

A Miniaturized Nanosatellite VHF / UHF Communications System

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ABSTRACT

This paper outlines the design and development of a VHF / UHF communications system for application in small satellites in LEO orbit.

Based on the VHF / UHF transceiver as used in the Delfi-C3 nanosatellite, the transceiver presented in this paper features full duplex capability by providing a VHF Binary Phased Keying (BPSK) downlink up to 9600 bit/s and a UHF Frequency Shift Keying (FSK) uplink up to 9600bit/s. Lower datarates can be accommodated as well. It is usable over a wide frequency range, allowing both the amateur radio and commercial frequency bands to be used. The entire transceiver is housed on a single Printed Circuit Board of 90 x 96mm, making it possible to apply the transceiver as a low rate telemetry / telecommand transceiver in spacecraft ranging from nanosatellites to microsattellites. The transmitter section includes a class E nonlinear power amplifier of which the supply voltage is modulated with envelope information in order to allow for processing of non-constant envelope (shaped) BPSK modulation while maintaining both high power and spectral efficiency.

This paper discusses the design and development of the VHF / UHF transceiver, the protocol used and the accompanying ground station software defined demodulation system. Special attention is given to the design methodology used.

INTRODUCTION

In small satellites, power is often the most limited resource available. With increasing payload capabilities and associated required data rates, achieving optimum downlink throughput for a given amount of consumed power is key to mission success. Driving factors are modulation scheme E_b/N_0 versus Bit Error Rate (BER) performance, required computing power (coding) and transmitter DC to RF efficiency. Achieving high DC to RF efficiency is especially important, but this requirement can be in direct conflict with the requirement for linearity in order to allow for non-constant envelope modulation schemes to be used.

The research and development efforts at ISIS on RF payloads and subsystems originate from this observation. The company has its roots in the CubeSat Community where the need for efficient communications systems is very high.

Operating in the nanosatellite domain for several years, ISIS has a good feeling for customer needs. ISIS focuses on affordable space systems with excellent performance, from a systems point of view. The transceiver developments are closely coupled to development efforts on small deployable antenna

systems, ground stations and operational concepts in order to optimize the complete space system, rather than only optimizing the transceiver design. However, space transceivers can be, and need to be, significantly optimized for nanosatellite applications.

The driving factors for increasing the data downlink capability of a communications system per unit of electrical power are the modulation scheme E_b/N_0 versus Bit Error Rate (BER) performance, the required computing power (coding), and the transmitter DC to RF efficiency. Achieving high DC to RF efficiency is especially important, but this requirement can be in direct conflict with the requirement for linearity in order to allow for non-constant envelope modulation schemes to be used.

DEVELOPMENT GOALS

The transceiver developed for the Delfi-C3 university satellite of Delft University of Technology formed the starting point of the transceiver development.² The transceiver was developed as part the author's final MSc thesis work at Delft University of Technology. From the current design that is currently flying on Delfi-C3 the following development goals have been formulated:

1. Develop an improved transceiver for small spacecraft that is also compatible with the CubeSat standard, based on the Delfi-C3 transceiver design.
2. The transceiver will be specifically designed for use in space. Rather than a modified terrestrial product as often used in small satellites.⁴
3. The transceiver will be a full duplex design enabling simultaneous command uplink and telemetry downlink. Using full duplex capability has a significant amount of advantages³
4. The transceiver shall feature a CW beacon for easy spacecraft acquisition as well as a low rate telemetry functionality
5. Obtain an easy to receive downlink on VHF with reduced complexity in the link.

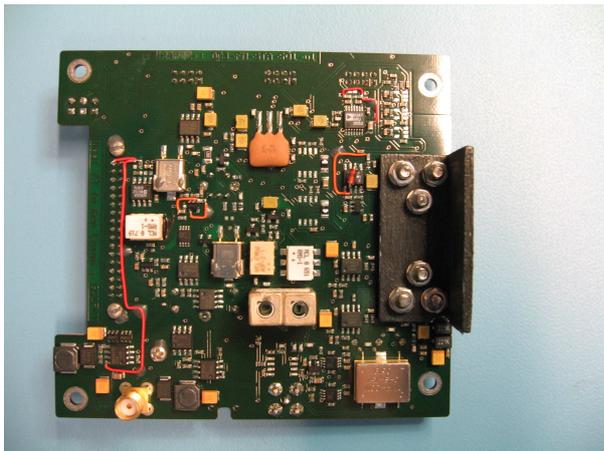


Figure 1 Delfi-C3 transceiver

PERFORMANCE REQUIREMENTS

Previous communications systems for small satellites such as CubeSats have often been based on adopting Commercial Off the Shelf systems.⁴ Although some of these systems have proven their usefulness, they are not optimally suited to use in the space environment.

