Investigation of Standard SEE Receiver with Stripline BPM Sensor

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4/9/24

Executive Summary

In anticipation of installation of stripline-style JLAB BPM sensors in the Hall A beamline for the upcoming Moeller experiment, a study was performed to compare the electronic SEE receiver response with a stripline-style sensor to that of traditional M15 antenna-style BPM. This was prepared in the lab, using an identical SEE system (assembled from spare CEBAF components), a Goubau Line stretched-wire scanner, a digital diagnostics receiver (DR), and a PC running EPICS and Matlab for simultaneous stimulus-response and data acquisition.

Scans were performed on both M15 and stripline-style BPMs, for which raw data as well as LMS-regressed data were compared, to identify differences in calculated position behavior and dynamic range. A scan zone of 1.5 cm x 1.5 cm was selected, to slightly over-scan the specified 1 cm x 1 cm active area.

Major differences were observed between the two sensors, which are most obvious outside 1 cm^2. While stripline and M15 BPMs provide similar output and performance for centered beam, the stripline has a 2 dB/mm slope (compared to 1 dB/mm for the M15), which consumes the nominal ~20 dB effective detector dynamic range for a given gain range, away from boresight. Users are cautioned to consider the effects of beam outside the accepted "sweet spot" for a standard SEE, or possibly consider non-standard SEE configurations.

SEE

A JLAB-style SEE rack was assembled in the lab, consisting of a VME crate having the IOC, RF, IF, and supporting cards installed, retaining standard field installation conditions as much as possible. External signals such as beam sync, 30 Hz, and ethernet were all provided, locally. A standard EPICS GUI was used for initial configuration and monitoring during operation, and with the exception of a "fixed-gain" measurement, was allowed to run in standard mode. Figure 1 contains the SEE rack and elements needed to produce the measurements.

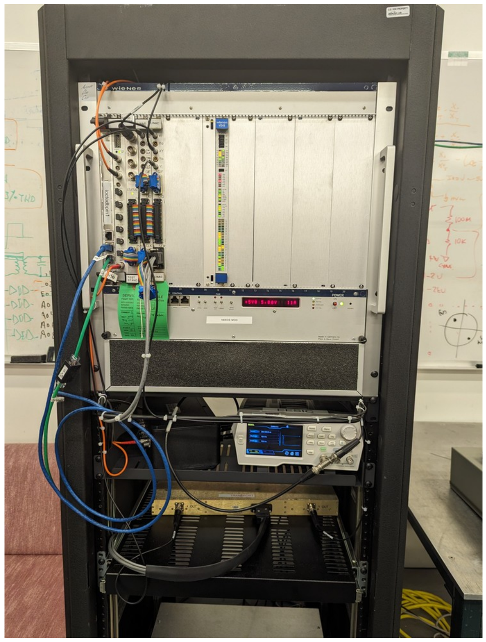

Figure 1. SEE BPM rack, assembled for testing M15 and stripline BPM sensors.

Data Acquisition

In addition to EPICS support, the lab PC implemented Matlab as a DAQ expedient. The STAC5 stepper motor controllers are TCP-IP controlled, which is also managed by Matlab. A custom GUI was created to provide independent motor control (ie. “jogging”) and also to create and execute the square raster scan pattern. A typical scan employs a 250 um step, followed by a ~2 second settling time (for wire vibration, etc.) and subsequent data capture of the four RF electrode voltages by the SEE (EPICS). These counts were individually retained, as was the EPICS-computed X-Y position for comparison. The SEE algorithm uses AGC to maintain an overall average count (~1100) for optimal ADC voltage range; a “minimum signal cutout” feature of the SEE will return a value of (0,0) for low signal levels, consistent with operational requirements when no beam is present in the accelerator. As a result, many of the SEE-computed data points are not usable, but for which the actual ADC counts are available for offline computation.

Matlab is also able to utilize it’s EPICS application to retrieve the network data, completing the stimulus-response measurement. While LabView is frequently used for similar experiments, the combined utility of advanced data processing, universal support, and relative ease with which to simultaneously communicate with the motors and SEE fell in favor of Matlab.

Sensor Measurement

A Goubau Line (“G-Line”) has been developed and implemented at JLAB for the purpose of characterizing and field-mapping the low-Q beamline components [1]. A single-wire transmission line exploits the Zennick-Sommerfeld-Goubau surface wave mode, which is then used as surrogate for the CW electron beam. Parameters such as X-Y sensitivity, cross-coupling, and variations in manufacturing are typically obtained during routine scans. A Danaher® X-Y stage is controlled using network-enabled Applied Motion STAC5® stepper motor controllers, and has an ultimate step size resolution of 0.25 um, orthogonality of <0.05 degrees, and repeatability of <10 um for duplicate scans. Detection is usually performed using a pair of HP 8508A vector voltmeters, and/or, more recently, a dedicated JLAB Digital Diagnostic Receiver (DR). Of course, the SEE system served as the primary detection platform for this specific campaign.

