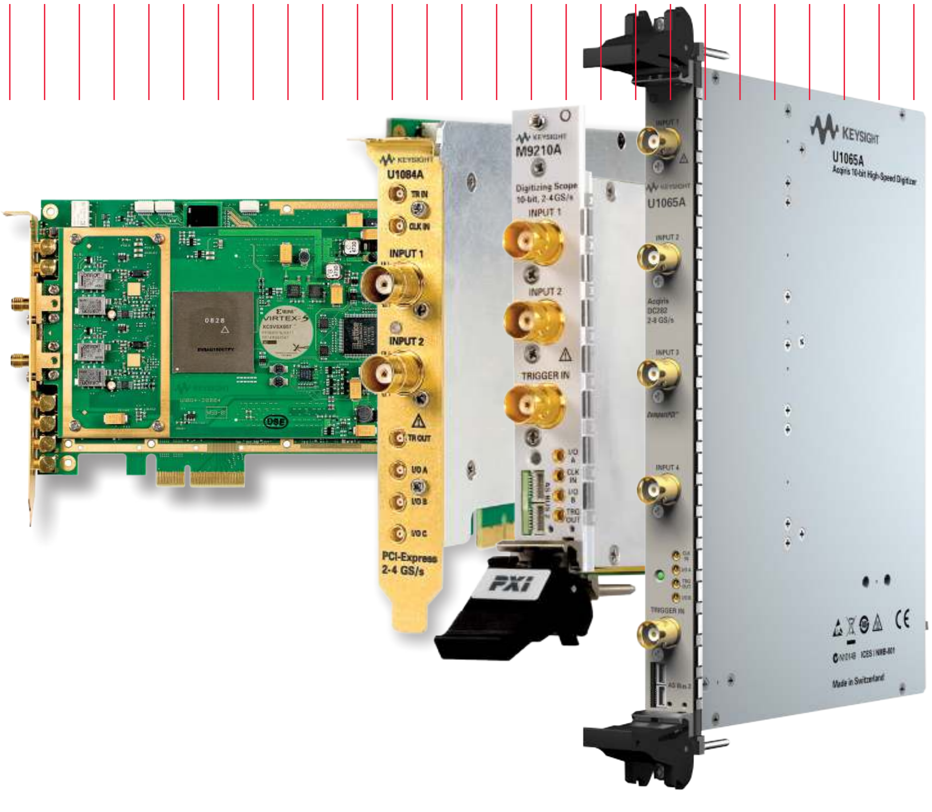
Keysight Technologies
Revealing Waveform Characteristics up to a Digitizer’s Full Bandwidth

Application Note



Introduction

Increasing the effective sampling rate when measuring repetitive signals

To acquire a signal accurately and without aliasing using a discrete sampling system such as a digitizer or oscilloscope, Nyquist showed that the sampling rate must be at least twice the rate of the highest frequency component in the measured signal. However, digitizer specifications often quote bandwidth not to this Nyquist frequency but instead to the system analog bandwidth. This value describes signal attenuation (to 3 dB) as a function of its frequency. This is often shown as a Bode plot.

When working with fast repetitive signals, in which the fastest signal components are more than half the frequency of the maximum sampling rate of the acquisition system, it may be possible to artificially increase the effective sampling rate of acquisition. This can accurately reveal waveform characteristics beyond the instantaneous Nyquist frequency, up to the full analog bandwidth of the digitizer.

Measuring higher-frequency waveforms

One way to enable a higher effective sampling rate is called random interleaved sampling or RIS (pronounced "riss"). This method creates a composite waveform by combining data from many lower-sampling-rate waveforms of the same signal, recorded out of phase with one another. RIS works only with stable repetitive waveforms that can be accurately acquired with a well-defined trigger position for each repeated acquisition. The oversampling factor will be an integer multiple of the real-time (single-shot) sampling rate.

