Saturn 5B with 5mm/40-degree "imaging" mirror set

This is a test of the ScannerMAX Saturn 5B with a mirror set capable of projecting a 5mm beam through a 40 degree scan angle on both X and Y axis. This particular mirror set it made for imaging, so the mirrors are located pretty close together.

The purpose of this test is to demonstrate sine-wave and triangle-wave scanning capability, at various frequencies ranging from 100Hz up to 1kHz, while recording all critical parameters for analysis.

Although this document presents data gathered for the Saturn 5B with 5mm/40-degree imaging mirror set, this document also sets forth general principles which are related to all galvo scanning systems. The results shown below in the tables and graphs shed light on how galvo systems work, and their limitations.

Power Supply Used, and Power Amplifier Limitations

The Saturn 5B scanners were driven with ScannerMAX Mach-DSP servo driver having +/-24V rails. This servo driver is capable of driving two scanners (dual axis driver) and it is in a compact package. For convenience and for low heat dissipation by the servo driver, it is designed to have a single-ended power amplifier. This means that the power amplifier can only deliver approximately +/-21 volts to the galvo coils.

Mach-DSP Servo Driver and PC Application Software

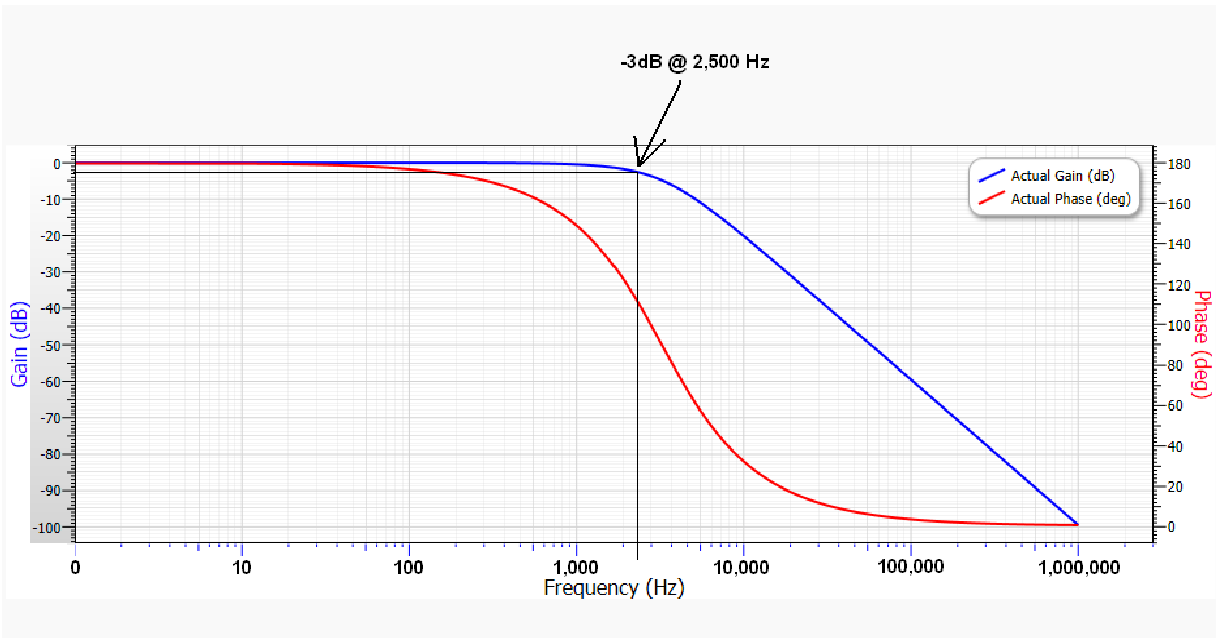
The Mach-DSP servo driver has accompanying Application Software that runs on a Windows-based PC. The software is capable of monitoring all parameters of the scanner during operation. The software also includes a built-in oscilloscope function. This comes in handy as it can be used to measure virtually any quantity of the overall scanning system. For example, the screen shots included in this report show four separate channels being measured. In most of the screen shots, the yellow trace shows "RMS Coil Current". The pink trace shows "Position", in mechanical degrees (optical scan angle is double that shown in the traces). The blue trace shows the "velocity" (first derivative of position). The green trace shows the coil voltage.

For all of the testing, we drove the input command signal using a function generator capable of generating sine-wave and triangle-wave waveforms. Due to the low-pass filter nature of a galvo scanning system, input command signal often has higher amplitude than the position signal. This is particularly true of the triangle-wave inputs.

FOUNDATIONAL CONCEPTS OF SCANNER MOTION

Galvanometer scanning systems accept an input called the “command input”. This is typically an analog signal, but it may also be a digital signal that represents an instantaneous angle you’d like the mirror to achieve. The actual mirror angle is called the “position”. Since galvanometers are electro-mechanical systems, the mirror angle (the position) cannot instantly achieve the commanded input. There is some delay between the command signal, and the actual mirror position. This delay is called the “tracking delay”, or sometimes referred to as the “tracking error”. For the same reason that the mirror position cannot instantly achieve the input command signal, the mirror position signal also cannot completely track the incoming command signal through all amplitudes and all frequency ranges.