The G-line conductor is a corrugated 160 um brass wire, sufficient for supporting the surface wave conditions, and is dimensionally representative of the CEBAF electron beam. The Goubau Line and supporting equipment are shown in Figure 2.

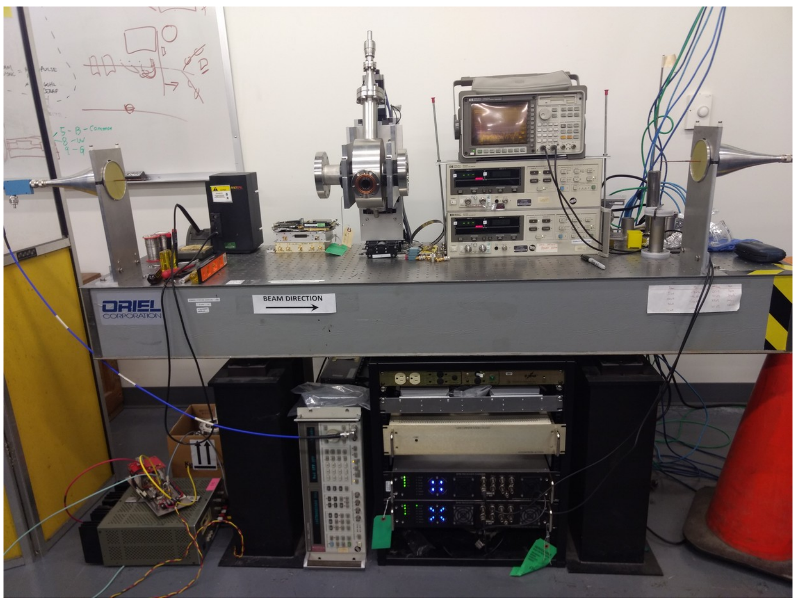

Figure 2. Goubau Line scanning system used to characterize diagnostics elements. A surface wave is imposed on the wire, which mimics a CW electron beam for low-Q field mapping. The resolution of the X-Y stage is 0.25 um.

M15 Scan

Results of the SEE + M15 scans produced the familiar JLAB field pattern. While the only specification for performance is "resolution of 100 um at 1 uA of beam current," the measured *accuracy* is actually around 100 um at 1 uA. The sensor was zero-ed as best as possible (empirically), followed by a 3-hour scan. The resulting data was subjected to a 2D LMS regression, to extract sensor constants, which are re-applied to the measured data. Error-vector magnitude is calculated and presented (numerically and graphically) for accuracy determination.

The EPICS-calculated position data was also recorded, along with the individual electrode voltages, since EPICS will occasionally threshold the output for low counts. Difference-over-sum position algorithm (using standard M15 sensitivity constant 18.81) was then applied. In addition to both of these outputs, the analysis with regression applied to the four-wire difference-over-sum data are shown in Figure 3.

