Extreme Bandwidth Analyzer & Correlator (EBAC)

Enabling Transformational Knowledge, Use and Control of the Electromagnetic Spectrum

National Science Foundation meeting
Extending Access to the Radio Spectrum (EARS)

07 October 2013

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Bozeman, Montana

Corporate Overview

S2 CORPORATION

— THE SPECTRUM in a FLASH —

EXTREME BANDWIDTH SENSING | RF SPECTRAL DOMINANCE | MULTI-FUNCTIONAL WITH RAPID RECONFIGURABILITY

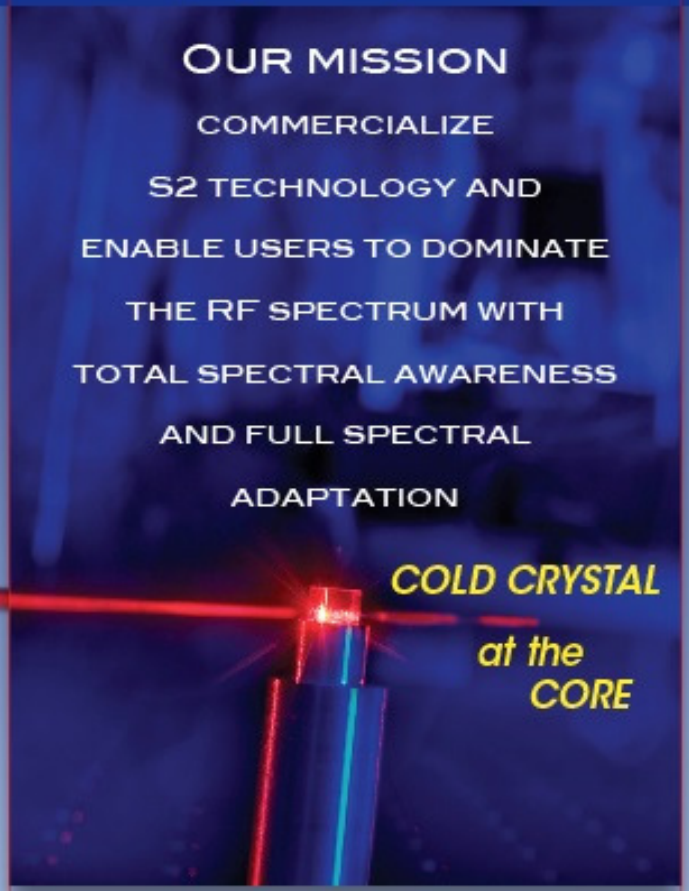
S2 CORPORATION

A DYNAMIC HIGH-TECHNOLOGY SMALL BUSINESS THAT PROVIDES UNPARALLELED RF SENSING AND SIGNAL PROCESSING SOLUTIONS USING OUR REVOLUTIONARY EXTREME BANDWIDTH PHOTONIC SPATIAL SPECTRAL (S2) HOLOGRAPHIC TECHNOLOGY

S2 Corporation facilities in Bozeman, MT

OUR MISSION

COMMERCIALIZE S2 TECHNOLOGY AND ENABLE USERS TO DOMINATE THE RF SPECTRUM WITH TOTAL SPECTRAL AWARENESS AND FULL SPECTRAL ADAPTATION



Contact: Kris Merkel, Ph.D., President / CEO, S2 Corporation, merkel@s2corporation.com

APPLICATIONS INCLUDE

ELECTRONIC WARFARE SUPPORT AND SIGNAL INTELLIGENCE

PERSISTENT RF SPECTRAL MONITORING

GEO-LOCATION BASED ON RF DIRECTION FINDING

ADAPTIVE AND COVERT RF COMMUNICATIONS

RADAR RANGE-DOPPLER RECEIVER

TRUE-TIME DELAY

ARBITRARY WAVEFORM GENERATION

ANALOG SIGNAL PROCESSING AND DATA MINING

We are the world leaders in S2 Technology

- Small Business Contractor
- Innovation protected with Patents & SBIR Rights
- $17M in R&D revenue in 7 years
- $16M in contributive partner R&D efforts

Problem Statement: The Escalation of RF Transmitters… and Lack of Spectral Awareness

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- The use of the RF/microwave electromagnetic spectrum (EMS) is proliferating. Radios and radars are being utilized in dynamic and unpredictable manners across the entire EMS.
- ***Total spectral situational awareness & full spectral adaptation are required*** for next generation interoperable RF receiver systems.
- Conventional electronic receivers are difficult to extend to extreme wideband operation.

Expanded RF Monitoring Requirements

- **ANALYZE** - Monitor the full RF spectrum, characterize signals of interest and their components in real-time with analytic functions for signals intelligence and emitter geolocation
- **CUE** – Identify RF activity (type & location) to other RF resources
- **ACT and ADAPT** - enable multi-function changes on-the-fly for reconfiguring modality/specifications and appropriately responding

RF Spectrum Processing Applications

- Persistent RF spectral awareness
- Accurate geo-location on transient RF
- Pulse/Signal estimation & identification
- Covert communications
- Analog signal processing, data mining, selection and filtering

S2 EBAC: Leap-Ahead Capability…
Not Just Another Spectrum Analyzer!

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- **An ideal radio frequency (RF) spectrum monitoring system measures ALL activity <u>wideband</u>, simultaneously, with <u>high fidelity</u> and <u>multi-functionality</u>**
- **Current systems do not offer this capability**
  - Narrowband (conventional) systems view the RF spectrum through a limited bandwidth…
    - *Typically using sweeping or stepped digitizers with narrowband capture windows (e.g. 100 MHz)*
    - *Probability of intercept is ~0.5% across a 20 GHz bandwidth; difficult to channelize over wideband*
  - Wideband digital >20 GHz systems would be desired, but suffer significantly from:
    - *Creating enormous, digital data sets (e.g. 50-100 Gigabytes/sec,) that must be processed and/or stored*
    - *Requiring massive digital processing, with ~10 Tera-operations per second, per antenna*
    - *Inherently poor dynamic range (<35 dB over 20 GHz), not expected to scale significantly higher in future*
- **S2's solution measures all frequencies simultaneously, all the time**
  - True WIDEBAND**: >40 GHz TODAY, 100% probability of intercept** w/ 100 kHz res. bandwidth
  - Superior spur free dynamic range: **400x higher** than 20 GHz digitizers (>60 dB over 20 GHz)
  - Far **better SWaP & cost** than what current systems could offer over wideband
  - Data flow of 1 Gigabytes/sec: **100x** reduction over current approaches
  - Enables real-time **low latency <1 ms** digital signal processing based signal assessment

…and also key…

  - **Multi-functional, frequency agile and reconfigurable on-the-fly**
  - Enables **remote antenna deployments** long distances from receiver, connected by fiber optics

S2 Extreme Bandwidth Analyzer & Correlator (EBAC): Simple Concept of Operation and Hardware Overview

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The Electro-Magnetic Spectrum (EMS)

End Result:
Total RF Spectrum Awareness, EMS Knowledge & Adaptation

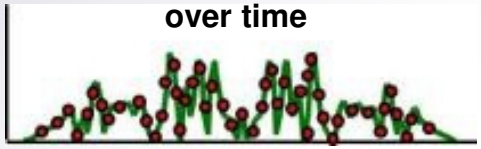
Wideband Antennas in remote locations

Analog voltage

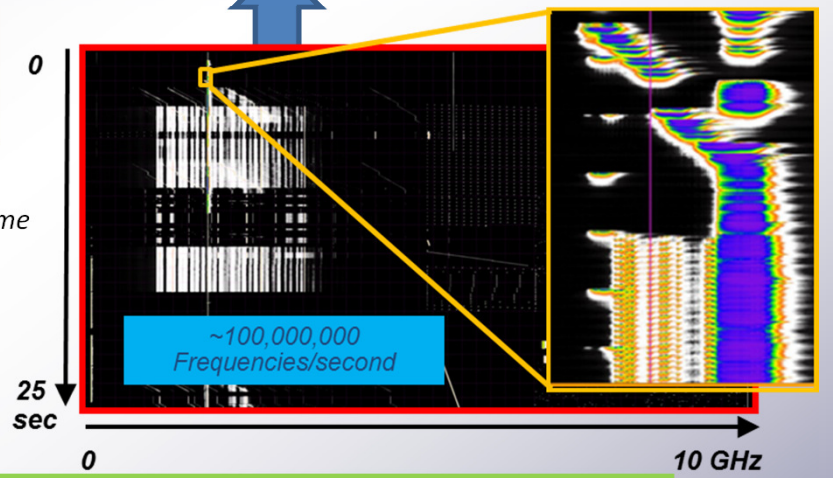
(1) *Antennas w/ RF conditioning generate a voltage. The voltage is input to a photonic modulator. Laser light goes in, modulated light comes out*

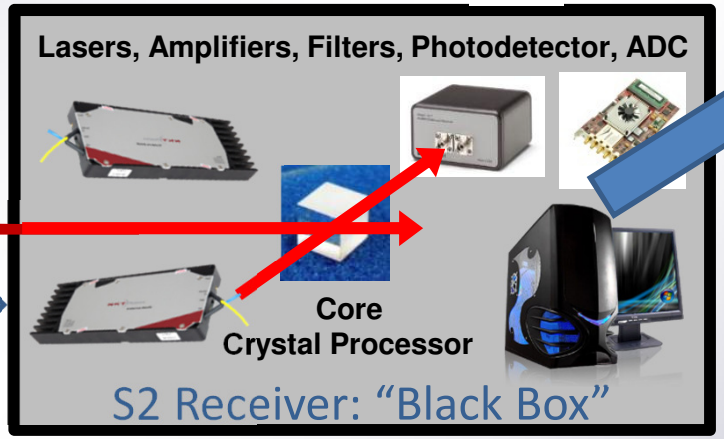
(2) *Rugged fiber optic cable brings the RF signal on laser light to the S2 receiver*

Digital output is a continuous data stream of RF spectrum over time



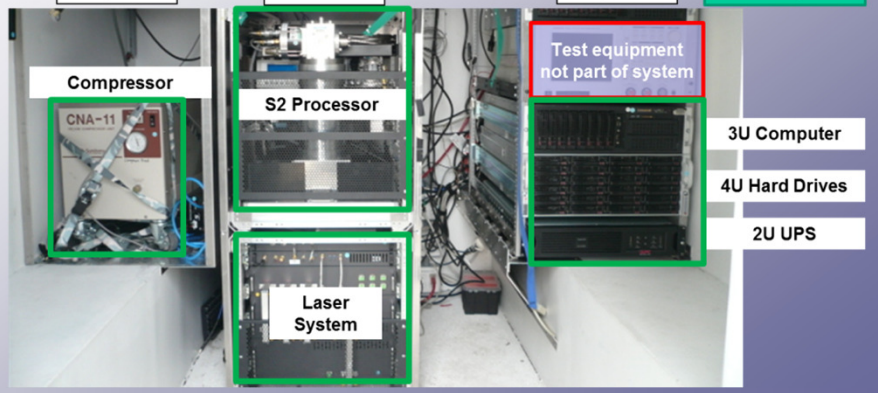
RF energy on high resolution frequency-time grid; Pulse & PRF sequence detection, modulation type; Lines of bearing for geo-location





(4) *Output: high resolution, wideband spectrum data*

S2 Prototype Hardware System Today, 0.5-18 GHz



Total SWaP

Size:	42U
Weight:	700 lbs
Power:	3,000 W

3U Computer
4U Hard Drives
2U UPS

(3) *Inside the S2 receiver, a crystal absorbs light & analyzes the RF signals; the readout process gets info out of the crystal & into computers*

Hardware Overview and Technical Approach for Multifunction Receiver

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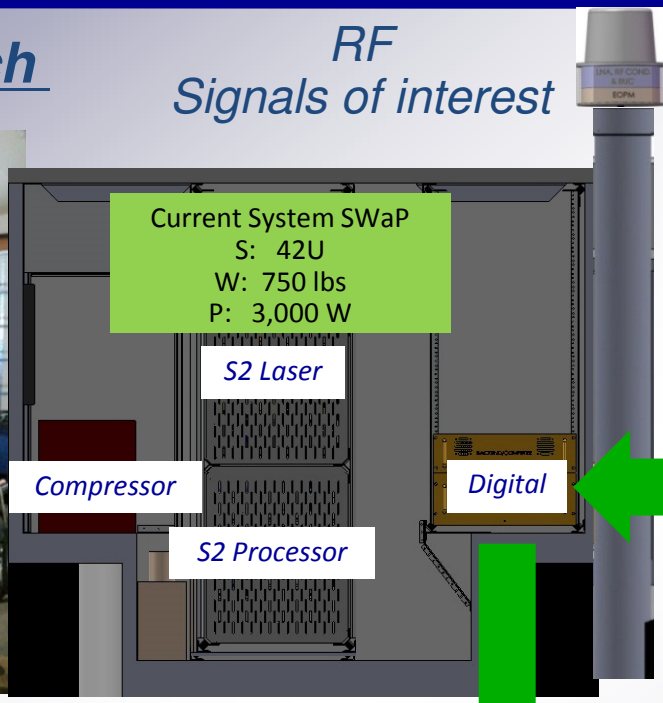
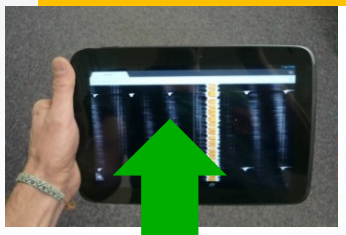
Technical Approach

RF Signals of interest



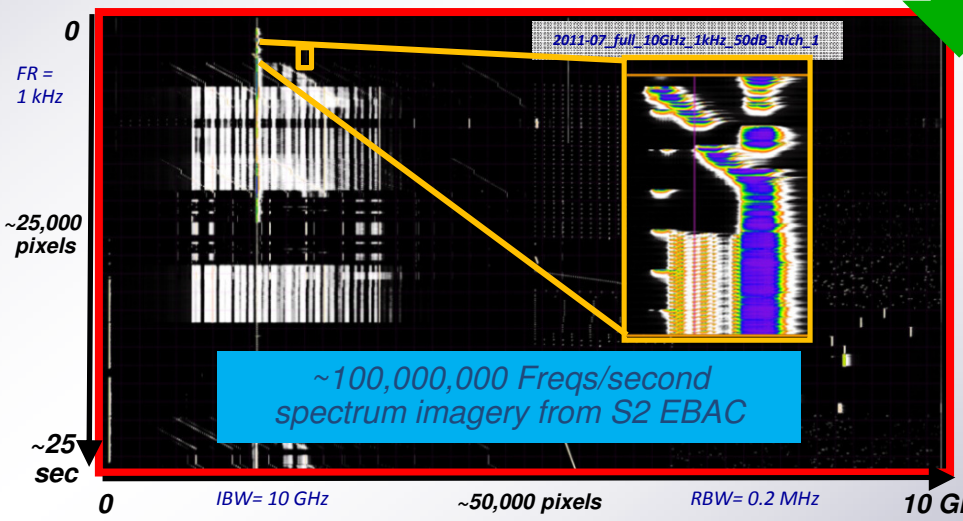
Analog wideband data fed from antenna to S2 system (mobile trailer mounted).



