Title: Nano-satellite constellation collecting global pre-earthquake signals for space-borne early earthquake detection

Primary Point of Contact (POC) & email: Richard Bui, tdvbui@.ntu.edu.sg

Co-authors: Charlie Soon, Tawon Uthaicharoenpong

Organization: Nanyang Technological University, Satellite Research Centre (SaRC)

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Need

Earthquakes killed 432,000 people and cost more than 235 billion US dollars of economic losses worldwide over the past five years. Out of the five most expensive natural disasters in history, four are earthquakes [1]. Unfortunately, there is still a lack of effective way to predict earthquakes to save life unlike other natural disasters.

Studies indicate that earthquake is linked to traits of earthquake lights, thermal anomalies, low frequency electromagnetic emissions, and ionospheric anomalies [2]. Currently, the studies of these traits are either based on laboratory experiment or coincidence data obtained from the earth's observation. It would be invaluable to gather this information collectively for the same location at the same time globally. Establishing a comprehensive database for researchers worldwide using the pre-earthquake signals to develop advanced early earthquake detection technologies will be very useful for the mankind.

Mission Objectives

By using a dedicated nano-satellite constellation, a database of global pre-earthquake signals is built up to fulfill the following objectives:

1. Gather global data on thermal anomalies, earthquake lights, low frequency electromagnetic emissions, and ionospheric anomalies.
2. Create an open database of pre-earthquake signals to facilitate the development of early earthquake detection technology.
3. Develop an early earthquake detection method based on pre-earthquake signal fusion (e.g. Kalman filter and genetic algorithm) and test on the nano-satellite constellation.

Upgrade the mission to early earthquake detection once the method is fully developed, and add more satellites to the constellation.

Concept of Operations

The constellation consists of two nano-satellites operating in the same sun-synchronous orbit at 600-km altitude with 2° arc angle separation. Each satellite is equipped with a mid-wavelength infrared (MWIR) 3.6-4.9 μm and a long-wavelength infrared (LWIR) 8-12 μm cameras, single-axis coil magnetometer, and S-band transceiver, to record pre-earthquake signals.

To capture earthquake lights and thermal anomalies: Sat-1 and Sat-2 will survey over a large area on Earth's surface for potential pre-earthquake signals. The LWIR cameras will detect possible thermal anomalies [3], while MWIR cameras look out for earthquake lights, and provide the thermal background reference for the LWIR images. The cameras have 66° FOV in wide-angle mode, and are inclined 33° in roll direction. So the combined FOV from Sat-1 & Sat-2 is 132°, corresponding to a 4968-km swath @ 600-km attitude. When there is a potential spots detected (with MCC's confirmation), the satellites will capture high-resolution IR images during the next few flyovers.

To record extremely-low-frequency (ELF) magnetic field disturbance: Sat-1 and Sat-2 will search for unusual pattern, i.e. ELF bursts, in Earth's magnetic field. Data from both satellites will be combined to effectively remove ELF bursts by self-induced satellite noise.

To observe ionospheric anomalies: Sat-1 will transmit a S-band beam at a specific angle (10.5° from nadir), so that the beam will bounce from Earth's surface, and receive by Sat-2. The received signal is then compared with signal from a direct inter-satellite link, to observe changes in signal strength and phase by ionospheric anomalies.

Figure 1 illustrates the concept of operation of the space-borne early earthquake detection nano-satellite constellation.

