EMC and RFI problems and solutions on the SUNSAT Micro-satellite

Garth W. Milne, E. Jansen, Jacques J. Roux, Jan-Albert Koekemoer and Pieter P.A. Kotzé

Abstract - **The 63 Kg SUNSAT micro-satellite includes VHF (144-146MHz) narrow band FM (NBFM) radio receivers for Amateur Radio service. Significant radio frequency interference (RFI) from data buses occurred, but was successfully screened from antennas with aluminium plates. Harmonics and noise of 650 kHz switching regulators drifted through receiver channels causing unpredictable sensitivity losses of up to 20 dB. Without shielding, the regulators generated signals at VHF of -85 dBm in a quarter wave antenna at 0.5m range. This is 34 dB above the noise floor of a 2 dB NF 18 kHz BW VHF receiver. Test results, solution methods, measurement techniques, and lessons learned are reported.**

Keywords - **RFI, micro-satellite, receiver, switching regulator**

I. INTRODUCTION

The 63 Kg SUNSAT micro-satellite is nearing completion at the University of Stellenbosch. After many launch delays of the P91-1 ARGOS mission on which it is a secondary payload, launch is likely for 17 December 1998. The satellite has been developed by M.Eng. students since 1992, and carries payloads for high resolution imaging, geodynamic research, and amateur radio. [1], [2], *(http://sunsat.ee.sun.ac.za)*

The satellite is complex, and is constructed of ten electronic trays, interconnected by a wiring harness containing about 2000 pins. With this level of integration, it was impractical to construct each function into a ‘black box’ and screen it from the exterior environment. It was also impractical to carry many interconnections via shielded wires, especially since many of these were made (by design) to be shorter than 5 cm and 10 cm.

Initial system design foresaw RFI problems and ensured the mechanical design would, in theory, allow the satellite to become a Faraday cage to prevent internal signals coupling to antennas. This precaution proved wise and necessary, and enabled RFI generated by computer data bus activity to be reduced to negligible levels. The greatest problem was caused by VHF harmonics of switching regulators, which drifted through the receiver bandwidths, and at times made us doubt if we could solve the RFI problem. This paper describes the causes of the RFI problems, how they were isolated, and how they were solved.

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Section 2 discusses the RFI design concepts applied in SUNSAT. Section 3 describes the RFI test programme, and the discoveries. Section 4 describes changes made to the satellite to reduce the RFI, section 5 looks at front-end and switching regulator shielding. Section 6 gives RFI suggestions recommended for such design exercises, section 7 looks at interesting observations and section 8 gives the conclusions.

II. RFI DESIGN CONSIDERATIONS ON SUNSAT

In conventional large electronic systems such as aircraft or geostationary satellites, much effort is required to prevent internal RFI from various sources from reducing the effective sensitivity of the radio receivers. Care is taken to shield each sub-system in expensive RF enclosures, and to filter or screen all power and signal conductors entering or leaving the unit. Frequently, wiring harnesses are enclosed in shielding braid, with large connectors to maintain the shielding integrity.

Maintenance and equipment commonality requirements further motivate creation of the system from a number of ‘black boxes’, each shielded and specified for operation in a hostile environment.

On SUNSAT, weight, size, and filtering complexities limited the use of RF enclosures for shielding of each sub-system. The large bending radius of screened harnesses made their use impractical, with the result that SUNSAT is in effect a single large electronic unit, where radio receivers and microcomputers have to co-exist.

A. *RFI requirements.*

SUNSAT's NBFM VHF receivers have an 18 kHz IF bandwidth and a sensitivity of -117 dBm (0.3 μV) for 10 dB SINAD in a 4.8 kHz -3 dB audio bandwidth. This high sensitivity is required if a hand-held amateur radio is to be able to communicate with the satellite, but makes RFI prevention more difficult. Ideally RFI should not perceptibly increase the receiver thermal noise level of -129dBm implying RFI levels approaching -140dBm.

