Modeling & Simulation Of A Novel DSP MSK Coherent Demodulator And Decoder For Optimizing A 'Little LEO' Microsatellite Communications System

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ABSTRACT This paper provides a background to modeling and simulation of a 'little LEO' microsatellite communications system, which includes a brief introduction of the UoSAT microsatellites, its 'store-&-forward' communications system, the experimental communications payload - the Digital Signal Processing Experiment (DSPE) and the in-orbit CPFSK/MSK modems experiments using PoSAT-1 DSPE. This paper concentrates on the modeling and simulation aspect of a research program optimize 'little LEO' microsatellite communications system by modulation / demodulation using DSP techniques. The advantages and disadvantages of simulation tools and the positive and negative experiences from modeling and simulation of the 'little LEO' microsatellite communications system and a novel DSP MSK coherent demodulator /decoder are presented.

1. INTRODUCTION

There is growing interest in using networks of small satellites in Low Earth Orbit (LEO) to provide a variety of communications services using very small terminals - ranging from world-wide data-collection and electronic file transfer at VHF/UHF to mobile and personal voice communications at LS bands. Communications satellites in LEO offer certain potential advantages when compared with traditional geostationary satellite communications systems, but LEO systems exhibit very different and demanding characteristics. When compared with geostationary satellite communications, a search of the literature has shown that the practical characteristics of the LEO VHF/UHF communications environment are poorly understood and thus optimized communications techniques have not yet been developed for these services.

The Centre for Satellite Engineering Research at the University of Surrey has pioneered microsatellite technologies for over a decade and has more than 45 orbit-years of experience in operating its UoSAT series of microsatellites in LEO [Sweet'92]. Ten UoSAT microsatellites (UoSAT-1, UoSAT-2, UoSAT-3, UoSAT-4, UoSAT-5, KITSAT-1, KITSAT-2, S80/T, PoSAT-1, HealthSat-2) have been constructed at Surrey and launched into LEO and, although they weigh only 50kg, they are capable of sophisticated functions and have very powerful on-board processing abilities. The UoSAT series of microsatellites are considered as the 'little-LEO' class small (micro)satellites which provide non-real-time (store-&-forward) interconnected 'Wireless' (portable) computing and digital information communications services [Ward'91] at VHF/UHF.

Microsatellites in LEO exhibit widely varying communication path & link characteristics, higher Doppler shift and a complex fading environment. The investigation of suitable communications techniques for the 'little-LEO' small (micro)satellites is being carried out with the aim to improve the communications throughput achievable to-&-from the microsatellite, as it transits the groundstation horizon, by optimizing the modulation and demodulation using DSP techniques.

During the course of the research, a Digital Signal Processing Experiment (DSPE) payload was designed, built and incorporated into the latest SSTL LEO microsatellite (PoSAT-1) [Sun'93]. The DSPE provides a flexible in-orbit experimental DSP-based communications test-bed to investigate practical solutions to these problems and to provide the possibility for developing an adaptive satellite modem which could vary dynamically the data rate and modulation according to the varying link characteristics.

The Digital Signal Processing Experiment (DSPE) on board PoSAT-1 consists of two digital signal processors from the TMS320 family, a 'C25 and a 'C30. Each DSP has its own memory space and interfaces to the other parts of the spacecraft. An ADC and DAC are included in the spacecraft baseband communication systems. This then permits the DSPE to modulate the downlink, and demodulate from the uplink. The DSPE can thus be switched to replace the hardware modem (modulators and demodulators) to test various modem techniques.

In-orbit communication experiments with the PoSAT-1 DSPE commenced with optimizing the currently used CPFSK system and was followed by a novel DSP-implemented MSK coherent modem in-orbit evaluation. The experimental results, including bench test results, have been presented in [Sun'94]. This paper will concentrate on the modeling and simulation aspects of the research program. The results of modeling and simulation will be presented in comparison with the laboratory bench and in-orbit tests.

