Title: The design of a 6U nanosatellite constellation for debris monitoring and passive tracking

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Need

Ever since the start of the space age, there has been more space debris in orbit than operational satellites. It is estimated that of the 23 000 pieces of debris larger than 10 cm currently orbiting the earth, less than 10% are functional spacecraft [1]. Orbital debris is composed mainly of nonfunctional spacecraft, abandoned launch vehicle stages, mission related debris and fragmented debris. The extreme high velocity of debris poses high risk to the success of space missions.

It is becoming widely accepted that without an active debris mitigation plan, the use of space is going to become quickly limited. One possible scenario of how the situation will play out if left unchecked is called the “Kessler Syndrome”. It is named after former NASA scientist Donald Kessler who laid the basic idea in 1978. It is the phenomenon where satellites would produce orbiting fragments, each of which would increase the probability of further collisions with other satellites and debris leading to the exponential growth of a belt or debris around the Earth. This would greatly affect future spacecraft missions. This has raised concern in the space community and resulted in the formation of the Space Situational Awareness (SSA), an initiative set up for space debris mitigation.

The current detection systems heavily rely upon ground-based radars and this makes it increasingly difficult to detect debris as they decrease in size due to a variety of reasons. This is mainly due to limitations in the current radar technologies and the power requirements of such a system which translates to large monetary costs of operating such a facility. Ground based radar can accurately detect debris pieces of sizes no less than 10 cm in LEO, hence thousands of smaller pieces go uncatalogued and can still potentially damage spacecraft [2].

Space agencies rely on various types of radar and optical methods to detect and track debris. The United States currently has the most resources as far as debris tracking equipment is concerned. The population of smaller pieces are calculated statistically using ground-based sensors. Space-based surveillance satellites are much more uncommon due to the high cost and complexity required when launching systems into space. The only other attempt ever made to detect debris in orbit was with the in-orbit debris sensors such as the GORID satellite, DEBIE satellite and HTV-5 JAXA experimental satellite. Unfortunately, the main aim of these sensors was to detect collisions and not to track debris so they do not contribute to the SSA [3].

Using CubeSats for in-orbit debris detection and tracking offer promising solution for the future of debris detection. This is because this setup eliminates the need for power intensive radars because they will be closer to the objects to be tracked. This will also allow for smaller objects to be tracked as higher frequencies can be used for the radar due to the absence of atmospheric interference of the radar signal. This paper will look at the implementation of such a radar in a 6U CubeSat for debris detection and tracking.

Mission Objectives

The primary objective is to create a 6U nanosatellite constellation that can be efficiently used to detect and track debris in LEO. The CubeSat constellation will focus mainly on LEO as it’s the only orbit that currently hosts human presence in space. It is also valuable to the space community because it is where 90% of the CubeSats that are launched by universities and the scientific research community are deployed. The current data that is available of debris distribution in near Earth orbits is only as accurate as the instruments that were used to collect the data. Ground radar stations and optical stations require a lot of power and huge financial capital to setup and maintain and are largely affected atmospheric conditions. Setting up a constellation of radar equipped CubeSats will go a long way in improving the accuracy of the current debris catalogues as they will have better coverage of LEO. Using LEO also guarantees that the CubeSat can be appropriately disposed of after they have completed their lifecycle by reentering and burning in the atmosphere. This will serve as a way not to add to the problem we are trying to solve.

Primary Objectives

1. Provide a new way to detect and track debris.

2. Develop a way to increase the accuracy of current debris models which are currently in use.

Secondary Objective
1. Provide a way to increase the current situational awareness on space debris.

Concept of Operations

The mission has four stages of operation. The satellite constellation is going to utilize LEO because of the ease and abundance of launch opportunities as secondary payloads. The orbital parameters are in Table 1.

Table 1. Orbital parameters.

Parameter	Name	Value	Units
Semi-major axis	a	350 - 400	km
Eccentricity	e	0.00115	-
Orbital Period	T	~ 90	minute

For greater coverage and to compensate for the rotation of the Earth there is a need to implement a constellation with equally spaced orbits at an angle of 60 degrees. Each orbit will have 5 CubeSats.

This is done to increase the coverage of data collection since the debris will also be moving relative to the Earth making it harder for data collection.

Stage 0: The launch and deployment of the CubeSat in their respective orbits. Once in orbit the satellites need to detumble and align themselves in the orbits.

Stage I: Once the ground station has confirmed that the satellites are functional, the command for the deployment of the radar will be sent.

Stage II: Once the radar has been successfully deployed and functional then the radar mission can start. The duty cycle of the satellites will be 25% such that one orbit will be used for data collection and three will be used for system cooling and data downlink.

Stage III: Once the data has been collected, the onboard computer will filter and compress the data in preparation for downlink to the ground station. An algorithm integrated into the CPU onboard applies filters for erasing any noise or echo in the signals before transmission.

