Introduction:
My work this semester has involved testing the analog-to-digital converters on the existing Ko Brain board, used on the Ranger robot, and testing the MAX1402, an analog-to-digital converter that has the potential to be used on future robots.

It is important to be able to gather reliable data from the robot for both feedback-based control of the robot during operation, and to investigate the state of the robot if anything goes wrong. If the robot falls, or behaves in a way that is seemingly anomalous, having accurate data from important sensors can facilitate debugging, whether it is a mechanical, electrical, or software issue.

Data analysis on the Ranger robot was being hindered by high noise levels on digital data which had been processed through analog to digital converters. The data originated from analog sensors, specifically output torque sensors on the ankles. The output data showed noise levels of around 40%, which required it to be extensively filtered in Matlab before it could be analyzed. Thus, no “real time” data analysis would be possible with such noisy data.

After testing the analog-to-digital converters (ADCs) on the Ko Brain board and the Ranger robot (Freescale Semiconductor 56F8347 and Analog Devices AD7490), it was determined that using an ADC chip with more than 12 bits of accuracy and features such as adjustable gain, multiplexed inputs, and low power would be best suited to gathering high quality data from a robot’s sensors.

Since acquiring data from these sensors requires relatively low sampling rates, in the kilosamples per second range, the sigma-delta converter architecture was considered as an alternative to more traditional converter architectures. This type of ADC has the benefits of low cost, high resolution, and low power, at the expense of limited bandwidth. Basically, a sigma-delta converter operates by oversampling the data (sampling at a much higher rate than the desired output rate), shaping the quantization noise so that most of the noise lies outside of the frequency range of interest, using a digital filter to remove the noise at high frequencies outside of the frequency band of interest, and using a decimator to reduce the data rate from the original sampling rate to the desired output data rate.

A search of the primary analog device manufacturers’ websites yielded four potential sigma-delta converters with the desired feature set. These included the Maxim MAX1402/3, the Texas Instruments ADS1174/8, the Texas Instruments ADS1112, and the Analog Devices AD73360L. Based on their available output data rates, adjustable input gain, number of available inputs, and power consumption, the Maxim MAX1402 was selected as the best option.

The Maxim MAX1402 offers 18 bits of resolution, with 16 bits of accuracy for data rates up to 480 samples per second (sps). It can scan between three fully differential or 5 pseudo-differential input channels, which would allow one ADC to gather data from multiple sensors. The input gain and offset are programmable to spread the input signal over the full input range. It also has input buffering to isolate the inputs from the capacitive loading of the gain and modulator circuitry. The chip utilizes a +5V analog supply, a +3V or +5V digital supply, and is SPI compatible. The converter's output data rate is programmable from 50 sps to 4800 sps.

Purpose:
The primary goal of this testing was to determine and attempt to eliminate the sources of noise on the Ranger, and select and verify a new ADC to use on future robots.

The purpose of the first set of testing, on the Ranger and a separate Ko Brain board, was to determine the source of noise on the output of the ADCs. This was accomplished by testing ADCs on the Ranger Robot as well as on the Ko Brain board under a variety of conditions. Using the Ko Brain board, tests were performed on an ADC internal to the board's microcontroller, the Freescale Semiconductor 56F8347, as well as one on an IC package external to the microcontroller, but still on the board, the Analog Devices AD7490. Using the satellite board on the Ranger, tests were performed on an ADC internal to the board's microcontroller, the Freescale Semiconductor 56F803.

The purpose of the testing on the Maxim MAX1402 was to determine the "real-world" noise levels present in the MAX1402 analog-to-digital converter as well as the chip's measured power consumption. The tests included several variables, including output data rate, input voltage gain, digital filtering, pseudo-differential or fully-differential inputs, input buffering, and clock frequency.

Conclusions:
Several valuable conclusions can be drawn from the Range and Ko Brain testing. Concerning practical data gathering, using unshielded, parallel analog input wires in the form of a ribbon cable caused more than 1% noise on the output. A solution to this is to use a shielded cable, such as a coaxial cable, for all data collection. A coaxial input cable was installed on the robot for this purpose and helped to eliminate some of the noise.

Electromagnetic interference is an important factor in ADC circuits. From the Ko Brain testing, it was determined that nearby circuits, such as the switching power supply circuit, could create electromagnetic interference which would be coupled onto the ADC circuit, creating noise on the output. Circuits must be designed and laid out to minimize interference, especially from power supplies and high current circuits such as the motor controllers.

