New Concepts for Improving Dynamic Range in (M)PDV Systems

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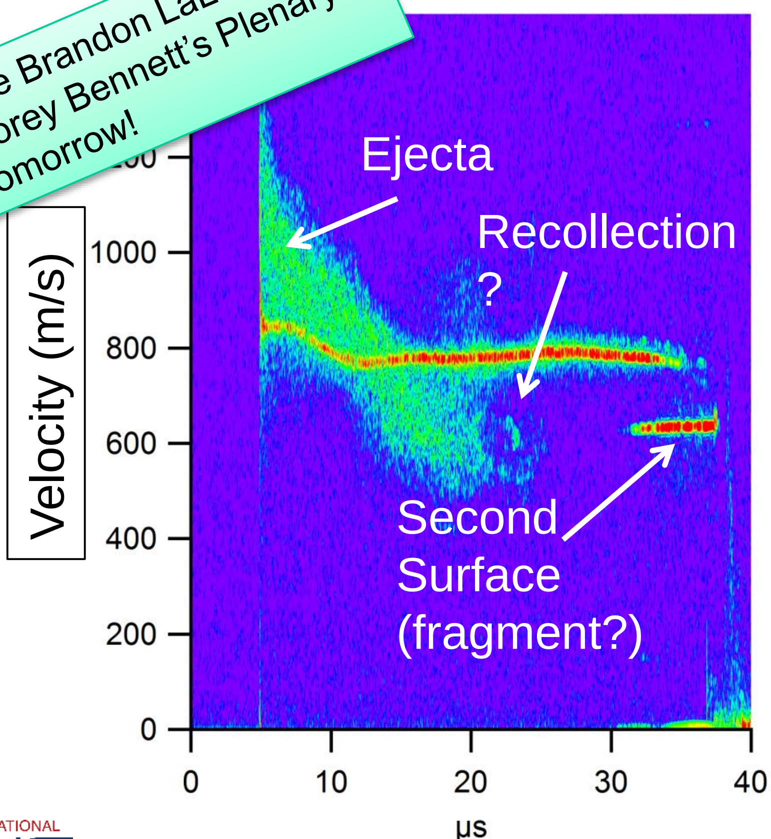
Overview

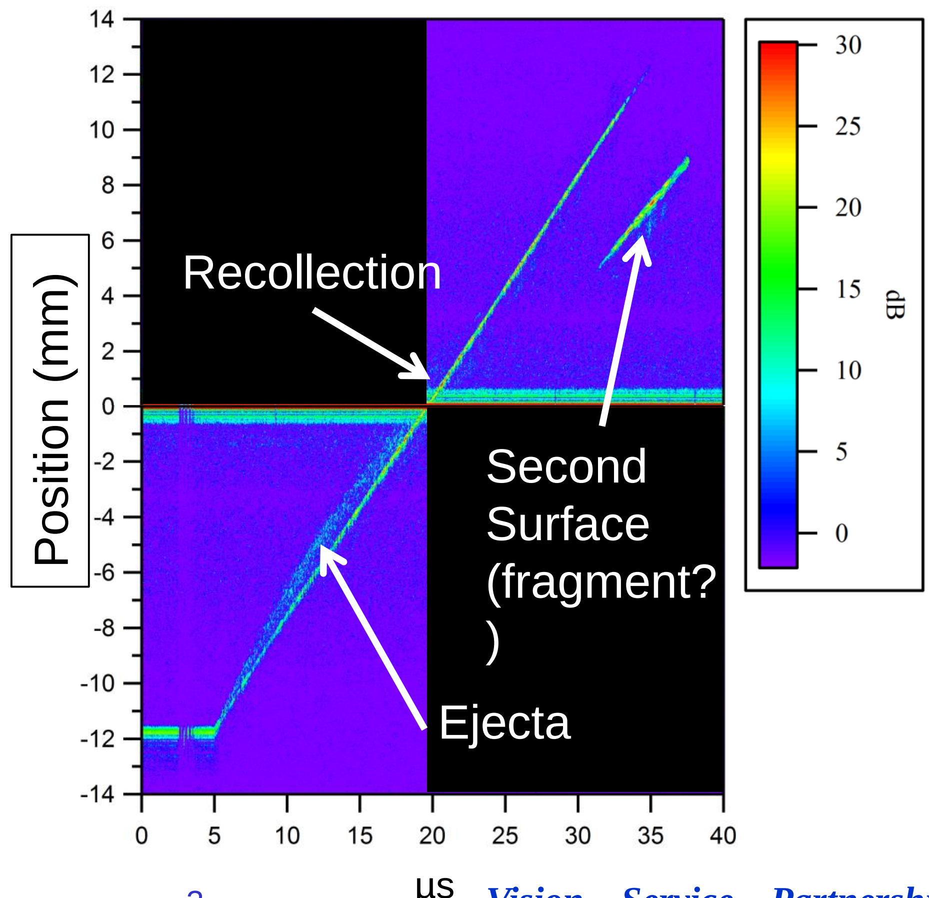
- Where are we now
  - Small signal return: Nearly shot-noise limited
  - Large signal return: effective-bits limitation
  - Role of EDFA's
- Deep-time Multiplexed PDV
- Modulated launch-light
- Dynamically refocusing probe optics
  - Resonantly-driven GRIN lens
  - Optically-actuated lens
- Conclusions and next-steps

Why "Dynamic Range?"

- Some experiments have low and/or widely-varying signal returns
- Some experiments have "clouds" of material obscuring the surface
- Limited launch power and probe efficiency

See Brandon LaLone and Corey Bennett's Plenary tomorrow!





Some back-end schemes have been tried

- Modulate the LO to increase RF amplitude
- Optical auto-gain control on signal return, using SOA
- RF gain control on back-end

- … none of these provide convincing performance improvements when peak light-returns are <-20 dBm

Low signal returns & the shot-noise limit

$$SNR \equiv \frac{\langle i_s^2 \rangle}{\langle i_n^2 \rangle} = 1 = \frac{\eta P_s}{h\nu * \mathrm{B}}$$

- At shot-noise limited signal-to-noise of 1:1:
  - B is bandwidth (Hz), η is quantum efficiency
- For 1550 nm light, we get:

$$P_{shot-noise-limit} = 10\log\left(\frac{B}{1\ MHz} * \frac{1}{\eta}\right) - 99\ dBm$$

- For η=0.7 (0.9 A/W), the shot-noise limit is -81 dBm in a 50 MHz BW
  - e.g. 2000-point FFT on a 50 GS/s record
- A modern, 6-bit (effective) scope will have ~ 68 dB from its noise floor to full-scale
- So, you should be able to see from the shot-noise limit up to -13 dBm!

EDFA effect on Small Signals

- Noise from LO-ASE:

$$\langle i_{ASE}^2 \rangle = 2\eta^2 e^2 \frac{P_{LO}(P_{ASE}/Hz)}{(h\nu)^2} * 0.5 * B$$

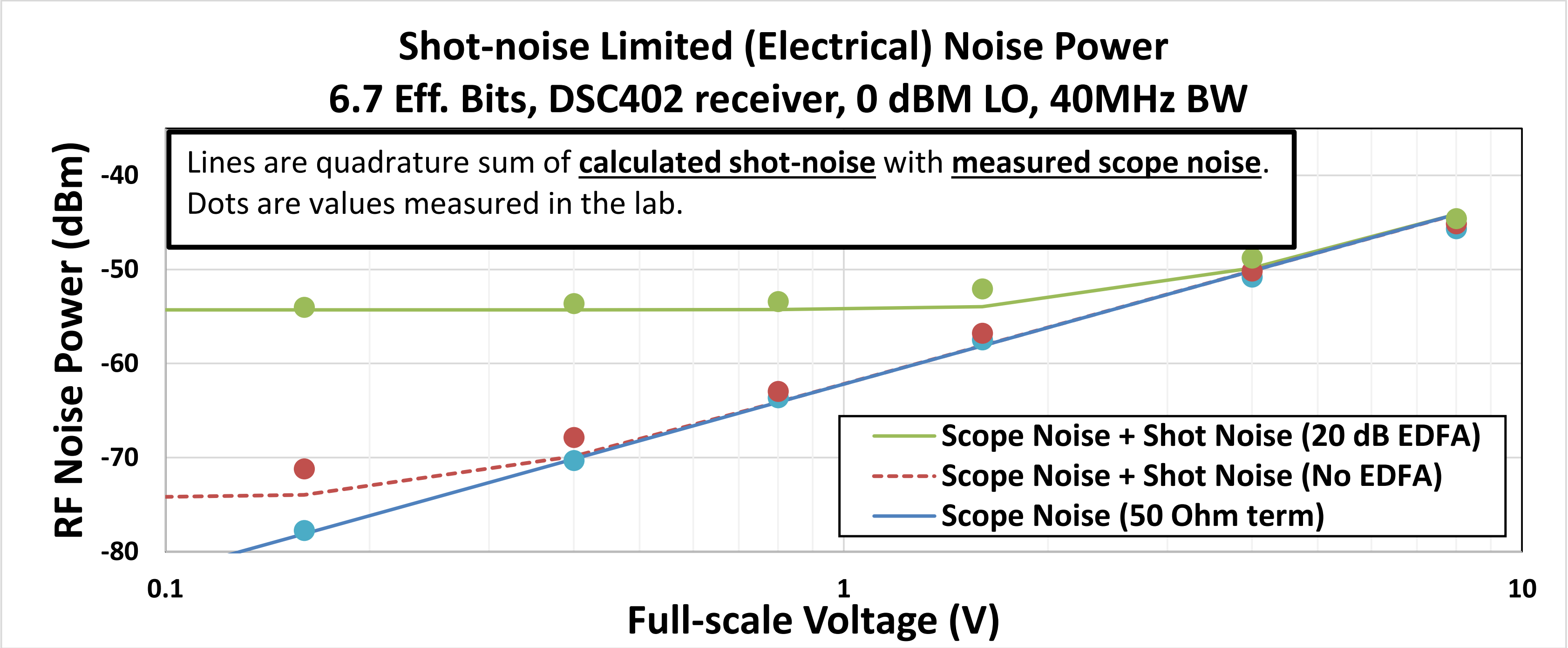
- Add that to the LO Shot-noise to get total noise:

