Dynamic range in a seismic channel

Michael L. Abrams[1*] and A. Keith Elder[2] provide a detailed analysis of the effective dynamic range of land seismic equipment along with some misconceptions.

There is much discussion in the land seismic business about the dynamic range of the acquisition equipment. Inevitably, this discussion leads to claims by various manufacturers of not just signal to noise ratio (SNR), but to 'how many bits' their instruments produce. We (the authors) thought the time was right to revisit the definition of dynamic range as it applies to seismic equipment, and evaluate how many useful bits our instruments actually produce.

Dynamic range, paraphrased from Wikipedia, is the ratio of the largest undistorted sine wave (RMS) to the RMS noise floor of the channel (http://en.wikipedia.org/wiki/Dynamic_range).

Also from Wikipedia, the theoretical dynamic range of a Q bit analogue to digital converter due to the quantization noise floor is 6.02*Q dB.

Note that the channel noise of any signal conditioning prior to quantization, as well as the quantization nose will combine to determine the actual dynamic range of the channel. Dynamic range is defined for our industry as 'the ratio of the maximum reading to the minimum reading which can be recorded by and read from an instrument without change of scale' (Sheriff, 2011).

Sometimes we also specify an instrument's total system dynamic range, which is the ratio of the maximum signal to the minimum noise level, considered across all the gains that the system can use.

In addition, one can claim that post processing of the digitized signal will improve the dynamic range from that which was recorded. Standard techniques such as stacking, filtering, etc. are known to provide such improvement. The key question to consider is how the additional noise improvement is limited (or not) by the characteristics of the recorded data.

In the following paper, we will investigate what can be reasonably claimed about the dynamic range of a seismic channel that uses the TI ADS1282 AD converter. This chip is used in systems from multiple equipment suppliers, so is a useful benchmark.

Sensor dynamic range

Though outside the investigation of this paper, it is well worth noting that the dynamic range of geophones have been seen to be 150 dB or better. And similarly, if we consider the dynamic range of the seismic signal environment, we have about 150 dB of range between the largest and smallest signals of interest. So, the desire to have a large channel dynamic range is not a useless quest. Ideally, this means an instantaneous dynamic range of 150 dB, not a total dynamic range of 150 dB for a seismic channel.

Ideal AD converter

As was noted above, the dynamic range of a Q bit converter when limited only by its own quantization noise is 6.02*Q dB. A 24 bit converter could be said to have 144.48 dB of dynamic range using this definition. A 32 bit converter would have 192.64 dB of dynamic range. Unfortunately, we are not limited by only the quantization noise of the AD converter.

Real AD converter SNR and ENOB

Another definition that is useful in our discussion is the effective number of bits (ENOB) of an AD converter. This is simply: (SNR (in dB) -1.76)/6.02 and tells us how many useful bits we actually have in the AD converter. ENOB is a handy tool for allowing us to roll all our noise sources for the seismic channel into one number and tell us how many bits we really have above the noise floor. Figure 1 is from the ADS1282 data sheet.

An inspection of Figure 1 reveals a few interesting facts:

- The largest SNR (and hence largest ENOB) occurs at the lowest gain and the slowest sample rate (smallest bandwidth).
- For any given gain, the SNR decreases by 3 dB as we double the bandwidth. This tells us that the internal converter noise source is flat across band, and we are simply getting less noise added in as we increase the decimation rate.
- For any given sample rate, we do not see a uniform decrease in SNR as we increase the gain. This tells us that there are two noise sources inside the converter, one associated with the preamplifier, and one associated with the circuitry that comprises the sigma-delta modulator.

The block diagram of the ADS1282 in Figure 2 shows this more clearly.

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There are two easily distinguishable noise sources: the mux/preamp input circuitry, and the 4th order sigma-delta modulator. And if we cared to add it in, we also have the theoretical quantization noise of the 32 bit output from the decimation filter. But it should be clear that is not a real factor, since the best SNR shown in Figure 1 above was 130 dB, 14 dB less than the theoretical 24 bit quantization noise.

It was communicated to us by TI that the noise of the ADS1282 has been characterized as follows.

- The mux/preamp noise is white, with a noise density of 5.5 nV/√Hz.
- The modulator noise is white, with a noise density of 60 nV/√Hz.

Using these numbers, we ran a MATLAB simulation of the ADS1282 at all gains and sample rates, and calculated SNR with 24 and 32 bit quantization. The results are in Tables 1 and 2.

Close examination of these two tables reveals virtually identical numbers at the corresponding gains and sample rates for each quantization level. The SNR values from this simulation are about 1dB better than the numbers in the data sheet (Figure 1 above). This is to be expected and would be the normal safety margin between internal and published numbers for a part of this nature.

It is worth emphasizing that there is no appreciable difference between the SNR of the ADS1282 noise simulation at 24 bit or 32 bit output. Just to look at this a little more, consider the Effective Number of Bits (ENOB) in both cases as seen in Tables 3 and 4..