The comparison testing between the internal and external ADCs on the Ko Brain board showed that in most cases, the external converter had lower noise levels than the internal converter. With an input resistance, the external ADC showed noise levels about 20 times less than the internal ADC. Thus, to gain more precision, an external converter is a better choice. Additionally, external IC packages are readily available with up to 18 bits of resolution, whereas most microcontrollers' internal ADCs only have 12 bits of resolution.

The tests using the load cell for an input show that the inherent noise in the MAX1402 at low output data rates is minimal. Changing the input voltage gain and buffering at higher data output rates only caused a slight increase in the noise levels; however, this is inconclusive due to the fact that there was no input "signal" in this case. At lower data rates, the input buffering and especially the higher voltage gain substantially increased the noise levels. This could be due to the fact that the circuitry for the input buffering and voltage gain adds some noise into the system.

The function generator tests show that the MAX1402 effectively filters out high frequency noise at all frequencies that are at least twice the data output rate, other than the sampling frequency and its harmonics. Increasing the input voltage gain had little effect on the output noise levels. For the 60 sps and 600 sps low noise configurations, the noise levels were only slightly higher for the 16x and 128x gain than those of the 1x gain. For the 600 sps low power configuration, the noise levels for the 16x and 128x gain were lower than those of the 1x gain.

The power consumption tests give an idea of the MAX1402 total power consumption and its relationship to different configuration variables. The total power usage of the chip ranges from 2.85 to 12.2 mW depending on configuration. The output data rate, digital filtering, and clock frequency all had an effect on the power consumption. As data rate increased, so did power consumption. Turning on more digital filtering, the so-called low noise mode, consumed more power than turning it off in low power mode. Figure 4 shows that the low power mode for both 600 and 1200 sps output data rates had comparable noise and power levels. The low noise mode for 600 sps, however, consumed much less power than low noise mode at 1200 sps, though they had comparable noise levels. This plot shows that the 60 sps and the low noise 600 sps configurations best optimize power and noise. The comparison between clock frequency and power consumption in Figure 5 shows that operation at the 4.9152 MHz clock frequency consumes slightly less power for the same data output configuration than the 2.4576 MHz clock frequency.

Execution of the testing has also revealed that configuring the MAX1402 is very straightforward. The function of all of the registers is clearly explained in the data sheet and they can be easily configured to change the mode of the device as desired.

Discussion:

For analog to digital converter circuit design in the future, a high resolution, external ADC package is preferred. Board layout must be optimized to shield the ADC circuit from EMI, especially that coming from elsewhere on the board. Additionally, care must be taken to prevent ground loops which would create a voltage differential between the ground levels at different points on the board. Thus, separate and well-designed analog and digital grounds are essential. Another consideration is that the voltage range of the analog input signal must match the voltage range of the ADC. A converter with programmable voltage gain may prove useful to maximize the number of levels utilized for a given analog input.

Overall, the MAX1402 analog to digital converter is an excellent option for acquiring data from various analog sensors on a robot. Since noise levels and power consumption increase substantially with increasing data rate, it is important to sample the data at as low a rate as possible, based on how quickly the analog input signal is changing. Most high frequency noise above 2x of the output data rate will be filtered by the chip, except for at frequencies corresponding to the sampling rate. Shielding the input wires or using a simple low-pass filter could remedy this issue if there is noise present at the sampling frequency. Care must be taken to eliminate noise frequencies less than 2x of the output data rate, because these will appear on the output as a signal.

To determine the efficacy of using the MAX1402 to acquire real data from the types of sensors that will be on a future robot, it might be helpful to connect accelerometers, gyroscopes, torque sensors, and other devices to the MAX1402 Evaluation Kit set-up. Tests to find the noise levels and power consumption for different configurations of the MAX1402 would help to determine the optimal ADC set-up for use on a future robot.

