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USING A VIRTUAL GROUND STATION AS A TOOL FOR SUPPORTING HIGHER EDUCATION

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ABSTRACT

Students in higher education, scientific and technological research want to communicate with the ISS, download live satellite images, and receive telemetry, housekeeping and science data from nanosatellites and larger spacecrafts. To meet this need, the Ecuadorian Space Agency (EXA) has recently provided the civilian world with an internet to orbit gateway (HERMES-A / MINOTAUR Space Flight Control Center) available for public use. This gateway virtually connects participating clients from around the world to a remote satellite ground station (GS), providing a broad community for multinational cooperation. The goal of the GS is to lower financial and engineering barriers that hinder access to science and telemetry data from orbit.

The basic design of the virtual GS on the user side is based on free software suites. Using these and other software tools, along with amateur radio equipment and a home-built antenna, the GS is able to provide access to orbit for a multitude of users without each having to go through the costly setup. In this paper, we present the design and implementation of the virtual GS in a higher education setting. We also discuss the basic architecture of the single existing system and the benefits of a proposed distributed system. Details of the software tools and their applicability to tracking, monitoring and processing are also provided as used by students performing GS operations.

As the GS was built with the CubeSat community in mind, we provide metrics of traceability of several CubeSats and NanoSats as well as details on the successful download and translation of housekeeping and telemetry. The TU-Graz, EXA and Michigan team as well as other members located in Japan have participated in various mission operations and have investigated real-time satellite data download and image acquisition. Students at these institutions undergo training with on-orbit satellites in preparation for their own use with future NanoSats after a successful launch.

Finally, we present results obtained by simultaneously downloading data and voice on four continents: North America (Michigan), South America (Ecuador), Europe (Austria) and Asia (Japan). This demonstration serves to illustrate the cooperative efforts and ability of the virtual GS in the tracking of satellites and education of students. The satellites tracked include HO-68, ITUpSAT1, UWE-2, BEESAT, SwissCube, SO-67, CO-57, 58, 65, 66, RS-22, RS-30, AO-51 and COMPASS1.

Key Words: EXA, HERMES, MINOTAUR, Internet-to-Orbit Gateway, Virtual Ground Station, Higher Education, Operational Modes, Telemetry, AMSAT, Real-Time, Simulation,

I. INTRODUCTION

With the growing market of CubeSats and other small satellites, students in higher education, scientific and technological research programs require communication access to low-Earth orbit. To meet this need, the Ecuadorian Space Agency (EXA)¹ has recently provided the civilian world with an Internet-to-orbit gateway, HERMES-A / MINOTAUR Space

Flight Control Center (SFC),^{1, 2} available for public use. This gateway virtually connects participating clients from around the world to a remote satellite ground station (GS), providing a broad community for multinational cooperation.

This gateway allows the research community to connect globally in support of inter-disciplinary space operations and provides synergy among diverse areas of research e.g. Meteorology, Space/Satellite

Engineering, Physics etc. Since one type of signal Automated Picture Transmission (APT) data from the National Oceanic Atmospheric Administration (NOAA),³ is transmitted on low-cost Very High Frequency (VHF) equipment, therefore, it is very popular in academia and research organizations and the amateur community.

In support of these efforts, tests were undertaken to examine the usefulness of all four modes of HERMES operations (Alpha, beta, Gamma and Delta⁴). These modes were conducted remotely to verify the capabilities of HERMES to use as a potential command GS for near-future university class NanoSat missions, e.g., University of Michigan's Radio Aurora Explorer RAX⁵ (Launch: end of 2010), Graz University of Technology, Graz, Austria's TUGsat1/BRITE⁶ (Launch: mid of 2011) and the successor AusTrian Lightning NanoSat (LiNSAT)^{7,8}.

