

# 20 GHz Instantaneous Bandwidth RF Spectrum Analyzer Measurements with High Sensitivity and Spur Free Dynamic Range

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**Abstract:** *The latest demonstrated performance specifications of a novel wideband radio frequency spectral sensor based on photonic technology are reported, including 20 GHz instantaneous bandwidth, ~400 million unique frequency measurements per second, two-tone spur free dynamic range >63 dB, variable resolution bandwidths to below 100 kHz, and high RF power sensitivity levels of <-130 dBm.*

**Keywords:** wideband RF spectrum analysis; spatial spectral holography

## Introduction

The paradigm of operations for radio frequency (RF) monitoring is rapidly moving towards “wideband sense and react”, given the proliferation of transmitters for radar and communication systems operating over more of the electromagnetic spectrum (EMS). A significant challenge for present and future military and commercial systems is to analyze signals over a wide bandwidth, out to 120 GHz, in real time without any scanning in frequency, and without any prior knowledge of the signals, carrier frequency, or modulation format.

For spectrum monitoring (SM), a receiver system must have a high spur free dynamic range (SFDR), so that the small signals of interest (SOI) are not mistaken for the false signals – spurs – that are generated by large signals, such as other SOIs, co-site interference, or jammers. The system should have fast update rates for tracking signals with fast pulse repetition frequency (PRF), with changing PRFs and wide bandwidth to handle frequency hops, and low latency to cue other systems or countermeasures. Such a system should also have high RF sensitivity.

Typical high sensitivity measurement systems “choke down” the bandwidth to get a lower noise floor, which can approach the thermal noise floor limit of -174 dBm/Hz, less the noise figure (NF) of the system. Typical narrow band measurement techniques use super-heterodyne detection at a fixed frequency and resolution bandwidth (RBW). For wideband coverage the local oscillator (LO) tunes across the desired bandwidth dwelling on each frequency sequentially [1]. Modern digital spectrum analyzers use digitizers and Fast

Fourier Transform (FFT) processing to enable higher instantaneous bandwidth measurements limited by mainly the digitizer performance [2]. In comparison, our spectral sensing system remains fully open to the entire bandwidth of interest, presently over 20 GHz and readily extendable to >100 GHz, operates with high sensitivity, high SFDR and generates 400,000,000 unique frequency measurements per second.

## Implementation and Analogy

Figure 1 shows a diagram of our implementation. The underlying sensing mechanism is a light absorbing crystal that makes millions of continuous and parallel RF spectral energy measurements of RF modulated laser light [3-5]. RBW can approach 10 kHz across 20 GHz of bandwidth as shown in this work. Detection of SOIs is done over the full IBW with superior performance in SFDR as compared to current state-of-the-art wideband digitizers [5].

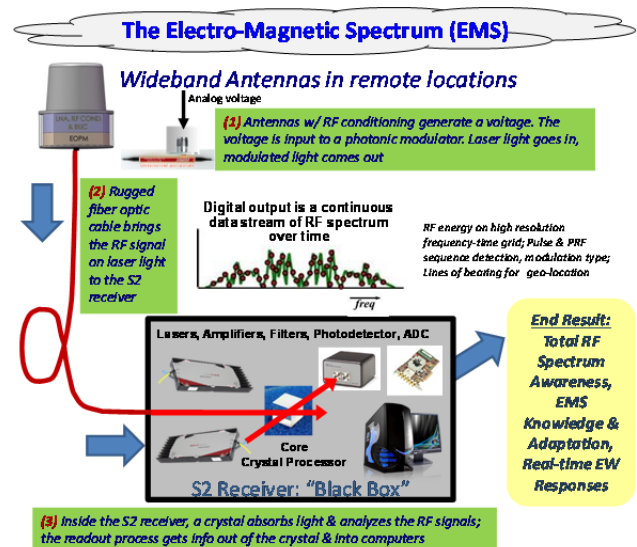


Figure 1. System diagram of the S2 approach

Additionally, SOI detection can have a high sensitivity with an underlying equivalent noise performance of the thermal noise limit in a ~10 kHz resolution bandwidth (RBW). Full spectrum readout scans are achieved, with a frame rate (FR) variable from 1-1,000 kHz. The displayed RBW is typically lower than that measured by the device, and is variable from 10 kHz to >10 MHz, as