Data Interaction and Visualization

End Goal: Real-time KNOW the spectrum

IBW= Instantaneous Bandwidth
RBW=Resolution Bandwidth
FR = Frame Rate



1 Gigabyte/sec digital data streamed to disk & processed in real time is spectrum knowledge. Advanced algorithms for Data Analysis required for spectrum learning and reasoning.

Own the spectrum >100 GHz spectrum coverage

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ONR
Revolutionary Research . . . Relevant Results

Own the Spectrum

"Provide Battlespace Awareness –
Know who is out there, where they are and what they are doing"

ES

Requires capability to:

- Continuously monitor all critical portions of the spectrum (RF/EO/IR)
- Quickly and accurately classify emitters/emitter function
- Provide Specific Emitter Identification (SEI)
- Precisely and rapidly locate platforms, people, things, events
- Conduct accurate long term monitoring/tracking
- Network sensors and share key info in near-real time

Dr. Peter Craig, Electronic Warfare
ONR312 Program Manger
wrote about S2 technologies in the Fall 2012 ONR Innovation Newsletter.

The article states that the S2 system "creates a super-vision of the EMS where such signal techniques as frequency hopping, chirping, or spectrum spreading become visible as patterns in a real-time frequency map… This ONR investment has resulted in a system that can simultaneously monitor all EMS emissions over a span of 40 GHz while resolving signals that are separated by only a few 10s of kilohertz – **and continuing research will increase this span to greater than 100 GHz**."

Navy SBIR Developed Technology, with investment from ONR and SPAWAR

S2 EBAC Applications and status of development

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- **S2's EBAC enables RF processing applications, including …**
  - SPECTRUM MONITORING — TRL6

NSF EARS

    - Spectral analysis "Ground truth" of RF activity, 24/7/365, recording, playback & visualization
    - Persistent and continuous with 500 Million frequencies per second
    - Amplitude on a dense frequency-time grid, 10,000 full bandwidth frames per second
    - Real-time signal estimation and displays with max hold, change detection, adaptive thresholds
  - GEOLOCATION OF TRANSMITTERS — TRL5
    - Real-time high resolution angle-of-arrival on each of 500 Million frequencies per second
    - Works on agile, short-up time, wideband Tx
  - SIGINT CUEING & WARNING RECEIVER — TRL4

NSF EARS

    - Real-time RF signal assessment and cueing of other narrowband receivers
    - Vector signal analyzer functions, signal internal modulation format
  - COMMUNICATIONS — TRL3
    - Covert Tx emissions between S2 nodes, and over long distances and/or at high bit rates
    - Adaptive spectrum usage, changing on-the-fly, simultaneously with other functions
  - SIGNAL PROCESSING — TRL4
    - Analog matched filtering and signal selection, data mining

TRL= Technology Readiness Level

S2 Functions and Hardware Configurations

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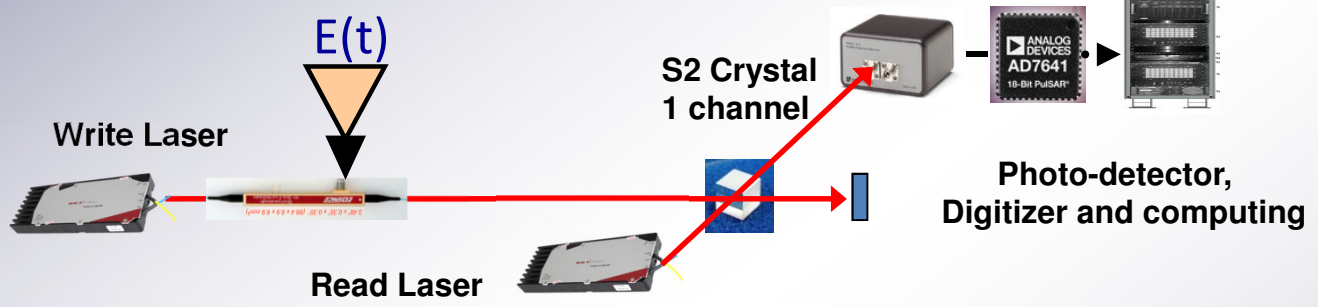
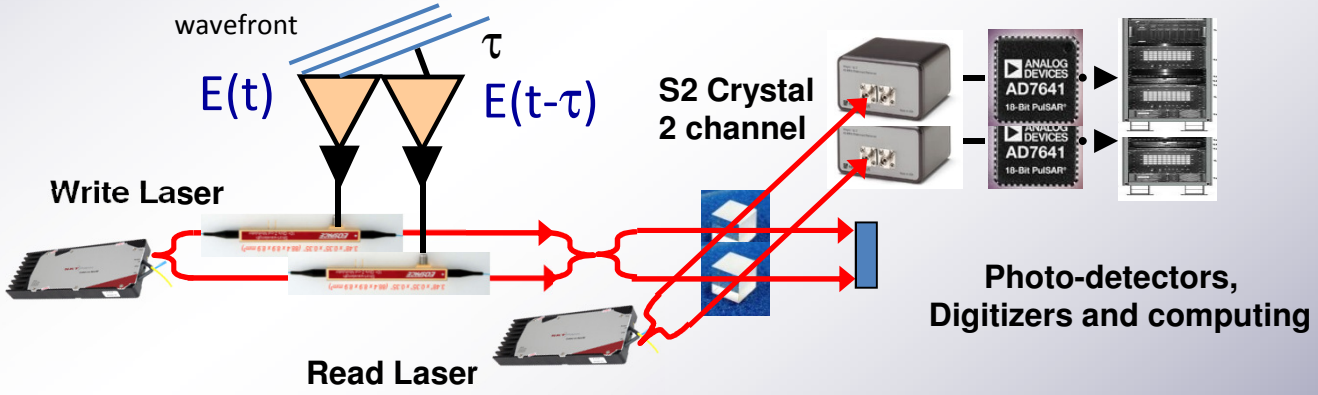
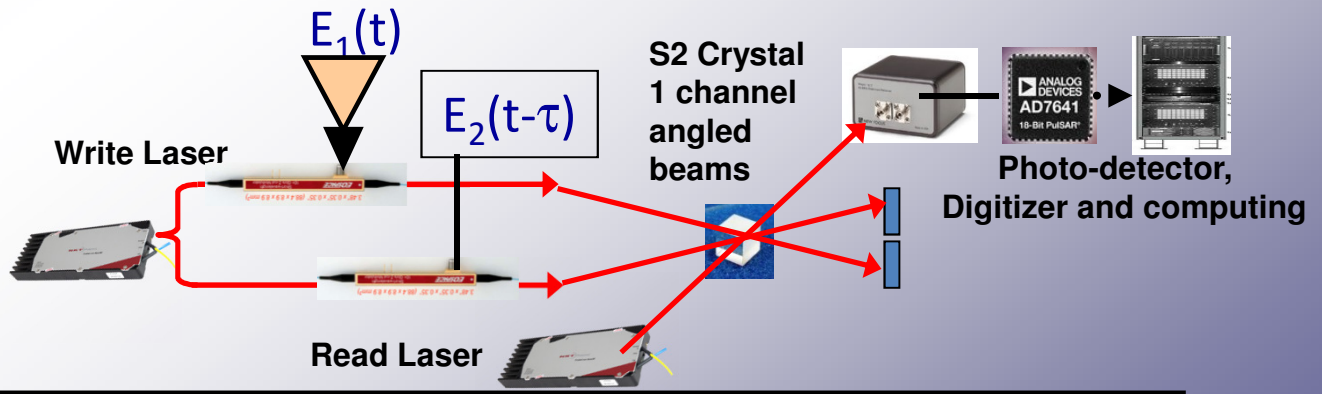
Spectrum Analyzer:
Output is
$|E(f)|^2$



Direction Finding
Spectrum Analyzer:
Output is
$|E(f)|^2$ and $\tau(f)$



Cross Correlator:
Output is
$E_1(f)\ E_2(f)e^{-i\omega\tau}$



S2 EBAC signal processing variations with hardware variations of a common platform

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Spectrum Monitoring

Use Case: RF Ground Truth Spectrum Recorder and EW Spectrum Management / Deconfliction System

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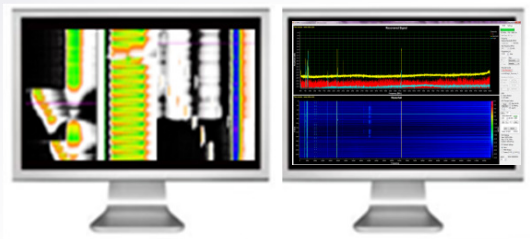
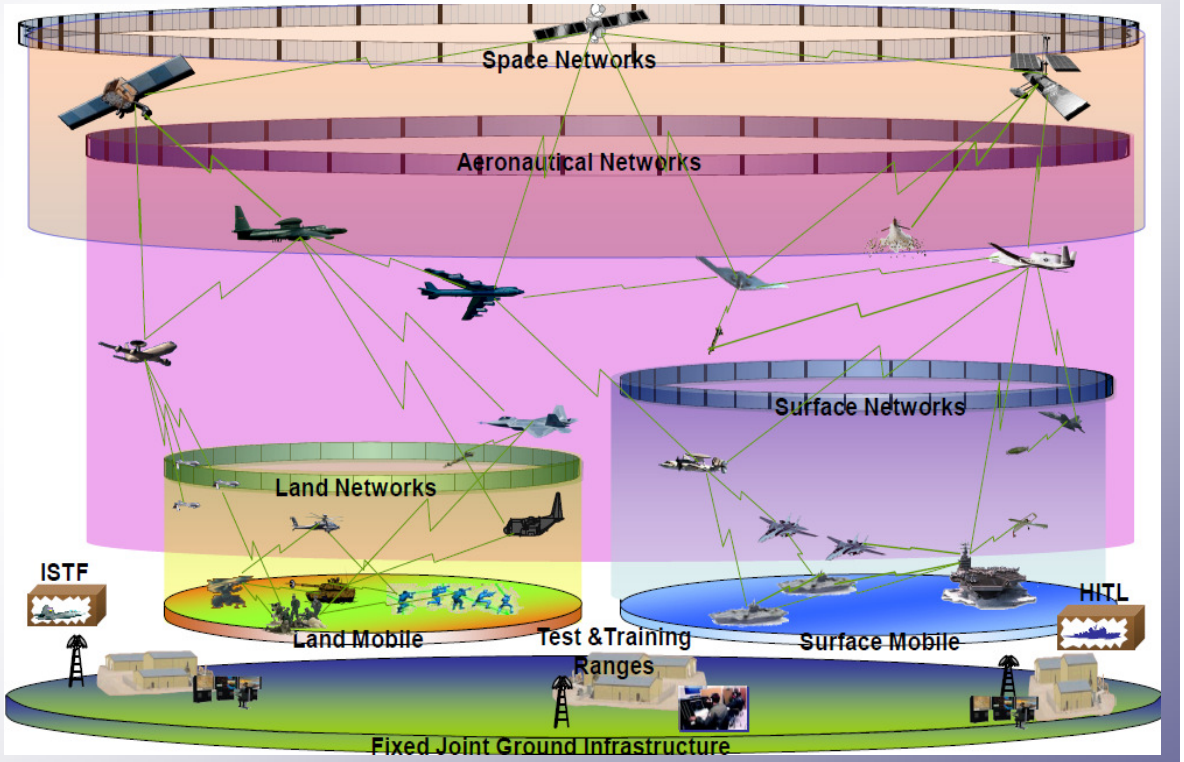
- Wideband antenna(s) and S2 spectrum recorder (0.5 – 40 GHz)
- RF spectrum monitoring 24/7/365 and >24 hour storage of continuous spectrum with playback for RF forensics
- Continuous RF spectrum management across all frequencies simultaneously for communications.
- Detection of waveforms and emitter information
- Tx assessment with change detection and alarms

- Near term adopters:
  - R&D Test & Measurement Users
  - Frequency Management Authorities, Communications users
  - Military Installations,
  - EW Test Ranges





S2 Extreme Bandwidth Coverage Enables Full Awareness & Control of the RF Spectrum During Testing, Training and Operations, Real-Time

Operating Parameters

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Key Performance Parameters (KPPs)	Offered by S2 Corp	Notes
Bandwidth	40 GHz	0.5 to 18 GHz demonstrated, 0.3 to 40 GHz planned, 120 GHz possible
Full frequency coverage	Full 0.3-40 GHz, or any partial span	More versatility for various frequency plans
Dynamic Range, Spur Free	>60 dB	Now >20 dB higher than best existing ADC over 10 GHz; paths forward to achieve >70 dB will be refined
RF Power Sensitivity	-110 dBm	Using >40 dB RF gain, other values possible
Functionality	Spectrum analysis (I only)	S2 provides actionable spectrum displays and can provide cueing to narrowband receivers
Frequencies/second	500,000,000	can scale higher
Frame Rate	2,000-50,000 fps	variable, see readout table
Resolution Bandwidth	10 MHz to 10 kHz	variable, see readout table
Added functionality #1	Phase estimation	as demonstrated on this NSF Ph1 STTR #1217637
Added functionality #2	Direction finding	as demonstrated on Navy Ph2.5 SBIR #N00014-12-C-0292
Added functionality #3	Communications	as demonstrated on NSF Ph1 SBIR #1143361

