. They would be in an out-of-ecliptic vertical orbit. They will use solar sails to reach high inclination. The proposed science missions are include Helioseismology and studying the magnetic fields of polar regions, polar view of corona, coronal mass ejections, solar radiance and also to link high latitude solar wind & energetic particles to coronal sources. Link to presentation given by Robert Staehle

The required instrumentation of the 6 satellites are:

- S/C1: Plasma + Mag Field
- S/C2: Energetic Particles + Mag Field
- S/C3: Cosmic Rays,
- S/C4: Magnetograph/Doppler Imager
- S/C5: EUV Imager
- S/C6: Coronagraph

5.3 Earth-Sun Sunward-of-L1 Solar Monitor (Concept)

The aim of this concept is to measure strong coronal mass ejections or other space weather from Sunward-of-L1 position to provide additional warning time to Earth. The science objective is to obtain plasma and magnetometer readings of solar wind from sunward-of-L1 position and to compare with L1 values from ACE or follow-on. Link to presentation given by Robert Staehle

6 Technology Demonstrations

6.1 Testing Satellite Tether Deployment and Operations

Satellite tethers can be used to create artificial gravity to aide in long term human missions by tethering a crew module to an object of equal mass and rotating the system. These systems need to be tested before they can be used for such operations. [50][51]

6.2 The CanX-4&5 Formation Flying Mission: A Technology Pathfinder for Nanosatellite Constellations

Accuracy and miniaturization of propulsion systems, attitude determination sensors, control systems, inter-satellite communication systems and relative position sensors is one of the key aspects for future small satellite missions. The two spacecrafts Can X-4&5 have been designed as a technology demonstrator of these capabilities as independent spacecraft but also to cooperate in flight formation. Both spacecraft will have access to the state vector of the other spacecraft wirelessly. In addition, the pair of small satellites has been equipped with a sub-meter relative position control, a centimeter-accuracy relative position determination, a GPS receiver, an on board computer and an inter-satellite communication system.[52]

Two charts have been given below (Figure 2 and 3) which show the various mission concepts that are possible in all the fields that have been mentioned above along with the science requirements that are required for each of these missions.

Mission Concepts

SCIENCE AREA	SINGLE CUBESAT	FEW CUBESATS	~20 CUBESATS	~100 CUBESATS	>> 100 CUBESATS
Dark Ages	DARE follow-on (lunar orbit)	DARE extension? (lunar orbits)	N/A	N/A	Tomography
EoR	Probably will be done from ground				
Extragalactic	N/A	N/A	Image individual strong sources	All-sky mapping	Deep, high dynamic range imaging
Galactic	Integrated spectra (RAE 2 done properly)	N/A	Image individual strong sources	All-sky mapping	Deep, high dynamic range imaging
Exoplanets	N/A	N/A	Initial LF searches	Deeper searches	Useful upper limits
Interplanetary Magnetic Fields	L4, L5 beacons for Faraday rotation	In-situ (sunward of L2 w/solar sails)	Faraday rot. with S/C along Earth orbit	High-res. Faraday rot. tomography	In-situ throughout inner heliosphere
Solar system Objects	Giant planet burst spectra (lunar orbit)	Giant planet source sizes (lunar orbit)	Localization & size of giant planet bursts	Imaging & det. of weak bursts	High quality imaging of solar system
Solar bursts	Solar AKR analog??	Type II trajectories?	CME shock tracking	Source morphology	Fainter & farther imaging & tracking
Discovery	Ant. Directivity modulation	Lunar ionosphere (via absorption)	Strong transients	Var. sources	???

Figure 2: Mission concepts for multiple agent systems in all fields (source: Presentation by Dayton Jones)

Science Requirements

SCIENCE AREA	FREQ RANGE	NO. OF ANTENNAS	ANG. RESOLUTION
• **Cosmology**			
– Integrated EoR, Dark Ages spectral signals	50-150, 20-50 MHz	1 or more	> steradian
– EoR power spectrum	50-150 MHz	> 1000	2 arcmin to ~ 2 degrees
– Dark Ages power spectrum	20-50 MHz	> 10,000	2-20 arcmin
– EoR tomography	50-150 MHz	> 100,000	1-10 arcmin
• **Extragalactic**			
– Fossil radio lobes, AGN duty cycles	~ 10 MHz	~ 300	1 arcmin
• **Galactic**			
– SNR as sites of cosmic ray acceleration	3-30 MHz	> 10,000	< arcmin
– Map emissivity of interstellar medium	1-30 MHz	~ 100	< 1 arcmin
– Extrasolar planets	1-30 MHz	~ 10,000	< 1 arcmin
• **Transient Sources**			
– Fast transients & pulsars (<< 1 second)	> 100 MHz	~ 100	Arcmin
– Slow transients, ISS (> 1 second)	10-100 MHz	> 100	Arcmin
• **UHE Particles**			
– Radio bursts from Moon	~ 10 MHz	1-100	Degrees
– Radio bursts from terrestrial atmosphere, ice caps	~ 10 MHz	10-100	Degrees
• **Solar System**			
– Jupiter, Saturn LF emission	< 10 MHz	~ 10	Arcmin
– Interplanetary turbulence	1-30 MHz	~ 1000	Arcmin
• **Heliophysics**			
– Track type II & type III bursts	0.1-30 MHz	~ 10-50	Degrees
– Map interplanetary magnetic field lines	0.1-30 MHz	~ 10-50	Degrees
• **Earth**			
– Image magnetosphere response to CMEs	0.1-1 MHz	> 10	Degrees
– Auroral Kilometric Radiation	0.1-0.5 MHz	~ 10	Degrees

Figure 3: Science Requirements for above missions(source: Presentation by Dayton Jones)

7 Our Mission Proposals

7.1 Division of Labor in Satellite

Every year we throw away satellites because they become worn out. But usually it's only one of the component that causes the problem. The other components work fine but is needlessly thrown away. This makes satellites as one of the major contributors to the build up of space debris. DARPA's Pheonix satellite re-servicing mission addresses these issues and tries to utilize functioning part of the satellites. But instead of trying clean up what has already happened (like re-using parts of defunct satellites), we propose a mission to reduce problems in the future. The idea is to apply division of labor. Instead of a one big satellite containing all the components, smaller satellites carrying one or two parts could fly in a constellation to represent a system as a whole. Some benefits are listed below:

Expandable: If more computing power is needed, a CubeSat carrying another CPU could join the constellation.

Customizable: Camera carrying CubeSat could be replaced with a CubeSat with different type of sensor. If there is free space in terms of data transfer or processing power, same or different company could send in just the sensor unit to collect data.

Reconfigurable: Working parts could be re-used for different missions.

Green: Creates less space waste.

7.2 Satellite Advertising

If CubeSats could carry reflective surface or an LED to make itself visible from earth, tightly controlled formation flying CubeSats could spell out a word or even form a display screen in great numbers. Indeed, it would be most likely only visible with the help of a telescope but just the existence of space ad would have great impact on the media. Along with star viewing, it would become "the thing" to look at. Depending on visible areas at that time, different advertisements could be displayed.

7.3 Orbiting Marker in Space

Controlled formation flying satellites could serve as a marker for vision based navigations. Multiple orbiting markers on some other planet could allow better pose estimation than existing star trackers.

7.4 Graveyard Orbit Transfer Service Formation Flying Proposal

7.4.1 Summary

At the end of a satellite's service life, a satellite standard exists for the disposal of a spacecraft. For a geosynchronous spacecraft, it is typical to deposit the satellite in an orbit with a perigee altitude above 36,100 km [53]. This orbit is chosen due to the small ΔV required to move a spacecraft into the orbit (approximately 7.4 meters per second) and the tendency for the spacecraft to not return to an orbit used by operating spacecraft [54]. Recently however, only about one-third of GEO satellite that have reached the end of their life time have successfully achieved a so called "graveyard orbit" [55]. The proposed formation flying spacecraft system seeks to increase the percent of spacecraft that successfully maneuver to a "graveyard orbit" in a cost effective manner.

7.4.2 Concept of Operations

As a proposed disposal method, consider a satellite in geosynchronous orbit that has just reached the end of its operational life time and cannot move to a graveyard orbit. A formation of CubeSat satellites (used for their extreme cost effectiveness) form together, dock with the dead spacecraft, and fire thrusters to move the dead spacecraft to a graveyard orbit. Because it is difficult to know ahead of time which spacecraft will successfully move themselves to a graveyard orbit and which will not, formation flight is essential to create re-configurable solutions for the many spacecraft that may or may not fail. There will be multiple types of 1U, 2U, and 3U CubeSats. Some CubeSats will serve as attitude and position controllers for the formation once formed together. Others will serve as major thrusters to move the dead satellite out of the geosynchronous orbit. Finally, the remaining CubeSats will act as fuel tanks for the system.

7.4.3 Proof of Concept CubeSat Mission

As a proof of concept, a 6U CubeSat could be launched along with three 1U CubeSats. The 6U CubeSat will act as a dead satellite. One of the 1U satellites will serve as a thruster, another as a fuel tank, and the final one as a controller of the formation. The controller will work to form a solution out of the three 1U CubeSats. The re-configured spacecraft will then dock with the 6U spacecraft and move it to a different orbit.

7.5 Optical Communication Mission

7.5.1 Summary

In the late 1970s, work began on an optical communications technology that could provide orders of magnitude more data transferred from deep space missions than was possible with conventional radio frequency techniques [56]. Major challenges for such a deep space system include the acquisition, tracking, and pointing for sub-micro-radian accuracy, the use of efficient lasers with moderate power and high modulation rates, and the use of fine-pointing mirrors [57]. The atmosphere of Earth, additionally, acts as a major obstacle for an optical communications system. Even on a clear day, the atmosphere can significantly attenuate an optical signal. Thus, an optical deep space network will require many more ground stations than the current deep space network. A recent study by Northrop Grumman concluded that even if six ground sites (double the size of the current deep space network) were selected, the array would only be operable 83% of the time [58]. Leveraging a formation satellite system in a deep space optical communications network can realistically solve several open problems in optical communication literature and could alleviate major pointing constraints that would be placed on future spacecraft missions if the optical deep space network were constructed.

