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A Remote I/O (RIO) Smart Sensor Analog-Digital Chip for Next Generation Spacecraft

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Abstract. The RIO Smart Sensor chip is APL's analog-digital, radiation-hardened, low-power, data acquisition device suitable for spacecraft and instrument data collection. The chip communicates over a standard serial I2C bus or a standard parallel bus. RIO, in its complete version, will measure temperatures using external thermistors, total ionizing dose using external radFETs, and voltages and currents. Its sensing capability can extend to other physical quantities such as photons, vibration, etc. A first version of this chip, is focusing on temperature measurements only (TRIO chip). TRIO measures 16 temperature channels using external platinum resistance thermometers (PRTs). It can also measure voltages only, using an external voltage reference. The TRIO chip contains all of the front-end analog conditioning circuitry, the analog multiplexer (MUX), a 10-bit analog-digital converter (ADC), memory, and both a serial I2C and standard parallel interface. TRIO can operate in a fixed mode, where only a particular sensor is addressed, digitized, and read out, or in a scanning mode where all 16 sensors are sequentially and continuously scanned, digitized, and stored into self-contained memory. This single chip system will be a valuable enabling technology for next-generation small spacecraft.

Introduction

A necessary function in any spacecraft or instrument is collection of engineering housekeeping data to monitor health status. Such data include temperatures from distributed sensors, and voltages and currents produced either directly from the various subsystems or from distributed transducers such as pressure transducers. Traditionally, engineering data were collected from the distributed sensors with dedicated wires to a central processing unit, which multiplexed, digitized, stored, and finally transmitted the data. This centralized approach, however, requires heavy, complex harness.

An alternative advanced approach is to use distributed data collection and to adopt a serial bus. A couple of meters of twisted pair can then replace heavy complex harness. Distributed processing lightens the burden on the central processing unit. New sensors can easily be added by just attaching to the bus and assigning a new address.

The enabling element for distributed data collection is the RIO chip. This smart data acquisition device provides the interface from the distributed sensors to the serial bus. In addition to the standard engineering sensors, RIO can handle many other distributed sensors, such as radFETs for total radiation dose monitoring. The RIO can also provide control actions via Digital-to-Analog Converters (DACs), and smart digital interfaces.

New Spacecraft Architectures

Traditionally, a satellite's electronic circuits have been organized in several subsystems, each housed in its own "black box". A more recent development in spacecraft architecture is APL's use of the Integrated Electronics Module (IEM) approach[1].

