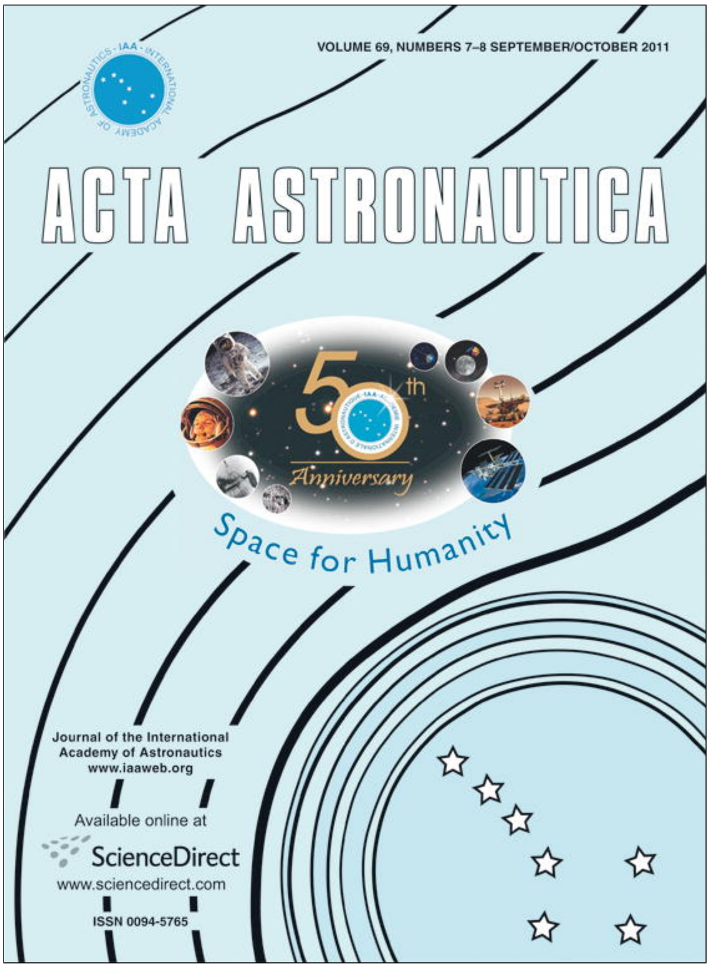
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Internet-to-orbit gateway and virtual ground station: A tool for space research and scientific outreach ☆

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ABSTRACT

Students in higher education, and scientific and technological researchers want to communicate with the International Space Station (ISS), download live satellite images, and receive telemetry, housekeeping and science/engineering data from nano-satellites and larger spacecrafts. To meet this need the Ecuadorian Civilian Space Agency (EXA) has recently provided the civilian world with an internet-to-orbit gateway (Hermes-A/Minotaur) Space Flight Control Center (SFCC) available for public use. The gateway has a maximum range of tracking and detection of 22,000 km and sensitivity such that it can receive and discriminate the signals from a satellite transmitter with power ~0.1 W. The capability is enough to receive the faintest low-earth-orbit (LEO) satellites. This gateway virtually connects participating internet clients 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 engineering data from orbit.

The basic design of the virtual GS on a user side is based on free software suites. Using these and other software tools the GS is able to provide access to orbit for a multitude of users without each having to go through the costly setups. We present the design and implementation of the virtual GS in a higher education and scientific outreach settings. 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 synchronous round-the-world tracking, monitoring and processing performed by students and teams at Graz University of Technology, Austria, EXA-Ecuador, University of Michigan, USA and JAXA who have participated in various mission operations and have investigated real-time satellite data download and image acquisition and processing. Students and other remote users at these institutions undergo training with in orbit satellites in preparation for their own use with future university-class nano-satellites' post launch space operations.

The exclusive ability of Hermes-A/Minotaur to act as a gateway between remote users (internet) and satellites (in orbit) makes the virtual GS at user-end more feasible for the long-term real-time nano/cubesats space operations. The only requirement is to have a mutual agreement between EXA and participating university/research organization and broadband internet connection at user-end. With successful and remote satellite tracking and downloading of real-time data from many operational satellites, the Hermes has been found a reliable potential GS for current and future university missions and a training platform for individuals pursuing space operations.