Instead, for this development, a bottom up approach was chosen in which the following driving requirements have been defined:

1. Orbital altitude range 300-1000km
2. Link margin > 10dB

MODULATION SCHEMES

Various modulation schemes are used for small satellite downlinks, variants of FSK and PSK are the most common. Generally, frequency and phase modulation schemes have constant envelope (by definition). But, their spectral efficiency can be poor. This can be solved by applying spectral shaping. This shaping, however, inherently introduces an AM component requiring the power stages to be linear. Table 1 summarizes some of the commonly used modulation schemes no small satellites and their properties. Only basic schemes are considered since higher order schemes such as QPSK or OQPSK are regarded to be too complicated for low rate links on VHF/UHF.

Table 1 Commonly used small sat modulation schemes and their properties

Modulation scheme	E_B/N_0 for BER 10^{-5}	Constant envelope?	Spectral efficiency
AFSK	23dB	Y	Bad
BPSK	9.6dB	Y	Bad
Shaped BPSK	9.6dB	N	Good

For this transceiver design, shaped BPSK was chosen where the bit shape over time has a predefined shape (e.g. raised cosine) in order to limit the occupied bandwidth.

THE ISIX PROTOCOL

The transceiver uses a novel communications protocol on the downlink, instead of the AX.25 protocol which is commonly used in small satellites for low-rate applications. Although the AX.25 protocol performs satisfactorily for most applications, it was never designed to be used for space-earth links and features some shortcomings, especially when used with BPSK modulation. For example, the continuous idle stream of flags has shown to cause false lock problems in Costas-loop based BPSK demodulators. Furthermore, AX.25 has a relatively high protocol overhead. Keeping this in mind, the ISIX protocol was developed, allowing for a smaller overhead and improved acquisition performance on the ground station side. A matching groundstation software package was developed in

JAVA, which incorporates software defined demodulation and automatic Doppler tuning of the BPSK downlink signal and subsequent protocol handling.

The basic structure of the ISIX protocol is similar to AX.25. Instead of flags, an idle stream sequence of 010101 is chosen, for optimal locking of the groundstation demodulator software. A 4 byte sync vector indicates the start of the frame, which is closed by a 16 bit CRC in order to provide basic data integrity.

Idle	Sync Vector	Header	Data	CRC
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Figure 2 High level ISIX protocol definition

CONCEPTUAL TRANSCEIVER DESIGN

Designing a space transceiver is a time consuming activity, and incremental updates are not that easily implemented. For example, the high frequency signals can be affected by the board layout of the PCB. A standardized transceiver design would be ideal from a development point of view, but customer needs directly contradict the use of a fully standardized transceiver product; every customer has its own wishlist of modifications and options. To offer a customizable system in order to meet customer needs without having to redesign the transceiver for every customer, call for some special measures.

A modular approach towards the transceiver design was selected to allow for incremental updates and improvements of the design, without affecting the overall layout and configuration of the product too much. A modular design with well established interfaces between the transceiver building blocks minimizes the impact of modification to the system level design and performance of the transceiver. As an additional feature, well defined modules and interfaces allow for the implementation of custom ASICs and of novel and disruptive technologies such as MEMS and MST.

One of the prototype transceiver modules (baseband modulator) is shown in figure 3.

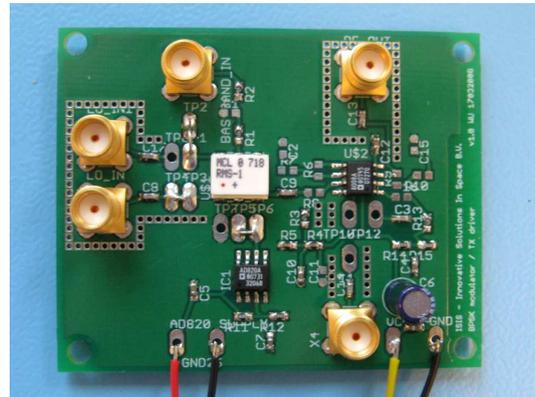


Figure 3 Baseband modulator prototype

TRANSMITTER EFFICIENCY

Transmitter (and especially the Power Amplifier) efficiency is the dominant factor determining the overall power consumption. Efficiency is often in direct contradiction with required linearity in order to process non-constant envelope (shaped) signals. These signals, however, can be processed by modulating the supply voltage of the PA with envelope information, while the PA itself processes the phase signal. Feedback techniques are available however to linearize the transfer characteristic of highly non-linear PA's. For this transceiver development, the use of a class E (switching) Power Amplifier is envisaged, the PA is currently under development.