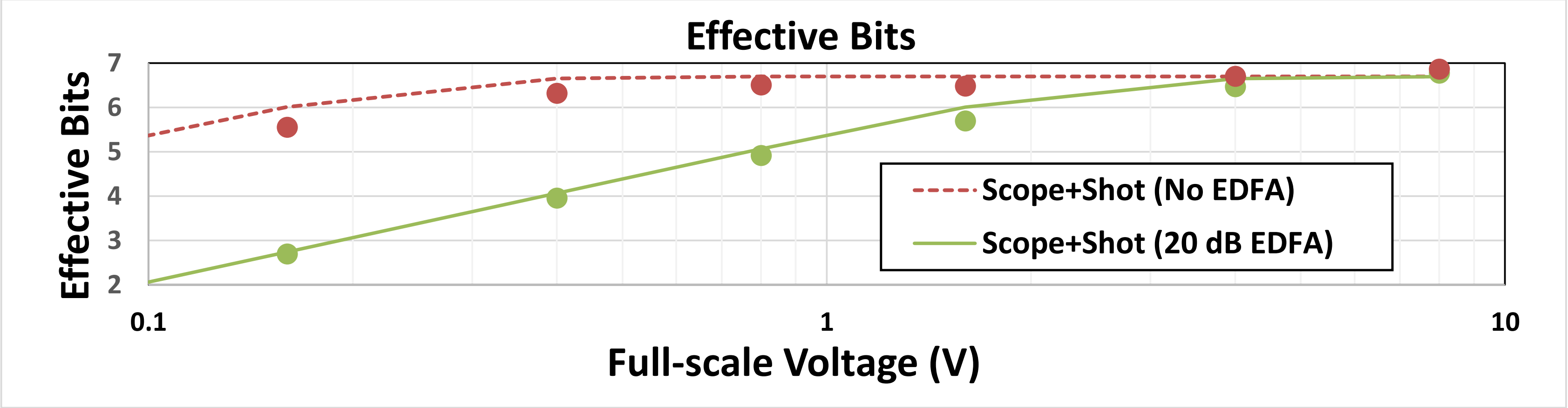
$$\langle i_{n\_TOTAL}^2 \rangle = \langle i_{LO\_SHOT}^2 \rangle \left(1 + \frac{\eta * (P_{ASE}/Hz)}{2 * h\nu}\right)$$

High-gain, fully inverted EDFA

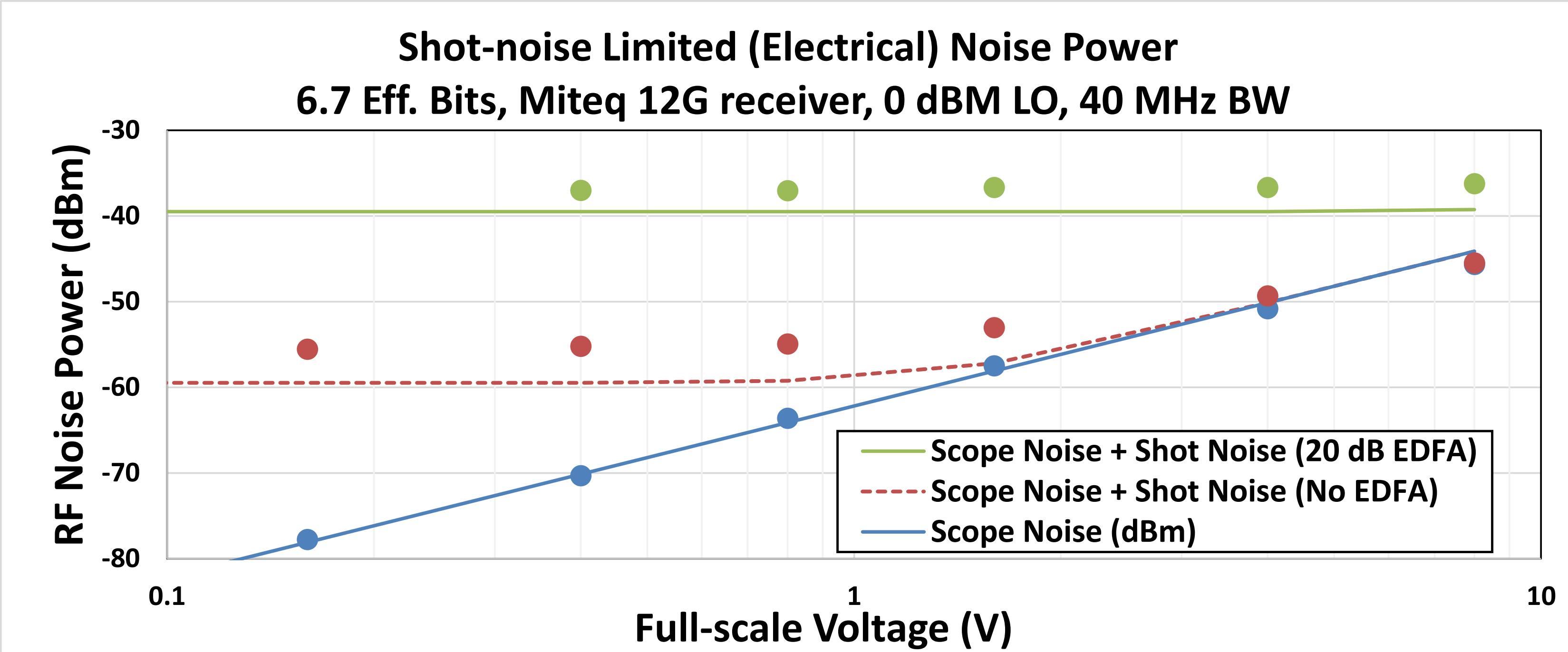
$$\langle i_{n\_TOTAL}^2 \rangle \approx \langle i_{LO_{SHOT}}^2 \rangle * \eta_{PD} * G_{EDFA}$$

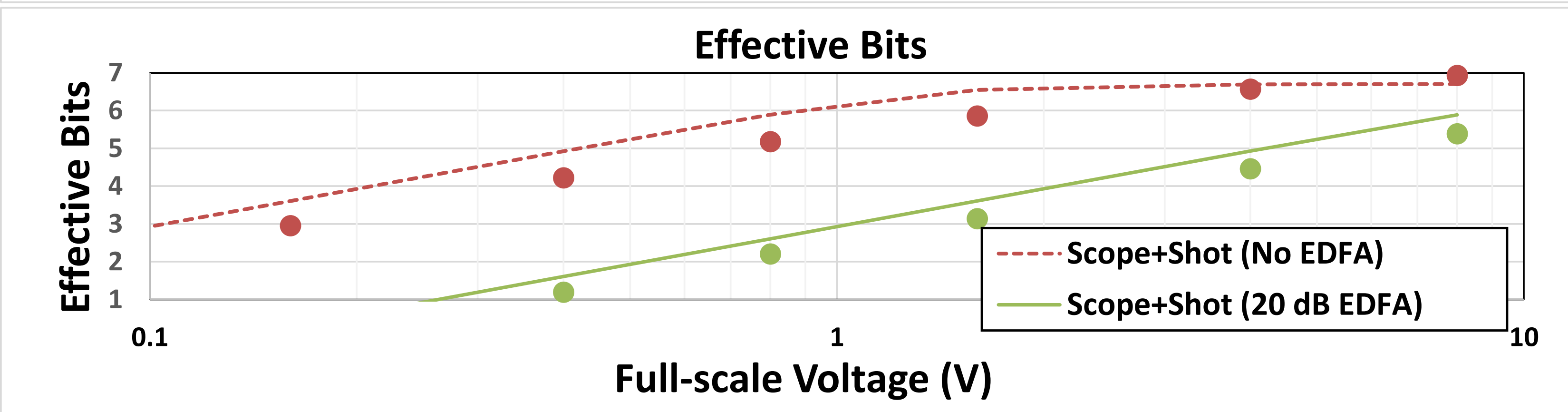
Lab Data: Discovery 402 Receiver





Lab Data: Miteq 12G Receiver





Top-end of the range: Heterodyne Signal Amplitude

PD current, from the textbook: $\langle i_S^2 \rangle = 2\left(\frac{e\eta}{h\nu}\right)^2 P_{LO}P_S$