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1. Introduction

With the growing market of cubesats and other small satellites, students in higher education and the researchers in scientific and technological research programs require communication through access to low-earth-orbit (LEO) satellites frequently as one of their major tasks. The ground-satellite communications are expensive yet highly significant for the success of a space mission and to envisage end-of-life (EOL) of the satellite mission by continuously monitoring the health of all sub systems onboard the satellite. One cost-effective possibility for honing skills is to use amateur satellite service [1] and an online internet-to-orbit (I-2-O) gateway [2,3] conceived and built by the Ecuadorian Civilian Space Agency (EXA) [4] publicly available to the space community. This gateway virtually connects participating clients around the world to a remote satellite ground station (GS), thus providing the broad research community to connect globally in support of inter-disciplinary space operations and to provide synergy among diverse areas of research, e.g. Meteorology, Space/Satellite Engineering, Physics, etc., for multinational cooperation. Hermes provides a platform for students pursuing higher education to perform hands on experiments covering practical research topics. Such topics in satellite/space engineering include virtual GS design, operational analysis and the use of application software to perform mission analysis.

The main purpose of this synchronous round-the-world test was to involve our international communities through the global experiment: the idea is to democratize access to space for education and academic use. The capabilities of Hermes-A as online and real-time system were verified by testing it remotely through all four modes of Hermes operations (Alpha, Beta, Gamma and Delta) (Section 4). After successful transmissions and receptions to/from variety of satellites the Hermes-A is now being used as a potential GS for current operational university-class nano-satellite missions, e.g. radio aurora explorer (RAX) [5] and Swisscube [6], and will be used for the Austrian lightning nano-satellite (LiNSAT) [7–10]. The results of all four modes are discussed in Section 6.

Other objective of Hermes is to give academic community an access to spacecrafts like the program "a satellite in the classroom" [11,12]. The program is based on one of the four modes of operation, Delta of the Hermes-A. It enables school kids to receive live scientific satellite signals to their classrooms and decode them in real-time, taking education to new heights in their country. The Hermes-A GS is also a powerful laboratory that allows us to experiment and learn for ourselves about the satellite technology from firsthand experience. It also serves other international institutions abroad and is sometimes used for national safety purpose by monitoring possible spacecraft collisions on its range of 6000 km, like the event of February 5, 2010 between Iridium-33 debris and the EPFL Swisscube [13].

The Amateur radio community has been involved with satellite communications over many decades. They have helped to establish standards in communication protocols as well as packet radio, satellite development and space operations. The most common protocol being used for university built nano-satellite communication is AX.25 [14]. By using this protocol with transmitting commands and receiving data from many satellites Hermes-A becomes 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.

Satellites in LEO ~ 1000 km have communication windows with GS for about 12–18 min per pass providing only brief communication possibilities throughout the day. While connected, among many applications the user may

- have half duplex (HDX) voice communication with analog satellites like AO-51, HO-68, SO-50, etc.,
- read spacecraft telemetry from almost all amateur satellites,
- receive housekeeping data by sending commands to activate transmitter of selected satellites like Compass-1 [15],
- hear voices from space using onboard digi-talkers and receive Slow Scan TV (SSTV) images from CO-66 [16],
- receive weather images from NOAA-15, 17, 18 and 19 (N′) using automated picture transmission (APT) [17] data from the National Oceanic Atmospheric Administration (NOAA) [18], transmitted on low-cost very high frequency (VHF) equipment that is very popular in academia and research organizations in the field of climate research,
- receive scientific satellites' earth observation images from Compass-1, Swiscube and SO-67.

Satellite tracking, telemetry/data decoding and monitoring health of above mentioned satellites using a virtual GS is a great opportunity for the students in space science/engineering to participate in space operations and post launch mission analysis. The requirement for a client is to have a broadband internet connection with a public IP address. To avoid any noticeable latency a 512 kbps connection is required. We verified multi-user test runs, that is, each participant experienced by tracking and receiving telemetry of satellites in real-time. All remote users decoded audio frequency (AF) signals like APT and telemetry/housekeeping data using suite of free software discussed in Section 5. We found that their internet connections were capable of handling the AF input load. In fact, Hermes-A manages bandwidth in such a way that more than thousand remote users can receive live NOAA satellites for real-time image processing with acceptable signal to noise ratio (SNR). These results were obtained by controlling the satellites remotely and simultaneously downloading real-time data and voice by users located on four continents namely Europe, North America, South America and Asia. These coordinated studies are presented to inform the community about latency effects and the advantages that collaborated space operations may provide. The learning technique we developed is "Hands on Space Communications Training". The big advantage of virtual GS is that no physical interaction with real equipment is required to accomplish all operations. Only one remote user at a time is legitimated to attain full control of Hermes-A. Multiple users have the capability of communicating with a satellite using virtual GS at remote places throughout the world. 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.

