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A NOVEL CONCEPT FOR EARTH REMOTE SENSING USING A BI-STATIC FEMTO-SATELLITE SWARM IN SUN SYNCHRONOUS ORBIT

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Recent developments in spacecraft design exploiting micro-electro-mechanical systems (MEMS) with sensing, computing, full-duplex communications and micro-power generation has introduced the prospect of a new class of low-cost, low-mass Femto-scale (10∼100g) spacecraft suitable for use in swarm and distributed missions. Current concepts for functional devices have been designed by exploiting existing technologies to develop femtosatellite prototypes. Distributed femtosatellites are considered as a solution to reducing the cost of conventional Earth remote sensing and monitoring missions. In this paper, we introduced a new preliminary design of femtosatellites using commercial off-the-shelf (COTS) technology, which can provide an acceptable level of mission capability and environmental survivability. This new design features high area-to-mass ratio that enables the femtosatellites to take advantage of solar radiation pressure (SRP) for orbit control without onboard propellant. Using the unique environment enabled by a dawn-dusk sun synchronous orbit, the femtosatellites would be under direct illumination during the entire orbit without eclipsing. What's more, it could maximize electrical power generation for the payload and enabling orbit control using SRP. The performance of a femtosatellite swarm for bi-static radar application is analysed with example scenarios.

I. INTRODUCTION

The concept of femtosatellites first emerged in May 1963 in the West Ford Experiment[1], a cloud of needles used as an artificial reflection layer for 8 GHz microwaves. The needles were 18 mm long and 0.018 mm diameter, reflecting received signals in all directions. Some 480 million copper needles were launched in the experiment. After two months, the needles spread to a 30 km thick and 15 km wide cloud at 3700 km altitude. Thirty years later, feasible and cost-effective solutions for femtosatellites were introduced as the "satellite-on-a-chip" concept in 1994[2]. Subsequently, many concepts were proposed, such as Co-Orbiting Satellite Assistant (COSA), PCBSat, WikiSat, PocketQub, PhoneSat, and ChipSat.

Moreover, radar was initially developed for the military purposes during World War II by calculating the range base on the direction of the antenna and time delay between radar and the target. Subsequently, Doppler shift was implemented in radar systems to measure the speed of the target. Doppler shift has also been used to achieve higher spatial resolution in a direction perpendicular to the beam direction. In 1951, Carl Wiley of Goodyear Aerospace used radar to capture two-dimensional images of targets which became the origin of Synthetic Aperture Radar(SAR)[3].

Earth remote sensing emerged from photography to multi-spectral images, with data on the Earth's surface supplied by airborne and the spaceborne platforms. SAR was not used for Earth remote sensing until the technology was released from military to civilian applications in the 1970s. SAR systems includes a signal source so it operates night and day, unlike optical sensors which depend on scattered sunlight. A wide range of Earth remote sensing applications based on SAR technology have been investigated and implemented.

Two example femtosatellites are now analysed in section II. One uses an optical sensor to capture images of the Earth's surface. However, in order to increase the utility of femtosatellites, bi-static radar for Earth remote sensing wii be discussed later in the paper.

II. CURRENT FEMTOSATELLITES

Many femtosatellite concepts, which aim for cost-effective applications have emerged recently. The common theme is that they use a minimal design to accomplish mission objectives. Simplifying and integrating subsystems are the most common ways to achieve this goal. Instead of conventional system architecture engineering that develops each sub-system individually, femtosatellites can be developed with integrated multifunctional sub-systems.

WikiSat

WikiSat is a femtosatellite with a sub 20g mass and dimensions of 141×30 mm[4]. It is a satellite developed to record and download Earth images in low Earth orbit (LEO). A prototype has been launched into a 250km orbit with a lifetime less than one month.

