

DEVELOPMENT OF AUTONOMOUS DISTRIBUTED GROUND OPERATION SYSTEM FOR PICO-SATELLITES UNDER LOW BAUD-RATE COMMUNICATIONS

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ABSTRACT

In this paper we describe autonomous ground operation system for CUTE-I in order to reduce the fatigue of ground operator in the first place. The system consists of 1) remote ground station controller, 2) autonomous beacon telemetry analyzer, 3) operation scheduler, 4) data broadcasting system, and so on. From the result of autonomous operation of CUTE-I we found out the issues of the system. Therefore we propose the next autonomous ground operation system for our next satellite Cute-1.7 + APD in order to solve the found issues in the second place. Moreover we describe autonomous distributed ground station system under low baud rate communication in the third place.

1. BACKGROUND

In this decade a lot of space agencies and universities all over the world have begun to develop small-satellite and pico-satellite enthusiastically and many satellites have already been launched into orbit and operated actually. We Tokyo Institute of Technology Laboratory for Space Systems (LSS) also developed our first pico-satellite CUTE-I (CUBical Tokyotech Engineering satellite-I) and launched it on 30th June 2003 from Russia using the Russian rocket (ROCKOT) as the piggyback satellite. We have already been operating CUTE-I for over 2-years without remarkable troubles since the launch. This fact shows the potentials of pico-satellite regarding the lower developing and launching cost, the short term of the development, and abundant launching opportunities by piggy-back launch. The latest technologies on semi-conductor, which realize small package, low power consumption, and low price in spite of the high performance, also contribute to developing pico-satellites greatly. On the other way, the limitation of electrical power from the solar cell for the reason of the small area of solar cell leads to restrict transmitting power of communication subsystem, thus most of pico-satellite must have low baud rate communications inevitably. Moreover we adopted amateur radio band as CUTE-I communication band because of the easy acquisition of transmitting frequency which is arranged and assigned internationally and easy development by using COTS

(Commercial Of The Shelf) amateur transceiver. The communication by using amateur band has often jammed by other amateur's use and we have experienced that the precious telemetry from CUTE-I were lost any number of times for this 2-years operation. Furthermore most of pico-satellite does not have actuators for controlling the attitude; therefore the level of the radio wave is also instability. By the way from over 2 years operation the human fatigue is not-ignored problem, the need of autonomous ground operation has been grown in recent month.

2. OBJECTIVES

The objectives in this paper are the followings.

- Developing autonomous ground operation system for CUTE-I.
- Making the problems of the CUTE-I autonomous ground operation system clear because CUTE-I is not developed supposing autonomous ground operation.
- Proposing autonomous ground operation system which solves the above problems for Cute-1.7 + APD that is our next developing satellite.
- Proposing distributed autonomous ground operation system in order to collect much precious telemetry data effectively.

3. EXISTING SYSTEM

3.1 CUTE-I

CUTE-I is our first handmade pico-satellite by student. CUTE-I is based on *Cubesat Design Specifications* defined by Cal Poly and Stanford Space Systems Development Lab. (SSDL), 10cm-cubed shape, and 1kg weight pico-satellite. The missions are 1) experiencing all procedures of developing, launching, and ground operating satellite system by students, 2) Demonstrating the fundamental and stable satellite bus leading to our next satellite which has more complex missions, 3) Demonstrating the short term and low-cost of development by using COTS devices. Table 1 shows the characteristics of CUTE-I and figure 1 shows the appearances of CUTE-I flight model and separation system which is also developed by LSS. CUTE-I has

been operational for over 2 years without remarkable troubles.

Table.1 Characteristics of CUTE-I

| Items | Descriptions | |
|-------------------------|--------------------------|-------------------|
| Shape | 10cm - Cube | |
| Weight | 1kg | |
| Main MPU | Renesas H8/300 | |
| Communication | Uplink | 144MHz |
| | | FM DTMF |
| | Downlink : Beacon | 430MHz |
| | | CW(Morse) |
| Downlink : Packet(FM) | | 430MHz |
| | | AFSK(Ax.25, SRLL) |
| Sensors | Gyroscope(3 Axes) | |
| | Sun Sensor | |
| | Accelerometer(3 Axes) | |
| | Thermo Sensor | |
| Generating Power (avg.) | 1.5W | |
| Battery | Lithium-Ion (Mn - anode) | |
| Solar Cell | Silicon | |
| Vehicle | Eurockot - Rocket | |
| Launch | 30th June, 2003 | |
| Orbit | 820km Sun-Synchronous | |

