VHF-Band Interference Avoidance for Next-Generation Small Satellites.

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ABSTRACT

The past decade has seen a dramatic increase in the number of satellites operating or proposing to operate within the VHF frequency band. Antennas, receivers and transmitters for both the ground and the space segment are readily available and inexpensive, whilst propagation conditions are very favourable. This allows communications to and from the satellite using low-cost omni-directional antenna based ground terminals. It is because of these attractions that many amateur and commercial satellites choose to operate within this band.

Unfortunately, the attractions of the VHF band has also lead to one of its greatest disadvantages: overcrowding. Low Earth Orbit satellite systems compete for spectrum, often having to coexist with other users. On any but the clearest channels, interference levels frequently make the link unusable—despite promising link budgets. Next generation small satellites making use of the VHF band must therefore be designed to operate within this congested environment.

This paper examines measurements of the long-term global interference environment obtained using the HealthSAT-II microsatellite. Analysis of the results reveals that levels vary with geographical location, frequency and time. An autonomous interference avoidance technique is then examined, which exploits the diverse nature of the communications environment, allowing efficient utilisation of the band, improving channel throughput.

INTRODUCTION

The VHF frequency band has been used for communications to and from Low Earth Orbiting satellites ever since the first experimental satellites were launched in the 1950’s [1]. The band has been chosen for use by a number of amateur and experimental satellites [2], with frequency allocations granted by the International Telecommunications Union (ITU) [3]. Recently the frequency band has seen the introduction of commercial “Little-LEO” systems. Constellations of Low Earth Orbiting satellites, providing services such as property tracking, store and forward communications, two way messaging and Email.

In this frequency band a range of proven techniques, equipment and other knowledge exist enabling the provision of world wide data communications services with a relatively modest network infrastructure cost, technical complexity, and low terminal cost. Antennas, receivers and transmitters for both the ground and the space segment are readily available and inexpensive when compared to those operating at higher frequencies. Propagation conditions are also favourable at these frequencies [4], allowing communications to and from the satellite using simple omni-directional antennas. It is because of these attractions that many amateur and commercial satellites operate within this band.

The attractions of the VHF band has also lead to one of its greatest disadvantages: overcrowding. Spectrum is a scarce resource, free spectrum non-existent. Services operating, or proposing to operate within the band must therefore often coexist with other systems, both terrestrial and satellite [5]. Interference therefore can become a limiting factor. On any but the clearest channels, interference levels frequently make the link unusable—despite promising free-space loss “link budgets.”

This paper presents results from in-orbit measurements of long term global frequency usage or interference, obtained using the HealthSAT-II microsatellite. These measurements show that the interference can cause significant degradation to fixed frequency communication systems operating within this band, often rendering the channel unusable for prolonged periods of time. Analysis of the measurements, however, reveals significant frequency, geographic and temporal structure,
suggesting possible interference avoidance strategies for next generation satellites.

The paper examines an interference avoidance technique, which exploits the diverse nature of the VHF communications environment, allowing efficient utilisation of the band, and improving channel throughput. Using a microsatellites onboard computer, GPS and frequency-agile receivers, the up-link channel is dynamically allocated depending on previous interference statistics and current channel conditions. In order to adapt to changes in channel conditions caused by the introduction of new services, and migration of old services, the system autonomously monitors and updates its on-board statistical interference model.

COMMUNICATIONS ENVIRONMENT

One of the main reasons the VHF band has been chosen for communications to and from Low Earth Orbiting satellites is because of the low path loss and favourable operating conditions, at these frequencies the atmosphere and ionosphere have little effect on the propagating radio wave. The link budget shown below, demonstrates how an acceptable service can theoretically be obtained between a microsatellite orbiting in a 650 km low earth orbit operating at 150 MHz, and a simplistic non-tracking omni-directional antenna based ground terminal.