Typical Spectrum Analysis vs S2 EBAC

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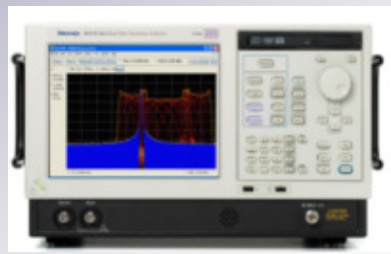
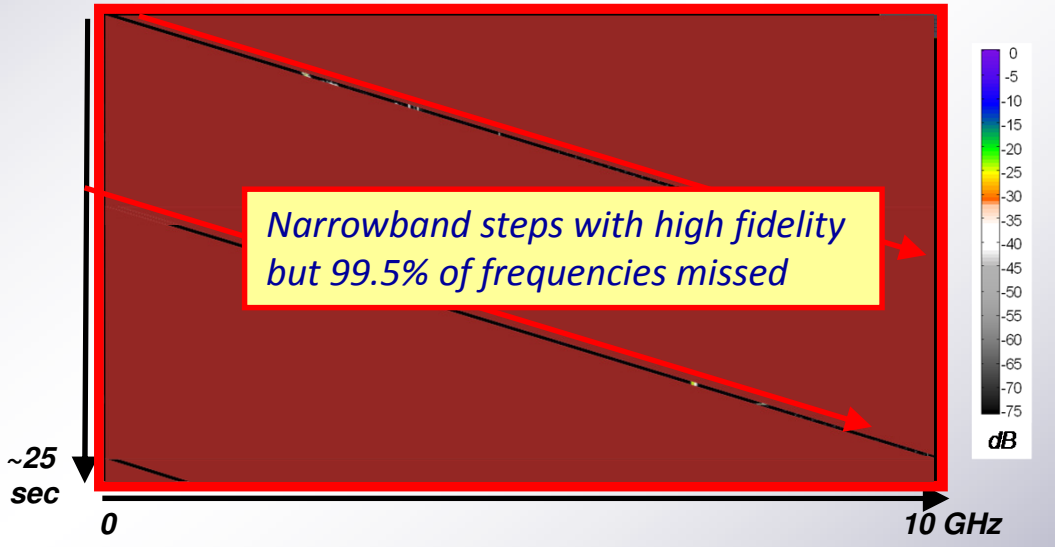
Conventional modern digital stepped FFT based spectrum output displayed as a spectrogram.

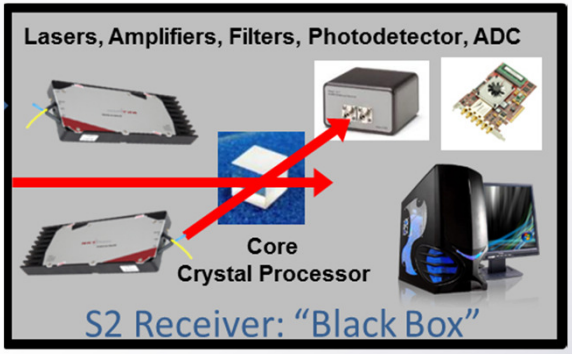
Commercial Real Time Spectrum Analyzer Tektronix RSA6120A IBW = 110 MHz, 75 dB SFDR

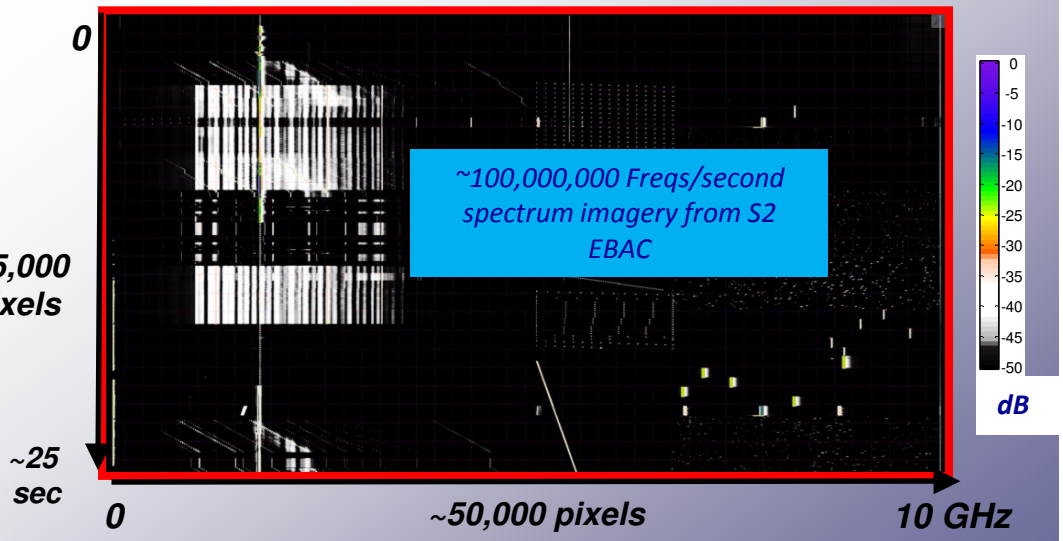




S2 EBAC continuous spectrum analysis digital data stream output displayed as a spectrogram.

S2 Real-Time Spectrum Analyzer IBW = 40 GHz, 60 dB SFDR





IBW= 10 GHz RBW= 0.8 MHz FR = 1 kHz

IBW= Instantaneous Bandwidth; RBW=Resolution Bandwidth; FR = Frame Rate

Display of S2 EBAC for Spectral Analysis

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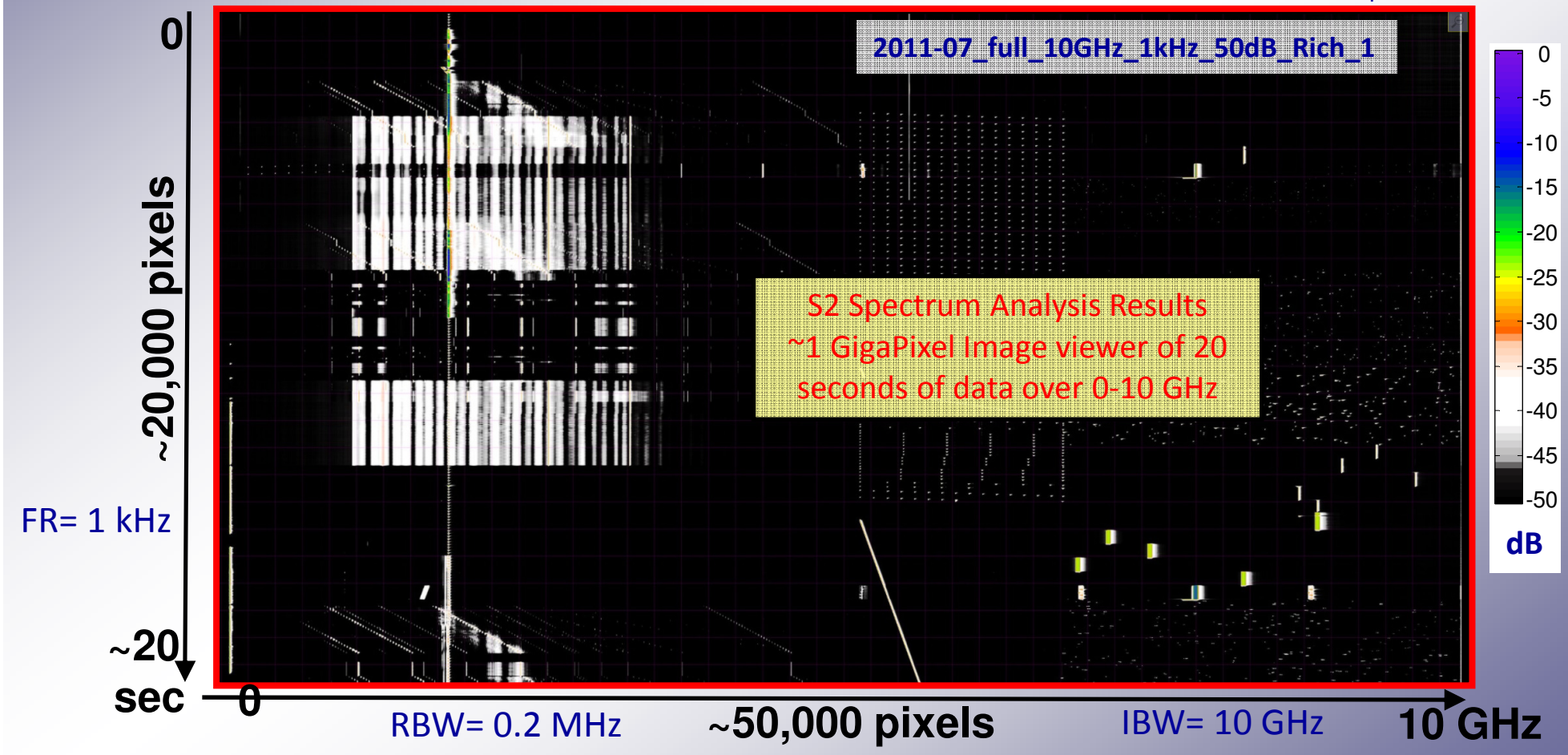
S2 EBAC output is a digital data stream displayed as a spectrogram [power(f) vs. time].

This image shows 10 GHz IBW, 200kHz RBW (50,00 frequency pixels per frame) and a frame rate updated 1,000 times per second.

Spur free dynamic range (SFDR) of this data was 50 dB, since improved to 60 dB.

IBW= Instantaneous Bandwidth
RBW=Resolution Bandwidth
FR = Update Rate



S2 EBAC Spectrum Analysis Images: Data visualization with display scaling

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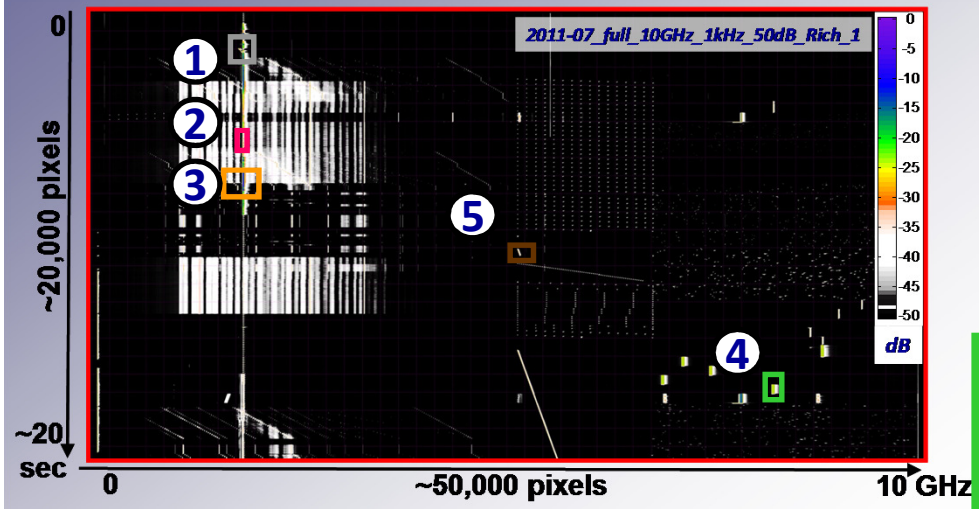