Power into 50 Ohms:

$$P(mW) = \frac{Transimpedance^2 * \eta^2}{16000\,\Omega\; * \; V^2} * GAIN_{OPT+RF} * P_{LO}(mW) * P_S\,(mW)$$

$$P_{RF}(dBm) = P_{LO}(dBm) + P_S\,(dBm) + 10log_{10}\left(\frac{Transimpedance^2 * \eta^2}{16000\,V^2\,\Omega} * GAIN_{OPT+RF}\right)$$

Power gain of O-E conversion
(~23 dBm for MITEQ 12 GHz receiver)

So, if you have your scope set to 2 V full-scale (+10 dBm), and you are using the Miteq 12G receiver (23 dBm OE gain) with 0 dBm LO, you would expect to fill your scope with -13 dBm of signal light on the receiver.

Back-end configurations that get us NEAR Shot-Noise limit

- InGaAs photodiodes at 1550 nm:
  - 75% quantum efficiency, or 0.9 A/W
- Commercial receivers (Miteq, Discovery, NewFocus) with nominal LO power of 0.5 – 2 mW
  - This gets us to regime where **LO shot-noise dominates** over other noise sources
  - Higher LO can bring signal (and noise) up into scope's range
- Bare photodiode(s) with low-noise amplifier and LO up to 30 mW
  - No advantage for (MPDV) over amplified receivers
- Add a commercial, low-noise EDFA preamp to any of the above
  - Raises both signal and noise without changing SNR
  - Good way to compensate downstream (e.g. multiplexing) losses
  - Can help bring signals into scope range
- Modern, high-bandwidth digitizers

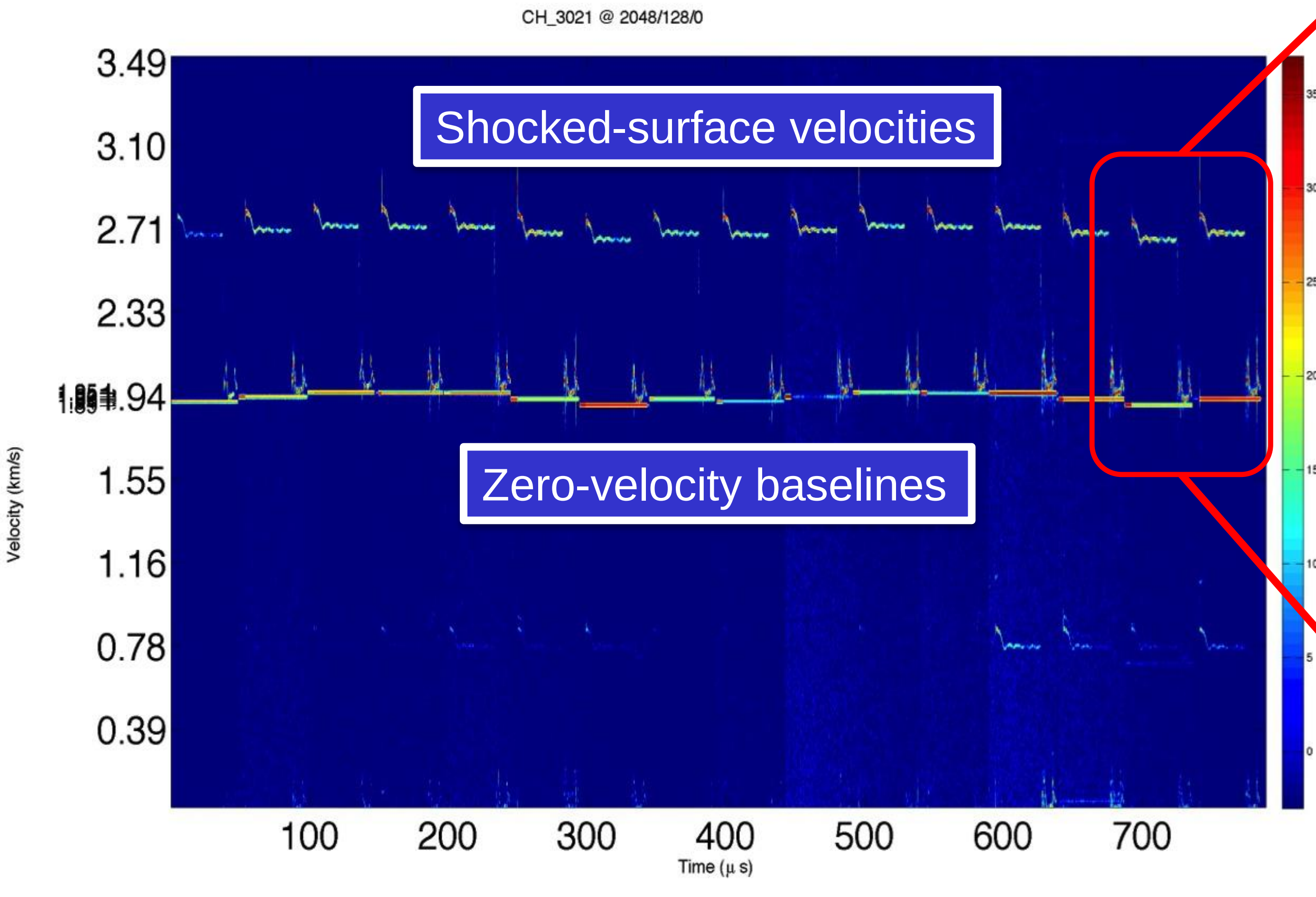
Deep-time Multiplexing

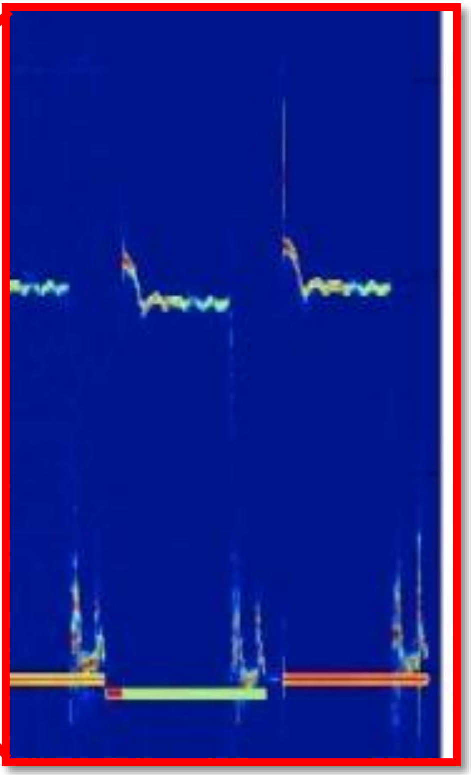
- Shot-noise-limited reality: LO shot-noise dominates
- Frequency-multiplexed (and early deep-time multiplexed) MPDV's have multiple LO's on receiver simultaneously
- The NOISE comes from all LO's, but each channel's SIGNAL comes only from its own LO
- We needed to *switch* the LO light with the signal light
  - Noise dropped by 4x (6 dB)

- Added benefits:
  - Easier to field
  - Data is easier to analyze
  - Less recording bandwidth required

Deep Time MPDV Spectrogram

- Data from deep-time multiplexed experiment
- 16 data channels multiplexed



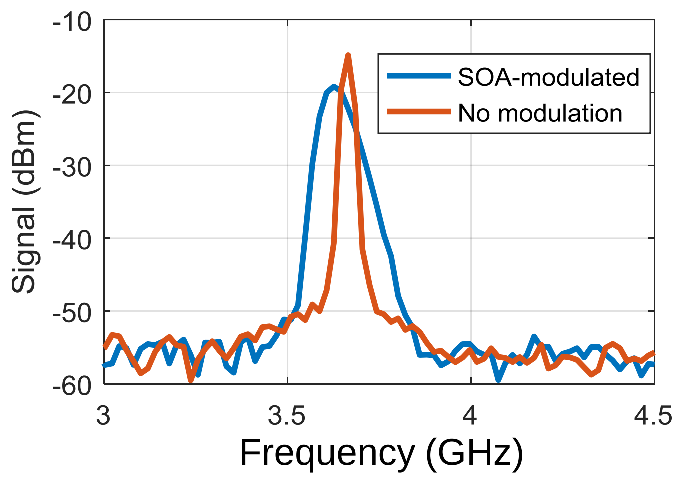


For weak returns, we just need more signal photons!

