"I CAN SEE YOU!" - HOW SATELLITE IMAGERY DICTATES THE NEED FOR SPEED

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Abstract

Microsatellites have developed significantly since the launch of Sputnik on 4th October, 1957. In 1981 the University of Surrey launched its own microsatellite, UoSAT-1, carrying, amongst other ground breaking equipment, the first civilian charge coupled camera. This small camera sent back crude black and white images of the Earth at a speed of 1200 bits per second. Some two decades later this class of satellite has shown itself capable of providing a reliable, high quality, multi spectral imaging service which can be used for a variety of purposes including crop monitoring, the detection of desertification, illegal logging and disaster monitoring. However, the increasing need for large scale images covering several spectral bands has driven the need for ever increasing data rates and higher transmission frequencies. This paper shows how these requirements have resulted in a new downlink subsystem to be flown on the next SSTL built satellite - NigeriaSat 2.

Introduction

On October 6th 1981 UoSAT-1 was launched on a Thor Delta rocket from Vandenberg Air Force Base in the USA carrying the first microprocessor flown on a microsatellite and a tiny GEC, MA357, charge coupled device (CCD). This was intended to provide an engineering test bed for future developments of camera systems using similar technologies. UoSAT-1 was designed, built, tested and launched within a very short timescale which left little time for circuit and system level refinements. However, the successful results from the mission showed that a determined group of enthusiastic engineers could produce an operational mission within a very short timescale.

UoSAT-1 was a University funded operation utilising students, staff and radio amateurs but laid the foundations of the fully commercial Surrey Satellite Technology Limited (SSTL) that today provides industry leading missions.

The Early Days

The UoSAT-1 camera was based around a two dimensional, 256 x 256 pixel imaging area. Each pixel was exposed to incident light that produced a charge in light sensitive storage sites. The exposure time was computer controlled as initially the light conditions expected in orbit were inconclusive. Once sufficient charge had been accumulated it was read, digitised and stored within a section of random access memory (RAM). The brightness of each pixel was stored as a 4-bit word capable of representing one of sixteen intensities or grey scales. Before transmission a suitable 1024 bit frame header was added and each new line signified by a 32 bit line synchronisation code word. Thus a complete line comprised 256 x 4 bits of image data with a 32 bit line sync code. A frame was similarly composed of a 1024 bit frame header and 256 lines. In total there were 271,360 bits of data that had to be transmitted (see Figure 1).

	Frame Header (32 x line sync = 1024 bits)	Line '0'
Line sync (32 bits)	**Image Data** (256 x 4 bits)	Line 1
Line sync	**Image Data**	Line 2
II	II	
II	II	
II	II	
II	II	
II	II	
Line sync	**Image Data**	Line 254
Line sync	**Image Data**	Line 255
Line sync	**Image Data**	Line 256

Figure 1 UoSAT-1 CCD Frame Configuration

In the first satellite there was no error detection and correction and transmission was carried out as a simple bit-stream.
At the time of launch the satellite downlink had been optimised to use widely available VHF radio amateur equipment and simple ASCII decoders made available by the advent of inexpensive personal computers. Consequently the modulation chosen was Audio Frequency Shift Keyed – Phase Modulation (AFSK-PM) utilising 1200 and 2400 Hz synchronous tones. There were a variety of data transmission rates available but the one chosen for camera data was 1200 bits per second. Thus it took 3.8 minutes to download a single 256 x 256 pixel image.

Images from UoSAT-1 were initially difficult to obtain due to the need for manual operation of the system from the groundstation and the fact that the satellite had to be spin stabilised after a partial failure of the intended primary attitude controlling gravity gradient boom. However, a diary software controller was uploaded to the on-board computer (OBC) that allowed scheduling of regular CCD experiments (see Figure 2).

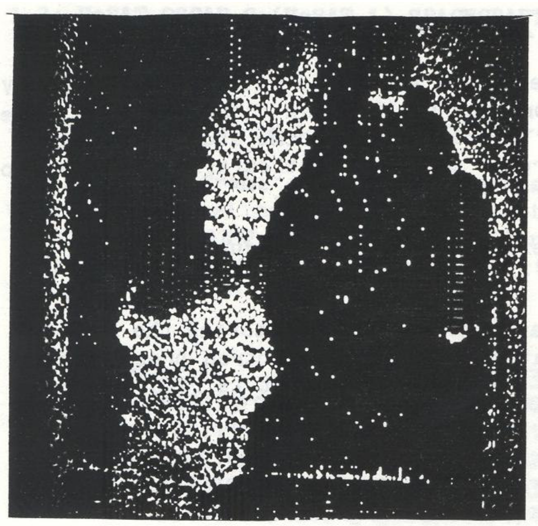

Figure 2 UoSAT-1 Image of Corsica

Whilst modest by todays standards, the CCD experiment allowed a greater understanding of the specifications that would enable a comprehensive Earth observation system to be developed in the future.