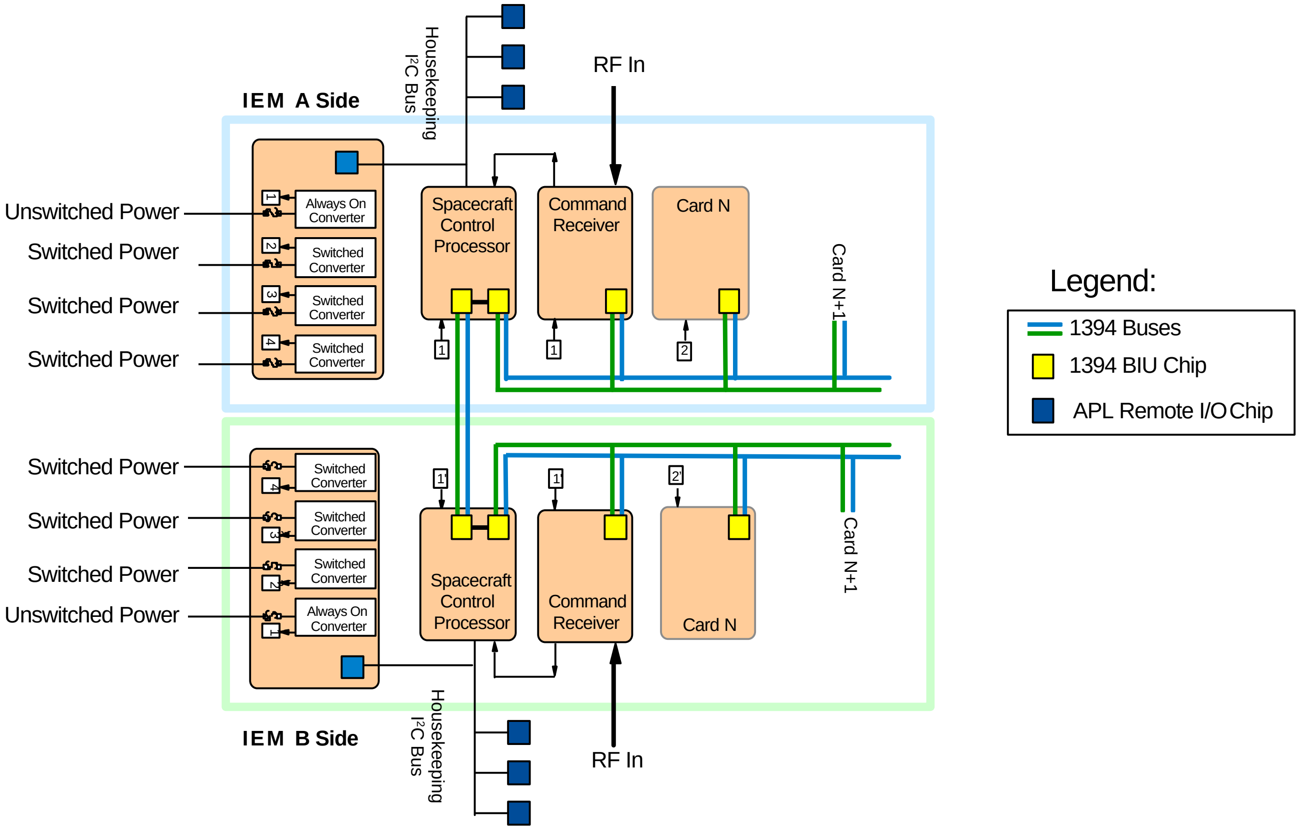

Figure 1: APL Integrated Electronics Module Configuration

Figure 1[1] is a block diagram of APL's integrated, scalable IEM architecture for future satellites. It minimizes development costs while maximizing mission flexibility. The APL IEM reduces most core spacecraft electronics into a single chassis that can be configured to satisfy a wide range of requirements.

Figure 2[2] is a block diagram of the JPL X2000 Bus Telemetry Collection Architecture. The X2000 bus is a generic system intended to support JPL's future planetary exploration programs. At least five missions are scheduled to use this bus: Europa, Champollion/Deep Space 4, Mars Sample Return, Pluto-Kuiper Express, and Solar Probe. APL's TRIO chip is distributed throughout the bus to measure temperatures with PRTs. The X2000 spacecraft typically needs a total of about 170 temperature measurements. TRIO bare die, in the parallel readout mode, will also be used in the microcontroller included in several spacecraft systems (Optical Communications Controller, Power Controller, etc.). In addition to temperatures, TRIO chips will be used with pressure sensors in the propulsion system, and for total radiation dose profiles throughout the spacecraft. This last function is important for the Europa mission.