A formation flying CubeSat mission offers a unique opportunity to demonstrate the technical viability of such a system. Such a mission, if pursued, would allow NASA to make significant progress towards goals laid out by the 2013 to 2022 Planetary Science Decadal Survey [59]. The Jet Propulsion Laboratory is currently conducting a systems engineering study of a base line deep space mission which could demonstrate optical communications technology [60]. Such a CubeSat mission could add significant value to such a demonstration. Figure 4 displays an overview of the concept of operations of such a deep space formation flight network.

7.5.2 Motivation

NASA, and in particular the Jet Propulsion Laboratory, has invested significantly in the use of optical communication technology in spacecraft. The scientific community has realized the potential of such a technology and in the 2013 to 2022 Planetary Science Decadal Survey claimed the technology "would be of major benefit for planetary exploration". The report also recommends demonstrating such a technology in flight over the next decade [59]. Due to its higher frequencies, optical communication technology is expected to enable the realistic use of synthetic aperture radar as well as other currently unusable remote sensing techniques in Mars and Saturn missions. The technology has an additional benefit of requiring smaller equipment of lower mass [61].

Major challenges with optical communication technology persists, however. Whereas the beam width of a radio signal from deep space may have a diameter on the order of a hundred times the Earth's diameter, optical signals would have a beam width approximately one-tenth the Earth's diameter [61]. Additionally, small Sun-Earth-Probe (SEP) and Sun-Probe-Earth (SPE) angles as

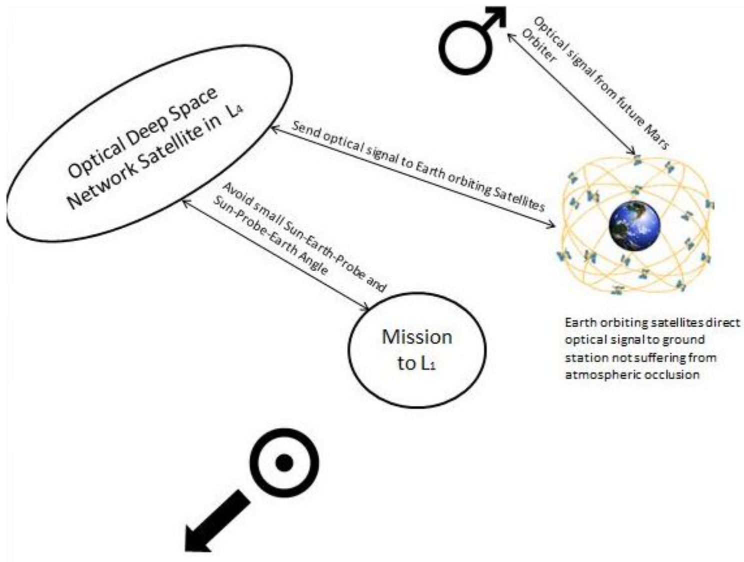

Figure 4: Mission Concept of Operations Overview

illustrated in Figure 5 can significantly saturate a signal [62]. Finally, weather on Earth can easily occlude an optical signal and a significant amount of research has been conducted to understand how weather attenuates a signal and how to properly predict the phenomenon [58] [63] [64] [65] [66] [67] [68]. A formation of spacecraft in Earth orbit and located at Lagrange points four and five can mitigate in the impact of the pointing, acquisition, and tracking problem on deep space satellites and can completely solve problems related to inclement Earth weather and small SEP and SPE angles.

7.5.3 Mission Concept of Operations

An initial concept of such a formation flight system include approximately 24 satellites in Earth orbit. This formation will serve two purposes. First, it will loosen the pointing requirements of a deep space satellite. This is the case, because, instead of using a signal with a beam width on the order of a tenth the diameter of the Earth to point to a small number of ground stations as weather permits, the signal beam can instead transmit to one of the formation satellites. Second, the formation can redirect a signal to a ground station anywhere on the planet. Thus, the impact of weather on the optical deep space network is significantly alleviated.

The second component of the formation flight system, is a set of satellites located in Lagrange points four and five. These spacecraft will allow deep space satellites experiencing small SEP and SPE angles to redirect their signal to these satellites, which, in turn, redirects the signal to the Earth orbiting formation. Thus, the SEP and SPE angle no longer will limit the operability of such a system.

7.5.4 Possible Proof of Concept CubeSat Missions

There are several possible CubeSat missions which could act as a proof of concept mission for the proposed formation flight system. A formation of five 3U CubeSats could be placed in medium

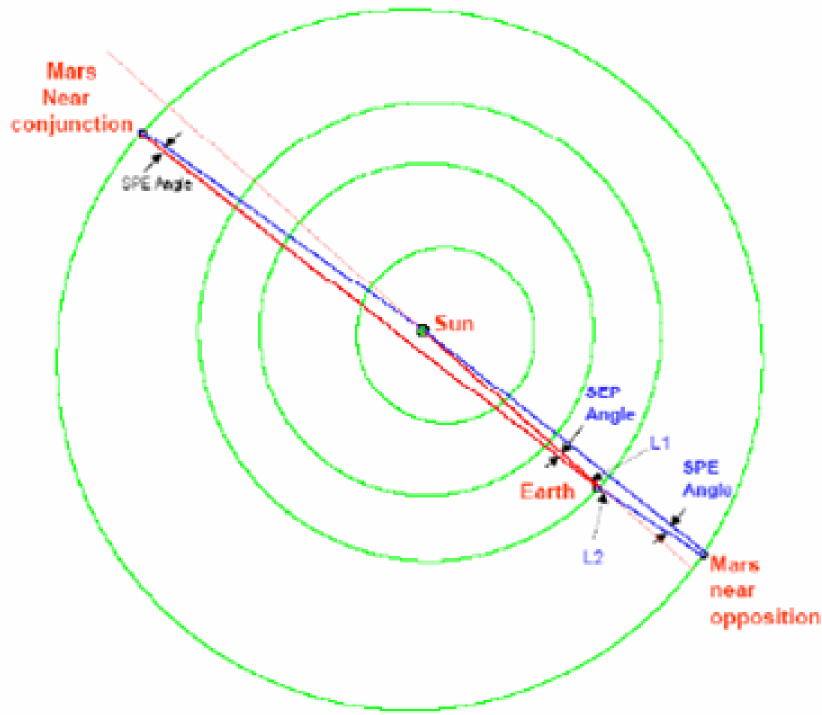

Figure 5: Sun-Earth-Probe and Sun-Probe-Earth Angles

Earth orbit. These CubeSats could be equipped with optical communication equipment developed by JPL's Optical Communication Group. One of the CubeSats could be designated as a "receiver." This receiver CubeSat would transmit optical signals to the ground or to other CubeSats. A distributed decision algorithm could then be used to direct the signal among the CubeSats to one of several ground stations.

An alternative mission could possibly involve collaborating with current work conducted by JPL on the development of a technology demonstration deep space mission. As part of the deep space mission, the JPL satellite would attempt to transmit optical signals to a formation of 3U CubeSats, which would then transmit optical signals to the ground using a distributed decision algorithm which would direct the signal among the CubeSats.

A final possible mission would be to send one CubeSat to Lagrange point one, a second to Lagrange point four or five, and place a formation of five 3U CubeSats in Earth orbit. Such a mission would demonstrate how a formation flying deep space optical network would solve the small SEP and SPE angle problem discussed in previous literature.

7.6 Fixed Satellite Service in Maintenance and Repair Industry

7.6.1 Summary

The commercial satellite industry is a large and relatively stable sector of the space industry providing services such as satellite television, radio, and broadband. These three applications alone are a $93.3 billion industry [69]. These satellites, meanwhile, are extremely costly for any corporation. A geosynchronous satellite such as the DirecTV-5, could very well cost in the neighborhood of $300 million [54]. The product line proposed in this paper, reduces the risk involved with such a system by offering a service to satellite service companies to purchase an attitude control insurance package. Thus, in the event of a failure in a satellite's attitude control system, the service would fix that satellite's system to ensure continued operation.

7.6.2 Motivation

To motivate the need for such a service for satellite operators, consider the satellite TV service company DirecTV. This company operates a fleet of satellites on missions greater than ten years. As of 2012, the company has insurance to cover the unamortized book value of a satellite in the event of a premature loss. However, the insurance does not cover the loss of revenue due to the loss of a satellite. Assuming a ten year mission, with a $300 million total mission cost and 17% profit margin. The loss of a satellite would on average cost the company $5.1 million in revenues every year [70]. Thus, the current proposal acts as an improvement on current insurance practices by not only insuring against the unamortized book value of a satellite, but also preventing the lost revenue the company would experience.

7.6.3 Concept of Operations

The improved satellite service solution would require a formation flight of many spacecraft. There would exist two kinds of spacecraft: a 1U satellite whose volume is dominated by a reaction wheel, torque rod, or control moment gyroscope (it will be assumed a reaction wheel is the chosen method of actuation) and a 2U satellite controller. The cubesat standard is used to capitalize on cost advantages. The 1U satellite will be passively stabilized to eliminate the need for any use of volume beyond a reaction wheel. The 2U satellite will contain all computing, thrusting, and other capabilities of a standard spacecraft. When a customer's satellite fails, the insurer would compute an optimal configuration by which attitude control could be regained. The passively controlled or position controlled formation would then reform into an attitude control solution and it would dock with the damaged spacecraft, which would then be repaired.

Technical challenges of such a project include optimal control of the formation, the customization of a solution for a broken spacecraft, and how the 2U satellite forms a solution for the broken spacecraft. Docking with the broken spacecraft and the subsequent control of the customer's spacecraft can also be a challenge.