The ENOB is exactly the same at each corresponding gain and sample rate for the 24 bit output and the 32 bit output from the ADS1282 noise simulation. And as we noted earlier, the best ENOB we see is 22 bits, two bits worse than the theoretical 24 bit quantization noise.

We can further put these numbers into perspective by looking at the dynamic range and ENOB versus preamp gain in Figure 3 below. The internal noise of the ADS1282 is in excess of the 24 bit output of the part, and significantly in excess of the 32 bit output at all gains.

Table 1. Signal-to-Noise Ratio (dB)(1)

DATA RATE (SPS)	PGA (High-Resolution Mode)							PGA (Low-Power Mode)						
	1	2	4	8	16	32	64	1	2	4	8	16	32	64
250	130	130	129	128	125	119	114	127	127	126	125	122	116	111
500	127	127	126	125	122	116	111	124	124	123	122	119	113	108
1000	124	124	123	122	119	113	108	121	121	120	119	116	110	105
2000	121	121	120	119	116	111	106	118	118	117	116	113	108	103
4000	118	118	117	116	113	108	103	115	115	114	113	110	105	100

(1) $V_{IN} = 20mV_{DC}/PGA$.

***Figure 1** From TI ADS1282 datasheet, revised May 2010.*

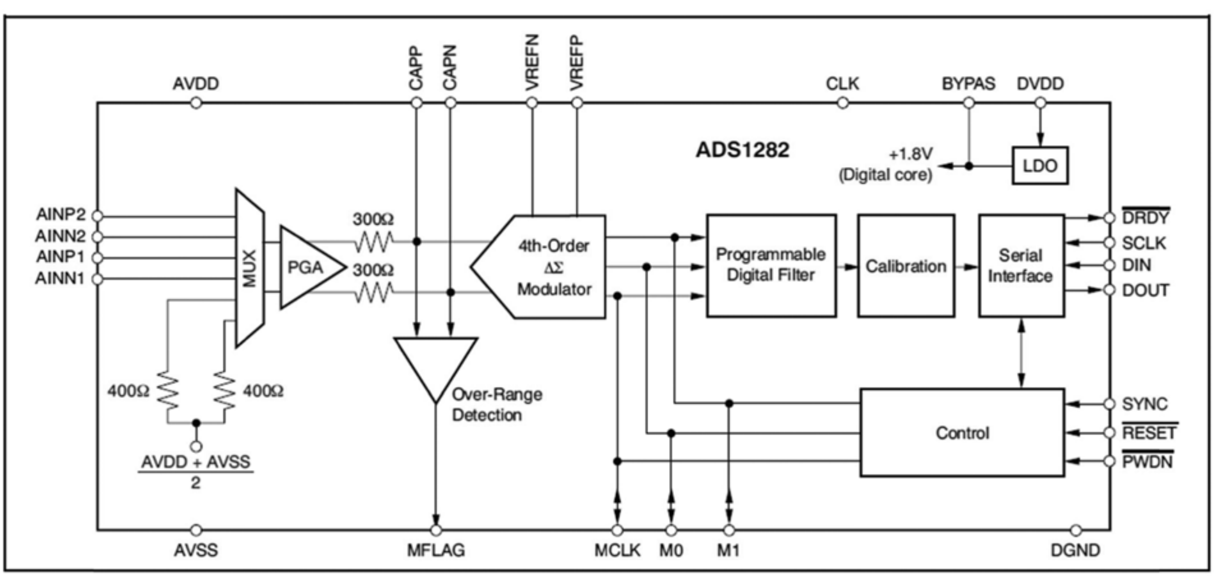

Figure 30. ADS1282 Block Diagram

***Figure 2** From TI ADS1282 datasheet, revised May 2010.*

SPS/PA	1	2	4	8	16	32	64
250	132	131	131	130	127	122	116
500	128	128	128	127	124	119	113
1000	125	125	125	124	120	116	110
2000	122	122	122	121	117	113	107
4000	119	119	119	118	114	110	104

***Table 1** 32 bit output SNR.*

SPS/PA	1	2	4	8	16	32	64
250	131	131	131	130	127	122	116
500	128	128	128	127	123	119	113
1000	125	125	125	124	120	116	110
2000	122	122	122	121	117	113	107
4000	119	119	119	117	114	110	104

***Table 2** 24 bit output SNR.*

SPS/PA	1	2	4	8	16	32	64
250	22	22	21	21	21	20	19
500	21	21	21	21	20	19	18
1000	21	21	20	20	20	19	18
2000	20	20	20	20	19	18	17
4000	20	20	19	19	19	18	17

***Table 3** 32 bit output ENOB.*

SPS/PA	1	2	4	8	16	32	64
250	22	22	21	21	21	20	19
500	21	21	21	21	20	19	18
1000	21	21	20	20	20	19	18
2000	20	20	20	20	19	18	17
4000	20	20	19	19	19	18	17

