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BIRDS-1 CubeSat Constellation Using Compact UHF Patch Antenna

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ABSTRACT BIRDS-1 satellites, a constellation of five identical 1U CubeSats, were designed, manufactured, assembled, integrated, and tested at LASINE Laboratory, Kyutech, Japan. Students from five nations (Japan, Ghana, Mongolia, Nigeria, and Bangladesh) collaborated to develop a number of CubeSats with coordinated ground coverage, named ‘‘Joint Global Multi-Nation BIRDS,’’ or abbreviated as ‘‘BIRDS.’’ To establish the downlink communication between satellite and Earth, an UHF patch antenna was utilized. Patch antennas offer an ideal solution to Cube satellite communication requirements due to their compact dimension and lightweight. However, the limited surface area available in CubeSats, conventional UHF and VHF patch antennas cannot be used. In this paper, a compact coaxial fed UHF (437.375 MHz) patch antenna system for 1U BIRDS-1 CubeSat (small satellite) is presented. The proposed antenna consists of a spiral meander line patch at the top side and partial ground plane another side of the substrate. A shorting pin has also been utilized to change the resonance to the required UHF band. For the intended 1U BIRDS-1 application, the goal is to mount on satellite body within a limited area of 1U BIRDS-1 satellite. The proposed antenna dimension ($0.105\lambda \times 0.047\lambda \times 0.002\lambda$ at 437.375 MHz) and characteristics are compatible with any CubeSat standard structure. A prototype of the antenna was developed with a 1.57-mm-thick single layer Roger's substrate having a relative permittivity of 2.2, and measured results are consistent with simulation. The proposed UHF antenna has integrated and tested with 1U BIRDS-1 satellite. Finally, the satellite was successfully launched on June 3, 2017, from the John F. Kennedy Space Center, the USA at Low Earth Orbit for earth observations, message relay, space environment, and technology demonstration through the International Space Station.

INDEX TERMS BIRDS, CubeSat, compact planar antenna, a small satellite, UHF.

I. INTRODUCTION

Cube Satellites are tiny cube-shaped small satellites with dimension 10 cm per edge and a mass less than 1 kg. The cubic structure encompasses a specific aluminum box with solar panels fitted to the exterior walls [1]. Antennas, usually flexible monopoles, are integrated perpendicular to the CubeSat faces, in the corners. CubeSats have been mainly utilized for university research work giving student's working encounter in developing and screening equipment for space [2]. However, it is very clear that the utility worth of CubeSats is usually quickly increasing. Reliable, high-performance, industrial CubeSats are actually obtainable and there might be an extremely persuasive case for CubeSats to be used in lots of applications, including technology marketing and sales communications, global observation, and technology demonstration. CubeSats usually use VHF and UHF communication for telemetry and telecommand applications. It's very challenging to design a small antenna for CubeSat communication system because of the CubeSat physical size constraint. Usually, impartial versatile monopole antennas are installed using one face of the satellite structure to establish up- and downlink communication. These antennas are rolled around the satellite before deployment and kept setup with monofilament assured utilizing a brief amount of Nichrome wire within the spacecraft. Upon deployment, a current is passed through the Nichrome wire, which heats and melts the monofilament and warp/unroll the antennas. The use of wire monopoles, though basic, raises serious concerns of deployment failure. For UHF and VHF band communication, large deployable antennas are needed that further raise failure potential. Among the primary design considerations of Cube satellites is usually an efficient and low-cost antenna. Microstrip patch antennas are among the main candidates for small satellite communication, especially because of their light-weight, low profile and body mounted features [3], [4]. There are many small satellites antennas are pointed out in various research article such as monopole antennas, wire antennas, printed inverted-F-shaped antennas (PIFAs), microstrip-patch antennas, helices, and patch excited cup antennas, were designed for telemetry, tracking, and command in the UHF, VHF band [5]–[7], but all of them are developed for larger than 1U CubeSat dimensions and compatible features.

Mathur et al., 2001 explained the look of UHF patch antennas for the USUsat nano-satellite which is usually a section of the ION-F constellation. The uplink antenna functioned at 450 MHz, with part length add up to 106.7 mm [8]. In the other end of the look spectrum, the task by [9] is an example of how suspended, electrically large areas can show quite significant bandwidths. Furthermore, resonant-size areas can produce benefits in the number 4-6.5 dBi and bandwidths of the few percents [6], [10]–[12]. Alternatively, 3-D structures comprising folded and stacked radiating areas offer average bandwidths and benefits combined, and may also become electrically small [13]. C. G. Kakoyiannis et al engineered a circularly polarized patch antenna that functions at 434.8-438 MHz using miniaturization techniques. The authors focus on the difficulties in developing patch antennas at UHF given the scale limitations of CubeSats, emphasizing the actual fact that electrically small antenna overall performance endures, and recommending the utilization of patch antennas at higher frequencies such as 2.4 GHz [14]. The first UoSAT spacecraft utilized VHF and UHF transmitters with related wavelengths of 2 m and 70 cm on constructions typically measuring 58 cm ×35 cm ×35 cm. The body of the spacecraft was shorter than the wavelengths included (SSTL, 2011). Kakoyiannis and Constantinou have designed a UHF band group (436.5 MHz) CubeSat Patch Prototype (CSPP) [15]. The rectangular imprinted CSPP antenna packed with inductive peripheral slits with a dimension of 170 mm × 120 mm. Podilchak *et al.* designed a concise antenna structure utilizing a four-element arrayed construction of folded-shorted areas for the procedure at 400 MHz with dimension 150 mm by 150 mm [16]. Tiago Freire et. al explained the look and implementation of the dual-band spring-steel monopole antenna that resonates at 438 and 146 MHz, the give food to set up for the antenna, and the look of the diplexer for use in a Nano-class satellite known as a 3U CubeSats. The extensive use of UHF and VHF bands for data and tone of voice marketing communications was also exhibited by the TURKSAT CubeSat task. The 25 % wavelength dipole antenna with a width of 3 mm and height of 50 cm operates at 145 MHz. Another antenna functions at 435 MHz and includes six-quarter wavelength dipoles like the receiver antenna [17]. A UHF band (400-450 MHz) antenna was used for Communication with a ground station (range) for space research using CubeSat [18]. For onboard LAPAN-TUBSAT microsatellite telemetry and telecommand applications, a little UHF music group (428− 468 MHz) antenna was manufactured which was monopole-like meander type linearly polarized and omnidirectional microstrip antenna with dimensions of 160 mm by 140 mm [19]. Besides, some UHF antenna band was also presented in the recent various literature for CubeSat or small satellite applications [4], [20]–[25]. The antennas offered by above studies are similar to the designed antenna performance. However, the mentioned dimensions are larger than the allotted space which is not compatible in 1U and 2U CubeSatellite.