2. Hermes-A internet-to-orbit gateway

The Hermes-A/Minotaur Space Flight Control Center (SFCC) shown in Figs. 1 and 2 is compliant with the Open Systems Interconnection (OSI) model. It has no Terminal Node Controller (TNC), as its main job is to convert protocols from one network on the ground (internet) to another network, or device in orbit by routing and translating the radio or laser waves to a protocol that can be understood by a user-end TNC. It also has full remote GS operation capabilities. Hermes serves transport, session and presentation layers. The application layer will remain on the user side. The client station is implemented using a software-TNC; Ham Radio Deluxe (HRD-DM780, Radio, Sat Track) [19] or MixW [20]. MixW has an advantage of using its notch filter feature to enhance the data reception. The final application lies at the user-end in OSI model. In this case the TNC has a big advantage to vary according to user requirement. The I-2-O gateway is of great significance to use it as a single-node command and control station for the satellites in a constellation such as the planned LiNSAT is comprised of three identical nano-satellites for global coverage.

3. Hermes-A/Minotaur implementation

Hermes-A/Minotaur is composed by the command and control center (CMC) shown in Fig. 1 and the Minotaur

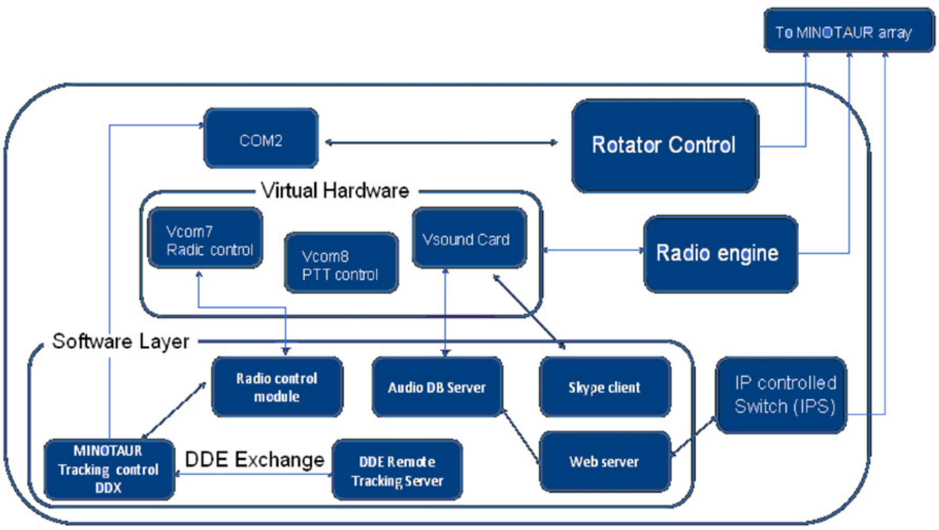

Fig. 1. Project Hermes command and control center (CMC) Minotaur engine implementation.

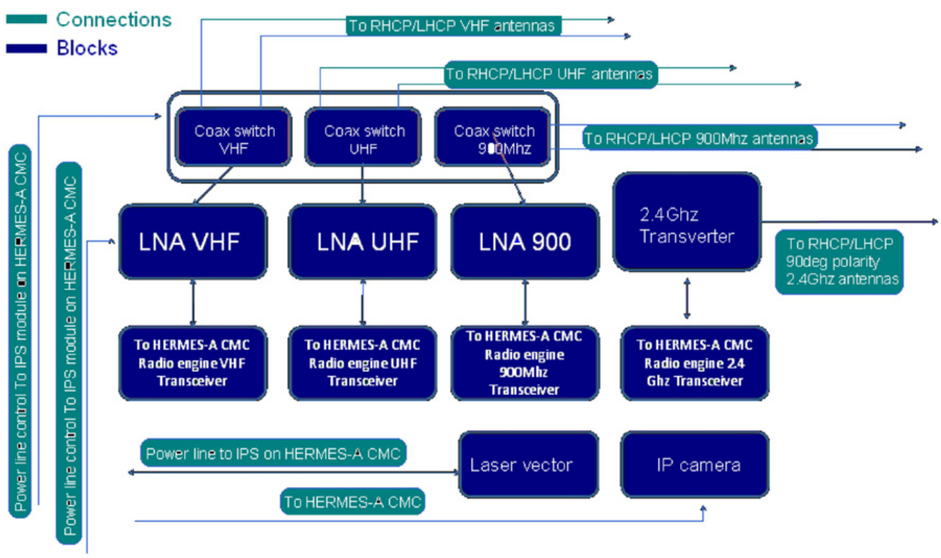

Fig. 2. Minotaur sensor array implementation.