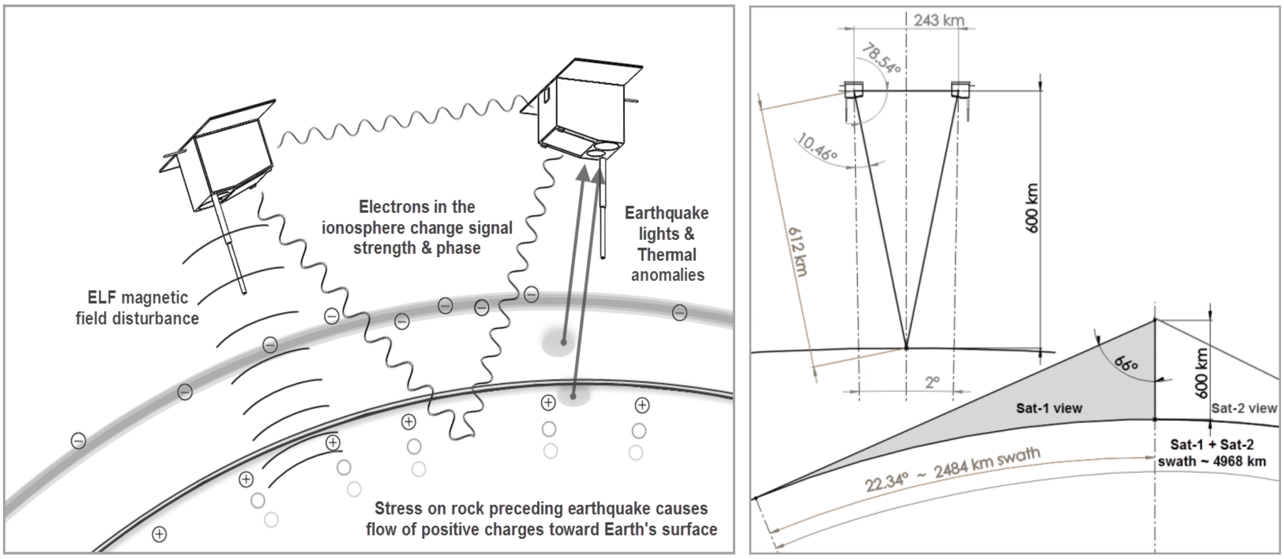

Figure 1 – Concept of operation (left) and constellation details (right)

The measurement of possible pre-earthquake signals is carried out in eclipse. This is to ensure that there is no IR reflection and the ionosphere is least affected by the sun. During eclipse, the satellites point to nadir for Earth observation. During day light, the satellites will perform sun tracking to harvest sufficient solar energy. The switching from sun pointing to nadir pointing and vice versa of the satellite is shown in Figure 2.

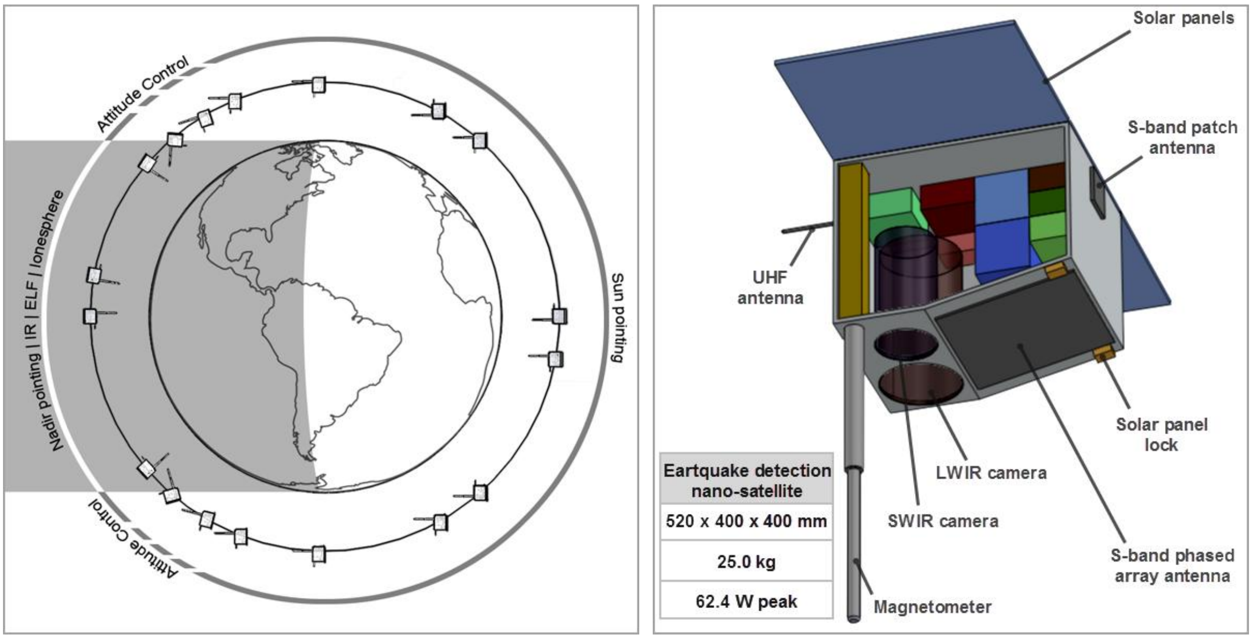

Figure 2 – Satellite operation modes (left) and conceptual design (right)