Fig. 1: WikiSat

The fourth version of WikiSat, shown in Figure 1, is built on a two-layer PCB with an ATmega168 avr microcontroller running open source Arduino firmware. An InvenSense ITG-3200 3-axis gyroscope and an STMicroelectronics LIS331HH 3-axis accelerometer are used for the inertial measurement unit (IMU) to measure the orientation and two pairs of magnetorquers maintain an Earth facing attitude. The onboard payload is a TCM8230MD camera to capture images at 640 × 480 resolution. The images are sent back to a ground station via the NRF24L01 2.4GHz low power transceiver and a synthetic aperture antenna made by 4 AT9520 multilayer chip antennas, which point the beam to Earth electronically. It uses a coin battery to provide power instead of solar cells to maximise performance during its short orbit lifetime.

Sprite

The Sprite satellite, shown in Figure 2, is a simple proof of concept femtosatellite[5]. Sprite is a 35×35 mm femtosatellite with a mass of 5g, developed by Cornell University and crowdfunded via Kickstarter. The idea is to create a 'personal spacecraft', that could be owned and operated on a low budget. Sprites were launched into orbit above 300km inside a 3U CubeSat called 'KickSat' on 18th April 2014. Unfortunately, the Sprites failed to deploy due to a clock reset and were lost during re-entry on 15 May 2014.

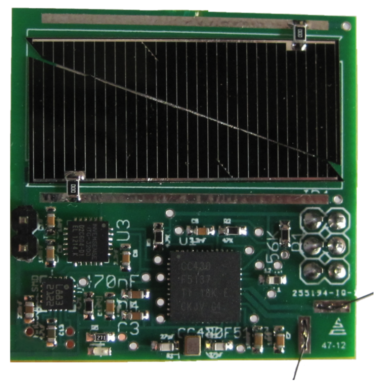


Fig. 2: Sprite developed by Cornell University

Sprite is designed as a free floating satellite without attitude control. A Texas Instruments CC430F5137 microcontroller running Energia firmware is used as the onboard computer. The IMU includes an InvenSense ITG-3200 3-axis gyroscope and a Honeywell HMC5883L 3-axis compass. Sprite is designed to send a beacon signal to ground via CC1101 radio at 437.240 MHz, which is integrated into the microcontroller. Two solar panels provide power for the microcontroller and communication. A comparison between WikiSat and Sprite is shown in Table 1.

	WikiSat	Sprite
Size	141 × 30mm	35 × 35mm
Weight	7.6g	5g
MCU	ATmega168	CC430F5137
Radio	NRF24L01	CC1101
Frequency	2.4GHz	437.240MHz
IMU	Gyroscope Accelerator	Gyroscope Compass
Power	Coin battery	Solar Panel
Payload	Camera	N/A

Table 1: Comparison between WikiSat and Sprite

III. PROTOTYPE DESIGN

A preliminary design of a femtosatellite using commercial off-the-shelf (COTS) technology has been developed to provide an acceptable level of mission capability and environmental survivability for a swarm radar mission. Based on previous concept for femtosatellites, the design goals are as follows: lightweight (∼10g), high area-to-mass ratio, integrated subsystems, passive thermal control, low-cost manufacture.

Having a high area-to-mass ratio enables the femtosatellites to take advantage of the solar radiation pressure[6] for propulsion without onboard propellant, extending its orbital lifetime. By integrating subsystems together, the size and weight of the femtosatellite can be minimized to provide additional payload capacity. Re-configurability would enrich the mission capability and system reliability. For example, femtosatellites could be re-configured as relays to extend the communication range of an individual device. Passive thermal control also protects the femtosatellite from extreme temperatures with minimum mass.

Figure 3 shows the block diagram of a femtosatellite preliminary design. It has been divided into two main parts, hardware and software. The main goal is to make the hardware part as simple as possible and push the boundaries of the software.

- Femtosatellite
  - Mechanical
    - Structure
    - Propulsion
  - Electrical
    - Data processing
    - Communication
    - Guidance & navigation
    - Power management
    - Applications

Fig. 3: Femtosatellite architecture

In order to accomplish the design specifications, the femtosatellite has been designed as a flat-bubble shape as Figure 4. The femtosatellite is built on Kapton film instead of a printed circuit board to reduce weight and provide flexibility. The extended Kapton film covers the core electronics to protect the electronics from radiation and provides passive thermal control. The thin film solar panel around the edge are not be covered.