As feedback technique, envelope feedback is under consideration. The principle of this envelope feedback scheme is shown in figure 4.

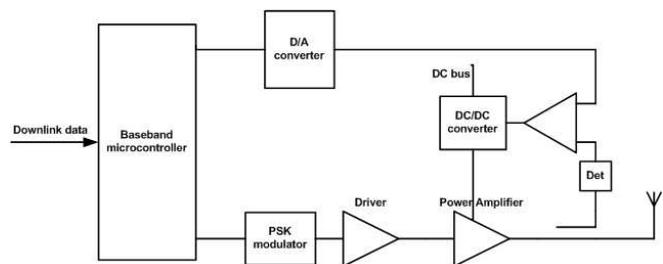


Figure 4 Envelope feedback transmitter architecture

Due to the relatively low datarate and bandwidth required, envelope feedback can be applied successfully in order to linearize the PA transfer.

Furthermore, using the feedback linearized class E amplifier allows for easy power agility by varying the PA drain / collector voltage.

BIT RATE AGILITY

The downlink signal is generated in a dedicated baseband microcontroller, connected to a digital to analog converter which generates the baseband waveform. In this way, the downlink transmitter is capable of generating frames with variable datarate, selectable settings include 1200, 2400, 4800, and 9600 baud.

LOCAL OSCILLATORS

Although being a compromise with regard to frequency agility, the local oscillators used are overtone crystal oscillators based on a new circuit concept that makes use of injection locked relaxation oscillators for selection of the correct overtone (US patent 6225872 by TU-Delft).¹ The circuit is well suited for complete on-chip integration. When in future the crystals are replaced by MEMS resonators, there will be no off-chip components left, which is of great importance for further miniaturization of spacecraft.

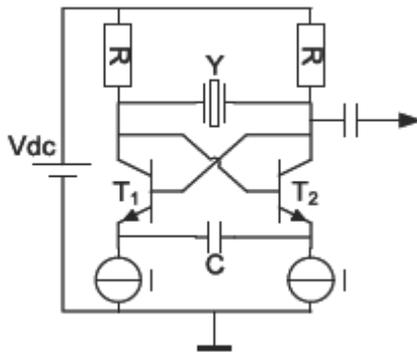


Figure 5 Crystal resonator synchronized relaxation oscillator

UPLINK RECEIVER

The uplink receiver is based on a well-proven FM receiver design, with special emphasis on selectivity and large signal handling capability rather than sensitivity in order to optimally perform in the LEO RF space environment. It can provide for telecommand functionality with datarates up to 9600 bit/s. The use of an FM receiver allows AFSK, FSK and GMSK modulation to be used as the uplink modulation scheme, using a discriminator – detector approach. The uplink receiver is designed such that it is always operational for reasons of mission safety.

TELEMETRY DECODING SOFTWARE

DSP telemetry decoding software has been developed, based on earlier developments for the Delfi-C3 satellite.

The software has been developed in the JAVA language, and is independent of which operating system is used. The software features coherent demodulation using a sweep-aided Costas Loop, and includes compensation for Doppler shift. Matched filtering detection using an integrate and dump ensures optimum performance. The software includes an algorithm for detecting the actual data rate in use.

FUTURE DEVELOPMENTS

ISIS is a workpackage leader in the ambitious Dutch research programme for Micro-Systems Technology (MST): MicroNed. Within this programme a number of research project are focusing on MST for micro-, nano- and picosatellites within the MISAT cluster. As a future development for the transceiver development ISIS will research the possibilities of implementing a number of innovative MST technologies into its transceiver design. The following aspects are currently under review to be implemented:

1. MEMS-based resonators for use in the local oscillators. An example of this local oscillator circuit is flown successfully on the Delfi-C3 satellite, using a quartz crystal as the resonating element. Replacing the crystal resonator with a MEMS resonator can significantly improve performance
2. MEMS-based filters for channel filtering and obtaining the required selectivity
3. Application of MicroCoolers for maintaining thermal balance of the heat-generating parts
4. Thermal energy scavenging techniques in order to regain part of the energy which is converted into heat, for instance in the power amplifier stages of the transceiver

The modular setup of the transceiver will allow these MST component to be integrated in the design and improve the overall system performance of the transceiver. An ISIS transceiver demonstrator with integrated MST modules has been selected as a technology demonstration payload onboard the Delfi-n3Xt mission from Delft University of Technology. This mission is the successor to the previously mentioned Delfi-C3 mission and contains, next to the transceiver payload, a number of other innovative technology demonstration payloads. The spacecraft is again a 3-Unit Cubesat and is now in the detailed design phase. The current schedule anticipates a launch of the spacecraft in 2010.

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