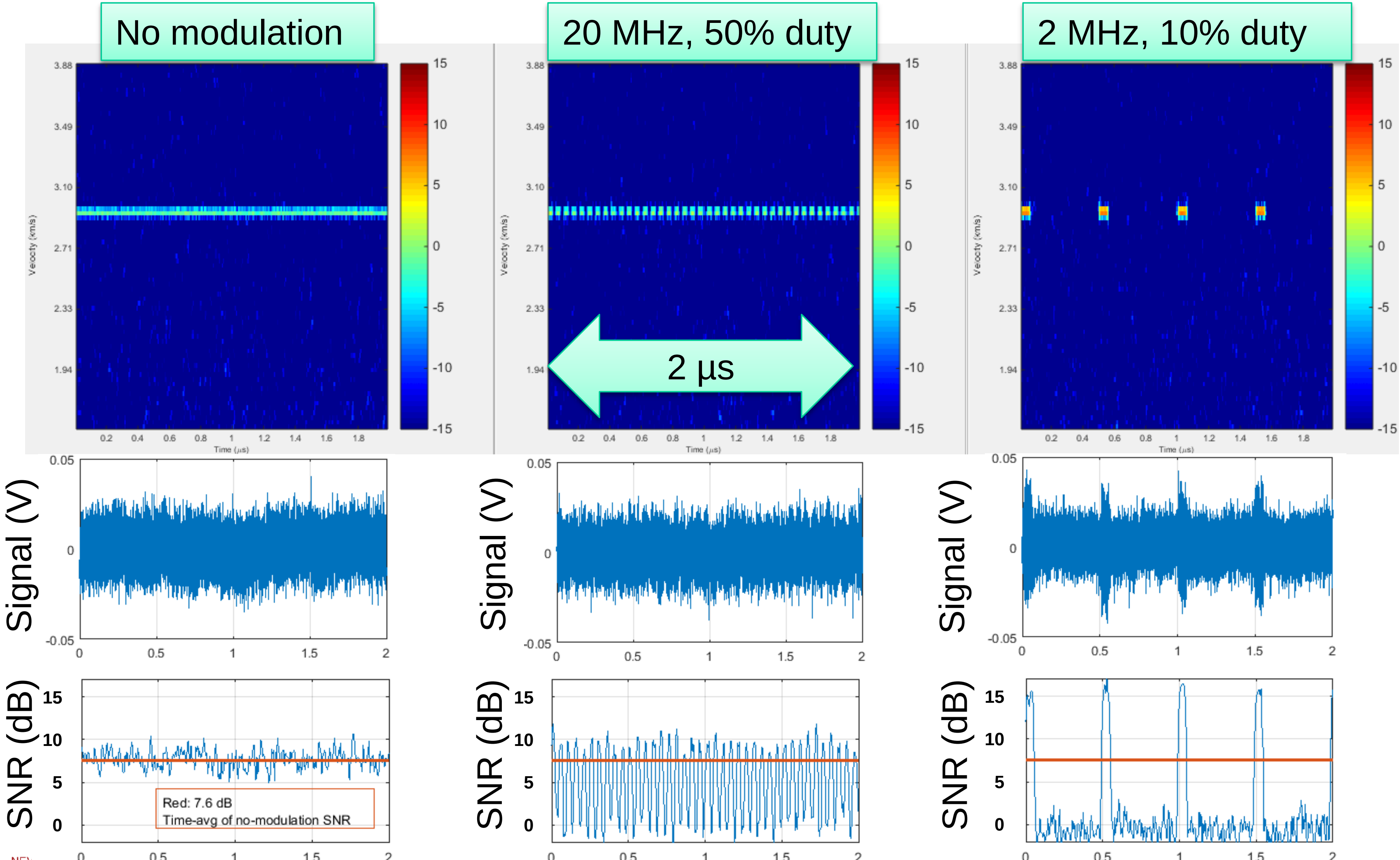
- Ground-rules:
  - CW light is limited to ~ 20 mW per channel
  - Total power through probe
  - Total power to surface
- Two approaches:
  - Increase the launch power without “breaking the rules”
  - Improve light collection for cases of ejecta obscuring surface

One solution: Modulated launch light

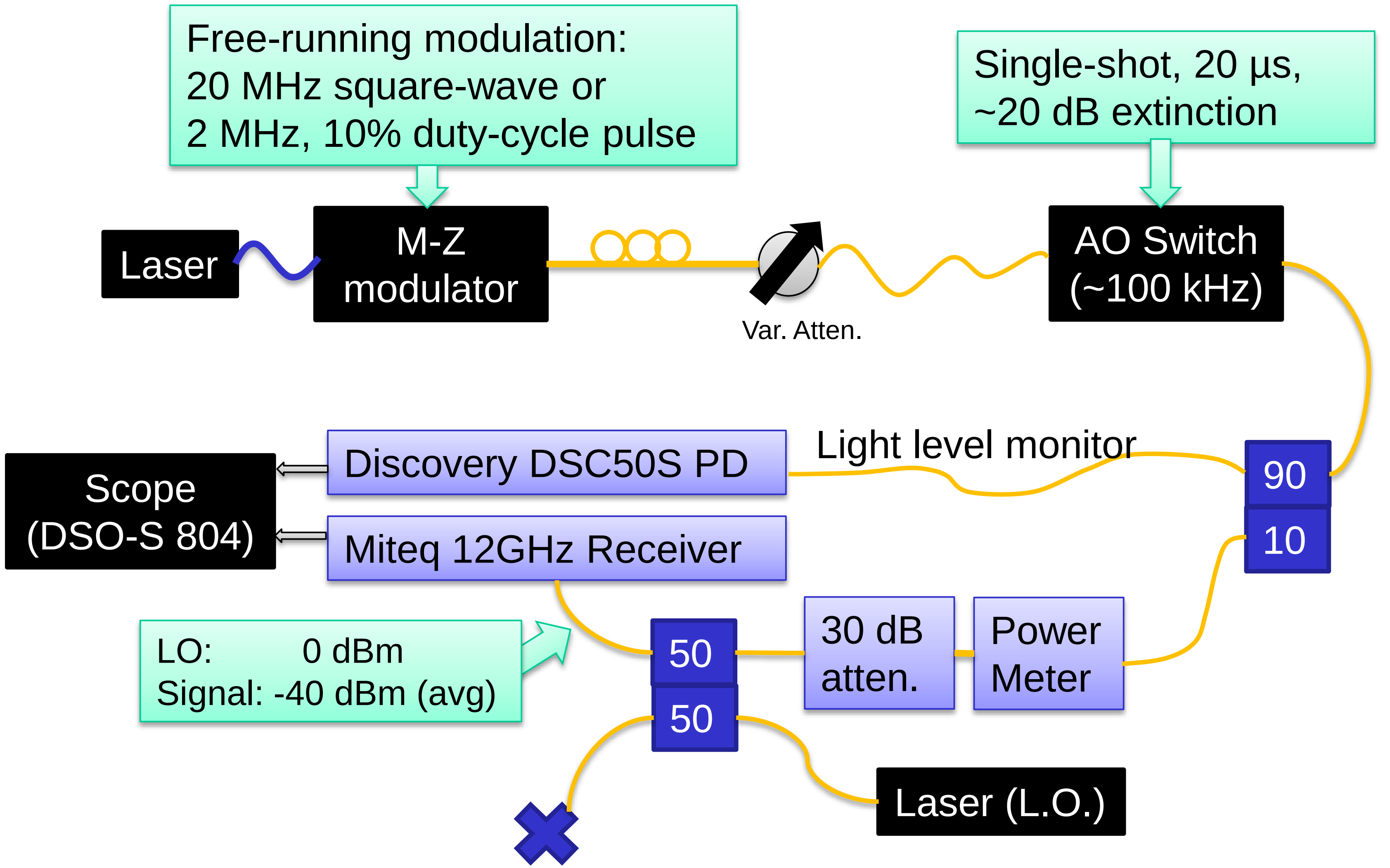
- AO modulator:
  - BW is good enough (50 MHz)
    - don't need Mach-Zehnder
  - High power handling
  - Polarization-insensitive
  - SOA broadens line when modulated
- FPGA-based control
  - 40 MHz master clock
  - 10 MHz ADC & DAC
  - Digital modulation line (up to 50 MHz square-wave)
  - Dual, programmable trigger inputs
- Modulation schemes
  - Free-running, e.g. 50% and 10% duty cycles
  - Triggered waveform
  - Feedback (~ 500 ns)