From the outset it was feared that RFI from the on-board computers would couple in to the VHF receiver antennas. We assumed that strong clock signals from computers would leak into antennas at levels approaching -50 dBm, making these frequencies unusable for reception. Since clock signals only occupy a small portion of the available frequency band, we decided to avoid these frequencies, and shift the clock frequencies if and when necessary.

Data signals on buses have a random nature, so act as broadband coloured noise with energy spread over the receiver band. Since one cannot avoid such unpredictable frequencies, adequate antenna screening was required primarily to prevent this source of RFI.

A. SUNSAT structure and RFI

The structure of the 45 cm × 45 cm × 63 cm SUNSAT satellite forms a screened box that if completely continuous, would prevent any RFI reaching the antennas that are mounted externally on the satellite. The satellite comprises ten electronic trays, each holding a large printed circuit board. The frames of the trays are compressed together by four corner tie rods to form the satellite structure.

The top plate contains many sensors, and feeds wires to umbilical plugs and sensors on the tip mass which deploys from the top plate. All the electronic signals running through the top plate of the satellite were thus filtered, either with 'D' type pi-section filter connectors, or with pi-section feed-through filters.

The mechanical design provided for wiring channels for a fast (memory I/O) and slow (telecommand and audio) data bus on either side of the satellite. These were planned to be electrically sealed by the back of the aluminium substrates of the solar panels. Carbon fibre panels were ultimately used, and the mechanical design team accepted the possible need to add RF screening plates between the satellite and solar panels.

SUNSAT contains a 10 cm diameter optical system for its imager, which can be rotated relative to the satellite. The optical path requires a 20 cm × 10 cm aperture on the bottom of the satellite, which is an obvious RFI risk. By preventing the data buses entering this lower tray, we hoped the multiple stages of RF isolation would prove adequate. Later measurements in a continuous aluminium box containing such an aperture showed about 50 dB attenuation inside the box with no clear dependence on screens added over the aperture.

III. RFI TEST PROGRAMME

RFI tests are one of a sequence of functional and safety tests intended to minimise risk of failure. Ideally they have their own undisturbed allocation of time and personnel. In real life they had to fit in with other higher priority needs and schedules, so they took place over a number of months.

The RFI tests had to be done on a system containing multiple receivers, frequencies, and modes of operation, causing a multi-dimensional test matrix, making tests time-consuming. Access to the full flight hardware also had to be negotiated from competing needs and teams, sometimes leading to non-ideal test scheduling.

A. RFI sensitivity loss measurement

SUNSAT uses receivers with limiting IF amplifiers, so large noise outputs occur with no input signal present. To measure the level of a noise-like interference to the receivers, the measurement method shown in Figure 1 was used. In this we couple either a 50 Ω termination or a test antenna through a directional coupler to the receiver

A modulated test signal is injected into the -20 dB coupler port to create a 20 dB SINAD receiver output while a 50 Ω load is connected to the antenna port. The 50 Ω load is then replaced with the test antenna, which will be either of the flight antennas, as they will be deployed during flight. This will take the satellite geometry and antenna positioning into account. The

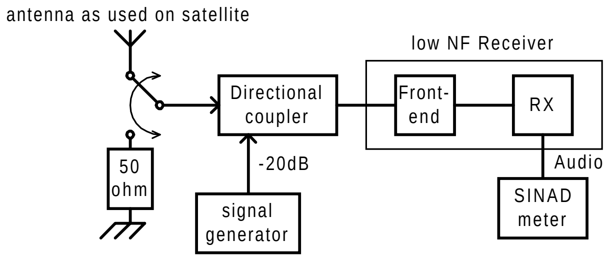

Fig. 1. Measurement set-up to detect the effect of noise radiated from the satellite.

increase in the injected signal level needed to return to 20 dB SINAD indicates the increase in noise floor of the NBFM receiver due to RFI received by the satellite antenna.

The benefit of this method is that we can compare in-satellite sensitivity directly with isolated test bench figures, we measure directly the loss in sensitivity, and we use the real satellite receiver, including its imperfections.