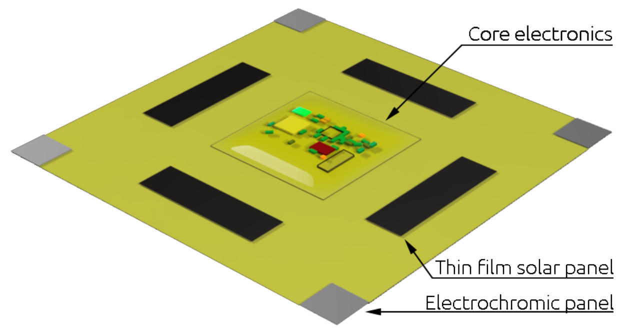


Fig. 4: Flat-bubble shaped prototype concept

The power provided by the solar cell is limited, thus a Texas Instruments MSP430F2274-EP Ultra-Low-Power microcontroller and CC2520 RF transceiver has been chosen to minimize the power consumption. MSP430F2274-EP is an enhanced version for defence, aerospace and medical applications. The main feature is the military temperature range, which improves survivability in extreme thermal conditions. Compared to other microcontrollers, the MSP430F2274 also includes two configurable operational amplifiers. This combination could be reconfigured in software for different objectives to enrich mission capability. In addition, the CC430 series is available for simple applications to reduce weight, which has an integrated microcontroller and sub-1GHz RF transceiver. The working temperature of −40 °C to 85 °C is a limitation for some applications.

Antenna

In order to maintain the high area-to-mass ratio and benefit from solar radiation pressure, flat antennas are considered for radar applications, for example, a patch antenna, microstrip antenna or Vivaldi antenna. Depending on the orbit and the required attitude angle of the femtosatellite, the antenna design could vary between a single and array design. A Vivaldi antenna is used in the preliminary design discussed later.

A surface mount chip antenna is used for communication between femtosatellites and the carrier spacecraft. It features a smaller footprint and a stable performance than other commonly used antennas.

Specification

Basic specifications of femtosatellite prototype design are shown in Table ?? to define the prototype requirements.

Size	95 × 95mm
Weight	15-20g
MCU	MSP430F2274-EP
Radio	CC2520
Frequency	2.4GHz
IMU	Gyroscope
	Accelerator
Power	Thin file solar panel
	Battery
Payload	Vivaldi Antenna

Table 2: specification

IV. SWARM ORBITAL DYNAMICS

Sun Synchronous Orbit

Common to most small satellites, the low power density of batteries is the main limitation of their performance. Therefore, a 'dawn-dusk' Sun synchronous orbit is frequently used in Earth remote sensing could provide constant solar flux without eclipse. In a dawn-dusk orbit, the orbit plane remains perpendicular to the incoming solar radiation. The femtosatellites would therefore be under direct illumination during the entire orbit without eclipse to maximise electrical power generation for the payload and enabling orbit control using solar radiation pressure. Figure 5 and 6 shows the mean orbital inclination and ground track of the Sun-synchronous orbit.

