3-8 Aeronautical Satellite Communications using WINDS

Tomoshige KAN, Norihiko KATAYAMA, and Takashi TAKAHASHI

Satellite communication has caught the attention of researchers as an effective means of communication in the absence of mobile communication systems on ground systems such as during the takeoff and landing of aircraft. At the time of aircraft's flight, a large-capacity communication is expecting for the use of entertainment for passengers on board. Its large capacity communication abilities will enable us to share detailed information, which is vital in times of disaster, such as movie images and ground data taken from synthetic aperture radar (SAR).

In this study, we report the development of aeronautical earth station for WINDS and result of the flight experiment of satellite communication between developed aeronautical earth station and WINDS. We measured propagation characteristics that is pattern of the Multi-Beam Antenna (MBA) which was mounted on WINDS, variation of the Doppler shift for Ka-band aeronautical satellite communications, and the antenna tracking performance. In this experiment, we can success to transmit large capacity data in a few minutes on the fly.

1 Introduction

Satellite communication can provide effective alternative tools to terrestrial communication systems for in-flight aircrafts and ships navigating off-shore, as well as, more importantly, in the case of large-scale disasters where terrestrial-based mobile phone communications may become severely crippled. Large-volume data communication is in dire need in race-against-time disaster situations for sharing real-time information such as dynamic picture images and topographical data on site. The need for larger communication capacity shows no sign of abating even in normal times, for example, for in-flight entertainment purposes.

NICT has been conducting research on the Wideband InterNetworking engineering test and Demonstration Satellite (WINDS)[1]. The project includes a variety of research related to mobile satellite communication such as the development and experimental operation of mobile earth stations mounted on a car [2] and on board a ship [3]. They are equipped with an antenna system capable of automatically detecting and tracking the WINDS satellite for uninterrupted communication during experiment/operation. As a part of the WINDS project, an Aeronautical Earth Station (AES) was developed to research in-flight satellite communication. This report describes an overview of the AES, and the outcomes from flight experiments which were carried out with the earth station on board the aircraft [4]–[6].

2 WINDS aeronautical earth station (AES)

The specifications of AES are listed in Table 1, and its configuration is shown in Fig. 1. The system has a 45-cm-diameter Cassegrain antenna as shown in Fig. 2. The transmission and receiving gain of the antenna are 38.7 dBi and 36.1 dBi, respectively. Other constituent elements include a 200 W high power amplifier (HPA), a low noise

Table 1 Aeronautical earth station (AES) specifications

Tx frequency	27.5-28.6 GHz
Rx frequency	17.7-18.8 GHz, 18.9 GHz (for receiving beacon)
Polarized wave	Linearly-polarized wave (V/H)
Antenna	Cassegrain antenna Diameter: 45 cm
Antenna gain	38.7 dBi (Tx) 36.1 dBi (Rx)
High power amplifier	200 W TWTA
G/T	13.2 dB/K
Antenna driving range	El: 25-65 deg Az: endless rotation
Tracking accuracy	<± 0.5 deg
Data rate	Regenerative mode Tx: 1.5, 6, 24, 51 Mbps Rx: 155 Mbps
User interface	Ethernet (1000 base-T)