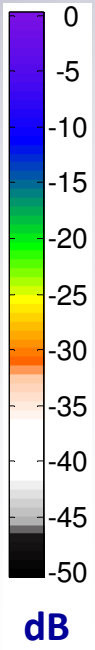

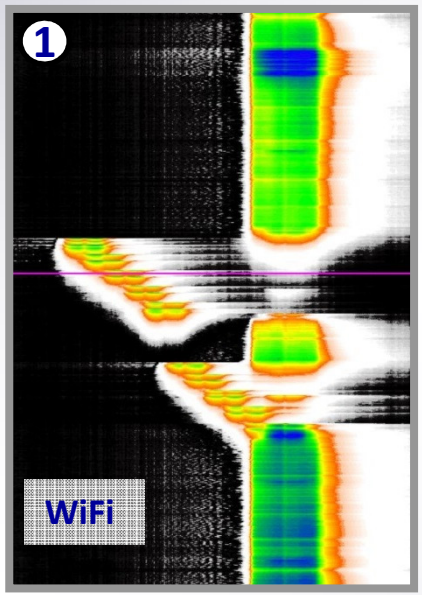

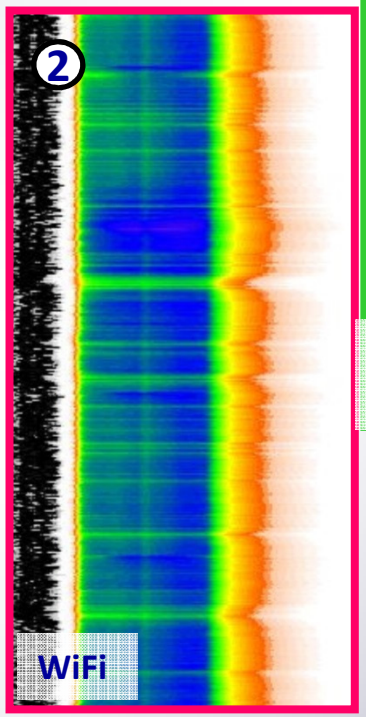

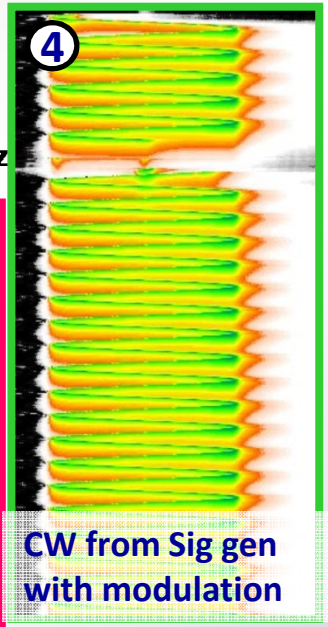

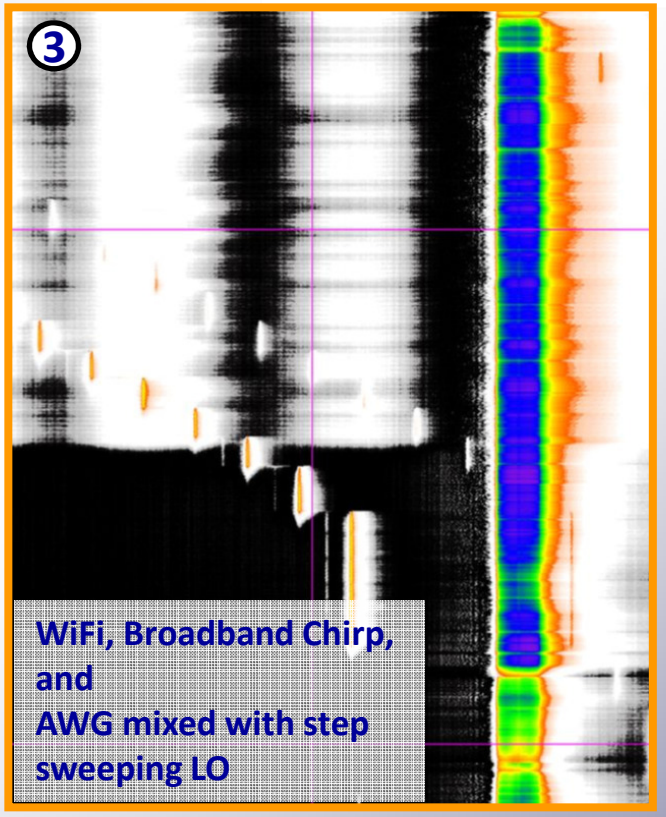

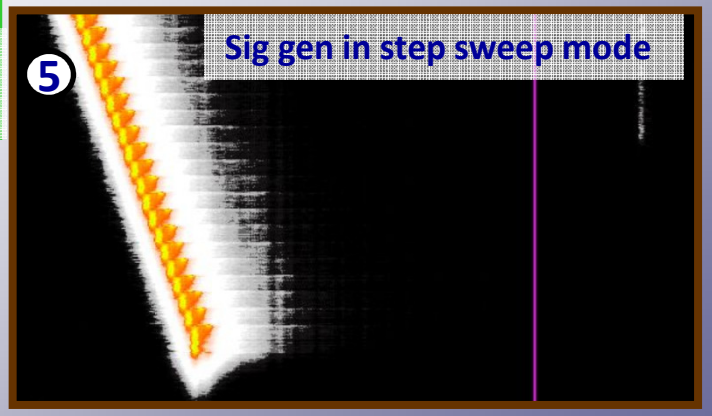

Example Data Capture: 1 min collection of Rich RF data with >60 dB Dynamic Range and -110 dBm sensitivity

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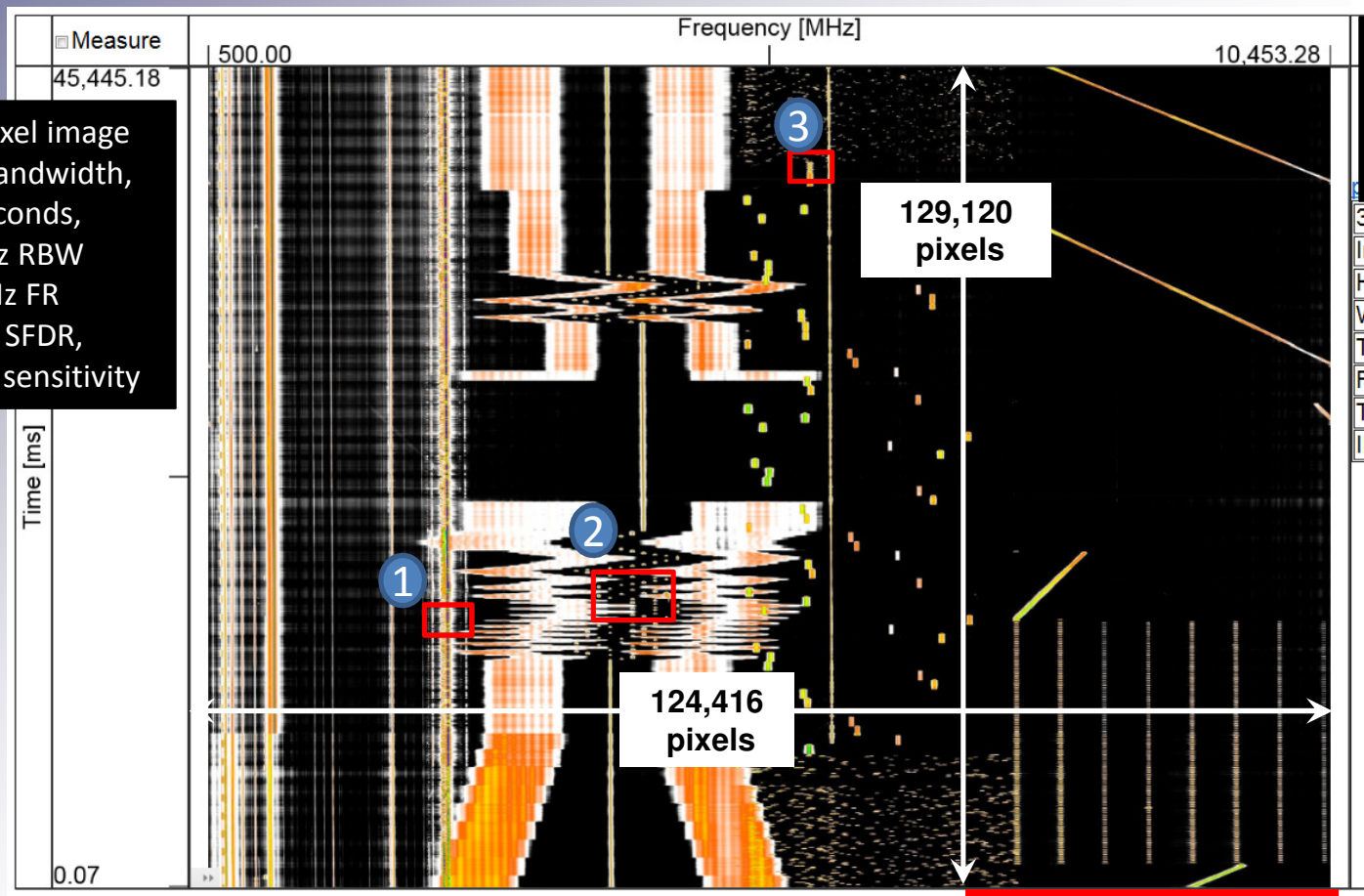
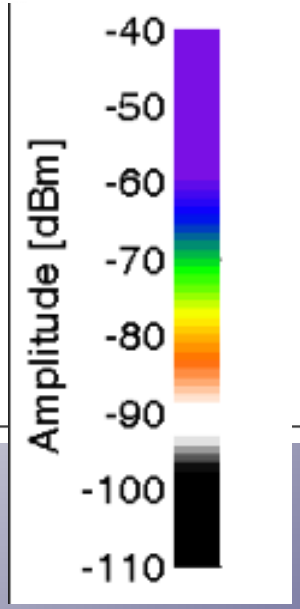
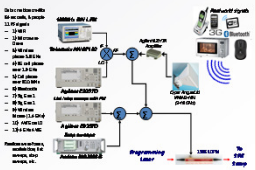
16 GigaPixel image
10 GHz bandwidth,
45 seconds,
80 kHz RBW
2 kHz FR
60 dB SFDR,
-110 dBm sensitivity

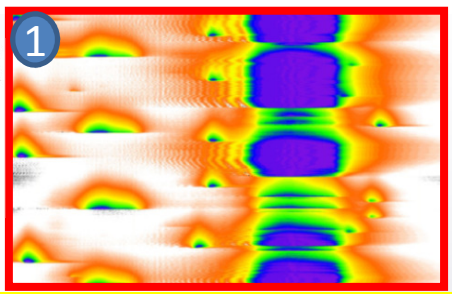


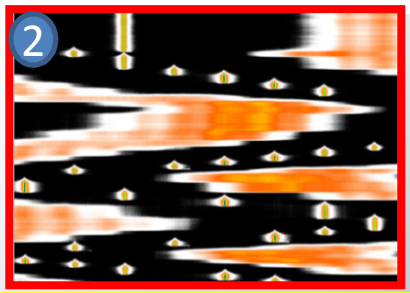
Laboratory spectrum capture of Rich RF environment using 13 sources

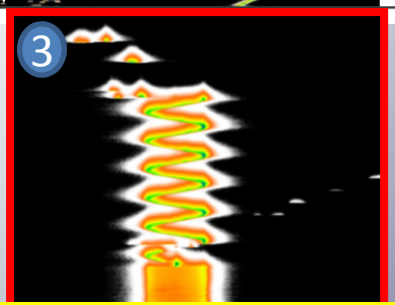
3		
Image Size:	16.1	Gigapixels
Height:	129,120	frames
Width:	124,416	freqs per frame
Time res:	500	µs per pixel
Freq res:	0.08	MHz per pixel
Total time:	64,560	ms
IBW:	9,953.28	MHz











One would need 7,800 HDTV monitors (120 x 65) to view every pixel in this image

Sensitivity and SFDR Measurements for Raw RF and Frequency Conversion with Gain

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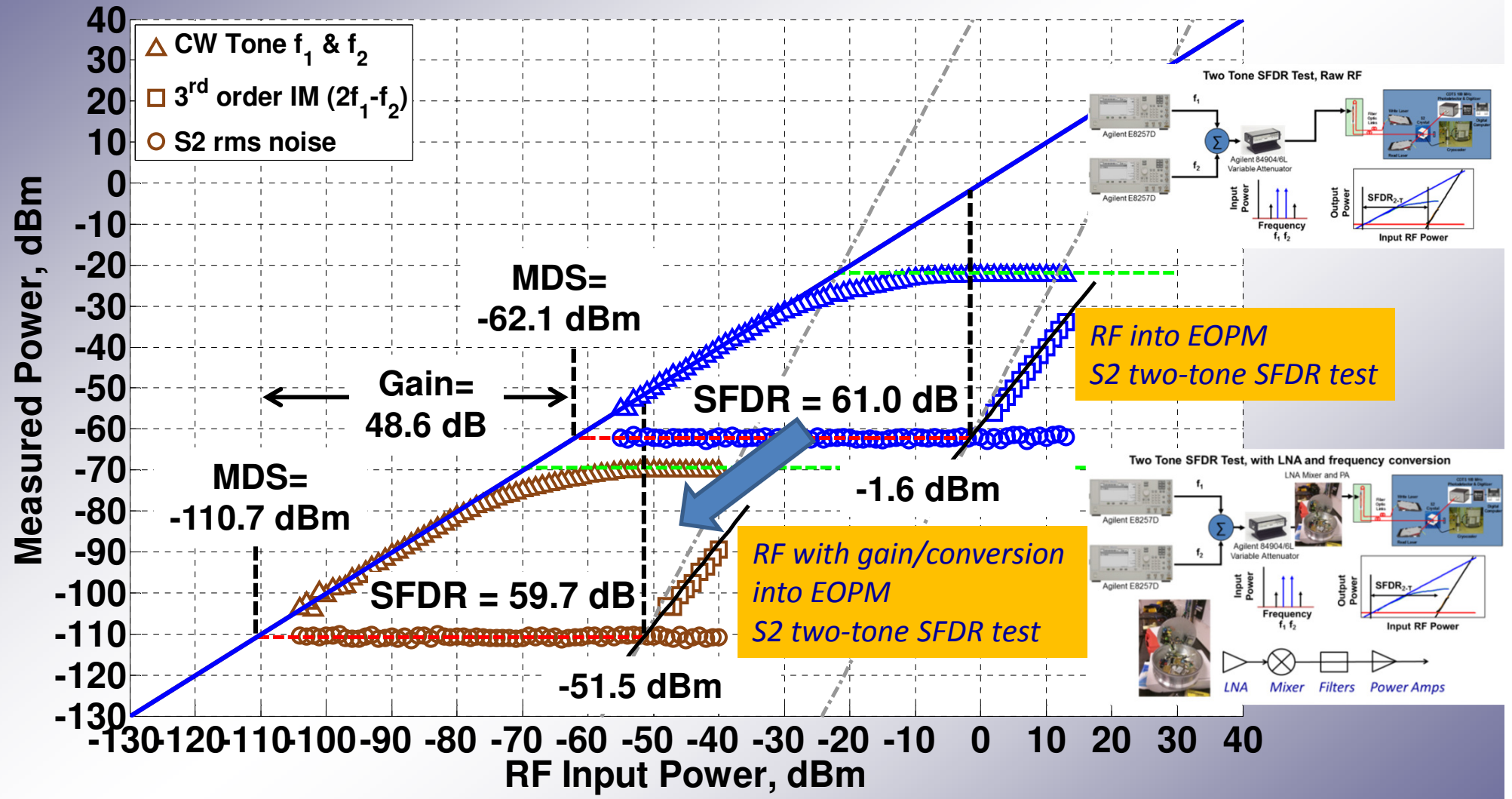
Two-tone Spur Free Dynamic Range (SFDR)



S2 with RF Gain (48 dB) Increases RF Sensitivity to -110dBm levels for 1 MHz RBW

Operating Parameters

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VARIATIONS IN S2 EBAC PARAMETERS WITH AGILE READOUT LASER

Digitizer Sample Rate	250	Ms/s
Digitizer Bandwidth	100	MHz
Photodetector Bandwidth	14	MHz
Pixels per RBW	2.5	

0.01 = RBW limit of crystal

BANDWIDTH per channel	0.5	1	2	5	10	20	GHz	Freq. Pixels per Frame	Time Pixels per second	FR Loss, dB
Read time, µs	**Frame Rate, kHz**	**RESOLUTION BANDWIDTH varying BANDWIDTH & FRAME RATE**								
500	**2**	0.01	0.02	0.04	0.10	0.2	0.4	125,000	2,000	-3.84
200	**5**	0.03	0.05	0.10	0.3	0.5	1.0	50,000	5,000	-1.53
100	**10**	0.05	0.10	0.2	0.5	1.0	2.0	25,000	10,000	-0.77
50	**20**	0.10	0.2	0.4	1.0	2.0	4.0	12,500	20,000	-0.38
20	**50**	0.3	0.5	1.0	2.5	5.0	10.0	5,000	50,000	-0.15
10	**100**	0.5	1.0	2.0	5.0	10.0	20.0	2,500	100,000	-0.08
5	**200**	1.0	2.0	4.0	10.0	20.0	40.0	1,250	200,000	-0.04