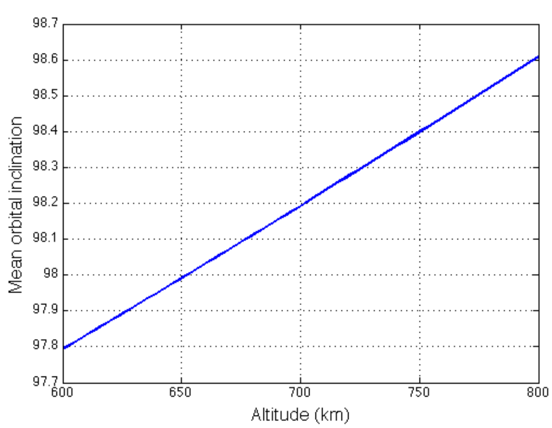


Fig. 5: Required inclination for Sun-synchrous orbit

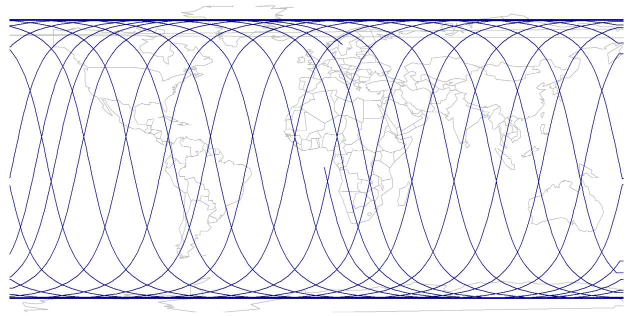


Fig. 6: Ground track for a 700km altitude Sun-synchronous orbit

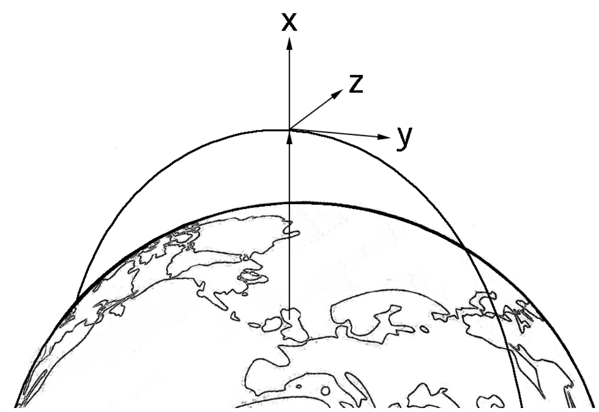


Fig. 7: Coordinate-system geometry for relative motion

Relative Motion

In the space environment, the periodic motion between two close objects with a relatively short distance between them is called relative motion. The period of this relative motion is the same as the period of the reference orbit about the Earth. In order to describe such relative motion, a coordinate system is introduced in Figure 7, where the x-axis is perpendicular to the Earth's surface from the centre of the Earth and the y-axis is aligned with the velocity vector of the circular orbit. An assumption is made that all objects are in nearly circular orbits. The linearised relative motion can be written in the form of the Clohessy-Wiltshire or Hill's equation[7]:

$$\begin{cases} \ddot{x} - 2\omega_n \dot{y} - 3\omega_n^2 x = a_x \\ \ddot{y} + 2\omega_n \dot{x} = a_y \\ \ddot{z} + \omega_n^2 z = a_z \end{cases} \quad [1]$$

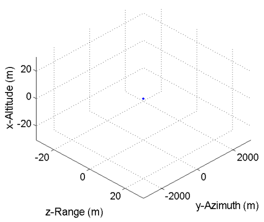
where:

$$\omega_n = \sqrt{\frac{\mu_{Earth}}{r_{chief}^3}} \quad [2]$$

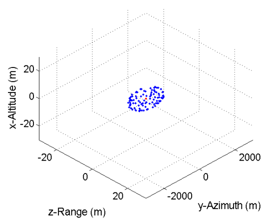
This relative motion model can be used to describe

ω: mean motion
μ: planetary constants
r: length of the semi-major axis

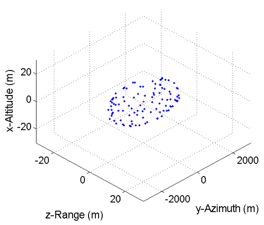
the position of a swarm of femtosatellites after being released from a carrier spacecraft. The motion in the x-axis and z-axis introduces challenges for radar signal processing due to focusing problems, requiring algorithms such as a non-linear chirp scaling method to achieve finer focusing. In addition, this model could be used to provide a better estimation of the femtosatellites' position when combined with other methods. With the same initial speed of 1 m/s in random directions, the geometry of a femtosatellite swarm can be simulated, as Figure 8.