To prove the cost model of this concept, consider DirecTV again. A $300 million satellite on a ten year mission has an 18% probability of experiencing failure due to the attitude control system. While failure is not equally likely throughout the ten years, failure before the end of year five is 11% [54]. Thus, such a service would be worth upwards of $27 million per satellite. Assuming a cost of $150,000 per 1U satellite, a cost of $300,000 per 2U satellite (each with a mass of 1 kg), and a launch cost of $3,409 per kilogram (on a Dnepr-1 rocket), launching a 100 kg formation would cost under $16 million. Assuming 25% of the formation is used by one satellite on average and the service charges $16 million for a 10 year policy, the company would make an average $1.2 million dollars a year per satellite. Now consider if the insurer contracted with DirecTV (12 satellites), EchoStar (22 satellites), SES S.A. (53 satellites), and INTELSAT (59 satellites). Such contracts would require 3650 satellites to be produced and an average yearly profit of $175.2 million could be anticipated.

7.6.4 Proof of Concept CubeSat Mission

For an initial proof of concept, a mission involving 5 CubSats is proposed. The first CubeSat is a 3U satellite such as ExoplanetSat shown in Figure 6. This 3U CubeSat will experience an attitude control failure during the mission. A 2U satellite will then create a solution from three 1U CubeSats. This solution will dock with the 3U CubeSat and provide attitude control. Additionally, inflatable structures could be placed on the 3U CubeSat so that its size is closer to a potential customer satellite.

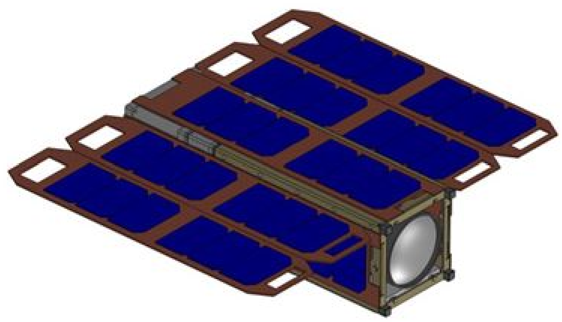

Figure 6: ExoPlanetSat [1]

7.7 3D Printing Replacement Parts For Dying Satellites

When satellites start to degrade or suffer from micrometeoriod impacts, replacement parts can revitalize a satellite that would otherwise need to be deorbited. Launching replacement parts can be expensive, in some cases more expensive than launching a new satellite. 3D printing new pieces for eligible satellites would reduce the upkeep costs of satellite constellations and potentially reduce the orbital debris.

3D printing technology for space (by Made In Space) is slated to be tested in orbit in 2014 and has already succeeded in parabolic flight tests. Limitations may exist as to size and placement of replacement part on the satellite, so it may be necessary to study a set of satellites with common buses, like TDRSS or GPS to assess what parts are possible to replace.

The satellite formation would have one or more satellites dedicated to printing and other satellites dedicated to removing and replacing the part on the broken satellite. The 3D printing could occur while the satellites travel to the orbit of the broken satellite. Formation flying would be necessary during the hand-off of the part and possibly also during the printing itself depending on the requirements of the printer.

7.8 Tracking Gamma Ray Bursts (GRBs)

A formation could be used to source GRBs through precise triangulation. With accurate measurements of inter-satellite distance and GRB incident time, the satellites could potentially increase the accuracy of GRB detection and positioning. [42]. This mission has since been proven unnecessary, because current satellites use gamma ray detectors and UV detectors together, with the UV detectors calculating the positioning. A formation of gamma ray detectors can still be useful to verify the measurements of current satellites like NASA's Fermi, or possibly to address gaps in coverage.

The gamma ray detector formation could also look for gamma rays emitted by thunderstorms. Fermi has observed the phenomenon, but it could possibly do with more study, to help Fermi differentiate between the real gamma ray signals and the thunderstorm generated gamma rays.[17] [18]

7.9 Tomography of the Ionosphere/Auroras

Depletion in ionospheric plasma can disrupt signal transferrance, and not much is known about the depletion zones. The formation would study how the depletions change and propagate so that scientists can create a model and further their understanding of the phenomenon. The satellites would be in a 360 km orbit at an inclination of 52 degrees [8][9]. These measurements can also help to show the interactions between the thermosphere and ionosphere [10].

Currently scientists studying auroras have to collapse their 3D models into two dimensions to verify them. The tomography created by the formation would allow the scientists to verify their models in 3 dimensions, much more accurately than the current process.

7.10 Inflatable De-Orbit Device

A formation of satellites could be used to test an inflatable, such as a de-orbiting device. Some of the satellites would not have inflatables to determine the difference between the satellites with de-orbiter and those without. The formation would not only test the inflatable deployment, but also the efficacy against standard orbit degradation.

7.11 Variable-Range Solar Coronography

Coronal mass ejections (CMEs) are a common phenomena in our Sun and they can have a significant impact in our daily life. CMEs release enormous amounts of plasma and energy into space inducing violent solar winds. If this wind reaches our planet it can alter the Earth's magnetosphere, cause remarkable aurora and malfunctioning in electrical distribution lines, interfere in our communications and even damage our satellites. For these reasons, the ability to predict and model the influence of CMEs on the Earth is of great importance. Therefore, several space missions are currently dealing with this issue, such as:

1. Solar and Heliospheric Observatory (SOHO): it is a monolithic spacecraft located at the first Lagrangian point (L1) and constantly facing the Sun. Among the various instruments that SOHO carries there are several that are dedicated exclusively to study the solar corona:

   (a) Large Angle and Spectrometric Coronagraph (LASCO) has become one of the most relevant instruments in SOHO. It consists of three different coronographs that focus their attention on a different area around the solar corona. Finally, the data and images collected from these three coronographs in three different nested regions around the Sun is blended to create a single image and data collection. In the following table there are several characteristics of these coronographs:

Coronagraph	Field of View (R_{sun})	Occulter	Spectral Bands	Objective -	Pixel Size
C1	1.1-3.0	Internal	Fabry-Perot	Mirror	5.6”
C2	1.5-6.0	External	BroadBand	Lens	11.4”
C3	3.7-30	External	BroadBand	Lens	56.0”

Table 1: LASCO Coronographs [2]

(b) Coronal Diagnostic Spectrometer (CDS) performs spectrometry of the atoms and ions in the solar corona and the transition region.

(c) Ultra Violet Coronagraph Spectrometer (UVCS) measures the spectrum characteristics of the highly ionized plasma in the solar corona, studying a region between 1.3 and 12 solar radii.

2. Solar Terrestrial Relations Observatory (STEREO) consists of two spacecraft that simultaneously take pictures of the solar corona from different positions in their orbit. Having two spacecraft looking at the same region has allowed this mission to create the first stereoscopic views of CMEs and other solar measurements.

The coronagraphs implemented in these missions have two main limitations. The first is that for a fixed distance between the occulter and the imaging sensor, the instrument is only capable of providing images of a finite region above the Sun's limb. Furthermore, if the instrument is focused on the study of the closest layers above the Sun's limb, the majority of the imaging element is shadowed by the occulting disk. The second limitation is the aperture due to size restrictions. Consequently, LASCO instrument includes three different coronographs with nested fields of view to create a full picture of the desired region around the Sun. Furthermore, LASCO is not able to provide stereoscopic images of CMEs, whereas STEREO does provide stereoscopic images, as it consists of two different spacecrafts, but only focuses on a certain region of the Sun's corona.

Formation flying satellites could mean a great leap in the study of the solar corona and CMEs. A range-variable stereoscopic coronagraph could be implemented with 4 formation flying satellites. Separating the occulter disk and the imaging element in two different spacecrafts will allow heliophysicists to focus their instrument on the desired area and even follow CMEs as they expand into space just by varying the distance between the spacecraft containing the occulter and the imaging element. Moreover, adding a pair of occulter and imaging spacecraft the mission will be able to provide stereoscopic images of CMEs. As we keep adding more spacecraft to the formation, the mission can either improve the stereoscopic data or enhance the field of view.

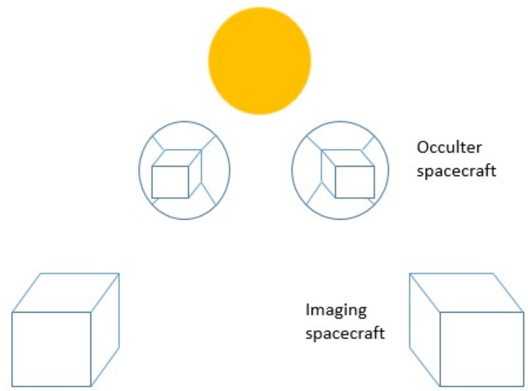

Figure 7: Range-variable stereoscopic coronagraph

To estimate the attitude requirements of this kind of mission, the following restrictions have been imposed. The occulter has to maintain a position in which the imaging sensor is never exposed to Sun's direct radiation. Therefore, the occulter shadows a circle equivalent to$1.05R_{sun}$±$0.025R_{sun}$. To do so, we propose a simplified system of 2 formation flying satellites with 3 DOF (d, θ, δ) represented in Figure 8

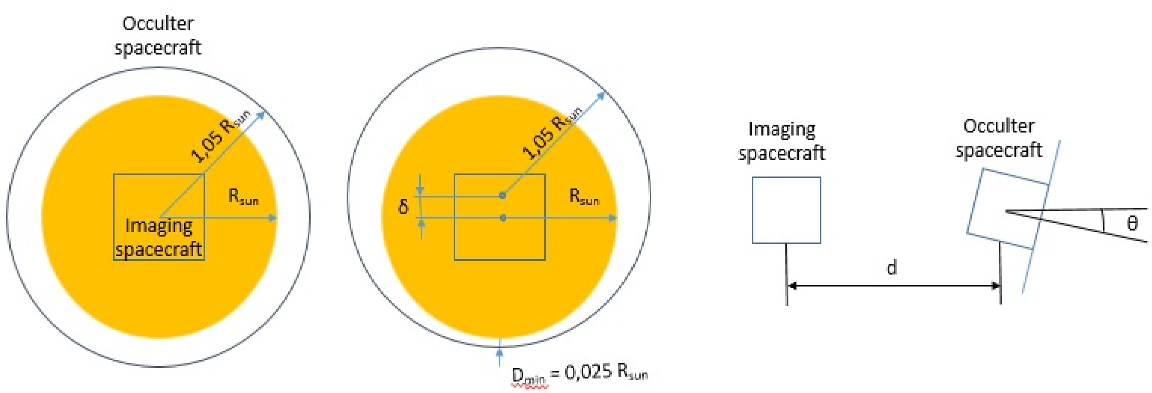

Figure 8: DOF for two Formation Flying Satellite Coronagraph

The following table contains an estimation of the attitude requirements for a formation of two CubeSats, assuming $\theta = 1^{\text{o}}$:

Radius of occulter (m)		0.243			0.487			0.974		
d_{max}(m)		50			100			200		
Δd(%)		±1	±0.1	±0.01	±1	±0.1	±0.01	±1	±0.1	±0.01
δ(m)	$\Delta\delta$(%)	$\Delta\theta$(º)								
0.1	±1	-	-	-	-	0.0022	0.0032	0.0133	0.0135	0.0135
	±0.1	-	0.0166	0.0194	0.0112	0.0207	0.0216	0.0225	0.0228	0.0228
	±0.01	-	0.203	0.0231	0.0131	0.0225	0.0235	0.0234	0.0237	0.0237
0.01	±1	0.0138	0.0191	0.0196	0.0138	0.0210	0.0217	0.0138	0.0219	0.0227
	±0.1	0.0175	0.0228	0.0233	0.0157	0.0228	0.0235	0.0147	0.0228	0.0236
	±0.01	0.0179	0.0232	0.0237	0.0158	0.0230	0.0237	0.0148	0.0229	0.0237
0.001	±1	0.0138	0.0228	0.0237	0.0138	0.0228	0.0237	0.0138	0.0228	0.0237
	±0.1	0.0138	0.0228	0.0237	0.0138	0.0228	0.0237	0.0138	0.0228	0.0237
	±0.01	0.0139	0.0228	0.0237	0.0138	0.0228	0.0237	0.0138	0.0228	0.0237

Table 2: Estimated requirements for two Formation Flight Satellite Coronagraph

In summary, the mission requirements obtained are achievable with current sensors and actuators available on the market. The proposed mission is feasible and could lead to a great improvement in the flexibility and data collection of heliophysics missions.

7.12 CubeSat landing swarm to track and model asteroid belts

An example of the current interest in the asteroid belt among the scientific community is the NASA's Dawn mission. This mission has already placed a spacecraft orbiting around the gigantic asteroid Vesta and now heading towards Ceres, where it is expected to unveil some of the interesting aspects of this body. Ceres is thought to be an icy dwarf planet capable of providing a reasonable explanation about the origin of water in Mars and Earth. Therefore, Ceres and some of the asteroids in this belt are quite interesting from an astrobiological point of view as they contain ice water. In addition, some asteroids have considerable amounts of metals and carbon compounds. Scientists believe that this region holds some important clues about the origin and evolution of the Solar System. Nevertheless the only outstanding mission to the asteroid belt indicates that there is still much work to be done to answer all the questions scientist ask now. For that reason, a swarm of CubeSats is a promising way to continue the exploration of the asteroid belt in an efficient and flexible way.

A swarm of CubeSats capable of landing on several asteroids has many profitable applications although initially flight formation will not be needed, the mission could be notably improved with the aided help of cooperating spacecrafts:

1. In an initial approach the CubeSats could provide accurate imaging and mapping of a wide variety of asteroids. After landing on the surface of the asteroid samples of them could be taken in order to study composition and origin.

2. The swarm of CubeSats spread all over the asteroid belt could be used to easily track smaller asteroids, improve the computational models of the asteroid belt and precisely estimate collisions or orbital variations of different asteroids.

3. These small satellites could be used to improve communications with more distant spacecraft and even create a network all around the asteroid belt. This will allow easy communications with spacecraft even though the Sun is in the way between the Earth and the spacecraft and therefore blocks the incoming and outgoing signals.

4. There has been much speculation about the industrialization of the asteroid belt and how this could supply materials and energy to missions in Mars or beyond. The swarm of CubeSats could set the foundation of this movement. Stackable CubeSats can lead to machine construction and consequently to the asteroid belt industrialization.

7.13 Sun Energy Collector

Harvesting energy has been and is still one of the critical aspects of a space mission. Some examples of this problem are:

1. The Mars Rover Opportunity, unable to perform its experiments on the slopes of mountains and sand dunes where the sun does not shine during the day. Hence, the mars rover has experienced important limitations in its operations due to energy restrictions.

2. Spacecraft traveling to the outer Solar System or even out of the Solar System require important amounts of energy for their propulsion systems in order to gain the needed velocity. Furthermore, the moons Europa and Enceladus, are thought to hide liquid water beneath their frozen surfaces and, therefore, have been classified as high priority for NASA and ESA. Consequently, there is an obvious need for cheaper sources of energy for interplanetary missions.

3. Satellites charge their batteries while exposed to the Sun's radiation. Then, when entering the night-side of a planet for a long period of time, satellites are sometimes forced to perform their science with low-power modes in order to save energy.

A group of formation flying satellites with deployable mirrors could be the solution for this scarcity of energy. The Sun is a constant and powerful source of energy in space. Accordingly, spacecraft and ground systems could benefit more from the Sun's energy than they are doing now. An orientable array of mirrors could be implemented in several spacecraft to provide energy to a wide range of missions:

1. Satellites in desperate need of energy could be rescued from thousands of kilometers away just by re-orienting the formation flying spacecraft. Or even better, critical satellites could be able to perform all their experiments during long periods in the dark side of a planet.

2. Vehicles and rovers on other planets or moons will have the ability to continue their research during the night and after long periods in shaded areas. For this, placing a group of formation flying satellites in orbit around the corresponding planet or moon will enable pointing a beam of light to those vehicles that require energy.

3. A beam of photons could be carefully pointed toward a solar sail to increase solar pressure and help the classical propulsion systems take the spacecraft to the outer Solar System. By this means, space agencies would be able to save millions of dollars in putting large quantities of combustible into space.

4. A group of formation flying satellites could be used as a test-bed to determine how light can be used to deviate a small asteroid from its trajectory.

7.14 Space Wake studies

The vacuum that has been generated by the best vacuum generators on ground have gone only go upto a particular level of purity. However, we can use the naturally available vacuum in space. The problem is that the vacuum available in LEO is not very pure. High purity vacuum can be obtained in higher orbits, but it is not feasible to reach those with CubeSats. This idea is that we can have a CubeSat with an inflatable disk-like structure, orbit around the earth in LEO. Studies show that this produces very highly pure vacuum in it's wake. We can have the other CubeSats follow in this wake to conduct any required experiments. Possible applications are: Understanding atmospheric density distribution, understanding wake patterns of satellites, producing highly pure materials etc. Formation flying is useful for this mission, it can be performed in LEO and 4-5 CubeSats might be ideal for it (depending on the application). A representational image has been shown in Figure 9.

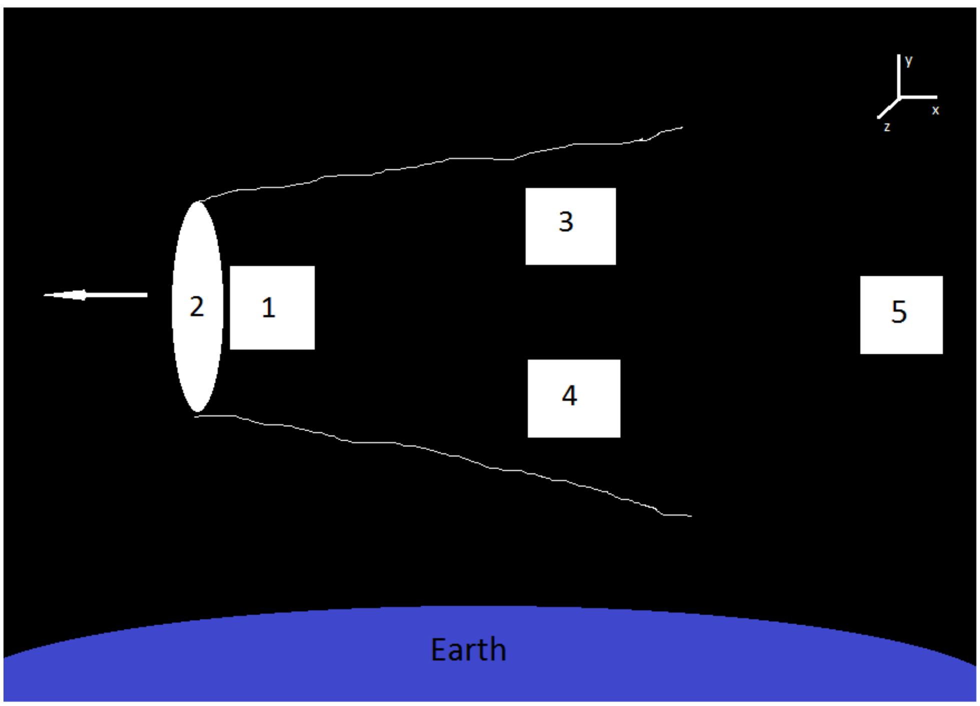

Figure 9: Space wake studies concept

The first or leader CubeSat in the above figure is denoted by 1. The oval denoted by 2 in the figure is the inflatable structure. The earth is shown below and the direction of motion is also indicated. CubeSats 3, 4 and 5 will follow in approximately that formation. The white line extending from the end of the inflatable structure is just a representation of the wake created (Note: This may not be how the wake actually looks). Each of the CubeSats will have a sensor in front of it which can measure the drag felt by it (I am not yet sure what this sensor would be). CubeSat 3 and 4 would feel less drag as they are in the immediate wake of the leader. CubeSat 5 would feel much more than 3 and 4 as it is farther away. Thus using the differential drag measurements of the leader and CubeSats 3 and 4, a density model of the atmosphere can be generated. A study on the how much drag is felt by CubeSat 5 while varying the distance between the leader and CubeSat 5 can also be done. We can also have additional CubeSats along the z axis using which we can measure the 3D variations.

