

USING DIGITAL SIGNAL PROCESSORS ON SMALL SATELLITES
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ABSTRACT

Digital Signal Processing integrated circuits (DSPs) have improved terrestrial communications systems by allowing the implementation of greatly improved transmitters and receivers. In applications from dial-up modems, to echo-free conference phones, to customer-specific hearing aides, DSPs have allowed the implementation of functions that would be impractical without them. However, DSPs have had limited use in small satellites due to lower available data rates and relatively high power consumption. Also, most of the existing DSPs have not been space qualified.

Improvements in semiconductor processes are allowing the construction of integrated circuits (ICs) with much smaller features. In fact, 0.6 micron processes are becoming generally available. Newer DSP ICs based on these processes have greater speeds and greatly reduced power consumption compared to their predecessors.

This paper covers the general use of DSP ICs in small satellites, where the power consumption of on-board circuitry must be minimized. It then discusses DSP power consumption, the achievable DSP data rates, general radiation hardness for the existing DSPs, and the advantages and disadvantages of using DSP-based communication

systems in small satellites.

The paper shows that the power consumption of presently available DSPs is now sufficiently low, and their processor speeds are now sufficiently high for application to some small satellite systems.

1. INTRODUCTION

Digital Signal Processing integrated circuits, DSPs, have many potential uses in small satellites. This paper concentrates on their use in small satellite communication systems, but the information in the paper will be useful for other applications.

Small satellite communication systems are usually power limited rather than bandwidth limited [1]. The small solar-cell area of these small satellites provides power in tens of watts rather than in the hundreds or thousands of watts of large geosynchronous satellites. Consequently, the overall power efficiency of the entire spacecraft communication system should be optimized. This includes not just the efficiency of the modulation itself, but also the efficiency of the required power amplifier (which must have the proper linearity), and the power consumption of the circuitry itself.

Cynetics has previously

investigated using DSPs for modulation and demodulation in small satellite communication systems. At that time, the DSPs consumed up to several watts more power than discrete implementations. In fact, in many cases, the DSPs would have consumed more power than was actually being transmitted. Since small satellites have limited power available, discrete implementation of the modulation and demodulation circuitry were preferred. The saved power was available for the payload, for improved signal-to-noise ratios, for smaller antennas, or for increased data rates.

However, the decrease in power consumption in the newer DSPs is obtained partly from the decreased feature size on the DSP chips. This decreased feature size causes an increase in susceptibility to radiation. Fortunately, DSP products have reached the maturity where radiation testing has begun on some of the available chips.

This paper discusses the power consumption and radiation hardness of DSPs. It then mentions possible uses for DSPs on small satellites. The paper concludes that the newer, power-efficient DSPs are suitable for use in the communication systems in small satellites, but that they must be properly shielded to achieve the necessary radiation hardness.

2. DSP POWER CONSUMPTION

When Cynetics first considered using DSP chips for modulation and demodulation aboard small satellites, DSP power consumption was several watts. Since a low-earth-orbit (LEO) satellite can easily communicate 9600 bits-per-second (bps) to a ground terminal

with only one watt of transmitted power, we considered this DSP power consumption to be too high. Conventional discrete implementations of the modulator and demodulator can consume less than one watt, so we felt that DSP power consumption should decrease to this level before DSPs should be considered further for modulation and demodulation.

Table 1 shows that the available DSPs have reached the low power consumption required for power constrained small satellites. The table also shows the evolution in DSP power consumption: The Texas Instruments TMS32010 consumed one watt maximum for a peak speed of 5 MIPS, while the TMS320C10 consumes only 165 mW for the same 5 MIPS speed. This is a decrease from 0.2 watts per MIP (TMS32010) to 0.033 watts per MIP (TMS320C10).

The advent of 0.6 micron CMOS processes promises to cut power consumption further since the dynamic power consumption is a proportional to the capacitance of the features in the chip. Thus, a linear-dimension decrease from 1.0 micron to 0.6 microns roughly decreases power consumption by a factor of $0.6 \times 0.6 = 0.36$. (The capacitance is proportional to the area of the feature. Other factors also affect the power consumption, so the decrease in the capacitance does not completely determine the decrease in the overall power consumption of the chip. Nonetheless, the capacitance related power of a 0.6 micron CMOS chip will be roughly 36% of the consumption of a 1.0 micron chip.)