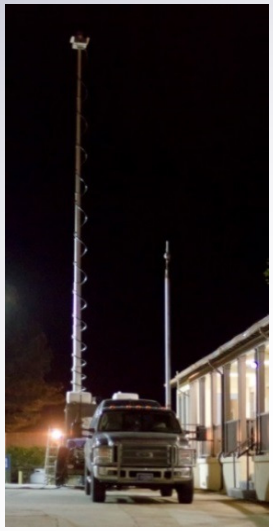
MHz

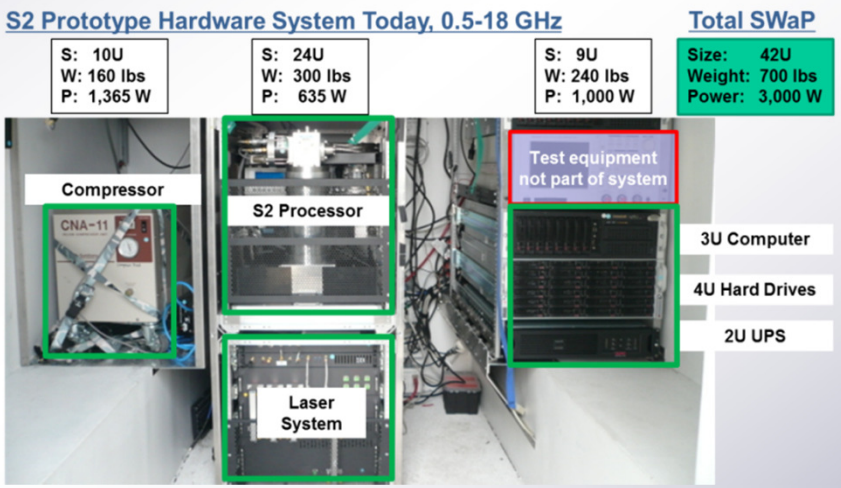
Variations in the RBW, IBW and FR can be made on the fly with the readout laser controller

0.5-18 GHz Field Testing efforts in 2013 For Spectrum Monitoring

S2 CORPORATION
— THE SPECTRUM in a FLASH —

San Diego, CA March 2013
Point Mugu, CA





TNT Camp Roberts, CA June 2013

Ft. Bragg, NC
October 2013
(planned)

Idaho National Labs
November 2013
(planned)

Mobile Shelter Mounted S2 System with Mast Antenna Deployment Used in Field Tests

Use Case Configuration: Spectral Monitoring System

S2 CORPORATION
— THE SPECTRUM in a FLASH —

- **Two antenna feed configuration S2 hardware with "lowest SWaP" metrics**

Total:
S: 32U (39 ft^3)
W: 500 lbs
P: 3,000 W

Specifications:
2 spectral monitoring channels, 1 or 2 antennas
Bandwidth 0.5-20 GHz, 20-40 GHz or 0.5-40 GHz
24 Hours of full recording

Antennas and RF

Connections:
a) Fiber optical and
b) electrical

System Racks

System Parts:
Antennas 75m from racks
S: 4U (5 ft^3)
W: 50 lbs
P: 100 W

Rack #1
S: 14U (17 ft^3)
W: 225 lbs
P: 2,300 W

Rack #2
S: 14U (17 ft^3)
W: 225 lbs
P: 600 W

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SIGINT
Phase Sensitive
Spectrum Monitoring

Phase sensing with Two-channel operation

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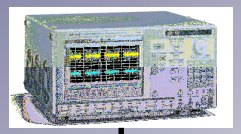
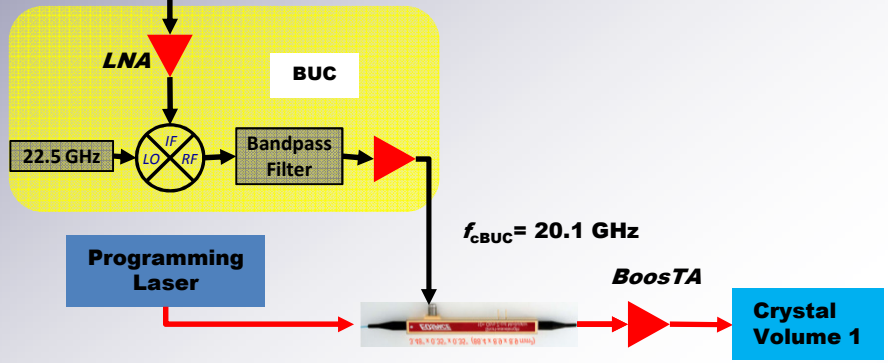
— THE SPECTRUM in a FLASH —

Spectrum Analysis:
1 channel system

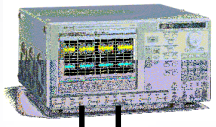


f_{cAWG}= 2.41 GHz

e.g. OOK, PSK and QAM signals



Phase Coherent Spectrum Analysis
2 channel system

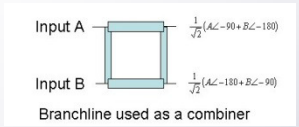


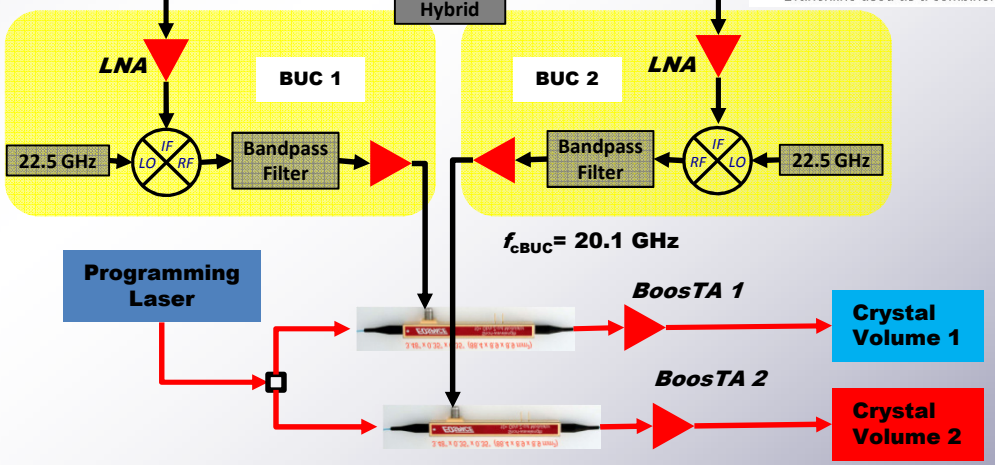
f_{cAWG}= 2.41 GHz

CH. 1 "Reference Signal"

CH. 2 e.g. OOK, PSK QAM signals, etc

RF hybrid

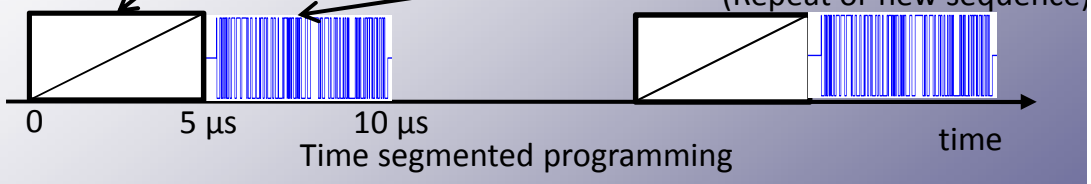




$$E_{SOI} = \cos\left(2\pi f_s(t-\tau)\right) P_n(t-\tau)$$

$$E_{ref} = \cos(2\pi f_c t + \pi\kappa t^2)$$

$$E_{SOI} = \cos\left(2\pi f_s(t-\tau)\right) P_n(t-\tau)$$



Readout pulse
Variable chirp rate
(1 GHz in 500 us
for these results)

Phase sensing with Two-channel operation

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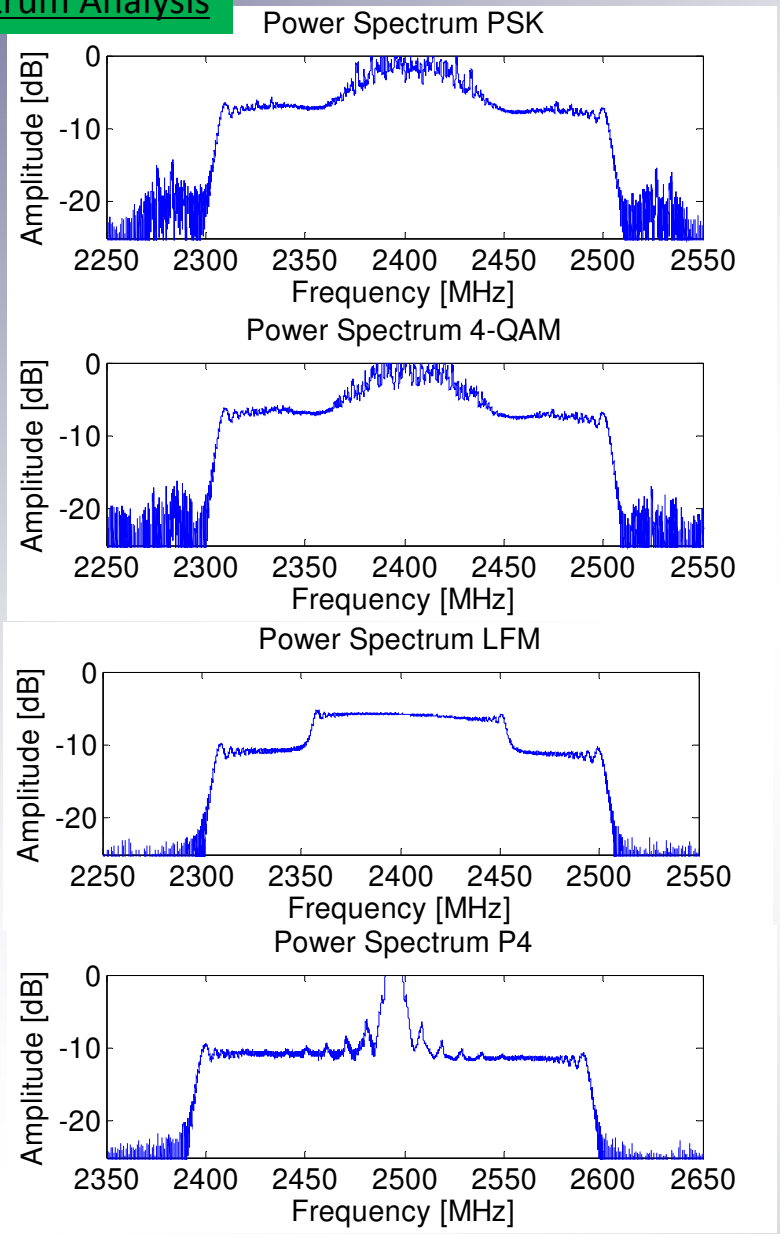
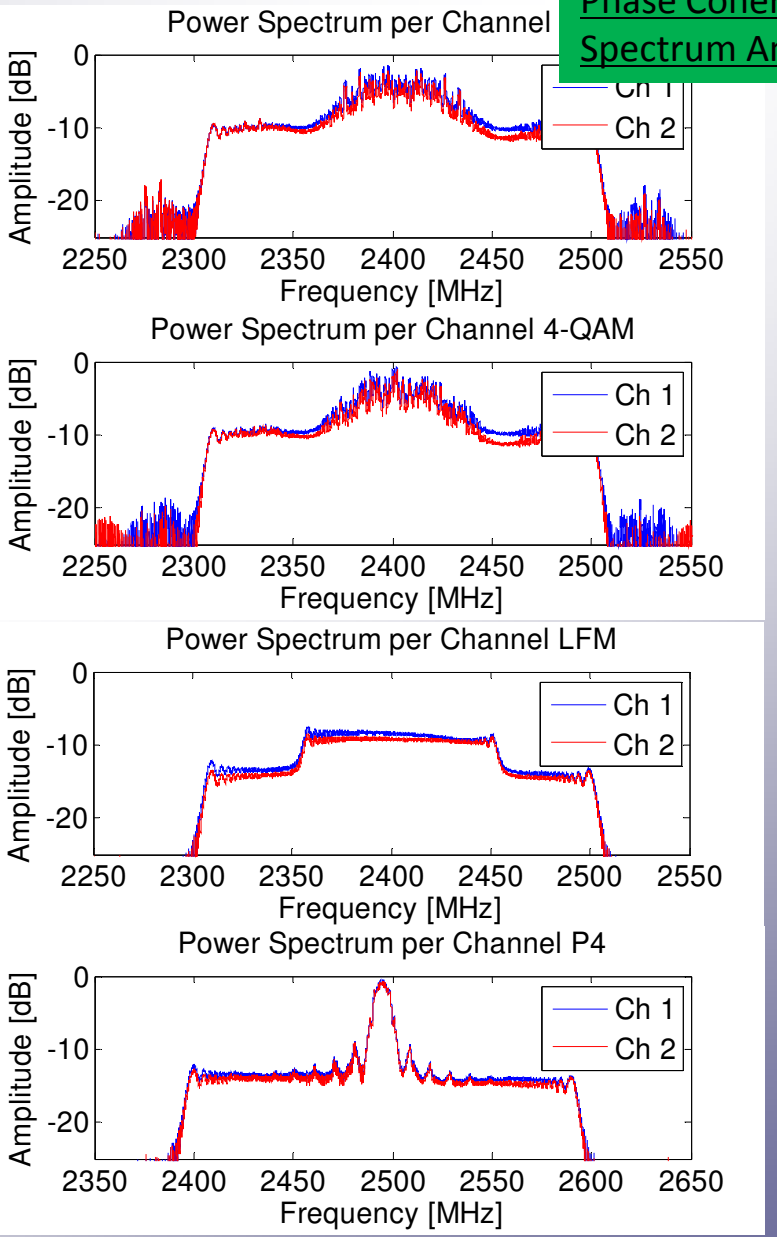
Spectrum Analysis