Figure 1.1 shows the mechanical architecture of PoSAT-1 and the module which the DSPE shares with another experimental payload - the Cosmic Ray Experiment (CRE).

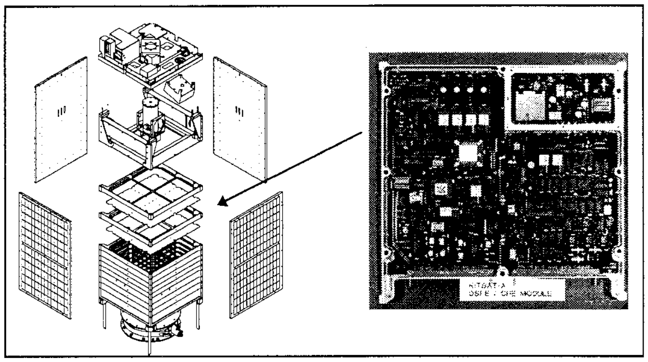

Figure 1.1 'Exploded' view of PoSAT-1 microsatellite structure and the DSPE/CRE module

2. COMPUTER SIMULATION TOOLS FOR COMMUNICATIONS

The most popular tools for simulating communications systems are *Signal Processing Worksystem* (SPW), MATLAB and *Communication System Simulation and Analysis Package* (COSSAP). The DOS version of MATLAB has been used for processing and plotting bench and in-orbit test results (e.g. averaging, FFT and IFFT) during the research. The design of a combined Nyquist pulse shaping and equalization filter has also been carried out and the effects of equalization has been simulated by the author's MATLAB program. An advantage of MATLAB is that it is easier to program, but it is very primitive when compared with advanced communication simulation packages - SPW and COSSAP. They combine graphic display with a simulation environment for communication systems and provide many useful communications model libraries. Users do not need to worry about how to record and display results and write everything from the beginning. The principle of these computer simulation packages is that the user only need to draw some layout similar to the system functional block diagram to simulate the functions and responses of the communications systems. These computer simulation packages are intended to provide universal research tools to communication engineers and researchers to check system designs and algorithms before implementation. The advantage of these computer simulations is that it speeds up research and improves the quality of system design.

SPW is a time-driven simulator which is more suitable to certain applications, however, it is more complicated to use and consumes more CPU time and memory when compared with the COSSAP. COSSAP is mainly a stream-driven simulator and simulation is correspondingly easier to construct and more suitable to multi-bit rate systems, but there are some difficulties in the initialization. SPW has better interfaces for converting simulation designs to DSP implementations, however, the conversion is very inefficient. After trading off both advantages and disadvantages, COSSAP was selected as a simulation tool for modeling and simulation of the 'little LEO' microsatellite communications system and a novel DSP MSK coherent demodulator and decoder.

3. SIMULATION OF A NOVEL DSP MSK COHERENT DEMODULATOR/DECODER

Coherent MSK is proposed in order to provide a potential 3dB advantage in link BER as a function of Eb/No compared to the non-coherent CPFSK techniques currently used in the UoSAT microsatellite communications system. Traditionally, coherent detection is not considered suitable for LEO satellite communications systems. However, the novel DSP-implemented coherent MSK demodulator/decoder exhibits considerable tolerance to frequency and amplitude variations in both laboratory bench tests and **in-orbit demonstrations**.

The novel MSK coherent demodulator/decoder is not a "standard" I-Q MSK coherent demodulator [Buda'72] but is an FFSK type of MSK demodulator. The decoder algorithm of this novel MSK demodulator was published by Massey [Mas'80] and Hodgart [Hod'92] completed the design of the carrier and clock recovery. Figure 3.1 shows the block diagram of the novel MSK coherent demodulator/decoder and Figure 3.2 is the design of the clock recovery. A DSP implementation of this MSK coherent demodulator /decoder has been carried out by the author using TMS320C30 assembler language on a C30 development system board operating at 9.6kbps.