In this article, a compact UHF microstrip patch antenna was developed for BIRDS CubeSat application. To achieve compact antenna dimension, a meander line patch was designed on one side of the substrate and partial ground plane was printed on another side of the substrate. Beside this shorting pin, technique was also utilized to increase the electrical length of the antenna. After optimizing the antenna parameters, a prototype was fabricated and measured in the lab. Then, the proposed antenna integrated and tested with 1U BIRDS-1 Satellite in LaSEINE Lab, Kyutech, Japan. Finally, the five 1U BIRDS-1 satellite with UHF patch antenna has successfully launched in the low earth orbit.

II. BIRDS-1 SATELLITE

Now a day's small satellites are getting more and more attention due to short incubation time, low cost, and availability of highly reliable and efficient COTS (Commercial off-the-shelf) components. Even a small group of university researchers can assemble, test, launch and operate in orbit if the launcher is available and if researchers are well trained. Recently, five-nation (Japan, Ghana, Mongolia, Nigeria, and Bangladesh) CubeSat constellation has been designed and named as "Joint Global Multi-Nation BIRDS," or "BIRDS". Five identical CubeSats are designed, manufactured, assembled, integrated, tested, and operated by the researchers where each country is responsible for one CubeSat. After the assembling and testing, with the help of Japanese National Space Agency, JAXA, it has sent to ISS (International Space Station) for deployment to the Low Earth Orbit (LEO). It is operated from ground station of each country and other collaborating countries by amateur radio band. Through this processes, it can be demonstrated that a 1U CubeSat can be built and operated successfully in a time frame shorter than two years even for countries with limited (or zero) satellite experience with proper design and planning. The mission of the BIRDS- the project is to make the first step toward an indigenous space program at each country by successfully building and operating the first satellite nation.

A. BIRDS-1 SATELLITE MISSION

The ultimate objective of this project is to build and operate the first satellite of nation that triggers the first step toward indigenous space programs in each country. Students can achieve this by learning the entire processes of a satellite program from mission planning to satellite disposal. It also helps lay down a foundation of the sustainable space program by accumulating human resource in universities. This has also created international networks to assist the growing space programs. In order to accomplish this, BIRDS project has been designed to make a constellation of five identical 1U CubeSat with six missions, such as, Camera (CAM), Digi-singer (SNG), Precise positioning(POS), atmospheric density measurement (ATM), constellation network operation (NET) and single-event-latchup (SEL).

B. BIRDS-1 SATELLITE CONFIGURATION

Five CubeSats are designed as 1U (10 cm cube and 1kg) with dimension 100 mm × 100 mm × 113.5 mm CubeSat that is identical (mass, design, payload, communication, ground station, etc.) to each other. Attitude is controlled by a permanent magnet and a hysteresis damper. Five faces are covered by 10 solar cells; each face contains 2 cells in parallel. Six NiMH rechargeable batteries (3S2P) have been decided to provide 5V and 3.3V bus systems. Since Kyutech has the heritage and experience of one small Satellites Horyu-2 [20] operation, most of the BIRDS architecture is based on Horyu-2. To avoid complicacy due to the wire harness, each CubeSat has been planned to follow so-called backplane style, where different subsystems module such as OBC, EPS, COM, ADCS, Cam, transceivers, was placed on a backbone like a rail, according to the design of UWE-3 of University Wurtzburg, Germany [21]. The solar panel was placed on five faces and one face is assigned to the antenna. For the UHF patch antenna, the dedicated area was 80 mm × 45 mm. Figure 1 was depicted the 1U BIRDS-1 satellite (a) structural configuration (b) Communication step c) Communication block diagram. From the Fig. 1(c) communication block, it was planned to use VHF 1200bps uplink and UHF (437.372-437.375 MHz) 1200/9600bps data downlink. Two Cameras and a patch antenna for the mission are mounted on the +Y face. Solar panels are mounted on other faces of the CubeSat. The access port and RBF pins are on the −Y face. The deployable antenna has deployed from both + Z and −Z axis. Separation springs for interfacing with the Japan Experimental Module Small Satellite Orbital Deployer (J-SSOD) are mounted diagonally on the rail standoffs on the − Z face of the CubeSat. Deployment Switches are mounted adjacent to the two separation springs. Preceding satellite HORYU -II, launched in the middle of the calendar year 2012, operates in the low UHF band. Nevertheless, the deployable character of UHF antenna combined with the non-rigid framework eventually resulted in failure of the UHF conversation after almost twelve months in LEO. Therefore imprinted UHF antenna with the physical restrictions and