Phase Coherent Spectrum Analysis



Summary of Results of Phase Sensing with Two-channel S2 operation

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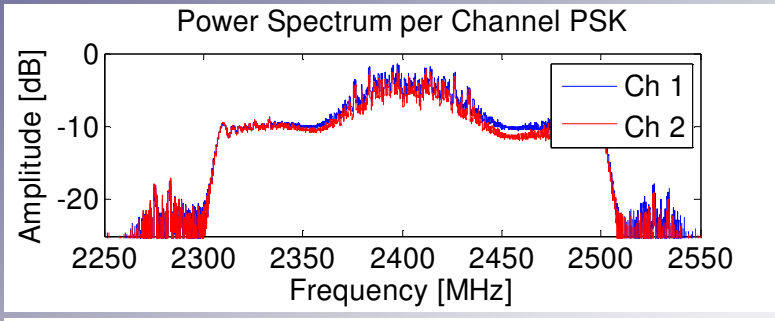
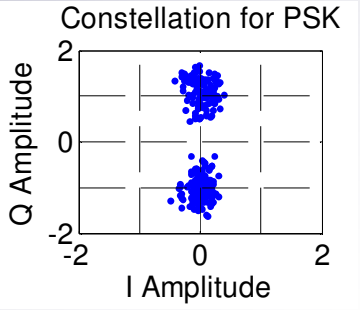
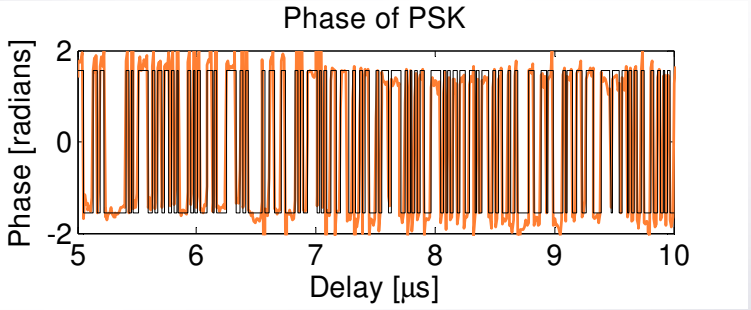
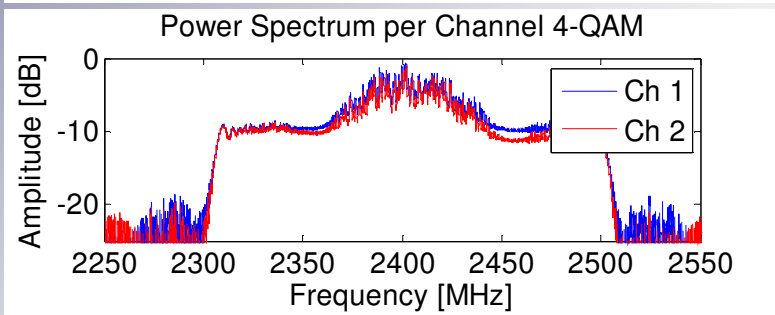
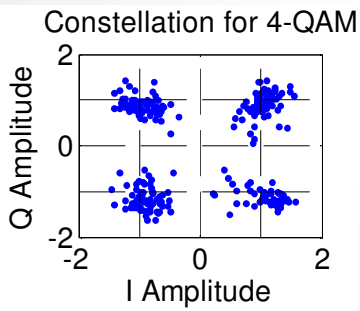
— THE SPECTRUM in a FLASH —

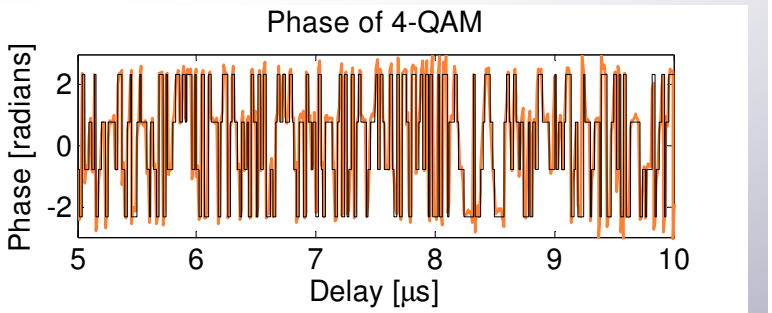


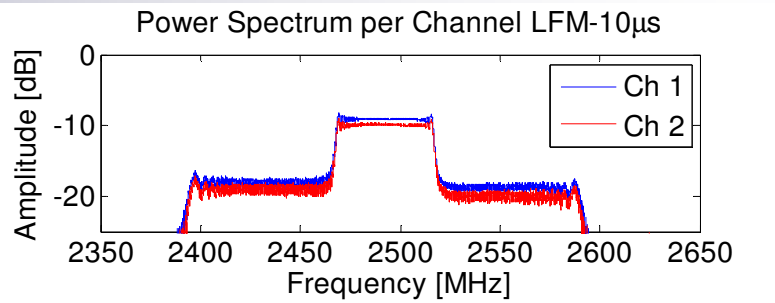


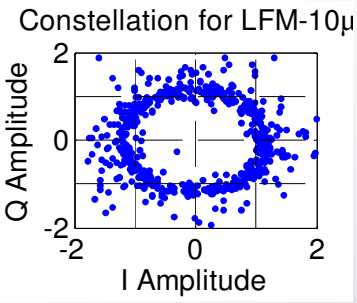


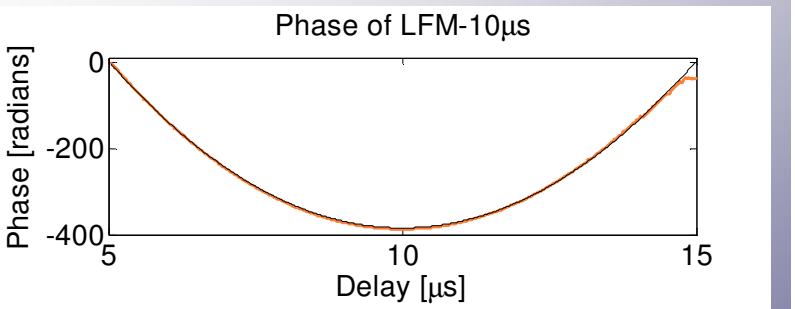


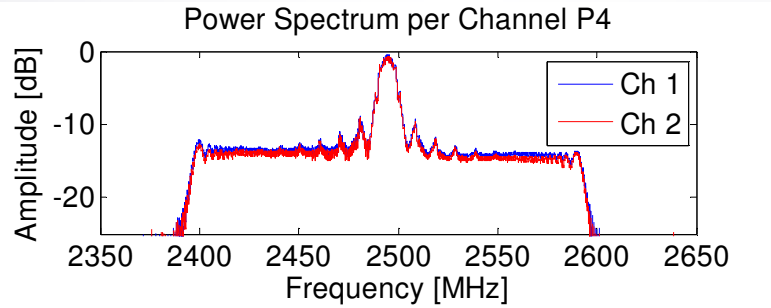


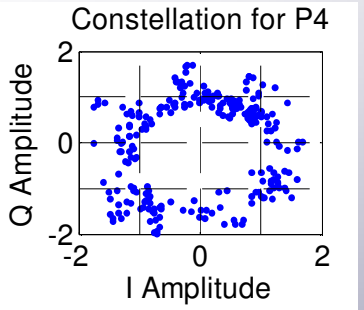


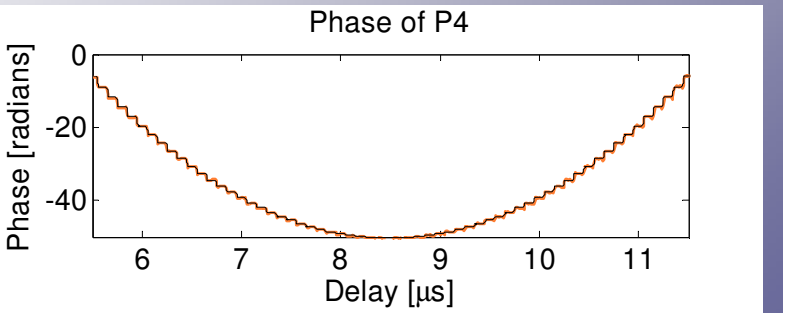












S2 CORPORATION
— THE SPECTRUM in a FLASH —

Performance Information and Comparisons

Exponential Progress in Key Performance Parameters Over the Past Decade

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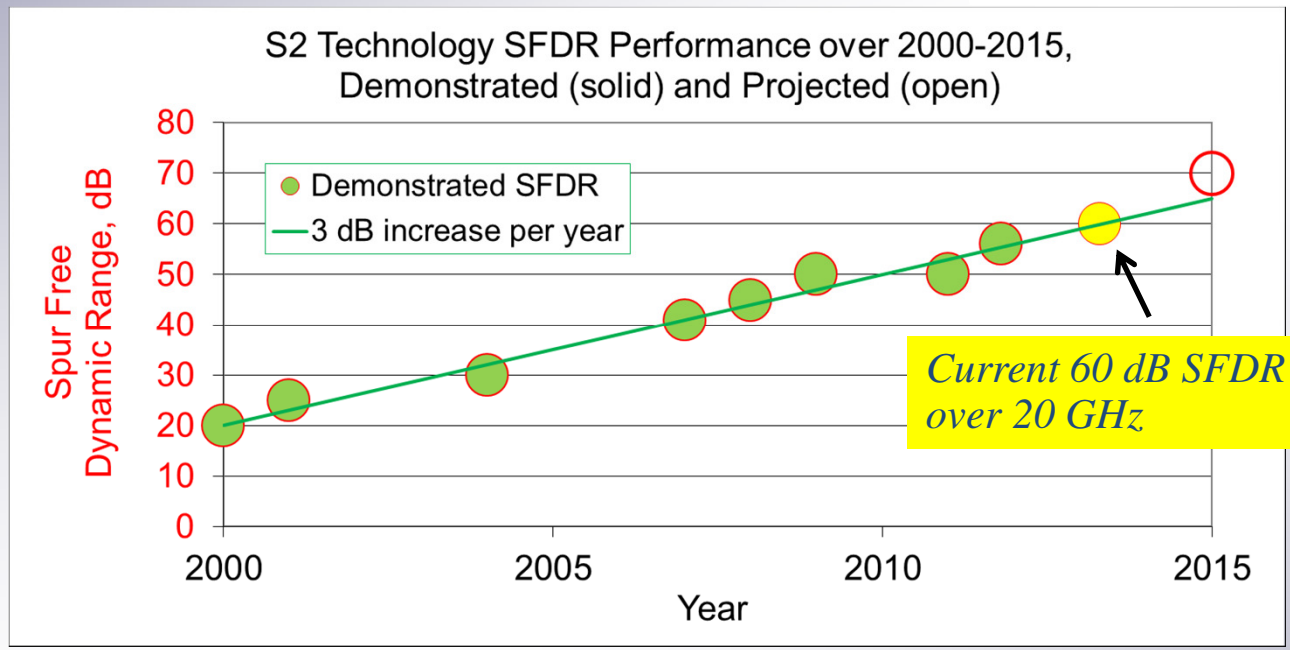
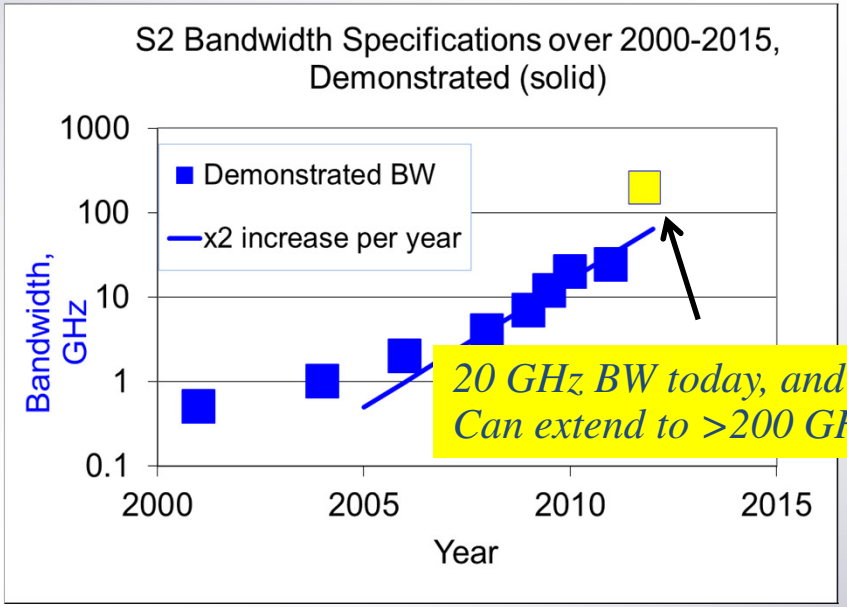
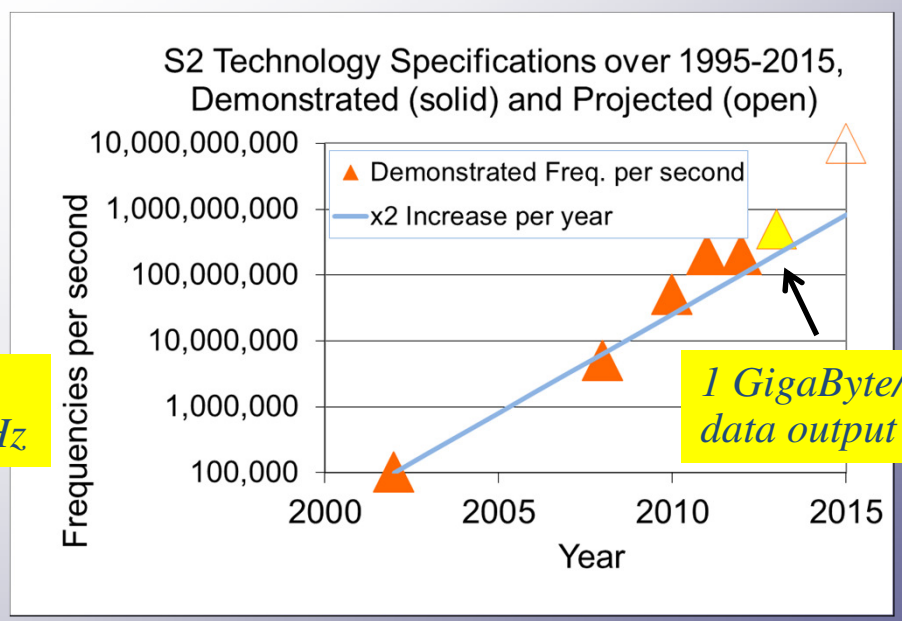
Significant performance increases in Dynamic Range, Bandwidth and Measured Frequencies per Second over decades, showing an astounding trend of performance doubling per year… with significant additional grow to capability