Regression Output:

```
Plots for SEE using M15 sensor.
Nominal beam current = 1uA
Scan range: +/- 0.75 cm
Scan resolution: 250 um
SEE ADCs simply cut out (read 0) when signal is low
SEE "minimum signal" is right at 100 nA.

M15:
Kx = 17.9
Ky = 18.4
D-theta = 0.4 degrees
RMS Error (1 cm) = 107.3 um
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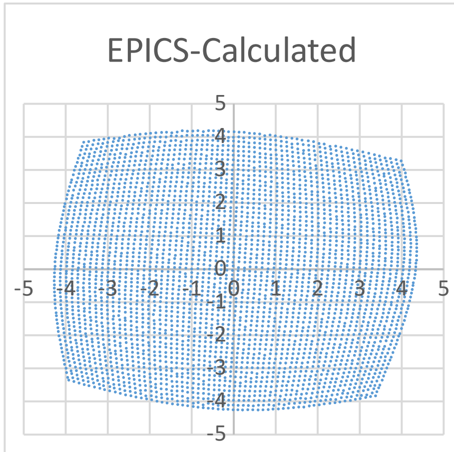
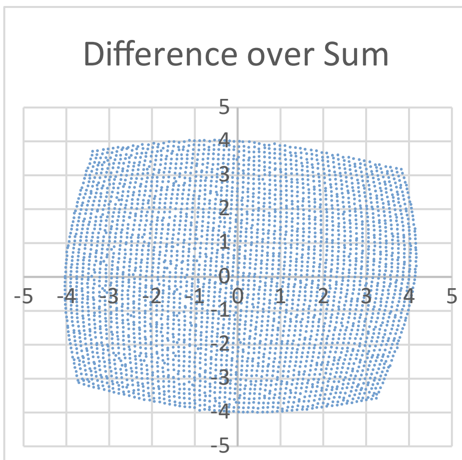
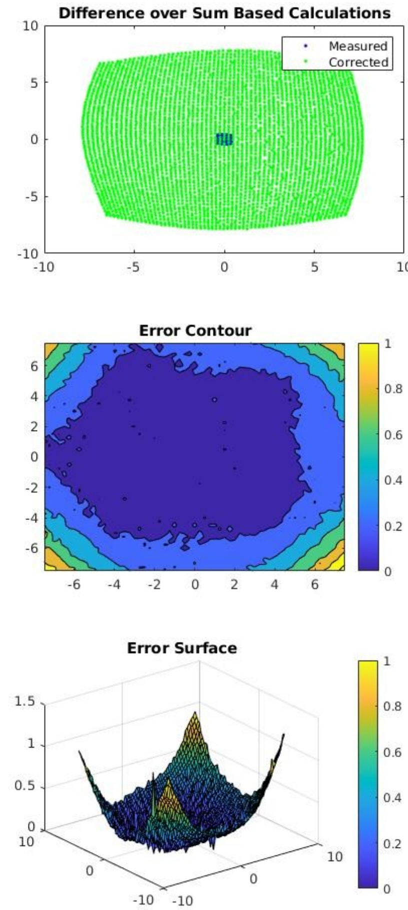


a.



b.



c.

Figure 3. SEE scan of M15 BPM sensor, using standard “auto-gain” mode. The dynamic range of the detection is consistent with that of the sensor, over a 1.5 cm^2 active area. The plot at (a) is directly reported from EPICS, which was allowed to calculate the position (units in mm). Plot (b) is an offline difference-over-sum calculation, using the four electrode voltages for computation, and applying a standard M15 sensitivity constant of 18.81. While appearing nearly identical, the former suffers from a “threshold” when any of the electrode voltages fall to extremely low values (and are represented by 0.0V). Regression analysis on raw scan data is shown in (c).

Stripline Scans

Similarly, the M15 sensor was replaced by a production JLAB stripline (S/N-22), and subjected to RF consistent with ~ 1uA of beam current. After performing initial stripline scans, it became apparent that there were differences, particularly outside the 1cm^2 active region. The suspected actions of auto-gaining and the behavior of the video detector suggested scans be performed in auto-gain (standard operations) as well as fixed-gain (non-standard) modes in order to understand the limitations, and make appropriate recommendations. The resulting data scans for auto-gain, fixed-gain (using accepted stripline S/N-22 sensitivity constant 9.95) and subsequent regression output appears in Figure 4. All were calculated, offline, due to the potential thresholding from the internal EPICS calculations.

Regression Output:

```
Plots for SEE using stripline (SPM).
Nominal beam current = 1uA
Scan range: +/- 0.75 cm
Scan resolution: 250 um
SEE ADCs simply cut out (read 0) when signal is low
SEE "minimum signal" is right at 100 nA.

