Cubesat
Literature Survey Report

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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 really small scales, it is now possible to actually design pico and nano satellites to meet certain required scientific goals. In this report, we are majorly 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 find out and understand the existing single, as well as multiple, satellite missions and some proposed concepts.
2. To find out 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 four different classes as Planetary Science, Earth Science, Astrophysics and Heliophysics. There is also two charts presented at the end of these four sections, which give an idea of the various concepts that can be realized along with their scientific requirements.

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 issues addressed are 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

2.3.1 Predicting Earthquakes through Ionosphere Monitoring

Early earthquake detection could help the third of a population that is affected by earthquakes. 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.[1] Something similar is scheduled to be launched by the Chinese in 2014, though not a formation[2].

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. [3, 4]

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. [5]

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

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 360 km orbits at an inclination of 52 degrees [6][7]. These measurements can also help to show the interactions between the thermosphere and ionosphere [8].

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[9] [10] [11][12][13].

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[14].

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 it could possibly do with more study and happen in conjunction with the GRB monitoring.[15] [16]

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. [17]. The formation may not be able to add to the science.

2.7 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. [18][19]

2.8 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]. Since it is more appropriate for a constellation than for a formation, it is not a great candidate for our project unless we wanted to create a 3D map. It would appear that other systems already make these measurements, but there are still areas of poor coverage that could be addressed [21].

2.9 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 here would be finding a detector array that would fit in our size constraints.

2.10 Formation Flying to Sample Volume of Magnetosphere

Use the formation of cubesats to create a more detailed 3D model of the magnetosphere, adding detailed dynamic measurements. This may not be necessary because of the twin satellites launched by NASA in Fall 2012. Also several earlier missions acheived similar results, not using formations but I doubt the information is still needed.[23] 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]

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. Perhaps extend to 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 high speed trajectory with low perihelion which would explore 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

Required Instrumentation: Plasma, solar wind, Energetic particles & cosmic rays, Magnetometer, 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 [25]. One study suggests an orbit of 6000-40000 km [26].

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 [27]. One study suggests the use of optical and radar telescopes to track the small debris [28].

4 Astrophysical Missions

4.1 Pinpointing the Source of Gamma Ray Bursts

The formation could be used to source GRBs through precise triangulation. If we could get the measurements of inter-satellite distance and GRB incident time accurately enough, we could potentially increase the accuracy of GRB detection and positioning. [29]. 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 [30]. 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 citeRef:Carroll2. Another possible mission would be imaging star fields [31]. To make the formation relevant, each satellite would need different a different type of instrument to further the science.

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 is a concept of 6 spacecrafts in highly inclined constellation. They would be in an Out-of-Ecliptic Vertical Orbit. It will use solar sail to reach high inclination. The proposed science missions are Dynamo: Helioseismology & magnetic fields of polar regions, polar view of corona, CMEs, solar radiance and 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

Two charts have been given below 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 1: 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 2: Science Requirements for above missions(source: Presentation by Dayton Jones)

All the missions that have been mentioned above have been plotted on graph as shown below. 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 do the same. They have been colour coded according to the mission class and bigger the size, the costlier the mission.