The basic design of the virtual GS (VGS) on the user side is based on suite of free software namely, Ham Radio Deluxe (HRD, -Radio, -Sat Track, -DM 780)⁹ and VRS-Remote Monitor (VRS-RM)¹⁰. The HRD functions as a proxy of the real GS located at EXA and VRS-RM (central server) works over the Internet using TCP/IP connection. There are three active channels on the VRS-RM. Ch-1 and Ch-2 are the main and sub transceiver audio frequency (AF) respectively while Ch-3 is for the reception of weather satellites. Optionally, Google Earth (GE)¹¹ can also be integrated with HRD to enhance the visualization.

Using these and other software tools, along with amateur radio equipment and a home-built antenna, the HERMES-A GS is able to provide access to orbit for a multitude of users without each having to go through the costly setup. The design and implementation of the VGS in a higher education setting is discussed in section III. We also discuss the basic architecture of the single existing system and the benefits of a proposed distributed system. Details of the software tools and their applicability to tracking, monitoring and processing used by students to perform GS operations are detailed in section IV. We also provide metrics of traceability of several CubeSats and NanoSsat as well as details on the successful download and translation of housekeeping and telemetry data using all four modes of HERMES operations as the GS was built with the CubeSat community in mind to allow access communicating their CubeSats through HERMES.

Finally, we present results obtained by simultaneously downloading data and voice on four continents: North America (Michigan), South America (Ecuador), Europe (Austria) and Asia (Japan). This demonstration serves to illustrate the

cooperative efforts and ability of the virtual GS in the tracking of satellites and education of students. The satellites tracked include HO-68, ITUpSAT1, UWE-2, BEESAT, SwissCube, SO-67, CO-57, 58, 65, 66, RS-22, RS-30, AO-51 and COMPASS1

The main purpose of this work was to involve our international communities in this global experiment: the idea is to democratize access to space for education and academic use. We believe that progress happens when the advances of science and technology reach the wider community, and that this is an opportunity to inspire the graduates through a collaborative approach to enhance their skills.

HERMES has provided a platform for students pursuing higher education to perform hands-on-experiments covering practical research topics. Such topics in satellite / space engineering include VGS design, operational analysis and use of application software to perform mission analysis.

The HERMES facilitates participating users in understanding the basic phenomena of satellite communications and space operations. The Amateur Radio¹² community has been involved with satellite communication over many decades and helped to establish standards in communication protocols, packet radio, satellite developments and operations. The most common protocol being used for university built NanoSat communication is AX.25¹³. By using many satellites transmitting with this protocol, HERMES has become a great platform to learn more about these interesting and applied fields. Many university student designers have worked closely with the amateur community to benefit from existing design and operations standards.



Fig. 1: Demonstration of HERMES at UNOOSA, Graz, 2009. Participants from 35 countries learnt the online, real-time system.

Satellites in low Earth orbit (LEO) ~ 800 -1000 km have communication windows with GSs for about 12-18 minutes per pass providing only brief communication possibilities throughout the day. While connected, among many applications, the user may

- have half duplex voice communication with analog satellites like AO-51, HO-68, SO-50 etc
- read spacecraft telemetry from almost all amateur satellites
- receive housekeeping data from selected satellites like Compass1
- hear voices from space using onboard digitaltalkers and Slow Scan TV (SSTV) images from CO-66
- receive weather images from NOAA-15, 17, 18 and 19 (N')
- get scientific satellites earth observation images like Compass1, SO-67 and SwissCube etc

Satellite tracking, telemetry/data decoding and checking health status of above satellites using a VGS is a great opportunity for the students in space science / engineering to participate in space operations and post-launch mission analysis. But this is not limited to higher education: A class of Ecuadorian 2nd graders has now learned to downlink and analyze NOAA weather image data.

As mentioned earlier, there is a requirement for the client to have broadband Internet with a public IP address. To avoid any noticeable latency, a 512 kbps connection is needed for a clear reception. We verified multi-user test runs, that is, each participant experienced tracking and receiving the telemetry of the satellite in real-time. All remote users decoded received AF signals 1) APT with WXTOIMG¹⁴ and 2) telemetry / housekeeping data using HRD-DM780 and/or MixW¹⁵. We found that their internet connections were capable of handling the AF input load.