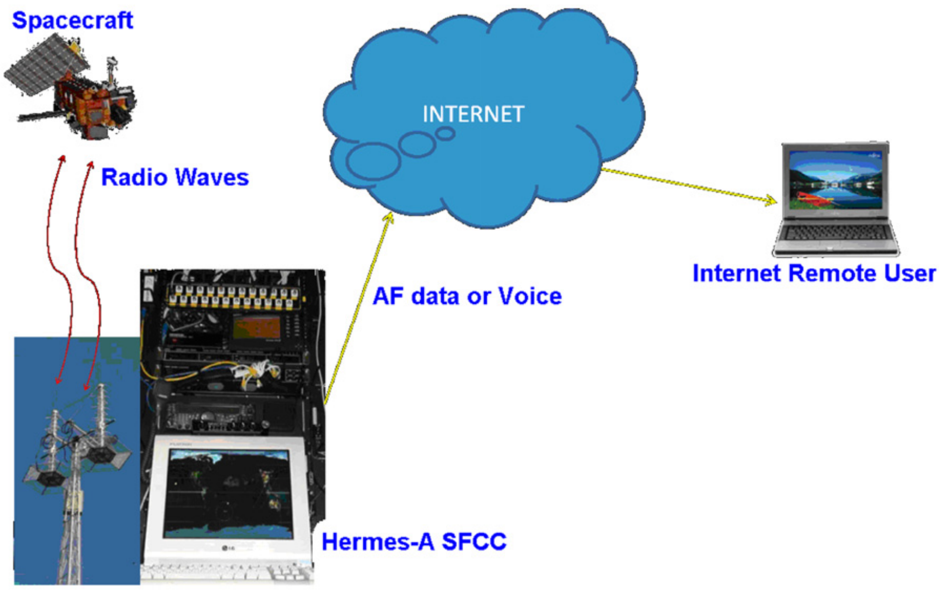

Fig. 3. Hermes-A: internet-to-orbit gateway at EXA, Guayaquil, Ecuador.

sensor array (Fig. 2). All received information from satellite will pass through Hermes-A (Gateway) in the form of AF and received by virtual GS anywhere in the world through the internet. The TNC transforms this AF into data received from the satellite, i.e. telemetry, housekeeping, scientific, engineering, etc. Therefore, a remote user connected to a university node, authorized to access Hermes, will serve as a virtual GS and can command and control the Hermes-A to transform it into an online and real-time remote GS. The scenario is shown in Fig. 3.

CMC houses the

- Hermes-A radio engine,
- audio processing module,
- AF internet server,
- database server,
- firewall and
- two control stations:
  1. first control station manages the radio engine and the antenna array tracking for the target spacecraft;
  2. second control station manages the data decoding process, space flight simulation and orbital prediction.

Minotaur antenna array is a 12 m tall, dual polarity, variable frequency resonator operating between 1.2 MHz and 2.4 GHz, while the Gorgon-B is a secondary array operating in the VHF narrow band, 137–138 MHz, well suited for NOAA satellites reception.

The Minotaur is equipped with advanced radio signal gathering from orbiting spacecraft (ARGOS). Its sensibility is enhanced to 0.002 W at 3000 km. Due to the location of Hermes-A the system has 0–180° view from North to South. ARGOS is right now in phase 3, is capable of enhancing a signal of 174 to 9 dB m through a free space path loss (FSPL) of 200 dB, and the full ARGOS capability is upto 320 dB. The new ARGOS manifold can allow transmissions to the Moon in 900 MHz industrial, scientific and medical (ISM) band, good for earth–moon–earth (EME) communications. Hermes can handle the following range of frequencies and SNR is enhanced by using ARGOS.

Range	22,000 km (Molnya satellite)		
Sensitivity	0.002 W		
Radio horizon	No barriers. Reception of RS 30, AO-51 as low as −1.7° (below horizon).		
Antenna	Helical with dual polarity right- and left-hand circular polarization (RHCP and LHCP) online switching capability		
2 m	18–172 MHz	RHCP/LHCP	70 dB
70 cm	320–500 MHz	RHCP/LHCP	75 dB
33 cm	830–950 MHz	RHCP/LHCP	320 dB
23 cm	2.2–2.6 GHz	RHCP	70 dB
QHA/APT	137 MHz (NOAAs)		20 dB

4. Operational modes

The gateway can operate in four modes of analog and digital space operations.

Mode A (Alpha): Reception of telemetry data from orbit and relay through internet.
Mode B (Beta): Half/full duplex (HDX/FDX) connection between computers on the internet and orbiting satellites.
Mode C (Gamma): HDX voice conversation between any computer on the internet and manned spacecrafts.
Mode D (Delta): APT/high resolution picture transmission (HRPT) signal reception from weather satellites to any computer on the internet.

5. Remote user virtual GS

The basic design of the virtual GS on the user side is based on the suite of free software namely

- Ham Radio Deluxe (HRD- Radio, Sat Track, DM780) [19];

- VRS Remote Monitor (VRS-RM) [21];
- optionally, Google Earth (GE) [22] can be integrated with HRD to enhance the visualization.

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 four channels on the VRS-RM for the audio frequency (AF).