Stage IV: Data will then be downlinked to the ground station for processing to determine the position, velocity, and size of debris.

Key Performance Parameters

The key piece of technology this mission requires is radar technology small enough to fit in a 6U CubeSat bus. The radar is not yet available commercially. The radar was developed by NASA, for an Earth observation mission called RAINCUBE. It is a Ka-band radar used to send and detect a 35.75 GHz signal[4].

The radar collects the following information:
- I. Doppler effect.
- II. Time delay (Delta T).
- III. Magnitude.

This information is used to calculate the position and velocity of detected debris. The radar deploys from a 1.5U cannister. The undeployed radar and the accompanying electronics have a total volume of 2.5U. The radar antenna has a resolution of a tenth of a degree which is enough to compensate for the satellite's displacement during delta T (which is about a hundredth degree). The characteristics of the radar are presented in Table 2 below.

1. The radar is quite power intensive to operate so the CubeSat will be equipped with paddles to increase the space to mount solar cells for power generation and quick recharging of the batteries.

2. The CubeSat also requires highly accurate attitude determination and control system (ADCS) to keep the spacecraft stable throughout the radar mission and to align the spacecraft solar paddles to the sun

to maximize charging. For this, the CubeSat will be equipped with a 3-axis active control ADCS system with reaction wheels for better control.

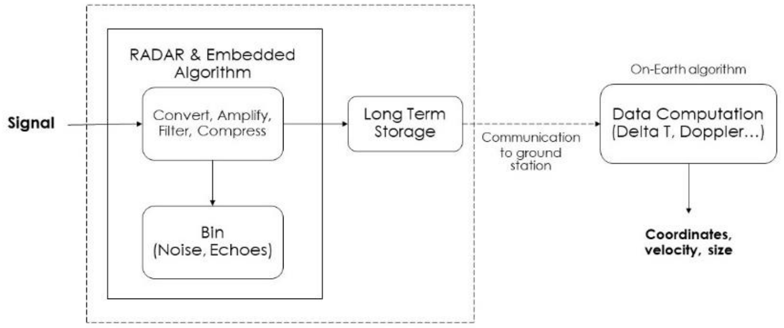
Table 2. Characteristics of Raincube's radar

RainCube Radar	Value
Instrument	Ka-Band radar
Frequency	35.75 GHz
Antenna	0.5m deployable
Horizontal resolution	<10 km
Vertical resolution	<250m
Sensitivity	20dBz

Research and design of a similar radar design with characteristics tailored for debris detection is possible but is beyond the scope of this proposal.

Space Segment Description

The mission will utilize a 6U nanosatellite CubeSat with a mass of approximately 12 kg in a constellation of 30 with 5 CubeSats in each orbit and the orbits will be evenly distributed in 6 orbits by a 60-degree difference in inclination. The constellation will be operated from the LEO. It will have two deployable solar cells embedded over the shorter side of the rectangular profiled spacecraft. The electrical power system (EPS) can generate power of up to 37W with deployable panels and the body mounted panels combined. The total average power consumption of each CubeSat is approximately 21.3W, which satisfies the calculated power balance in Table 3. The main payload will be the deployable radar which will constitute 2.5U of the 6U satellite volume. The onboard data processing system will be responsible for processing the data before transmission to the ground station via the communications subsystem which will employ an S-band communication system for data downlink. Attitude determination and control subsystem (ADCS) of each CubeSat will require precision of less than 5 degrees. Hence, ADCS will consist of one inertial measurement unit (IMU) sensor, six sun sensors, one star tracker, three magnetorquers, and three reaction wheels.



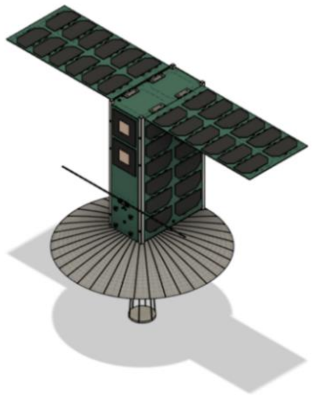


Figure 1. Data flow algorithm. **Figure 2. Conceptual model.**

Operation of the radar produces a lot of heat but due to the limited amount of available space on the 6U CubeSat bus, the satellit will employ passive thermal management. Included below in Table 3 is the power and mass budget analysis.

Table 3. Power and Mass budget analysis.