***Table 4** 24 bit output ENOB.*

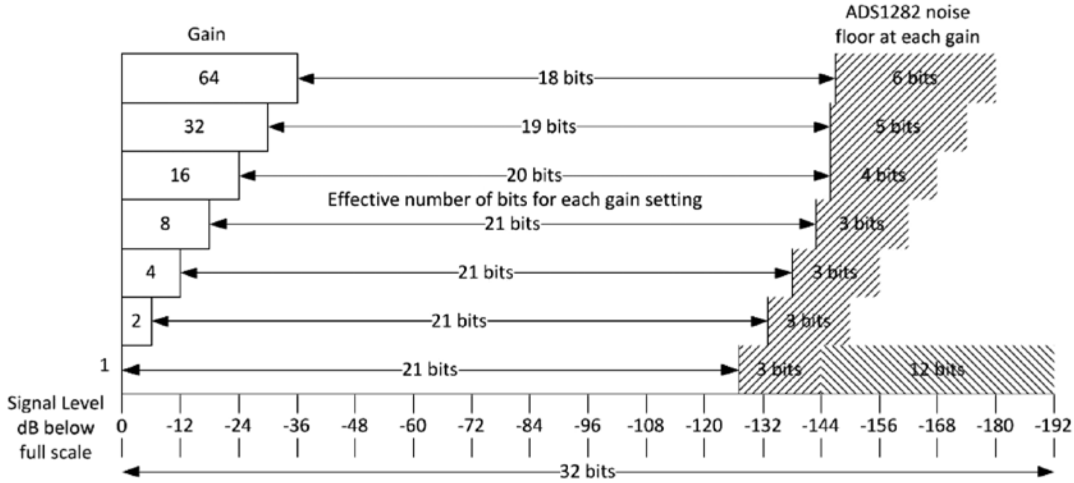

Figure 3

Small signal simulation

We used the simulation to look at the performance of the ADS1282 for very small signals. We input a 250 nV peak sine wave (about the size of the smallest seismic signals we normally see) to the simulator and calculated the SNR and ENOB for both 24 bit and 32 bit outputs. We also then stacked 16 records and calculated the SNR and ENOB on the resulting stacks. Note that the stacking was done in 32 bits, as it would be done in the field, with output at 24 bits at the end of the stack.

Note that for very small signals, increasing the gain of the AD converter does increase the ENOB. There is no improvement of ENOB beyond a gain of 32, and there is only a slight degradation in ENOB if the gain was limited to 16. For a view of the extremes, see the two following plots (Figure 4 and 5) comparing a gain of one and a gain of 64. Note the level of the wideband noise. At the higher gain, it is 20 dB lower, compared to the sine wave peak amplitude. At very low signal levels, the modulator noise is a larger factor than the mux/preamp noise.

The SNR and ENOB numbers are virtually identical at the corresponding gains and sample rates between Table 6 (24 bits) and Table 5 (32 bits) below.

For the sake of complete comparison, see below in Figure 6 and Figure 7 the same sine waves as plotted below in Figure 4 and 5, except with 24 bit output. There is no appreciable difference in the signal and noise characteristics from the 32 bit output.

There is no significant difference between the SNR and ENOB of 32 bit versus 24 bit output after the stacks. Note that the number of effective bits increases as we think it should: a stack of 16 gives us a 12 dB improvement in SNR, or two more bits.

For the sake of completeness, spectrums of the sine wave after stacking with 32 bit output are shown below in Figure 8 and 9. The spectrums of the sine wave after stacking with 24 bit output are shown in Figure 10 and Figure 11.

As expected, the white noise decreases and the coherent signal improves in the stack, and there is no appreciable difference in the signal and noise at corresponding gains between the 24 bit and 32 bit cases.

Testing of an actual seismic channel

A last test was done to confirm that the actual performance of a seismic channel using the TI ADS1282 closely matched up with the simulation results for the ADS1282. There is considerable experience with the chip and the performance of the channel, and they are known to correspond well. But, it was considered prudent in the context of the 24 versus

SNR	SPS/PA	1	2	4	8	16	32	64
	250	-9	-3	3	8	11	12	12
	500	-12	-6	0	5	7	9	9
	1000	-14	-9	-3	2	4	6	6
	2000	-18	-12	-6	-1	1	3	3
	4000	-20	-15	-9	-4	-2	0	0
ENOB	250	-2	-1	0	1	1	2	2
	500	-2	-1	0	0	1	1	1
	1000	-3	-2	-1	0	0	1	1
	2000	-3	-2	-1	-1	0	0	0
	4000	-4	-3	-2	-1	-1	0	0

Table 5 *32 bit output SNR and ENOB single sine.*

SNR	SPS/PA	1	2	4	8	16	32	64
	250	-9	-3	3	8	10	12	12
	500	-12	-6	0	5	7	9	9
	1000	-15	-9	-3	2	4	6	6
	2000	-18	-12	-6	-1	2	3	3
	4000	-21	-15	-9	-4	-2	0	0
ENOB	250	-2	-1	0	1	1	2	2
	500	-2	-1	0	0	1	1	1
	1000	-3	-2	-1	0	0	1	1
	2000	-3	-2	-1	-1	0	0	0
	4000	-4	-3	-2	-1	-1	0	0