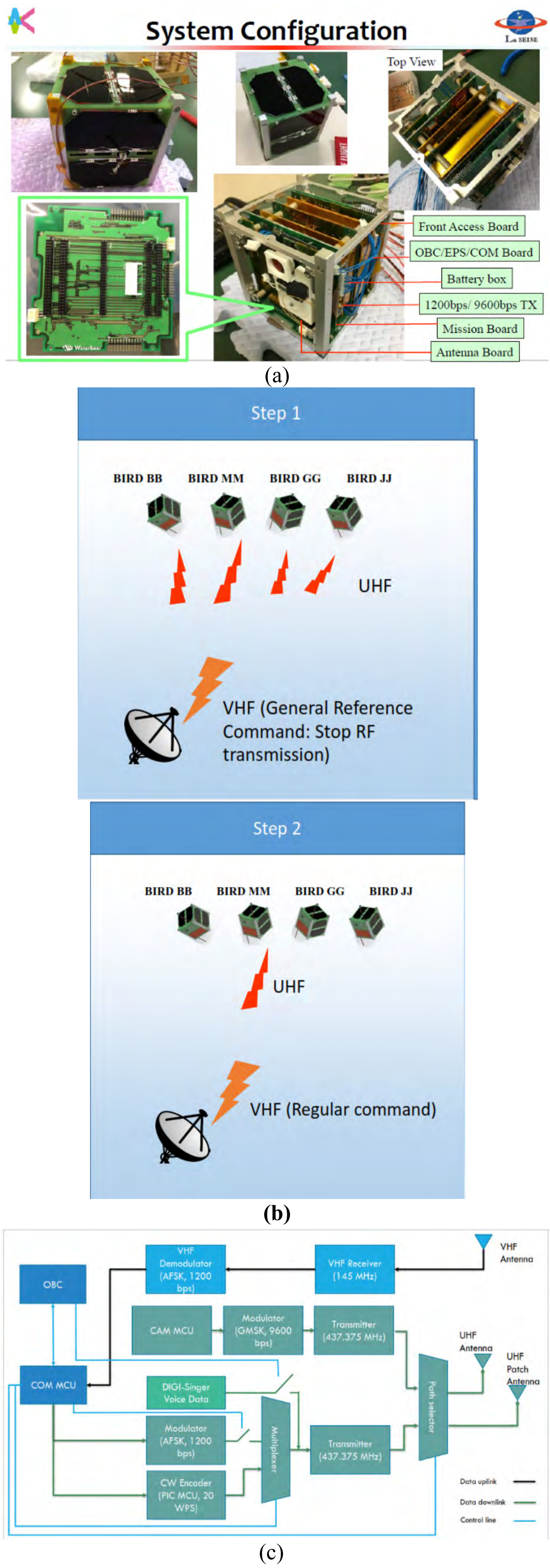


FIGURE 1. 1U BIRDS-1 satellite (a) structural configuration (b) communication step (c) communication block diagram.

requirements, defined by the objective protocol and evaluation of the prior HORYU-II, HORYU-IV and BIRDS objective mission data are summarized in Table 1 [4], [22].

TABLE 1. BIRDS UHF band antenna requirements.

Requirement	Specified value
Operating Frequency	437.372-437.375 MHz
Frequency Band	100 KHz (Min)
Maximum Dimension	80 mm×45 mm×2 mm (Max)
Thickness	10 mm (Max)
Polarization	Linear Polarization
Peak Gain	Positive Gain
Antenna weight:	~100 gm (max)
Return losses	<-10 dB
Connector type	MMCX coaxial fed
Radiation Pattern	Omnidirectional
Substrate Material	Space Compatible
Mounting	CubeSatellite body

III. ANTENNA GEOMETRIC LAYOUT DESIGN

The antenna design was started with a survey of state of the art patch antenna technology for CubeSat's satellites and various miniaturization techniques. Several recent references were also studied from the books, journal proceeding, research articles. The design involves a different combination of miniaturization techniques of patch antennas like folded meander line [23], [24], partial ground plane [25], and shorting pin [26] for small satellite applications. Commercial electromagnetic software based on finite element method (FEM) and Method of Momentum (MoM) was used to obtain the optimized design parameters. A parameter such as reflection coefficient, radiation pattern and efficiency has been studied. Rogers's substrate has been considered as a substrate material of the proposed antenna design because its high-reliability characteristic's for aerospace applications [27]. For restrictions of 1U BIRDS-1 cube satellite space, 50-ohm MMCX (Micro-Miniature Coaxial) coaxial probe feed line has been utilized for design requirements. The patch was connected through a drilled hole in the substrate and ground plane and feed line was adjusted for MMCX connector. To design a $\lambda_0/4$ resonant patch antenna at 437.375 MHz would require dimensions of ~172 mm excluding a ground plane which is totally unsuitable for 1U BIRDS-1 satellite. This size constraint means that a $\lambda_0/4$ antenna can be an impractical and significantly reduced amount of antenna sizes is, therefore, necessary. However, reducing the size can negatively impact the efficiency, gain, and bandwidth of the antenna [28]. Figure 2 depicts the schematic layout of the proposed design of the UHF antenna. The patch antenna structure is based on spiral and folding techniques and the partial ground plane that covered UHF band. The radiating antenna length is calculated about $\lambda/4$ (λ is the wavelength) and is optimized to 437.375 MHz. To decrease the resonant length, the radiating element is first folded using a turn square-spiral section with feed line. To further decrease the electrical size, a capacitive loading,

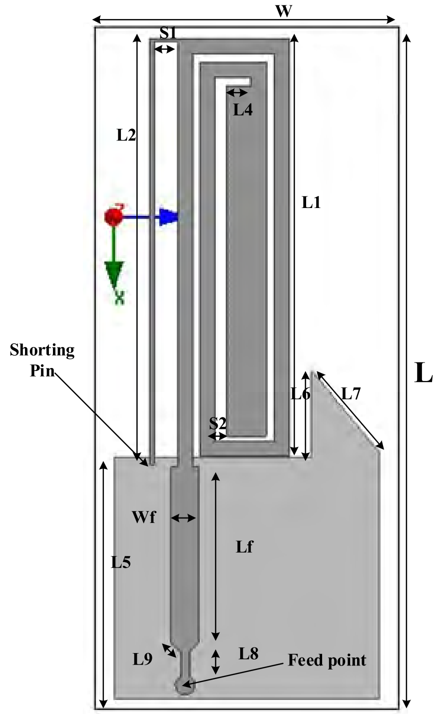


FIGURE 2. Schematic layout of the proposed overall design of the UHF antenna.

in the form of a rectangular patch, is then placed in the middle of the spiral section. An inverted L shaped antenna configuration is achieved using a shunt inductance which is used to allow matching of the antenna impedance through shorting pin to 50 ohms without the need for discrete coordinating components. Finally, a small triangular capacitive stub is printed on the ground plane in order to allow a degree of fine-tuning of the antenna's resonant frequency. The proposed antenna is mechanically robust, compact in profile, lightweight, and good thermal properties and thus suitable for space applications. Due to the use of an MMCX coaxial fed line and the narrow width of the meander patch, the proposed antenna can easily fit within narrow space within the communication device. Final optimized design parameter of the realized antenna geometric layout is presented in Table 2. From simulated surface current distribution magnitude at 437.375 MHz which is shown in **Figure 3**, large current flows in the spiral and inductive section with a smaller current flow on the capacitive stub. The analysis unveils that resonant frequency is mainly determined by the full total electrical amount of the feed line with the spiral section as well as the perimeter amount of the capacitive loading patch section.