SPM:
Kx = 6.9
Ky = 8.8
D-theta = 7.3 degrees
RMS error (1 cm) = 118.5 um
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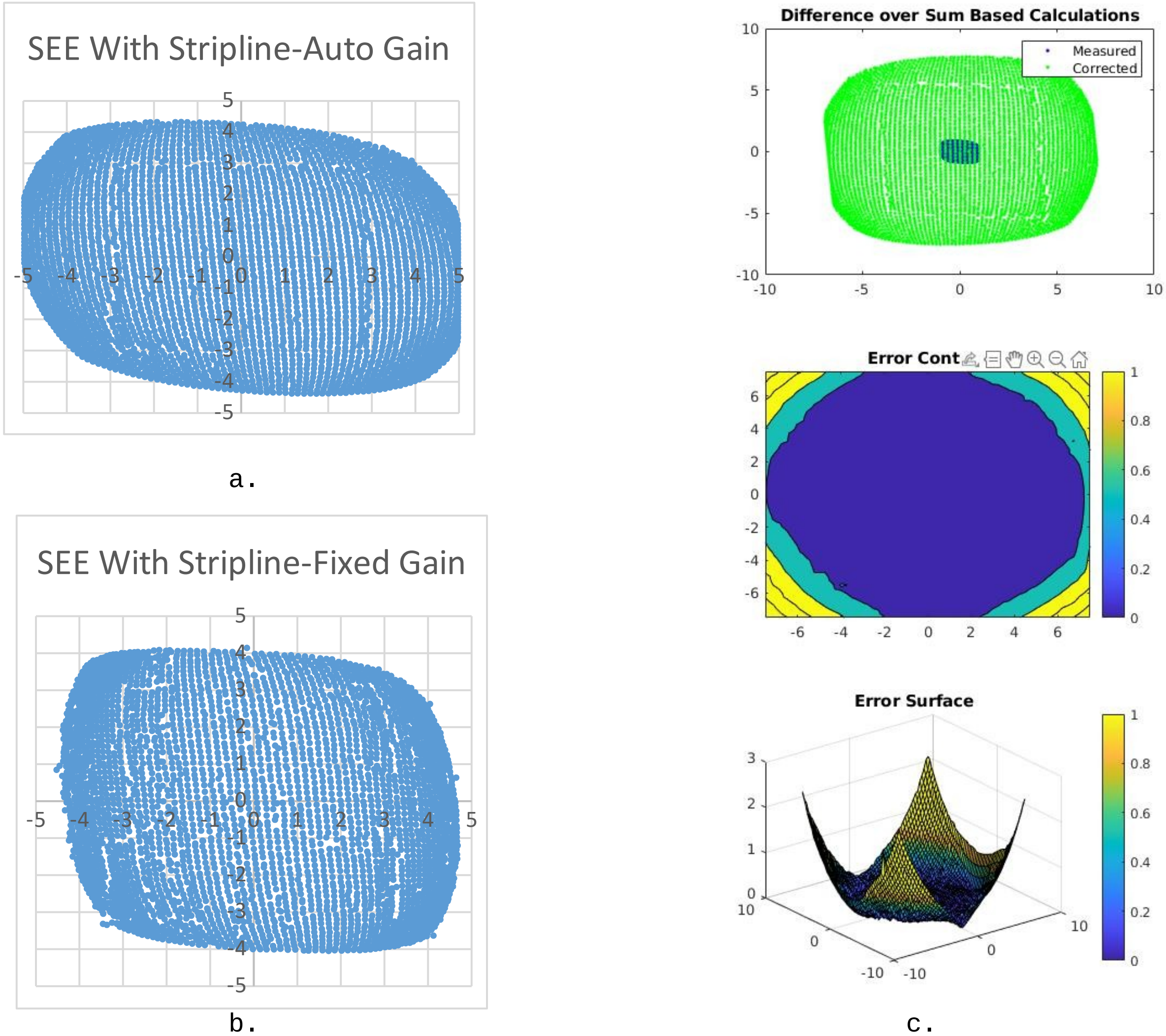
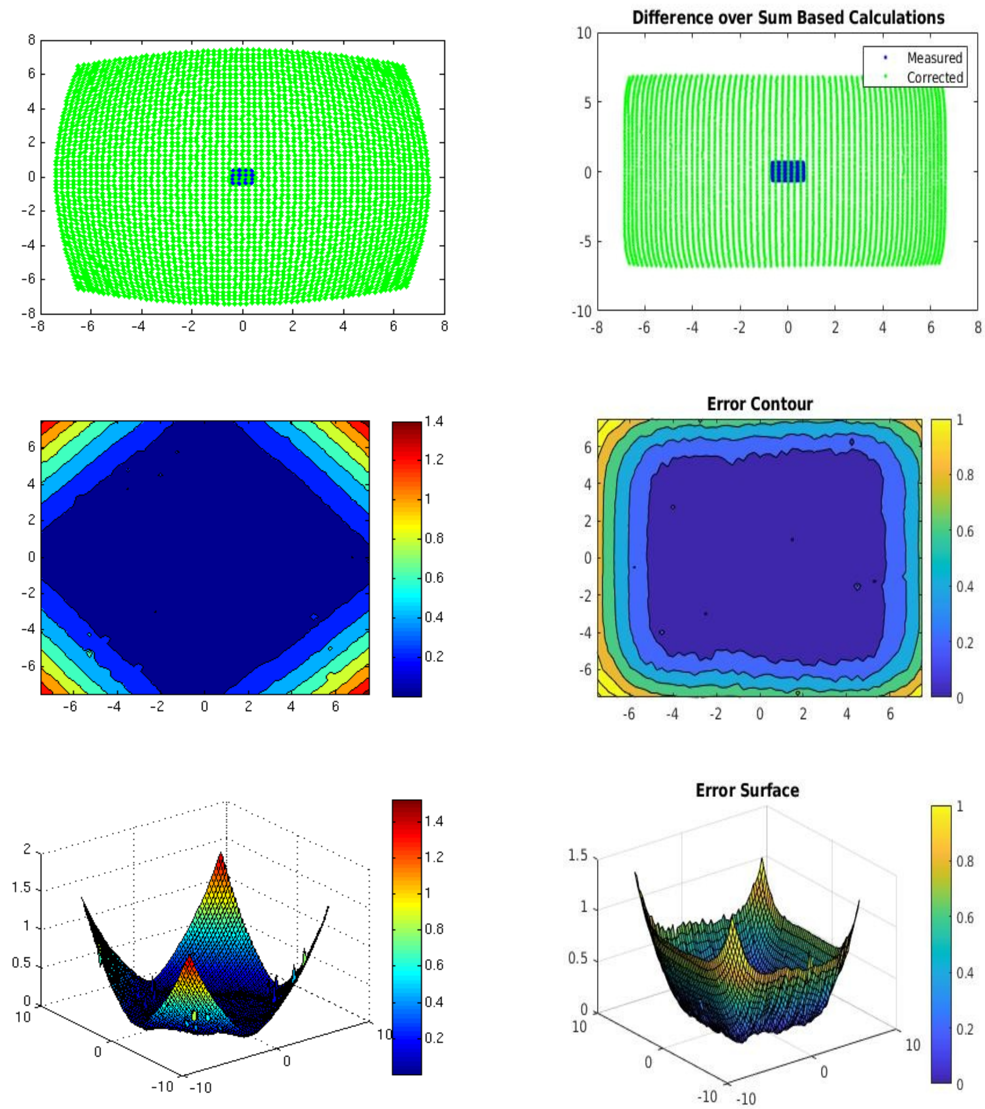