limited by IBW and FR, as indicated by the readout parameters shown in Figure 2. Note, not only can the readout laser change its FR, but also can achieve any IBW over its frequency extent, which allows much more flexibility than shown in this table. In Figure 1, the RF to light conversion occurs at the antenna, and fiber optic cables are used to feed from the antenna to the receiver, which provides low-loss, long distance, reduced electromagnetic interference, and lowering size, weight and power (SWaP) at the antenna. The complete spectrum monitoring system offers better overall system SWaP and cost over comparable digital system architectures [5], and which increases when running multiple antennas into one receiver. Other extensions in capability include RF monopulse direction finding [4,5], vector signal analysis, and correlation for communications, radar, and data mining.

Read time, $\mu\text{s}$	Frame Rate, kHz	FREQUENCY PIXEL WIDTH		Freq. Pixels per Frame	Time Pixels per second
1,000	1	0.05	MHz	409,520	1,000
500	2	0.10		204,760	2,000
200	5	0.24		81,904	5,000
100	10	0.48		40,952	10,000
50	20	0.96		20,476	20,000
20	50	2.4		8,190	50,000
10	100	4.8		4,095	100,000
5	200	9.6		2,048	200,000
2	500	24.0		819	500,000
1	1,000	48.0		410	1,000,000

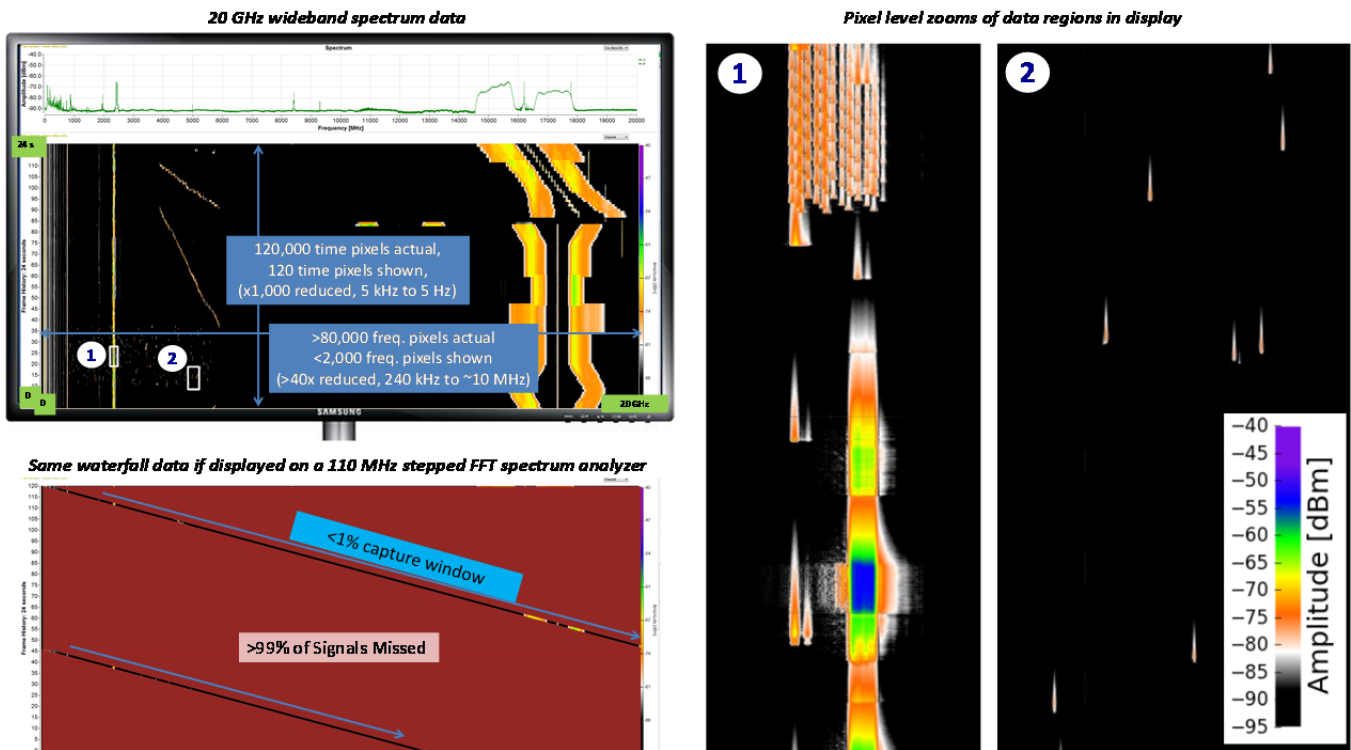
Figure 2. Variations in the readout laser for a 20 GHz IBW scan in terms of FR and RBW.

