AN INTEGRATED CIRCUIT FLOATING POINT ACCUMULATOR

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Many scientific instruments flown on spacecraft perform the functions of counting the rates at which different events take place, temporarily storing the accumulated data, and then transmitting the data to the spacecraft telemetry system. In some cases, it is also important to compress the bits required for transmission to conserve telemetry space. Goddard Space Flight Center has developed a large-scale integrated circuit (Type 623) which can perform pulse counting, storage, floating point compression, and serial transmission, using a single monolithic device. Counts of 27 or 19 bits can be converted to transmitted values of 12 or 8 bits respectively. Use of the 623 has resulted in substantial savings in weight, volume, and dollar resources on at least 11 scientific instruments to be flown on 4 NASA spacecraft. The design, construction, operation, and application of the 623 are described.
All measurement values are expressed in the International System of Units (SI) in accordance with NASA Policy Directive 2220.4, paragraph 4.
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AN INTEGRATED CIRCUIT FLOATING POINT ACCUMULATOR

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INTRODUCTION

The Goddard Space Flight Center (GSFC) of the National Aeronautics and Space Administration (NASA) is responsible for the development and flight of a number of scientific instruments flown on spacecraft which involve event-counting in the measurement of charged particles, gamma rays, and other physical phenomena. In such an instrument, there are typically a number of logically different events which can occur. The instrument usually has a number of different detectors or detector elements from which pulses must be accumulated separately. It may be necessary, for example, to distinguish between particles arriving from different directions, or particles with differing energies. As a result, it may be desirable for a single instrument to separately and independently count as many as 64 different pulse signals simultaneously. In some cases, the exact count of events occurring in a known interval is the desired information to be telemetered. However, it is also frequently true that because of the random nature of the subject events, the exact count has little more statistical significance than a truncated or compressed value, which would have the advantage of requiring less telemetry transmission space. In such cases, a device known variously as a floating point accumulator or logarithmic compressor is used. This device converts the exact-count information into a truncated count value and an exponent in such a way that the maximum percentage error between the actual count and the telemetered value is kept fairly uniform regardless of count value.

Because of the relatively large number of floating point accumulators needed, the International Sun-Earth Explorer (ISEE) Project at NASA/GSFC commissioned development of a custom large-scale integrated (LSI) circuit to perform this function. Each LSI circuit would replace up to ten small- and medium-scale integrated circuits, resulting in substantial savings in cost, weight, and volume. The circuit was developed by GSFC and is known as the Type 623 Floating Point Processor (figure 1).

The 623 is designed to accumulate a pulse count of up to 27 bits \((1.3 \times 10^8\) pulses), convert it to a floating point value of 12, 10, or 9 bits (user option), and provide for serial data interface to a typical spacecraft telemetry system. A fourth mode allows conversion of 19 bits \((5 \times 10^5\) pulses) to 8 bits.
Figure 1. Type 623 floating point processor.
GENERAL DESCRIPTION

The Type 623C microcircuit is a monolithic, P-channel metal oxide semi-conductor (PMOS) device, packaged in a 22-lead flatpack. As shown in figure 2, the circuit consists of input pulse-gating logic, a 27-bit counter (and shift register), A, a 7-bit shift register, X, a 5-bit counter-shift register, Y, and assorted floating point conversion logic. Input pulses are accumulated in counter A. (The input-pulse-gating logic may be used to inhibit counting in applications where several 623 circuits are accumulating pulses from the same source, but during different time regimes. This is typically used to differentiate arrival direction when using a rotating or scanning detector.) At the end of the counting interval a “convert” pulse is applied to pin 15. At this time, further counting is inhibited and a floating-point conversion is performed in which the most significant bits of the number in A are shifted to the X register, and an exponent is placed in the Y register. The counter is then reset at the end of the “convert” pulse and a new counting interval may be begun. The floating point value is available in the X and Y registers to be shifted out serially to the telemetry system as required.

In an ideal case, the original count N would be expressed simply

\[ N = X \cdot 2^Y \]

But, because of the particular mechanics used to implement conversion in the 623, its re-conversion algorithm is considerably more complex. The 623 has the capability of converting counts to floating point values in four different formats as described in table 1. For example, a count not exceeding 27 bits may be converted to a 12-bit result in which 7 bits represent the truncated count X, and 5 bits the exponent Y.