Key Performance Parameters

1. LWIR and MWIR images combined from Sat-1 and Sat-2 have a swath wider than 2700 km at 600 km attitude, in wide-angle mode, for 100% Earth's surface coverage per day.
2. LWIR images with ground sampling distance (GSD) less than 90 m, and MWIR images with GSD less than 30 m, at 600 km attitude, in high-resolution mode.
3. Magnetometer and ELF receiver with sensitivity of 10 pT/√Hz at 1 Hz, and frequency response of 1-1000 Hz.
4. S-band antennas with gain over 21 dBi, and steerable in ±12° range [4], for feasible Earth-bounced beam between the nano-satellites.
5. Data (IR images, S-band beam's signal strength and phase shift, ELF bursts) to be stored for at least 1 month, for comprehensive sample from pre-earthquake, post-earthquake, and normal periods.

Orbit/Constellation Description

The constellation details are shown in Figure 1. Sat-1 and Sat-2 are separated at approximately 2° (243 km distance), in a 600-km sun-synchronous orbit. Sun-synchronous orbit is essential for this observation mission, to have the satellites passing by a region at the same time every day. So the global pre-earthquake signals collected for a region will be at a specific time of the date, and are easier for analysis.

At 600-km attitude, the satellites will complete an orbit in 95 minutes, with 35 minutes in eclipse to perform their mission. Every day the satellites will circle the Earth about 15 times, and by orbit perturbation, will span through whole Earth's surface.

Possible launchers for this nano-satellite constellation are DNEPR and ISRO's PSLV.

Space Segment Description

The conceptual design of the nano-satellite with its scientific payloads is shown in Figure 2. Key specifications are listed in Table 1.

Table 1 – Power, mass, and link budget

Power, mass, and link (payload) budget			Power Watt	Mass gram
	STTC	Structure and thermal control	–	6000
Satellite bus	PCDM	Power conditioning & distribution	2.00	400
	OBDH	On-board data handling	5.00	400
	ADCS	Attitude determination & control (RWs, sun sensor, star tracker)	7.50	2200
	COMM	UHF transceiver	4.00	200
		Antennas (UHF, S-band patch)	1.00	200
Payloads	IR	LWIR camera with 15-100mm F/1.4 zoom lens	10.00	5000
		MWIR camera with 15-300mm F/4 zoom lens	10.00	2100
	ELF	Induction magnetometer	2.50	1100
	Iono-sphere	2x S-band transceiver	10.00	800
		S-band phased array antenna	–	1000
		Peak Power (with 20% margin)	**62.40 W**	
Power	Solar panels	2 deployable panels + 1 fix panel, 40cm x 52cm, 30% GaAs cells	180 Wp	4500
	Battery *(DoD ≤ 20%)*	2s10p, 2600mAh Li-ion cells, 7.2V	26 Ah	1100
		Max. load energy throughout eclipse	37.4 Wh	**Total 25.0 kg**
		Max. avg. load power in eclipse	64.18 W	

Earth–bounced (a) & Inter-satellite (b)	Unit	(a)	(b)
EIRP	**dBW**	**24.0**	**9.0**
. TX power	dBW	4.0	4.0
. TX antenna gain	dBi	21.0	6.0
. TX line + pointing losses	dB	-1.0	-1.0
Path loss	**dB**	**-172.0**	**-150.8**
. Free-space loss	dB	-161.8	-147.8
. Polarization loss	dB	-3.0	-3
. Atmosphere attn.	dB	-2.0	n/a
. Reflectivity *(worst case: 0.3)*	dB	-5.2	n/a
G/T	**dB**	**-8.3**	**-23.3**
. RX antenna gain	dB	21.0	6.0
. RX line+pointing loss	dB	-1.3	-1.3
. System noise temp.	dBK	-28.0	-28.0
C/N (= EIRP + Path loss + G/T + 228.6)	**dB**	**72.3**	**63.5**
C/N required (9600bps, 10dB Eb/N0)	dB	56.8	56.8
System Link Margin	**dB**	**15.5**	**6.7**