An overview of the implementation follows:

- A laser is modulated by RF from antenna(s), which is the process of RF up-conversion to optical frequencies.
- The modulated laser beam then is spread in frequency, which irradiates an array of millions of "power meters" in a crystal, illuminating all of these simultaneously, and each analyzes a subset of the RF spectrum.
- Each "power meter" is a set of about 10 billion atoms in each in a 10 kHz channel, over 0.001 cubic centimeters of a cooled crystal that absorbs light.
  - For 20 GHz IBW, there are ~2,000,000 "power meters", each with ~10 kHz bandwidth, each with a dedicated RF band-pass filter.
  - Each "power meter" has an integration time and decay on the order of milliseconds.
  - The "power meters" continuously analyze the input spectrum with 100% probability of intercept.
- The power meters are read out sequentially by a frequency scanning laser, with amplitude variations that become voltages on a photo-detector, then digitized to show the level reading of each "power meter".
  - For example, as shown below, 20 GHz spectrum can be readout with 240 kHz displayed resolution at 5,000 frames per second, or other combinations.
  - Other 20 GHz IBW combinations are shown in Figure 2.

## 20 GHz SM Experimental Results

Representative continuous spectrum capture results are shown in Figure 3. The display shows the current spectrum at the top, and a waterfall spectrogram in the bottom pane. The software allows real time frequency measurements updated at high definition video resolution and frame rates. In real-time view mode, maximum-hold and averaging are options for the screen displays. The upper trace shows a single max-hold result, which here represents the maximum of 1,000 frame captures (here, updated at a 5 Hz video rate reduced from 5 kHz). A frequency binning max-hold function allows the x-axis data to be reduced in the frequency dimension (here, by ~40x, 240 kHz expanded to ~10 MHz). Thus, the total waterfall image is ~40,000 times smaller than the underlying data file. Each setting is user configurable to accommodate various operating requirements for display update rate and temporal resolution. The underlying data files are streamed to disk to allow playback and viewing after collection, and to processors for real time analysis. The data in Figure 3 is a full 20 GHz spectrum display, readout every 0.2 ms (5 kHz FR), and where the waterfall is displayed in color coded amplitude in the spectrogram over a 24 second time period (history time is also variable), while the RF inputs are varied. In this screen view, the amplitude scale is thresholded at about -87 dBm to show small (white) signals on a clean (black) background. Signal generation provided rapidly changing spectral content with a combination of wideband signal generators, arbitrary waveform generators, and antennas collecting ambient RF signals including Wi-Fi, Bluetooth, radio stations, a microwave oven, a cordless phone, and other RF signals in the environment. The wide bands seen in the spectrogram are an AWG creating a band-limited, band changing and carrier changing pseudorandom noise sequence mixed on a frequency agile LO. For this data, 81,904 frequencies per scan are collected for 5,000 frames per second, and displayed for 24 seconds history (120,000 pixels along the y-axis), while the actual data file extends for several minutes and can be continuous with sufficient disk storage. Each data file per second of spectrum history is thus 409,520,000 measurements, so that at full resolution, the data in the 24 second waterfall spectrogram is actually a 10 Gigapixel image. These full scale high resolution data files can be viewed on web browsers, with zoom and measurement functions for frequency and time difference between signal events [6]. Zoom windows labeled "1" and "2" in the image show the true resolution of the data without screen pixel limits and without any max-hold in time. These callouts are cropped versions of a full resolution spectrogram of the data. In this view, all signals show tails that are stored measurements in the crystal decaying in time. Callout 1 shows the 2.4 GHz band revealing details of Wi-Fi and Bluetooth signals. Call out 2 shows a small portion of a wideband frequency hopper around 5 GHz.