In order to compare the novel DSP-implemented MSK coherent demodulator/decoder with the classical Buda's MSK demodulator, both were implemented in COSSAP to confirm and understand the advantages of this novel MSK demodulator. Computer simulation is a good research tool to easily and quickly implement and compare various systems when a real implementation would consume too much time and can in practice be impossible, and to carry out theoretical analysis when it may be very difficult or impossible to describe a system in a close form mathematical formula.

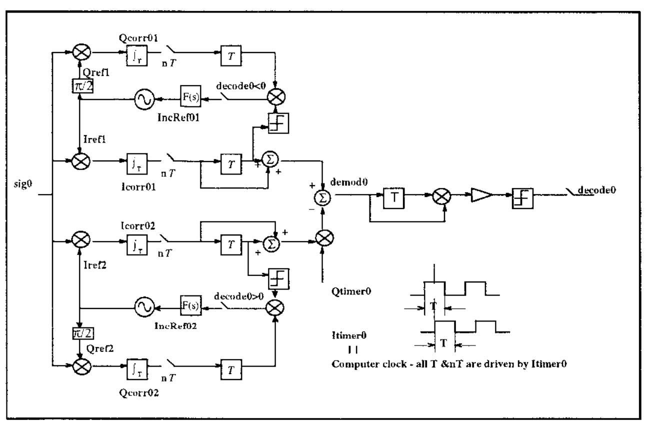

Figure 3.1 The MSK coherent demodulator/decoder

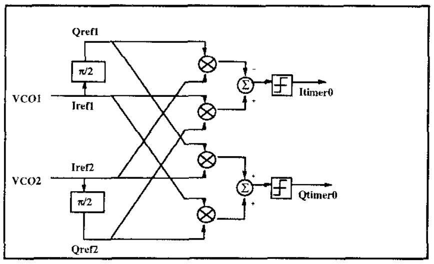

Figure 3.2 The clock recovery

COSSAP's libraries are designed for simulation of complex digital signal processing algorithms at baseband, however, both the algorithms of this MSK demodulator /decoder and Buda's MSK demodulator are real digital signal processing algorithms at RF band, therefore, the implementations are not easy. Many hierarchical and primitive models were created by the author during the simulation in order to implement and test both algorithms.

Functional tests have been first carried out after the implementation of the novel MSK demodulator in comparison with the bench test in order to confirm the correct simulation implementation. Figure 3.3 exhibits one of novel points of this MSK demodulator/decoder, which is the design of joint carrier, clock and data recovery. The VCO's control voltage of the carrier recovery is switched by the decoded data.

Characteristics of both MSK demodulators have been thoroughly examined in a LEO satellite communication environment by computer simulation. Obviously, in-orbit evaluation is more valuable because results make use of a real LEO satellite communication environment. However, quantitative results are very difficult to obtain from in-orbit evaluation when satellites transit the groundstation within a limited time whilst bench tests require a channel simulator, which is not available. Figure 3.4 is Bit Error Rate Test of this novel MSK demodulator/decoder in additive white Gaussian noise, which gives 2dB improvement on BER performance compared with non-coherent CPFSK system and is identical to the result of the bench test. Figure 3.5 shows the novel MSK demodulator is a non-data aided coherent demodulator, which outputs correct data even in acquisition range. Figure 3.6 illustrates the acquisition characteristics of the demodulator. Figure 3.7 shows the Doppler tracking simulation. The Doppler shift is simulated within ±200Hz because the accuracy of the Doppler steering program is ±100Hz.

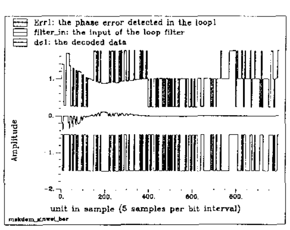

Figure 3.3: the top trace is the phase error detected in the loop1 for decoding data mark, the middle trace is the VCO control signal after the switching off the phase error corresponding to data space, and the bottom trace is decoded data space for switching.