The above method was also used with a high quality VHF receiver replacing the satellite receiver when we wished to determine the levels of RFI external to the satellite, and we had found the satellite's receiver had RFI problems of its own.

IV. RECEIVER AND VHF RFI TESTS

SUNSAT's technical specification listed a number of EMI and RFI tolerance tests for the receivers. In the rush to integrate the VHF tray for an earlier slipped launch date, these were skipped and replaced with tests of the overall tray where receiver sensitivity was measured. Test results show that no RFI was experienced at this integration level. Later we discovered that interference from the switching regulators varied with test conditions, and had not been detected in these first integration tests.

A. SUNSAT RFI tests

In November 1997, the whole satellite was integrated, and RF sensitivity tests performed to verify the sensitivity of the receivers. The background noise in the SUNSAT laboratory is typically 20 dB above a receiver's noise floor, so a quiet test facility was needed. The anechoic chamber in our Department is intended for microwave antenna measurements, so it has no RFI screening. We thus had to do tests in a good screened room intended for noise figure measurements.

The first tests showed a sensitivity loss of up to 18 dB [3] on some VHF receiver channels. In addition, measurements did not appear fully repeatable. The screened room has no electro-magnetic (EM) absorbers, so it acts as a cavity resonator, making radiated measurements questionable. Attempts to enclose all radiating gaps in the conductive satellite's structure with foil were also unsuccessful in stopping RFI coupling to the antennas, and doubt arose as to the possibility of quieting the satellite.

In his last tests, the second author disconnected various trays of the satellite and showed that the loss in sensitivity on some channels remained, *even with the VHF tray operating alone.* Early in 1998, SUNSAT was disassembled and the VHF tray removed. Laboratory tests showed that the VHF tray was itself generating interference caused mainly by the switching regulators.

SUNSAT has many switching regulators, so 1 nF ceramic bypass capacitors were added directly to all of their input and output pins to cause a low impedance path to ground at VHF frequencies. This solved most of the RFI caused by the switching regulators.

B. Switching regulators

Exact RFI sources on the VHF and UHF tray was 'sniffed' out using a 'rubber-duck' VHF antenna for electrical field measurement and a small loop antenna for magnetic field measurement. A 'floating scope' probe easily showed the high electric field near the inductor of the switching regulator package. Spectrum measurements of signals from this probe showed switching regulator noise and harmonics to be the main RFI contributor.

The 650 kHz switching frequency of the converter changed slightly as the power supply voltage or load current varied (or when finger pressure was applied to the regulator). At VHF, various harmonics of the 650 kHz fundamental frequency drifted through the receiver band as the supply voltage varied. The switching regulator's frequency spectrum was also not clean between major spectral components since a small amount of duty cycle jitter produced residual frequency modulation, raising the noise floor in the gaps between spectral lines.

It was difficult to notice these harmonics on a standard spectrum analyser with a -100 dBm noise floor (3 kHz resolution bandwidth and 10 MHz scan-width.) Lowering the resolution bandwidth or scan-width, to reduce the noise floor leads to difficulties in seeing the noisy harmonics, because of the slow scan speed, which illustrates how difficult it was to measure this noise and to solve these problems.

The level of switching regulator RFI was quantified by measuring received signal levels from a switching regulator module with no load and with input adequately filtered. The module induced -85 dBm signals (3 kHz BW) at VHF in a quarter wave antenna located 50 cm away. These distances are typical of the satellite geometry, and show that *the module on its own* could radiate fields 34 dB above the VHF receiver's thermal noise level.

Solving this RFI problem was postponed until after the 'make or break' tests due to a scheduled reservation at Houwteq.

C. 'Make or break' tests

The tests on the VHF tray indicated the RFI level had dropped markedly, and we wondered if further changes to the flight model boards were warranted. We did not know if RFI from the on-board computers, possibly leaking through our filtering onto the top plate, would exceed the RFI from the switching regulators, which would make it pointless to make more drastic efforts to lower the VHF tray RFI. This led to the following strategy.