Table 6 *24 bit output SNR and ENOB, single sine.*

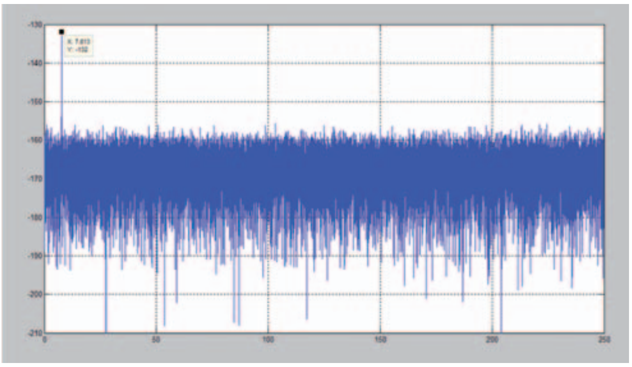

Figure 4 *Single sine, gain one, 250 Hz bandwidth, 32 bit output.*

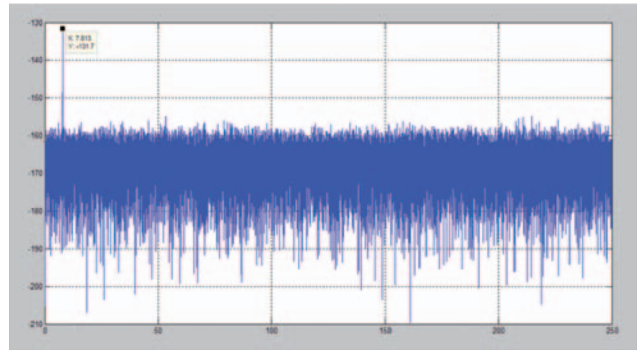

Figure 6 *Single sine, gain one, 250 Hz bandwidth, 24 bit output.*

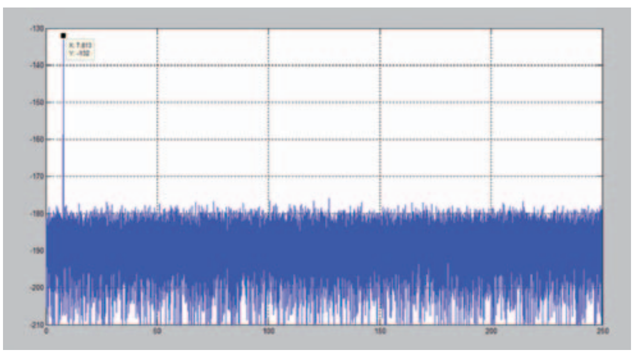

Figure 5 *Single sine, gain 64, 250 Hz bandwidth, 32 bit output.*

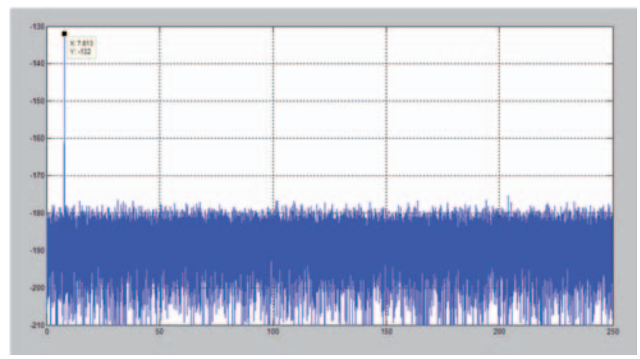

Figure 7 *Single sine, gain 64, 250 Hz bandwidth, 24 bit output.*

SNR	SPS/PA	1	2	4	8	16	32	64
	250	3	9	15	20	23	24	24
	500	1	6	12	17	20	21	21
	1000	-3	3	9	14	17	18	18
	2000	-6	0	6	11	14	15	15
	4000	-9	-3	3	8	11	12	12
ENOB	250	0	1	2	3	3	4	4
	500	0	1	2	2	3	3	3
	1000	-1	0	1	2	2	3	3
	2000	-1	0	1	1	2	2	2
	4000	-2	-1	0	1	1	2	2

Table 7 *32 bit output SNR and ENOB, stack 16.*

SNR	SPS/PA	1	2	4	8	16	32	64
	250	2	7	13	18	22	24	24
	500	-1	5	11	16	19	21	21
	1000	-3	3	8	13	16	18	18
	2000	-6	0	6	10	13	15	15
	4000	-9	-3	3	8	10	12	12
ENOB	250	0	1	2	3	3	4	4
	500	0	1	2	2	3	3	3
	1000	-1	0	1	2	2	3	3
	2000	-1	0	1	1	2	2	2
	4000	-2	-1	0	1	1	2	2