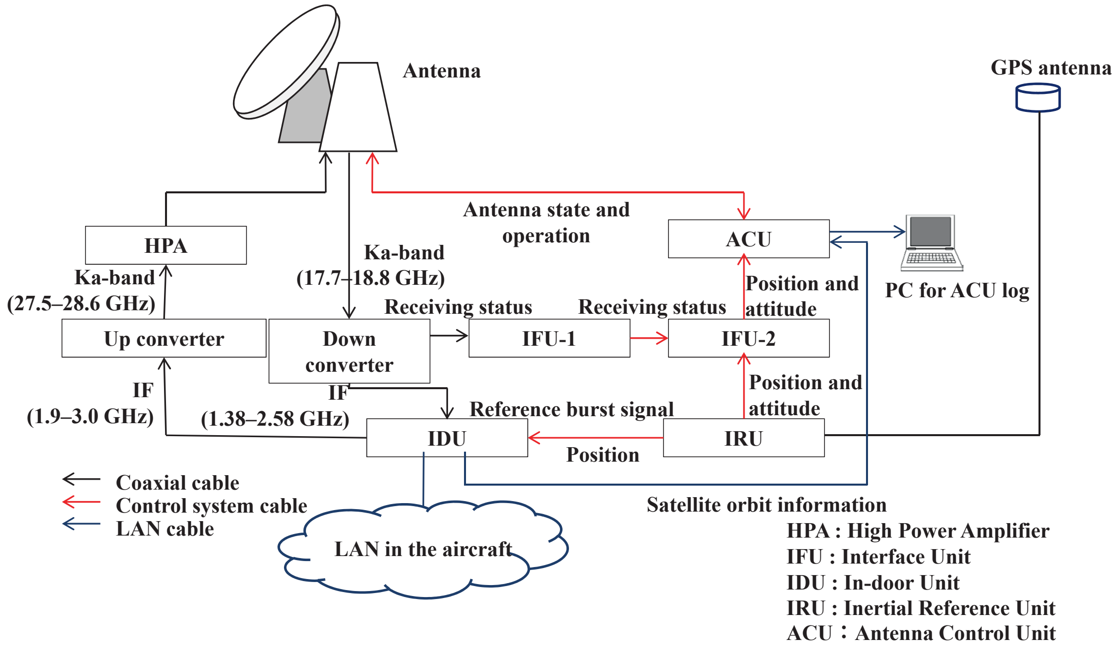

Fig. 1 Configuration of AES

Fig. 2 External appearance of AES antenna

Fig. 3 The aircraft used in the experiment: Gulfstream-II

converter (LNC) and modulator and demodulator.

The antenna system on board AES calculates the positional relation between it and the satellite from two information sources: an on-board GPS receiver and IRU (Inertial Reference Unit). Based on this information, it drives an antenna control unit (ACU) to control the radiative direction of the antenna for automatic detection and tracking of the satellite. It also provides an interlock function to automatically stop transmitting in such disabling situations as: too large tracking error, or could not receive the signal from satellite. This helps avoid interference quickly.

3 Flight experiment

3.1 Experiment overview

The WINDS AES was mounted on a Gulfstream-III [7] provided by Diamond Air Service, Inc. In addition to the earth station, the plane was mounted with a spectrum analyzer for receiving level measurement, a PC for the data transmission tests, and another PC for data logging. Figure 4 shows the photographs inside the cabin illustrating the earth station and other measurement devices. Figure 5 shows the network configuration used in this experiment.

A satellite circuit was connected between the following stations: AES, satellite, and fixed ground station (Kashima). The plane was operated based in Nagoya Airport (managed by Aichi prefecture) and flew above the area covered by the Chubu beam of the WINDS multi-beam antenna (Fig. 6).