We did not know if signals on the VHF antennas on top of the satellite were receiving RFI coupled through wires to the outside, from the wiring harness, internal PCB currents, or signals leaking out between the electronic trays. It is extremely difficult to establish if a potential RFI source is contributing to interference if other paths are present since RF signals vary with almost every

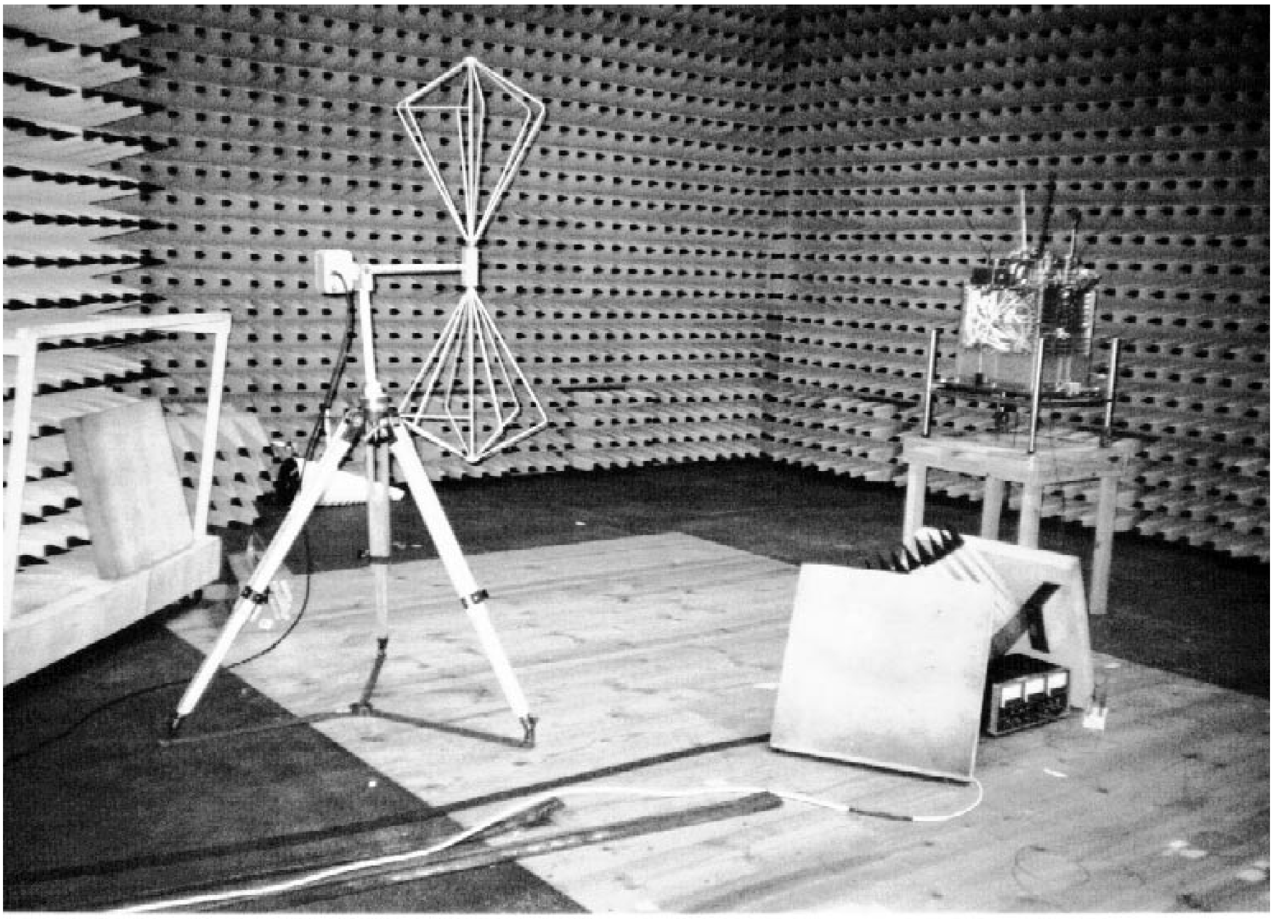

Fig. 2. Houwteq's RFI screened chamber.

change in wire or dielectric (people!) location.