Multiple users will have the capability of communicating with a satellite using VGS at remote places throughout the world as they work in international community and this can play a major role in the development of satellite related fields by sharing their earned knowledge through collaborating with space agencies like EXA.

II. HERMES I-2-O GATEWAY

The HERMES GS does not include a terminal node controller (TNC) as it has been developed to work as an Internet-to-orbit gateway (I-2-O)² for an

Internet user to connect satellites in space. Therefore, TNC resides at the user end. Since operations began in Sep. 2009, many users around the world have tested and verified its capabilities. Delta is the only mode of Hermes that does not need a control interface to track the satellite for data reception. Optionally, however, users can track the NOAA satellites using MINOTAUR for practice. Once the signal reaches the clients computer, many software packages can be used for signal analysis like HRD - DM780 and MixW.

Contrary to standalone normal GS, the HERMES receives the telemetry and other data from LEO satellites and sends AF via real-time relay to remote users all over the world. The received AF is post-processed by TNC: a software HRD-DM 780 or MixW on VGS as decoding program at user end. For an online reception of the AF feed, the only requirement is to have VRS-RM running on the user PC.

III. REMOTE USER VGS

A GS can have many different implementations:

A Normal GS has an antenna, amplifier and transceiver, where the operator is locally stationed with speakers and a microphone and/or other signal processing and analysis tools.

A Remote GS is the same as above, but the operator has some kind of connections to control the radio and is otherwise located elsewhere.

An Autonomous GS has the same as above, but the operator is replaced with a computer handling the transmissions, receptions and scheduling

A VGS has the interface of the radio sent online so that the client sees the whole thing, but interacts through a proxy like HRD or SatPC32¹⁶ etc. This is closely related to a remote GS.

HERMES is a GS and gateway at the same time. From the user side, a remote user with a PC and the software HRD (that acts as proxy of HERMES) is said to be a complete VGS. Software TNC like HRD-DM 780 or MixW is used rather than a hardware TNC. HERMES provides a control interface to capture the satellite and the carrier wave (in other words: Hermes is like wireless router and TNC is a PC).

All received information from satellites will pass through HERMES (Gateway) in the form of an AF and is received by the VGS anywhere in the world (fig. 2). The TNC transforms this AF into data from the satellite, telemetry, housekeeping, scientific, engineering, etc.

Authorized GS users are able to gather scientific / engineering data not destined for the ordinary user, and to command any one of the spacecraft's

subsystems. The most important requirement for mode Beta and Gamma is to hold an Amateur license¹⁷.

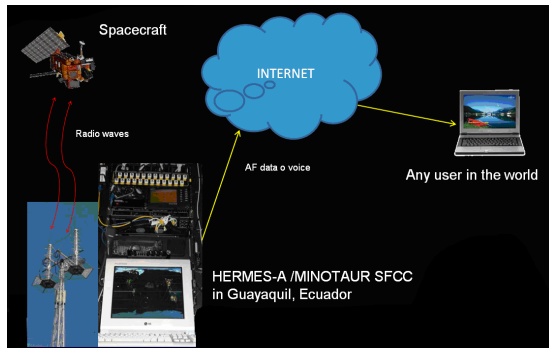


Fig. 2: HERMES, Internet-to-orbit gateway, all modes setup at EXA

IV. OPERATIONAL MODES

The HERMES is capable to handle four modes of operation. The details are as follows.

Alpha Mode: Data Receiving Only

In this mode of operation, the user only receives the AF input of the target spacecraft (i.e. RS-30).

The HRD - Sat Track program has an automated Doppler compensation algorithm. It lets the remote user select target satellites and commands HERMES-A to track the satellite accordingly and manage the Doppler frequency shift.