Company	Part #	Speed	mW/MIP	MAX PWR	Process	TOT DOSE
TI	TMS32010	5 MIPS	200	1 Watt	NMOS	
TI	TMS320C10	5 MIPS	33	165mW	CMOS	
TI	TMS320C25	10 MIPS	92	925mW	CMOS	6.5 Krad
TI	TMS320C30	16.6 MIPS	181	3 Watts	CMOS	5 Krad
TI	TMS320C40	200 MOPS		850mW	CMOS	
MOT	DSP56001C21T	10.25 MIPS	44	455mW	HCMOS	15 Krad
MOT	DSP96002RC40	60 MFLOPS	125	2.5 Watt	CMOS	
AD	ADSP2100	8.192 MIPS	58	475mW	CMOS	40 Krad
AD	ADSP2100A	12.5 MIPS	63	790mW	CMOS	
AD	ADSP21020	60 MFLOPS	100	2 Watts	CMOS	40 Krad

TABLE 1. Power consumption and radiation hardness of several DSPs [2,3,4,5,6,7].

In one case that we investigated, a board-level digital demodulator consumed more than 20 watts. This demodulator can demodulate up to 50 Msps (mega-symbols-per-second), and can demodulate frequency-shift-keying (FSK), bi-phase-shift-keying (BPSK), quadra-phase-shift-keying (QPSK), minimum-shift-keying (MSK), as well as quadrature amplitude modulation (QAM), quadrature-partial-response-signalling (QPRS), and other modulations. Studies undertaken for Cynetics have shown that a QAM digital demodulator can be implemented in a single 0.65 micron CMOS chip. This 0.65 micron chip would consume less than 2 watts at 5 volts, or less than 1 watt at 3.3 volts.

The decrease in required power from going to smaller-feature CMOS processes comes at a price however. The smaller features are more susceptible to single-event upsets (SEUs), single-event latchups (SELs), and other radiation effects. DSP radiation hardness is discussed in the next section.

3. DSP RADIATION HARDNESS

3.1. General Information.

Although no truly space-qualified DSPs are known to the authors, several DSP types have been flown on space missions. These were verbally reported to have been the military versions of DSPs from Texas Instruments, Motorola, and Analog Devices [5,6,7]. Specifically, we note the stated inclusion of a Texas Instruments TMS320C25 in a Mars observer mission [5].

As mentioned previously, DSP chips with small features will be more susceptible to radiation. In fact, the system designer should expect total dose limits at levels of 5 to 50 Krads, as described below.

3.2 Preliminary Radiation Hardness of Several Existing DSPs. We stress that the information in this section is preliminary in nature. Some of it is from conversations with the companies involved. Direct comparisons of the total dose numbers may not be appropriate since differing dose rates may have been used to obtain the data. This data should be understood as a starting point for further investigation by those who use the information. In particular, we suggest that the parties listed in the corresponding references be contacted for the most current information.

Texas Instruments [5]. The TMS320C25, which was previously mentioned as having flown on a Mars mission has been reported to experience failures at total doses of 6.5 Krads with a 40 MHz clock, and 5.5 Krads with a 50 MHz clock. Dose rate was 1×10^8 rad(Si)/sec.

Analog Devices [7]. Analog Devices' ADSP2101 have been flown in spacecraft. The performance is reported to remain within specifications for total doses of

up to 30 to 50 Krads. (This assumes a tactical dose rate used for the tests; a lower, space-level dose rate, results in a higher total dose specification.) Note that the device may remain functional even if it not operating within specifications. Analog Devices recommends that the ASDS2101 not be used in a radiation environment because of the susceptibility of the onboard memory and the dynamic circuitry to radiation.

Motorola [8,9]. Motorola has begun radiation testing of its 56001 DSP. Preliminary results of this testing are available from Motorola (see references). These preliminary results have shown functional failure at roughly 6 to 9 Krads. A 12.5 micron epitaxial layer was added to the sample parts. With annealing, the epitaxial part was still able to function after 30 Krads. The preliminary report concludes that it may be reasonable to expect the modified part with the 12.5 micron epitaxial layer to survive over 30 Krads of total dose radiation.

The 56001 non-epitaxial parts had dose rate latch-up thresholds of 3×10^8 rad(Si)/sec. With the 12.5 micron epitaxial layer, the latch-up threshold was extended to greater than 4.5×10^{10} rad(Si)/sec, an improvement of two orders of magnitude.

Internal upset for both expitaxial and non-epitaxial parts occurred between 3×10^8 rad(Si)/sec and 5×10^8 rad(Si)/sec.