<table>
<thead>
<tr>
<th>Maximum Count Size (bits)</th>
<th>27</th>
<th>27</th>
<th>27</th>
<th>19</th>
</tr>
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<tbody>
<tr>
<td>Bits in Result</td>
<td>12</td>
<td>10</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>Bits in Y</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Bits in X</td>
<td>7</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Mode Control Voltages:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M19</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>J</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>K</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

A serial data input pin is provided so that a number of 623 parts may be connected in series. A tri-state type output is also provided, so that strings of 623 parts may be multiplexed using a common connection at pin 22.
Figure 2. Type 623 floating point processor, block diagram.
GSFC PMOS PROCESS

GSFC has had a pilot production capability for P-channel MOS circuits since 1969, and has produced experimental and prototype circuits on a very low volume basis. GSFC has produced approximately 80 different types of circuits for satellite projects such as the Orbiting Solar Observatory, the High Energy Astrophysics Observatory, and the International Ultraviolet Explorer. The 623 alone is in use on 11 different experiments to be flown on International Sun-Earth Explorers (3 spacecraft) and on TIROS-N. The GSFC process is compatible with that used by several industry sources, and in fact, manufacturing (excluding electrical testing) of “flight” 623C parts has been done by American Microsystems Inc. (AMI).

The particular process used involves the application of ion-implantation to produce depletion resistors and “low-threshold” enhancement transistors on the surface of a “111-” oriented, N-type silicon wafer. Six levels of photo-masking are used to control P+ diffusion, gate-oxide regions, oxide-contact-hole regions, metal deposition, depletion-resistor implant, and protective-oxide removal, respectively. The photo-tools are prepared using a computer-aided microcircuit artwork system (CAMAS), which in turn controls an automated pattern generator. The smaller aluminum lines shown in figure 1 are 7.5-μm wide, while the chip itself is approximately 3-mm square. Chips are connected to the flat package using thermo-compression bonded, 25-μm gold wire.

A more detailed description of PMOS processes may be found in Reference 1. A short description of some related circuits designed at GSFC is included in Appendix A.

USER INTERFACE INFORMATION

The 623 devices are supplied in a 22-lead round flatpack (see figure 3) which is usually shipped in a plastic carrier to facilitate handling and testing.

As with all MOS devices, precautions should be taken to avoid the possibility of static electric damage in handling and installation. To reduce the possibility of damage, a static protection circuit (figure 4) is used on each input lead to protect the gate oxide. The voltage on any pin, measured relative to pin 1, must therefore be maintained between +0.5 V and -20 V to prevent damage to the device. The bottom of the case is electrically connected to pin 1.

The 623 is designed to draw a typical power supply current of 1.2 mA on pin 20 (-V1) and 15 μA on pin 21 (-V2). Because these currents are relatively insensitive to power supply voltage in the operating range of -6 to -12 volts for -V1, power for a 10-V supply is typically 12 mW.

The timing of the data interface between the 623 and the host instrument is shown in figure 5. The convert signal (pin 15) must be high for a minimum of 5 ms during which counting is inhibited. The clock signal must be low for a minimum of 10 μs before and after the
falling edge of the convert signal. The most significant bit of Y will appear at pin 22 within 10 μs after the falling edge of the convert pulse (if tri-state signals I1 and I2 are both positive). The serial output changes state (and the serial input is sampled) at the falling edge of the clock, which should not exceed 100 kHz (square wave). The pulse input signal should not exceed 1 MHz (square wave), should be normally low, and should have a minimum pulse width of 400 ns.
The threshold or switching point for input signals to the 623 will be between -1 V and -4 V measured relative to pin 1 (+V). As a result, care must be taken that input signals substantially attain the positive rail voltage while not exceeding it by more than 0.5 V. This requirement can cause difficulty, especially with regard to the high-speed pulse input signal.

An overflow-prevention option is available at pin 5. If this pin is connected to one of the input gate terminals, counting can be inhibited at approximately half of full-scale, preventing the possibility of ambiguous data. The pin 5 output does not have a pull-down resistor, so an external resistor of about 100 kilohms is required between pin 5 and pin 20 (-V1).

A two-transistor gate for use in implementing user logic is available at input pins 6 and 8 such that if either pin is low, the output pin 7 is clamped to +V with a resistance of about 2 kilohms.

Parts intended for space flight use are tested by computer-automated equipment and by a printed report generated for each serialized part. An outline of this test and other quality procedures may be found in Appendix B.

DATA CONVERSION ALGORITHMS

The following algorithms are used to recover the original binary count, C, from the telemetered values of X and Y. In the serial data, the value of Y is shifted out first, followed by X. The most significant bit of each is transmitted first.