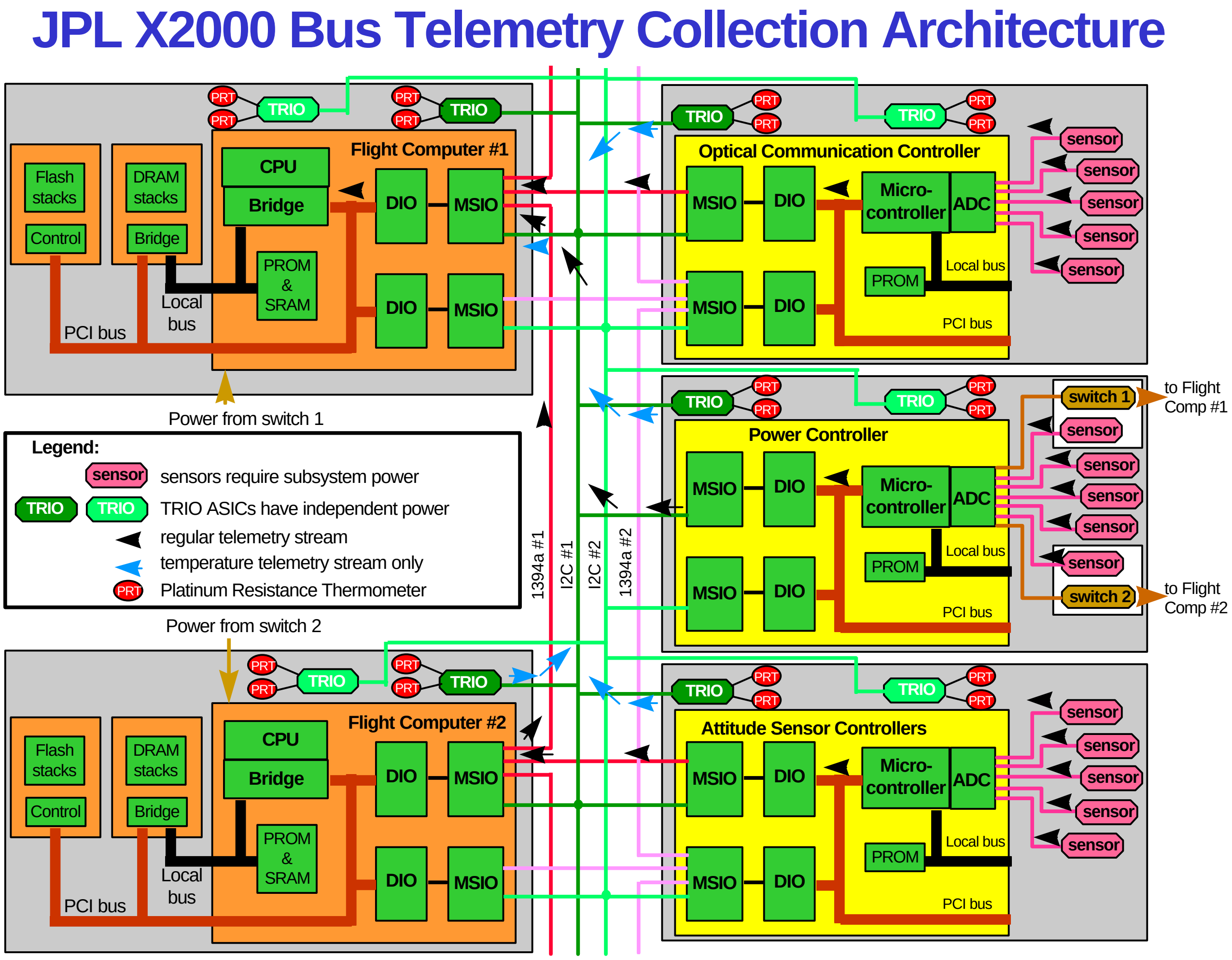

Figure 2: JPL X2000 Spacecraft Bus Telemetry Collection Architecture

In both APL's and JPL's bus architectures, spacecraft subsystems are implemented on single circuit boards. The subsystems communicate over an IEEE 1394 high-speed, low-power, serial bus within the IEM, an innovation introduced by APL[1]. Additionally, both bus architectures use a low-speed, low-power, digital serial bus (I2C) to collect status and engineering housekeeping data.

The Inter-Integrated Circuit (I2C)[3] bus was selected for the low-speed engineering data collection because of its simplicity, reliability, and wide industrial use. The I2C bus was originally developed by Philips Semiconductors to connect peripheral chips to microcontrollers and is widely used in industrial embedded control applications. I2C is a very simple bus running at two standard speeds, 100 kbps and 400 kbps. Custom implementation with enhanced drivers can increase the speed up to ~4 Mbps. The I2C specification does not include provisions for data transmission error detection or correction. However, this is not significant for engineering data collection because multiple samples are commonly processed before any decision is made. Extending I2C to control actions needs more attention. We are currently evaluating several straightforward, albeit nonstandard, protocol extensions that can be layered on top of I2C when the most reliable communications are needed.