Figure 4. SEE scan of stripline sensor (S/N 22) in both auto-gain mode (a) and fixed-gain mode (b). Fixed-gain was optimized to use the entire dynamic range of the particular gain setting, eliminating signal dropout observed in auto-gain mode. The accepted sensitivity for stripline S/N-22 (9.95) was applied to (a) and (b). Regression analysis is presented in (c), for which the LMS-computed values were applied.

The typical stripline installation in CEBAF involves the sensor, mated with the digital diagnostics receiver. Resolution, sensitivity and dynamic range are all greatly improved over the SEE, which was designed for beam transport from ~100 nA to 1 mA [2]. As a comparison, Figure 5 demonstrates the improvement of M15 and stripline (S/N-22) sensor measurements by the DR, for which field distortions are solely artifacts of the sensor, and not the electronics (particularly outside 1 cm^2). This measurement was performed with an RF level representative of 100 nA.



a. b.

Figure 5. Comparative data for M15 (a) and stripline (b) BPM sensors measured with a JLAB DR receiver, having an RF level representative of 100 nA. The faithful measurement (having larger dynamic range than an SEE receiver) demonstrates field distortions of the actual BPM sensor, with only minimal electrical measurement effects.

SEE Detector

The SEE IF employs a somewhat antiquated quasi-synchronous (QS) detector, originally designed for low-level signals associated with color and monochrome television receivers [3, 4]. While still advertising (ca. 1969) expanded linearity and dynamic range, it does lack the performance of current analog detectors. Nevertheless, reliable position measurements are possible, especially for beam delivery. The specifics of the detector include a 33 dB conversion gain, a 2 MHz output detection bandwidth, maximum input signal of ~150 mV_{rms}, and 8 *VDC* output signal. The SEE BPM IF implementation is shown in Figure 6.

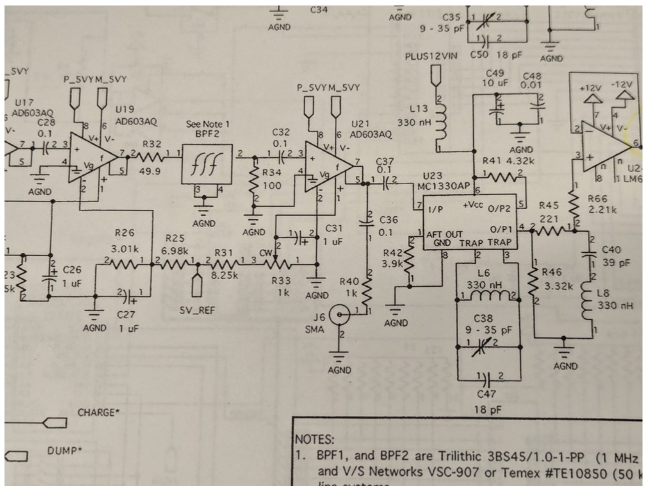


Figure 6. IF circuit fragment, showing the implementation of the ubiquitous Motorola MC1330A video detector, labeled as "U21." The output of the detector is ultimately sampled by a VME-3115 A/D board, and available through EPICS.

In general, the detected signal contains the information, *m(t)*, the carrier, $\cos(\omega_c t)$, the Local Oscillator (LO) with potential amplitude fluctuations, *n(t)*, frequency mis-tuning, $\Delta\omega$, and phase fluctuations, $\varphi(t)$ [5]:

$$s(t)=m(t)\cos(\omega_c t)[1+n(t)]\cos[(\omega_c+\Delta\omega)t+\phi(t)]$$

$$s(t)=\frac{1}{2}m(t)[1+n(t)]\cos[(\Delta\omega)t+\phi(t)]+\cos[(2\omega_c+\Delta\omega)t+\phi(t)]$$