IV. ANTENNA PERFORMANCE ANALYSIS

A prototype of the proposed antenna was fabricated and measured, as illustrated in Figure 4. Experimental results are measured using Agilent N5227A PNA microwave network analyzer. Figure 5 displays the return-loss magnitude while a function of the frequency for the designed UHF patch

TABLE 2. Optimized dimension of the proposed antenna.

Parameter	mm	Parameter	mm
L	72	*L5*	25.5
W	32	*L6*	9.152
L1	44.195	*L7*	11.245
S1	2.47	*Lf*	18.56
S2	0.905	*L8*	2.64
L4	2.53	*L9*	1.371

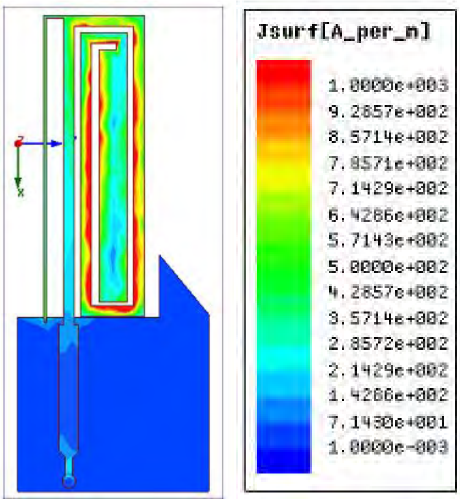
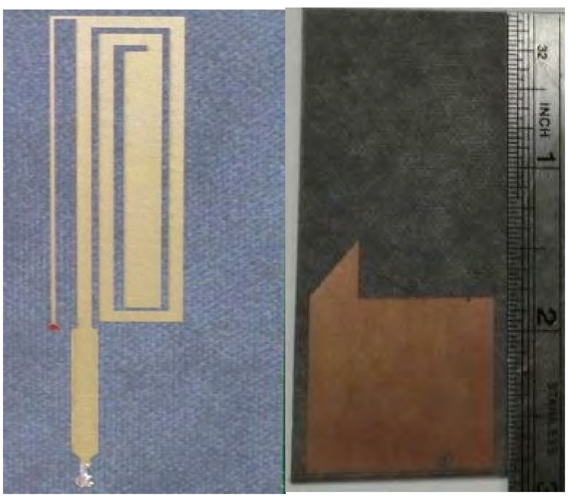


FIGURE 3. Surface current distribution of the proposed UHF antenna.



(a) (b)

FIGURE 4. UHF antenna prototype (a) Top view (b) Bottom view.

antenna system. Specifically, the figure displays the outcomes obtained by way of EM numerical simulations, computed with CST, and by measurements, performed by utilizing a PNA microwave network. Both simulations (dashed line) and experimental (straight line) outcomes highlight that the antenna is usually well matched at the required operating frequency satisfying the necessity on the S_{11} is well below the value of -10 dB at 448 MHz-418 MHz(Relative Bandwidth 6.92%) which cover the desired operating frequency range from 437.372-437.375 MHz. Moreover, the measured frequency behavior is in a very good agreement with the simulation results. The radiation characteristics of the proposed UHF antenna with satellite structure was measured

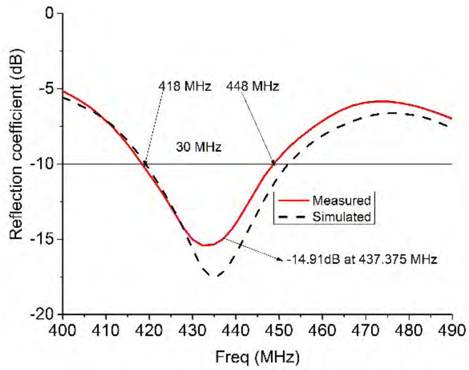


FIGURE 5. The simulated and measured reflection coefficient of the UHF antenna.

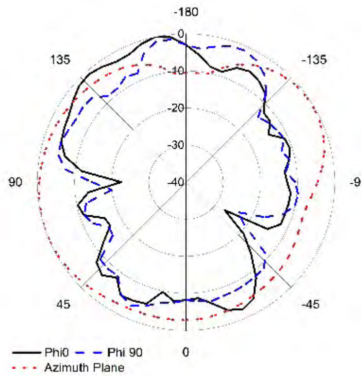


FIGURE 6. 2D measured radiation pattern of the antenna.

FIGURE 7. Flight model of the 1U BIRDS-1 satellite.

TABLE 3. Summary of the proposed BIRDS UHF antenna.

PARAMETER	SPECIFICATION
Operating Frequency	418-448 MHz
Frequency Band (-10dB)	30 MHz
Dimension	72 mm ×32 mm× 1.52 mm
Thickness	10 mm (Max)
Polarization	Linear Polarization
Realized Gain	0.55dB
Efficiency	56%
Antenna weight:	10 gm
Return losses	<-10 dB
Connector	50 Ohm MMCX coaxial fed
Radiation Pattern	Omnidirectional
Substrate Material	Rogers 5870
Mounting	CubeSatellite body

in Satimo near-field measurement systems. The measured normalized radiation pattern at the resonant frequency is presented in Figure 6. The total efficiency of the proposed UHF antenna at the resonance frequency is approximately 56% with 0.55 dB of realized gain and 1.01 dB peak gain. The measured radiation pattern in both azimuth and elevation planes 437.375 MHz is illustrated in Figure 6, where it can be observed that the antenna shows nearly omnidirectional radiation pattern at azimuth plane. A summary of the antenna is presented in Table 3. The performance of the proposed antenna has been compared with existing UHF antennas, tabulated in Table 4. Considering the comparison criteria in the lower UHF band, it can be seen that, the proposed antenna is a potential candidate for Cube satellite communication system.