To create an effective rate that exceeds the analog-to-digital converter (ADC) sampling rate, RIS needs a mechanism that accurately positions trigger events that fall between the sample clocks. This can be achieved with trigger time interpolation (TTI), which accurately positions trigger arrival to within a few picoseconds. This TTI resolution determines the maximum oversampling factor and the oversampling accuracy. Because TTI is implemented in most Keysight digitizers, RIS is easily implemented in user-written software.

TTI enables RIS, which can be used to create an accurate representation of a signal with the maximum frequency reaching up to the analog bandwidth limit of the digitizer. However, this process will increase the time required for waveform acquisition because the signal waveform of interest must be repetitively captured, and the new sampling interval components acquired bin by bin.

Describing the process

This note begins with a brief review of the conventional sampling approach that rapidly and sequentially builds a data record. It then discusses how to achieve a higher effective sampling rate with TTI and RIS. The note includes an example code listing as well as references that offer more information on RIS sampling and the use of TTI.

Reviewing conventional sampling

In the conventional approach, a digitizer rapidly and sequentially builds a data record that contains a specific number of evenly spaced bins. This is accomplished at a precise sample rate with sample-and-hold technology capturing successive waveform values (Figure 1). These are converted into digital representation using an ADC and the results are accumulated in the data record (Table 1).

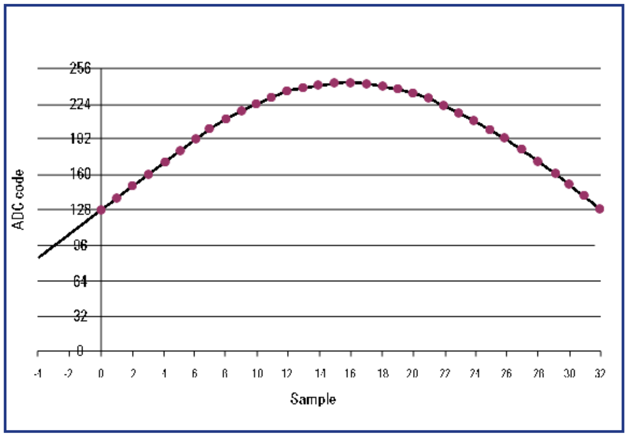


Figure 1. Digitizers usually build a data record with a sequential set of evenly spaced samples

Bin number	Time (ns)	8-bit ADC data
0	0.0	128
1	0.5	139
2	1.0	150
3	1.5	161
4	2.0	172
5	2.5	182
6	3.0	192
7	3.5	201
8	4.0	209
9	4.5	217

Table 1. First ten bins of a data record with 2 GSa/s sampling on a sine wave as shown in figure 1.

The maximum bandwidth of a measured signal that can be resolved with a sampling system is the Nyquist frequency, which is half the sampling rate of the digitizer[1]. Conventional sampling quickly builds the data record by proceeding directly from bin 0 to bin N. The data record is then ready for further handling: display in the time domain, conversion into frequency spectra via fast Fourier transform (FFT), demodulation analysis, and so on.

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[1] *It is common practice, however, to use a factor of 2.5, which provides some margin.*

Achieving a higher effective sampling rate

To achieve a higher effective sampling rate, users can manipulate the sampling process through successive acquisitions of a repetitive waveform in which there is no correlation between the ADC clock and the external signal. With this method, the ADC captures different points on the waveform during successive cycles of acquisition and creates bins within a "time width" that is equivalent to the ideal sample interval. You can think of these as "sub-bins" that exist within (and subdivide) the bins that occur in conventional sampling.

Understanding RIS

RIS, a form of equivalent-time sampling, increases repetitive-signal sample rates by creating a composite waveform with sampled data combined from multiple lower-sampling-rate waveforms. However, this approach works only with repetitive waveforms that have a well-defined trigger point. RIS will potentially identify waveform characteristics up to the digitizer's analog limit, rather than the Nyquist frequency as defined by the instantaneous sampling rate.