After the satellite is locked through HERMES, the remote user receives the satellite AF on VRS-RM channel 1 or 2 from the PC soundcard via the Internet. The MCP / Soft TNC transforms this AF into the required data. The HERMES saves the AF as a sound file for accessing and processing it later.

The remote VGS user can see the MINOTAUR antenna array tracking the satellite online as the array has 2 IP cameras¹⁸, one on-board and one outside, pointing to the array. Fig. 3 shows both camera views.



Fig. 3: The Minotaur Array onboard and external camera view: Important for VGS user to see live tracking

ODR Experiment

To test HERMES reliable communication, we tested it in the ODR (Omni Directional Reception) state and shut down the low noise amplifier (LNA). ODR is a state of Minotaur array at MEL (90 degrees Elevation, looking zenith direction). We received signals from RS-30, CO-58 and AO-51 telemetry signals with acceptable signal to noise ratio (SNR). From all of our experiments, it is evident that even in worst cases we are getting some signals from very faint satellites.

The suite of free softwares used to accomplish this and other modes of operation is shown in fig. 4.

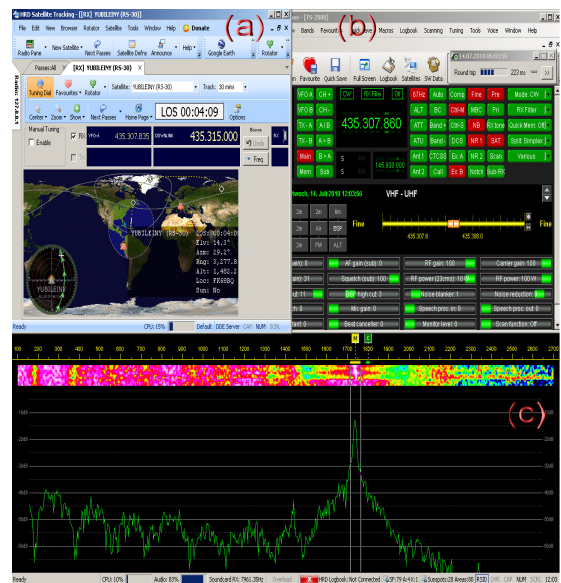


Fig. 4: Alpha mode with Russian satellite RS-30 tracked and received TLM beacon well below horizon (-1.6 deg. Elevation angle). Fig(a) is a screenshot of HRD-Sat track, Fig (b) HRD-Radio and fig(c) is showing the received and analysed telemetry beacon with HRD-DM780 in real-time

Reception below horizon

The MINOTAUR is a high gain and highly directional antenna that we use to receive telemetry signals from the above mentioned satellites at below horizon ~ - 1.7 degrees. A gain plot of the antenna showing sensitivity as a function of azimuth is shown in fig. 5.

The other factors improving the signal quality could be ionospheric effects. The signals can be reflected off the upper atmosphere at certain wavelengths, therefore atmospheric and ionospheric conditions play a major role in the wave propagation. VHFDX¹⁹ is showing current long distance communication using ionosphere (Sporadic E-layer in particular). This layer, as the name suggests, is not

static and is used by amateurs for trans-ocean communication. During this period of time, uplink to satellites is not frequent but downlink can be established easily.

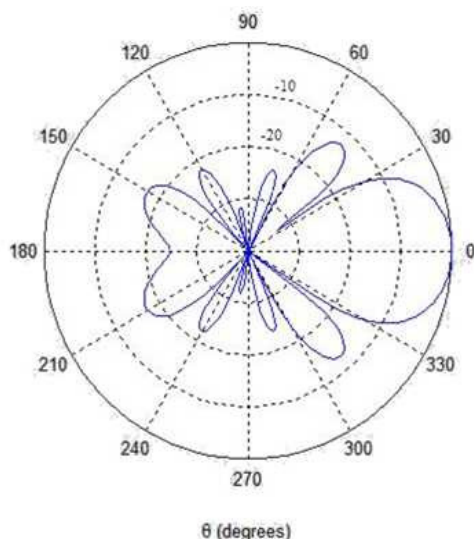


Fig. 5: Minotaur antenna radiation patterns

Additionally, there is a huge body of water around HERMES as seen by north-bound satellites. The reflections from the surface could be another reason for below horizon reception.