The flight experiment served the following four-fold

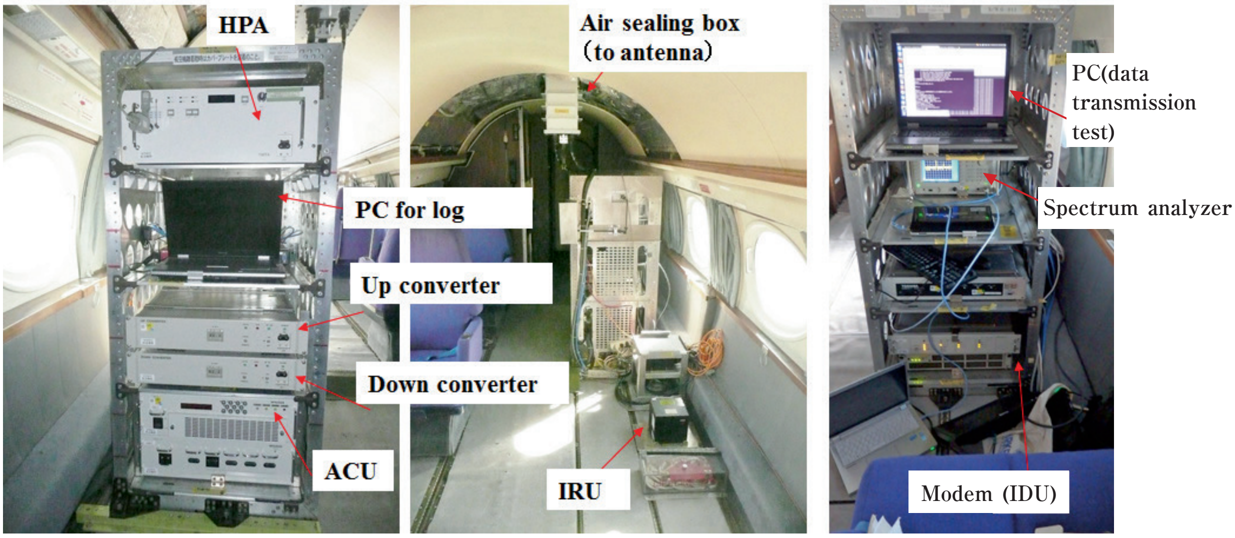

Fig. 4 The earth station and measurement devices on board the plane

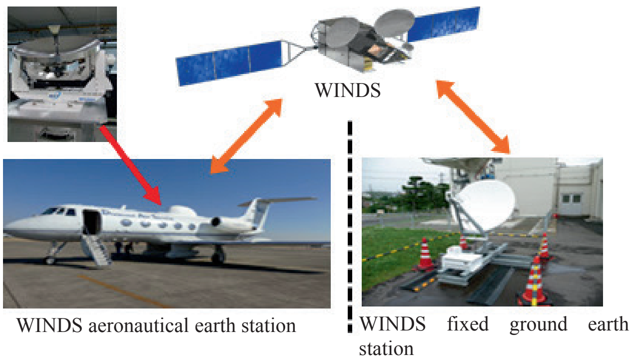

Fig. 5 Network configuration

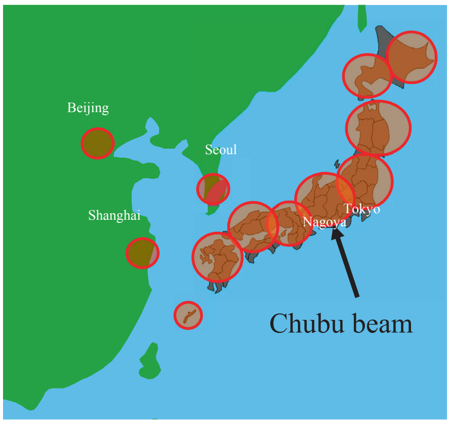

Fig. 6 Areas irradiated by WINDS multi-beam antenna

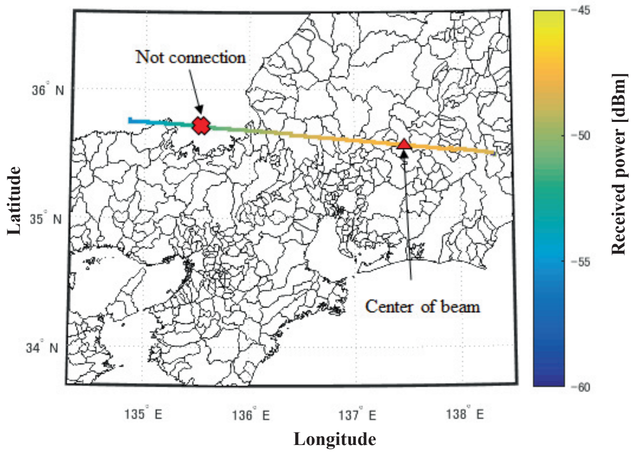

Fig. 7 Received power map during a straight flight

objectives: (a) antenna pattern measurement: propagation measurement to verify the antenna pattern of the MBA Chubu beam; (b) antenna tracking characteristics: the flight experiment includes figure-of-eight and banked flight to investigate the tracking characteristics of the antenna; (c) data transmission: investigation of the effect of flight on the rate of data transmission; and (d) transmission of a large-volume file, in which image data files acquired by Pi-SAR [8] are used to test file transmission performance.