We thus decided to make the most perfect Faraday cage to enclose the satellite below the top plate, to establish whether RFI was leaking through the top plate, and then indicate what RFI levels would be feasible if good flight quality RF screens could be made.

Tests were conducted in the Houwteq EMI test facility to avoid the uncertainties in previous tests (Figure 2). We hoped that measurements could be made outside the test chamber in the isolated and largely unused building. Our RFI test method using a good VHF receiver indicated background noise about 15 dB above the thermal noise level. Inside the chamber, no increase in noise level was detected as we swapped from the 50 Ω termination to the test antenna, but only after some electrically noisy power supplies and computers had been removed or disabled. In this process we found that the satellite's VHF receiver still had a sensitivity loss of more than 5 dB at some frequencies and supply voltages, so we swapped to the sensitive commercial receiver for remaining EMC tests.

The first test with no shielding on the four sides showed a 19 dB maximum sensitivity loss with certain services active [4]. Next, the whole satellite below the top plate was enclosed in the continuous aluminium box, and RFI radiation from the satellite measured. The good quality VHF receiver did not show any decrease in sensitivity as the satellite was activated. This meant the connections to the top plate were adequately filtered and that sensitivity losses previously measured must be from noise radiating or leaking from the sides of the satellite.

The continuous box was removed, and simple non flight-compatible tin plates were experimentally attached to the satellite's four sides (Figure 3 – take note of the top plate's RFI complexity). These provided equally good screening. Removing the two plates from the satellite sides not housing the buses produced an insignificant increase in RFI (1-2 dB).

The final result was that only the fast and slow bus had to be screened. Screening the fast bus and slow bus imperfectly had reduced RFI by about 18 dB. We thus decided to add the screening plates to the satellite, and were encouraged to make a further serious attempt to reduce the switching regulator noise on the VHF tray.

V. Ultimate Switching Regulator Noise Reductions on the VHF Tray.

The VHF receivers still showed 5 dB sensitivity degradation due to RFI caused by switching regulator harmonics situated on the desired receiving frequency when the input 14V supply changed.

A. Front-end shielding

The front-end was investigated to verify power supply filtering and shielding quality. A linear power supply was used to feed the front-end while the switching regulator was kept operating. No sensitivity improvement occurred, indicating that RFI on the front-end power feeds was not the dominant effect.

Next the RFI sealing of the front-end was investigated since the cross-hatched ground plane had been covered (our error) with green solder mask, making contact possible only at screw holes. A proper tin ground plate was thus placed underneath the aluminium RF box. The sensitivity improved somewhat, but not sufficiently for this to be the dominant effect (1-2dB).