A. BIRDS-1 CubeSat LINK BUDGET ANALYSIS

When arranging CubeSat missions, an essential fact is the power budget expected simply by the radio communication subsystem, which allows a CubeSat to switch information with ground stations and/or additional CubeSats in the orbit. The power budget a CubeSat can devote to the communication subsystem is bound by the stringent restrictions on the full total power available, due to its compact dimension and light-weight that limit the sizes of the CubeSat power components like batteries and solar power panels [35]. Amongst the various electronic modules of a CubeSat, the radio communication system is an essential one, since it allows the CubeSat to switch information and connect to ground stations and also with other CubeSats. Therefore the designing the communication system of a CubeSat entails a link budget evaluation to determine power requirements, select appropriate equipment, and set up modulation parameters for signal transmission and reception. The purpose of radio link design is to make sure that a trusted communication link could be established between a radio transmitter and its own associated receiver if adequate power is offered by the radio receiver to close the link that is to meet up a required signal to noise ratio (SNR) value. We've summarized the downlink frequency link budget in Table 5 by available link budget equation to judge digital data radio link [36]:

$$\begin{aligned} SNR_{dB} &= 10\log_{10}(\frac{E_b}{N_0}) \\ &= 10\log_{10}(\frac{P_tG_tG_r}{kT_sRL_p}) \\ &= P_{t,dBm} - 30 + G_{t,dBi} + G_{r,dBi} - L_{p,dB} \\ &\quad - 10\log_{10}k - 10\log_{10}T_s - 10\log_{10}R \end{aligned} \quad (1)$$

TABLE 4. Comparison of characteristics of different UHF antennas.

REF. NO.	ANTENNA TYPE	OPERATING FREQUENCY (MHZ)	ANTENNA DIMENSION (MM)	GAIN	REMARKS AND COMPATIBILITY OF CUBESAT
[14]	Microstrip patch	435-437	170×120×6.4	0.7 dB	Too large to fit with 1U Nanosatellite Incompatible
[29]	Dipole	430	160	2.15 dB	Compatible but externally mounted with satellite Structure
[30]	Fractal-shaped	700-4710	120×120×1.6	1.71 dB	Not compact enough. Does not cover lower UHF frequency (450 MHZ) Incompatible
[31]	Printed patch	410-485	220×220×28.5	5.2 dB	Too large for 1U, 2U Nano satellite Incompatible.
[32]	Microstrip patch	384-410	150×150×37	0.4 dB	Low gain with large dimension Incompatible
[33]	Monopole	146 & 438	513.6× 10×10	2.06 dBi at 146 MHz 3.35 dBi at 438 MHz	Compatible but deployable complexity
[34]	Monopole	435-438	175	2.35 dBi	Compatible but Deployable complexity
Proposed	**Printed Patch**	**437.372-437.375**	**72×32×1.52**	**1.01 dB**	**Compact and compatible to 1U, 2U CubeSat**

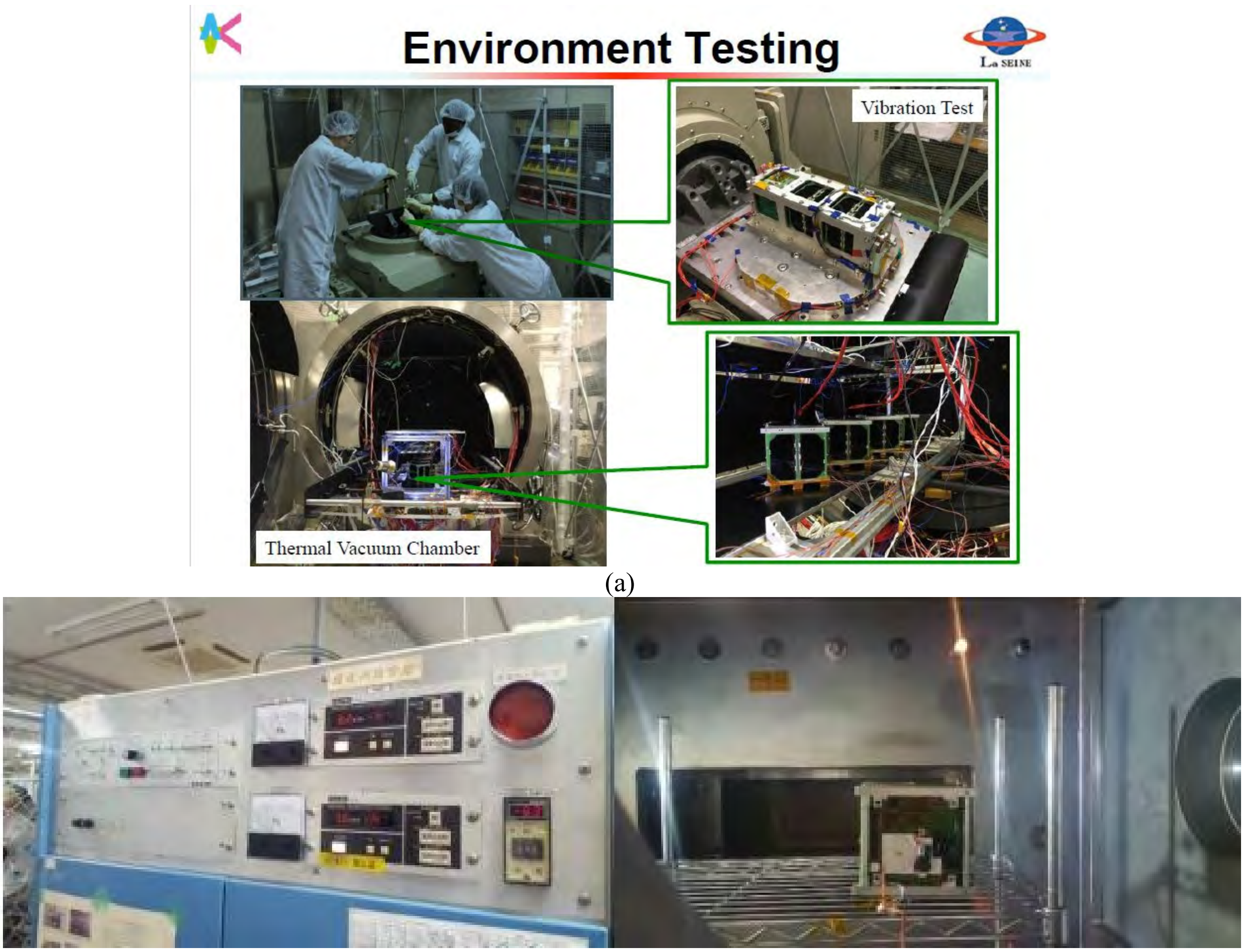
TABLE 5. Summary of the link budget analysis of BIRDS 1 CubeSat downlink communication.