SwissCube Rotation Rate:

As compared to TU Graz GS, the spin rate determined by HERMES was low due to its location near the equator. Another source calculating history of spin rate in 2009 is as under: Apr 26 => 21 rpm, Mar 12 => 26 rpm, Feb 06 => 28.5 rpm, Sep 28 => 37 rpm by DK3WN²⁰. On 29th June 2010, at TU-Graz GS, noise beeps repeating every 4sec (spinning) => 15rpm

Due to magnetic field variations, the SwissCube appears to function normally over Ecuador (above Equatorial region) and spins wildly over higher latitudes i.e., in Austria, Germany, Switzerland and Netherlands. So, it may be a better option for Swiss to communicate with their satellite through HERMES using VGS rather than their own ground system.

Voices From Space:

The CO-66 CubeSat from Nihon University²¹ in Japan has an onboard digipeater and user can hear a digitalk voice talking and then it sends an SSTV image over an FM carrier. The image is decoded in real-time by the VGS using DM780. Sometimes, user has to apply manual slant correction on the image due to calibration errors.

In fact the voice of a school grade teacher along with a choir of children voices can inspire students to send their voices into space. The project KRONOS²² is working on the same philosophy using LASER to send human voice into deep space.

Beta Mode: Data Transceiving

In this mode of operation the user is able to receive the AF input of the target spacecraft in range and also transmits to it. Half-duplex communication is established if the spacecraft is operating in a single band only, but full duplex communication can be established if the spacecraft operates in mixed modes like Mode U/V or Mode J. Many Amateur satellites in beta mode use AFSK packets to transmit housekeeping data. These packets data can be decoded using either TNC along with Radio Transceiver or sound card of PC and a decoding software like MixW (VGS - software TNC). For this mode, we worked with COMPASS1²³ to command it with specific sequence of dual tone multi-frequency (DTMF) tones to activate its transponder for transmission of Continuous Wave (CW) telemetry beacon and AFSK housekeeping data. At the user end, the data was analysed in real-time, shown in fig. 6.

A Skype²⁴ based transmission link is sometimes difficult to use for DTMF tones and requires proper isolation from the receiving link.

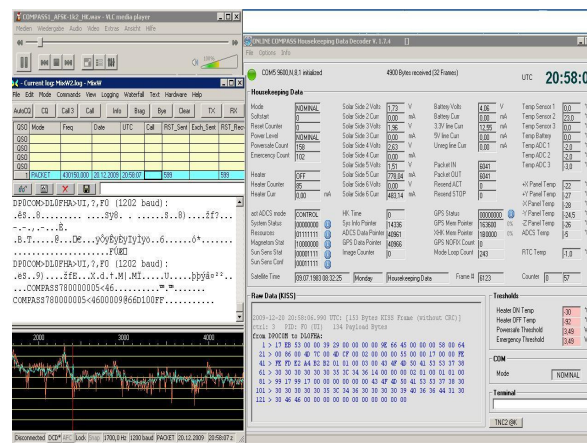


Fig. 6: Mode Beta: Compass-1 tracked, commanded with activation codes and housekeeping data was analysed in real-time

Gamma Mode: Voice Transceiving

This mode of operation is used to establish a half duplex voice communication with a manned / unmanned spacecraft in orbit. (e.g. AR-ISS, AO 51 etc).