- Ch-1: main transceiver (TRX);
- Ch-2: sub TRX;
- Ch-3: for the reception of weather satellites;
- Ch-4: AF reception of the real-time video relay from the Ecuadorian first satellite (Pegasus), launch, mid 2012.

The PC running this tracking program determines azimuth/elevation angles of antennas vs. time and drives antenna rotators to compensate spacecraft relative movement. As a result, the antenna points correctly to the spacecraft and follows its movement in the orbital velocity vector above the horizon from the acquisition of satellite (AOS) till the loss of satellite (LOS). The tracking system also compensates Doppler shift on the transmit (Tx) and receive (Rx) frequencies due to the significant relative movement between spacecraft and GS. These frequencies are shown on the HRD-Radio software as VFO-B and VFO-A, respectively. The Doppler shifting is managed internally in the decoding radio receiver by a series of linked PLL management circuits with a bandwidth of 250 kHz. The signal is stable enough to be interpreted by the software on the user-end without fading or distortions. Also, the gain of the array guarantees a strong signal even 1° below the horizon as many users sometimes experience [13]. The virtual GS setup at user-end using a suite of softwares as a proxy of real hardware located at EXA is shown in Fig. 4.

Satellite tracking, remote controlling of communication radio, acquisition of data and post processing are generally too complicated to be processed and displayed by one or two computers alone. The remote users have generally distributed processing of the entire setup using several PCs with multiple displays.

While this setup has been tested on a single laptop a common distribution is as follows:

First PC performs communications control using HRD-Radio and Hermes web interface [23] to start/end the process, antenna polarity selection (Fig. 5) and the IP antennas (onboard and external view [24]) shown in Fig. 6. Second PC functions orbital control using HRD-Sat Track, HRD-Antenna Rotator (Alphaspid RAS; working on local PC at EXA and the results are shown remotely at user-end) on first monitor and the GE on other display. Third PC carries out decoding/data processing using HRD-DM780 or MixW as a network client of the first and second PC, so the decoding program can track the frequency changes. Fourth PC works orbital simulation by running STK simulations of the current NOAA satellite, showing the orbital mechanics data in real-time. STK real-time simulations are well synchronized so that when the footprint of the satellite in full 3D simulation touches the antenna, the AF is received by all participating remote users. If a faster PC is used then both HRD-Radio and HRD-Sat Track can be run on a single computer.

6. Operational modes: results

The Hermes is capable of handling four modes of operation. The results of receive-only modes, Alpha and Delta are detailed in [13]. In this paper we focus only on transmission modes, i.e. Beta and Gamma along with the constraints in the next sections.

6.1. 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 using Skype [25] based transmission through Hermes-A. Hermes-A accepts all transmissions encapsulated in AF. HDX communication is established if the spacecraft is operating in a single band only, but FDX communication can be established if the spacecraft

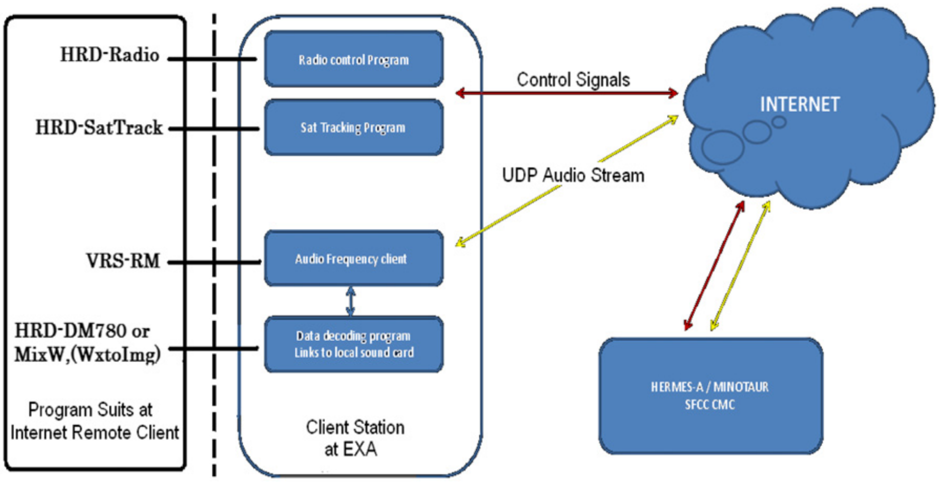

Fig. 4. Virtual ground station setup using suite of free software.

operates in mixed modes like Mode U/V or Mode J. Many Amateur satellites in beta mode use audio frequency shift keying (AFSK) with different speed e.g. 1200 or 9600 baud packets to transmit housekeeping data. These packets data can be decoded using either TNC along with radio transceiver or PC soundcard using decoding software like MixW (software-TNC). For this mode we commanded Compass-1 [15] with a specific sequence of dual tone multi frequency (DTMF) tones to activate its transponder. As a result, the satellite transmitted continuous wave (CW) telemetry beacon and AFSK housekeeping data. At the user-end the data was analyzed in real-time as shown in Fig. 7. The Skype based transmission link is sometimes difficult to use for DTMF tones and requires proper isolation from the receiving link. For transmission modes (Beta and Gamma), only authorized users (Amateur license [26] holders) can transit to the satellites.