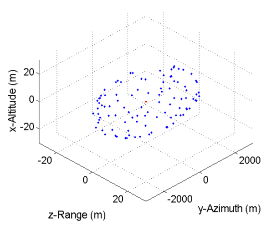
(a) t = 0s



(b) t = 300s



(c) t = 600s



(d) t = 900s

Fig. 8: Swarm dynamics

V. BI-STATIC RADAR APPLICATION

The Earth remote sensing application to be considered is Synthetic Aperture Radar (SAR). SAR is a technique that uses a large virtual antenna that is formed by relative motion between the radar and target to achieve high-resolution images.

For the Sun-synchronous orbit Earth remote sensing considered in this paper, a Vivaldi antenna[8] is chosen to maximise the solar panel efficiency and take advantage of solar radiation pressure for orbit control, as shown in Figure 9.

Compared to monostatic SAR system, bi-static SAR receives echos from different locations[9]. The time delay is the combination of transmitter-to-target and target-to-receiver delay. In this application, the carrier spacecraft and femtosatellites are the transmitter and receivers respectively.

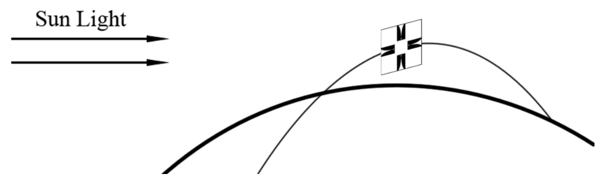


Fig. 9: Sun facing femtosatellite with Vivaldi antennas

The transmitted signal used in the simulation is described by Equation 3 and the demodulated received signal for bi-static configuration is described by Equation 4.

$$s_{tx}(t) = w_r(t) cos\{2\pi f_o \pm \frac{\pi B_0 t^2}{T_r}\} \qquad [3]$$

$$s_{rx}(t,\eta) = \sum_{m=0}^{M-1} \Big[F_m w_r \left(t - \frac{R_{tx}(\eta,m) + R_{rx}(\eta,m)}{c}\right) w_a(\eta - \eta_c) e^{-j2\pi f_o \left(\frac{R_{tx}(\eta,m)+R_{rx}(\eta,m)}{c}\right) + j\pi K_r \left(t - \frac{R_{tx}(\eta,m)+R_{rx}(\eta,m)}{c}\right)^2}\Big] + n_m(t,\eta) \qquad [4]$$

where:

t: quick time
w_r: transmit window
f_o: carrier frequency
B_0: bandwidth
T_r: chirp pulse duration
η: slow time
F_m: attenuation factor
R: range to target
c: speed of light
w_a: antenna gain factor
n: Gaussian noise (AWGN)

SAR Performance Evaluation

An example scenario is developed to evaluate the performance of the bi-static femtosatellite swarm. A carrier spacecraft with 200 femtosatellites is in orbit around the Earth at 700 km altitude. According to Equation 2, the orbital speed is 7.5 km/s with an assumption of circular orbits. Femtosatellites are released 15 minutes in advance of imaging from the carrier spacecraft with an initial speed of 1 m/s in random directions. The main parameters are listed in Table **??**.

Carrier Frequency	4.5 GHz
Bandwidth	100 MHz
Pulse Repeat Frequency	3000 Hz
Duration	3 s
Chirp Pulse Duration	10 μs
Orbit Altitude	700 km
Swath Range	140 km
Velocity	7.5 km/s
Femtosatellite Release Speed	1 m/s

Table 3: Parameters

Raw SAR data generated from Equation 4 is processed by a Range-Doppler Algorithm (RDA) to produce the image. The offset between the carrier spacecraft and femtosatellites are corrected based on their position. An airliner showed in Figure 10 is used as a target. Figure 11 is the image from mono-static configured SAR used as a benchmark.