3.3 DSP Summary. The radiation information for the above mentioned DSPs is included in Table 1.

3.4 Memories. A second source of possible radiation caused errors in

satellite DSPs is single-event upsets in off-chip memories. The University of Surrey's UoSat radiation experiments have shown that dynamic random-access memories (DRAMs) can be expected to experience on the order of 5×10^{-6} single-event upsets per bit per day [10,11,12,13]. The same experiments have indicated that static random-access memories (SRAMS) experience one tenth the SEU rate of DRAMS [12].

3.5 Similar Microprocessors. The Applied Physics Laboratory of Johns Hopkins University has performed radiation tests on an Intel 80186 microprocessor [14]. These tests showed an expected 0.3043 upsets per day [14, p.8] with a peak upset rate of 4.6 upsets per day for a low-earth orbit. Although the 80186 and DSPs are different devices, this data can give some sense that DSPs operating with large off-chip RAMs can see significant upsets from both the memory and the DSP itself.

3.6 A Cautionary Note. The Combined Release and Radiation Effects Satellite (CRRES) experiments showed that "NASA's previous radiation models have certain deficiencies which for certain orbits could overestimate or underestimate radiation doses by one to two orders of magnitude" (Gary Mullen in [15]). CRRES found that multiple upsets from proton-initiated chain reactions in memory chips were far more likely than had been initially expected. This is consistent with the findings of the UoSat team [12]. Memory shielding should be increased in light of this information. Memory error correction should also be considered. Such error correction should use physical separation of 1 X N memory chips in a physical interleaving/de-interleaving scheme to prevent the outputs from

multiple-event upsets from occurring within a single byte and overwhelming the error correction method.

4. DSP USES ON SMALL SATELLITES.

4.1 General Comments. Since DSP chips are primarily microprocessors, they can be used for a variety of tasks onboard small satellites. Of course, since DSP architectures and instruction sets are optimized for signal processing, their primary uses will be for signal processing tasks, including communications. In addition to communications, several other possible uses are mentioned below.

4.2 Communications. DSP chips can perform modulation and demodulation at "near-baseband" frequencies. For communications, the DSP can also perform:

1. Data Compression. The DSP can perform straight compression of data of any type using the appropriate compression algorithm. Image compression can be performed on still frames. (Full-motion-video compression is beyond the capability of present DSPs).

2. Image Processing. Images can be pre-processed onboard the satellite before transmission. This can be viewed as another form of data compression.

3. Forward Error Correction (FEC). FEC can be performed by the DSP. This can be done in real-time for low data rates, of off-line or in parallel for higher data rates.

4. Memory Error Correction (MEC). As mentioned previously, single and multiple event upsets can be expected in spacecraft memory. DSPs can be used for MEC to protect

against these upsets. This could be done as a shared task by the same DSP used for communications modulation and demodulation, provided the data rates are sufficiently low.

5. Trans-Modulation. Since modulation and demodulation in DSPs are performed by calculations, any modulation type can be used, provided that the required calculation rate is within the capacity of the DSP. Thus, a message can be received on an FSK uplink and re-transmitted on a BPSK downlink. In this way, a DSP-based small satellite could allow communication among a wide range of previously incompatible terminals.

4.3 Signal Conditioning. DSPs can perform onboard signal conditioning for control and instrumentation on the satellite.

4.4 Control. A DSP which is under utilized on other tasks can be used as a time-shared controller for onboard tasks, including satellite and payload control.

5. CONCLUSIONS

Digital Signal Processor integrated circuits, DSPs, now achieve sufficiently low power consumptions to allow their use on power-constrained small satellites. These devices can be used for several communications tasks, including: modulation and demodulation, data compression, image processing, forward error correction, memory error correction, an trans-modulation. DSPs can also be used on a time-shared or independent basis for signal conditioning and control.

However, the DSPs themselves, and off-chip memories (especially DRAM, as opposed to SRAM), are

susceptible to radiation. The DSPs can be expected to have total-dose limits in the range of 5 to 50 Krads for existing devices. Since satellites in low-earth orbits can experience total dose radiation levels of 100 Krads over four years [16], proper radiation shielding of DSPs and memories is required. In addition, error detection and correction of memory should be considered. Where possible, masked-ROM (read-only-memory) should be used for program memory. (With masked-ROM program memory, instructions are encoded in metal interconnections which are radiation-hard by their nature.)

With proper radiation shielding and error correction, DSPs can provide enhanced communications and on-board processing for small satellites.

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