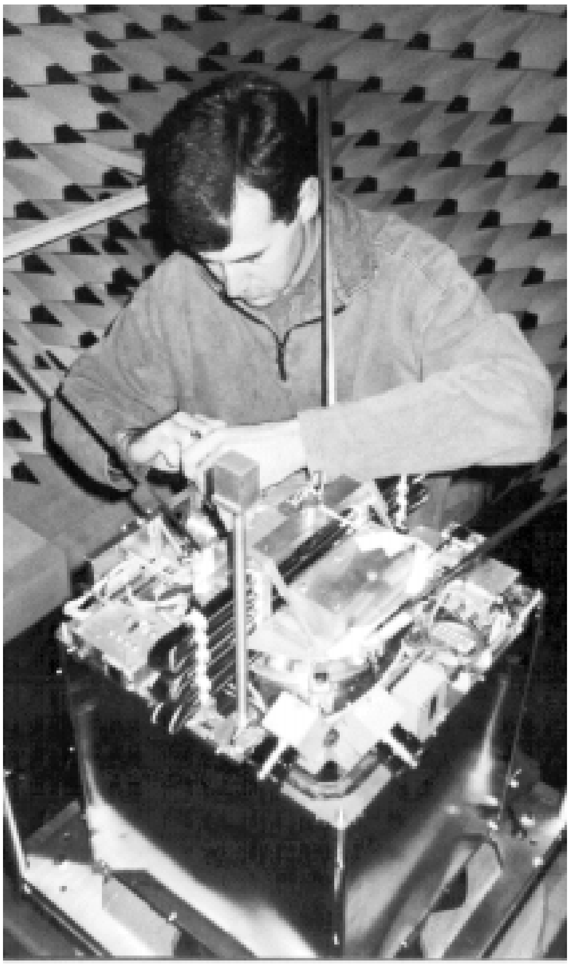

Fig. 3. SUNSAT with screened tin plates on the four sides

The next step was to investigate whether the aluminium lid of the RF enclosure made a continuous connection with the rest of the enclosure. A conformal coating spray was used to add mechanical stability to the components placed on the PCBs, and some overspray had landed on the aluminium RF enclosure. The transparent spray could not be seen on the alodined aluminium enclosure, but could be felt and detected with an Ohmmeter. The top lids thus could only be guaranteed to make contact at screw points, which left some further doubt on screening effectiveness.

Figure 4 shows a block diagram of the two VHF

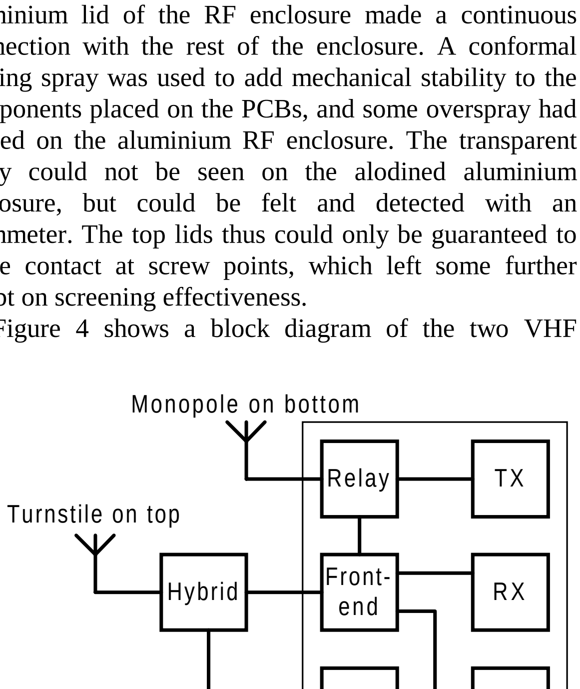

Fig. 4. SUNSAT's VHF receivers

receiver systems on the SUNSAT satellite. The main differences between the receivers are the antennas and transmitter-receiver combining circuits used. The front-end is shared by both systems so that both receivers may be connected to any antenna for redundancy.

The receiver with the relay feed was found to lose 20 dB in sensitivity due to RFI. The insulated cross-hatch shield was again the cause, and was easily corrected with a conductive ground plate under the relay box.

Remaining RFI was non-reproducible and could not be tracked down to a single coupling means from the switching regulators. This meant that improved shielding of the front-end would be difficult to implement, with weight and rework consequences.

Figure 5 shows the VHF tray with all the different RF modules screened in their aluminium boxes, all with feed-through filters on power and signal lines. Figure 5 shows that the most sensitive part of the VHF tray, the receiver preamplifier (the big module - bottom right) was situated next to the regulators (right side of preamplifier) - an unfortunate choice. Magnetic fields from the converter's inductor could thus easily induce square wave 650 kHz noise unto the 14V-power line routed underneath the regulator - another unfortunate mistake. This power line passes around the PCB, acting as a good radiator. This supply line also runs underneath the antenna relay box (small box in top corner), that was mentioned previously.