Data:

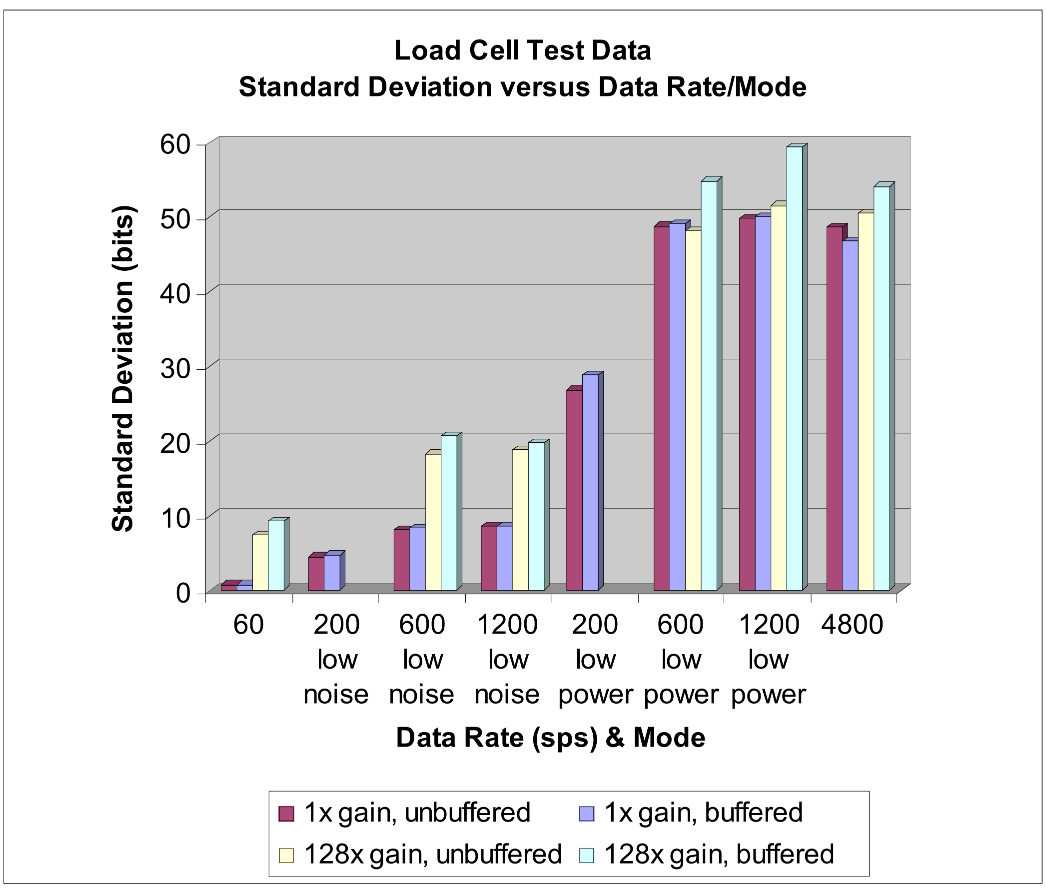

Figure 1.