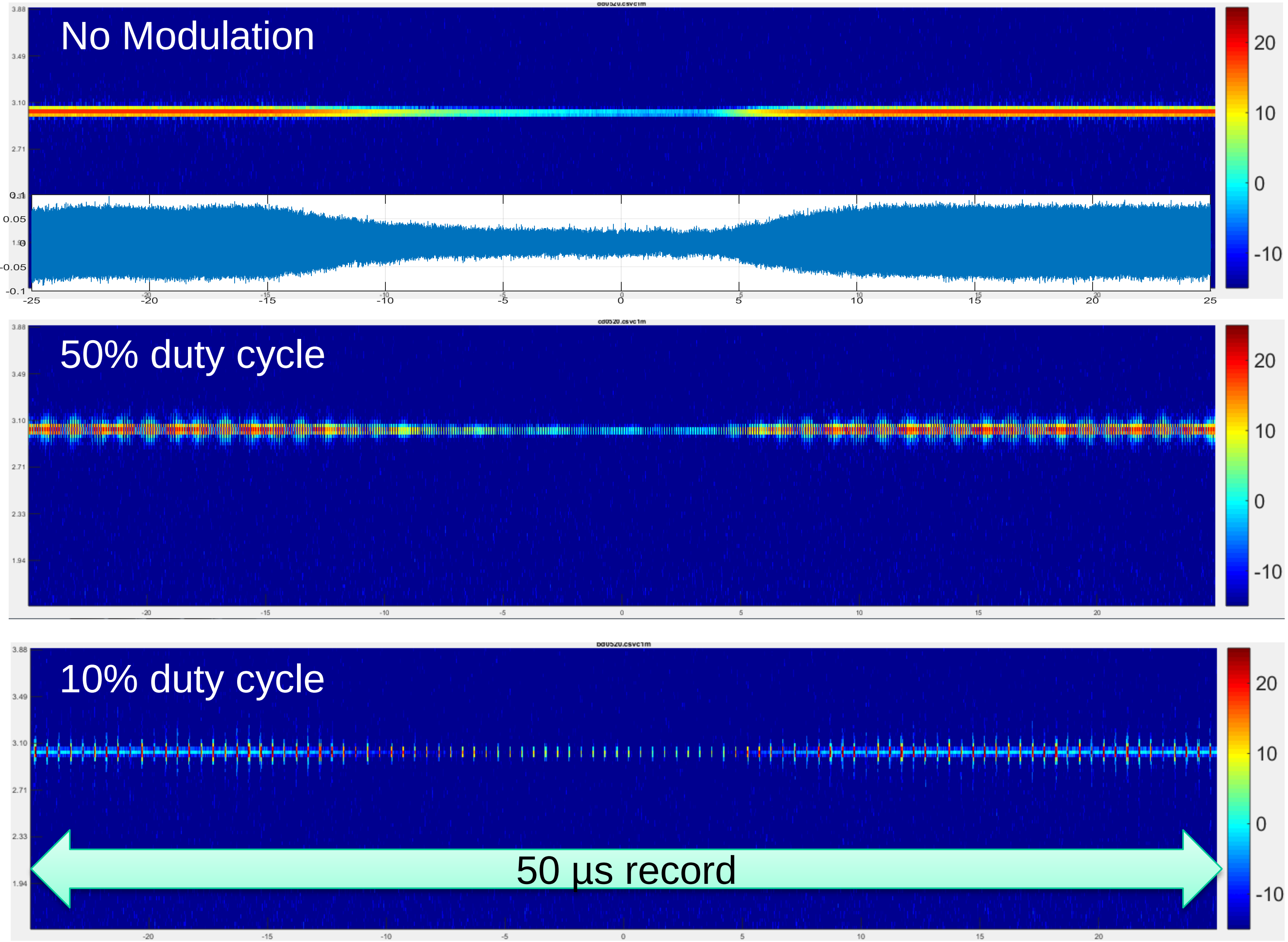
Free-running modulation, -60 dBm time-average signal



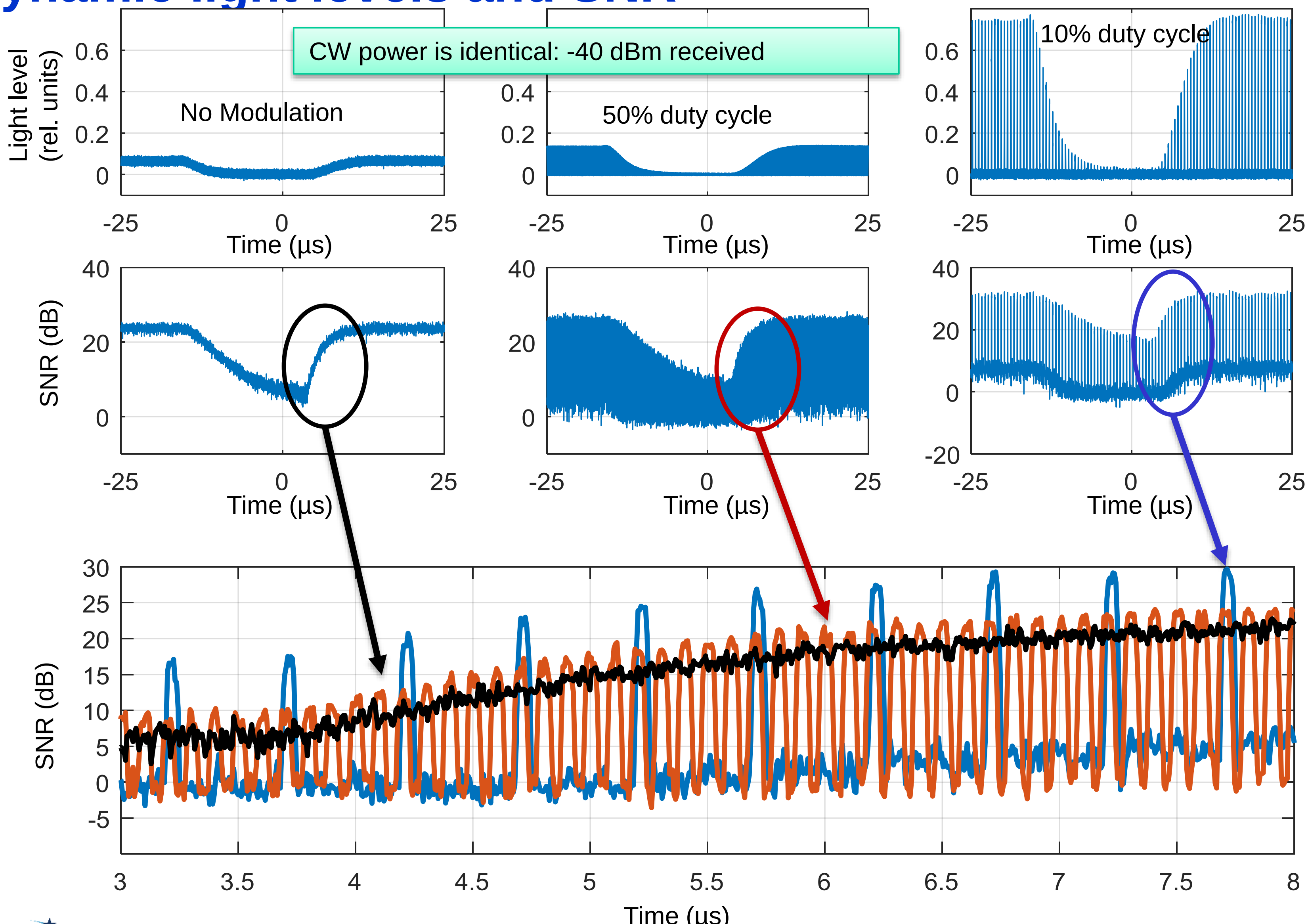
Lab simulation of dynamic signal loss



Dynamic signal loss, -40 dBm to -60 dBm



Dynamic light levels and SNR



Launch-modulation: next steps

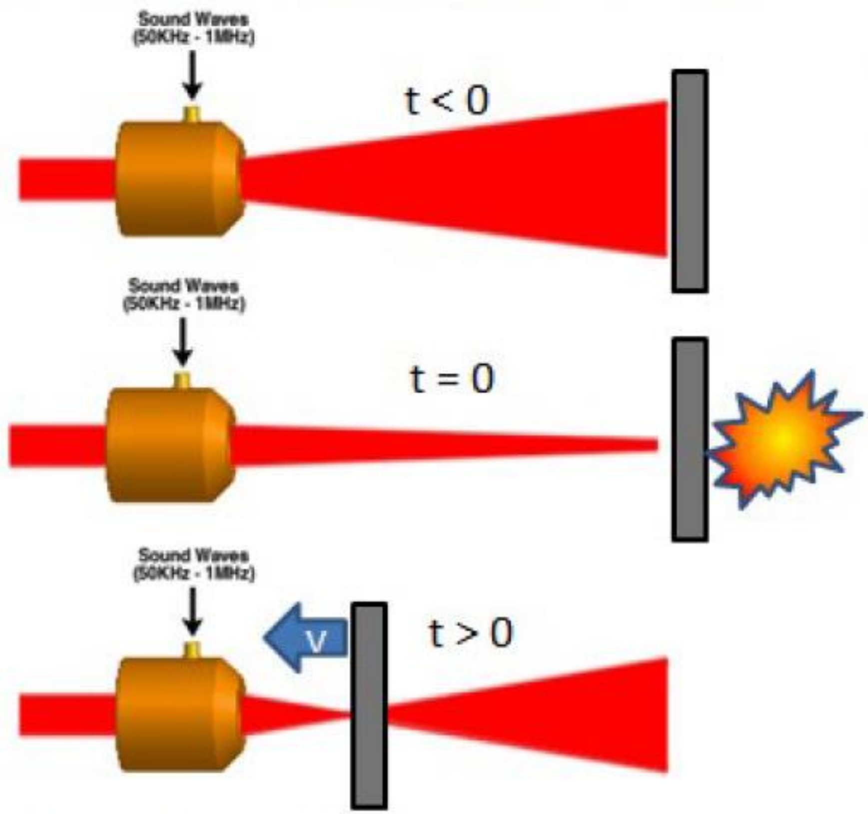
- Build up real-time modulation system:
  - FPGA
  - 50 MHz AO Switch
- Implement modulation schemes:
  - Free-running, variable duty cycle
  - Triggered, programmable output
  - Feedback on return light level (< 1 μs)
- Field this system on small-scale shots at NSTec / STL
  - Summer 2016