In Keysight software code, RIS is typically implemented through use of the horizontal waveform position ("horPos") values obtained from a digitizer (see page 9 for an example code listing). The program gradually fills all of the bins in the data record with horPos values. On the fly, the program selects and orders the acquired data segments into pre-defined bins (the sub-bins). Once the entire data record is filled, the data can be displayed as a single high-sample-rate waveform.

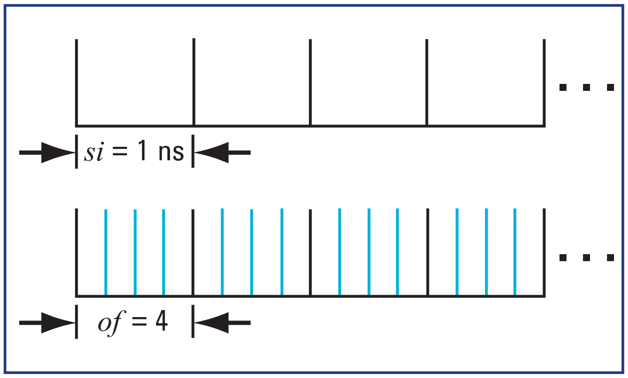


Figure 2. Oversampling by a factor of 4 within a 1-ns sampling interval yields an effective sampling rate of 4 GSa/s

To determine the effective sampling rate, the first step is to determine the oversampling factor (of), or the ratio of the RIS effective sampling rate to the real-time sampling rate. The of is an integer multiple of the real-time sampling rate with the horPos value in the sampling interval, or (si) range. Figure 2 shows the relationship between conventional and RIS-based bins, for a digitizer operating at 1 GSa/s, oversampling by a factor of four ($of = 4$) within a 1-ns sampling interval ($si = 1$ ns) creates four bins per conventional bin and provides an effective sample rate of 4 GSa/s.

The underlying hypothesis is that the ADC sample clock is not correlated with the external (measured) signal. If this is true, the horPos values will be random and uniformly distributed over the allowed interval. You can improve RIS acquisition accuracy if the time differences between accepted horPos values are located within the ideal RIS sampling interval (si / of). Further, the horPos values must be nearly centered in each bin, with the allowed range around the center determined by the oversampling accuracy (oa) parameter.

Enabling RIS with TTI

When using a digitizer, there are three instrument setup variables with which to position the acquired waveform in time:

- **sampInterval** is the sampling interval, or inverse of the sampling frequency
- **nbrSamples** is the number of samples to acquire
- **delayTime** is the nominal trigger delay

These values are highlighted in Figure 3.

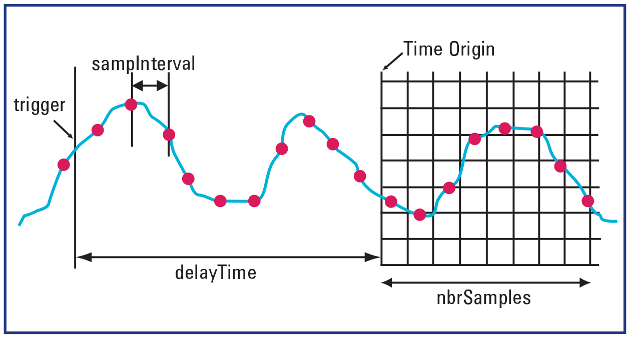


Figure 3. The acquired waveform can be positioned in time using sampling interval and delay time

Conventionally, the nominal trigger delay is measured relative to the beginning of the trace, or the left edge of a real or virtual display grid. It represents the time from the trigger to the start of waveform recording. A positive number indicates a post-trigger acquisition, or when the reading begins after the trigger. Conversely, a negative number is a pre-trigger acquisition. Keep in mind the acquisition runs before a trigger occurs; the delayTime controls the time between the trigger and when the acquisition is stopped.