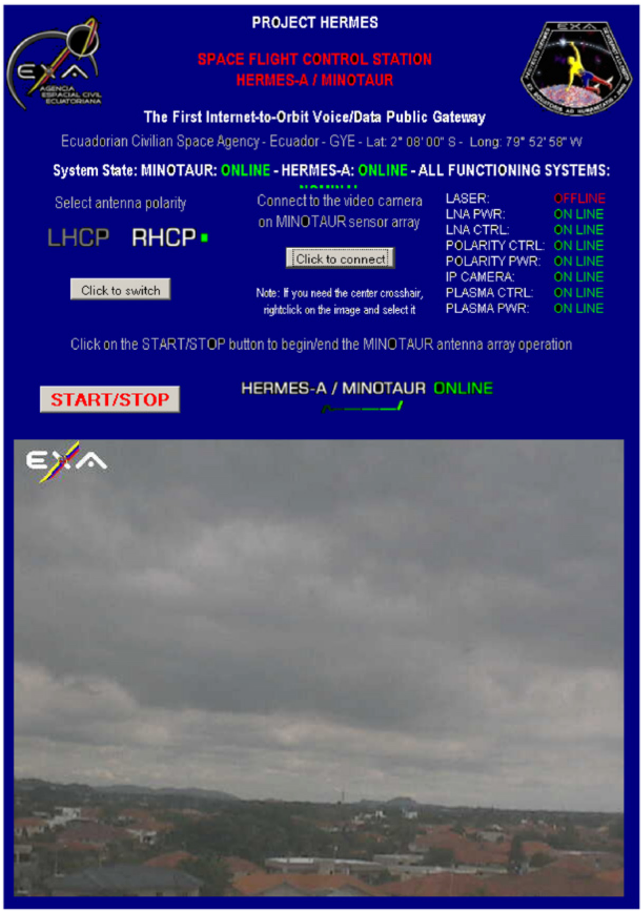

Fig. 5. Communications control using Hermes web interface to run/stop the process and antenna polarity selection.

6.2. Gamma mode: voice transceiving

This mode of operation is used to establish a HDX voice communication with a manned/unmanned spacecraft in orbit. (e.g. AR-ISS, AO-51, etc.). These 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, i.e. AO-51, which uses 67 Hz sub audible tones to activate the onboard Tx for voice communication [27]. Any user in the world holding an amateur license can accomplish this. The Hermes GS can be used to command a satellite in modes Beta and Gamma by remote users. Any form of activation codes encapsulated in AF can be transmitted to satellite for receiving telemetry/housekeeping data.

Like Beta 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 onboard 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/her voice via microphone and pressing the Tx button on HRD-satellite track. As the communication is HDX re pressing the button enables 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 helpful to mute other audio sources within the PC like voice announcements from HRD help.

The high round trip time (RTT $>$ 250 ms) hindered this mode to be accomplished. The traceroute shown in Fig. 8 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 application programming interface (API) and we will pursue it in near future.

Fig. 6. Onboard and external IP camera view. An important web interfaces for remote users to monitor live satellite tracking.

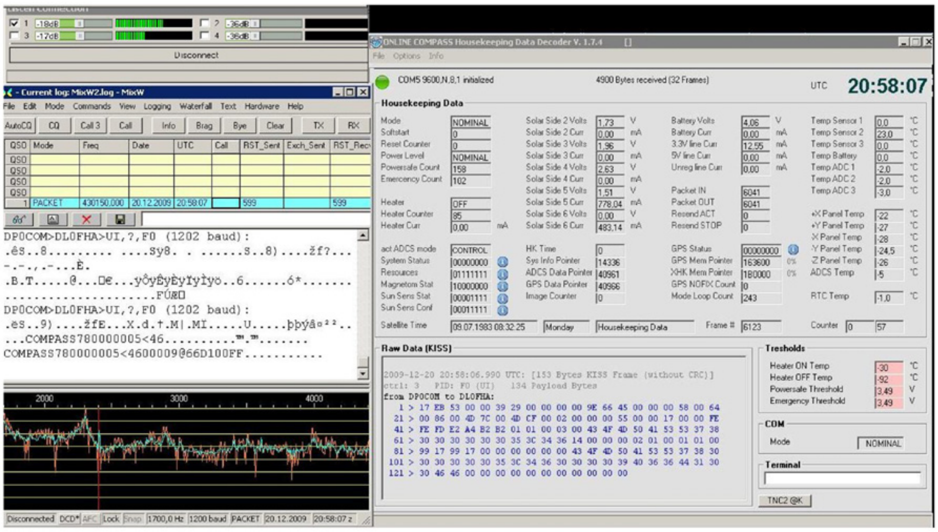

Fig. 7. Mode Beta: Compass-1 tracked, commanded with activation codes and housekeeping data was analyzed in real-time.