The Disaster Monitoring Constellation

The imaging experiments carried out by UoSAT-1 and subsequent missions provided the experience upon which the current revenue generating operational services are based. It was quickly realised that there was a niche market for medium resolution images with a fast re-visit time such that the same area could be repeatedly imaged. This was particularly important for humanitarian disaster relief work and investigating such activities as illegal logging [2]. To achieve the required revisit times it was proposed to launch a constellation of satellites, each owned by a separate country. The satellite owners could use the images for their own national programs but agreed to donate a part of their resources for humanitarian ends. The first satellites in the DMC had a ground sampling resolution of 32m. These satellites have provided many years successful service but are now reaching the end of their planned life. These spacecraft will shortly be replaced by a new generation of platforms and imagers, the first of which will be NigeriaSat-2.

Current Requirements

NigeriaSat-2 has two cameras, a medium (MRI) and very high resolution imager (VHRI). The VHRI multispectral (red, blue, green and near infra-red) camera dictates the maximum data rate so is investigated here in more detail. For a 20km swath width with a multispectral ground sampling distance of 5m and panchromatic ground sampling distance of 2.5m, five CCD's are required. Each pixel is stored as a 10 bit word and a scene is defined as an area of 20km x 20km. Thus the panchromatic component is 8000 x 8000 x 10 pixels and the multispectral component comprises 4 x 4000 x 4000 x 10 pixels. A small header is added along with GPS data to position stamp the scene. In total some 1.3 Gbits are required for just one scene (see Figure 3).

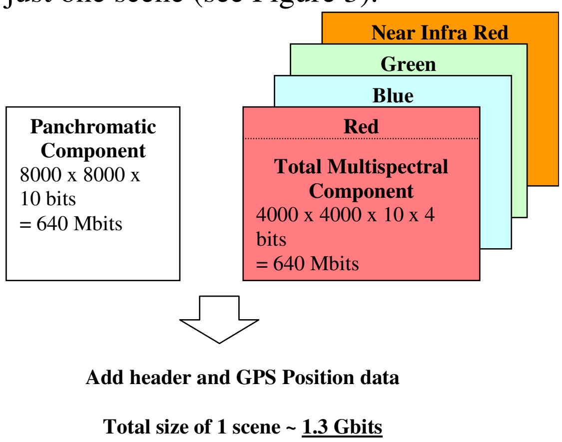

Figure 3 VHRI Scene Composition

The customer also required 100 scenes a day to be downloaded to a near equatorial groundstation. With a groundstation at this location all images, amounting to some 130 Gbits of data, needed to be downloaded during the 36 minutes of reception opportunities a day. To allow for additional data files and provide suitable margin a data rate of at least 80 Mbits/s was required. To facilitate higher data rates a wider section of the allocated frequency spectrum was required thus the existing S-band downlink was replaced with an X-band link.

Link Budgets

In order to support the higher data rates identified by the system requirements various link budgets were run. The key requirement in terms of system engineering was to increase the received power at the groundstation. Consider the simplified downlink shown in Figure 4.

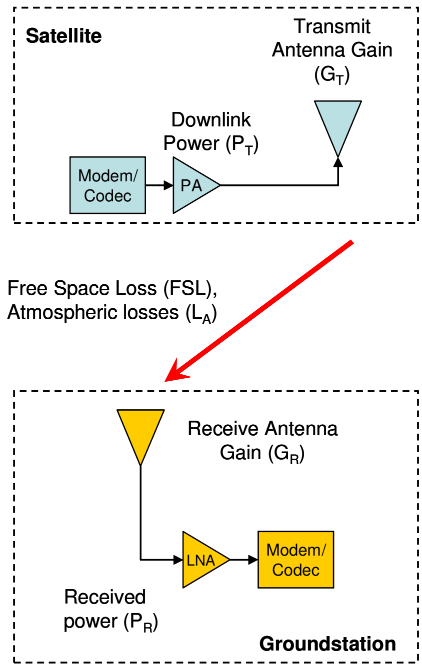

Figure 4 Simplified Downlink

Then:-

$$P_R = P_T \times G_T \times G_R / (FSL \times L_A)$$

The free space and atmospheric losses were fixed whilst substantial increases in downlink power were not possible without a significantly larger satellite. Augmenting the size of the groundstation dish would have significantly increased the cost of the signal reception suite. Therefore it was decided to marginally increase the downlink power and increase the gain of the downlink antenna.