The RIO Chip

APL's RIO device was specifically developed for distributed data acquisition. RIO is a radiation hardened, single chip, multichannel, data acquisition system that can digitize many types of engineering data; it connects directly to the I2C bus. RIO also connects to a standard parallel bus for local microcontroller data acquisition, as shown in Figures 1 and 2. RIO, in its complete version, will measure temperatures using external thermistors, total ionizing dose using external radFETs, and voltages and currents. The sensing capability can extend to any other physical quantity that can be transduced to voltage or current form. The RIO can also contain digital-to-analog converters, analog and digital comparators, counters, programmable timers, and smart digital interface to perform local control actions.

The TRIO Chip

A first prototype version of RIO, focusing on temperature measurements has been successfully developed (the TRIO chip, Figure 3). TRIO measures 16 temperature channels using external platinum resistance thermometers (PRTs). It can also measure voltages only, using an external voltage reference. The TRIO chip contains all the front-end analog conditioning circuitry, the analog MUX, a 10-bit ADC, memory, and both a serial I2C and a standard parallel interface. TRIO can operate in a fixed mode where only a particular sensor is addressed, digitized, and read out, and in a scanning mode where all 16 sensors are sequentially and continuously scanned, digitized, and stored into memory. The memory then can be independently read out from either the serial or the parallel interface.

Description of Operation

The Front End

Generally, a voltage measurement is a comparison and digitization against a stable voltage reference. Similarly, a temperature measurement can be a comparison of a temperature sensitive passive resistive element against a temperature insensitive element. In the TRIO, each high temperature coefficient PRT element is compared against a very low temperature coefficient resistor R_c.

The front end circuitry interfaces to the sensors, providing the required biasing and signal conditioning for interfacing to the ADC.

The temperature measurement is based on a current source defined by an opamp and resistor R_c, as shown in the upper left. Resistor R_c is connected from the negative terminal of the opamp to the V_{dd} rail. The positive terminal of the opamp is set to $0.8V_{dd}$ with a resistive voltage divider from rail to ground. With this connection, the value of the current source is $I = 0.2\ V_{dd}/R_c$, and therefore is linearly dependent on V_{dd}. Current I is forced through the analog MUX, sequentially to each of the PRTs connected to the T0 - T15 terminals. The voltage developed on each PRT is therefore:

$$V_{temp} = 0.2\ V_{dd} * R_{PRT}/R_c \qquad (1)$$

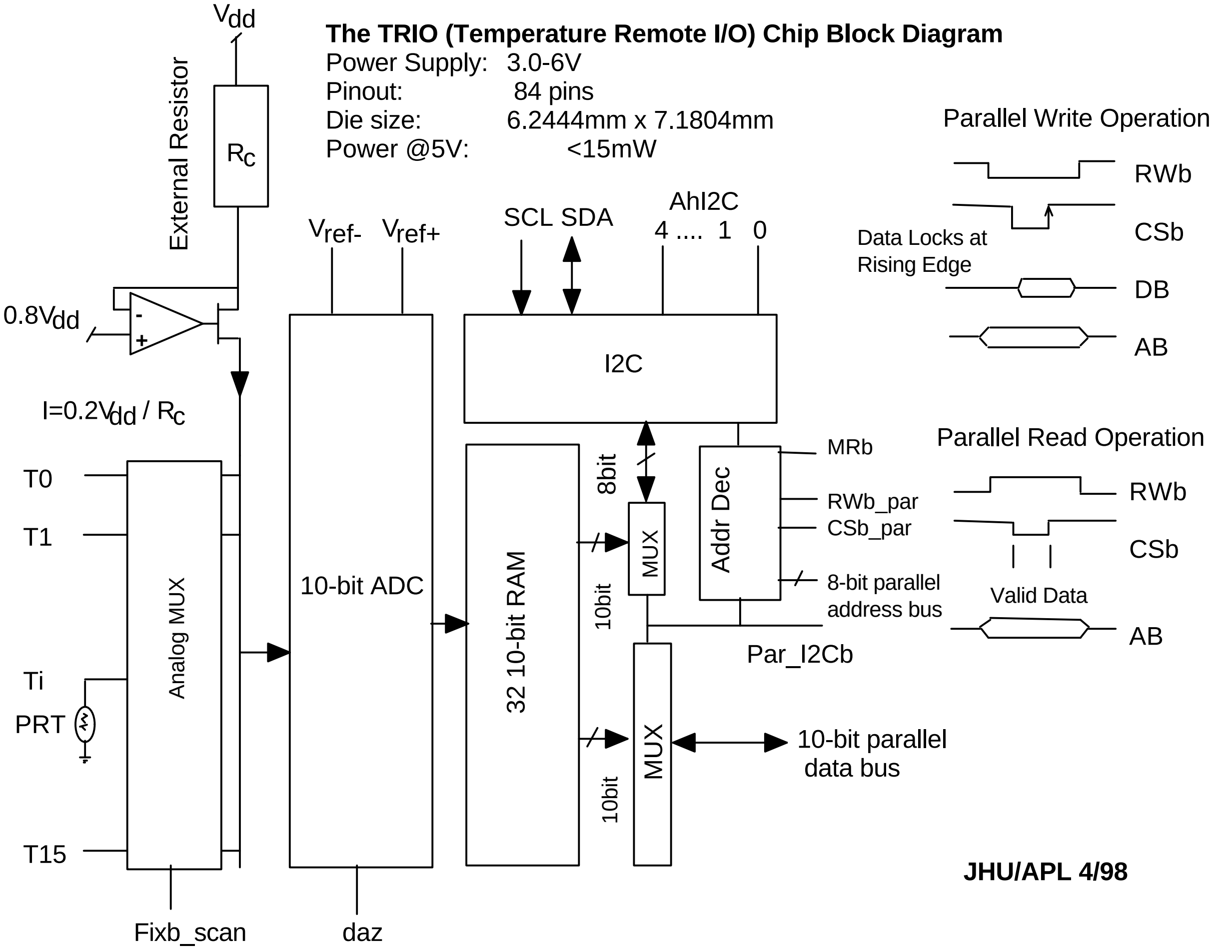

Figure 3: The Temperature Remote I/O (TRIO) chip block diagram

It is obvious from this expression that the power supply dependence of V_{dd} can be easily compensated for by making the reference voltage of the ADC be power supply dependent. It is clear that R_c should be selected with a temperature coefficient much less than PRT, in order to compensate for operational temperature variations. R_c is a small size chip resistor external to the TRIO chip. To be more precise, the temperature coefficients of the PRT should be > 2 * 1024 that of R_c for a 10-bit resolution ADC and < 0.5 LSB error, assuming the same temperature extremes for the PRTs and R_c. The value of R_c also sets the scale of the current in order to normalize the various PRT voltage values to the ADC voltage conversion range.

There are commercially available low-cost, mil-spec PRTs, that are highly linear in a broad temperature range with a broad range of nominal ice temperature values. One such is from Rosemount Aerospace, with an ice temperature value of 5 kΩ, and linear in the temperature range -200 to +200 ^{o}C. The temperature variation is ~ +20 Ω / ^{o}C and the temperature coefficient is ~ +4000 ppm. Expression (1) then says that the temperature coefficient of R_c, should be < 2 ppm.

The analog MUX is composed of large CMOS switches to achieve low ON resistance. The value of the switch resistance does not affect the accuracy of the measurement because the temperature voltage is sensed on the sensor after the switch. However, it is important to have low ON resistance value, compared to the PRT, in order to contribute less to saturation and to increase the speed in the voltage transfer mode. The MUX can be configured to operate in a fixed or a scanned mode. In the fixed mode, only a particular sensor is addressed and read out. In the scan mode all the sensors are scanned, digitized, and sequentially stored into on-chip memory.

The time constant associated with the development of the temperature voltage is $\tau_{temp} = R_{PRT} * C_T$, due to the total capacitance C_T at each node. The capacitance C_T is mostly due to the twisted pair from the TRIO chip to the PRT. A typical value is ~ 200 pf / m. Thus there is a wait time needed for each sensor before starting the ADC, to achieve any desired resolution. For a 10-bit ADC, assuming a 0.1 LSB accuracy, the maximum wait time needed is:

$$t_w / \tau_{temp} > - \ln (0.1/2^{10}) \sim 9.2 \qquad (2)$$

For a maximum R_{PRT} resistance value of 10 kΩ, t_w is > 18.4 μs per meter. The wait time is programmable, based on the conversion clock, to accommodate different loads and PRT values.