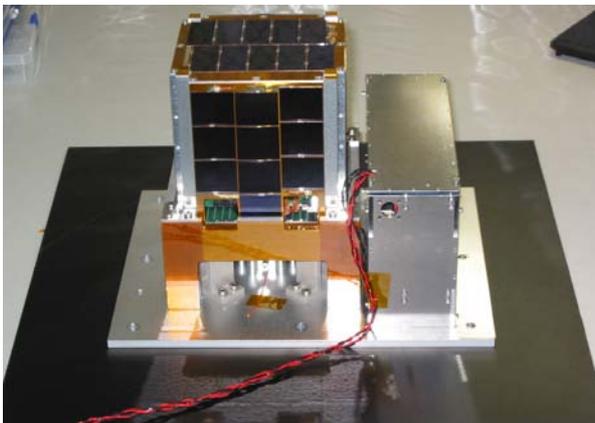


Fig.1 CUTE-I Flight Model

3.2 CUTE-I Communication Subsystem

CUTE-I always transmits CW (Continuous Wave) beacon including Morse code by using 430MHz amateur band with interval among frames in order to reduce the power consumption. The beacon telemetry include important house keeping data of CUTE-I health, for example, 1) voltages of internal secondary battery, solar cells, and buses, 2) current of discharging or charging, 3) temperature of the battery, and 4) current status of CUTE-I. CW beacon is the one way of the lowest power consumption and suitable low power satellite such like CUTE-I whose power of transmitting is only 80mW. On the other hand the frequency range of CW beacon is very narrow (~500Hz); therefore we must strictly adjust frequency of receiving. Although our ground station system is able to calculate the orbit and Doppler shifting using SGP algorithm and the latest orbital information at NORAD (North American

Aerospace Defense Command), The narrow frequency range needs more detailed human-based adjustment in order to decode the CW beacon normally by using CW decoder. Figure 2 shows normal CW beacon frames.

| |
|---|
| CUTE 69 A5 51 80 DA 3CC0 4700 FF FF 82 BE |
| CUTE 75 A4 50 80 D7 3CC0 4700 FF FF 81 BD |
| CUTE 6F A4 50 7F DA 3CC0 4700 FB FC 81 BD |

Fig.2 CUTE-I CW Telemetry (3 Frames)

CUTE-I also has FM packet downlinking communication which is faster baud rate (~1200bps) than CW beacon, requires much power consumption of transmitting, and includes of all CUTE-I data, for example, gyroscope data, accelerometer data, sun sensor data, and so on. CUTE-I is not able to transmit FM packet continually because of the limitation of generating power from the solar cells. Thus ground operator confirms the condition from CW primary telemetry and sends permission command to transmit FM telemetry for only a few minutes. Regarding with uplink of CUTE-I adopts DTMF signal which is the same way as tone of telephone on FM radio wave. CUTE-I command system adopts the double-checked way that consists of recognition and execution; therefore operator must confirm the recognition command before execution commands. Since the recognition command is included in the CW beacon, it is difficult to judge the recognition command except for human-check because the CW beacon telemetry has much noise as we mentioned. Not only CUTE-I but most of next generational pico-satellites of the other developers will adopt the same procedures of operation which are 1) checking satellite condition from low-powered beacon, 2) uplinking the permission command of high-baud rate transmitting for limited minutes compared to the left of internal battery.

3.3 Ground Station System

We developed the ground station system at the same time of developing CUTE-I. The ground station is not specified for CUTE-I operation but general operation of any satellite. The system is superior to system extensibility, data reusability, and low-cost by using the latest Internet technologies and XML (Extensible Markup Language) document technologies.

Functions of general ground station not to be related to the scale of the system can be classified into four main groups.

- Function of controlling ground station equipments
- Function of storing and managing the data of ground station

- Function of analyzing, presenting, and publishing the data.
- Function of administrating and utilizing ground station.

Developed ground station system is multi-layered distributed system which consists of the following abstract 4 layers which are in charge of these 4 functions whose communication between these layers was connected by IP (Internet Protocol) network and XML data handling.