**Ground Station Parameters.**
- Antenna Gain: 3 dBi
- HPA Output: 40 W
- Feed Loss: 0.5 dB
- EIRP: 18.5206 dBW

**Channel Parameters.**
- Free Space Loss: -132 → -146 dB
- Polarization Losses: 3 dB
- Additional Losses: 0.5 dB

**Satellite Parameters.**
- Antenna Temp: 180 dBi
- Antenna Gain: 0 → -10 dBi
- Antenna Feed Loss: 0.5 dB
- Ambient Temp: 293 K
- Rx NF: 12 dB
- Te: 4350.7 K
- Tsyst: 4543.0 K
- Rx G/T: -37.1 dB/k

Where \( F_{MHz} \) is the transmit frequency, and \( D_{km} \) is the distance or range of the satellite, calculated by:

\[
D_{km} = \frac{\sqrt{(E_r + S_a)^2 - (E_r \cdot \cos(\alpha \cdot \text{rad}))^2 - E_r \cdot \sin(\alpha \cdot \text{rad})}}{2}
\]

Where \( E_r \) is the effective Earth radius, \( S_a \) is the altitude of the satellite and \( \alpha \) is the elevation angle of the satellite in radians.

\[
E_r = 6378.137 \text{ km} \quad S_a = 650.0 \text{ km}
\]

**Figure 1. Free Space Loss**

For the case of this link budget, and further analysis a simple model has been used, which gives an approximation of satellite antenna gain as a function of elevation angle.

**Figure 2. Representative Antenna Pattern**

\( ^2 \) Spacecraft antenna gain, is a function of both satellite elevation and current spacecraft attitude. Figure 2, shows a representative antenna pattern.
Figure 3. Antenna Gain Approximation.

Operational Parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>15000 Hz</td>
</tr>
<tr>
<td>Baud Rate</td>
<td>9600</td>
</tr>
<tr>
<td>Eb/No Required</td>
<td>13.5 dB *3</td>
</tr>
<tr>
<td>Eb/No Estimated</td>
<td>21.35 ( \rightarrow ) 24.8 dB *4</td>
</tr>
</tbody>
</table>

*3 Required Eb/No gives an operating bit error rate of \( 1 \times 10^{-6} \), assuming non-coherent demodulation of FSK.

*4 An estimation of the Eb/No is obtained from:

\[
\text{EbNo} = \frac{P \cdot L_i \cdot G_t \cdot L_s \cdot L_a \cdot G_r}{k \cdot T_s \cdot R}
\]

Where:
- \( P \) = Transmitted Power
- \( L_i \) = Feed Losses
- \( G_t \) = Transmit antenna gain
- \( L_s \) = Free Space Loss (FSL)
- \( L_a \) = Tx Path Losses (Miscellaneous)
- \( G_r \) = Receive antenna gain
- \( K \) = Boltzmans constant
- \( T_s \) = System temperature
- \( R \) = Data rate of the system

Link Margin

Margin \( 7.85 \rightarrow 11.3 \text{ dB} \) *5

*5 Link margin can therefore be seen to vary with satellite elevation angle. Varying between 7.85 dB and 11.3 dB, as shown in Figure 4.

Whilst communications between a simple omnidirectional antenna based ground terminal and the satellite result in a 7-11 dB link margin, a further increase can be obtained by using higher gain tracking antenna, and higher power amplifier, as shown below.

Tracking Ground Station Parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna Gain</td>
<td>13 dBi</td>
</tr>
<tr>
<td>HPA Output</td>
<td>500 W</td>
</tr>
<tr>
<td>Feed Loss</td>
<td>3.5 dB</td>
</tr>
<tr>
<td>Link Margin</td>
<td>25.8 ( \rightarrow ) 29.4 dB</td>
</tr>
</tbody>
</table>

Figure 4. Link Margin

Figure 5. High Power Ground Station Link Margin
OPERATIONAL EXPERIENCE.

Whilst the link budgets appears promising and shows that even the simplest of ground terminals can theoretically operate with a moderate link margin, operational experience has shown that the practical reality is often somewhat different. Interference within this band can block a given channel for prolonged periods, often rendering the channel unusable. This is clearly illustrated in Figure 6 below.

The above figure shows a comparison between the actual and expected signal strengths during a 50° pass over a groundstation in the UK. The solid line is a measurement of the received signal strength taken as the HealthSAT II satellite transited the groundstation. The dashed line shows the signal level expected at the satellite using a groundstation with a similar specification to that described in the link budget on the previous page.

During this pass there are periods where the measured signal strength is greater than that transmitted by the ground station, effectively blocking the channel.