Implementation Plan

The Satellite Research Centre (SaRC) is an established satellite research centre in Singapore. It has an operational 105kg micro-satellite (i.e. X-SAT) built totally in-house. The satellite has operated in orbit for a year with more than 200 imaging operations and 1000 pieces of 12m resolution satellite images.

SaRC has a nano-satellite development team comprising 2 project managers, 10 research engineers and 10 PhD students reporting to the centre director Prof Low Kay Soon. Each year, SaRC trains 50 undergraduate students to work on various aspects of satellite technology, under the Undergraduate Satellite Program.

The centre is well equipped with vacuum and thermal chambers, class 5k clean room, Helmholtz cage, precision motion simulators, sun simulator, solar array simulators, etc. SaRC MCC includes a VHF/UHF ground station, a 6.1m S-band ground station, and a 13m X-band ground station via its partner CRISP. These facilities have been used to operate X-SAT and will also be used to operate a pico-satellite VELOX-P and nano-satellite VELOX-I to be launched by 2013.

The cost for the project including launch is estimated to be $5.3 Million. The project development will take 2 years and the mission will last for 3 years. The details are shown in Figure 3.

Stage	Cost $ mil
Payload prototypes	0.60
Engineering model	0.60
Sat-1 & Sat-2 FM	1.20
Systems tests	0.30
Development cost	2.70
Launch	2.00
Operating cost (3 years)	0.60
Grand total	**5.30**

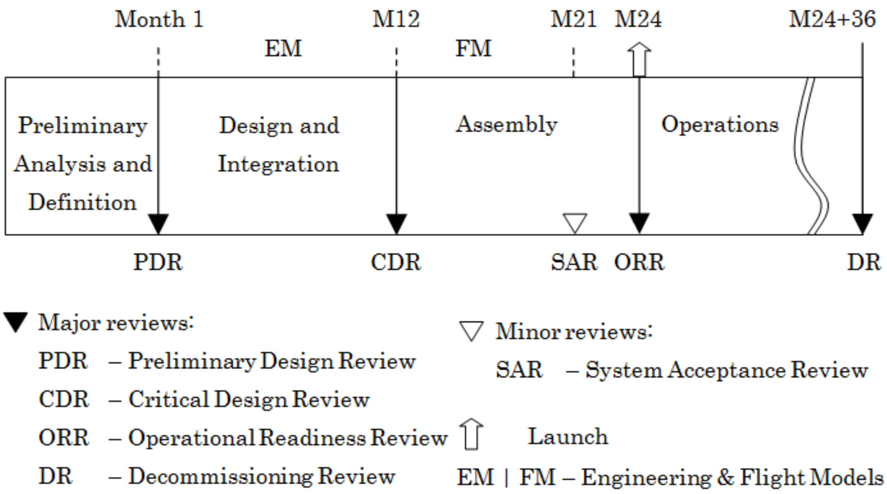

Figure 3 – Cost estimation and development plan

Risks

1. **Programmatic:** The main issue is the availability of funding for the satellite development and the launch. Collaborating with partners is one approach to realize the program.
2. **Technical:** The failure of constellation deployment may make the ionospheric payload (Earth-bounced and inter-satellite S-band links) not feasible. If the separation angle is 10°, instead of 2°, the satellites must turn ±30° more in pitch, which will affect the IR payloads.
3. **Operational:** Security issue of revealing IR images of countries may hinder the building of the open global pre-earthquake signals database. We will investigate setting resolution limits and filter sensitive information if necessary.

References

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[2] F. T. Freund, "Pre-earthquake signals – Part I: Deviatoric stresses turn rocks into a source of electric currents", Nat. Hazards Earth Syst. Sci., 7, pp. 535-541.

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