- Equipments Control Layer: Controlling ground station equipments, e.g., antenna direction, radio frequency.
- Data Store Layer: Storing and management all data of ground station.
- Business Logic Layer: Analyzing and calculating data regarding ground station and satellite and presenting data with data store layer
- User Layer: Administrating ground station and seeing and using ground station data.

The functions of each layers, for example, orbital calculation and orbital estimation on business logic and antenna direction control on equipment control layer, are common to any ground station. We developed the ground station framework software which includes these common functions; moreover the framework can easily implement additional component modules for specific satellite. Thus, we can extend this ground station system by the minimum development. Figure 3 illustrate the multi-layered ground station system.

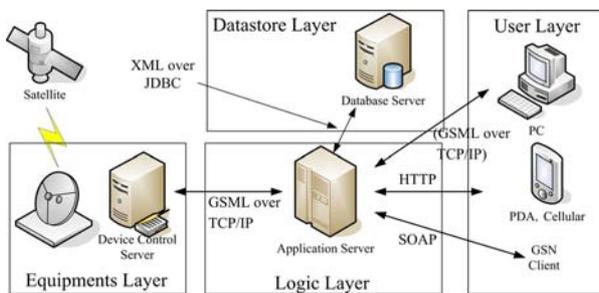


Fig.3 Multi-Layered Ground Station System.

This framework manages all ground station data as XML data. GSML (Ground Station Markup Language) manages all status of ground station equipments, for example, antenna direction, radio frequency, received telemetry data, and sending command data as XML data. GSML is handled between logic layer and equipment layer via TCP/IP socket communication protected by PPTP (Point to Point Tunnelling Protocol) or IPsec (IP Security) and stored into datastore layer. Since logic layer has XSLT (XSL Transformation)

engine module on the framework, all XML data in datastore layer can be converted to suitable for users. Figure 4 illustrates result of orbital calculation by using converted SVG (Scalable Vector Graphics) which is one of XML schemas, on general web browser. By this web-based and XML-based framework, worldwide general people and researcher who want satellite telemetry for their research and can see and reuse the precious space data easily.



Fig.4 Web-based Orbit Map

3.4 Developing CUTE-I Ground Station and Operation.

We developed CUTE-I ground station system by use developed ground station framework as mentioned above. From the launch of CUTE-I operator have been operating CUTE-I using this developed system on the procedures such like the followings.

1. CUTE-I becomes to be visible from our ground station, then ground station system begins to control antenna direction and radio frequency automatically.
2. Operator must adjust frequency strictly for correct CW beacon decoding as we mentioned above.
3. Operator judge the permission of FM packet transmitting the from the CW beacon telemetry.
4. Operator uplinks recognition command and execution command for FM transmitting. Before sending execution command, operator must confirm the correction of recognition command from CW beacon telemetry including much noise.
5. Ground station system begins to analyze FM packet telemetry on Logic layer automatically.
6. After operation, operator confirms received telemetry data and reports the operation.

3.5 Problems from the Experience of CUTE-I of over 2 years' operation

Several problems are appeared from the actual 2 years' operation such like the followings.

- Serious exhaustion of operators (laboratory's members): CUTE-I always becomes to be visible 3 times on early morning and 3 times on evening for the reason of sun-synchronous orbit. The operation on early morning leads to destroy regular office life.
- Much tasks to analyze and report after operation.
- Reducing motivation and tension for operation.
- Jamming by other illegal amateurs: not only telemetry but it is very difficult to pass uplink command. We experienced that I can not uplink only 1 command on 1 visible pass many times. Figure 5 illustrates actual received CW telemetry including much noisy data in the frame compared to Figure. 2.

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CUTE 74 A5 57 80 DB 2277 4700 FA FC 81 BD CUT E B U4
SHI ITT 80 D9 2277 47 E FHE S WT MTD T EE EI E EEE M
TIE EVE I E HEHEE EEE I TEN EE E E E T AE E D E E
D TTM 6 A4 4E 7F II IUT 77 4700 FE FF 81 BC CUTE 7D A4
SEE K TGE T NEI H CUTE 8C A4 55 IE EO D9 33H NI H TTT
700 BE SIE E T 0 BB CUNI VBH EA A TTA T ES E ITE A
57 8MMT Z 6 TTTM FB 4700 FF FF 8 CUTE 78 A5 57 80 D8
3BD5 4700 FF FF 7F BB CUTE 94 A5 51 80 DA 3C18 4700
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Fig.5 Actual CUTE-I CW Telemetry Jammed by Noise.