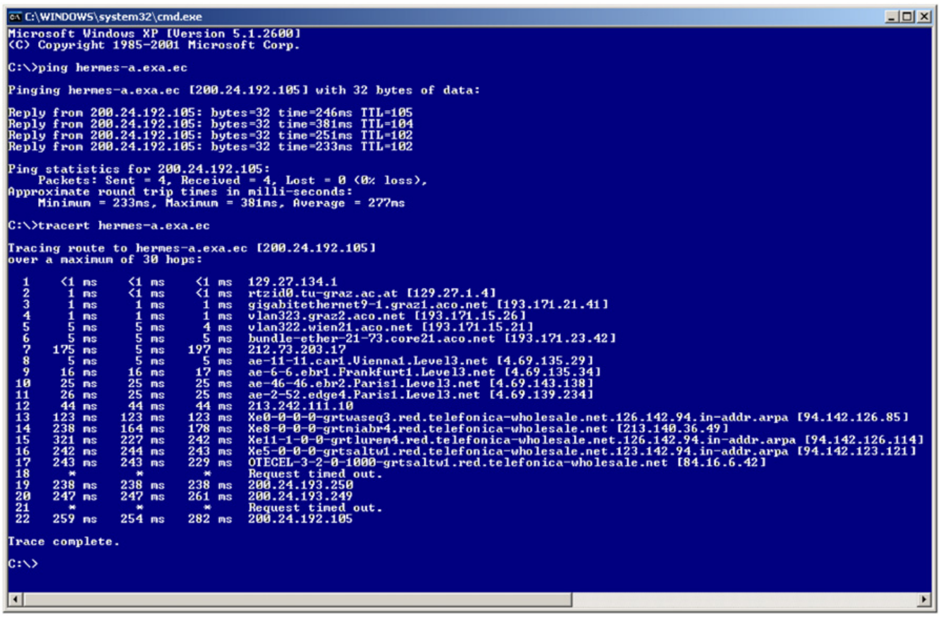

Fig. 8. Current 'traceroute' as per February 1, 2011, of Graz, Austria–Hermes, EXA.

7. Constraints

7.1. VRS-RM/port blocking/firewall

It has been observed that VRS-RM freezes due to saturation and requires a reset every few months. Secondly, one remote user in Japan had an issue with port blocking due to firewall security at their organization, so was unable to access Hermes remotely.

To resolve these problems at both ends and as a redundant protocol, a 'broadwave interface' was created as an alternative to VRS-RM but not a complete replacement. Hermes typically allows access through the 'broadwave interface', meant to be used over port 80 when access to port 264 is not possible due to firewall issues. It requires static IP (authenticated by Hermes) to use as this provides a layer of security on the router. Another option is to use voice over IP (VoIP), e.g. Skype for delta mode only when using Minotaur for satellite tracking. It works in all modes, but as stated earlier VRS-RM is the first option in all cases. To avoid further issues a web interface was created for availing all channels like VRS-RM. The remote users can get AF signals by accessing a remote interface on port 94 to process the images after the pass is completed. The AF.wav of all NOAA and other accessed/tracked satellites (last seven days) are available on the EXA server for later analysis.

7.2. Network latency

A good internet connection with RTT < 50 ms was assumed to be required for remote operations. Many internet service providers (ISP) between a remote user node and Hermes-A are not offering upto the mark connections as revealed by 'traceroute' and observed in all four modes of operations. It was found that the RTT is usually greater than 250 ms which does not allow for synchronous links to Hermes. The 'traceroute' and RTT are shown in Figs. 8 and 9. We found that frequency shift during ± 3 min maximum elevation angle (MEL) was so high that HRD-Sat Track could not function its automated Doppler compensation properly. The manual frequency adjustment was necessary during this time window. The network latency problem lasts only for 3–4 min during 14–18 min pass.