	Unit	FM 9600	FM 1200	CW beacon	Digi-singer
Beam objective(s)	[-]	Backup FM (mission and satellite off-time housekeeping (OTHK)	Satellite real-time HK (RTHK), backup FM (mission and OTHK)	Beacon transmission	Digi-singer data
Type of emission	[-]	F1D	F2D	A1A	F3E
Orbital altitude	[km]	410	410	410	410
Slant range distance at 10 degree	[km]	1473	1473	1473	1473
Transmitting central frequency f_c	[Hz]	437375000	437375000	437375000	437375000
Bandwidth	[Hz]	2.600.E+04	1.600.E+04	5.000.E+02	1.600.E+04
Transmitter output P_t	[W]	0.8	0.8	0.1	0.8
Transmitter output	[dBW]	-0.96910013	-0.96910013	-10	-0.96910013
Maximum power density	[dBW /Hz]	-4.512.E+01	-4.301.E+01	-3.699.E+01	-4.301.E+01
Light speed C	[m/s]	3.000.E+08	3.000.E+08	3.000.E+08	3.000.E+08
Transmission power supply loss	[dB]	1	1	1	1
Transmitting antenna gain G_t	[dBi]	0.55	0.55	0.55	0.55
EIRP transmission	[dBW]	-1.41910013	-1.41910013	-10.45	-1.41910013
Transmitting antenna pointing loss	[dB]	1	1	1	1
Free space path loss L_p	[dB]	148.6	148.6	148.6	148.6
Polarization loss	[dB]	3	3	3	3
Atmospheric absorption loss	[dB]	0	0	0	0
Rain attenuation	[dB]	0	0	0	0
Reception power supply loss	[dB]	2.16	2.16	2.16	2.16
Receiving antenna pointing loss	[dB]	1	1	1	1
Receiver's received power	[dBW]	-1.255.E+02	-1.255.E+02	-1.345.E+02	-1.255.E+02
G/T reception	[dB/K]	-10.93	-10.93	-10.93	-10.93
Receiving antenna gain G_t	[dBi]	18	18	18	18
Demodulator loss	[dB]	1	1	1	1
Receiver noise	[dB]	2	2	2	2
System noise temperature T_s	[K]	300	300	300	300
System noise temperature	[dBK]	24.77	24.77	24.77	24.77
Sky noise temperature degradation	[dB]	0	0	0	0
System required data rate	[bps]	9600	1200	100	
Modulation scheme	[-]	GMSK	AFSK	CW	F3E
Acceptable BER	[-]	1.00E-06	1.00E-06	1.00E-06	1.00E-06
Boltzmann constant k	[J/K]	1.38E-23	1.38E-23	1.38E-23	1.38E-23
Boltzmann constant	[dBW/ Hz·K]	228.6	228.6	228.6	228.6
Required Eb/No	[dB]	11.5	11.5	11.5	11.5
Received C/No	[dBHz]	62.6	62.6	53.6	62.6
Required C/No	[dBHz]	51.32	42.29	31.50	20.59
System margin	[dB]	11.3	20.3	22.1	42.0

Where P_t is transmitted power, G_t and G_r are the transmit antenna gains, L_p is the propagation path loss, k is Boltzman's constant, T_s is the system noise temperature and R is the data rate. To guarantee the effectiveness of the BIRDS-1 link budget analysis, additional terms have contained in the over equations to take into account other link losses and to add a system link margin. Besides for the analysis of the BIRDS-1 link budget, several potential sources of power loss was incorporated in the system margin with reasonable estimates.

V. ANTENNA INTEGRATION AND TESTING WITH SATELLITE BODY

The final module of the 1U BIRDS-1 satellite Flight Model is depicted in **Figure 7**. A UHF band patch antenna is attached to the satellite body for transmitting application. After integration of the UHF band antenna through non conducting glue with the satellite body, different tests were performed in the Laboratory of Spacecraft Environment Interaction Engineering (LaSEINE), Kyutech, Japan.



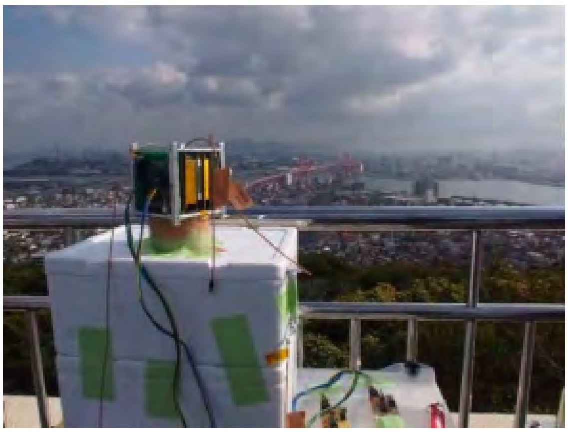
(a)

(b)

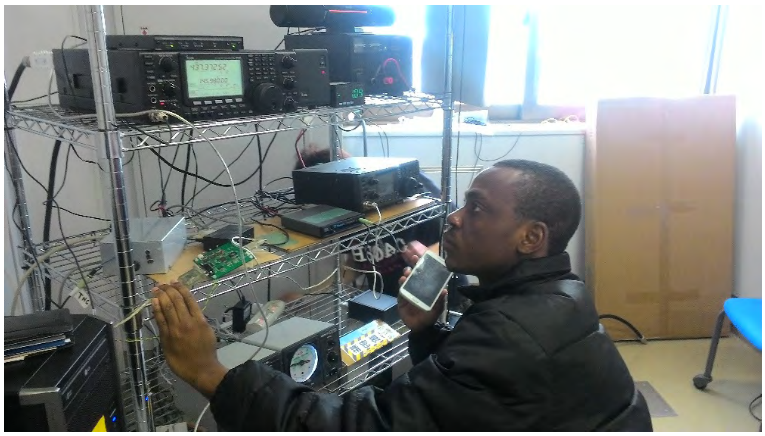
FIGURE 8. a) Launch conditions: vibration test b) environment conditions: vacuum test and thermal vacuum test.