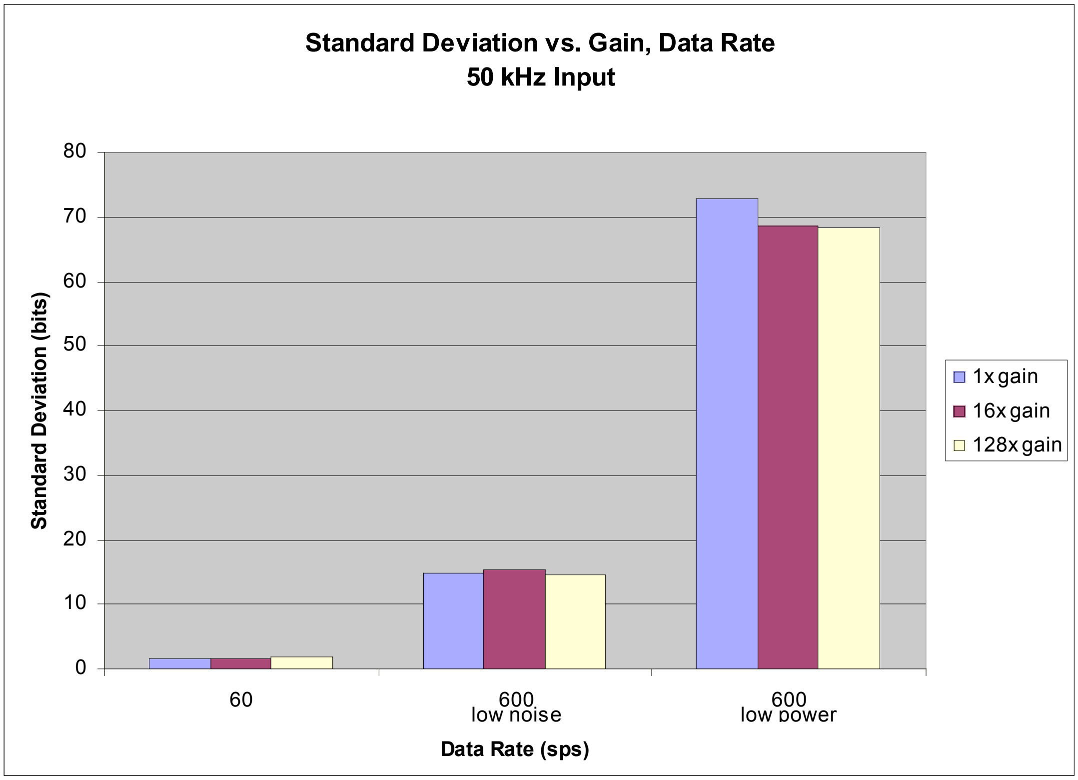

Figure 2.

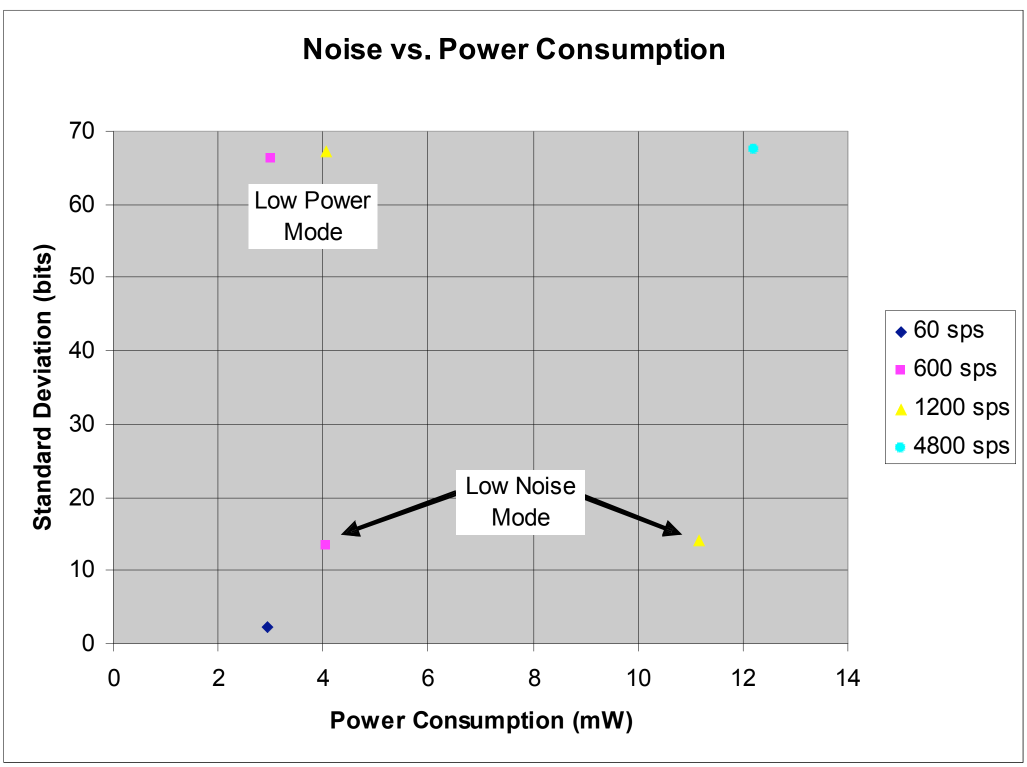

Figure 3.