Because triggers typically occur asynchronously to the sampling clock, the time between the trigger and next sample occurs at a random time between zero and sampInterval. However, the true time reference point for any waveform acquisition is not the sampling time but rather the trigger point, which is attached to a specific feature of the waveform (e.g., a positive- or negative-going transition to a specific level).

To maintain a highly stable display, you must know the time between the trigger and the next sampling clock to within a fraction of the sampling interval—and then arrange the displayed data points so that the trigger point remains in a constant position. Trigger time interpolation allows the positioning of triggers to accuracy within few picoseconds. This is critical when creating variable-persistence displays, cumulative-history displays or highly zoomed random-interleaved displays that are generated from overlaid waveform segments.

Figure 4 completes the picture of RIS waveform capture by indicating the horizontal offset value (hOffset) and the horizontal position value (horPos). The random variation in trigger position, and therefore horPos, makes it possible to achieve a higher effective sampling rate and thereby reveal greater detail in the sampled waveform.

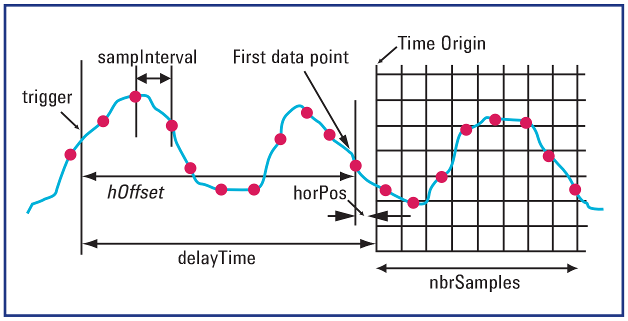


Figure 4. Sub-bins are created by random variation in horizontal position (horPos) relative to the waveform.

TTI accuracy

The accuracy and repeatability of this process depends on the performance of the digitizer. Table 2 presents a set of relevant example specifications from the Keysight high-speed digitizers.

Product number	Description	Maximum analog bandwidth	Maximum real-time sample rate	TTI accuracy	Maximum theoretical RIS sample rate
U1061A	Acqiris 8-bit high-speed PXI digitizers	1 GHz	1–2 GSa/s	5 ps	200 GSa/s
U1062A	Acqiris 10-bit high-speed PXI digitizers	3 GHz	2–4 GSa/s	15 ps	66 GSa/s
U1063A	Acqiris 8-bit high-speed cPCI digitizers	250 MHz	0.5–1 GSa/s	5 ps	200 GSa/s
U1064A	Acqiris 8-bit high-speed cPCI digitizers	1 GHz	1–4 GSa/s	5 ps	200 GSa/s
U1065A	Acqiris 10-bit high-speed cPCI digitizers	3 GHz	2–8 GSa/s	15 ps	66 GSa/s
U1066A	Acqiris 12-bit, high-speed cPCI digitizers	300 MHz	420 MSa/s	5 ps	200 GSa/s
U1067A	Acqiris 8-bit high-speed PCI digitizers	250 MHz	0.5–1 GSa/s	5 ps	200 GSa/s
U1070A	Acqiris 12-bit high-speed PCI digitizers	300 MHz	50–420 MSa/s	5 ps	200 GSa/s
U1071A	Acqiris 8-bit high-speed PCI digitizers	1 GHz	1–2 GSa/s	15 ps	66 GSa/s
U1084A	Acqiris 8-bit high-speed PCIe digitizers with on-board signal processing	1.5 GHz	2–4 GSa/s	15 ps	66 GSa/s
M9210A	10-bit PXI-H digitizing scope	>1.4 GHz bandwidth in 50 Ω	2–4 GSa/s	15 ps	66 GSa/s
		>300 MHz bandwidth in 1 MΩ	2–4 GSa/s	15 ps	66 GSa/s
M9211A	10-bit PXI-H UWB IF digitizer	3 GHz	4 GSa/s	15 ps	66 GSa/s

Table 2: Keysight digitizers are well-suited to the RIS/TTI technique

How fast is too fast?