Electrically-actuated lens: TAG Optics

- Resonantly-driven, cylindrical liquid cell
- Density modulation creates gradation of index:
  - Compression: converging focus
  - Rarefaction: diverging focus
- For IR operation, standard resonant frequencies are 140 – 340 kHz
- Higher resonant frequencies have smaller effective apertures
- Need to figure out relationship between focal length (or effective focal length), S2’’, and collection efficiency

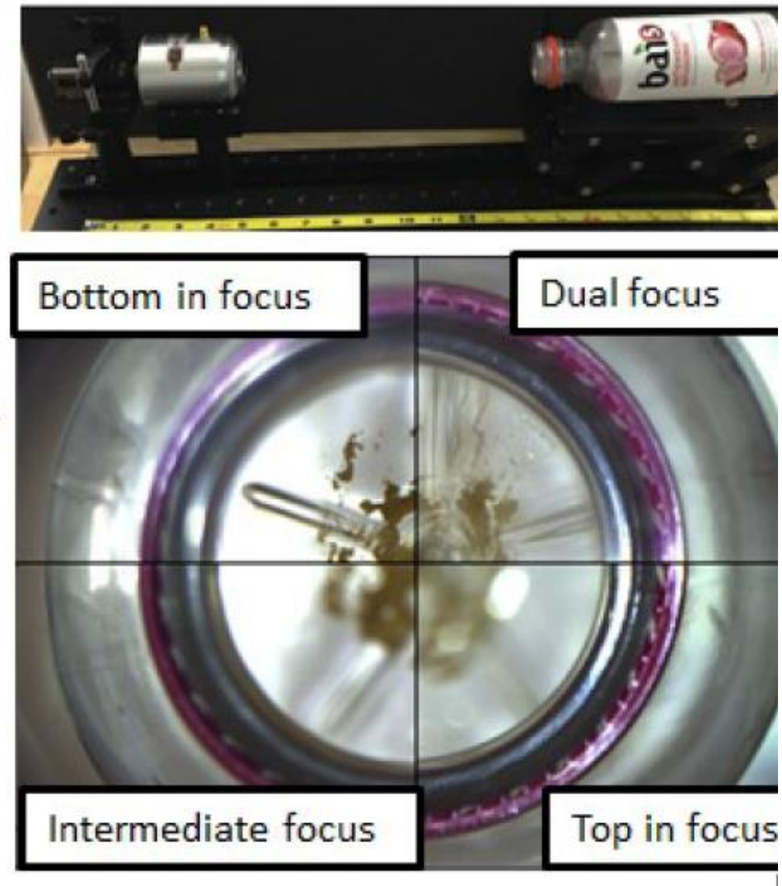
Original concept: Track the Surface

GRIN Lens refocusing with period of 1 – 20 μs



Source: tag-optics.com

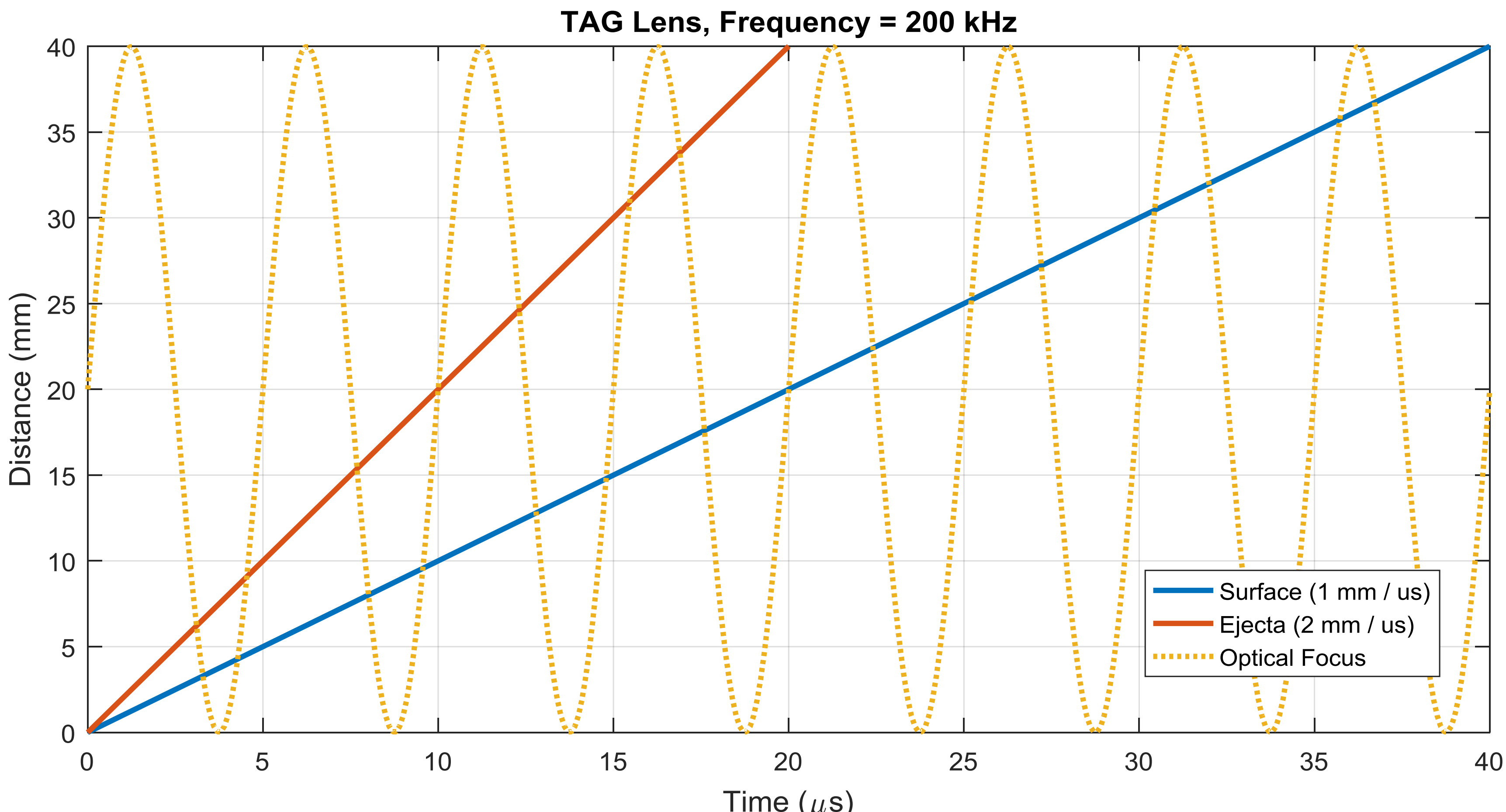
Lab demo with juice bottle



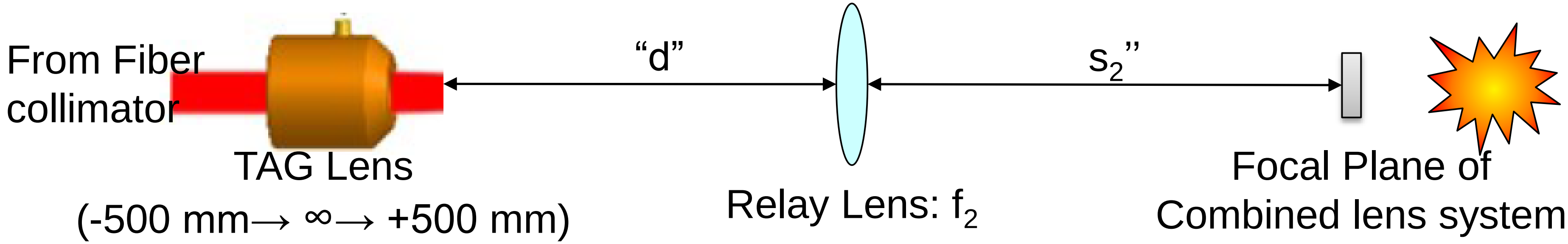
But… resonant frequencies are too high for 10 μs experiments!