IN-ORBIT MEASUREMENT

Using an existing in-orbit microsatellite, developed by Surrey Satellite Technology Limited (UK), it has been possible to perform measurements of received signal strength at various frequencies within the VHF frequency band. These measurements give an indication of long term global frequency usage or interference environment. One can consider usage of these frequencies by other users, be it terrestrial or satellite, as a form of interference, which must be accommodated for successful system operation.

HealthSAT II, launched in 1993, utilises up-link frequencies within the 148-150 MHz band. Its primary mission is to provide digital Store and Forward electronic mail communications to small ground stations in remote areas of the world. Although the satellite is not specifically designed to perform detailed interference or frequency usage studies, the flexible nature of the SSTL microsatellite platform [6,7] provides a versatile environment in which such surveys can be undertaken.

HealthSAT II is in a circular Low Earth Orbit (LEO) at an orbital height of 800 km, inclination of 89.5 degrees and has an orbital period of 100 minutes. A series of typical ground tracks for HealthSAT II are shown in Figure 7, with the satellite moving westwards along the track in a retrograde orbit. A coverage circle is also shown for the satellite, the coverage circle is wider than the spacing between successive passes, and as a result the entire Earth's surface is covered in 12 hours, making the orbit ideal for providing digital Store and Forward communication services for Email like applications.

A block diagram of the HealthSAT II communications payload is shown below in Figure 8. The VHF receivers and UHF transmitters are used in conjunction with the on board computer and software, allowing data to be uploaded and stored on the satellite, and to be retrieved on demand elsewhere. To the user the satellite simply appears just as a simple file server or remote bulletin board.

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Redundant On-Board Computers (OBC) are employed, and together the OBC modules provide over 50MByte of solid state memory allowing any type of digital data such as text and images to be stored as files. Sophisticated mechanisms for controlling and monitoring the spacecraft are implemented in software, which is reloadable in orbit. In LEO the satellite is out of range of the control ground station for extended periods, but the OBC allows autonomous control tasks to be executed under a multitasking operating system. Furthermore, the OBC can be instructed to execute commands according to schedule files; and store telemetry in Whole Orbit Data (WOD) files.

A number of status points are made available to the satellite telemetry system to aid pre-launch and in-orbit testing, as well as enhancing standard operations. The measurements include a Received Signal Strength Indicator (RSSI), the mean output voltage of the quadrature detector (DISC), and the control voltage for the Automatic Frequency Control (AFC).

**RSSI** – Received Signal Strength Indicator

The RSSI measurement provides an indication of the total signal power measured within the 20 kHz receiver bandwidth.

**DISC** – Discriminator Voltage.

The DISC measurement is a direct indication of the frequency error on the uplink.

**AFC** – Automatic Frequency Control Voltage.

The AFC voltage can be used to determine if the uplink signal is properly compensated in frequency, and remains within the AFC range.

Whilst the RSSI telemetry channel gives an indication of channel occupancy, frequency usage or interference level, little further information can be gathered regarding the nature of the interfering signal. Nevertheless, by repeatedly measuring interference levels over the same area, an estimate can be made regarding the interference environment for that geographical location.

**ANALYSIS.**

The microsatellite schedule and Whole Orbit Data survey facility are used to measure the global interference levels. The on board computer samples the receiver signal strength at one second intervals over a twenty-four hour period. Such surveys have been repeated on a daily basis since September 1996, the data being downloaded after every survey. Figure 9 shows one such raw survey file. It shows that there are periods where there is a complete absence of signals, whilst there are also periods of considerably higher levels.

Before analysis can be undertaken upon the raw data, it must first be calibrated. Figure 10 shows the calibration of the received signal strength indicator in volts as seen by the on-board telemetry system, for incident power at the antenna input. It shows that the useful linear region of the signal strength indicator is for incident powers from -130 to -85dBm, and that the indicator limits for larger incident powers.