4 Experimental results

(a) Antenna pattern measurement

Figure 7 shows the level of received power from the MBA's Chubu beam as measured along the flight route indicated. The aircraft flew straight through the center of the beam at an altitude of 5,300 m. Time variation of received power during the flight is shown in Fig. 8. The maximum received power was at the beam center and communication ceased at a point more than 172 km from the center of beam. Figure 9 shows a characteristic antenna pattern as plotted against the distance from the center of the beam. The red plot in the figure indicates the pattern obtained at the initial check-out. In the initial check-out, antenna beam measurements were conducted by

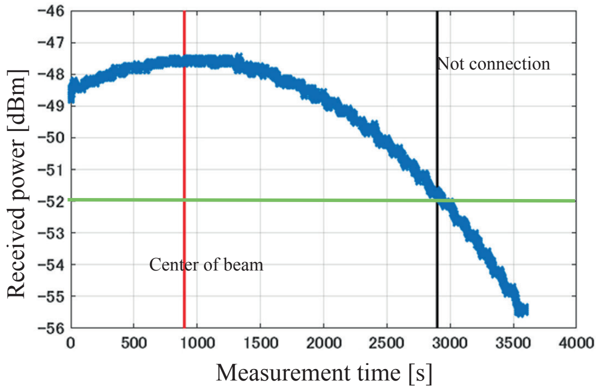

Fig. 8 Variations of received power during a straight flight

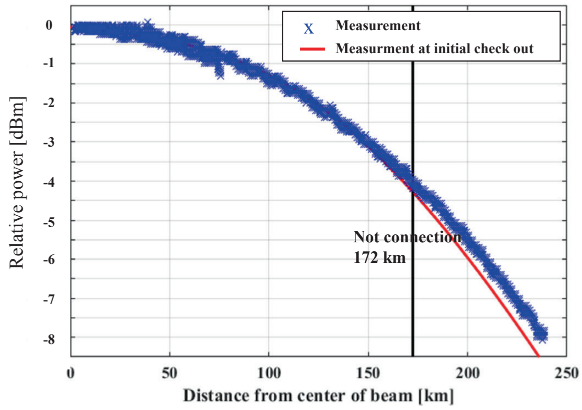

Fig. 9 Antenna pattern of MBA Chubu beam

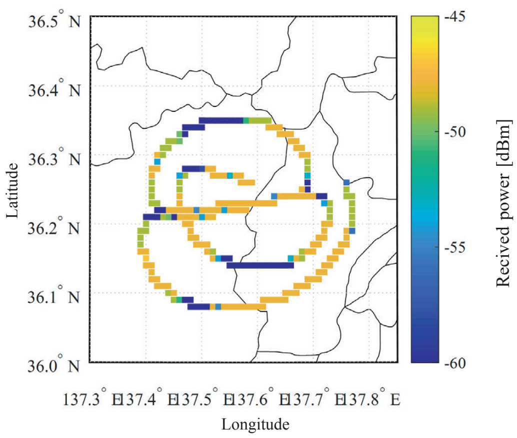

Fig. 10 Figure-of-eight flight pattern used to study antenna tracking characteristics

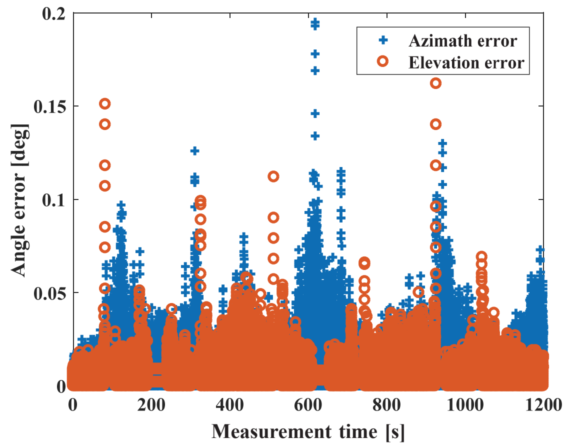

Fig. 11 Time variation of angular error during the figure-of-eight flight

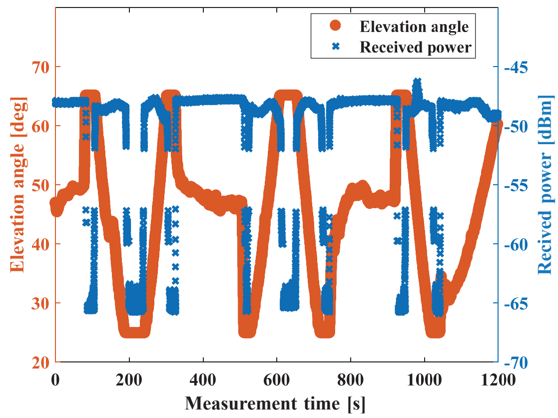

Fig. 12 Time variation of elevation angle and received power during figure-of-eight flight

moving the antenna's sub-reflector mirror.