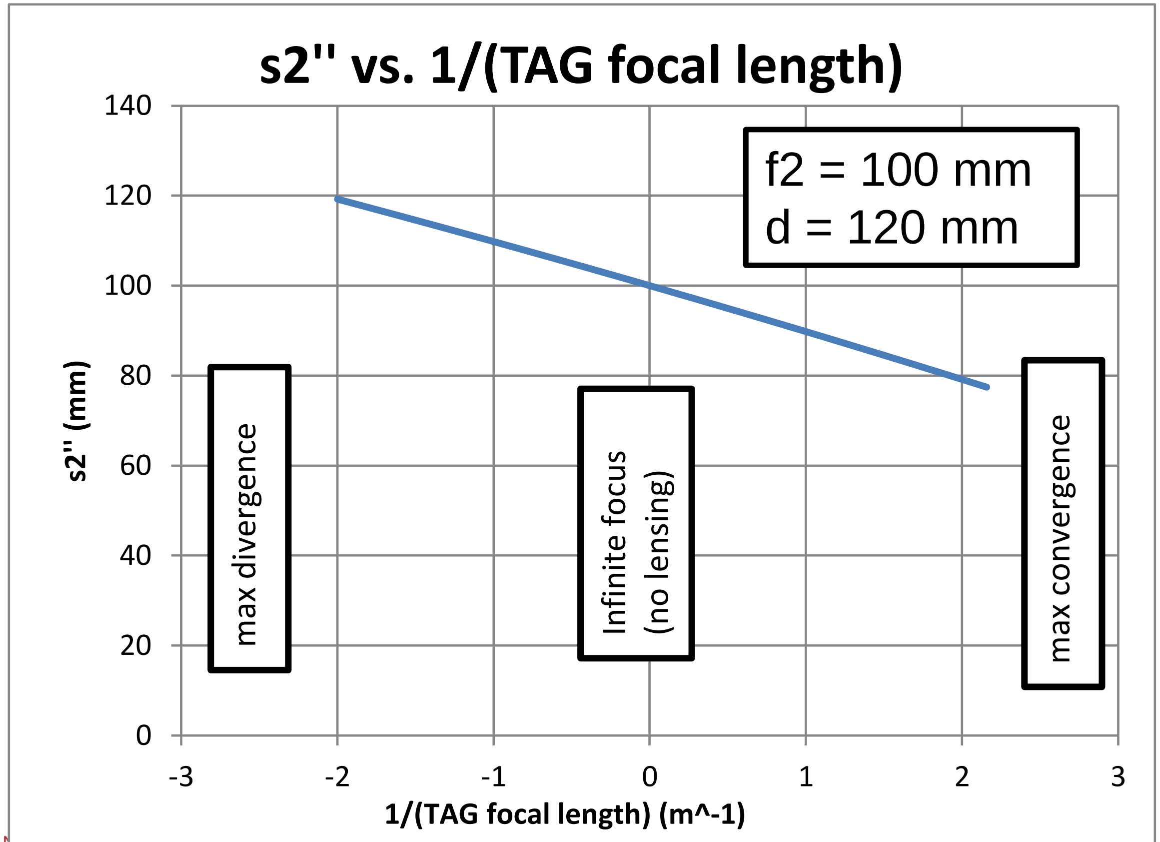
Next Approach: Free-running

Each object passes through focus twice every 5 µs



Optical relay for TAG Lens



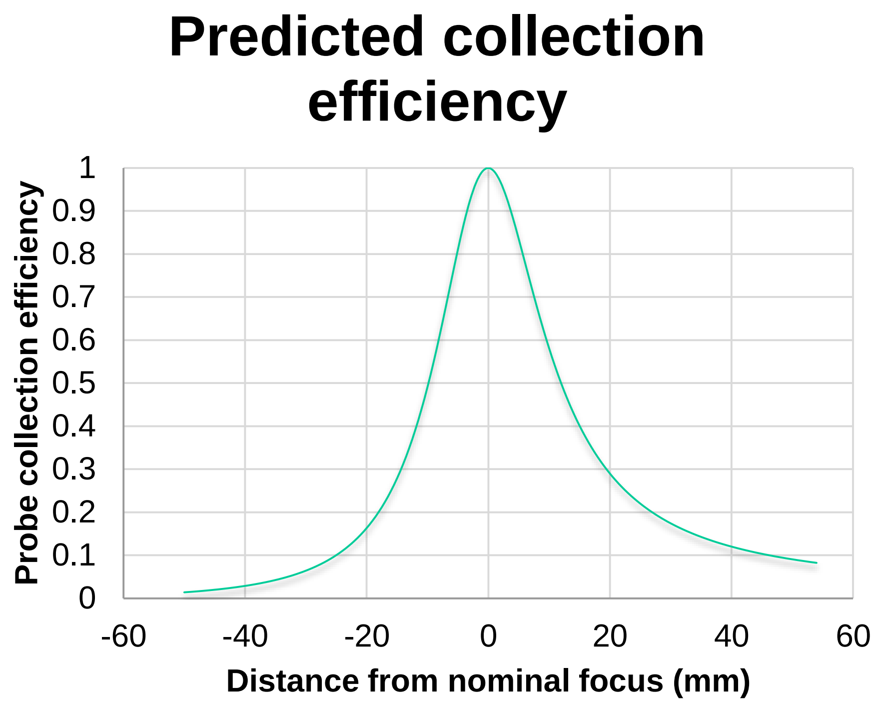


For this configuration:

- Focal point slews between 75 mm and 120 mm from relay lens.
- Demonstration shots will use right-angle pellicle to protect fixed optical system

Expected optical performance

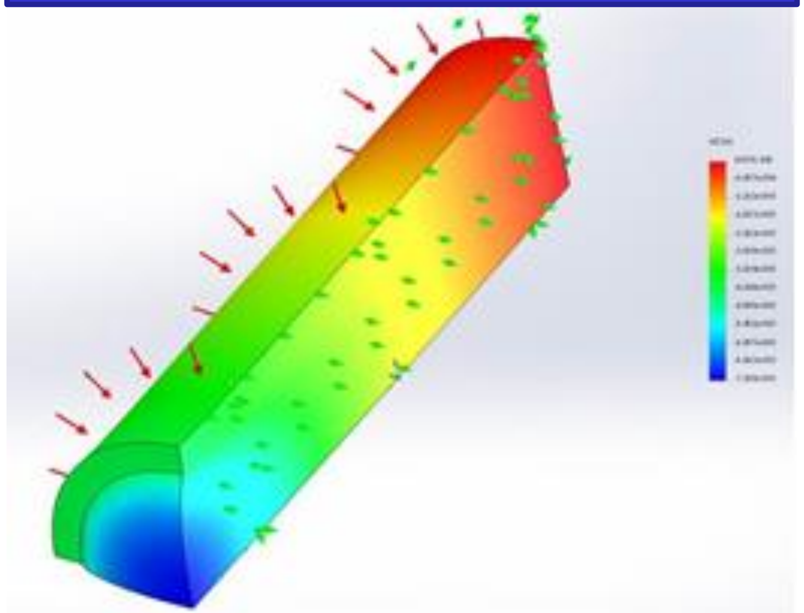
- Predictions are for 5-10 dB rejection of objects 20 mm from nominal focus
- Should improve tracking of surface behind ejecta