As the internet speed is never constant and the calculated results always vary due to multiple router hops for the remote client to get into Ecuador. The changes in network latency are the consequences. The immediate effect is seen with freezing the HRD during satellite pass acquisition. From command and control point of view Hermes is tested for Alpha and Beta mode with excellent results, but Voice Mode (Gamma) is difficult to accomplish with such an issue for remote operations. None of the participating users was able to reduce RTT less than 150 ms (50 ms requirement). The 'traceroute' points out that the bottleneck is somewhere just before Ecuador. As the internet infrastructure is better in Europe but 5 ms time does not help out. The HRD, 'ping' and 'traceroute' all validate that the RTT is ~250 ms even when the internet usage is not so much here in Graz, Austria and other remote users' site. Due to asynchronous option in HRD settings 'elastic band' effect to automated Doppler compensation is observed frequently.

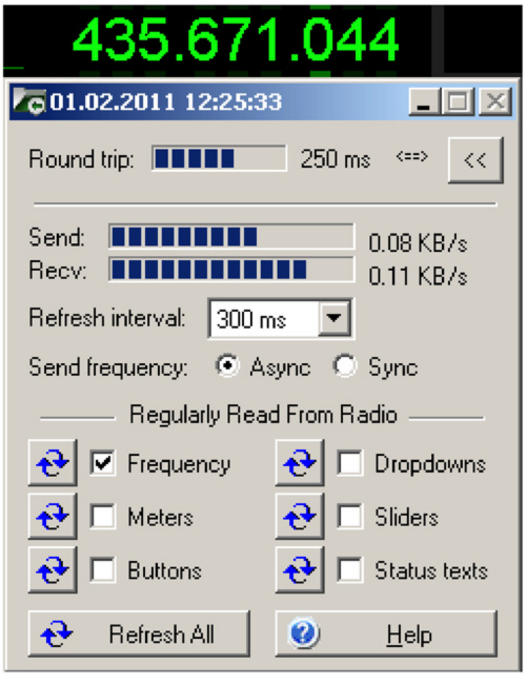

Fig. 9. Round trip time from Graz Austria to Hermes Ecuador at remote user node.

8. Amateur 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 entitled bands (e.g. 2 m, 70 cm band). Most of the AMSAT or/and university-class nano-satellites are/will be communicating with their nano-satellites like RAX, TUGSat1 and LiNSAT to these frequency bands. Furthermore, as a redundant confirmation the remote users must all the times stay in contact with local operators in Ecuador to turn off the system if required (as per US, Ecuadorian, Austrian and Japanese law). For modes 'Alpha and Delta' certainly anyone can receive a satellite data without holding a license. The relevant information is tabulated in Table 1.

9. Future tasks

Our field SFCC design is very compact, economical, portable and easy to maintain, hence we believe the expansion plan goals are achievable and realistic. Hermes expansion in Europe, UAE, India and Pakistan is in the development phase. In its final configuration the network can offer more than an hour of uninterrupted connection between internet users and the satellite in orbit, representing a significant boon for long-term multi satellite communications.

As Hermes continues development it is likely that enough users will begin using it to require some scheduling tasks. There currently is no scheduling software on the Hermes computer and this will likely need to be implemented on the user-end. In addition, the wider user community will also have to be studied to see patterns of use and find appropriate methods to assign times

Table 1
Information about all four modes of satellite operations.

Issues/modes	Alpha	Beta	Gamma	Delta
Modulation	CW, USB	CW, FM	FM	AM, FM
data reception	Telemetry AF receive-only	HDX data Tx, Rx. FDX, if dual mode	HDX analog AF Tx, Rx, FDX if dual mode	Weather AF receive-only
Amateur license	No	Yes	Yes	No
Sync. loss	No	No	No	Yes
Network latency	Yes	Yes	Yes	No/Yes
Satellite tracking	Yes	Yes	Yes	No/Yes
Doppler shift (detectable at AF)	Yes	Yes	Yes	No
Accomplished	Yes	Yes	No (API: future task)	Yes

(large operational loads, critical tasks, etc.) as the requirements for the satellites evolve.

As Hermes-A is only the first of a series of GS, the data collected regarding automatic operations will be critical for future use. With several stations operating automatically a user anywhere in the world can connect, monitor and control a formation of satellites from their laptop, a capability that has not been realized by the small satellite community.

10. Conclusions

The Hermes-A embodies an excellent laboratory for space operations and research worldwide through internet. 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 such as tracking, controlling and decoding university-class satellites transmissions.

The virtual GS provides evidence that it can be a key to acquire most of the data/voice related knowledge in space/satellite science/engineering. We demonstrated a synchronous round-the-world test of the Hermes-A by a distributed team that was able to track, download and decode amateur satellites transmissions using a suite of free softwares.

Among many constraints, port blocking and network latency issues were worked out. After a successful and remote satellite tracking, monitoring and downloading real-time data from many operational satellites, the Hermes-A has proved reliable and capable enough to be used as a potential GS for current and future university missions and a training platform for individuals pursuing for space operations.

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