Table 8 *24 bit output SNR and ENOB, stack 16.*

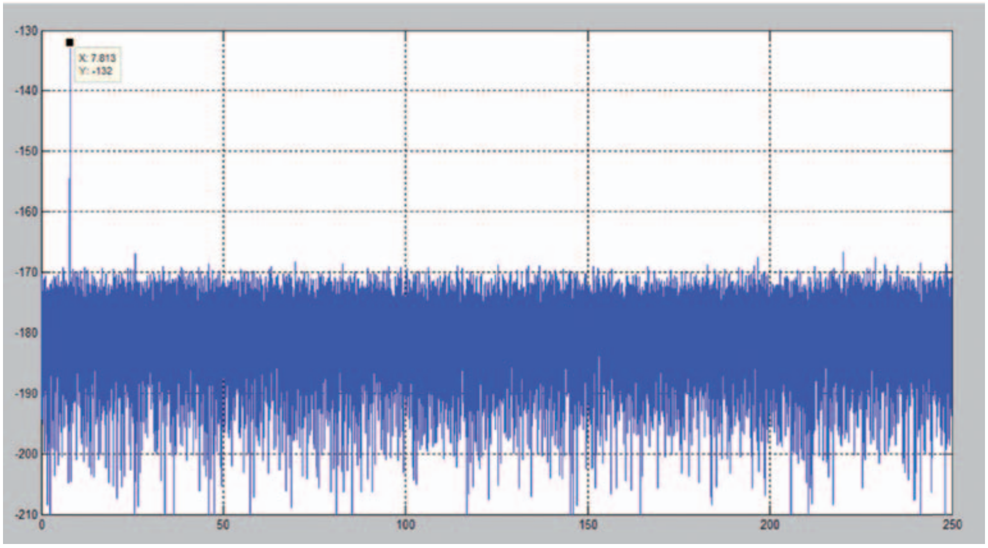

Figure 8 Stack 16, gain one, 250 Hz bandwidth, 32 bit output.

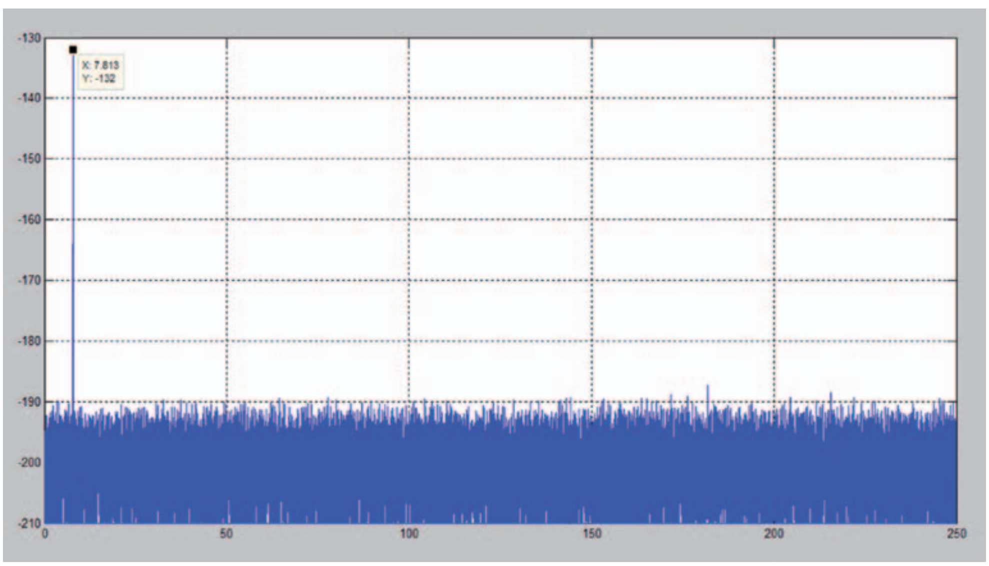

Figure 9 Stack 16, gain 64, 250 Hz bandwidth, 32 bit output.

32 bit discussion to show that the actual performance of the channel performs in the same fashion as simulations.

The data was taken using a test system and a seismic system analog board incorporating the ADS1282. The data was written out in a binary format from the tester as 32 bit AD counts, and then read by a MATLAB file and made into 24 bit and 32 bit equivalent voltages for analysis. EIN was evaluated for all preamp gains, and a sample rate of 500 samples per second. THD was computed for a gain of 1, and the same sample rate. A further test was done by splitting the THD test record into 16 singles and stacking them coherently on the sine wave.

As we did in the simulation above, we will look at the SNR and ENOB. Refer to Tables 9-12 below.

As it is easy to see, the numbers are identical for 24 or 32 bit output at the corresponding gains.

The THD, SNR and ENOB are identical for 24 bits and 32 bits on a single sine record.

Comparing the 24 bit and 32 bit data shows no difference in the corresponding singles or in the corresponding stacks. The improvement in the stack of 16 is the expected 2 bits in SNR and ENOB.

For the sake of completeness, we can calculate the total dynamic range using these test signals and show it in Table 13.

The total dynamic range (the ratio of maximum signal to the minimum noise) is exactly the same for the 24 bit and 32 bit output from the seismic channel. It is within the normal specification for a seismic channel.

In Figure 12 we can see the plots of the data for the single record and the stacks. They follow the same pattern as in the simulation data, and confirm graphically what we have seen below in the numbers in Tables 11 and 12.