When tuned properly, the galvanometer scanning system as a whole behaves like a 2-pole low-pass filter. The bandwidth of the filter depends on the gains that are used inside the servo loop. Higher gains provide for higher bandwidth, and also for shorter tracking delay. These tests were performed with the system tuned with 2.5kHz –3db bandwidth, as illustrated below.



Although not highlighted very vividly in this report, the tracking delay is 150uS with this tuning. Input and output signals are shown on the very last page of this report, before the conclusions.

FOUNDATIONAL CONCEPTS OF POWER CONSUMPTION AND HEAT GENERATION

Relationship between Torque, Inertia, Scan-angle and Frequency

RMS Torque Required = Inertia * (Angle / Magic Number) * Frequency^2

RMS Torque Required is the “continuous” torque in Dyne*Centimeters

Inertia is the total system inertia (rotor+mirror+mount) in Gram*Centimeters squared

“Magic Number” is our way of simplifying a complex classic = 4.11 for an Angle specified in mechanical degrees (peak-to-peak), or 8.22 for an Angle specified in optical degrees (peak-to-peak).

The relationship shows that, for a given Inertia (in this case scanner and mirror set), if you increase the scan Angle, then Torque must be increased by the same amount. However, for a given Inertia and scan Angle, if you want to increase Frequency, then Torque must be increased by the square of the desired frequency increase.

Torque and Coil Current have a linear relationship

A galvanometer scanner has a motor that is driven by coil current. Torque is generated by the scanner in linear proportion to the current flowing through the coil.

Following the discussion above, it means that in order to double the scan angle, this requires twice the Torque, and thus twice the coil current. However, to double the Frequency, this requires a quadrupling of the Torque, and thus a quadrupling of the coil current.

Heat generated inside the scanner (which must be removed by the user) is proportional to the ***square*** of current

Since the coil (or coils) inside all galvanometers have electrical resistance, heat will be generated inside the scanner as a result of being driven by the servo driver. The heat is proportional to the *product* of coil voltage and current, or proportional to the *square* of either voltage or current. The most common way to formulate this is that **heat = current^2 * coil resistance**.

Most important thing to understand – relationship between Scan-Angle, Frequency and Heat

Since the heat is proportional to the square of the current flowing through the coil, what this means is:

- Heat generated by the scanner is proportional to the ***square of scan angle***
- Heat generated by the scanner is proportional to the ***fourth power of frequency!***

TABLE NOMENCLATURE AND DEFINITIONS

Tables below are presented with information related to the electrical- and heat-related parameters that result from scanning at various frequencies.

The ***Angle*** is the optical peak-to-peak scan angle that was performed by the scanners. As is the case with a 2-pole low-pass filter, the scan angle is attenuated as the frequency is increased. The attenuation isn't too great, because the low-pass filter bandwidth was set for 2.5kHz, and we are only exploring frequencies up to 1kHz.

The ***Coil Voltage*** is the peak-to-peak voltage applied to the cable (in this case a 3-meter cable) that is then connected to the Saturn 5 galvo.

The ***Coil Current*** is the RMS current flowing through the scanner, in Amps. RMS current is used for convenience, since it is related to the RMS torque needed to move the mirror, and also related to the heat generated by the scanner.

The ***Coil Power*** is the resulting heat, in Thermal Watts, that is dissipated by the coil (generated by the scanner during scanning), which must be removed by the user.

The ***Amplifier Power*** is the heat, in Thermal Watts, that is generated by the transistors that are a part of the servo driver that drives the scanner. This heat must also be removed by the user.

The ***Power Supply Current*** is the current drawn by each power rail (same current for each of the +24V and –24V power rails).

Although it is somewhat counter-intuitive, power supplies are specified in terms of "average current" (related to the power being delivered) while scanners are specified in terms of "RMS current" (related to the heating of the scanner coil). Because of this, it is not a simple matter to gage power supply requirements by looking at the RMS current drawn by a scanner. Average current supplied by the power supply will always be lower than RMS current driven into the scanner.

Moreover, if a scanner is consuming 2 amps of current, half of this current is supplied by the positive supply rail and the other half is supplied by the negative supply rail (i.e. 1 amp from each supply rail).

And as a final point regarding Power Supply Current, the Mach-DSP requires about 0.2 amps from each power rail just to operate internal circuits and to idle the power amplifier, so this represents a minimum power draw. At low frequencies, this idle current is the dominant current drawn by the system.

Sine-wave drive

For the sine-wave testing, the function generator was set to an amplitude that would command a 40-degree peak-to-peak optical scan angle, for frequencies between 100Hz and 900Hz. For the 1kHz frequency sine-wave, the input was reduced to 33 degrees.