An approximation for this calibration curve is given by the following equation

\[ \text{Rssi}_{\text{dBm}} = 0.028 \times \text{Rssi}_{\text{Volts}} - 175.0 \]
As the time for each telemetry sample is known, it is possible to process the calibrated RSSI telemetry file, calculating the sub satellite position for each sample, in doing attributing each sample to a point upon the satellites ground track. A geographical map is then divided into 1° by 1° bins and the mean value found for the samples in each. Figure 12a and Figure 12b show the mean received signal strength for two frequencies surveyed in this campaign. Areas shown in blue equate to regions of low interference, whilst regions shown in red indicate high levels. The most important thing to note from these results is that the areas of high interference differ with geographical location and frequency, leading one to believe that frequency diversity can be employed as an interference countermeasure.

As the majority of the interference can be deemed to be man made, one would expect the interference to also exhibit some form of time structure, for example low interference at night when users are sleeping, and higher levels during the day. Since the time and ground track position for each telemetry sample is known, the local time can be calculated and the data sorted into different time periods. Once sorted the mean value can be calculated for each geographical bin. The diagrams below, Figure 13, show the HealthSAT-II receiver frequencies divided into two time periods, one corresponding to day the other night. It can clearly be seen that the interference over particular geographical locations is substantially less during the nighttime period.
The limiting factor with the preliminary global interference measurements has been the limited number of frequencies upon which the measurements have been made. With the recent launch of FaSAT-Bravo and TMSAT both carrying an experimental scanning receiver, this shortfall will be addressed. The new satellites will be able to scan across a 12 MHz band, from 140MHz - 152 MHz, in 5 kHz steps. Allowing information to be gathered.

**INTERFERENCE MODEL.**

It has been seen from the results obtained from the HealthSAT-II measurement campaign, and other measurements performed using S80/T, that the levels of interference vary with geographical location, frequency and time. In order to exploit the channels diverse nature, a global interference model has been generated. This model divides the Earth into a number of regions, or zones. Associated with each of these zones is an ordered list of preferred frequencies. Since the interference level has also been seen to vary with time, each zone has a number of lists each corresponding to a separate period of the day, an example is shown in Figure 14 below.

![Global Interference Model](image)

*Figure 14. Global Interference Model.*

The division of a particular region into a number of lists, each corresponding to a particular period of the day, is dependent upon the orbit of the spacecraft. In a sun synchronous orbit such as the HealthSAT-II orbit, the spacecraft transits a particular geographical location at approximately the same time of day and night. In this instance two lists would suffice, one corresponding to the daytime period, the other the night. In a non sun-synchronous orbit, the time at which the spacecraft transits a particular location changes, four lists could therefore be used, each corresponding to a six hour period of the day.

The list provides a sub set of frequencies from within the VHF frequency band that are deemed to have the least amount of interference. The list being ordered such that the highest ranking entry has the least likelihood of interference. Since the operating environment is constantly changing, with the introduction of new services and the removal of old, it is important that the model is continuously updated. What may have been the preferred operating frequency at one time may quickly become unusable with the introduction of a new service into the band.

In order for the spacecraft to make use of this model it must be able to determine its own sub satellite position, and calculate the local time at that point. Position information can usually be obtained from the spacecraft's attitude control software or an on-board GPS receiver. It is equally important that the model is maintained, requiring a programmable receiver that can be used to scan and update the frequencies within the list.

**INTERFERENCE AVOIDANCE.**

A scheme has been devised which will improve the performance of a digital store and forward communications system used upon several commercial and amateur low Earth orbit microsatellites [7]. The principles are however equally applicable for use by other systems. The scheme exploits the geographical, frequency and time diverse nature of this communications environment. Dynamically allocating the spacecraft receive frequency depending upon the interference level, allows the spacecraft to avoid potentially high levels of interference, thus improving the communication systems operating environment.

![Store & Forward Payload](image)

*Figure 15. Store & Forward Payload.*

The existing store and forward communications payload is shown above in Figure 15. The scheme has many similarities to that of the terrestrial packet radio system, satellites employing such a store and forward system are often referred to as pacsat's (packet radio satellites). The existing scheme uses a number of 9600 baud non-coherent FSK up-links, and a single 9600 baud FSK down-link [8]. The modulation scheme, whilst not as theoretically efficient as other schemes [9], was chosen because of its simplicity and proven robustness. Used in conjunction with an ARQ protocol the scheme provides error free communications between the ground station and the satellite.
Multiple access is achieved using an AX.25 link protocol with satellite controlled TDMA arbitration. This does not imply that groundstations will have to be locked to a common time base, rather that the satellite manages groundstation access by dividing the uplink into time slots, with a different slot for different users. Whilst the store and forward task is idle, the satellite transmits an Invitation frame which invites groundstations to reply. Upon hearing this, the groundstation computer will start a random back off timer, after which it will transmit a Transaction Request packet on the uplink. When the spacecraft hears one of these Transaction Requests, it connects to the station heard and begins a message transaction using a standard AX25 protocol. When the transaction is complete the task goes back into the idle state. The protocol therefore divides the uplink time into portions: an ALOHA portion during which all groundstations can transmit, and a contention-free portion during which one groundstation has the entire uplink to itself.