S2 EBAC Compared to Wideband Digitizers for Spur Free Dynamic Range

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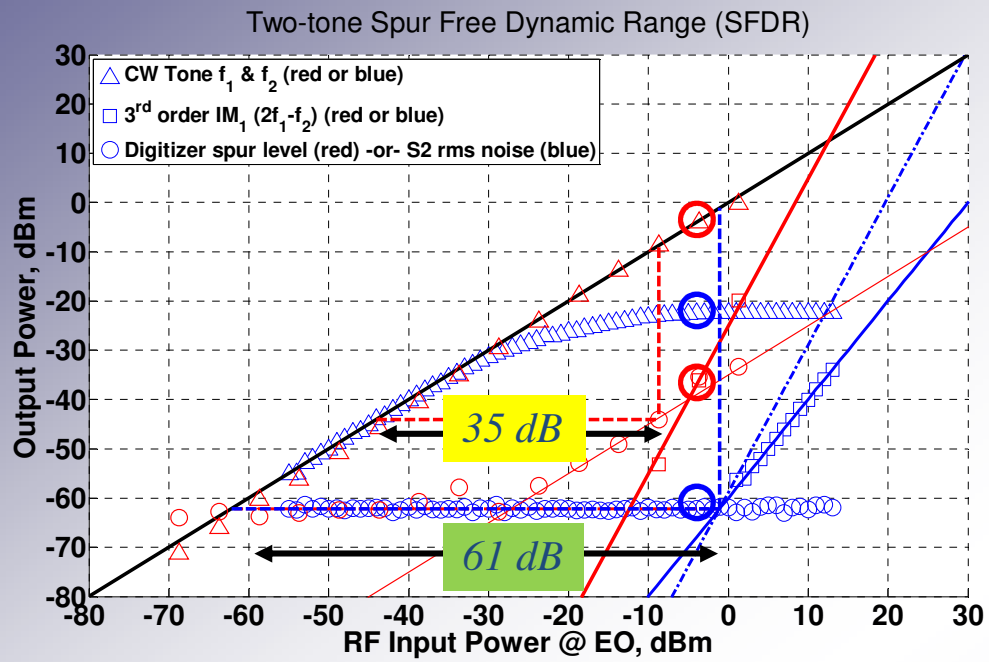
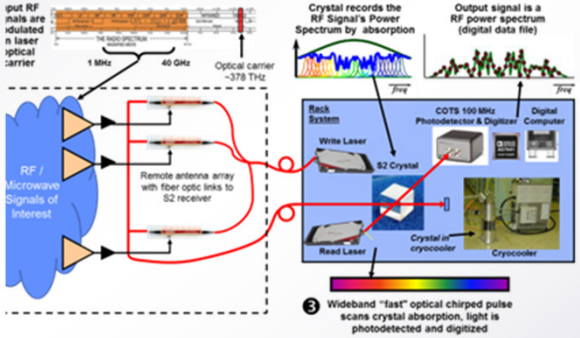


50 Gs/s digitizers have a sea of digitizer spurs above its noise floor with:

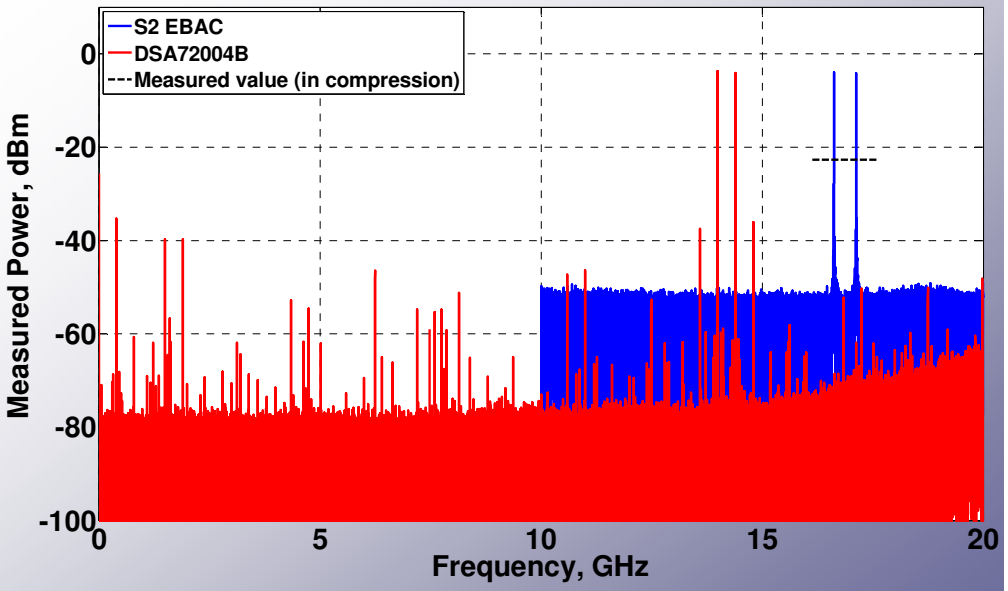
- *40 dB SFDR over 10 GHz &*
- *35 dB SFDR over 20 GHz*

S2 has a flat noise floor with:

- 60 dB SFDR over 20 GHz



S2 EBAC vs Tektronix DSA72004B
RF power in = -4 dBm



S2 EBAC has x400 better dynamic range (26 dB) than 20 GHz wideband digitizers

Baseline Digital Technology for Spectrum Analysis

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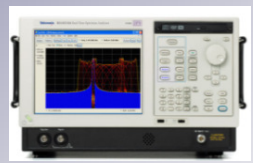
Narrowband ADCs and modest digital computing can provide continuous monitoring …

e.g. Tektronix RSA6120A



with high sensitivity
>70 dB SFDR

…but, with low bandwidth
110 MHz

Desired:
Continuous monitoring

Continuous Monitoring, 100% POI

S2 EBAC

offers the combined desired attributes

Sensitivity 20 dB higher than 50 Gs/s ADC s

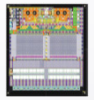
Bandwidth >20 GHz and scaling to >100 GHz

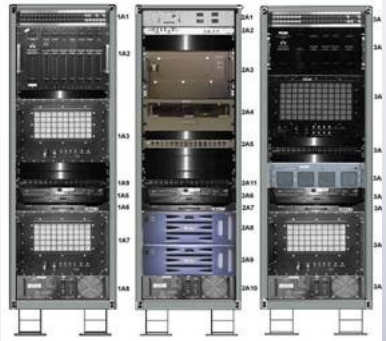
Desired: High sensitivity with >60 dB SFDR

Desired:
Bandwidth >20 GHz

Wide Bandwidth >20 GHz ADCs followed by racks of computers could provide continuous monitoring

ANALOG TO DIGITAL CONVERTER
FUJITSU
56GSa/s 8-bit





with high bandwidth
>20 GHz

…but, with poor sensitivity
~35 dBc SFDR

SFDR = Spur Free Dynamic Range

Current approaches are limited in combined performance…
S2 EBAC combines the desired attributes

Comparison of Conventional Spectrum Analysis Technology to S2 EBAC

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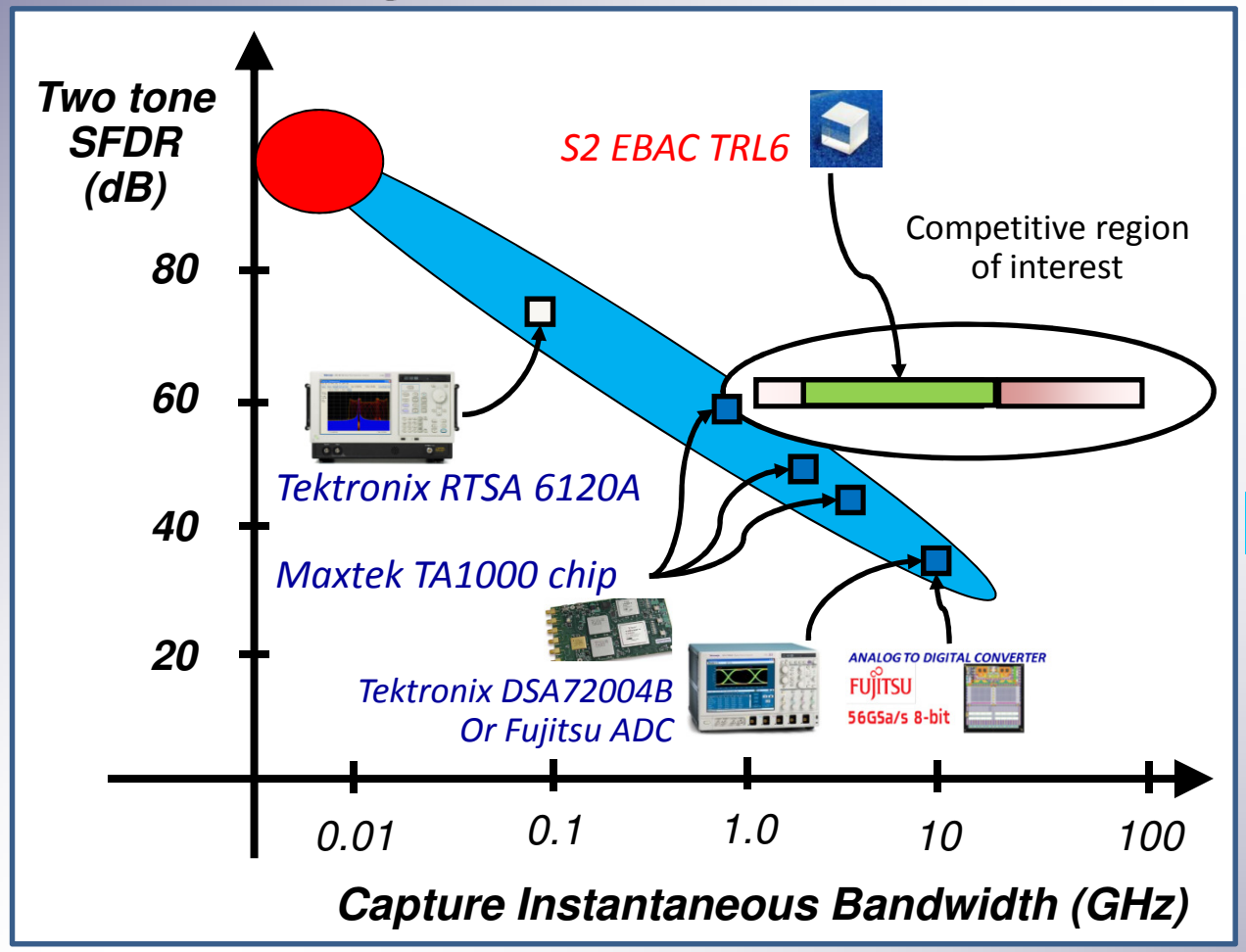
- Analog Conventional Scanning Spectrum Analyzer
- Digital Spectrum Analyzer FFT based
- Analog Photonic S2 EBAC Spectrum Analyzer



Probability of Intercept over 40 GHz

Swept carrier -- 0.01%

0.1 GHz Digital FFT ------ 0.25%

S2 EBAC ---------- 100%

1-40 GHz Digital FFT -- 2.5-100%

IBW = Instantaneous Bandwidth
SFDR = Spur Free Dynamic Range
POI = Probability of Intercept

S2 EBAC offers 100% probability of intercept 40 GHz coverage with same fidelity of a 1 GHz digitizer

Digital Wideband Spectrum Analysis: Disadvantage of Large Number of Required Computations

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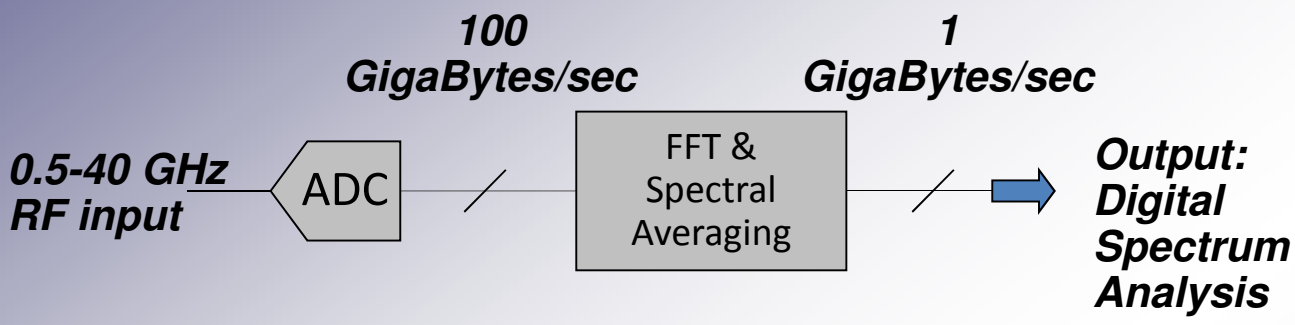

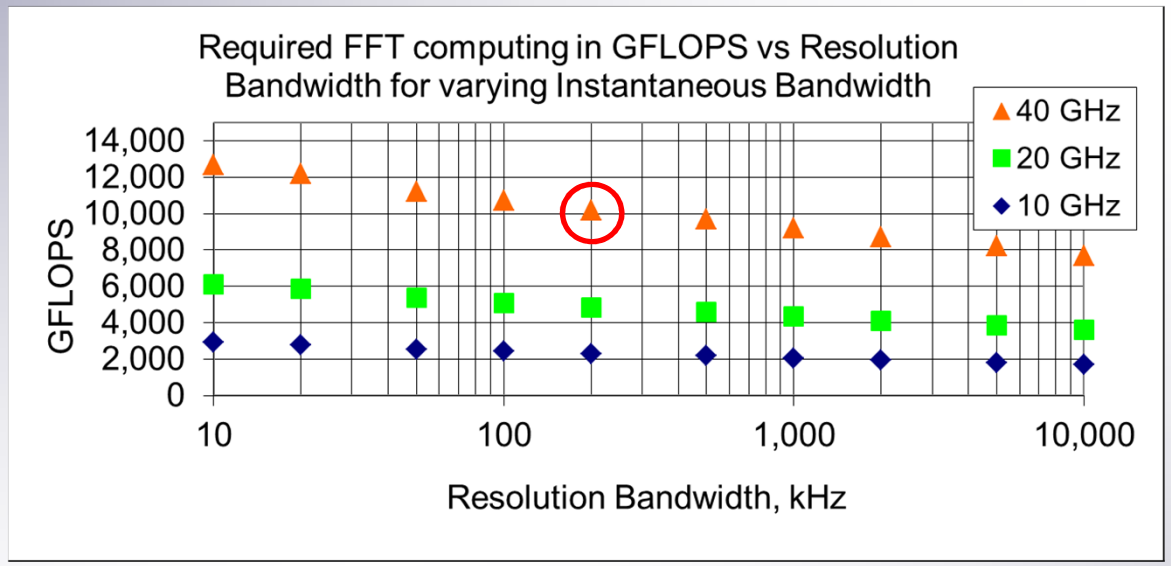

334 GFLOPS of FFTs per Kepler K20x GPU

32 GPUs in 8 chassis

4 GPUs per chassis

Estimate of 32 GPUs:
(Nvidia Kepler K20X)
in 8 computer chassis

Size:	32U	(8 x 4U)
Weight:	720 lbs	(8 x 90 lbs)
Power:	16 kW	(8 x 2 kW)

Digital SA solutions are computationally intensive… for IBW=40 GHz, RBW=0.1 MHz, FR=2 kHz a whopping **10 TeraFLOPS** of FFT computing is required per antenna.