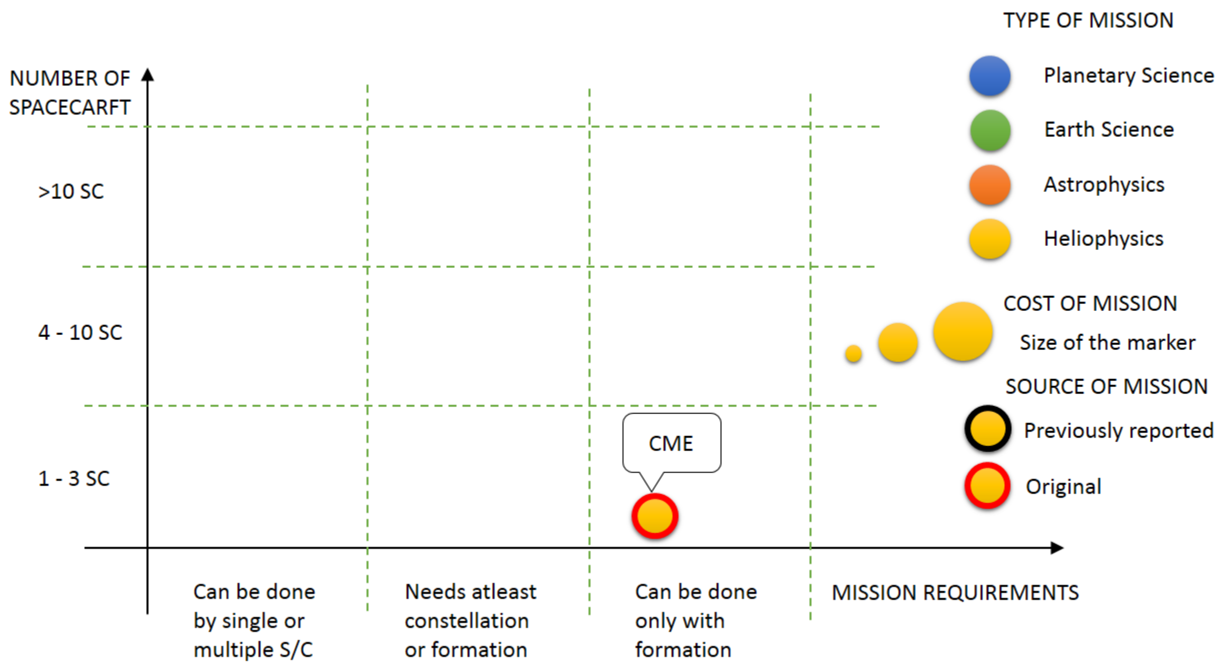


Figure 3: Mission Categorization

6 Actuators and Sensors

Below are attached the images that have been found regarding this. They are taken from the presentations given by J. Mueller and Matt Bennett.

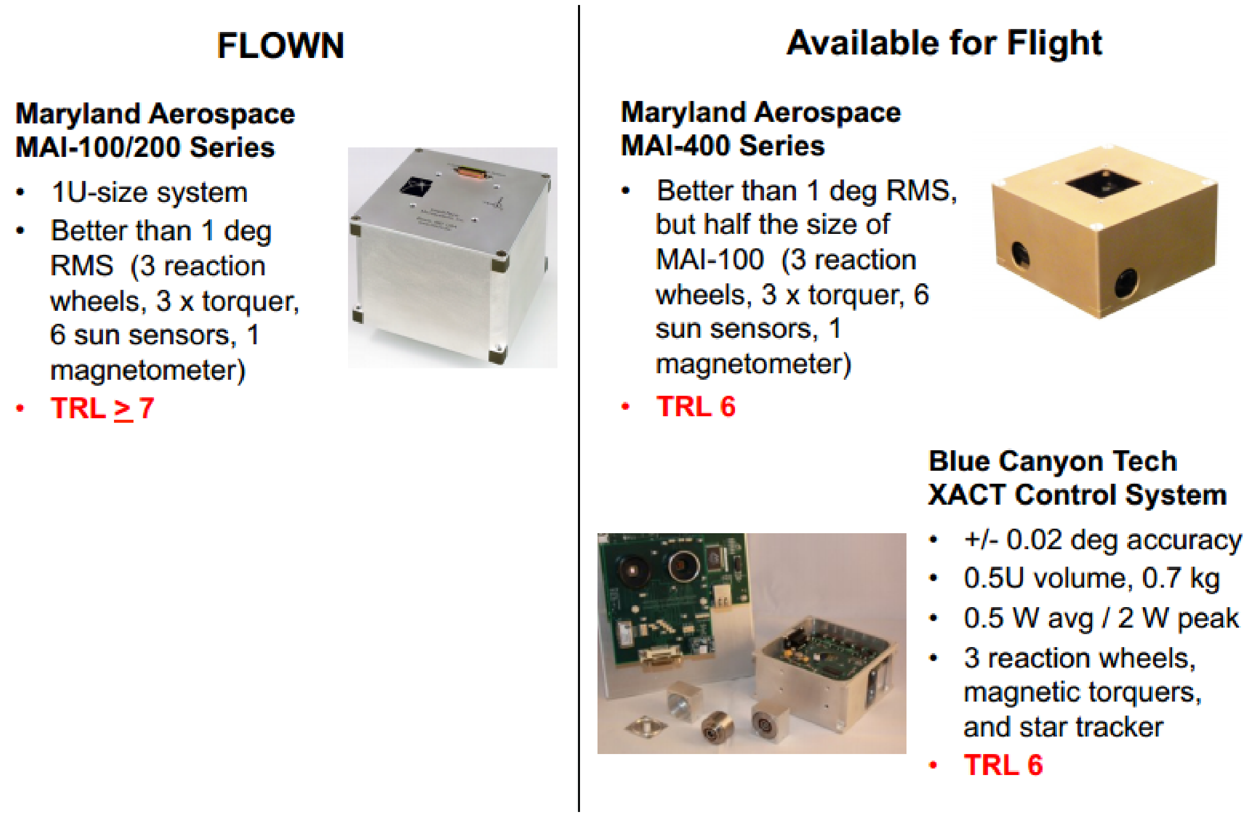
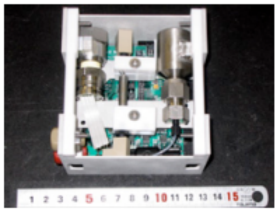