Now-a-days, almost all mode gamma satellites are locked for security reasons and to save power during eclipses. To unlock, they require a set of pre-defined codes to transmit by the GS within visibility / communication window like AO-51, which uses 67 Hz sub-audible tones to activate the onboard transmitter (Tx) for voice communication. Any user in the world holding an amateur license can accomplish this. In the same way, the HERMES GS can be used to command a satellite in Mode Beta and Gamma by remote users. Any form of activation codes encapsulated in AF can be transmitted to satellite for receiving telemetry/housekeeping data

In this mode, the user receives and transmits AF to/from the satellite/spaceship through a PC soundcard via internet using Skype. As stated earlier, AO-51 requires a sub-audible tone at 67 Hz to activate its transmitter. The tone does not disturb conversations between the two remote users connected through the satellite. After the link is established, a remote user transmits his voice via microphone and pressing the Tx button on HRD-Satellite Track. As the communication is HDX, repressing the button starts Rx to receive the response. Moreover, no isolation between audio output and audio input is required to prevent echoing, but it is recommended. Additionally, it is beneficial to mute other audio sources within the PC, like the voice announcements from HRD help.

The high round-trip-time (> 250ms) hindered this mode to be accomplished. The trace-route (fig. 7) confirmed that the bottleneck was somewhere in between Ecuador and remote user place. The solution to this problem has been worked out as a tunnel interface using the API and will be designed in a future task.

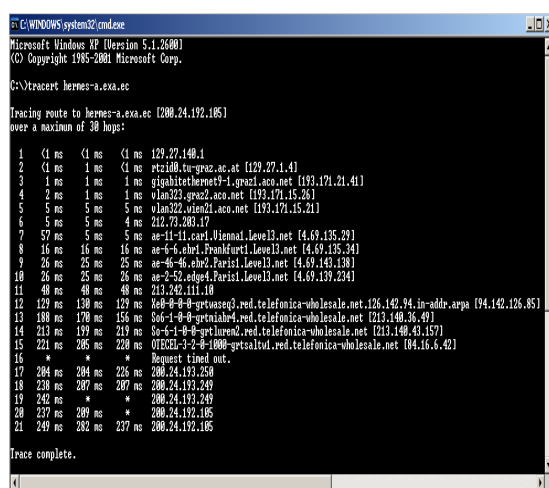


Fig. 7: The current traceroute as per June 14, 2010, of Graz, AUSTRIA – HERMES, EXA.

Delta Mode: Weather Satellite Data Receiving

In this operating mode, the user receives the AF input from a passing NOAA satellite transmitting an APT signal and decode it to translate into image as the spacecraft passes over HERMES-A gateway. APT data is transmitted continuously as an analogue signal using amplitude modulation (AM) with a 2400 Hz subcarrier on an FM carrier. This mode is thoroughly discussed in our project Agora⁴.

V. VGS IMPLEMENTATION

The PC running tracking program determines the azimuth / elevation angles of antennas versus time and drives antenna rotators. As a result, the antenna points correctly to spacecraft and follows its movement in the orbital velocity vector from AOS till LOS. The tracking system compensates the Doppler shift of transmit and receive frequencies due to significant relative movement between spacecraft and GS. These frequencies are shown on HRD – Sat Track as VFO-B and VFO-A respectively.

To handle all of the computational tasks required by the various software platforms used, the following configuration was established.

1st PC performs Communications Control using HRD-Radio and HERMES Web Interface²⁵ IP Antenna Cams (Onboard + External) and Antenna Polarity Selection. The web interface is shown in fig. 8.