Digital 40 GHz spectrum analysis requires massive computing

40 GHz Spectrum Analysis Operation Comparison: Wideband Digital vs. S2 EBAC

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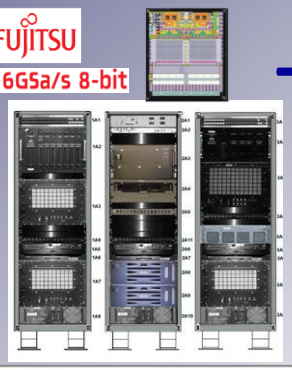
ANALOG TO DIGITAL CONVERTER

FUJITSU
56GSa/s 8-bit



+

Vs.

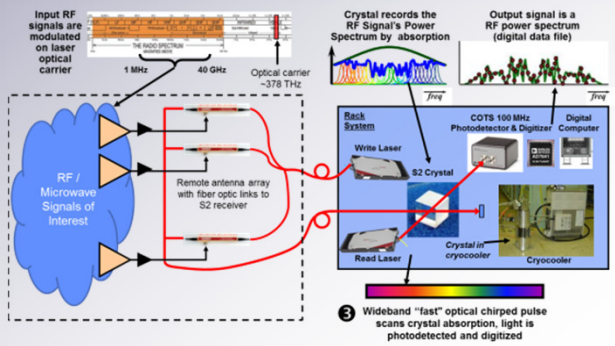
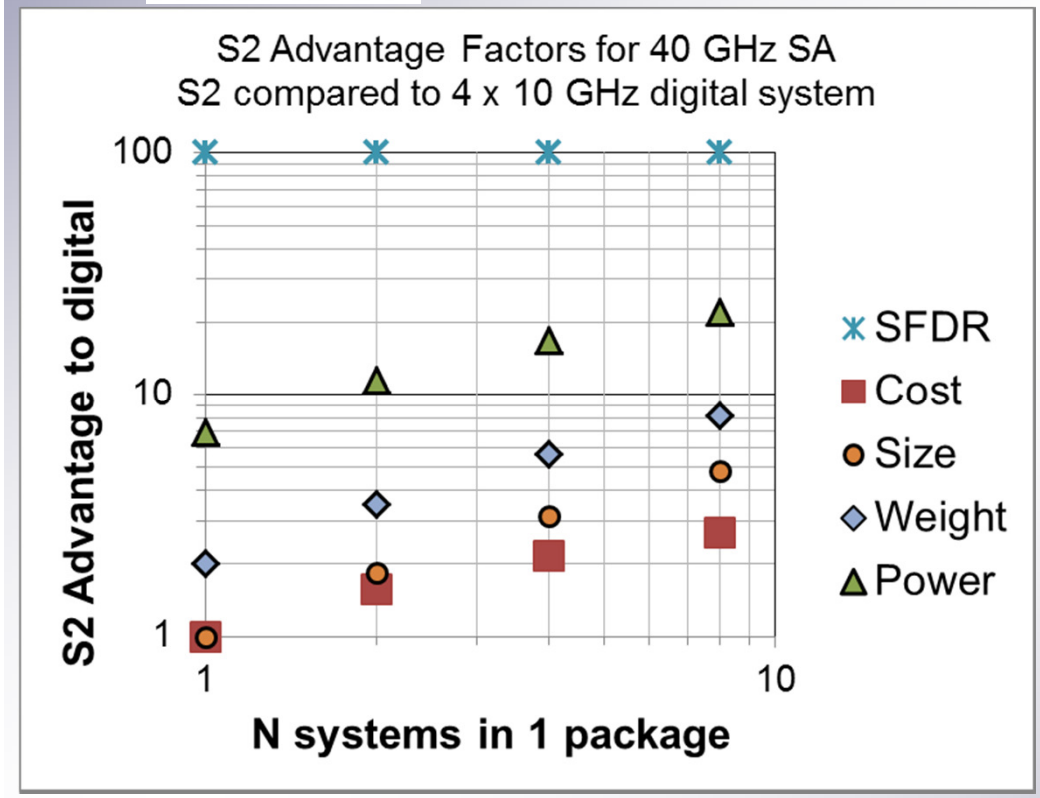
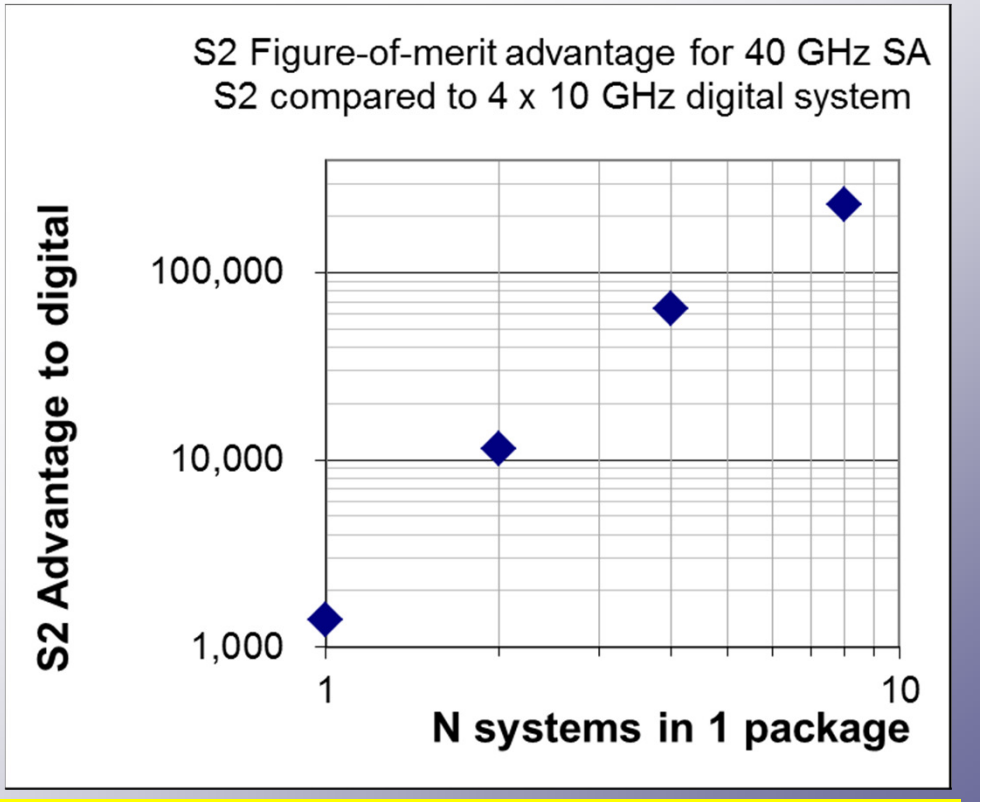


Figure of Merit

$$= \frac{SFDR_{2\text{-}T}}{(Cost \times Size \times Weight \times Power)}$$





Massive advantages for S2 processing in combined metrics over digitizers and computing

Highly Efficient FFT Computing:
S2 EBAC Compared to Digital FFT systems

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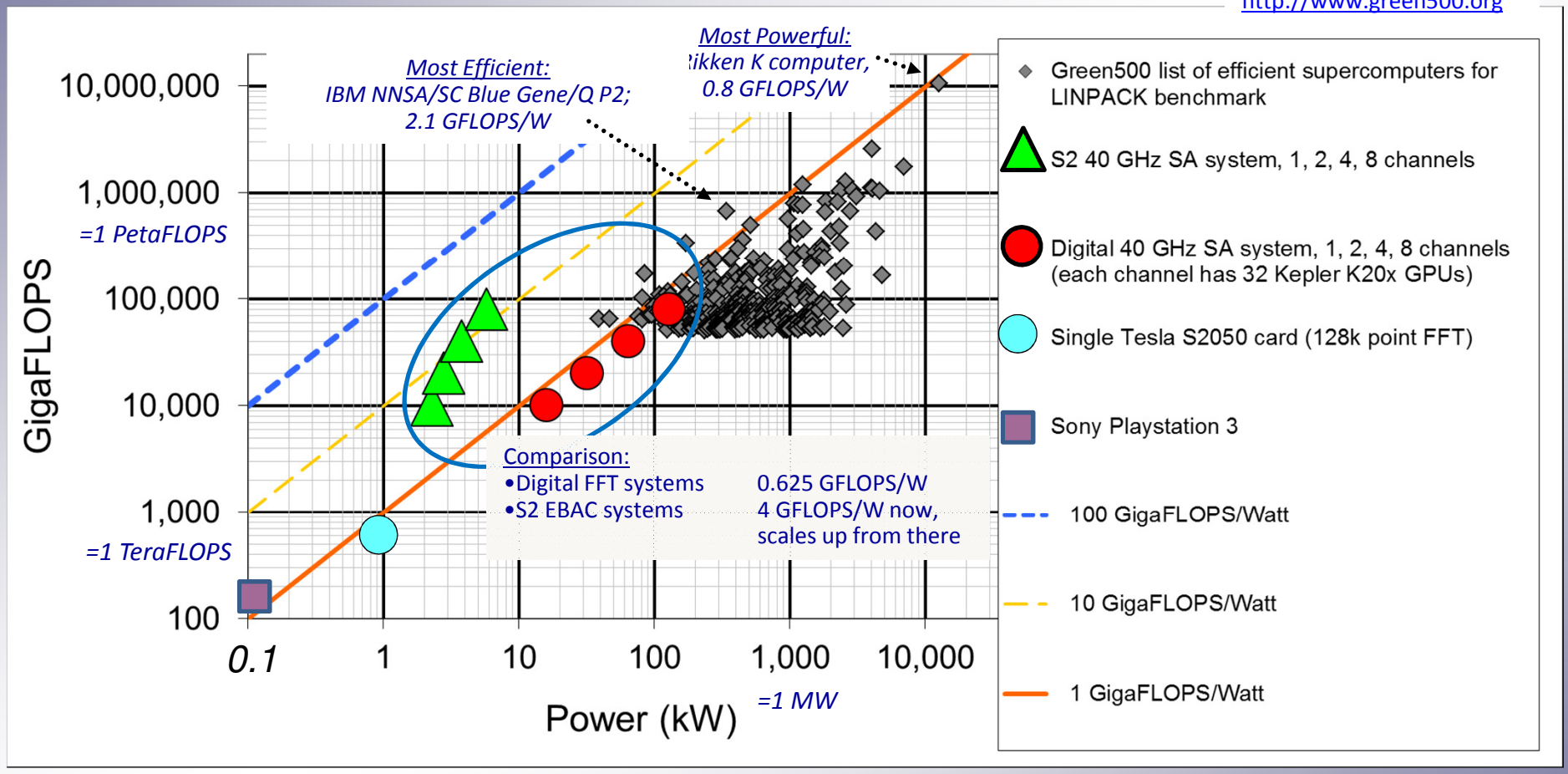
FLOPS = Giga Floating Point Operations per Second

REFERENCE:
http://www.green500.org



S2 EBAC's analog wideband Fourier Transform processing is a highly efficient computational engine… surpassing the best Fast Fourier Transform (FFT) computers by more than an order of magnitude

Summary of S2 EBAC Leap-Ahead Capabilities

S2 CORPORATION
— THE SPECTRUM in a FLASH —

- **S2's EBAC enables applications including …**
  - SPECTRUM MONITORING - Ground truth recording, 24/7, playback & visualization
  - GEOLOCATION OF TRANSMITTERS - Real-time high res. angle-of-arrival on agile, short-up time Tx
  - SIGINT CUEING & WARNING RECEIVER - Real-time RF signal assessment
  - COMMUNICATIONS - Covert Tx emissions between S2 nodes, long distance, high bit rate
  - SIGNAL PROCESSING - Analog matched filtering and signal selection, data mining
- **S2's EBAC offers…**
  - True instantaneous bandwidth (IBW) performance: >40 GHz today and scaling to >120 GHz
  - High spur free dynamic range (SFDR) over full IBW: >60 dB today, and scaling to >70 dB
  - High sensitivity: >-110 dBm over 1 MHz resolution bandwidth with >60 dB SFDR
  - Low SWaP receiver hardware systems
  - Handling many antennas in a single receiver
  - No need for massive digital computing at antennas
  - Remote antenna deployment at far distances from the S2 receiver with fiber connection
- **S2's EBAC is readily implementable…**
  - Uses 80% COTS components and 20% modified COTS/GOTS specialty components
  - Rugged packaging in standard racks/ hardside cases and/or in mobile configurations

S2's EBAC Enables Transformational EMS Knowledge, Use and Control TODAY