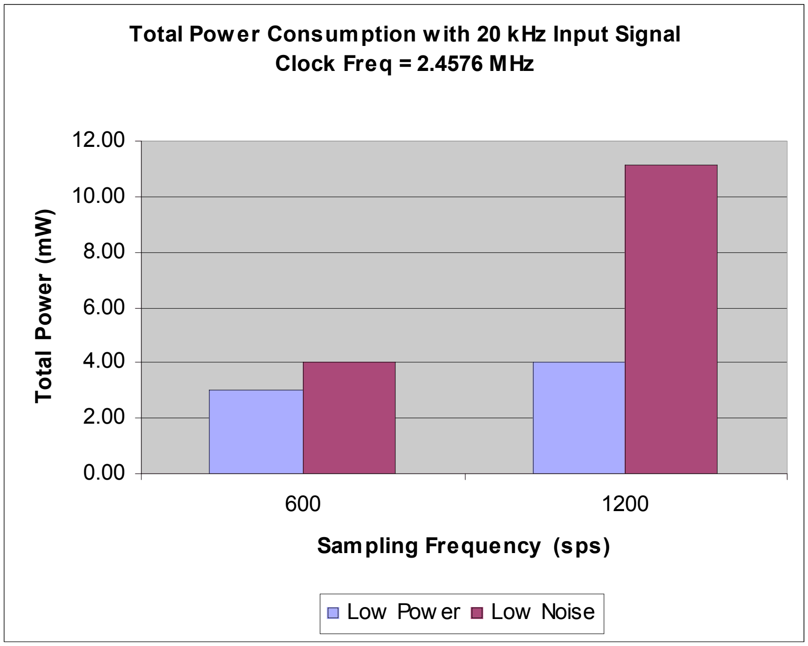

Figure 4.

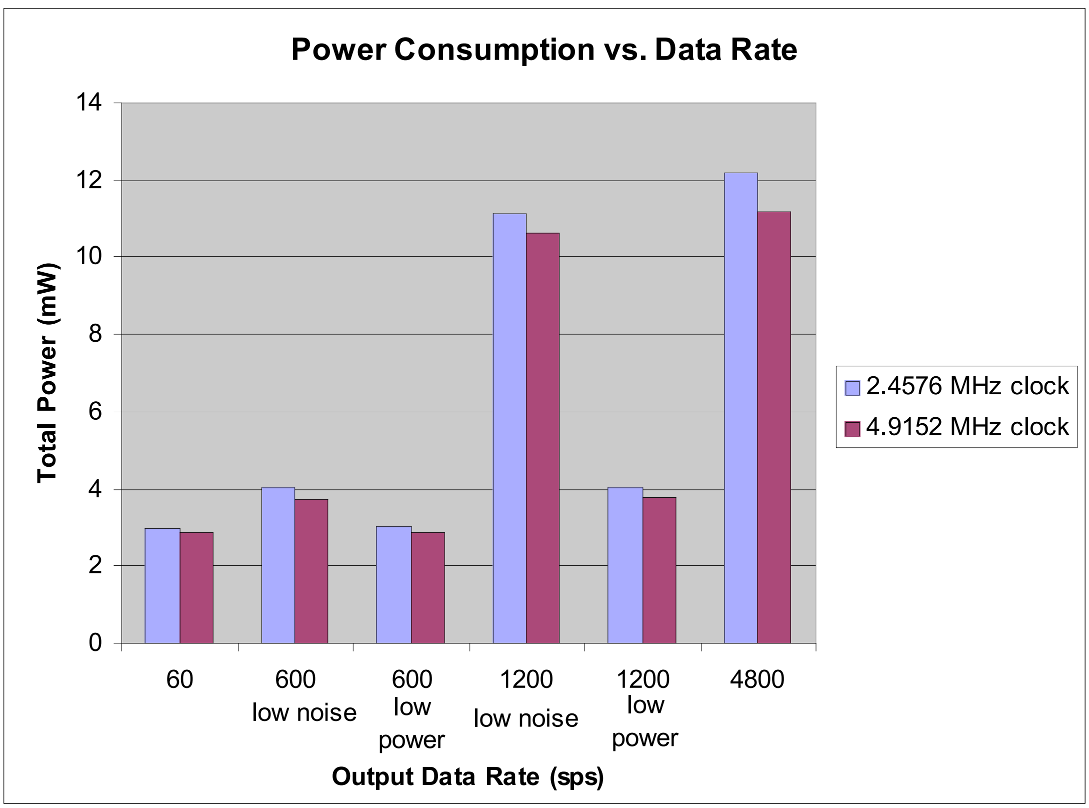

Figure 5.