4. CUTE-I AUTONOMOUS OPERATION SYSTEM

From the above problems we tried to develop CUTE-I autonomous operation system in order to reduce the load of operators. Since CUTE-I is our first satellite, we did not consider autonomous operation at the developing term. Thus we were aiming at realizing autonomous operation as possible, make the impossible points to realize clear, and reflect to develop our next satellite CUTE-1.7 + APD.

4.1 Remote-Controllable Ground Station System

The most serious cause for operator's fatigue is to go to the ground station system on such early time. This ground station framework is based on IP network on the communication between layers; therefore operator can control and administrate ground station system from all over the world. In this time we developed 1) remote AC(Alternating Current) controller (Figure 6) via IP network in order to reduce power consumption of ground station system, 2) remote camera system in order to watch the situation on remote site, and 3) remote audio transfer system via VoIP (Voice over IP). By using these additional remote-controlling systems we can operate CUTE-I from our home via broadband Internet. With regarding to the communication delay

issue between home and ground station this framework can solve it by local feedback for high-speed control frequency such as controlling radio frequency with Doppler shifting.

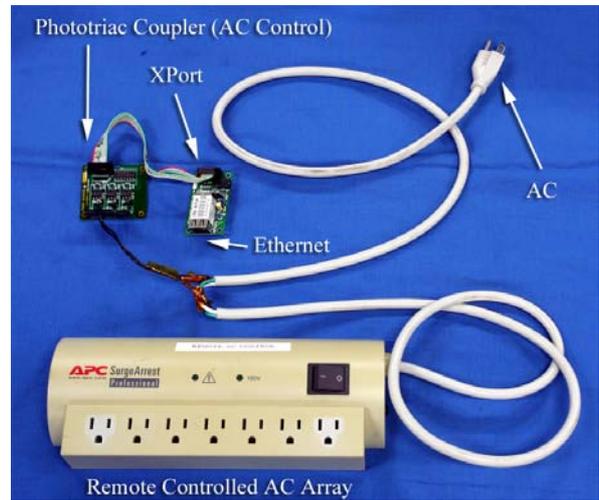


Fig.6 Remote AC Controller

4.2 CUTE-I CW Telemetry Analyzer

CUTE-I always transmits CW telemetry as illustrated Figure 2 without noise such like Figure 5. We intended to develop automatic CUTE-I CW telemetry analyzer with new algorithm showed the followings.

- Position timer to detect data area of 1 frame: 1 frame of CUTE-I CW telemetry is transmitted for about 30 second. This timer is started while detecting header - "CUTE" - and stopped after 30 second. The timer count contributes to estimate CW data.
- Data Prediction from past average data: This function searches appropriate data in noisy CW telemetry synchronizing position timer.

Although we tried to develop this automatic analyzer testing several new algorithms, the software can not archive proper analyzing because of too much random noise such like Figure.5.

4.3 CUTE-I Real Time Operation Web System

For reducing the load of dealing with received data and reporting after operation, we developed real time operation web system. This system can convert GSML and CUML (CUTE-I Markup Language) which include CUTE-I telemetry to XHTML (Extensible Hyper Text Markup Language) using XSLT real time engine module on logic layer. This system we can see the telemetry data on web browser in real time and contribute to reducing tasks after operation.

4.4 Data RSS Feeding System.

We developed RSS (Rich Site Summary) feed broadcasting system for the data of ground station status and CUTE-I telemetry. RSS is very remarkable data format and data distribution system. By This developed RSS feeding system, worldwide people and researcher can access easily by using general RSS reader and their original software. Suppose ground station system writes down Weblog about the result of operation including satellite telemetry automatically.

4.5 Ground Station Operation Scheduler

For autonomous operation we developed operation scheduler which is web-based scheduling considering security (SSL: Secure Socket Layer). Operator can access this system by web browser, cellular phone, and PDA (Personal Digital Assistance) from anywhere and schedule automatic operation. This scheduler generates the list of visible pass of any satellite and operator can select the target pass to operate.

The followings show the procedure of operation by this autonomous ground station system.