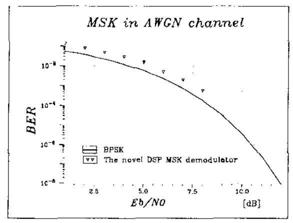

Figure 3.4 BER test

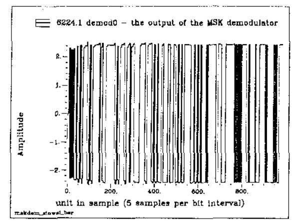

Figure 3.5 Output

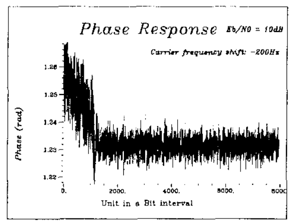

Figure 3.6 Acquisition

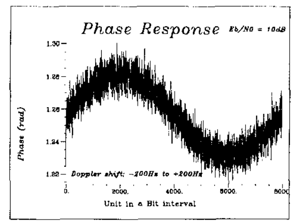

Figure 3.7 Doppler tracking

In comparison, Buda's demodulator takes at least 100 times longer to lock up and very intolerant to frequency change. These dynamic characteristics of the demodulator have been examined in computer simulation, which are not easy to check using bench tests and even more difficult in orbit.

4. MODELING OF THE CHANNEL DISTORTION AND EQUALIZATION

A previously unknown non-linearity in the satellite on-board RF modulator was identified in the in-orbit MSK modem evaluation which restricted the performance of MSK on PoSAT-1 using random data, therefore, much research has had to rely on computer simulation. The effects of distortion and equalization on this novel MSK demodulator/decoder have also been examined using COSSAP.

The effect of bandwidth limitation was first examined in COSSAP by inserting a filter in baseband of the MSK modulator. Figure 4.1 shows that the demodulator is working well when the bandwidth of the baseband filter is 7.5kHz , which explains why the demodulator can cope with the narrow band receiver (15kHz IF filter corresponding to 7.5kHz baseband filter). However, the demodulator stops working while the bandwidth of the baseband filter is changed to 2kHz (refer to 4.2), which simulates the distortion of RF modulator restricting the performance of MSK random data. The examination shows that the tolerance to the bandwidth limitation corresponds to a minimum 5kHz bandwidth in baseband. Figure 4.3 shows that the distortion does not have effect on the 1010101 ... data pattern, which was observed at the in-orbit evaluation. These simulations confirm that intersymbol interference caused by the channel distortion stops the demodulator working with random data.

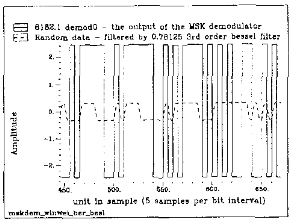

Figure 4.1 the filtered baseband random data & demod0 while the bandwidth of the bessel filter is 7.5kHz

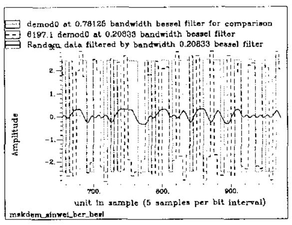

Figure 4.2 random data

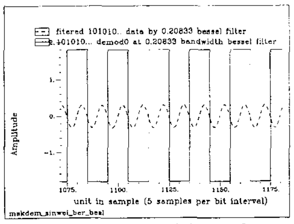

Figure 4.3 101010... data

Equalization was proposed to compensate the distortion of the on-board RF modulator, which was measured in a time domain using step response. The step response of PoSAT-1 channel is recorded by the Hypersignal Workstation, averaged and differentiated in MATLAB to get the impulse response (refer to Figure 4.4). The channel module in COSSAP is an FIR filter and the coefficients of this FIR filter correspond to the impulse response of the PoSAT-1 channel which is read into COSSAP by the **DITERM** function. Then the actual effect of the distortion on the MSK demodulator was examined by inserting this channel module in baseband of MSK modulator. Figure 4.5 shows the distorted random data and Figure 4.6 shows that the demodulator stops working with random data. The step response equalization filter was designed based on the channel step response and the Nyquist pulse shaping with a roll off factor α=1 plus zero forcing equalization filter was designed based on the channel impulse response in MATLAB. These equalization filters were simulated using the **FIR** module in COSSAP and the coefficients of these FIR filters read in by the **DITERM** function. Figure 4.7 is the eye pattern observed at the output of channel module and the input of the channel module is the predistorted Nyquist pulse, which is produced by the equalization filter module. This allows thorough modeling of effects of the channel distortion and equalization on the demodulator.