From Table 2 we can see that the RIS technique allows the multiplication of the sampling rates to tens or hundreds of times faster than the real-time capabilities of the ADC. However, attaining these theoretical limits requires a signal that is repeatable and stable over the entire acquisition, with a time distribution of triggers that allows each bin (of the width of the TTI accuracy) to be filled with one sample point. In practical terms, sampling to these limits is wasteful, creating more data than is needed, and more data to capture and process. For accurate measurement, sampling rates need only exceed twice the rate of the highest frequency component in the measured signal.

Keysight high-speed digitizers

RIS enhances real-world measurements

Today, random interleaved sampling or RIS is being used in a variety of applications:

Ultrasound

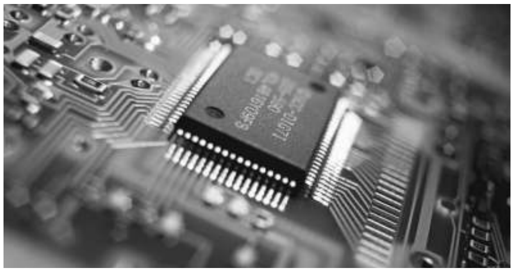
For biological studies and analyzing hard ceramic components, ultrasonic inspection can typically use frequencies up to 100 MHz with some components up to 500 MHz. Such inspection also requires high dynamic range to distinguish small echoes in the return signals.

Light detection and ranging

LIDAR measures scattered light properties to identify the range and characteristics of a target. With sufficient bandwidth, LIDAR receiver detectors and electronics capable of creating short pulses will achieve better target resolution.

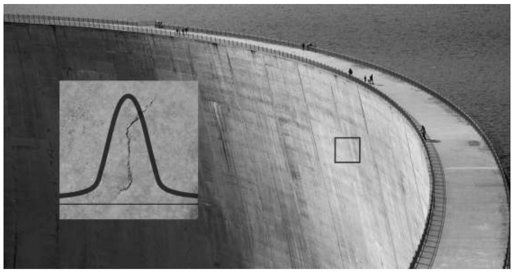
Time-domain reflectometry

TDR determines the characteristics of a transmission medium by observing reflected waveforms. By generating the same input signal multiple times, RIS can help extend higher-frequency components of the system, and the minimum system rise time, up to the analog bandwidth of the system.



Fiber sensor or distributed Bragg reflector (DBR)

Using optical fiber, fiber sensors are not only the means for relaying signals from a remote sensor to the electronics that process the signals: they have also become the sensors themselves. A DBR is formed within a fiber by doping, heating or otherwise treating the fiber to create multiple layers perpendicular to the fiber axis. With each layer boundary causing a partial reflection of an optical wave, the interaction of the fiber with its environment—due to changes in temperature, strain, chemical interactions, and so on—can be monitored through the optical response of a fast light pulse sent into the fiber.



Scanning a possible approach

The graph in Figure 5 illustrates the difference between a simple, non-RIS sampled (noRIS) waveform compared with a RIS sampled waveform obtained with oversampling factor (of) = 10, oversampling accuracy (oa) = 100 (whole bin width) and with of = 10, oa = 20, respectively. The range was limited to ±10 percent of the bin width around the center of the bin.

Taking a closer look at Figure 5, there is a visible improvement in the measurement for the higher frequency components between the non-RIS and the waveform obtained with of = 10, where the sampling rate exceeds the Nyquist rate. It is a little more difficult to see any improvement between the waveforms obtained with of = 10 and oa = 100.

Once the sampled waveform is captured in a loop, a waveform amplitude value is assigned to the corresponding bin using its horPos value. An acceptable horPos value falls within the of and oa parameters. The current horPos value and waveform are replaced only if the new value is more precisely centered in the bin. RIS acquisition is completed when all bins are assigned a horPos value and waveform amplitude.