1. Operator select visible pass from the list generated by ground station operation scheduler via web browser.
2. Ground station framework prepares to turn on ground station system by remote AC controller and turn on remote camera and microphone, and then begin to track satellite automatically.
3. Operator adjust slight frequency offset and analyze CW telemetry including noise from remote site.
4. Ground station framework stores telemetry data into datastore layer as GSML and CUML automatically, publishes the data as the web page or RSS.

4.6 Result of Autonomous Operation

For the problems appeared from long-term operation we developed autonomous operation system and this system contributes to reduce the load of operator. On the other hand there is a problem with regard to noisy telemetry. To solve this problem we are proposing telemetry protocol of Cute-1.7 + APD.

5. Cute-1.7 + APD Autonomous Operation System

5.1 Satellite Summary

“Cute-1.7 + APD” is our second developing satellite which is 10cm x 10cm x 20cm as shape and 2kg as

weight. We have a plan to launch Cute-1.7 + APD on the winter 2005 and now are developing FM (Flight Model). The missions are 1) demonstrating COTS-based satellite which has PDA as the main computer, 2) Controlling attitude by 3-axes magnetic torquer and supplying the opportunities of on-orbit experiment to worldwide researcher, 3) Demonstrating the de-orbit mechanism by electro dynamic tether, and 4) Demonstrating APD(Avalanche Photo Diode) . Table 2 shows the specifications of Cute-1.7 + APD. Cute-1.7 + APD also adopt amateur radio band. We are proposing telemetry protocol to realize autonomous operation.

Table.2 Specifications of Cute-1.7 + APD

| Items | Descriptions | |
|-------------------------|--------------------------|--|
| Shape | 10cm * 10cm * 20cm | |
| Weight | 2kg | |
| Main MPU(PDA) | Hitach NPD-20WL x2 | |
| Communication | Uplink (Command) | 144MHz FM GMSK(Ax.25, SRL) |
| | Uplink (Public) | 1.2GHz FM GMSK(Ax.25, SRL) |
| | Downlink : Beacon | 430MHz CW(Morse) |
| | Downlink : Packet | 430MHz FM GMSK(Ax.25, SRL) |
| | Sensors | Gyroscope(3 Axes) Sun Sensor CCD Camera APD (Avalanche Photo Diode) Magnetresistive Sensor (3 Axes) Thermo Sensor |
| Generating Power (avg.) | 3.0W | |
| Battery | Lithium-Ion (Mn - anode) | |
| Solar Cell | GaAs | |
| Launch | Winter 2005 | |

5.2 Synchronized Querying Downlink

We proposed “Synchronized Querying Downlink” in order to analyze telemetry on low baud rate including much random noise. Figure 7 illustrates the operation flow.

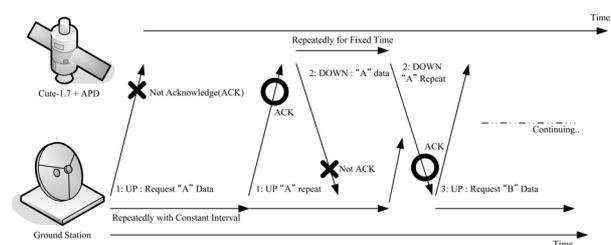


Fig.7 Synchronized Querying Downlink

1. Ground station send query data “A” to satellite and send the query command including a certain interval repeatedly.
2. Satellite recognizes query data “A” then downlink actual data “A” to ground station. Satellite repeatedly downlinks data “A” until a certain time.
3. If ground station received actual downlink data “A” then send the next query data “B”.

4. By repeating the above sequences ground station system can collect and analyze CW telemetry efficiently.

Cute-1.7 + APD adopts this synchronized querying downlink for not only CW telemetry but also area downlinking of large image data by the internal CCD camera. This synchronized querying downlink contributes to realize the complete autonomous operation. On the other way, this system has possibility to downlink the same data repeatedly; therefore the amount of downlink data decreases naturally. For this issue we are proposing the distributed ground station system at the following sections.

5.3 Distributed Synchronized Ground Stations

Since CUTE-I uses amateur band as the communication band, the noise problem by jamming has occurred, however amateur band has some merits more than demerits. The most wonderful merit is that many amateur users receive telemetry data on the all over the world. In the actual CUTE-I operation for over 2 years we received the precious telemetry from worldwide amateur users. Moreover Japanese some amateur users receive CUTE-I telemetry everyday now. There is a potential to solve the noise problem by these distributed world ground stations collaborating to complement the lack of data by jamming. In this section we are proposing distributed ground station system in order to realize the following functions.