The ADC

The ADC digitizes the voltage generated by the front end signal conditioning circuitry. The topology was selected for rail-to-rail input dynamic range, good linearity, monotonicity, and low power. Speed is not critical for this application, so it was sacrificed for low power and simplicity. The selected topology also minimizes the effects of total radiation dose. The ADC[4] is a 10-bit successive approximation type. The operation is based on a 10-bit DAC, a comparator, and a successive approximation algorithm. The DAC comprises a resistive ladder and analog switches. The comparator is designed for rail-to-rail input common mode voltage and low offset.

The only ADC function that can be influenced by total radiation dose is that of the comparator. Special care was taken in the layout and in the biasing of the comparator to minimize dose effects, using experimental results and experience gained from past optimized designs[5,6]. To further reduce offset related errors, the ADC was provided with an optional digital auto–zeroing mode, (controlled by pin "daz") with a small cost in conversion speed.

The ADC performs conversions between V_{ref-} and V_{ref+}, which can be externally set by the user. For the temperature measurement, the difference V_{ref+} - V_{ref-} must be V_{dd} dependent in order to compensate for its variation. A simple way to apply this is to connect V_{ref-} to ground and V_{ref+} to V_{dd}. The ADC can operate in the power supply range 3-5 volts. The clock can be externally provided or internally generated. The maximum conversion rate is ~25 k samples/sec, and the power dissipation is ~5 mW at 5 volts.

Memory – Serial and Parallel Readout

The digitized information is stored in 10-bit memory registers. There are 32 locations available, anticipating extension of the number of sensors in a next chip version. The memory is written by the ADC, and read out independently by the parallel or the serial interface. Special design care was taken to avoid write/read timing conflicts as well as to minimize Single Event Upsets[5].

The TRIO chip has two selectable modes of read out: a serial I2C interface and a standard parallel interface. The serial interface is advantageous for remote data collection, whereas the parallel interface is best for local microcontroller applications. The parallel bus has a standard 8-bit address bus, 10-bit data bus, and the required strobe signals.

The I2C interface is a compact custom design, with special output driver implementation to boost the speed up to 4 Mbps, well beyond the maximum spec of 400 Mbps. This capability was added to anticipate use with high bandwidth sensors. Fault protection is obviously very important in a serial bus application. A special driver design also protects the bus against device failure. In case of a bus short, each device performs an autocheck, and if it is responsible for the bus failure it is self-isolated The current I2C implementation has a hard select address depth of 5-bits, which allows addressing 32 slave TRIO devices, with a provision to extend to 7-bits (128 devices). We also plan to enhance the I2C functionality to a master capability, in order to allow operation in a multimaster bus. In a multimaster bus, each device will act independently as a master to allow decision actions, alarm settings, etc. This will increase the “smartness” of the device[3].

Voltage Mode Operation

The initial TRIO chip can measure temperatures only or voltages only. The voltage measurement, however, needs an external voltage reference for the ADC since there is not one available onchip in the present version. The temperature measurement does not need a voltage reference because the reference element is the low temperature coefficient resistor R_c.

Voltage sources to be measured should be connected to terminal T0 through T15. Voltage mode is achieved simply by disconnecting the external resistor element R_c in order to allow the ADC input to be determined by the corresponding voltage source (see Figure 3). In addition, to save power, the current source operational amplifier can be turned off by simply disconnecting its biasing. Future RIO implementations will have a simple commandable selection of the voltage mode. It is assumed that each voltage source to be measured has a value within the ADC voltage reference window V_{ref-} to V_{ref+}; also it should be $V_{ref-} \geq 0V$, $V_{ref+} \leq V_{dd}$ and $V_{ref+} > V_{ref-}$.Each input T0 - T15 has a built in overvoltage protection.