X-Band Power Amplifier

The migration of the payload downlink from S-band to X-band necessitated the construction of frequency converters and a new power amplifier. The team had no experience of this frequency and were constrained by a short development time and the need for the amplifier to work first time and for several years in a space environment.

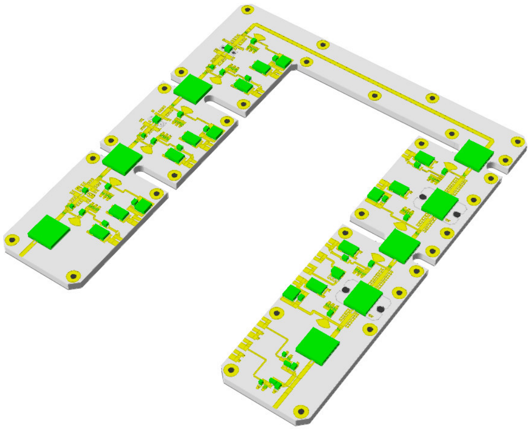

Figure 5 PAX Circuit Board

In line with the well tried desire to adopt heritage technologies GaAs MESFET's were used as the active devices. The power output and gain required were found from the link budget and the gain partitioned according to device availability. Standard commercial off-the-shelf devices were used rather than the more expensive space standard offerings in line with the "affordable access to space" methodology. Ideally full non-linear models would have been available from the manufacturer which would have allowed full simulation of compression effects and accurate design of the input and output impedance matching networks. Unfortunately, these were unavailable and simple S-parameters had to suffice. In small and medium signal environments these are adequate. However, as the input signals increase in amplitude the devices are forced into saturation the gain decreases and spectral spread increases. The design was therefore made flexible enough to allow manual tuning. Whilst in no way an elegant solution this was an acceptable overhead for the low volume, high reliability amplifiers being produced.

Figure 6 Complete X-Band Transmitter

The circuit was constructed on a thick metal backed, thermoset ceramic loaded plastic substrate (see Figure 5). The metal backing acted both as an efficient heat sink / spreader and component carrier, the transistors being simply fitted to pockets milled out of the ceramic and metal support material. Each stage was surrounded by isolators and mounted in its own cavity. Whilst most likely over engineered, this helped ensure correct operation without oscillations when the amplifier chain was finally integrated.

During alignment some tuning was required, as expected, but this was quickly achieved using copper tape soldered directly to the impedance matching sections.

Thermal compensation of the amplifier was accomplished using passive temperature sensitive attenuators. These components have high loss at cold temperatures which counteracts the increasing gain of the amplifier chain.

A conventional printed circuit board co-located in the same module box provided the power supply sequencing for the MESFET's necessary for reliable operation along with telemetry feedback of key parameters (temperature, forward power and current consumed).

In operation the PAX (Power Amplifier, X-band) module is mounted directly to the satellite structure to facilitate heat dissipation. Several PAX modules are already operating on current Earth observation missions.

Antenna Pointing Mechanism

Previous Earth observation missions allowed the satellite to slew the camera off nadir i.e. the camera was no longer limited to capturing images immediately below the satellite but could look to one side. However, the satellite was then returned to a nadir position before the images were downloaded. This scenario allowed the use of isoflux antennas. Isoflux antennas are useful in this environment as they provide equal power flux density on the ground and counteract the change in free-space loss with range to maintain a near constant link margin.

However, one central requirement of the NigeriaSat-2 mission was to be able to download data whilst capturing off nadir images (see Figure 7). This prerequisite precluded the use of omni-directional and isoflux antennas on a power limited microsatellite. In order to maintain the link budget and not require a significantly larger (and unsustainable) power amplifier or dramatically larger and more costly groundstation antenna the satellite transmit antenna had to be investigated.

Improved antenna gain is achieved by forcing the available power into a narrower beam thus one cannot have a high gain omni-directional antenna. Fortunately the satellite only needed to communicate with one groundstation at a time so it was perfectly acceptable to direct the available power in the direction of the receiver thus relieving the specification of transmit amplifier and receiving dish.

Several methods of concentrating and directing the transmitter power or making the imager optics agile were considered [1]. These included:-

- Switched antennas.
- Electrically tracked antennas.
- Mechanically steered antennas.
- Steered mirror in front of camera.