![Dynamic Channel Allocation Scheme](image)

*Figure 16. Dynamic Channel Allocation Scheme.*

A block diagram of the proposed dynamic channel allocation store and forward payload is shown above in Figure 16. The payload uses a dedicated calling channel receiver, a number of communications receivers, scanning receiver, GPS, on-board computer, and a single down-link transmitter. The scheme works by dynamically allocating the spacecraft receive frequency depending upon geographical location, time, and current channel occupancy. The difference therefore between this and the existing store and forward communications scheme is that the receiver frequencies are not fixed, and are allocated dynamically.

The interference model, as described earlier, is used to provide control over the frequency selection process. The satellite keeps track of its current ground track position and time, using these to select which ordered frequency list is to be used at any given instance. A scanning receiver is used to update the frequency list, and to monitor channel occupancy, allowing the model to be autonomously maintained.

Whenever a communications receiver becomes free, the task issues an Invitation frame informing all ground stations of the frequency of the calling channel to be used. There is some benefit in using a fixed frequency calling channel, allowing the system to cater for fixed frequency ground terminals. A ground terminal wishing to upload data to the satellite would then issue an Upload Request packet [10], specifying a number of parameters including message length, and station type. Station type simply refers to whether the ground terminal is fixed frequency or frequency agile.

Upon receiving an Upload Request, the satellite examines the frequency list, selecting the channel with the least likelihood of interference, the unused receiver is set, and a channel occupancy measurement taken. If the channel is found to be clear, an Upload Acknowledgement is transmitted to the groundstation containing the frequency of the upload channel. Should the channel be found to be occupied then the next frequency in the list is considered, and so on until a clear channel is found.

The satellite monitors the channel throughput. If during the course of the upload throughput starts to deteriorate, the scanning receiver examines the next favourable channel, if found to be clear a Frequency Change packet is sent to the groundstation. The frequency is then changed, and communication continues upon the new frequency. By dynamically varying the satellites receive frequency in this manner it is possible to avoid occupied channels and interfering signals.

**IN-ORBIT DEMONSTRATION.**

Two microsatellites designed and built by Surrey Satellite Technology Limited (UK), launched this year have an experimental payload suitable for the in-orbit demonstration of the dynamic channel allocation scheme. The "Data Transfer Experiment" is a dual redundant programmable receiver and digital signal processing module.

Able to be programmed to any channel within the 140 - 152 MHz range, in 5 kHz steps, the payload has been specifically designed for performing in-orbit "Little-LEO" up-link communications research.
A detailed in-orbit measurement campaign is currently underway accumulating the necessary information required for the generation of the initial interference model. Whilst previous measurement campaigns have provided the preliminary results, these have been limited to a small number of frequencies and the new campaign is surveying a much larger frequency set. Demonstration of the dynamic channel allocation scheme is scheduled for early next year.

CONCLUSIONS

This paper has shown some of the results obtained from the HealthSAT-II a global interference or frequency usage measurement campaign. The results, whilst limited to a small number of frequencies have shown that levels vary considerably with geographical location, time and frequency.

A global interference model has been described. The model divides the Earth's surface into a number of regions, each having an associated ordered list of preferred frequencies. Since the channel is constantly changing it is important that the model is continually updated. This has been achieved using a spacecraft task that autonomously scans through the channels and updates the model.

Dynamically allocating the satellites receive frequency based upon local time, geographical location, and current channel conditions allows occupied channels and periods of interference to be avoided, thus improving the communications environment. This paper has described a system that improves upon an existing low earth orbit store and forward communications scheme. Although designed for a specific application, the technique is equally applicable to other systems.

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