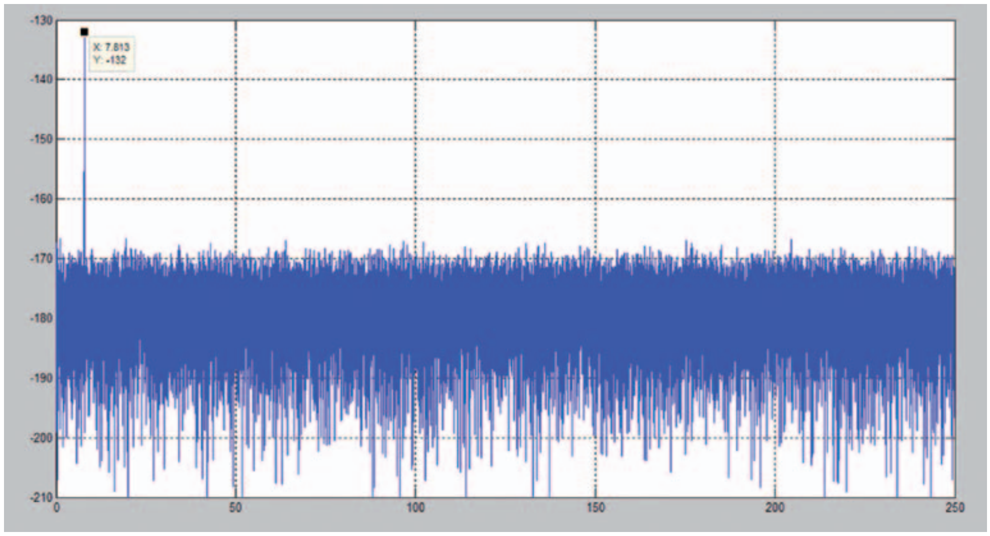

Figure 10 *Stack 16, gain one, 250 Hz bandwidth, 24 bit output.*

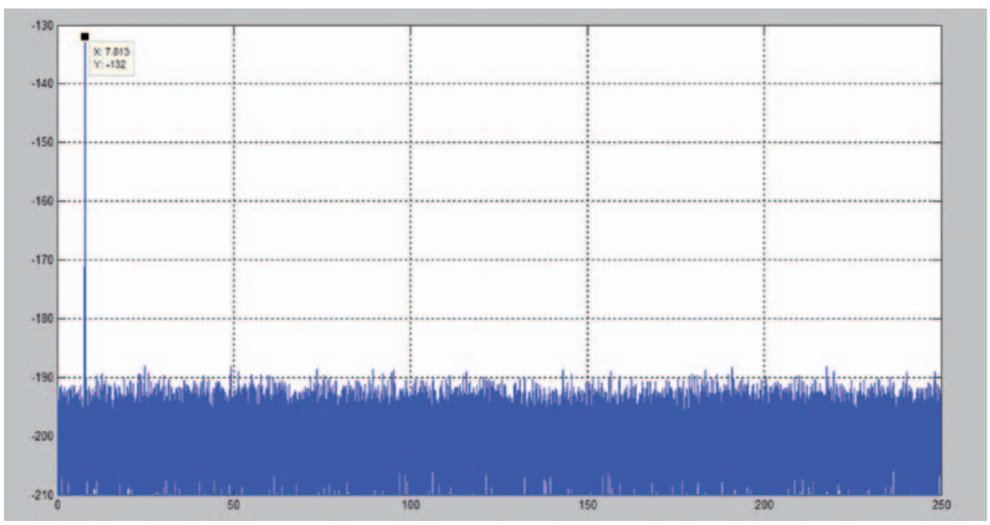

Figure 11 *Stack 16, gain 64, 250 Hz bandwidth, 24 bit output.*

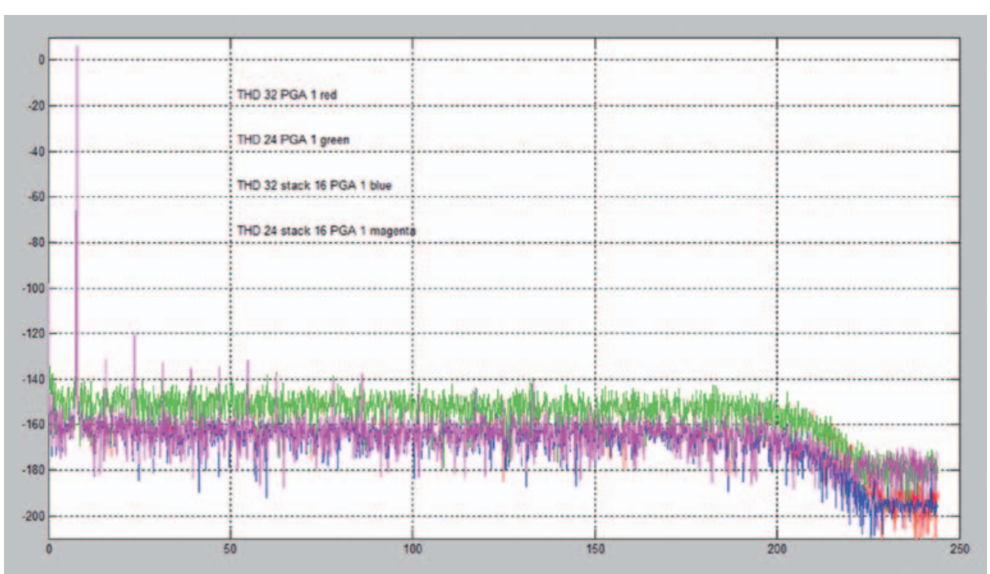

Figure 12 *Graphs of 24 bit versus 32 bit data.*

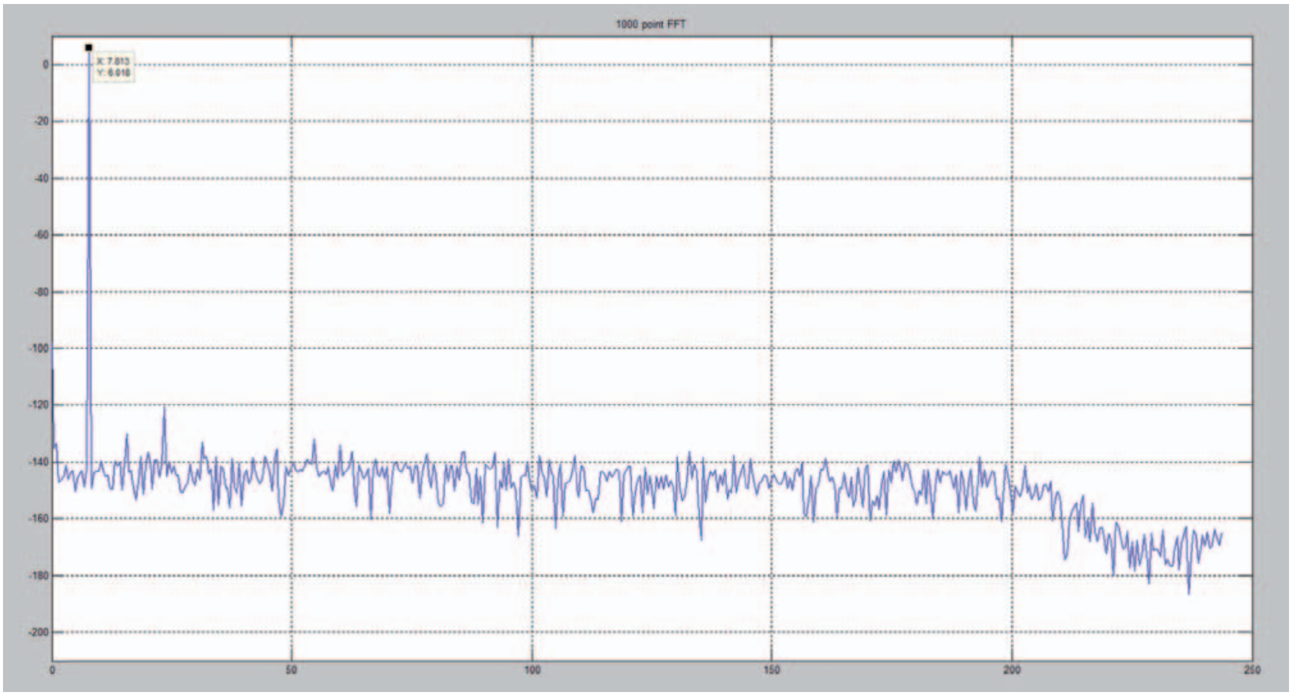

Figure 13

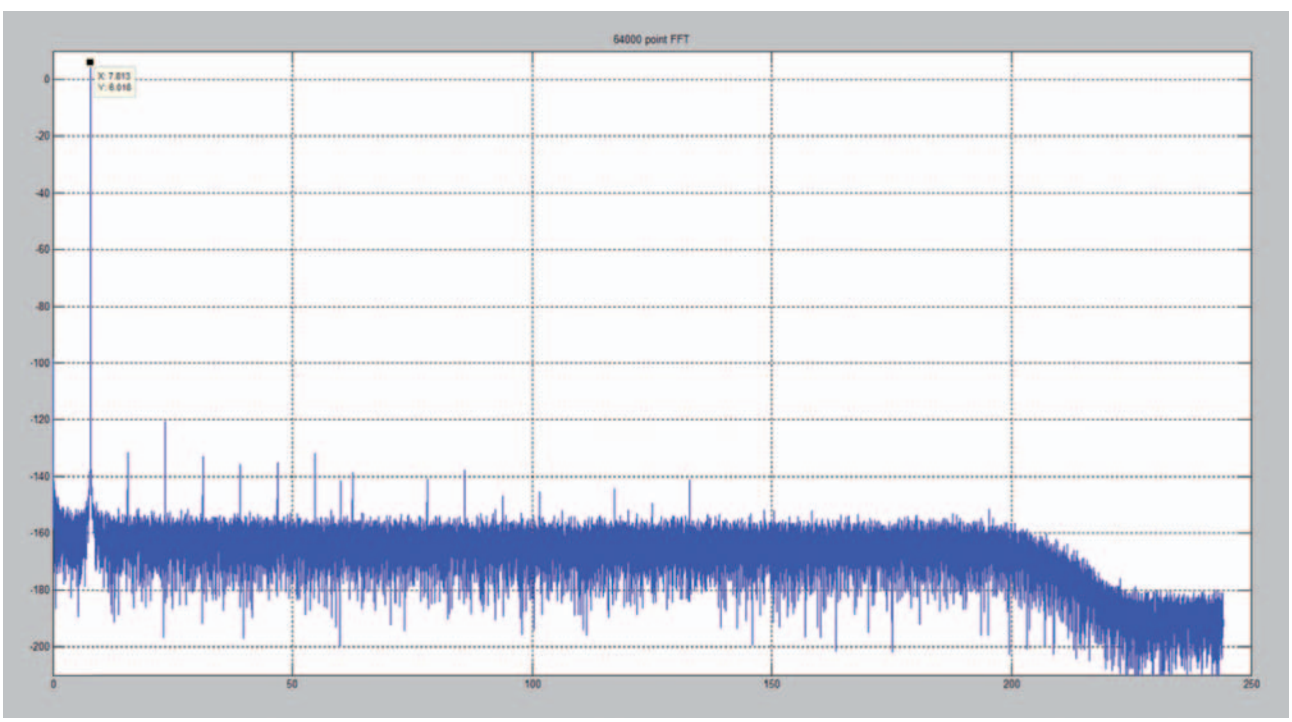

Figure 14

The only difference in the graphs is in the filter stop band where the additional resolution of the 32 bits is evident. As expected, we see a SNR improvement in the stack, and the graphs are the same except for small differences in the filter stop band.

Dynamic range fallacy

We wanted to examine one more issue that can be misleading in the discussion of dynamic range: the comparison of sine wave peak value to the amplitude of the noise floor. We will use the same data that was gathered for the actual channel

AD 32 bits		Gain 1	Gain 4	Gain 16	Gain 64
SNR	500 SPS	127	126	121	109
ENOB	500 SPS	21	21	20	18

***Table 9** 32 bit output SNR and ENOB.*

AD 24 bits		Gain 1	Gain 4	Gain 16	Gain 64
SNR	500 SPS	127	126	121	109
ENOB	500 SPS	21	21	20	18

***Table 10** 24 bit output SNR and ENOB.*

AD 24 bits		Gain 1	AD 32 bits		Gain 1