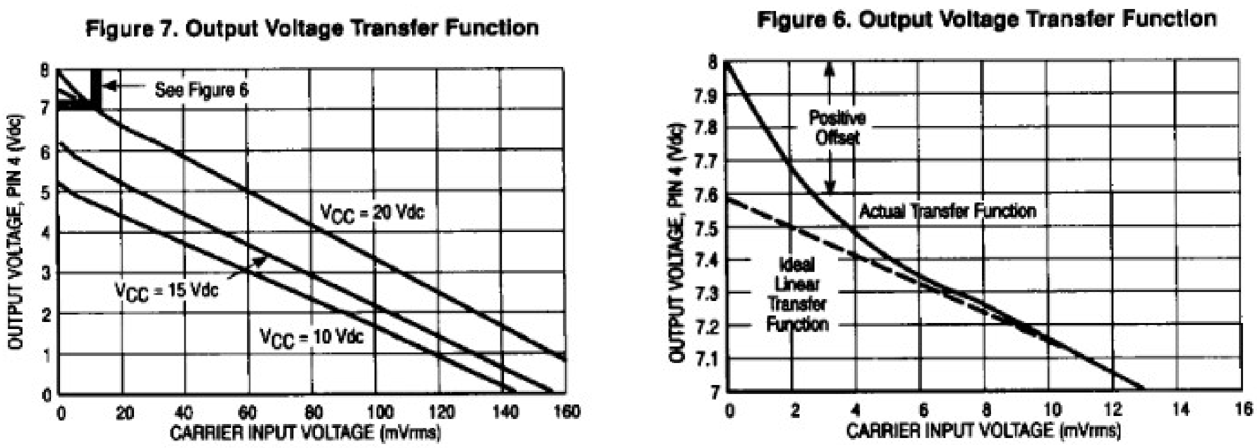
which, after filtering:

$$s(t)=\frac{1}{2}m(t)[1+n(t)]\cos[(\Delta\omega)t+\phi(t)]$$

For a low-level amplitude-limited LO signals, additional noise is imposed on the signal due to the amplitude-to-phase noise conversion of the limiter, affecting both the frequency, $\Delta\omega$, and the phase, $\varphi(t)$, which are each independent, random variables. The detector then adds the excessive phase noise

onto the output signal amplitude, since it is derived from the cosine of the angle between the recovered carrier and that of the input signal.
While QS detectors can improve output SNR for low-level signals (extending detection range, compared to non-coherent detection), the derived LO can suffer a threshold effect, whereby signal is lost as a result of the reference LO losing lock due to the excessive combination of amplitude and phase noise.

The MC1330A has a published output response for it's input voltage range, and shown in Figure 7. While this is linear for strong signals, the deviation from linearity is provided by the inset, and is consistent with the prediction. If full-scale input is given as 150 *mV*, the usable linear dynamic range of the device is from ~8 mV < *V* < 150 mV, or 25 dB. This represents the difference between a large signal from an electrode, versus the smaller signal detected on the opposite electrode, as a result of position offset. The M15 has a sensitivity of 1 dB/mm, which for a beam offset of 7.5 mm wrt boresight will result in a 7.5 db difference between electrode signals; the stripline sensor, with 2 dB/mm sensitivity, will create 15 dB of signal difference.



a. b.

Figure 7. Transfer function response of a Motorola MC1330A video detector IC, providing output vs. input voltage characteristics. The ~150 mV carrier input voltage range shown in (a) deviates, considerably, for signal levels below ~10 mV, as depicted in inset (b). The usable dynamic range for use as a BPM is ~25 dB.

SEE Auto Gain

In normal operation, the SEE provides an AGC function to the IF signal (pre-detection), so as to maintain a nominal 4-wire ADC EPICS readback of 1100 counts (4096 counts, F.S.). While this does not present any problems with near-boresighted signals (whereby all 4 electrodes are represented by the same voltage levels), offset signals encounter a dynamic range limitation, additionally compressing the MC1330A response. The subsequent ADC is a 12-bit converter, but which has only 10-11 effective number of bits (ENOB) in dynamic operation. Therefore, a full-scale range is limited to ~2000 counts.

As an example, for a fixed-gain measurement (in any given range), the maximum ADC readback in EPICS is ~1700, which would presumably represent a full-scale 150 *mV* output from the MC1330A.

However, restricting the maximum signal to 1100 counts reduces the detector output range to ~93 mV. Since the low-end non-linearities begin around 8 *mV,* the actual dynamic range is reduced to ~20 dB, which is approaching the offset depiction given for the stripline BPM measurement, with its 2dB/mm sensitivity. The condition is most severe when measuring opposite corners (incurring up to an additional 6 dB degradation), since now the 4-wire, 1100-count maximum is shared by two neighboring (and orthogonal) electrodes, reducing their individual ADC/EPICS readback ranges to 550. The resulting dynamic range falls to ~14 dB, which is the critical point for the stripline, at the edges of the 1.5cm^2 measurement zone.