Ko Brain ADC Testing

Testing with Grounded and Constant Voltage Inputs, Input Resistance & Capacitance
2/29/2008

Input Source	*Noise Level*	*Internal*	*External*	*Difference (Int - Ext)*
Ground	*Amplitude*	32	50	
	Counts	4	3.125	0.875
	Percentage	0.10%	0.08%	0.02%
1.5 V battery	*Amplitude*	40	65	
	Counts	5	4.0625	0.9375
	Percentage	0.12%	0.10%	0.02%
1.5 V, 10 kΩ	*Amplitude*	300	32	
	Counts	37.5	2	35.5
	Percentage	0.92%	0.05%	0.87%
1.5 V, 10 kΩ, 22 nF	*Amplitude*	N/A	47	
	Counts	N/A	2.9375	
	Percentage	N/A	0.07%	
1.5 V, 22 nF	*Amplitude*	N/A	53	
	Counts	N/A	3.3125	
	Percentage	N/A	0.08%	
1.5 V, 100 kΩ	*Amplitude*	475	32	
	Counts	59.375	2	57.375
	Percentage	1.45%	0.05%	1.40%

Input Source	*Signal Level*	*Internal*	*External*
1.5 V battery	*Min. Amplitude*		-12,416
	Max. Amplitude		-12,368
	Min. Counts		-776
	Max. Counts		-773
1.5 V, 10 kΩ	*Min. Amplitude*		-12,416
	Max. Amplitude		-12,384
	Min. Counts		-776
	Max. Counts		-774
1.5 V, 10 kΩ, 22 nF	*Min. Amplitude*		-12,417
	Max. Amplitude		-12,368
	Min. Counts		-776
	Max. Counts		-773
1.5 V, 22 nF	*Min. Amplitude*		-12,432
	Max. Amplitude		-12,385
	Min. Counts		-777
	Max. Counts		-774
1.5 V, 100 kΩ	*Min. Amplitude*	15,375	-12,432
	Max. Amplitude	15,850	-12,400
	Min. Counts	1,922	-777
	Max. Counts	1,981	-775

Note: Counts of external = amplitude / 16; Counts of internal = amplitude / 8

Ranger ADC Testing

Testing with Grounded and Constant Voltage Inputs at Different Sources
2/25/2008

Input Source	***Noise Level***	***External***
Ground	*Amplitude*	8
(at board)	*Counts*	1
	Percentage	0.02%
Ground	*Amplitude*	80
(buffer input)	*Counts*	10
	Percentage	0.24%
1.5 V battery	*Amplitude*	400
(~2m ribbon cable)	*Counts*	50
	Percentage	1.22%

Load Cell Test Data		**4/18/2008**	
Unbuffered, 1x gain		Buffered, 1x gain	
Data Rate (sps)	**Std Dev (bits)**	**Data Rate (sps)**	**Std Dev (bits)**
60	0.68885	60	0.73247
200 low noise	4.42940	200 low noise	4.71687
600 low noise	8.10397	600 low noise	8.30974
1200 low noise	8.48667	1200 low noise	8.60406
200 low power	26.82460	200 low power	28.89060
600 low power	48.80230	600 low power	49.18580
1200 low power	49.80060	1200 low power	50.12610
4800	48.62370	4800	46.87230
Unbuffered, 16x gain		Buffered, 16x gain	
Data Rate (sps)	**Std Dev (bits)**	**Data Rate (sps)**	**Std Dev (bits)**
60	1.30016	60	1.31796
600 low noise	8.96012	600 low noise	8.38106
1200 low noise	8.45769	1200 low noise	8.05575
600 low power	48.21050	600 low power	48.13940
1200 low power	50.66640	1200 low power	48.03570
4800	51.86920	4800	49.35360
Unbuffered, 128x gain		Buffered, 128x gain	
Data Rate (sps)	**Std Dev (bits)**	**Data Rate (sps)**	**Std Dev (bits)**
60	7.39412	60	9.21599
600 low noise	18.18370	600 low noise	20.61750
1200 low noise	18.73880	1200 low noise	19.72790
600 low power	48.15740	600 low power	54.84550
1200 low power	51.59180	1200 low power	59.32190
4800	50.50860	4800	54.11740