The algorithms for the 19-bit mode are different from those of the 27-bit mode. In each case the telemetered Y value must be converted to an N value using the appropriate lookup table (tables 2 and 3).
### Table 2
Y to N Lookup Table for 19-Bit Mode

<table>
<thead>
<tr>
<th>Y</th>
<th>N</th>
<th>Y</th>
<th>N</th>
<th>Y</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>6</td>
<td>14</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>1</td>
<td>11</td>
<td>7</td>
<td>13</td>
<td>12</td>
<td>4</td>
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<tr>
<td>2</td>
<td>10</td>
<td>8</td>
<td>8</td>
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<tr>
<td>3</td>
<td>1</td>
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</tr>
<tr>
<td>4</td>
<td>12</td>
<td>10</td>
<td>2</td>
<td>15</td>
<td>5</td>
</tr>
</tbody>
</table>

### Table 3
Y to N Lookup Table for 27-Bit Modes

<table>
<thead>
<tr>
<th>Y</th>
<th>N</th>
<th>Y</th>
<th>N</th>
<th>Y</th>
<th>N</th>
<th>Y</th>
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<tbody>
<tr>
<td>0</td>
<td>13</td>
<td>8</td>
<td>21</td>
<td>16</td>
<td>XX</td>
<td>24</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>24</td>
<td>9</td>
<td>16</td>
<td>17</td>
<td>8</td>
<td>25</td>
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<tr>
<td>2</td>
<td>23</td>
<td>10</td>
<td>15</td>
<td>18</td>
<td>7</td>
<td>26</td>
<td>XX</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>11</td>
<td>22</td>
<td>19</td>
<td>XX</td>
<td>27</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>12</td>
<td>17</td>
<td>20</td>
<td>9</td>
<td>28</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>13</td>
<td>20</td>
<td>21</td>
<td>XX</td>
<td>29</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>11</td>
<td>14</td>
<td>19</td>
<td>22</td>
<td>27</td>
<td>30</td>
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</tr>
<tr>
<td>7</td>
<td>26</td>
<td>15</td>
<td>18</td>
<td>23</td>
<td>10</td>
<td>31</td>
<td>2</td>
</tr>
</tbody>
</table>

In the 19-bit mode, the algorithm is as follows

\[
\text{If } X = 15 \text{ and } Y = 6, C = 0 \\
\text{If } Y = 5, C = X + 1 \\
\text{Otherwise, } C = 1 + (X + 16) \cdot 2^N
\]  

(1)
In the 27- to 12-bit mode

\[
\text{If } Y = 22 \text{ and } X = 127, \quad C = 0 \\
\text{Otherwise, } C = 1 + (X + 128) \cdot 2^{(N-8)}
\]  (2)

In the 27-bit modes, certain values of \(Y\) should never occur. These are denoted in table 3 by "XX." Fractional parts of a result are discarded.

In computer processing of data produced in the 19-bit mode, it may be more advantageous to look up the result in a table rather than to calculate it using algorithm 1. This information is provided in Appendix C where \(X\) and \(Y\) are expressed as a single octal number and \(C\) is expressed as a decimal number.

The information given by the table or by the algorithms represents the lowest value of input count which would result in the given \(X\) and \(Y\) values. For example, the table entry (octal), 143, represents an \(X\) value of 3 and a \(Y\) value of 6 \((N = 14)\). Using either algorithm 1 or Appendix C, the minimum input count is 311297. However, any input count between 311297 and 327680 would result in a code of 143. The mean value of all such input counts is therefore 319489, and for this reason, the user may desire to substitute 16.5 for 16 in algorithm 1 and 128.5 for 128 in algorithm 2 to recover the mean value rather than the lowest value of count.

The maximum count that may be accumulated without overflow is 507904 in the 19-bit mode and 133693440 in the 27-bit mode. If the overflow prevention option is used, counting will be inhibited at approximately half scale (262145 for 19-bit mode, 67108865 for 27-bit mode).