7.15 Open source CubeSat Testbed

We can have a mission in which we launch a set of 4-5 CubeSats in LEO flying in a basic formation. The architecture of these CubeSats will be open to the public so that anyone can write code for it. The limitations and the capabilities of the CubeSats will be clearly listed and everyone would have to follow it. They can send us the code and we can then upload it to the CubeSats which will perform them in real time. This is like a tested for CubeSat algorithms. A lot of people now would have algorithms that they would like to test, but might not have access to satellites. This is again ideal for us as it's in LEO, 4-5 CubeSats will be sufficient and formation flying is essential. The second advantage of this is the additional source of funding which can be charged for people to test their code on our testbed. The third advantage is that it will just be a technology demonstration from our end without having to worry much about the physics or science behind the missions, thus allowing us to define the requirements. The problem is that, the lifetime of the testbed would be low as of now (1-2 months). However, it is a reasonable assumption that this would increase as new technologies are developed.

8 Actuators and Sensors

Listed in this part of the report is a set of sensors, actuators, and thrusters that could potentially be used on Cubesats from 1U to 3U. There is a wide range of sensors and actuators available for use depending on size, weight, and performance constraints. While thrusters currently on the market are generally of a lower technology readiness level than the available sensors on the market, there are still a range of options among available thrusters to choose based on size, weight, and performance constraints as well.

Additionally, there are several integrated attitude determination and attitude control products available on the market. These systems usually are quite compact and contain star trackers, sun sensors, and reaction wheels among other sensors and actuators. Finally, the end of this report presents a short list of general suppliers that can be considered in the future for sensor and actuator parts as well as parts for other systems on the cubesat.

8.1 Inertial Measurement Unit(IMU)

Most inertial measurement units (IMU) or inertial navigation systems (INS) include sensors for both position estimation and attitude estimation.

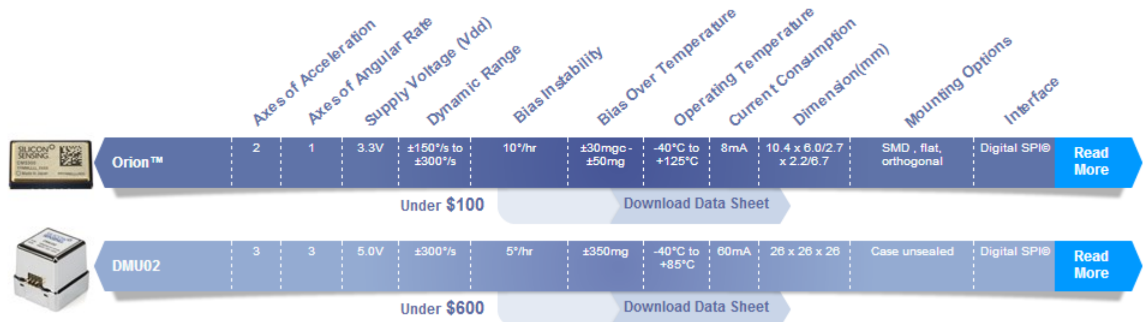

Figure 10: IMU's from Silicon Sensing (source: link)

MEMS Inertial Sensors

Accelerometers

Group	Part Number	Range (g)	Output Type	Sensing Axes	BW Typ (kHz)	Sensitivity	Noise ($mg/\sqrt{Hz}$)	Voltage Supply (V)	Supply Current (mA)	Temperature Range (°C)	Package	Additional Features
MEMS Accelerometers	ADXL103	±1.7, ±18	Analog	1	2.5	100 mV/*g* to 1000 mV/*g*	0.11	3.0 to 6.0	0.7	–40 to +125	5 mm × 5 mm × 2 mm LCC	Low noise, low tempco
	ADXL78	±35, ±50, ±70	Analog	1	0.4	27 mV/*g* to 55 mV/*g*	1.1	4.75 to 5.25	2.2	–40 to +105	5 mm × 5 mm × 2 mm LCC	
	ADXL001	±70, ±250, ±500	Analog	1	22	2.2 mV/*g* to 16 mV/*g*	3.3	3.135 to 6	2.5	–40 to +125	5 mm × 5 mm × 2 mm LCC	Ultrawide bandwidth
	ADXL203	±1.7, ±5, ±18	Analog	2	2.5	100 mV/*g* to 1000 mV/*g*	0.11	3.0 to 6.0	0.7	–40 to +125	5 mm × 5 mm × 2 mm LCC	Low noise, low tempco
	ADXL206	±5	Analog	2	2.5	312 mV/*g*	0.11	4.75 to 5.25	0.7	–40 to +175	13 mm × 8 mm × 2 mm SBDIP	Ultrahigh temperature
	ADXL278	±35, ±50, ±70	Analog	2	0.4	27 mV/*g* to 55 mV/*g*	1.1	4.75 to 5.25	2.2	–40 to +105	5 mm × 5 mm × 2 mm LCC	
	ADXL335	±3	Analog	3	1.6	300 mV/*g*	0.15	1.8 to 3.6	0.35	–40 to +85	4 mm × 4 mm × 1.45 mm LFCSP	
	ADXL326	±16	Analog	3	1.6	57 mV/*g*	0.3	1.8 to 3.6	0.35	–40 to +85	4 mm × 4 mm × 1.45 mm LFCSP	
	ADXL337	±3	Analog	3	1.6	300 mV/*g*	0.175	1.8 to 3.6	0.3	–40 to +85	3 mm × 3 mm × 1.45 mm LFCSP	
	ADXL325	±5	Analog	3	1.6	174 mV/*g*	0.25	1.8 to 3.6	0.35	–40 to +85	4 mm × 4 mm × 1.45 mm LFCSP	
	ADXL327	±2	Analog	3	1.6	440 mV/*g*	0.25	1.8 to 3.6	0.35	–40 to +85	4 mm × 4 mm × 1.45 mm LFCSP	
	ADXL377 ***New***	±200	Analog	3	1.6	6.5 mV/*g*	2.4	1.8 to 3.6	0.3	–40 to +85	3 mm × 3 mm × 1.45 mm LFCSP	3-axis, high-*g*
	ADXL350 ***New***	±1, ±2, ±4, ±8	Digital	3	1.6	2 m*g*/LSB	0.25	2.0 to 3.6	0.45 to 0.166	–40 to +85	3 mm × 4 mm × 1.2 mm LGA	Min/max tempco, low power, FIFO
	ADXL312	±1.5, ±3, ±6, ±12	Digital	3	1.6	2.9 m*g*/LSB	0.34	2.0 to 3.6	0.17	–40 to +105	5 mm × 5 mm × 1.45 mm LFCSP	
	ADXL345	±2, ±4, ±8, ±16	Digital	3	1.6	3.9 m*g*/LSB	0.52	2.0 to 3.6	0.03 to 0.14	–40 to +85	3 mm × 5 mm × 1 mm LGA	Low power, FIFO
	ADXL362 ***New***	±2, ±4, ±8	Digital	3	0.2	1 m*g*/LSB	0.18	1.6 to 3.5	0.002	–40 to +85	3 mm × 3.25 mm × 1.06 mm LGA	Ultralow power, deep FIFO, built in multiple sample activity/inactivity detection, external sync
	ADXL346	±2, ±4, ±8, ±16	Digital	3	1.6	3.9 m*g*/LSB	0.34	1.7 to 2.75	0.03 to 0.14	–40 to +85	3 mm × 3 mm × 1 mm LGA	Low power, FIFO
	ADXL213	±1.2	PWM	2	2.5	30%/*g*	0.16	3.0 to 6.0	0.7	–40 to +85	5 mm × 5 mm × 2 mm LCC	Low noise, low offset tempco, PWM output
	ADXL212	±2	PWM	2	0.5	12.5 %/*g*	0.5	3.0 to 5.25	0.7	–40 to +85	5 mm × 5 mm × 2 mm LCC	Low noise, low offset tempco, PWM output
iSensor® MEMS Accelerometer Subsystems	*Digital Accelerometers*											
	ADIS16003	1.7	SPI	2	5.5	—	0.11	5	1.5	–40 to +125	7 mm × 7 mm LGA	Internal temperature sensor
	ADIS16006	5	SPI	2	2.2	—	0.2	5	1.5	–40 to +125	7 mm × 7 mm LGA	Internal temperature sensor
	Inclinometers											
	ADIS16203	±1.7; ±180°	Digital	1	2.25	0.025°/LSB	—	3.3	11 (normal); 0.5 (sleep)	–40 to +125	9 mm × 9 mm LGA	Vertical mount, tilt and acceleration outputs, programmable alarms, digital filtering
	ADIS16209	±1.7; ±180°	Digital	2	0.05	0.025°/LSB	0.19	3.3	11 (normal); 0.14 (sleep)	–40 to +125	9 mm × 9 mm LGA	Dual-mode, high accuracy (0.1°) tilt and acceleration outputs, programmable alarms, digital filtering
	ADIS16201	±1.7; ±90°	Digital	2	2.25	0.1°/LSB	—	3.3	11 (normal); 0.5 (sleep)	–40 to +125	9 mm × 9 mm LGA	Tilt and acceleration outputs, programmable alarms, digital filtering
	ADIS16210	±1.7; ±180°	Digital	3	0.05	—	—	3.3	18 (normal); 0.23 (sleep)	–40 to +125	15 mm × 24 mm × 15 mm module	Tri-axis, single command frame alignment, programmable alarms, serial number and device ID
	Impact Sensors											
	ADIS16204	±70	Digital	2	0.4	8.407 m*g*/LSB	1.8	3.3	12 (normal); 0.15 (sleep)	–40 to +105	9 mm × 9 mm LGA	Programmable event recorder, peak sample/hold
	ADIS16240	±19	Digital	3	1.6	51.4 m*g*/LSB	0.48	3	1 (normal); 0.1 (sleep)	–40 to +85	12 mm × 12 mm BGA	Programmable event recorder, peak sample/hold
	Vibration Sensors											
	ADIS16228 ***New***	±18	Digital	3	5	0.3052 m*g*/LSB	0.248	3.3	40 (normal); 0.23 (sleep)	–40 to +125	15 mm × 24 mm × 15 mm module	Embedded FFT analysis, low noise, multiple capture modes, programmable windowing/filtering, serial number and device ID
	ADIS16223	±70	Digital	3	22	4.768 m*g*/LSB	3.3	3.3	43 (normal); 0.23 (sleep)	–40 to +125	15 mm × 15 mm × 15 mm module	
	ADIS16227	±70	Digital	3	22	1.192 m*g*/LSB	3.3	3.3	43 (normal); 0.23 (sleep)	–40 to +125	15 mm × 15 mm × 15 mm module	Embedded FFT analysis