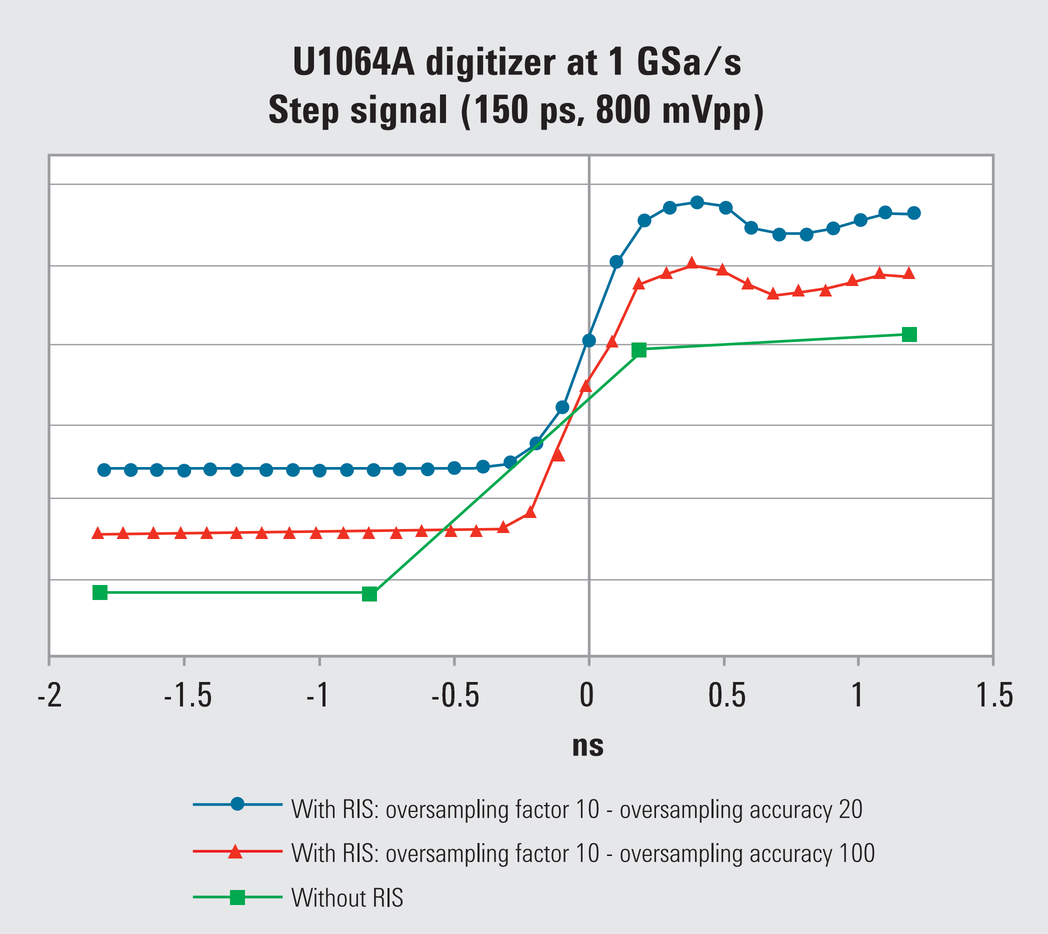
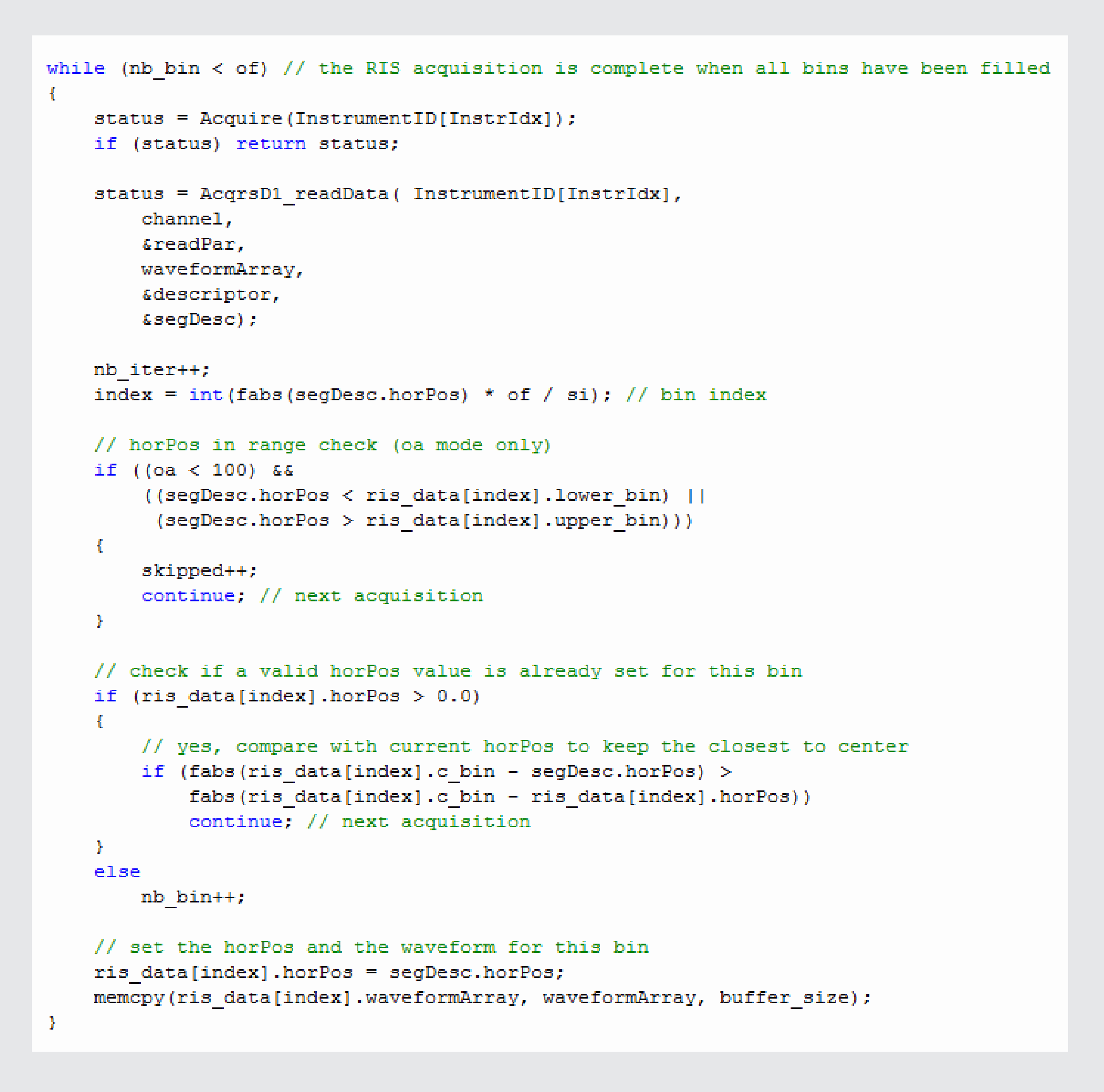