The upper earth atmosphere contains several unstable particles and free radicals like atomic oxygen due to the high energy radiation from the sun [37]. The atomic oxygen readily attaches to any metal surface to cause 'rusting'. Thus the antennas were subjected to a high velocity (up to 10 km/s) jet of atomic oxygen in a test chamber. The stream is created using a 5.5 JCO_2 laser. The plasma environment encountered in LEO is mimicked in the LEO chamber. The pressure is maintained at 10^{-4} Pa to resemble the conditions of upper earth atmosphere. The chamber is equipped with an Electron Cyclotron Resonance plasma source to generate about 10^{12} m^{-3} plasma density. Furthermore, it uses metal halide lamps to evaluate the performance of solar cell arrays. Any arcing is detected using the discharge position identification system and the high-speed discharge waveform acquisition system. The primary objective of this chamber is to analyze the performance of the solar cell arrays, communication antennas and experimental apparatus in low-pressure environments with the presence of plasma. The microwave test chamber exposes the satellite prototype to high power microwave from 100 KHz to 10 GHz under ultimate vacuum condition of 10^{-5} Pa. The thermal cycling chamber, illustrated in Figure 8, periodically varies the temperature from -200 to 200 °C at 10^{-5} Pa. This chamber tests the structural integrity of the internal circuitry, antennas and sensory equipment at the harsh extreme temperatures experienced in LEO operations. Several mechanical and vibration stress tests are carried out on the entire satellite structure to assure, it is with the capacity of withstanding the accelerations and vibrations experienced through the release process. Vibration testing exposes the satellite structure to three types of acceleration, i.e. sine, random and shock, at varying forces up to 87 kN. No visible cracks were observed on the UHF antennas after the rigorous mechanical testing. After the different environmental test of the satellite, Long Distance Test, and End to End Test was performed to verify uplink and downlink communication between satellite and ground station. Figure 9 shows the long-distance test setup, EM (Electro-Magnetic) setup Ground station, and the communication test result. The BIRDS-1 CubeSat was setup in the inside Takatoyama Park, Japan, and Kyutech ground station. The distance between transmitter

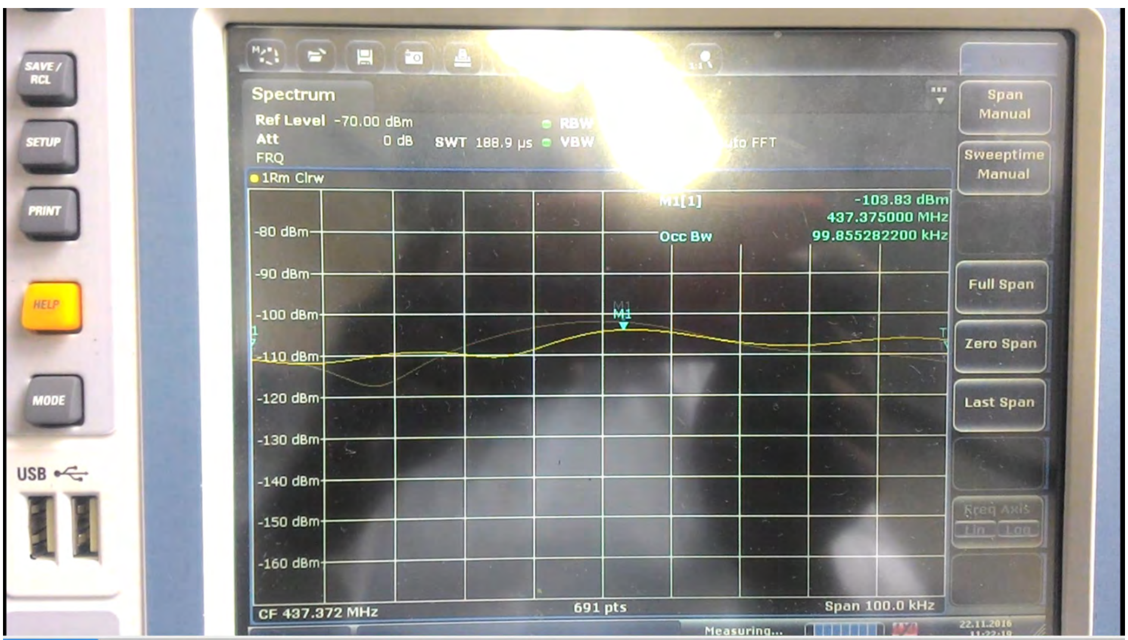
(a)



(b)



(c)



(d)

FIGURE 9. (a) BIRDS long-distance test setup (b) BIRDS EM Setup (c) communication test ground station and d) communication test result.

FIGURE 10. Five BIRDS-1 satellite with two J-SSOD.

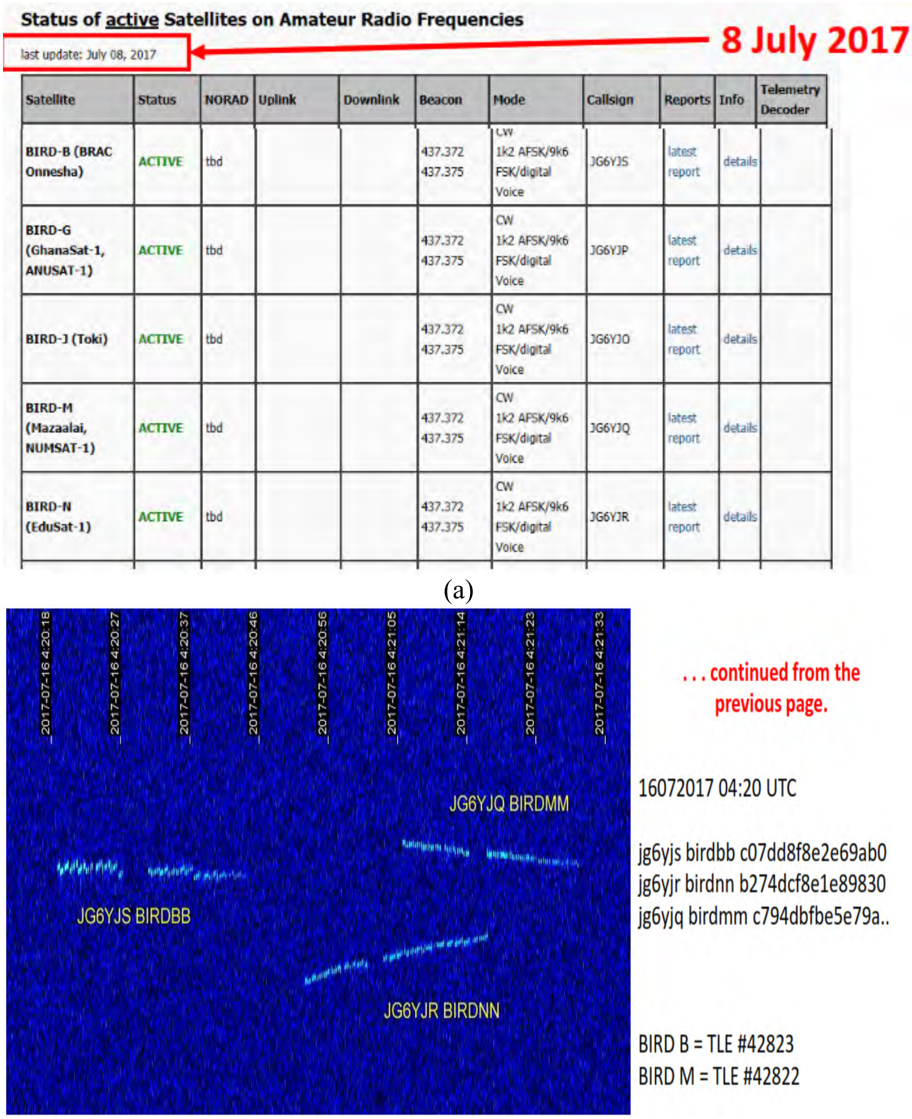
(a) (b)