Conclusions

RMS error measurement for both sensors were similar within the 1 cm x 1cm area, hovering around 110 um. A CEBAF beam diameter is typically ~150 um, so the error in accuracy is within one beam width for each. Overall field distortion from SEE produced a discrepancy between established can constants (k_x, k_y, delta θ).

If beam is expected to fall outside the nominal 1cm x 1cm zone, considerations include SEE fixed-gain mode with signal level optimization, use of M15-style sensors, or modern receiver architecture (eg. DR, RF lock-in) is recommended.

The SEE uses a 12-bit ADC, which has a nominal dynamic ENOB of 10-11 bits. While this implies a dynamic range of > 60 dB, EPICS AGC attempts to regulate the number of ADC counts to “1100,” whereby the MC1330A detector range is limited to near the range exhibited by the voltages resulting from positions outside the 1 cm^2 “sweet spot,” (prescribed by the SEE BPM system requirements). It may be the case that a near-match replacement with better dynamic range exists for the MC1330A (eg. LM1823?), requiring minimal (eg. a carrier board) circuit modification to implement. Of course, an upgraded IF card is an additional consideration.

JLAB has produced (in limited quantities) shortened (aka “stubby”) M15 sensors, which maintain most of the attributes of the standard model (k~16mm, 1.2 dB/mm). Prints exist, and could provide an option.

Kudos for help and assistance from Chad Seaton, Seth Green, and Xuan Ngyuen from the I&C Group.

References

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2.T. Powers, R. Ursic, L. *Doolittle,* and J. Wagner, “Design, Commissioning and Operational Results of Wide Dynamic Range BPM Switched Electrode Electronics,” Proc. 7th Beam Inst. Workshop, Chicago, IL., 1996.