All the above facts indicated that it would be difficult to make the VHF tray insensitive to strong fields. Previous thoughts about enclosing the dual switching regulators had been restricted to on-board solutions. These all appeared difficult to implement reliably on flight hardware. The final solution was to remove the regulators off the PCB and mount them from the sidewall in a specially milled aluminium case. By enclosing and potting the regulators in this conductive box and passing input and outputs through feed-through filters, the switching RFI was reduced to the point where it cannot be detected on any receiver as the input voltage was changed slowly from 11-15V. Before this final measure, a switching regulator harmonic would cause a 5 dB sensitivity decrease at the desired receiving frequency of 145.825 MHz when the input voltage was about 12.5V.

VI. INTERESTING OBSERVATIONS

One switching regulator of the same type didn't produce any harmonics on the spectrum analyser. Curiosity was aroused, until an oscilloscope showed that the converter's control loop was in a low frequency limit cycle. The RFI was present, but at a peak noise density lower than stable converters because the RF energy was spread over the band. Changing this regulator's load and input voltage could stabilise its loop, causing strong spectral concentrations to re-appear. These facts emphasise how careful one needs to be using switching regulators in a radio receiver environment.

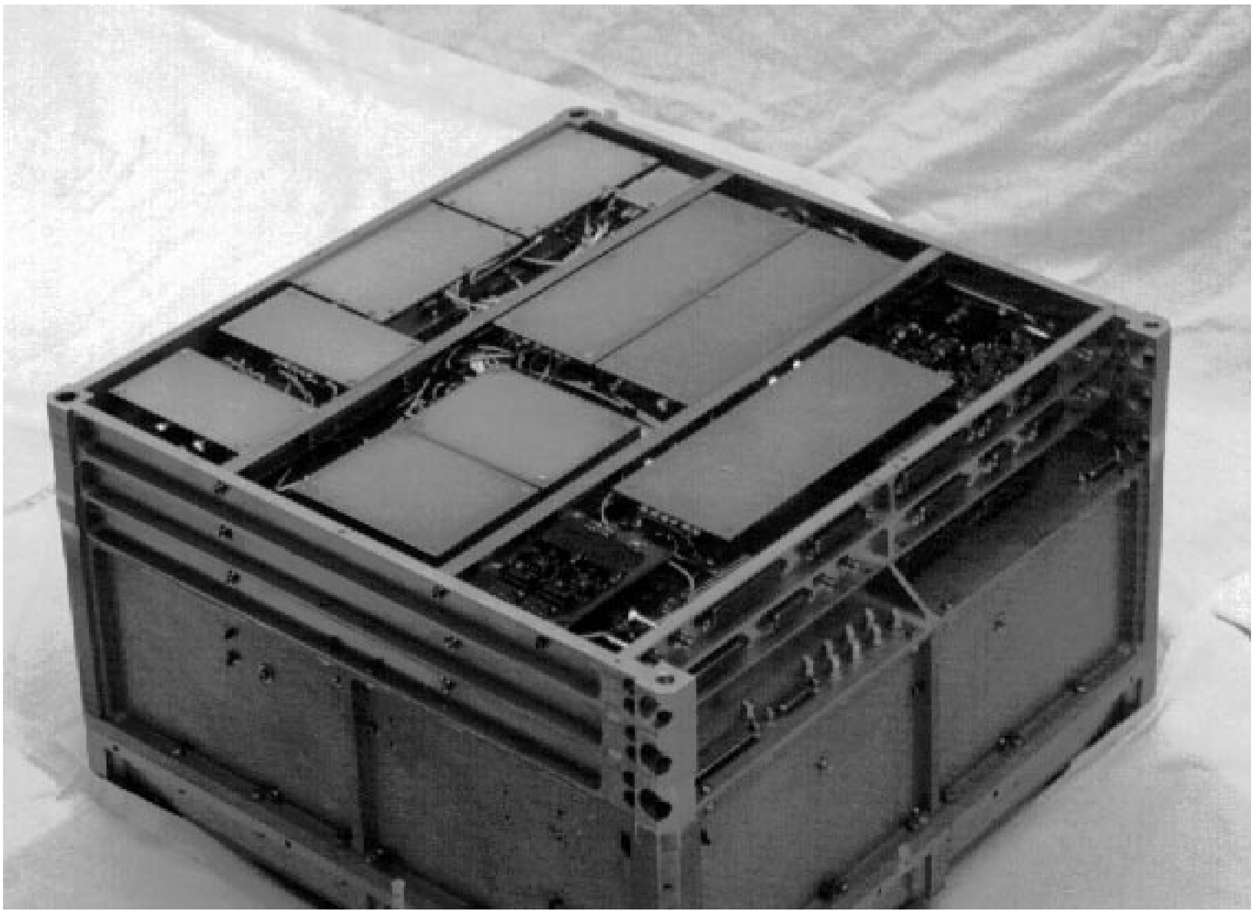

Fig. 5. Photograph of the VHF tray

VII. Lessons learned, recommendations to reduce RFI or possible RFI problems

a) Switching regulators may have the advantage of high efficiency, but are potential noise generators. Make sure the benefits outweigh the potential RFI.

b) Assume that you will need to completely enclose a switching regulator in a metallic screen with feed-through connecting leads, particularly if your system includes VHF receiver antennas.

c) When switching regulators are used in a communication system design, the regulators must be analysed and the radiation and coupling of the electric and magnetic fields must be measured in early design stages.

d) In a design, a preliminary set-up that simulates the final completed product must be constructed to verify the RFI influence of the switching regulators on the rest of the circuitry, and particularly the antennas.

e) Variations in switching regulator's load current and input voltage will cause their switching frequency to change. This can lead to unwanted harmonics changing frequency on and off the desired receiver frequency, with consequences of non-repeatable test results.

f) The different modules that form the communications system must be tested separately against power supply interference. This will determine whether the different modules can withstand RFI caused by switching regulators or fast switching circuits.