FIGURE 11. a) First deployment: Japan (Toki), Ghana (GhanaSat-1), and Mongolia (Mazaalai) b) second deployment: Bangladesh (BRAC Onnesha) and Nigeria (Edusat1).

and receiver place was taken 4KM. All the position and distance was depicted in Fig.9 with side view and google map. The free space path loss at operating frequency during the long distance test was approximately 97 dB. To account for additional free space path loss of the orbital altitude, which is 137 dB, in this long distance test, a 40 dB attenuator was attached between the base-station antenna and receiver. Ground Station sends a command to the BIRDS-1 EM to perform Digi-Singer, Camera, and POS missions. Upon receiving the mission data, the ground station measured the signal strength and successfully decoded the mission data.

VI. BIRDS SATELLITE LAUNCHING IN LEO

After completing the flight model of five 1U BIRDS, the satellites were handed over to JAXA Tksuba center, Japan. The two long white cases are J-SSOD pods. JEM Small Satellite Orbital Deployer (J-SSOD) is a system for deploying small satellites designed and constructed relative to 1U CubeSat design specification that transfers the satellites from Japan Experiment Component Kibo's airlock to the area environment and releases them on orbit. As shown in Figure 10, three BIRDS-1 CubeSat's were in one J-SSOD pod, and the other two BIRDS-1 CubeSat's were in the other J-SSOD pod. The J-SSOD is lifted to the ISS on a SpaceX Falcon 9 CRS-11 rocket from John F. Kennedy Space Center, USA on June 3, 2017. Finally, five ''BIRDS project'' CubeSat's were successfully deployed into orbit from the Japanese Experiment Module ''Kibo'' of the International Space Station (ISS) on 7 July 2017 which is shown in Figure 11. On 8 July 2017, the amateur radio community certified that all BIRDS-1 satellites are active which is depicted in Figure 12.



Status of active Satellites on Amateur Radio Frequencies

last update: July 08, 2017

Satellite	Status	NORAD	Uplink	Downlink	Beacon	Mode	Callsign	Reports	Info	Telemetry Decoder
BIRD-B (BRAC Onnesha)	ACTIVE	tbd			437.372 437.375	CW 1k2 AFSK/9k6 FSK/digital Voice	JG6YJS	latest report	details	
BIRD-G (GhanaSat-1, ANUSAT-1)	ACTIVE	tbd			437.372 437.375	CW 1k2 AFSK/9k6 FSK/digital Voice	JG6YJP	latest report	details	
BIRD-J (Toki)	ACTIVE	tbd			437.372 437.375	CW 1k2 AFSK/9k6 FSK/digital Voice	JG6YJO	latest report	details	
BIRD-M (Mazaalai, NUMSAT-1)	ACTIVE	tbd			437.372 437.375	CW 1k2 AFSK/9k6 FSK/digital Voice	JG6YJQ	latest report	details	
BIRD-N (EduSat-1)	ACTIVE	tbd			437.372 437.375	CW 1k2 AFSK/9k6 FSK/digital Voice	JG6YJR	latest report	details	

FIGURE 12. (a) Status of the active 1U BIRDS Satellites on UHF Band Frequencies (b) BIRDS-1 CW beacon signals visually displayed by DK3WN (Mike in German).

VII. CONCLUSION

A compact UHF band patch antenna system compatible with 1U BIRDS-1 CubeSat constellation has been presented in this paper. The antenna has been designed on the basis of the specifications of the 1U BIRDS satellite mission but is suitable for more general cases. The antenna consists of a folded meander line patch, shorting pin and partial ground plane with coaxial probe fed and it is realized in a planar technology achieving a compact size, low profile and geometric characteristics. A prototype of the proposed antenna has been realized. The measurements of the fabricated antenna in an anechoic chamber, in terms of impedance matching and radiation pattern, show a good agreement with simulation results. The antenna was also mounted with BIRDS satellite body structure and tested in different environmental test and long distance communication test in LASINE lab, Kyutech, Japan. Finally, the five 1U BIRDS satellite were successfully deployed in LEO from BIRDS-1 satellites on 7 July 2017 at the J John F. Kennedy Space Center, Florida, USA. The preliminary mission for this CubeSat is Earth observation by a COTS camera and Outreach through Digi-Singer, a sound relaying COTS device. UHF amateur radio band has been used while interlinking the ground station of five countries.

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AUTHOR CONTRIBUTIONS

Md. Samsuzzaman and Salehin Kibria made considerable contributions to design, evaluation, fabrication, performance analysis with integration of the satellite body and final writing. Mohammad Tariqul Islam participated in the conception and critical revision of this article for important intellectual content. Mengu Cho provided necessary instructions and support for experimental purposes of using LaSEINE Lab, Kyutech, Japan.

CONFLICTS OF INTERES

The authors declare no conflict of interest.

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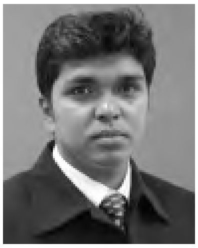

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