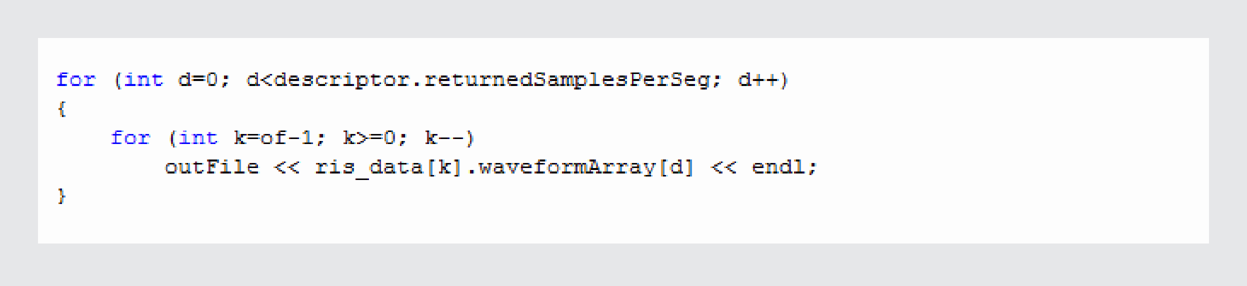
Figure 5. Adjusting the oversampling accuracy (oa) for narrower (fractional) bin width provides greater detail