The data from the flight experiment showed good agreement with those obtained from the initial check within the 170 km range from the center of the beam, and the deviation remained within 0.5 dB even at a 240 km distance from it. The agreement between the flight experiment data and initial check-out has proved the sustained accuracy of WINDS since its launch 8 years ago. This experiment has also proved that the flight experiment data taken with its measurement point moving uninterrupted agrees well with those from single-point measurements gained by moving the antenna's sub-reflector.

(b) Antenna tracking characteristics

Figure 10 shows a figure-of-eight flight route and the received power levels mapped on it. The blue sections indicate lowered received power, where the plane is flying in the east-west direction. Because the satellite is located to the south of the plane, banking of the plane gives rise to larger elevation angle variations of the earth station when it is flying in the west-east direction than in other directions. Figure 11 shows the time fluctuations of azimuth and elevation angle during the figure-of-eight flight. From the figure, it can be seen that the error is 0.2° at the maximum, meeting the criterion for tracking accuracy, i.e. no greater than ±0.5°. Figure 12 shows time fluctuations of elevation

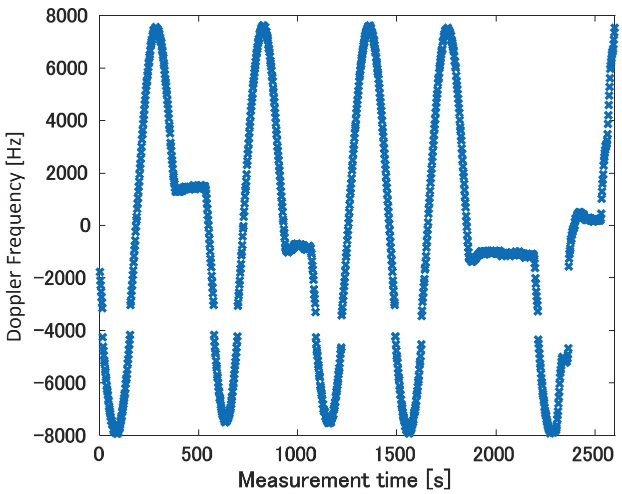

Fig. 13 Time variation of Doppler frequency during figure-of-eight flightt

angle and received power level. As seen from the figure, during the flight test, the plane banked more steeply than usual and the antenna was no longer aligned with WINDS when the elevation angle was above 65° and below 25° so that the received power dropped out. The received power stabilized for elevation angles in the range of 25°–65°. Note that the plot is not shown in the vertical range between -52 dB and -57 dB. This was intentionally done to exclude the time zone where excessively low received power level is reported due to the following reason: received power of the communication signal is received at certain timings during the received level measurement, which is significantly low as compared with the normal received power level. As described above, the data from the flight experiments verified that AES satisfied the required specifications on tracking characteristics.

Figure 13 shows the characteristics of the Doppler shift during flight in Fig. 8 patterns. The maximum Doppler shift was 7.9 kHz. The theoretical value during flight at a speed of 720 km/h is 8.2 kHz. The difference between these values is 4%, which indicates that the actual value was approximately equal to the theoretical value. It can be concluded that when designing the frequency-tracking performance of a modem for a high-speed mobile earth station, the theoretical value can be calculated from the station's speed. In this case, since we are using a geostationary satellite, we do not have to consider Doppler shift due to the satellite's relative velocity. Note that the Doppler plot in the figure has missing sections near -4,000 Hz, which result from temporary incapability of the system to detect signal due to IDU's local leak.