CIRCUIT OPERATION ANALYSIS

Device Physics

The 623 is implemented using only the three circuit elements (active devices, depletion resistors, and capacitors) which can be produced using the monolithic PMOS process. Active devices are enhancement-type P-channel transistors with a nominal threshold voltage \((V_{th})\) of approximately -2 V. The current carrying capacity of the transistor (when turned on) is governed by the physical size of the device, which is denoted on the schematic drawings by a channel width-to-length ratio. (For example, a 20:1 device will have half the resistance exhibited by a 10:1 device under a given circumstance.) The resistors are depletion-type P-channel transistors which act as current sources to power the active portion of the circuitry. The current supplied by such a device is a function of physical size. For the GSFC process it is approximately 45 \(\mu\)A for a unity width-to-length ratio. (For example, a 1:10 depletion resistor will supply a current of about 4.5 \(\mu\)A.) MOS capacitors may be made in sizes up to about \(10^{-11}\) farads.
Cell Descriptions

The 623 employs over 1000 devices to implement 40 register flipflops, 2 monostable timing circuits, and a free running clock oscillator as shown in the interconnection diagram (figure 6). Figure 6 references various subcircuits or "cells." The most important cell is the shifting counter flipflop shown in figure 7 which consists of two latch flipflops interconnected by logic to form the master-slave flipflop configuration. In this case, the logic can be used to configure the flipflop to act as either a counter or a shift register stage. The circuit counts when the signal C is negative and the signals SC and SC are positive. For shifting, C is positive and the shift register clocks are applied to SC and SC. A high speed version, A, is used in the first 3 bits of the A register; the lower power C version is used elsewhere.

The switch cell S (figure 8) is used to switch between two different signal sources. Source IN is selected when C is positive; source B is selected when C is negative.

The "one-shot" multivibrator of figure 9 is used to generate a fixed length pulse following the positive going edge of an input signal. MOS capacitors and depletion resistors are used to provide the required time delay.

A free running oscillator (figure 10) provides clock waveforms during the conversion process. When I is negative, the clock is inhibited. The clock starts synchronously with the release of the I signal to avoid difficulties with partial clock pulses.

A clock driver (figure 11) provides the necessary two-phase clock signal for shifting the A, X, and Y registers. The "I" input (when negative) forces both phase outputs to be positive.

Assorted small gates and the tri-state output driver are shown in figure 12. Because of the threshold characteristics of the active pull-down device, a separate power supply connection (pin 21) is provided. Unless this supply is several volts more negative than pin 20, the serial output will not be a "rail-to-rail" signal but will stop short of the negative supply. If the reduced logic swing is acceptable, pin 20 and pin 21 can be connected to the same supply.

Figure 13 shows details of two large gate circuits. Note that the gate symbology on figure 6 is for negative true signals.

Sequence of Operations

The sequence of operations is shown in figure 14. At the leading edge of the convert pulse, counting of the A register is inhibited, the X register is reset to zeroes, and the Y register is reset to ones. The counter is allowed to settle until the end of the OS1 signal. A is then reoriented to shifting mode and the A and X registers are shifted to the right until stopped by the conversion control logic. During shifting, ones are introduced into the left end of the A register and the Y register is incremented for each shift. In the 27-bit modes, shifting is stopped when a one is shifted into flipflop X35. The next seven most significant bits of the count are then in the X register. If A were all ones, 8 shifts would have occurred, if A were all zeroes, 35 shifts would occur before shifting was halted. In the 19-bit mode, shifting
Figure 6 Interconnection diagram.
Figure 7. Shifting counter register

Figure 8. Switch cell SW23.
Figure 9. Multivibrator cell.

Figure 10. Clock oscillator, cell OSC2

Figure 11. Clock driver, cell CD12
Figure 12. Output driver and miscellaneous cells

Figure 13. Logic gates
is stopped when X35 contains a one, or when the least significant 4 bits of the count are in
the most significant 4-bit positions of the X register (22 shifts). To eliminate ambiguity
between these two cases, the Y register is incremented an additional time, if X35 is a zero
after 22 shifts. Following the falling edge of the convert pulse, the A register is reset to ones
and counting is reenabled. The X and Y register are configured for shifting with lengths
controlled by the mode control signals and with clock inputs connected to pin 17. Data can
be shifted out at any time prior to the next convert signal.

**Radiation Resistance**

Ionizing radiation (such as that encountered in a planetary trapped-radiation belt) has a
damaging effect on semiconductor devices. For PMOS, the primary effect is the introduction
of positive charge sites in the gate oxide which tends to reduce the current in the depletion
resistors, eventually to zero. Since the speed of the circuit is dependent on current, radia-
tion failure occurs when the device speed is reduced below that required for a particular
application. Radiation tests have been performed on the 623 by the National Oceanic and
Atmospheric Administration (NOAA) in connection with a TIROS-N instrument*, where
the failure criterion was the inability to count 1 MHz pulses. Twelve 623 flight parts were
irradiated with Cobalt-60 and failed at exposures of between 9400 and 23500 (average
16000) rads (silicon).