The following code sample demonstrates one way to acquire and build a complete set of bins:



```
while (nb_bin < of) // the RIS acquisition is complete when all bins have been filled
{
    status = Acquire(InstrumentID[InstrIdx]);
    if (status) return status;

    status = AcqrsD1_readData( InstrumentID[InstrIdx],
        channel,
        &readPar,
        waveformArray,
        &descriptor,
        &segDesc);

    nb_iter++;
    index = int(fabs(segDesc.horPos) * of / si); // bin index

    // horPos in range check (oa mode only)
    if ((oa < 100) &&
        ((segDesc.horPos < ris_data[index].lower_bin) ||
         (segDesc.horPos > ris_data[index].upper_bin)))
    {
        skipped++;
        continue; // next acquisition
    }

    // check if a valid horPos value is already set for this bin
    if (ris_data[index].horPos > 0.0)
    {
        // yes, compare with current horPos to keep the closest to center
        if (fabs(ris_data[index].c_bin - segDesc.horPos) >
            fabs(ris_data[index].c_bin - ris_data[index].horPos))
            continue; // next acquisition
    }
    else
        nb_bin++;

    // set the horPos and the waveform for this bin
    ris_data[index].horPos = segDesc.horPos;
    memcpy(ris_data[index].waveformArray, waveformArray, buffer_size);
}
```

The final steps are to interleave the acquired horPos values in the correct order and then build a waveform with a time increment (*ti*) value between samples, equal to the sampling interval (*si*) divided by oversampling factor (*of*):



```
for (int d=0; d<descriptor.returnedSamplesPerSeg; d++)
{
    for (int k=of-1; k>=0; k--)
        outFile << ris_data[k].waveformArray[d] << endl;
}
```

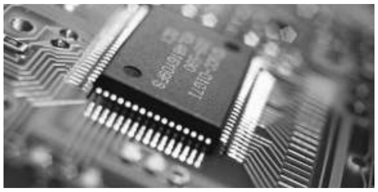
Conclusion

When working with fast repetitive signals, TTI-enabled RIS can reveal waveform characteristics up to the full analog bandwidth limit of the digitizer. This can be especially useful when the analog bandwidth of the digitizer is higher than the Nyquist frequency at the maximum sample rate of the digitizing channel.

The TTI mechanism accurately positions the acquisition trigger between sample clocks and records that data with each waveform. This added timing accuracy makes it possible to acquire repetitive waveforms and create sub-bins of time (with associated data) within the conventional time bins of the ADC. The net result is an effective sampling rate that is an integer multiple of the digitizer’s maximum sampling rate. In this way the full analog bandwidth of a digitizer can be used, even when the maximum real-time sampling rate of the digitizer defines an inadequate Nyquist frequency.

This approach has been leveraged in applications such as ultrasound, LIDAR, TDR and fiber sensors that utilize repetitive waveforms and can benefit from greater detail in the waveform display.

To learn more about Keysight digitizers that support RIS and TTI, please visit
www.keysight.com/find/embedded-digitizers



Related information

Product Brochures

- Keysight U1061A: Acqiris 8-bit high-speed PXI digitizers, Keysight publication 5989-7361EN
  http://cp.literature.keysight.com/litweb/pdf/5989-7361EN.pdf
- Keysight U1062A: Acqiris 10-bit high-speed PXI digitizers, Keysight publication 5989-7111EN
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