Gyroscopes (continues on next page)

Group	Part Number	Range (°/sec)	Output Type	BW Typ (Hz)	In-Run Bias Stability (°/Hr)	Angle Random Walk ($°/\sqrt{Hr}$)	Linear Acceleration Effect(°/sec/*g*)	Sensitivity	Bias Tempco (°/sec/°C)	Sensitivity Tempco (ppm/°C)	Non-Linearity (% FS)	Voltage Supply (V)	Supply Current (mA)	Start-Up Time (ms)	Temperature Range (°C)	Package	Additional Features
MEMS Gyroscopes (All Single Axis)	ADXRS644	300	Analog	1000	9	0.6	0.015	9 mV/°/sec	—	—	0.1	6	3.5	50	–40 to +105	7 mm × 7 mm × 3 mm BGA	Vibration immune, min/max specs across temperature range, ultralow noise
	ADXRS646	300	Analog	1000	12	0.6	0.015	9 mV/°/sec	—	—	0.1	6	3.5	50	–40 to +105	7 mm × 7 mm × 3 mm BGA	Ultrahigh stability, vibration immune, min/max specs across temperature range, ultralow noise
	ADXRS642	250	Analog	2000	20	1.2	0.03	7 mV/°/sec	0.02	308	0.01	4.75 to 5.25	3.5	50	–40 to +105	7 mm × 7 mm × 3 mm BGA	High vibration immunity, industrial grade typ specs
	ADXRS624	50	Analog	1000	60	2	0.1	25 mV/°/sec	0.07	462	0.1	4.75 to 5.25	3.5	50	–40 to +105	7 mm × 7 mm × 3 mm BGA	Min/max specs across temperature range
	ADXRS623	150	Analog	3000	60	2	0.1	12.5 mV/°/sec	0.14	462	0.1	4.75 to 5.25	3.5	50	–40 to +105	7 mm × 7 mm × 3 mm BGA	Min/max specs across temperature range
	ADXRS622	250	Analog	2500	60	2	0.1	7 mV/°/sec	0.10	308	0.1	4.75 to 5.25	3.5	50	–40 to +105	7 mm × 7 mm × 3 mm BGA	Min/max specs across temperature range
	ADXRS652	250	Analog	2500	60	2	0.1	7 mV/°/sec	0.10	308	0.1	4.75 to 5.25	3.5	50	–40 to +105	7 mm × 7 mm × 3 mm BGA	Industrial grade typ specs
	ADXRS620	300	Analog	2500	60	2	0.1	6 mV/°/sec	0.11	308	0.1	4.75 to 5.25	3.5	50	–40 to +105	7 mm × 7 mm × 3 mm BGA	Min/max specs across temperature range
	ADXRS649	20,000+	Analog	2000	200	15	0.03	0.01 mV/°/sec	—	—	0.1	5	3.5	3	–40 to +105	7 mm × 7 mm × 3 mm BGA	High rotation rate up to 50,000°/sec, industrial grade typ specs
	ADXRS453	300	Digital	77.5	16	0.9	0.01	0.0125°/LSB	0.0034	207	0.05	3.15 to 5.25	6	100	–40 to +105	9 mm × 9 mm × 4 mm LCC VMP, 10 mm × 10 mm × 3.5 mm SOIC	Calibrated over temperature, vibration immune, in-plane and out-of-plane sensing
	ADXRS450	300	Digital	80	25	0.9	0.03	0.0125°/LSB	0.02	462	0.05	3.15 to 5.25	6	100	–40 to +105	9 mm × 9 mm × 4 mm LCC VMP, 10 mm × 10 mm × 3.5 mm SOIC	High vibration immunity, industrial grade typ specs, in-plane and out-of-plane sensing

For more information on ADI MEMS inertial sensors, visit our website at *www.analog.com/MEMS*.

ANALOG DEVICES

Gyroscopes (continued)

	Part Number	Range (°/sec)	Output Type	BW Typ (Hz)	In-Run Bias Stability (°/Hr)	Angle Random Walk (°/√Hr)	Linear Acceleration Effect (°/sec/*g*)	Sensitivity	Bias Tempco (°/sec/°C)	Sensitivity Tempco (ppm/°C)	Non-Linearity (% FS)	Voltage Supply (V)	Supply Current (mA)	Start-Up Time (ms)	Temperature Range (°C)	Package	Additional Features
iSensor MEMS Gyroscope Subsystems (All Single Axis)	ADIS16060	80	Digital	1000	—	—	0.1	0.0122°/LSB	0.11	—	0.1	5	4.3	10	–40 to +105	8 mm × 8 mm × 5 mm LGA	
	ADIS16080	80	Digital	40	—	—	0.2	0.0976°/LSB	—	—	0.15	5	7	35	–40 to +85	8 mm × 8 mm × 5 mm LGA	
	ADIS16136† ***New***	480	Digital	380	3.5	0.167	0.017	0.00007°/LSB	0.00125	35	0.05	5	120	180	–40 to +85	36 mm × 44 mm × 14 mm module	External clock option
	ADIS16133†	1200	Digital	335	6	0.75	0.03	0.05°/LSB	—	16	0.008	5	88	181	–40 to +85	36 mm × 44 mm × 14 mm module	Wide dynamic range
	ADIS16135†	350	Digital	335	6	0.75	0.03	0.0125°/LSB	—	16	0.008	5	88	181	–40 to +105	36 mm × 44 mm × 14 mm module	
	ADIS16265†	320	Digital	330	25	2	0.2	0.0183°/LSB	0.005	25	0.1	5	41	165	–40 to +105	11 mm × 11 mm × 5 mm LGA	Range scaling

†Includes part specific factory calibration, programmable filtering, and digital self-test.
For multiaxis solutions, see the MEMS Inertial Measurement Unit (IMU) selection table.

*i*Sensor MEMS Inertial Measurement Units (IMUs)

		Range				Gyroscope									Accelerometer					
Part Number	Output Type	Gyro (°/sec)	Acceler-ation (*g*)	Magnetometer (gauss)	Barometer (mbar)	In-Run Bias Stability (°/hr)	Angle Random Walk (°/√Hr)	Bias Tempco (°/sec/°C)	Linear Acceleration Effect (°/sec/*g*)	Sensitivity (°/sec/LSB)	Sensitivity Tempco (ppm/°C)	Non-Linearity (% FS)	Alignment (°)	BW Typ (Hz)	In-Run Bias Stability (m*g*)	Start-Up Time (ms)	Voltage Supply (V)	Temperature Range (°C)	Package	Additional Features
4 Degrees of Freedom																				
ADIS16305	Digital	300	3	N/A	N/A	22	1.85	0.006	0.02	0.0125	20	0.1	0.1	330	0.037	180	5	–40 to +85	23 mm × 31 mm × 8 mm module	Low profile
6 Degrees of Freedom																				
ADIS16445 ***New***	Digital	250	5	N/A	N/A	12	0.6	0.005	0.015	0.0025	40	0.1	0.05	330	0.075	—	3.3	–40 to +85	24 mm × 37 mm × 10 mm module	Programmable operation and control, wide dynamic range, external clock option, single command self-test
ADIS16385	Digital	300	5	N/A	N/A	6 (z); 21 (x, y)	0.75 (z); 1.9 (x, y)	0.001 (z); 0.004 (x, y)	0.03 (z); 0.05 (x, y)	0.0031	40	0.1	0.05	330	0.05	210	5	–40 to +105	36 mm × 47 mm × 39 mm module	High precision on yaw axis
ADIS16375	Digital	300	18	N/A	N/A	12	1	0.005	0.013	0.013	40	0.025	0.05	330	0.13	500	3.3	–40 to +85	44 mm × 47 mm × 14 mm module	Continuous bias estimator, single command self-test, delta angle/velocity, continuous bias estimator, programmable FIR filtering
ADIS16362	Digital	300	1.7	N/A	N/A	25	2	0.01	0.05	0.0125	50	0.1	0.05	330	0.041	180	5	–40 to +105	23 mm × 23 mm × 23 mm module	High sensitivity accelerometer, external clocking option, burst mode reads
ADIS16364	Digital	300	5	N/A	N/A	25	2	0.01	0.05	0.0125	50	0.1	0.05	330	0.1	180	5	–40 to +105	23 mm × 23 mm × 23 mm module	Narrowed temperature calibration range, external clocking option, burst mode reads
ADIS16365	Digital	300	18	N/A	N/A	25	2	0.01	0.05	0.0125	50	0.1	0.05	330	0.2	180	5	–40 to +105	23 mm × 23 mm × 23 mm module	Wide temperature calibration range, external clocking option, burst mode reads
ADIS16334	Digital	300	5	N/A	N/A	25	2	0.005	0.05	0.0125	40	0.1	0.05	330	0.1	180	5	–40 to +105	22 mm × 33 mm × 11 mm module	Small footprint/height, single command self-test
ADIS16485 ***New***	Digital	450	18	N/A	N/A	6	0.3	0.0025	0.009	3.052×10^{-7}	35	0.01	0.05	330	0.032	500	3.3	–40 to +85	44 mm × 47 mm × 14 mm module	Programmable FIR filtering, 2.46 kHz sample rate, single command self-test, delta angle/velocity, continuous bias estimator, linear-*g* compensation
ADIS16367	Digital	1200	18	N/A	N/A	47	2	0.01	0.075	0.05	40	0.1	0.05	330	0.2	180	5	–40 to +105	23 mm × 23 mm × 23 mm module	Wide dynamic range, external clocking option, burst mode reads
9 Degrees of Freedom																				
ADIS16405	Digital	300	18	2.5	N/A	25	2	0.01	0.05	0.0125	40	0.1	0.05	330	0.2	220	5	–40 to +105	23 mm × 23 mm × 23 mm module	Magnetometer
10 Degrees of Freedom																				
ADIS16407	Digital	300	18	2.5	10 to 1200	25	1.9	0.01	0.05	0.0125	40	0.1	0.05	330	0.2	220	5	–40 to +105	23 mm × 23 mm × 23 mm module	Barometer
ADIS16488 ***New***	Digital	450	18	2.5	10 to 1200	6	0.3	0.0025	0.009	3.052×10^{-7}	35	0.01	0.05	330	0.1	500	3.3	–40 to +85	47 mm × 44 mm × 14 mm module	Programmable FIR filtering, 2.46 kHz sample rate, programmable soft-iron correction matrix, programmable hard-iron correction, single command self-test, delta angle/velocity, continuous bias estimator, linear-*g* compensation
ADIS16480 ***New***	Digital	450	18	2.5	10 to 1200	6	0.3	0.0025	0.009	3.052×10^{-7}	35	0.01	0.05	330	0.1	500	3.3	–40 to +85	47 mm × 44 mm × 14 mm module	Extended Kalman filter, ±0.1° static angle accuracy, ±0.3° dynamic angle accuracy, programmable FIR filtering, 2.46 kHz sample rate, programmable soft-iron correction matrix, programmable hard-iron correction, single command self-test, delta angle/velocity, continuous bias estimator, linear-*g* compensation
ADIS16448 ***New***	Digital	1000	18	1.9	10 to 1200	14	0.6	0.005	0.015	0.01	40	0.1	0.05	330	0.12	205	3.3	–40 to +85	24 mm × 37 mm × 10 mm module	Programmable operation and control, wide dynamic range, external clock option, single command self-test