Fig. 10: Example airliner

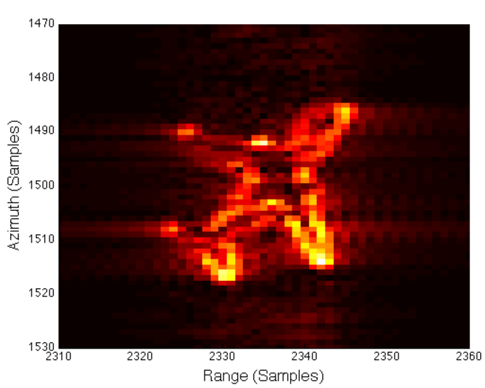


Fig. 11: Mono-static SAR image

Test 1

Figures 12 to 16 show the images produced from different quantity of femtosatellites under 60 dB Gaussian noise. The airliner is invisible in Figure 12 and Figure 13 when using 1 or 20 femtosatellite receivers. When there are up to 50 femtosatellites, the airliner starts to appear in the images, as in Figure 14. However, the difference between Figure 15 and Figure 16 is not clear, even with twice the number of femtosatellites.

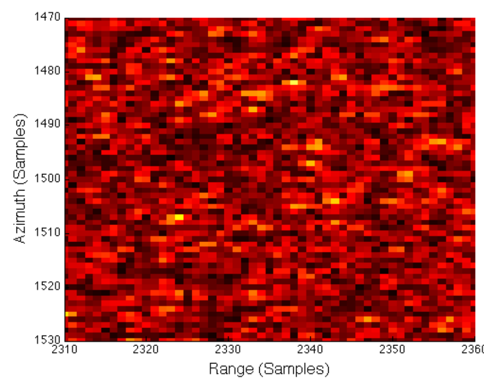


Fig. 12: Image from 1 femtosatellite with 60 dB noise

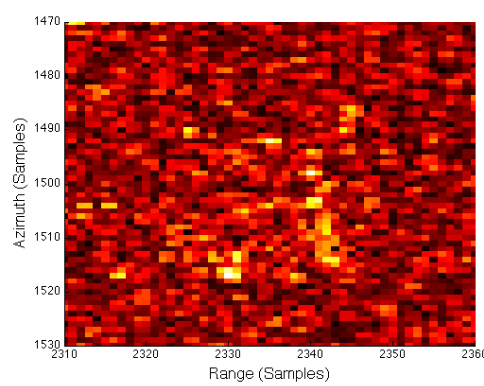


Fig. 13: Image from 20 femtosatellites with 60 dB noise

Test 2

Figures 17 to 20 show the processed images under different Gaussian noise levels. All images are processed based on the received data from 50 femtosatellites. Figure 17 presents a similar result with 40 dB Gaussian noise compared to the benchmark in Figure 11. As the noise level increases, the airliner becomes less visible and hard to identify.