Optically Actuated Lens

- Objective: actuate dynamic lensing *through the fiber*

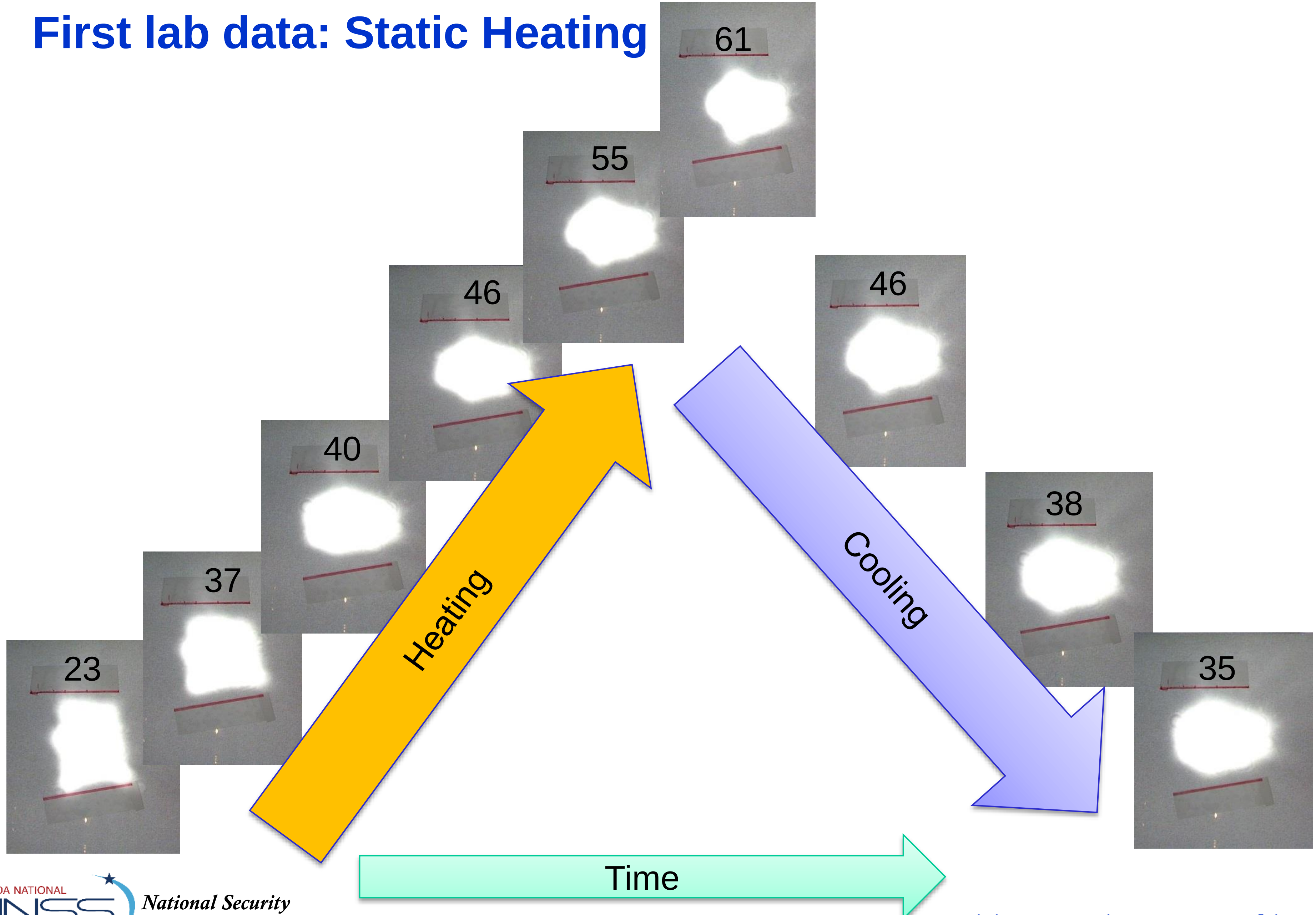
100 µm polymer fiber in steel tube



Polymer expansion (+30°C) causes deformation and end. Focal length ~40 mm

Next steps:
- Test simulation predictions:
  - Measure optical focusing
  - Measure physical deflection
- Custom fiber-draw with doped polymer
- Assemble dynamically actuated probe
- Test on dynamic shots

First lab data: Static Heating



Physical feasibility

- Volume ~ 1 mm^3
- Mass ~ 1 µg
- Energy to heat by 10° C ~ 10 µJ
- Power in 10 µs ~ 1 W

- Use current-pulsed, high-power laser diodes
- Use cladding-pumped fiber to deliver pump + signal

Dynamic-refocus: Next steps

- TAG lens
  - Assemble optical test bench in lab to quantify dynamic-range improvement during resonant operation
  - Begin designing dynamic experiments
- Optically actuated lens scheme
  - Mechanical modeling of larger polymer fibers
  - Verification of mechanical modeling: optical and physical
  - Begin considering pump and absorber system that could create the lensing desired

Summary: Places to gain dynamic range

- We are within a few dB of the shot-noise limit with back-end hardware
- Where can we squeeze more dynamic range?
  - Modulate launch power
    - More launch photons → more DR
    - May still run up against backscatter and probe power-handling limitations
  - Dynamically refocusing probe optics could improve collection over a wider range of probe-surface distances
    - Potentially useful in discrete-probe configurations
  - Balanced detection
    - Need better selection of lab-friendly receivers
    - 3 dB more signal (using 50/50 combiner)
    - More efficient use of LO power
    - Rejection of common-mode power swings

Backup slides

Shot-noise limit (Optical power)

$$SNR \equiv \frac{\langle i_s^2 \rangle}{\langle i_n^2 \rangle} = 1 = \frac{\eta P_s}{h\nu * \mathrm{B}}$$

$$P_{shot-noise-limit} = \frac{B \ * \ h\nu}{\eta} = \frac{B \ * 1.28 \times 10^{-19} J}{\eta} = \frac{B}{1\ MHz} \frac{1.28 \times 10^{-10} mW}{\eta}$$

$$P_{shot-noise-limit} = 10 \log\left(\frac{B}{1\ MHz} * \frac{1}{\eta}\right) - 99\ dBm$$

SNR relationship to Effective-Number-of-Bits (ENOB)

Normalize for fraction of full-scale used

SNR increase by using frequency-domain analysis

$$SNR_{f,dB} = (6.02 \times \text{ENOB}) + 1.76 + 20\log\left(\frac{2A}{V_{FS}}\right) + 10\log\left(\frac{N_{FFT}}{2}\right)$$

ENOB = effective bits for digitizer, V_{FS} = full scale voltage, A = RMS amplitude of applied signal (See Wiley Encyclopedia of Electrical and Electronics Engineering, Vol. 18, J. Blair)

Number of bits as function of SNR, fraction of full-scale, FFT Points

"Frequency-domain Number of Bits"

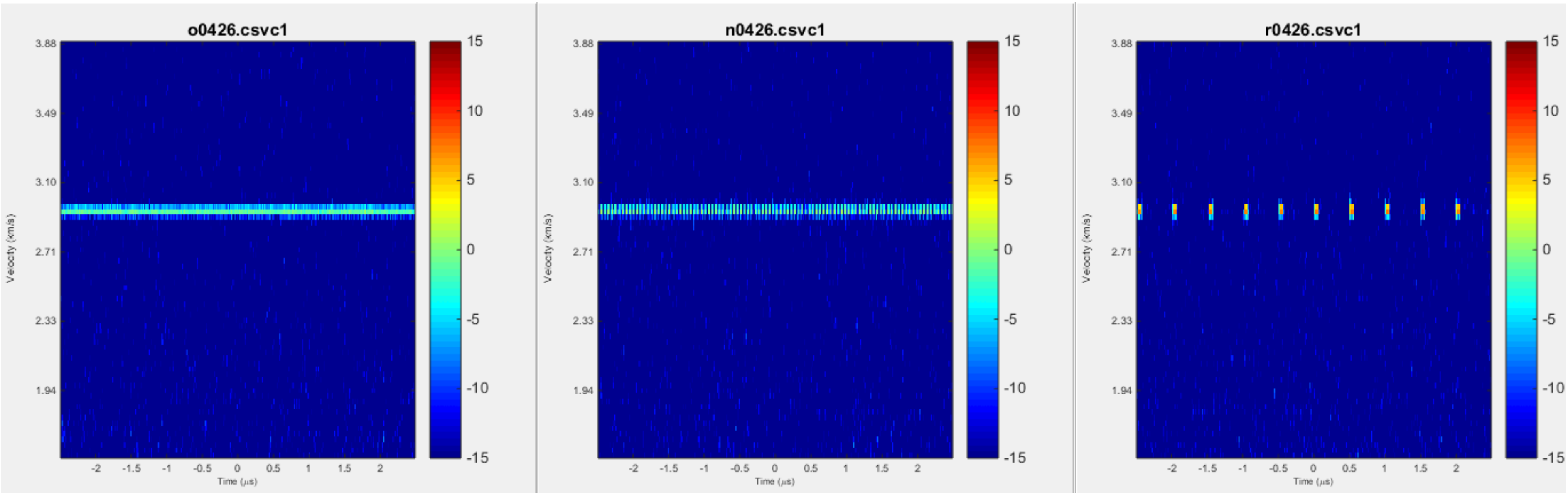
$$\text{FNOB} = \frac{1}{6.02}\left[SNR_{f,dB} - 1.76 - 20\ log\left(\frac{2A}{V_{FS}}\right) - 10\ log\left(\frac{N_{FFT}}{2}\right)\right]$$

"signal" cancels out…

$$FNOB = \left(\frac{1}{6.02}\right) * \left[10\log\left(\frac{V_{FS}^2}{50\Omega} * 1000\right) - noise_{dbm} - 7.78 - 10\log\left(\frac{N_{FFT}}{2}\right)\right]$$

… Just a noise measurement! Measure with receiver on, LO power at nominal.

Full-time (5 μs) spectrograms of free-running modulation



Advantages to balanced receiver

- For deep-time MPDV, no problems when LO switches
- Don't throw away LO or signal photons
  - 3 dB signal gain for 50/50 combiner
  - Not a problem if you are already using 90/10 combiners
- ASE-ASE is common-mode
  - Not commonly a problem
  - In balanced receiver, suppressed by 20-30 dB