Error Sources and Calibration

Temperature measurement errors can result from variation of the input offset voltage, V_{ofamp} of the current source operational amplifier, the non-linear part, $R_{PRTnl}(T)$, of the PRT resistance versus temperature, the variation of the input offset voltage V_{ofcmp} of the ADC comparator, and the non-linearity of the ADC. ADC non-linearity error can be measured for each chip, and if necessary, removed by post-calibration. In the temperature measurement mode, the sum of errors at the input of the ADC can be seen in the expression:

$$V_{temp} = (0.2\ V_{dd} - V_{ofamp}) * (R_{PRT} + R_{PRTnl}(T)) / R_c + V_{ofcmp} \qquad (3)$$

Any non-linear $R_{PRTnl}(T)$ variation can be calibrated for, if necessary, by a look-up table. However, as mentioned, there are available PRTs with excellent linearity within a broad temperature range. Comparator offset can be removed by operating the ADC in the autozeroing mode, with some conversion speed penalty.

There is a convenient way to remove both offset induced errors by simply using a low temperature coefficient resistor, identical to R_c, as a calibration sensor in one of the sixteen channels. This calibration sensor should correspond to a fixed temperature and therefore any electronically induced error can be removed, based on the known temperature.

In the voltage mode, sources of error are the offset variation of the ADC comparator (which can be removed by operating the ADC in the autozeroing mode), the variation in the ADC reference voltage, and the ADC non-linearity.

Experimental Results

Prototype TRIO chips were fabricated in a triple-metal, single-poly, 0.8μm bulk CMOS, radiation hardened process. The die size is 6.2444 x 7.1808 mm and the pin out is 84 pins, many of which are for testing. Experimental parts were packaged in an 84 pin PGA package. Preliminary testing results indicate that TRIO is fully functional in both the temperature and the voltage modes, as well as both the scanning and the fixed modes. In the temperature mode the chip was tested for power supply rejection and results indicated that < LSB accuracy is maintained for power supply in the range 3 - 6 volts. The power dissipation in the scanning temperature mode and a conversion rate of ~20 k samples/sec, was measured to be < 15 mW @ 5V.

The operation of the ADC was verified in both the standard and autozeroing modes, for sampling rates up to 10 k samples/sec. Preliminary measurements of the ADC differential nonlinearity (DNL) and integral non linearity (INL), for one TRIO chip, are shown in Figures 4 and 5. The DNL was within ±0.5 LSB and the INL within 1 LSB. These preliminary measurements might carry some measurement uncertainties, but the results are generally satisfactory for a prototype chip.

Prototype TRIOs will be tested and characterized in detail before a final production for any flight program. Testing and characterization will include flight operational temperature range, 3–6 volts power supply, and total radiation dose up to 10 Mrad. Chips will also be tested and characterized for latchup immunity and SEUs under a high energy beam with LET up to ~120 MeV*cm^2/mg. Test results will be used to optimize the final design before production of flight devices.

Conclusions

Mixed analog-digital custom integrated circuit technology can play an important enabling role in the development of next-generation compact, lightweight, low-power, autonomous spacecraft. By mastering this technology, a complex circuit can be reduced to a microchip that can be space qualified and flown.