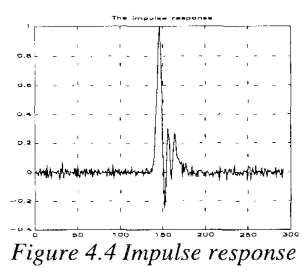

Figure 4.4 Impulse response

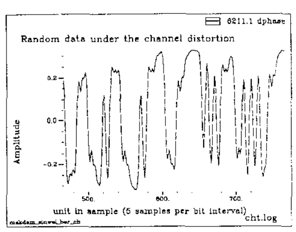

Figure 4.5 Random data

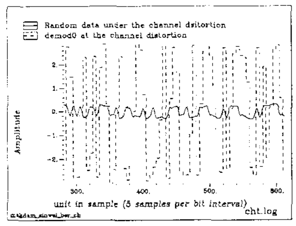

Figure4.6 channel distortion

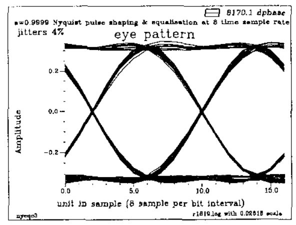

Figure 4.7 Equalization

5. BE CAREFUL WITH COMPUTER SIMULATION

These communication simulation packages are far from ideal, therefore, simulation results should be evaluated very carefully by comparison with results from laboratory bench or in-orbit tests. Problems encountered in simulation of the novel DSP MSK demodulator/decoder are presented in this section.

5.1 Voltage Controlled Oscillator

In COSSAP, a Voltage Controlled Oscillator (VCO) is implemented by a integrator (**INT1**) and a sine function operator (**SIN**). Figure 5.1 shows the envelope fluctuation of the sinewave which is generated by this implementation. This problem is caused by an integration error, which is that a calculation using a limited word length introduces an insignificant error but an accumulation of 'insignificant errors' results in a noticeable error. This envelope fluctuation is only observed during a long term simulation and obviously, it causes inaccuracy in Bit Error Rate test at high signal to noise ratio (Eb/N0). A primitive model (**VCOCOR**) has been written by author to solve this problem. Figure 5.2 shows the sinwave without envelope fluctuation which is generated by this primitive model. This primitive model is developed based on the following principle:

$\mathrm{Sin}(\varphi 1) = \mathrm{Sin}(\varphi 0)\times\mathrm{Cos}(\Delta\varphi) + \mathrm{Cos}(\varphi)\times\mathrm{Sin}(\Delta\varphi)$

$\mathrm{Cos}(\varphi 1) = \mathrm{Cos}(\varphi 0)\times\mathrm{Cos}(\Delta\varphi) - \mathrm{Sin}(\varphi 0)\times\mathrm{Sin}(\Delta\varphi)$

where, $\varphi 0$ is the previous phase, $\varphi 1$ is the current phase and $\Delta\varphi$ is the phase increment.