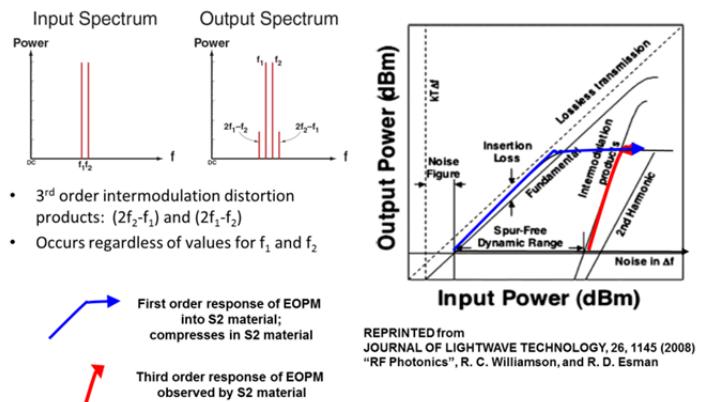
**Figure 3. Demonstration of 20 GHz continuous spectrum monitoring over 24 seconds for many dynamic RF signals (upper left). The full data image is 40,000x more dense than shown in the spectrogram display, and two zooms of the pixel level detail are shown (right). For comparison, a rendering of the same spectrogram for a 110 MHz stepped FFT spectrum analyzer is shown (lower left).**

### 20 GHz SM Sensitivity and SFDR Measurements

For RF sensitivity and two tone SFDR measurements, the system can be operated in two different modes: one with higher SFDR and less sensitivity, and the second with higher sensitivity and less SFDR. Results of these two different modes can be seen in Figure 5. For all these SFDR and sensitivity measurements, two CW input signals with the same amplitude are summed and varied with a variable RF attenuator. The RF power levels were measured in parallel with the setup on a super-heterodyne spectrum analyzer, which was calibrated to an RF power meter. At the peak input amplitude, the two CW tones produce third order intermodulation distortions in the electro-optical phase modulator (EOPM). As the amplitudes of two CW frequency tones are decreased the intermodulation terms are reduced and eventually drop below the noise floor of the system. The overview of this process is also shown in Figure 4. In the S2 system the primary tone compresses due to limited absorption in the crystal, but the intermodulation is not caused by this compression, but rather from the EOPM. The observed spurs are only third order intermodulation distortion, which are created in the EOPM, and these are tracked and plotted.

Figure 5 (left) shows the best results to date of the S2 system in terms of SFDR. In the upper right plot, the results are shown for RF input without gain. The inset shows the full 10 GHz spectrum display, which has in

this case 125,000 points in frequency with a frame rate of 2 kHz. These results yield a two tone SFDR of 63.2 dB and a minimum detectable signal (MDS) of RF sensitivity of -64.7 dBm.



**Figure 4. Overview of SFDR measurements and S2 response**

Note that the MDS is specified by calculating the intersection of the primary signal strength (with a slope of 1) with the root mean squared (RMS) calculation of the noise floor in a region as indicated in the inset where no signal is present. The third order intermodulation term arises from the electro-optical modulator (the RF mixer in this setup), which then is recorded in the spectrum readout. The lower trace in Figure 5 (left) shows the enhanced sensitivity of -122 dBm and only slightly reduced SFDR of 62.0dB with RF gain stages.