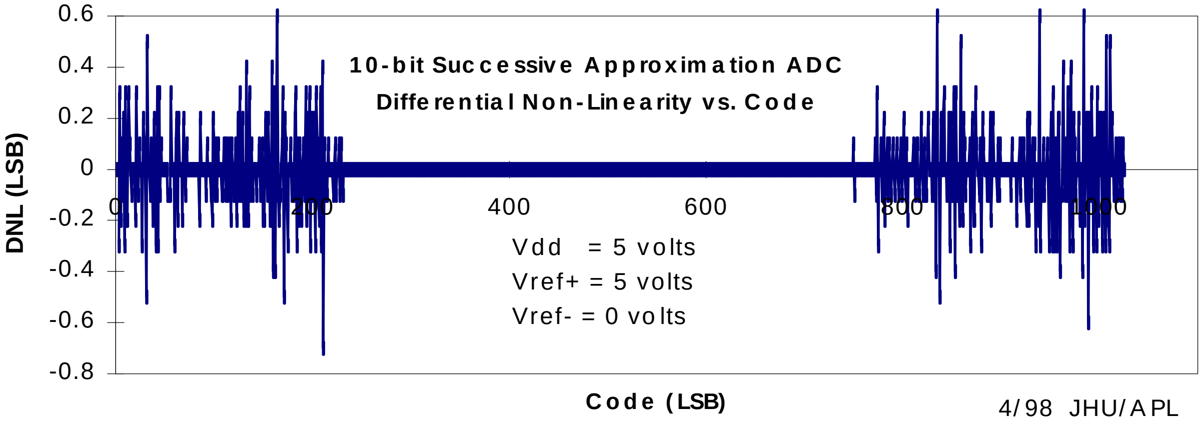

Figure 4: Preliminary measurements of the ADC DNL for one TRIO chip

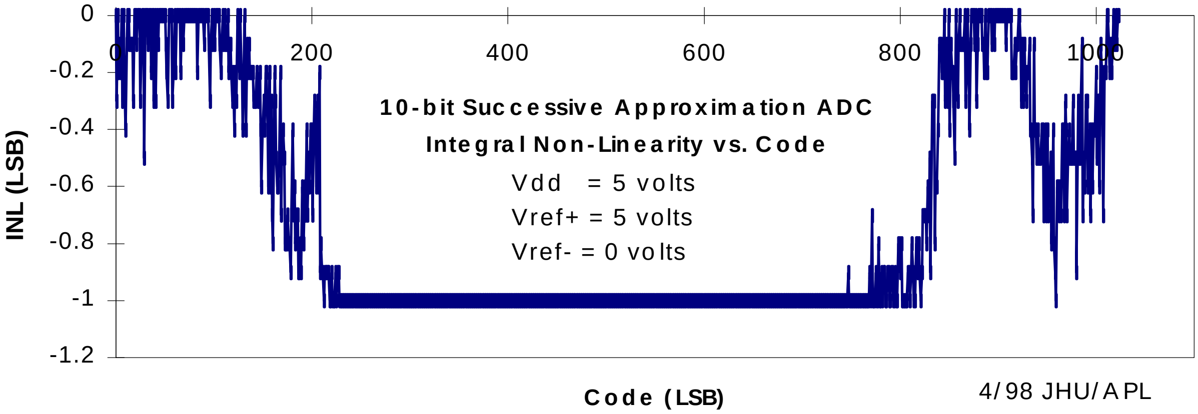

Figure 5: Preliminary measurements of the ADC INL for one TRIO chip

A first version of a smart sensor data acquisition and control device focusing on temperature measurements was successfully developed. The next complete version of the chip will interface to several types of sensors.

The TRIO device is baselined for JPL's X2000 generic spacecraft bus, being developed to support NASA's New Millenium missions. Of course, the RIO chip is part of all APL's new spacecraft designs. The TRIO device allows distributed data acquisition and serial transmission, thus eliminating complex and heavy harnessing and simplifying spacecraft design. The first candidate mission is Europa, to explore Jupiter's moon in a highly intensive radiation environment. In this mission, it is highly desirable to measure the total radiation dose of the ambient environment as well as the penetrating profiles in various depths of the spacecraft. Four more JPL missions are also candidates to use the TRIO chip. The broad acceptance of this device by NASA indicates that this single chip system will be a valuable enabling technology for next-generation small spacecraft.

Acknowledgments

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Authors Biography

Nick Paschalidis is a member of the Senior Professional Staff in JHU/APL's Space Department. He received his Diploma and PhD degree in Electrical Engineering from The Demokritus University of Thrace, Greece. He pursued his research project as a graduate student at JHU/APL, before joining the laboratory as a postdoctoral fellow. His area of expertise is advanced mixed signal microelectronics for spacecraft and instrument systems, as well space physics data analysis and modeling. He is lead investigator for advanced analog-digital ASICs for instrumentation on the NASA Cassini and IMAGE missions. He was a member of Space Department's Advanced Satellite Technology Committee and is a member of NASA/JPL's New Millennium Program Microelectonics IPDT, responsible for strategic roadmapping on advanced microelectronics. He is co-Investigator on a NASA PIDDP program for ultraminiature particle detector, and is Principal investigator for a NASA/JPL project to deliver several hundred Smart Sensor RIO devices for the X2000 program.