All ADI MEMS IMUs include part-specific factory calibration and programmable filtering, unless noted.

ANALOG DEVICES

The information in the above table has been taken from the product web page.

8.2 Position Estimation Sensors

Name	Mass	Size	Accuracy	Type	TRL	Comment
Aerocube-4 GPS [71]	NA	NA	$\pm 20m$	GPS receiver	NA	Orbit determination once per day or as power system permits

Table 3: Available position estimation sensors

8.3 Attitude Estimation Sensors

Some attitude estimation sensors and actuators were obtained from the small satellite conference organized by KISS in 2012. They are shown in the image given below. Apart from this, a table containing actuators and sensors from other sources has also been given below.

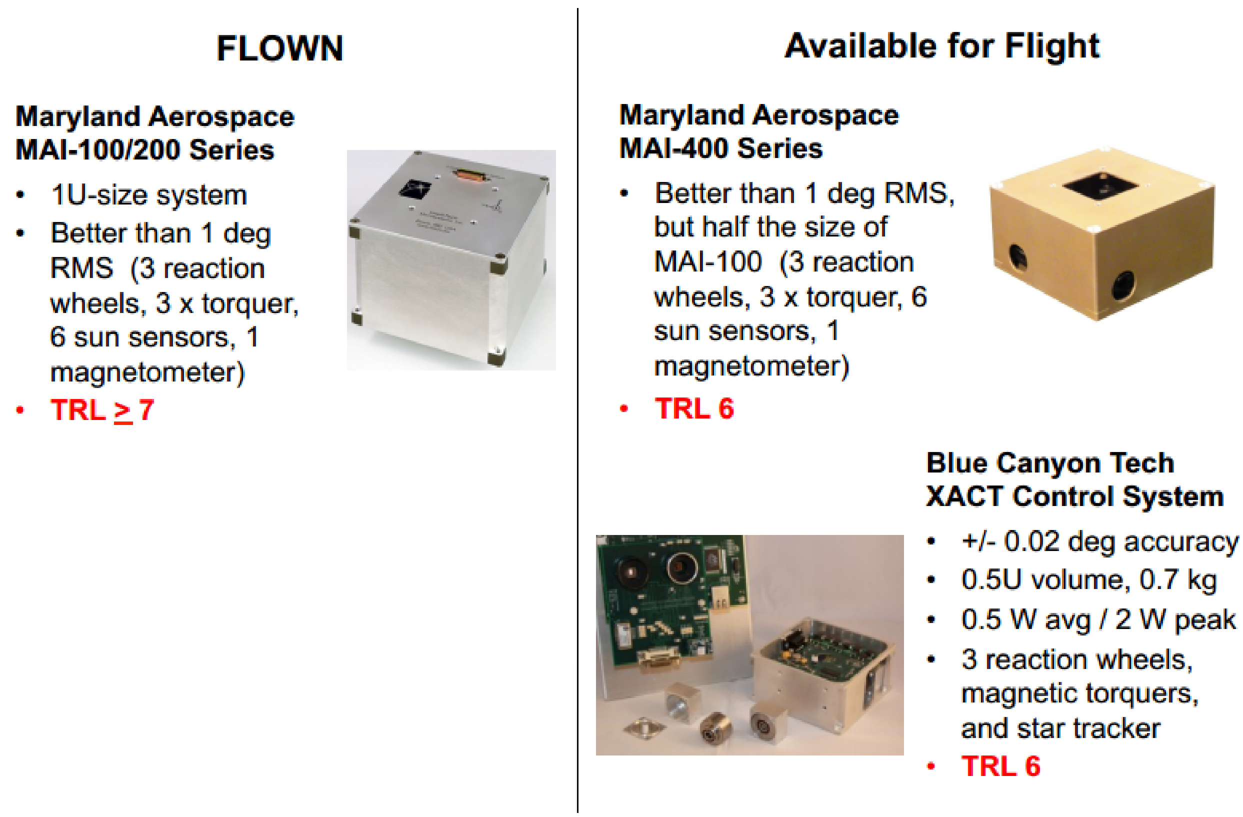

Figure 11: Current attitude control sensors and actuators (source: Presentation by Matt Bennett)

Name	Mass	Size	Accuracy	Type	TRL	Comment
Blue Canyon Technologies Nano Star Camera 1 [72]	<0.5 Kg	< 5 x 5 x 10 cm	7-24 arc-sec	Star Tracker	NA	<0.5W power consumption
SD085-23-21-021 (source: link)	NA	3.76 x 1.5 x 3.3 mm	NA	Sun Sensor	9	
Melexis MLX90615 (source: link)	NA	4.7 x 4.7 x 2.7 mm	0.5 deg over 0 to 50 deg C	Earth Nadir Sensor	9	
Honeywell HMC6042 (source: link)	NA	5 x 3.6 x 1.0 mm	0.15 milli-Gauss	2-Axis Magnet	9	
Honeywell HMC1041Z (source: link)	NA	1.15 x 4 x 1.25 mm	0.15 milli-Gauss	1-Axis Magnet	9	
Space Micro Coarse Sun Sensor [73]	10 g	1.27 (diameter) x 0.90 (height) cm	5 deg of 1 axis knowledge	Sun Sensor	9	
Space Micro Medium Sun Sensor [73]	36 g	2.43 (diameter) x 3.49 (height) cm	1 deg of 2 axis knowledge	Sun Sensor	9	
Berlin Space Technologies ST-200 [74]	50 g	30 x 30 x 38.1 mm	30 arc-sec (pitch/yaw), 200 arc-sec (roll)	Star Tracker	7	
Digital Fine Sun Sensor CubeSat-Shop [75]	35 g	34 x 32 x 21 mm	0.1 deg	Sun Sensor	7	
Magnetometer [75]	15 g sensor, 150 g electronics	Sensor: 10 x 10 x 5 mm, Electronics: 90 x 30 x 11 mm	Sensitivity: 10 nT	Magnetometer	9	
CubeSat Sun Sensor [75]	< 5 g	33 x 11 x 6 mm	< 0.5 deg	Sun Sensor	7	

Table 4: Available attitude estimation sensors

8.4 Inter-satellite Distance Sensors

Name	Mass	Size	Accuracy	Type	TRL	Comment
Nexus S [76]	129g	123.9 x 63 x 11 mm	1.53 m , 3 deg @30 m	Vision	NA	
IBIS4-1300 [77]	NA	NA	$<$ 100 arc-s	Vision	NA	Vision based Star Tracker a Topology (for formation ing). Does not talk ab satellite detection methods

Table 5: Available inter-satellite distance sensors

8.5 Actuators

Name	Mass	Size	Accuracy	Type	TRL	Comment
Aerocube-4 Retractable wings [71]	NA	2 wings, each 9 x 10 cm	N/A	Extending Wings	7	Uses wings to adjust in-track formation for 3 satellites
Blue Canyon Technologies Micro Reaction Wheel [72]	150 g	43 x 43 x 18 mm	NA	Reaction Wheel	NA	Momentum: 18 mNms, Max Speed: 6000 RPM, Torque: 0.6mNm, Lifetime: $>$ 3 years, Nominal power consumption: $<$ 0.1W, Peak power: $<$ 1.0W, Op Voltage: 5 to 15 V
BCT Integrated Attitude Control for Cubesats [72]	$<$ 0.7 Kg	$<$ 10 x 10 x 5 cm (0.5U)	Spacecraft Pointing Accuracy: 0.003 deg (1-sig) for 2 axes, 0.007 deg (1-sig) for 3rd axis Integration Package	NA	NA	Spacecraft Lifetime $>$ 1 year, Nominal Power consumption: $<$0.5 W, Peak Power: $<$2.0W, Slew Rate (8kg, 3U CubeSat): $>$ 10 deg/sec
Sinclair Interplanetary RW-0.007-4 [78]	90 g	50 x 40 x 27 mm	NA	Reaction Wheel	7	Nominal Torque 1 mNm, Nominal Momentum 7 mNm-sec, Supply Power 0.1 W to 0.7 W
Sinclair Interplanetary RW-0.01-4 [78]	120 g	50 x 50 x 30	NA	Reaction Wheel	7	Nominal Torque 1 mNm, Nominal Momentum 10 mNm-sec, Supply Power 0.1 W to 0.7 W