THD	500 SPS	-126	THD	500 SPS	-126
SNR	500 SPS	121	SNR	500 SPS	121
ENOB	500 SPS	20	ENOB	500 SPS	20

***Table 10** THD and SNR during THD.*

Single					
AD 24 bits		Gain 1	AD 32 bits		Gain 1
THD	500 SPS	-126	THD	500 SPS	-126
SNR	500 SPS	123	SNR	500 SP	123
ENOB	500 SPS	20	ENOB	500 SPS	20
Stack 16					
AD 24 bits		Gain 1	AD 32 bits		Gain 1
THD	500 SPS	-126	THD	500 SPS	-126
SNR	500 SPS	134	SNR	500 SPS	134
ENOB	500 SPS	22	ENOB	500 SPS	22

***Table 11** THD and SNR of a single compared to a stack of 16.*

	24 bits	32 bits
Total dynamic range	146	146
ENOB	24	24

***Table 12** Total dynamic range.*

analysis above, and look at spectrum plots from various length FFTs on the data.

In Figure 13, we see the spectrum from a 1K FFT. The SNR is 123 dB. The sine wave peak is 6 dB and is 146 dB above the noise floor. Does this mean that the dynamic range is 146 dB, or 24 bits? No, it does not, as that ratio is the ratio of an RMS signal to noise spectral density. Dynamic range is the ratio of an RMS signal to RMS noise.

We can take this to the extreme by looking at the 64K FFT spectrum in Figure 14. The SNR in this graph is exactly the same as in Figure 13, 123 dB. The sine peak is 166 dB above the noise floor, simply because we have many more bins into which the RMS noise is spread. Does this mean that we now have 166 dB of dynamic range, or 28 bits? No, it does not. We are still looking at an SNR of 123 dB.

Conclusions

In theory and in reality, a seismic channel using the best available technology today (TI ADS1282) will have the same performance with 24 bit data output from the part and 32 bit data output from the part.

What is important is that all signal processing of the ADS1282 data done inside seismic acquisition unit must be done at 32 bit precision (or better) before the data is formed into 24 bit words for data transmission. With respect to small signal performance of the ADS1282, there is probably no reason to run the part at a gain of more than 32.

In order for the seismic channel to improve further, we will need an AD converter that makes more usable bits. Given our seismic signal needs, a converter that provided 28 real bits would give us the instantaneous and total dynamic range we want without requiring a PGA in front of the converter.

Reference

Sheriff, R.E. (2011) *Encyclopedic Dictionary of Applied Geophysics*. SEG, Tulsa, 4th Edition, 111.