Figure 4: Current attitude control sensors and actuators

This is not available of the shelf as of now. They had said it will take 1-2 years in December 2012. It will be a TRL 6 when it becomes available.

Given below is a table showing what can be achieved using the state of the art controllers and actuators(as on December 2012).



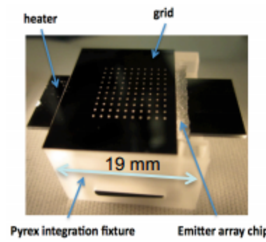
CanX-2 SF_6 Cold Gas Thruster (50 sec Isp)
TRL ≥ 7

VACCO Butane Thruster (90 sec Isp)
TRL ≥ 7

Clyde Space PPT (590 sec Isp)
TRL 6

Mini Resisto-Jet

Thruster Type	Resisto-jet	PPT	FEEP (Indium)	FEEP (Cesium)	Colloid	Miniature Ion
Thrust (mN)	0.1 - 10	0.002 - 0.7	0.001 - 1	0.001 - 1.4	0.001 - 1	0.5 - 3
Isp (sec)	75-150	500 - 1500	6,000 - 9,000	6,000 -9,000	100 - 1,500	3000 (typ.)
Ibit (Ns)	10^{-6}	10^{-4} - 10^{-6}	10^{-8} (est.)	10^{-8} (est.)	10^{-8} (est.)	TBD
Specific Power (W/mN)	1-5	70 - 100	60	60	1	30
Propellant	Water	Teflon	Indium	Cesium	Glycerol, Ionic Liquids, Formamide	Typ. Xenon

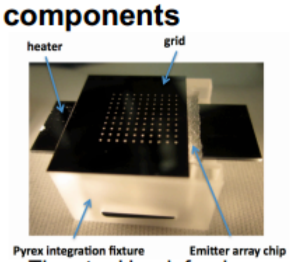


Micro Electrospray Thruster (5,000 sec Isp)

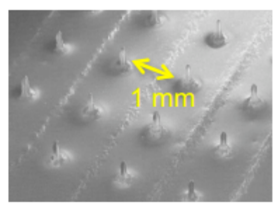
These technologies now enable CubeSats to perform proximity operations, deep space maneuvers, or orbit changes from initial deployment orbits

Figure 5: Current thrusters

MEP thruster is based on same electrospray physics with highly scalable microfabricated components



Thruster Head, feed system and reservoir



Microfabricated Emitter Array

Integrated MEP thruster/feed system module:
Size: 1.9 x 1.9 x 1.2 cm (4.3 cm^3)
Number of emitters: >100
Thrust: 10-100 uN
Mass: < 100 g (head, reservoir, PPU)
- no pressurized reservoir or valve required
Cost: ~ much lower with batch microfabrication

Figure 6: Micro-Electric Propulsion specifications

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 7: Current state of the art in all fields

7 Conclusions

Formation Flight CubeSats are capable of great contributions to science and technology 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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