Function Generator Test Data				
04/27/2008, 04/28/2008, 05/08/2008				
Input Freq (Hz)	Data Rate (sps)	Mode	Gain	Std Dev (bits)
0 (DC)	60		1	2.1656
0 (DC)	60		128	2.1360
0 (DC)	600	low noise	1	13.4587
0 (DC)	600	low noise	128	13.7798
0 (DC)	600	low power	1	66.3367
0 (DC)	600	low power	128	63.1516
0 (DC)	1200	low noise	1	14.1654
0 (DC)	1200	low noise	128	13.2721
0 (DC)	1200	low power	1	67.2389
0 (DC)	1200	low power	128	71.9104
0 (DC)	4800		1	67.5594
0 (DC)	4800		128	66.4122
2.00E+03	60	low noise	1	1.7742
2.00E+03	600	low noise	1	15.0999
2.00E+03	1200	low noise	1	76.0251
4.00E+03	60		1	1.5654
4.00E+03	1200	low noise	1	13.3888
4.00E+03	2400	low noise	1	74.7930
4.00E+03	2400	low power	1	115.3320
8.00E+03	60		1	1.7284
8.00E+03	600	low noise	1	15.3934
8.00E+03	1200	low noise	1	15.2707
8.00E+03	4800		1	107.5470
5.00E+04	60		1	1.5548
5.00E+04	60		16	1.6283
5.00E+04	60		128	1.7279
5.00E+04	600	low noise	1	14.8411
5.00E+04	600	low noise	16	15.2876
5.00E+04	600	low noise	128	14.6958
5.00E+04	600	low power	1	72.7320
5.00E+04	600	low power	16	68.5494
5.00E+04	600	low power	128	68.4082
5.00E+04	1200	low noise	1	12.7666
5.00E+04	1200	low power	1	64.4905
5.00E+04	4800		1	71.2521
1.00E+05	60		1	2.0263
1.00E+05	600	low noise	1	15.1620
1.00E+05	600	low power	1	66.3712
1.00E+05	1200	low noise	1	14.5099
1.00E+05	1200	low power	1	65.7870
1.00E+05	4800		1	66.1363
2.50E+06	60		1	2.1957
2.50E+06	600	low noise	1	13.5365

2.50E+06	600	low power	1	71.7638
2.50E+06	1200	low noise	1	13.1928
2.50E+06	1200	low power	1	70.8079
2.50E+06	4800		1	66.9399

MAX1402 Power Consumption								
4/28/2008	**20 kHz input signal**							
					Total		**Analog**	
Clock Freq. (MHz)	**Data Rate (sps)**	**Mode**	**V Total R8 (mV)**	**V Analog R7 (mV)**	**Current (mA)**	**Power (mW)**	**Current (mA)**	**Power (mW)**
1.024	80	16 bit	8.90	4.20	0.89	4.45	0.42	2.10
1.024	400	low noise	9.00	4.20	0.90	4.50	0.42	2.10
1.024	400	low power	6.50	2.50	0.65	3.25	0.25	1.25
1.024	800	low noise	24.20	17.70	2.42	12.10	1.77	8.85
1.024	800	low power	9.10	4.20	0.91	4.55	0.42	2.10
1.024	1600	N/A	24.40	17.70	2.44	12.20	1.77	8.85
2.048	80	16 bit	8.00	4.10	0.80	4.00	0.41	2.05
2.048	400	low noise	8.00	4.10	0.80	4.00	0.41	2.05
2.048	400	low power	6.00	2.40	0.60	3.00	0.24	1.20
2.048	800	low noise	22.30	17.50	2.23	11.15	1.75	8.75
2.048	800	low power	8.10	4.10	0.81	4.05	0.41	2.05
2.048	1600	N/A	22.30	17.50	2.23	11.15	1.75	8.75
2.4576	60	16 bit opt power	5.90	2.40	0.59	2.95	0.24	1.20
2.4576	600	low noise	8.10	4.10	0.81	4.05	0.41	2.05
2.4576	600	low power	6.00	2.40	0.60	3.00	0.24	1.20
2.4576	1200	low noise	22.30	17.50	2.23	11.15	1.75	8.75
2.4576	1200	low power	8.10	4.10	0.81	4.05	0.41	2.05
2.4576	4800	N/A	24.40	17.70	2.44	12.20	1.77	8.85
4.9152	60	16 bit opt power	5.70	2.40	0.57	2.85	0.24	1.20
4.9152	600	low noise	7.50	4.00	0.75	3.75	0.40	2.00
4.9152	600	low power	5.70	2.40	0.57	2.85	0.24	1.20
4.9152	1200	low noise	21.30	17.40	2.13	10.65	1.74	8.70
4.9152	1200	low power	7.60	4.00	0.76	3.80	0.40	2.00
4.9152	4800	N/A	22.40	17.50	2.24	11.20	1.75	8.75
					Min	**2.85**	**Min**	**1.20**
					Max	**12.2**	**Max**	**8.85**