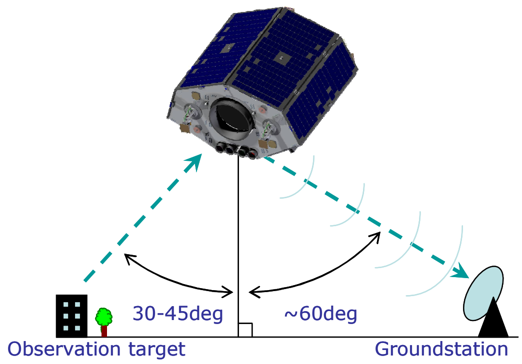

Figure 7 Agile Downlink Requirement

Placing a mirror in front of the optics was considered a high risk strategy due to potential mechanical disturbance of the optical configuration and wear out issues. The pointing accuracy of the mirror would have also made it an expensive option. Switched antennas would have been potentially easy to implement, but many antenna elements would have been required for the coverage specified. Electrically steered antennas, though having potentially high gains, were felt to be overly complex for such a mission and suffer from poor axial ratio at high off-nadir angles. Thus it was decided to fly a mechanically steered directional antenna.

A mechanically sturdy, circularly polarised horn antenna was developed that provided a 3dB beamwidth of 27°. This antenna was constructed such that by altering the position of the feed either right or left hand circularly polarised signals could be propagated.

The off-pointing requirements for taking images and transmitting data at the same time defined the dynamic characteristics of the antenna pointing mechanism (APM) whilst the weight and size of antenna determined the dimensions.

Figure 8 The Antenna Pointing Mechanism

The final equipment (see Figure 8) has an azimuth range of ±270° and an elevation range of ±110° with a maximum slew rate of 20°/sec degrees per second and pointing accuracy of <0.5°.

Discussion

In addition to the hardware upgrade described there were significant changes made over the years to the coding of the signals. Differential and convolutional coding is now carried out for error detection and correction and quadrature phase shift keying will become the preferred modulation scheme. Indeed there has been a considerable push towards higher efficiency modulation and coding to meet demanding spectral requirements placed on satellite operators [4].

The increasing complexity of images has dictated an almost exponential increase [3] in downlink speeds (see Figure 9). This is due to the increasing sophistication of the customer and the discovery of new applications dictating wider spectral bands and more detailed images.

The aim of the RF designer has been to keep pace with the downlink requirements whilst remaining within the frequency spectrum allocations made for satellite traffic and producing equipment at affordable prices.

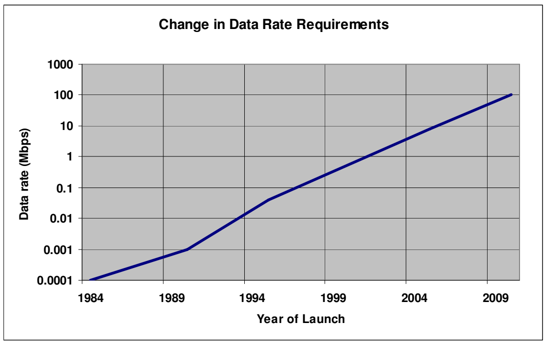

Figure 9 Change in Data Rate Requirements

It is interesting to note that if the proposed NigeraSat-2 scenes were transmitted using the hardware available on UoSAT-1 it would take in excess of twelve and a half <u>days</u> to transmit a single image rather than the 12 seconds the new high performance equipment will facilitate.

Nigeriasat-2 will actually carry two APM's, one operational the other as a back-up. Potentially the data rate could be doubled by simultaneously transmitting on left and right handed circular polarisation.

Conclusion

This paper has highlighted the way in which the demand for increasingly higher resolution images has forced RF engineers to improve the capabilities of the downlink in a cost effective manner.

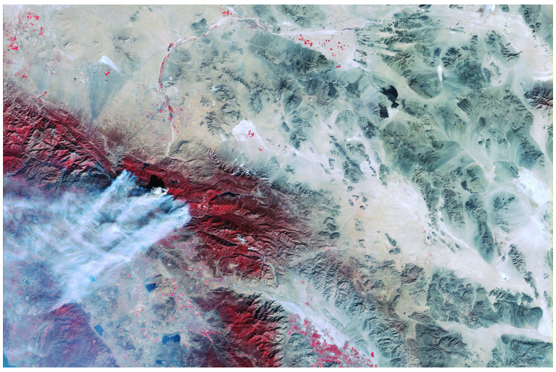

Figure 10 Forest Fires in California

Once upon a time simple black and white images tantalised people with the possibilities of commercially viable services mounted on responsive and affordable microsatellites. These possibilities have now been converted to reality (see Figure 10).

References

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