Subsystem	Component	Part description	Mass (g)	Average Power Consumption (W)	COTS/ Custom
Comms	Tx/Rx S-band antenna	ISISPACE S-band patch antenna	<50	2	COTS

OBC	Onboard Computer	---	~200	~1	Custom
EPS	Battery	GOMspace NanoPower BPX	500	6	COTS
	Power module	GOMspace Nanopower P60	191	0.6	COTS
	Solar panels	eHaWK 27L-50B (85W)	600	---	COTS
ADCS	3 axis ADCS	Cubespace ADCS	554	0.571	COTS
	6 sun sensors	Cubespace cubeSense	0.03	0.1	COTS
	Star sensor	Cubespace cubeStar	55	0.284	COTS
	3 Magnetorquers	EXA MT01 Compact Magnetorquer	225	0.75	COTS
Payload	Ka-band radar	Modified RainCube radar	5500	~10	Custom
Structure	6U structure	6U CubeSat structure	~ 1000	--	Custom
Total			**8875.03**	**21.31**	

Table 4. Link Budget Analysis.

		Unit	**Data Downlink**	**UHF Uplink**
Frequency		MHz	2245	437.5
Modulation			BPSK	GMSK
Data Rate		bps	9600	4800
Transmission Side	Output Power	W	1	50
		dBm	30.00	47.0
	Line Loss	dB	3.0	3.0
	Antenna Gain	dBi	6.50	10
	EIRP	dBm	33.5	54.0
	Antenna Pointing Loss	dB	3.0	3.0
Satellite Positiion	Altitude	m	4.00E+05	4.00E+05
	Elevation	deg	10	10
	Range	m	1.44E+06	1.44E+06
Path	Path Loss	dB	162.6	148.4
	Polarization Loss	dB	3.0	3.0
	Atmospheric Losses	dB	1.0	1.0
	Ionospheric Losses	dB	0.5	0.5
Receive Side	Isotropic Signal Level at Antenna	dBm	-136.6	-101.9
	Antenna Pointing Loss	dB	3.0	3.0
	Antenna Gain	dBi	6.5	2.15
	Line Loss	dB	3.0	3.0
	Receive Power at LNA Input	dBm	-136.1	-105.8
	LNA Gain	dB	20.0	-
	Effective Noise Temperature	K	300	-
	Thermal Noise	dBm/Hz	-173.8	-

	Signal-Noise Ratio (Eb/N0 or S/N)	dB	17.9	-
	BER		1.00E-05	-
	Required SNR	dB	9.8	-
	Receiver Sensitivity	dBm	-120	-120
Link Margin		dB	3.9	14.2

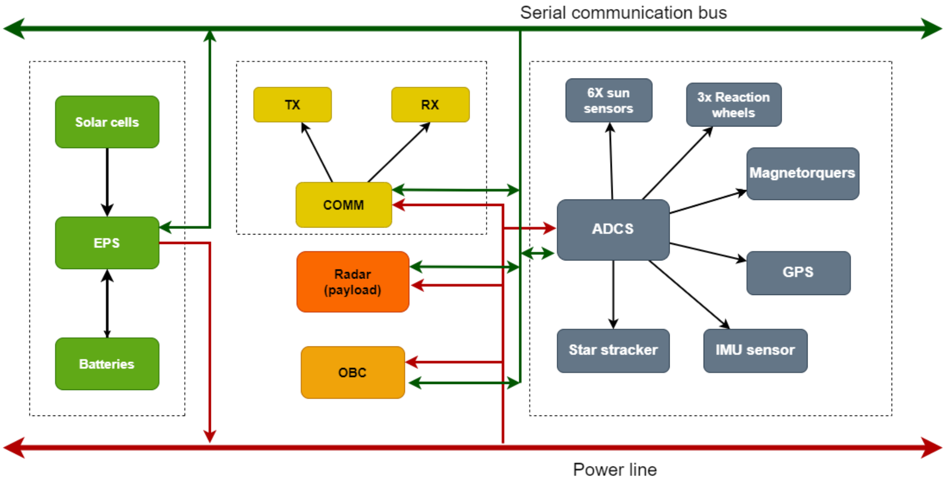


Figure 3. System Diagram of the CubeSat

Implementation Plan

The project can be easily carried out at Kyushu Institute of Technology (Kyutech), as the organisattion has a steller track record of working with cubeSats. The design, development and testing of the satellite constellation would require facilities which include but not limited to the following:

1. Clean rooms
2. Anechoic chambers
3. Vibration testing facilities
4. Thermal Vacuum Chambers
5. Shock testing facilties

All these facilities are available at Kyutech which should considerably lower the cost of development. The availablility of people with experties in different field will also be an added advantage. The total life cycle of the constellation should take no more than three year. With two years of development and one year of operations before disposal of the CubeSat.

The main risk points for this project are:

1. The financial constraints needed to work on multiple satellites at the same time.
2. The human resources needed for the project since Kyutech is a learning institution.
3. The time needed to design/aquire the low-cost radar suitable for debris monitoring.
4. The current shortage in electronic components might present a challenge when developing multiple satellites concurrently.
5. Launching the constellation in LEO conventionally using the KiboCUBE module might prove to be a challenge which will require an alternative solution.

References

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