- Complementing telemetry data by distributed ground stations
- Collecting telemetry data in worldwide.
-

5.4 Data Specifying System

Although worldwide amateur users have sent the CUTE-I telemetry to us via e-mail, the mail format is not standardized and it was difficult to merge the data into our database. Thus the way of specifying data is indispensable in order to build distributed ground station system. Cute-1.7 + APD manages the transmit time and the data type for all transmitting data in on-board computer and synchronizing the transmitting information with our main ground station system. Main ground station broadcasts the transmitting information to distributed sub ground stations via Internet. Sub ground station can specify the received telemetry from the receiving time by using the transmitting information. Therefore Cute-1.7 + APD transmit telemetry synchronizing with Julian Date. Main ground station publishes this transmitting information via Web Service based on SOAP (Simple Object Access Protocol) or real time RSS feeding. Figure 8 illustrates the data flow of this system.

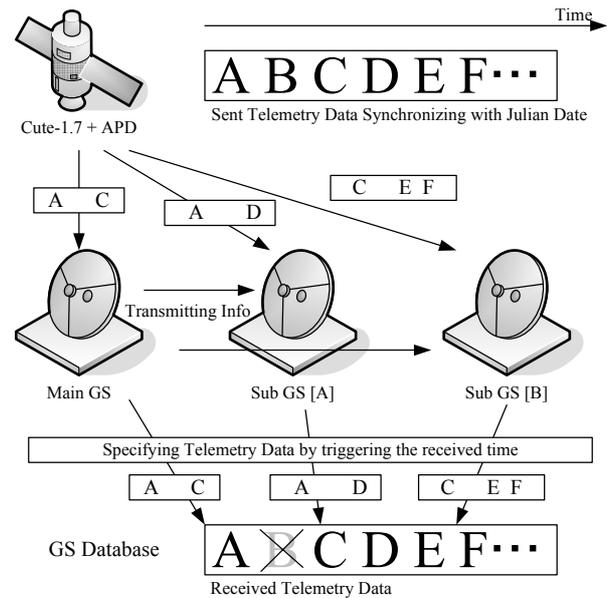


Fig.8 Data Specifying System.

5.5 Satellite Internal Clock Synchronization

Cute-1.7 + APD must have accurate internal clock in order to manage transmitting information. Internal Clock refers to the PDA internal clock with much margin of error. Thus ground station system synchronizes with Cute-1.7 + APD internal clock on every pass by sending accurate Julian Date. We will measure the handling time from transmitting Julian date to updating the internal clock strictly by the launch and consider the handling time on the actual synchronizing.

5.6 Cute-1.7 + APD Variable CW Telemetry

Figure 9 illustrates Cute-1.7 + APD CW telemetry frame. Cute-1.7 + APD can change telemetry format due to the above data specifying system. By changing the telemetry format Cute-1.7 + APD can transmit many kinds of telemetry data under the low baud rate communication.

| CUTE | AAAAA | CCCC | DD | EE | FF | GG | HH | II | JJ | ... | NN |
|--------------|----------------------|------------------|-----------------|--------------------|---------------------|----------------------------------|-----------------|-----------------|-----------------|-----|-----------------|
| Frame Header | Julian Date (5bytes) | Satellite Status | Battery Voltage | Solar Cell Voltage | Battery Temperature | Battery Charge/Discharge Current | Variable Data 1 | Variable Data 2 | Variable Data 3 | ... | Variable Data N |

Fig.9 Cute-1.7 + APD CW Frame Format

6. CONCLUSION

In this paper we developed CUTE-I autonomous ground operation system in order to reduce the load of operator. The system consists of remote ground station controller, operation scheduler, and autonomous data analyzer and so on. Thanks to this developed system we could operate CUTE-I from remote site such as our home via Internet, however a problem on autonomous telemetry analyzer occurred for the reason of broken telemetry data jammed by noise. To solve the problem we proposed synchronized querying downlink system for Cute-1.7 + APD. This system contributes to complete autonomous ground operation. Moreover we proposed distributed ground station system. This system solves the serious problem that is the difficulty to merge telemetry data from distributed ground stations by data specifying system. By building this distributed ground station system actually we can collect much precious telemetry data from distributed ground stations even if the communication speed is low baud rate.

7. REFERENCES

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