While a phase increment is small, $\mathrm{Sin}(\Delta\varphi) \approx \Delta\varphi$, error (e) is calculated in the following formula:

$e = \mathrm{Sin}(\varphi 1)^2 + \mathrm{Cos}(\varphi 1)^2 - 1$

The error e is used to calculate $\mathrm{Cos}(\Delta\varphi)$ for the correction:

$\mathrm{Cos}(\Delta\varphi 1) = \mathrm{Cos}(\Delta\varphi 0) - e1 + e0/2$

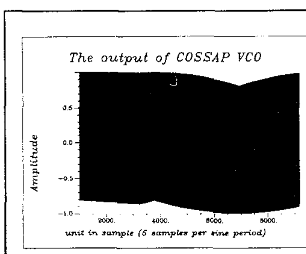

Figure 5.1 Fluctuation

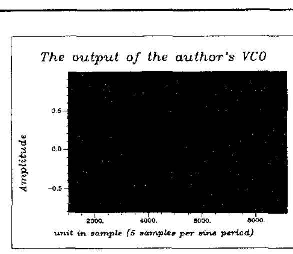

Figure 5.2 the author's VCO

5.2 Initialization & Delay

COSSAP is a stream-driven simulator, therefore, it is very difficult to imagine the timing relationships when there are several complicated feedback loops in an implementation of a multiple bit rate system, which is unfortunately the case for simulation of the novel DSP MSK demodulator/decoder. This is reflected as an initialization problem. Normally, a delay model is used for a system initialization in COSSAP. The position of the delay model for initialization is very important and it should be inserted in the 'starting point'. This is normally one of the inputs of the model, with the other input driven by the simulation source, otherwise the delay causes changes on the loop parameters. The determination of the 'starting point' may cause a 'chicken & eggs' problem. The delay time is determined by the number required for the initialization. Alternatively, the problem can be solved by modifying the model at 'starting point' to have initialization function. Several COSSAP models are modified by the author to provide initialization functions.

5.3 Bit Error Rate Test in AWGN channel

The BER curve of the novel DSP MSK demodulator always crossed the BER bench mark curve of BPSK and was also very different from the result of bench tests when additive white Gaussian noise is simulated by **AWGN** from the COSSAP real signal processing library and the channel is a RF channel rather than an I-Q baseboard channel, which is mostly used in computer simulation. **AWGN** is described as a baseband module, therefore, a BER test has been carried out by inserting **AWGN** in baseband of the system and the result is that no error is counted even at Eb/N0=1dB, which is obviously wrong. The problem was finally solved by converting the real RF signal to I-Q baseband signal, which goes through a complex channel model (**AWGNQC**), and then converting back to real RF signal.

6. CONCLUSION

A new generation of LEO communications satellites will require novel, adaptive techniques in order to overcome the varying link characteristics as the satellites transit the user. The research program, to optimize data throughput during the limited communication times available using LEO satellites, has been supported by the PoSAT-1 Digital Signal Processing Experiment (DSPE) payload, which provides a realistic in-orbit test-bed to support practical research into various modulation/demodulation methods. Communication System Simulation and Analysis Package (COSSAP) has been used to speed up and enhance the quality of the research. The tolerance to the LEO satellite communication environment of the novel DSP MSK demodulator has been confirmed in simulation when compared with a 'standard' MSK demodulator. The modeling of channel distortion and equalization was explained the results of bench and in-orbit tests and confirmed the following conclusions:

- A novel DSP implemented coherent MSK demodulator has achieved 2 dB improvement in BER performance on lab. bench test & in-orbit demonstration with considerable tolerance to frequency and amplitude variations.
- The in-orbit channel measurement and equalization have improved the communications channel characteristics.

Computer simulation helps theoretical analysis, which sometimes is very difficult or impossible to describe in a close form mathematical formula. However, the use of computer simulation should be used with care. A computer simulation result becomes really valuable and useful only after it is verified by a bench test and in orbit evaluation.

An enhanced DSPE is under development for the new microsatellite FaSAT-a (will be launched in July 1995) based on the experiences with the PoSAT-1 DSPE. The research associated with the FaSAT-a DSPE will concentrate on optimizing the communication with portable/movable, and even hand held terminals and establishing an adaptive communications system - continuously optimizing modulation, data rate, and coding in response to the varying link and traffic characteristics. Certainly, computer simulation will play an important role.

7. ACKNOWLEDGMENTS

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