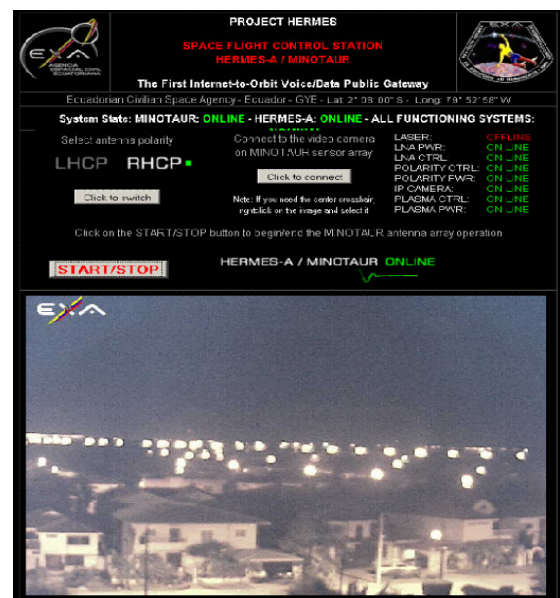


Fig. 8: The communications control using HERMES web interface to run/stop, antenna polarity change and onboard IP camera. The most important interface for remote users.

2nd PC functions orbital control using HRD-Sat Track, HRD-Antenna Rotator (AlphaspidRAS; working on local PC at EXA results shown remotely at user end) on 1st monitor and GE on the other.

3rd PC carries out decoding / data processing using HRD-DM780 or MIXW as a network client of the 1st and 2nd PC, so the decoding program can track the frequency changes.

If a faster user PC is used, HRD-Radio and HRD-Sat Track can both run on a single computer.

VI. FUTURE TASKS

As HERMES continues development, it is likely that enough users will begin using it to require some scheduling tasks. There is currently no scheduling software on the HERMES computer and this will possibly need to be implemented on the user end. In addition, it is recommended for the wider user community to study the patterns of use and find appropriate methods to assign time slots (large operational loads, critical tasks, etc) as the requirements for the satellites evolve.

VII. LICENSE REQUIREMENT:

The most important requirement for all remote users participating in the "hands-on-experiments" is to hold an amateur license to transmit on amateur allocated bands (e.g. 2m, 70cm band), where most of the AMSAT or/and university class nanosatellites are/would be communicating with their NanoSats like RAX, TUGSat1 and LiNSAT. The HERMES accepts all transmissions encapsulated in AF.

Almost all universities are allocated to have 2m and 70cm frequency bands, remote users are licensed to transmit within these bands for transmissions in "Mode Beta" and "Gamma". Furthermore, as a redundant confirmation, remote users were all-the-times in contact with local operators in Ecuador as well, and they were responsible to turn off the system if required (as per US, Ecuadorian, Austrian and Japanese law). For mode "Alpha and Delta", certainly, ANYONE can receive with or without a license. The relevant information is tabulated in table 1.

VIII. CONCLUSIONS

The HERMES has proved to be a useful tool for educating students in the development of a small satellite program, as the success of these missions depends on the post-launch space operations. It has also served as a motivational platform by providing a method for students to have access to space communications otherwise they would not.

The students in higher educational Space/Satellite research used VGS within a collaborative effort for a synchronous round-the-world test of the HERMES to have hands on experience and to share the earned knowledge: new paradigm for advancement of science and technology.

The VGS provides evidence that it can be a key to acquire most of the data / voice related knowledge in space / satellite science/engineering.

By performing most of the operational modes, we have verified HERMES as a potential GS for RAX, TUGsat1, and LiNSAT.

Issues/ Modes	Alpha	Beta	Gamma	Delta
Modulation	CW, USB	CW, FM	FM	AM, FM
Data reception	Receive-only	Telemetry AF FDX if dual mode	HDX Data Tx, Rx Tx, Rx, FDX if dual mode	Weather AF receive only
Amateur License	No	Yes	Yes	No
Sync. Loss	No	No	No	Yes
Network	Yes	Yes	Yes	No/Y
Latency				es
Satellite	Yes	Yes	Yes	No/Y
Tracking				es
Doppler Shift		Yes	Yes	
(Detectable at AF)	Yes			No
Accomp- lished	Yes	Yes	No	Yes

Table 1 : The information related to all four modes, Delta, Alpha, Beta and Gamma

IX. ACKNOWLEDGEMENTS

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* The date of access to all URLs in the references is Sep. 7th, 2010