g) Be careful when running long power supply busses to all the different modules in a communications system. Any noise generated by switching regulators that is not properly filtered will couple on to these and be routed to other parts of the system or radiate unwanted fields.

h) Transparent conformal spray used for mechanical support of components may cause screened boxes with lids to make poor electrical contact leading to poor RFI shielding. It also changes the property of some RF components causing a change in circuit behaviour.

i) Feed-through filters cannot always be used for filtering of power and signal connections. They may cause unnecessary attenuation to high frequency signals, and their capacitance on op-amp outputs causes many op-amps to oscillate.

j) It is also important to ground coaxial connections properly on both ends of the cable when used to connect different modules to each other.

k) Different switching regulators with a lower switching frequency and slower rise time can also be used to minimise high frequency noise radiation. Crystal controlled switching regulators may be used to keep open spaces in the spectrum between switching harmonics fixed.

l) Place noisy components (like switching regulators) far away from the sensitive part of a receiver (like the front-end).

m) Sensitive parts in communications systems like receiver front-ends must be properly shielded and power and signal lines must be properly filtered. Special care must also be taken where receiving antenna cables are routed.

n) Continuous electrical contact must be made between an RF enclosure and its lid. Slits in these enclosures tend to cause field lines to make abrupt changes that can lead to EM fields leakage or radiation.

VIII. Conclusions

Shielding the fast and slow bus of the satellite with aluminium plates reduced RFI received by the satellite antennas by about 20 dB. Sensitivity was no longer degraded by RFI.

Switching regulators on the VHF tray itself were a major cause of RFI. These were ultimately shielded in an aluminium housing with pi-section feed-through filters providing the necessary power filtering. Together with proper shielding of the receiver front-ends the RFI leaking into the receivers was reduced to below the thermal noise of the receiver.

The 435-438 MHz UHF receivers were largely insensitive to RFI from the switching regulators used on their tray. The natural f^{-2} attenuation of the switching regulator harmonics is the probable explanation.

This paper has recorded how the RFI problems on this complex electronic system were measured, identified and solved. A set of rules the authors will apply to a future similar system to help solve and minimise RFI problems has been presented.

A. Acknowledgements

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