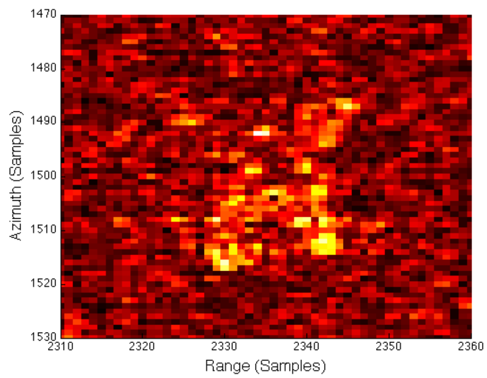


Fig. 14: Image from 50 femtosatellites with 60 dB noise

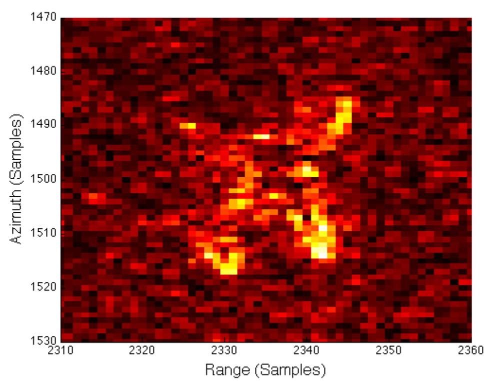


Fig. 15: Image from 100 femtosatellites with 60 dB noise

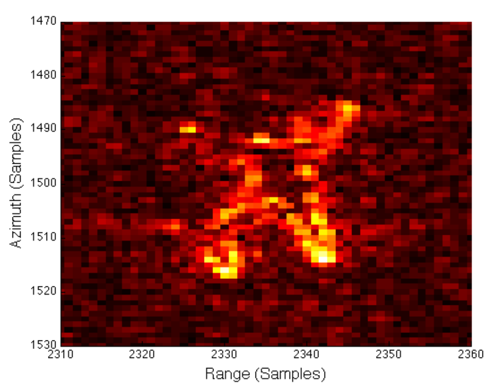


Fig. 16: Image from 200 femtosatellites with 60 dB noise

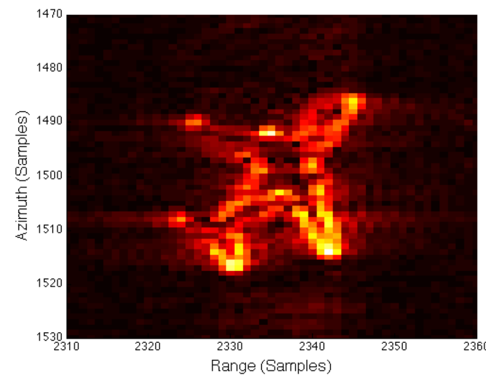


Fig. 17: Image from 50 femtosatellites with 40 dB noise

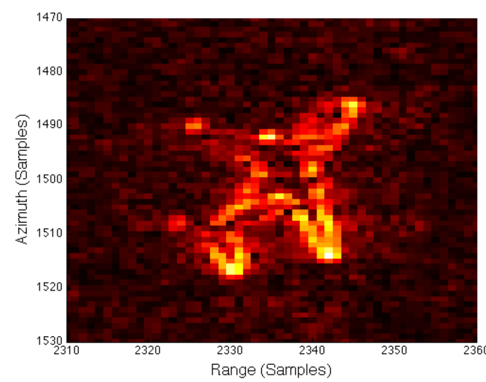


Fig. 18: Image from 50 femtosatellites with 50 dB noise

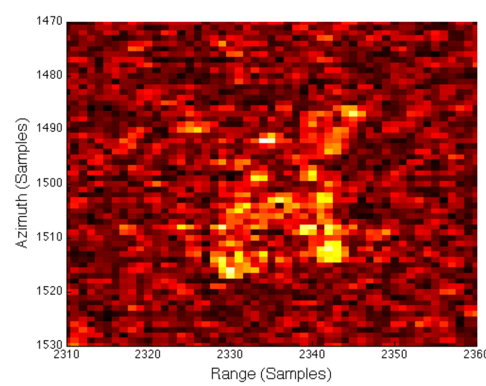


Fig. 19: Image from 50 femtosatellites with 60 dB noise

VI. CONCLUSION

In this paper, a novel concept for Earth remote sensing using a bi-static femtosatellite swarm in Sun-synchronous orbit has been proposed to explore the mission capability of the femtosatellite swarm concept. The preliminary prototype design features a low-cost, high area-to-mass ratio concept to maximise solar power generation and take advantage of SRP for attitude control. Example scenarios were simu-

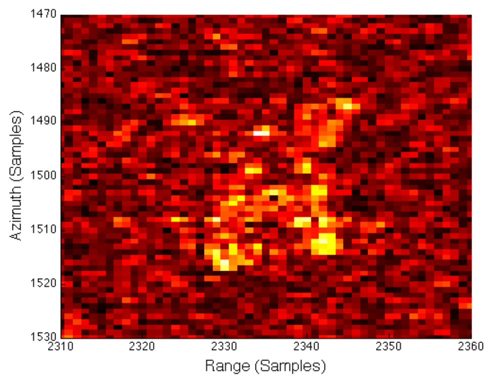


Fig. 20: Image from 50 femtosatellites with 70 dB noise

lated for evaluation by using a bi-static SAR model. The results show the potential of femtosatellites as receivers. In addition to Earth remote sensing, a bi-static femtosatellite swarm could be also used for target detection such as ships with automatic identification system (AIS) turned off or airliners with beacon turned off. With femotesatellite swarms, bi-static SAR performance could improve against noise. Bi-static SAR performance could be further improved by applying advanced signal processing algorithms which will be investigated in future work.

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