Typically, the 623 will operate properly on initial testing for pulses between 2 and 3 MHz.
If the devices had been screened to eliminate those with an initial counting speed of less than
2.5 MHz (half of the samples), the first failure would have been at 13500 rads, and the average
failure dose would have been 18600 rads. Similar results would have been obtained if the
half of the 12 samples with lower power had been eliminated. (The samples ranged between
9.8 and 12.0 mW.)

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CONCLUSION

The 623 circuit performs pulse accumulation and count compression functions in a single monolithic unit. When used to replace conventional, MSI implemented, logarithmic compressors in space physics experiments, this circuit can result in substantial reductions in cost, weight, and volume. The design permits easy interfacing with contemporary spacecraft telemetry systems.
REFERENCE

Brief descriptions of some related PMOS circuits currently being developed at GSFC are presented below.

The 632 (figure A-1) is in the design phase and consists of four 19-bit floating point accumulators with serial output registers connected in series. This unit will involve 139 flipflops and approximately 3100 devices on a chip measuring 5.2 mm by 5.6 mm, mounted in a 28-lead flatpack. Power requirement is expected to be approximately 30 mW, and operation is similar to the 623.

The 633 (figure A-2) is in the production phase for use on Solar Maximum Mission (SMM) and International Sun-Earth Explorer (ISEE) spacecraft. It consists of two binary counters parallel-coupled to two shift registers and is used in cases where linear rather than floating point accumulation is desired. The counters and shift registers can be electrically programmed to any of 6 different lengths, up to 24 bits. This circuit has 101 flipflops on a chip 4.6 by 4.3 mm, mounted in a 28-lead flat package.
Figure A-1. GSFC type 632 quad 19- to 8-bit floating point processor.
Figure A-2. GSFC type 633 dual counter register.
APPENDIX B

ACCEPTANCE TEST PROCEDURE

The following is keyed to the corresponding section of the serialized test report.

1. Module Type 6231
   TIROS-N test at 10 V except as indicated below. International Sun-Earth Explorer test sequence 623 is identical except the nominal voltage level is 7.75 V and the functional tests are executed at 9.75, 7.75, and 5.75 V.

2. Bond Test
   Lead continuity is checked by applying +10 V through 100 kilohms and accepting only 0.5 to 0.9 V.

3. Breakdown Test
   Output and power supply pins are measured for less than 10 μA current when connected to -30 V.

4. Saturation Test
   Load resistors are connected to chip outputs, and the resulting output voltages and calculated resistances are listed. The acceptance levels are 4.5 kilohms max.

5. Threshold Test
   The serial input line is measured to determine minimum and maximum position of the one/zero threshold relative to +V.

6. Input Leakage Test
   All input pins are screened for 10⁻⁵ μA maximum leakage at -30 V.

7. Power Consumption
   Power at nominal voltage is measured.

8. Functional Tests
   Unit is tested at 12 V, 10 V, and 7.75 V.
   a. Unit is tested for shifting at 100 kilobits/second.
   b. The inhibit lines are tested.
   c. Proper conversion at 1-kHz-count input rate is verified for 0, 1, and 17 counts in the 12-bit mode, 0, 1, and 19 counts in the 8-bit mode, and zero counts in the 10-bit mode.
   d. The freeze inputs are tested.
   e. The aux gate is tested.
   f. High speed (2 MHz) counting and conversion are checked for 4, 7, 13, 33, 513, and 132097 counts in the 12-bit mode.
   g. The DCL overflow signal is checked (507904 counts).
Other quality procedures performed on flight units include:

a) Scanning electron microscope inspection of sample chips
b) 100-percent prebond optical inspection
c) 100-percent preseal visual
d) Temperature cycle 5 times - (65° to +150°C)
e) Centrifuge 20,000 G
f) Fine leak test \(5 \times 10^{-8} \text{ cc/s Helium}\)
g) Gross leak test
h) 100-percent final visual
i) Power on burn-in for 100 hours at 125°C
# APPENDIX C

## 623 OCTAL CODE TO COUNTS CONVERSION TABLE

### 19-BIT MODE

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<th>Octal</th>
<th>Counts</th>
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</tbody>
</table>

*Example: 1234 in octal corresponds to 28 in counts.*

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*NASA-Langley, 1977*
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