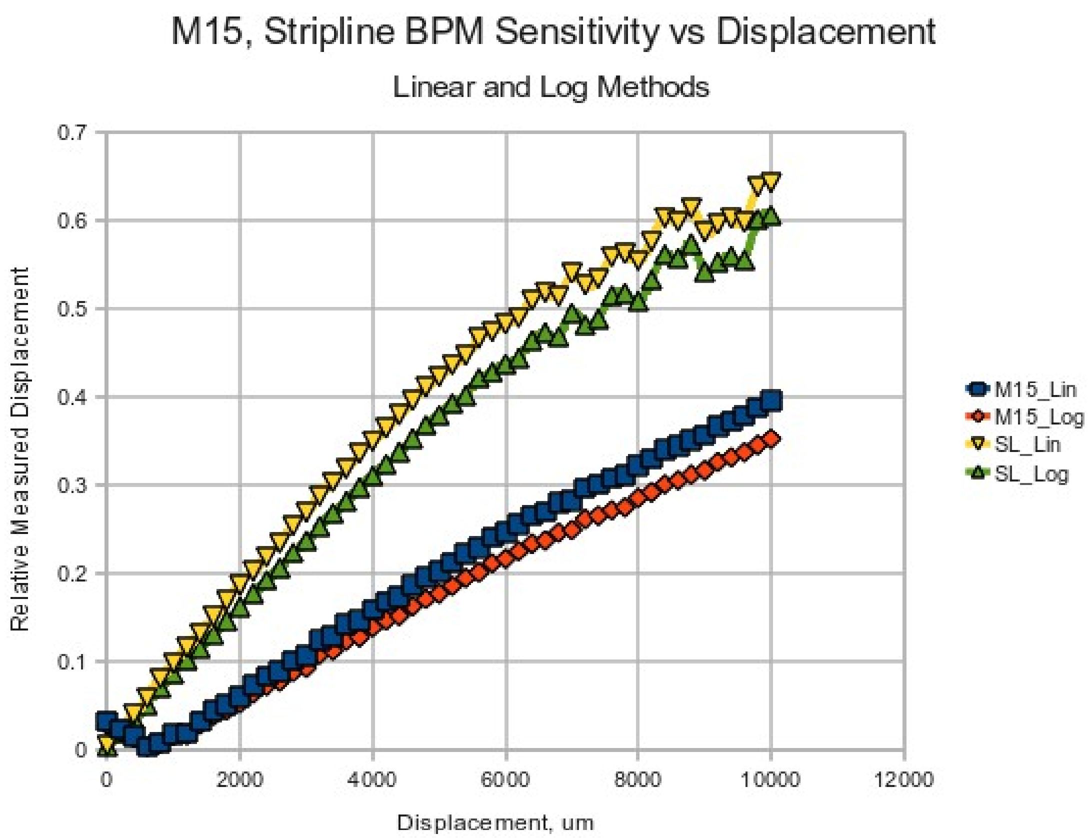
3. MC1330A Datasheet

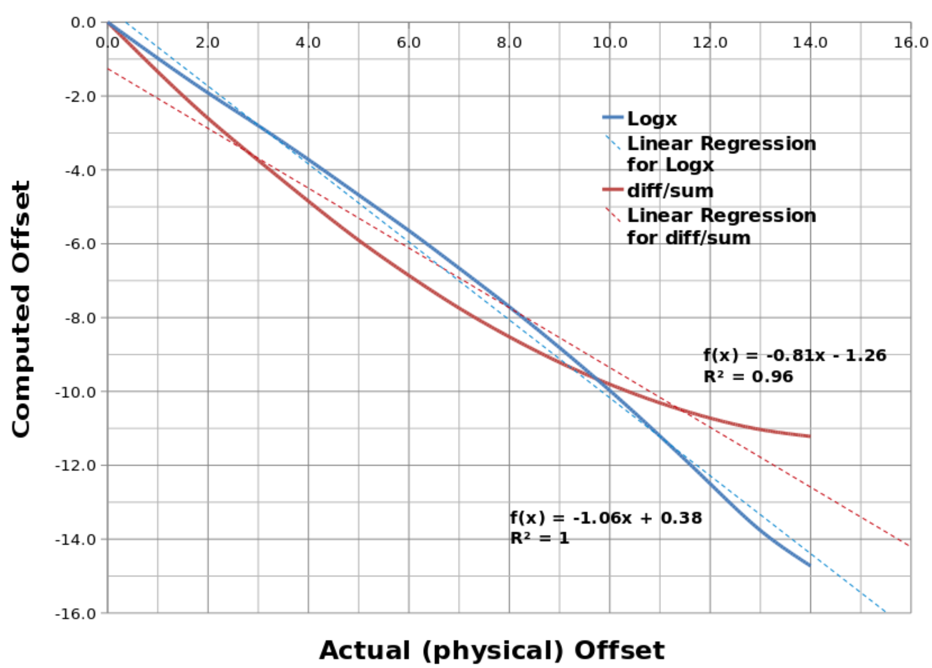
4. G. Lunn, “A Monolithic Wideband Synchronous Video Detector For Color TV,” IEEE Trans. On Broadcast and Television Receivers, July, 1969.

5. M. Schwartz, “Information, Transmission, Modulation and Noise,” 2nd Ed., McGraw-Hill, NY., NY., 1970.

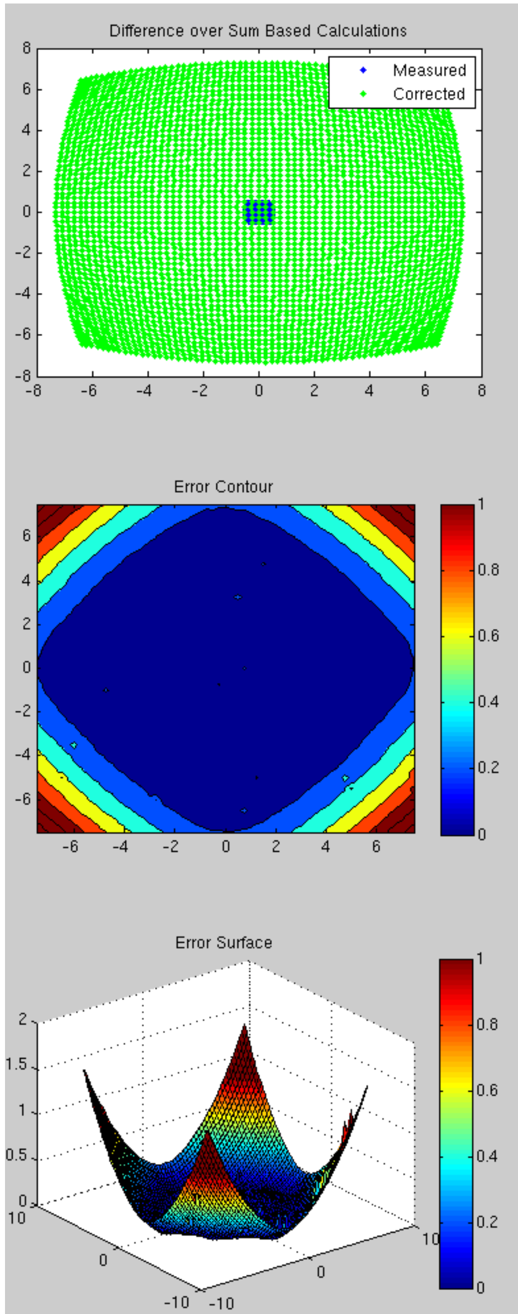
Appendix I: M15 and Stripline Sensor Sensitivities

(3-Port Network Analyzer)





Appendix II: "Stubby" M15 Scan
(performed at high RF level)



$k_x = 15.46$
$k_y = 15.52$
RMS (1cm) = 87.4 um
Delta Theta = 0.041 degrees