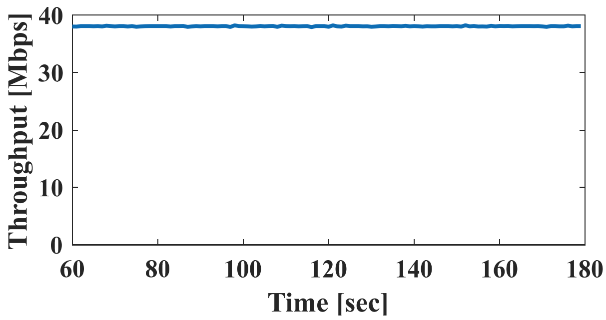

Fig. 14 UDP based throughput characteristics

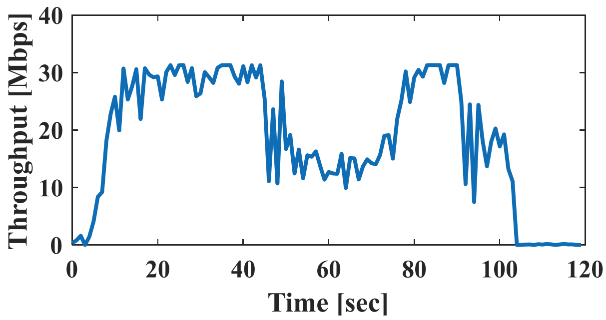

Fig. 15 TCP based throughput characteristics

(C) Data transmission

Up-link throughput characteristics from AES were investigated, wherein the following two communication protocols were tested using iperf [9]: UDP (User Datagram Protocol) and TCP (Transmission Control Protocol). The measurements were made, while in a stable flight situation, using the regenerative 51 Mbps mode of WINDS. Figure 14 shows the throughput characteristics of UDP communication. The figure indicates stable communication at the data rate of 38 Mbps.

Figure 15 shows the throughput characteristics when TCP is used. These results show that stable communication is possible at 31 Mbps. Since congestion is controlled between terminals according to the state of the line with this protocol, the value fluctuated when using TCP. This test showed that communication speed was recovered even after an instantaneous interruption occurred, causing a delay time of over 500 ms.

(d) Large-volume file transmission

To evaluate the time required to upload large volume files, a high-resolution image captured by Pi-SAR (Polarimetric and Interferometric Airborne Synthetic Aperture Radar) was uploaded from AES to a web server. It took 1 minute, 18 seconds to upload the 192 MB file. This translates into a data communication rate of about

20 Mbps from an aircraft. This high-speed data communication capability enables the system to perform required tasks in quick turnaround: acquiring Pi-SAR observation data, conversion to transmission format, and transmission to an earth station. The speed will be of great help to assist quick judgment and response at the time of a disaster.

5 Concluding remarks

NICT has developed an AES system to be used in a Ka-band satellite communication system, and mounted the station on board a plane to conduct flight experiments. The objectives were broadly two-fold: verification of the antenna pattern extended by the Chubu beam of the WINDS MBA, and tracking characteristics of the antenna implemented in AES. In addition, measurements were made to evaluate data transmission characteristics and file transfer performance during a flight.

The measurement results verified excellent agreement between the current antenna pattern and that obtained by initial check-out carried out after the launch of WINDS. The results also proved that the antenna satisfied design specifications and confirmed its capability to perform stable communication within the given tracking range. In-flight experiments confirmed that data transfer can be performed at the rate of 38 Mbps using UDP and 31 Mbps using TCP. Transfer of large-volume files in the air was successfully conducted at the rate of 20 Mbps.

As described above, the experiment showed the capability to establish communication between the air-borne earth station and a satellite system at the rate of several tens of Mbps using the Ka band, indicating the feasibility of its use for sharing information among disaster-stricken areas, as well as for in-flight entertainment applications.

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Tomoshige KAN, Dr. Eng.

Researcher, Space Communications Laboratory, Wireless Networks Research Center
Satellite communication propagation

Norihiko KATAYAMA, Dr. Eng.

Researcher, Space Communications Laboratory, Wireless Networks Research Center
Satellite communications, Propagation, Network

Takashi TAKAHASHI

Associate Director, Space Communications Laboratory, Wireless Networks Research Center
Satellite communication