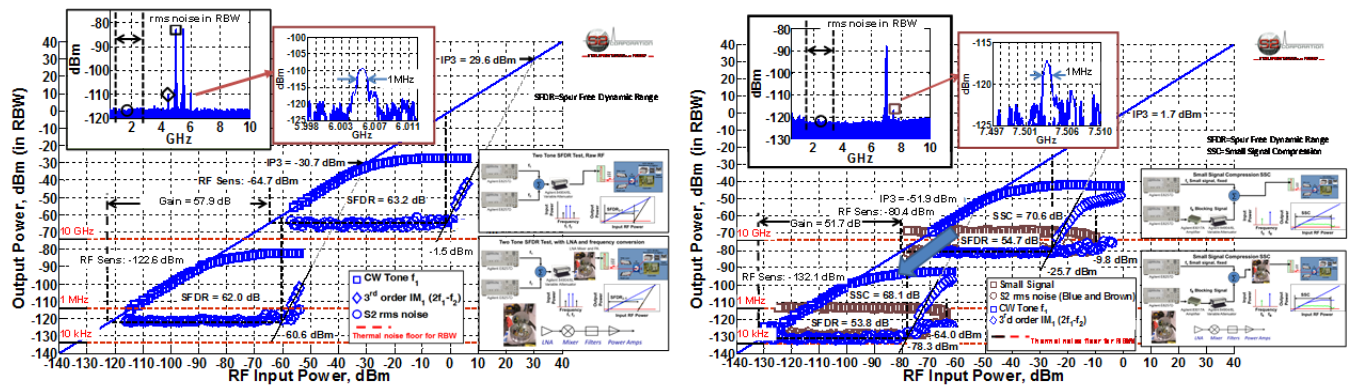


Figure 5. SFDR and sensitivity of an S2 demonstrator in the higher SFDR mode (left) and higher sensitivity mode (right).

RF gain included a low noise amplifier (LNA) and a power amplifier (PA) before the EOPM. As shown in the inset, in the case with RF gain a block-upconverter (BUC) stage was used that mixed RF signals from 0.5-10.5 GHz up to 12-22 GHz, which does not in this case limit the SFDR. Through the addition of the BUC between the LNA and PAs, an additional 57.9 dB of gain is applied, and the sensitivity is translated down to a level of -122.6 dBm. Figure 5 (right) shows the best sensitivity results, both with and without the use of RF gain. These results show lower SFDR than that in Figure 5 (left). In the main plot of Figure 5 (right) the upper right trace is a result of the no gain RF input. As shown, these results yield a SFDR of 54.7 dB and a MDS of -80.4 dBm. The lower left trace in Figure 5 (right) shows the enhanced sensitivity of -132.1 dBm and only slightly reduced SFDR of 53.8dB when using the LNA, BUC, and PAs, all placed before the EOPM. Through these stages, an additional 51.7 dB of sensitivity is achieved from RF gain. At this alternative setting, the sensitivity without gain is ~15 dB better. With RF gain, the sensitivity is ~10 dB better, and the MDS is approaching a thermal noise floor equivalent to a 10 kHz bandwidth. Also measured and plotted in Figure 5 (right) is the small signal compression (SSC) of the S2 system. For this measurement, a very strong signal connected to a variable RF attenuator is summed together with a very weak, fixed amplitude signal before being programmed by the EOPM. As the amplitude of the strong signal is increased, the small signal will exhibit compression. The SSC range is measured by lowering the big signal amplitude until it is no longer distinguishable from the noise floor of the system and then increasing amplitude in 1dB steps until the small signal compresses by 3dB.

A functional block diagram of the SSC setup is shown on the right side of Figure 5, lower image. The S2 spectrum analyzer screen shot showing the frequency and relative amplitude of the strong signal to the weak signal is shown in the inset of Figure 5 (right). The plot of the results of the no RF gain SSC measurements was measured to be 70.6 dB. With RF gain and a BUC in the setup, the measurement showed SSC of 68.1 dB.

## SUMMARY

Updated specifications for wideband EMS monitoring technology have been presented, with over 20 GHz of bandwidth, narrow frequency resolution of <1 MHz, with high sensitivity and high two tone limited spur free high dynamic ranges. Improvements to extend bandwidth beyond 100 GHz and to >70 dB in SFDR are in progress. Work on other functions, including direction finding, are being pursued. Software to analyze this data stream in real-time is being developed.

## Acknowledgements

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6. Full images available for viewing on company website [www.s2corporation.com](http://www.s2corporation.com)