Sinclair Interplanetary RW-0.03-4 [78]	185 g	50 x 50 x 40 mm	NA	Reaction Wheel	9	Nominal Torque 2 mNm, Nominal Momentum 30 mNm-sec, Supply Power 0.1 W to 1.5 W
Berlin Space Technologies iACDS-100 [74]	250 g	95 x 90 x 32 mm	«1^o pointing,(30 arc-sec in Pitch/Yaw, and 200 arcsec in Roll for att. Determination)	Integrated ACDS product	6	Power (Nom/Peak): 0.5W/1.8W, Actuators: 3 Reaction Wheels, 3 Magnetorquer, Sensors: Star Tracker, 3-Axes MEMS Gyro, Magnetometer, Accelerometer
MAI-400 ADACS CubeSat-Shop [75]	694 g	10 x 10 x 5 cm	Integrated ACDS product	7	NA	Sensors: 3-axis magnetometer, coarse sun sensor, EHS camera, Actuators: 3 torque rods
MAI-300 Single Axis Reaction Wheel [75]	317 g	68.5 x 68.5 x 33.0 mm	NA	Reaction Wheel	7	Max Torque: 0.625 mNm
MAI-201 Miniature 3-Axis Reaction Wheel [75]	640 g	76.2 x 76.2 x 70 mm	NA	Reaction Wheel	7	Max Torque: 0.625 mNm
MAI-200 ADACS [75]	907 g	100 x 100 x 78.75 mm	NA	Integrated ACDS product	7	Max Torque: 0.625 mNm

Table 6: Reaction Wheels, Extending Wings, and Integrated Packages

Name	Mass	Size	Accuracy	Type	TRL	Comment
Clyde Z-Axis Magnetorquer	50 g	100 x 100 x 4.3 mm	NA	Torquer	NA	magnetic moment of 0.19Am^2
SSBV magnetorquer rod	<30 g	Length 7cm x Diameter 9mm	NA	Torquer	NA	Magnetic moment: >0.2Am^2
CubeSat Magnetorquer Rod [75]	30 g	Length 7 cm, Diameter < 9 mm	NA	Torquer	NA	Magnetic moment: 0.2 Am^2
CubeTorquer [75]	22.25 g	Length 60 mm, Diameter 10 mm	NA	Torquer	NA	Magnetic moment: 0.2 Am^2

Table 7: Available Magnetorquers

8.6 Thrusters

Figure 11 gives information on the thrusters, which was obtained from the small satellite conference organized by KISS in 2012. They are shown in the image given below. Apart from this, a table containing actuators and sensors from other sources has also been given below.

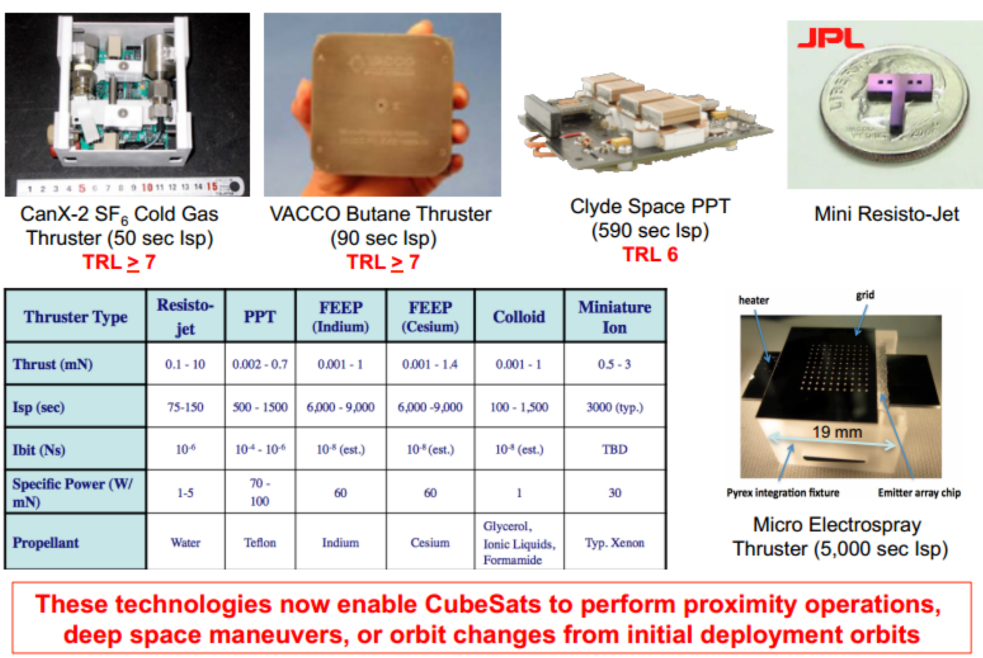

Figure 12: Current available thrusters (source: Presentation by Matt Bennett)

Name	Mass	Size	Isp	ΔV	Thrust	System Power	Comment
Spence Pressure-fed electrospray [79]	<1.15 Kg	0.56 U	800	151 m/s	0.7 mN	< 9W	
Micro-pulsed plasma thruster [79]	<0.55 Kg	0.5 U	700	63 m/s		2W @ 2hz fire	Impulse: 0.5 mN-s primary, 0.13 mN-s ACS
Unpressurized (wicking feed) electrospray [79]	<0.4 Kg	0.4 U	750	76 m/s	0.1 mN	1W	
Microresistojet (MRJ) [79]	< 1.25 Kg	1.0 U	150	60m/s	2-10mN	3-15W	
RF Ion [79]	<1.25 Kg	1.25 U	1800	244m/s	0.067 mN	10W	
Green monopropellant [79]	< 1 Kg	0.5 U	240	130m/s	0.5N	15W	
Nanosatellite Micropropulsion System [79]	300 g	NA	50s-100s	NA	nominal: 100 uN to 10 mN	< 2 W	Pointing Res: 0.1 arcsec

Table 8: Thrusters available off the shelf

Name	Mass	Size	Isp	δV	Thrust	Comment
Ion electrospray [80]	NA	1/3 U	2500	200m/s	0.1 mN	
μVAT	150g	40x 40x 40mm	1000	NA	5.4μN	Turn 90 degrees in 10 minutes.
YUsend-1 SPT [81]	94 g	NA	NA	NA	0.15 mN	

Table 9: Thrusters not yet available off the shelf

8.7 Potential Suppliers

Some of the potential suppliers that can be used to procure the required components have been listed below.

- CU Aerospace

- Blue Canyon Technologies
- Melexis
- Analog Devices
- Silicon Sensing
- Sinclair Interplanetary
- Berlin Space Technologies

Given below is a chart showing what can be achieved using the state of the art controllers and actuators(as on December 2012). Thus, this has to be kept in mind while designing the mission.

Typical Parameter	1U	3U
Mass	1.3 kg	4 kg
Volume (Before Deployment)	10x10x10cm	10x10x34cm
Solar Arrays	Fixed (few deployable)	Fixed Deployable and Articulated
Power	~3 W avg fixed	~8W avg body-fixed ~25W avg deployed
Battery	2200mAh	4400mAh (0.2U)
Antenna	Monopole / Dipole	Dipole, Turnstile, Patch 0.5m dish (1U)
Comms	UHF / VHF	S-Band, UHF/VHF
Data Rates	9600 kbps	3 Mbps demo'd
Attitude Control	~5 deg control (passive)	1-10 deg (torquer) ~0.02-1 deg (RW) (0.5U)
Attitude Determination	~3-4 deg (gyro, sun, mag)	<1 deg (horizon sensor) ~40 arcsec with star tracker (1 U)
C&DH	RISC, ARM Some Linux-based	RISC, ARM, Linux, FPGAs
Propulsion	None	Cold Gas, EP, Solar Sail (<100 m/s)
Deployables	Antenna	Antenna, Panels, Tethers, Boom (0.5m), Solar Sail (5m)
Demonstrated Lifetime	9 years + (XI-IV)	9 years + (Quakesat)
Payload Volume	0.5U max	0.5-2U

Figure 13: Current state of the art specifications achievable in all fields (source: Presentation by Matt Bennett)

9 Conclusions

Formation flight CubeSats are capable of great contributions to science and technology such as:

1. To avoid spacial and temporal ambiguities

- Multipoint measurement of plasma density
- Multipoint measurement of electric and magnetic fields (geomagnetic storms)
- Multipoint measurement of proton and electron fluxes
- Planetary Atmospheric spectroscopy

2. Earth monitoring (a constellation should be enough)
    - Agriculture and vegetation management
    - Weather prediction models
    - Oceanography
    - Disasters assessment
    - Measurements of compounds on the atmosphere
    - Pollution
    - CO_2 or H_2O cycle (or any other compound)
    - Doppler sensing of winds
    - Temperature sensing

3. Testbed for mobile phone electronics for satellite intercommunications or satellite-ground communications

4. To carry a web and remove space junk

5. To maneuver with solar sails

6. To explore asteroids (spider cubesat swarm, could be the basis to industrialize asteroids)

7. Automated 3D mapping (google maps or any other applications)

8. Observation of gravitational waves

9. Interferometry
    - Exoplanet detection
    - Infrared telescopes
    - Gamma-ray telescopes
    - X-ray telescopes
    - Visual spectrum telescopes
    - Radio Telescopes

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