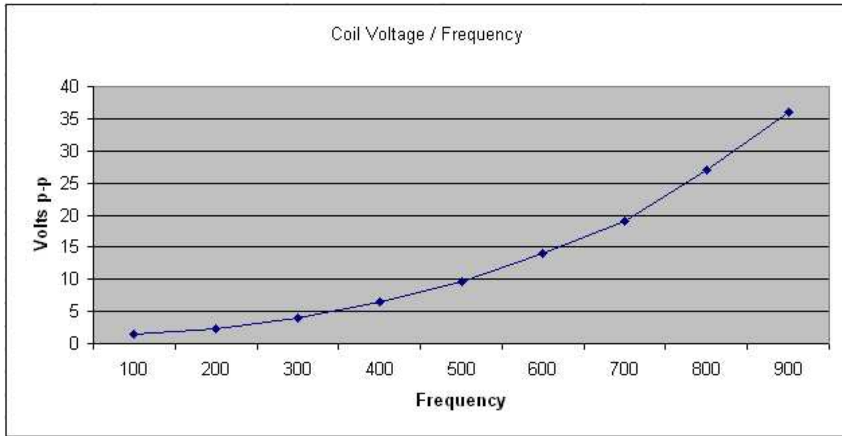
Freq	Angle (p-p)	Coil Voltage (p-p)	Coil Current (RMS)	Coil Power (watts)	Amplifier Power (watts)	Power Supply Current (amps)
100	40.0	1.4	0.05	0.005	1.0	0.23
200	39.9	2.2	0.2	0.08	4.2	0.3
300	39.7	4.0	0.5	0.5	10	0.43
400	39.5	6.4	0.85	1.5	17	0.6
500	39.3	9.6	1.3	3.8	25	0.83
600	39.1	14	1.9	8	33	1.1
700	38.9	19	2.6	15	40	1.4
800	38.7	27	3.5	28	45	1.8
900	38.4	36	4.5	48	40	2.2
1000	32.0	36	4.5	49	40	2.2

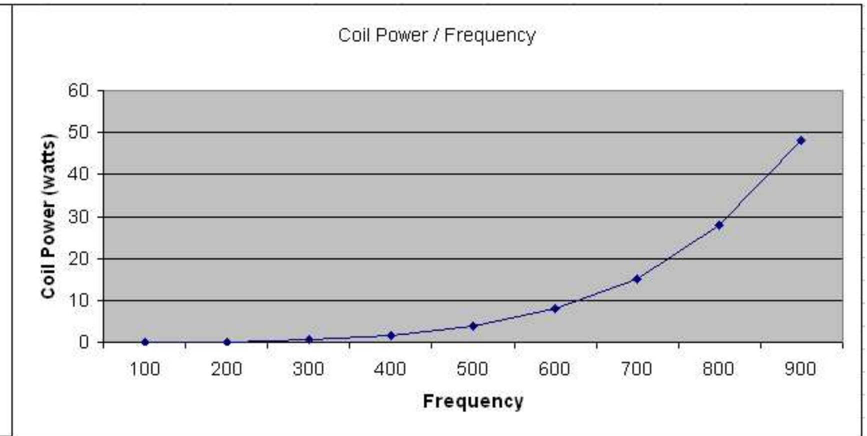
At 900Hz, the RMS Coil Current is 4.5 amps. This is pretty close to the 4.7 amps max specified by the datasheet. Likewise, at 900Hz, the scanner is generating 48 watts of heat, which is pretty close to the 55-watt max specified by the datasheet. Indeed it would be challenging for the user to operate the scanner on a sustained basis, at this scan angle and this frequency or higher.

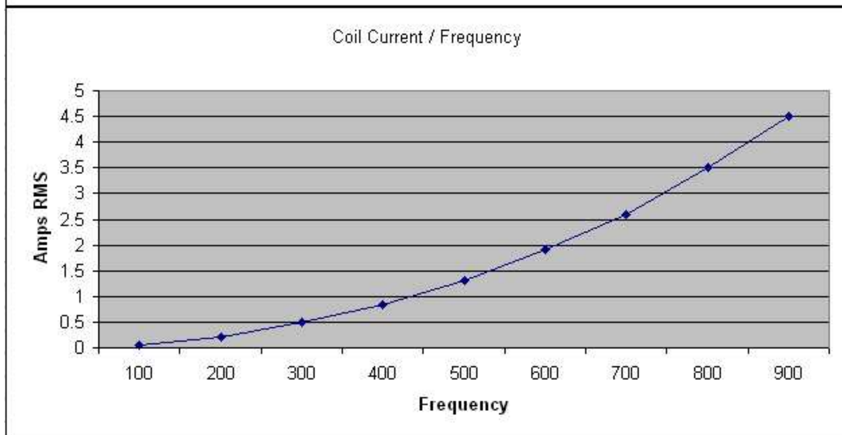
Operation at 1kHz with a 40-degree drive input would exceed the RMS Coil Current and Heat dissipated by the scanner, and thus scan amplitude was reduced to an angle with power dissipation and coil current limitations similar to that of 900Hz.

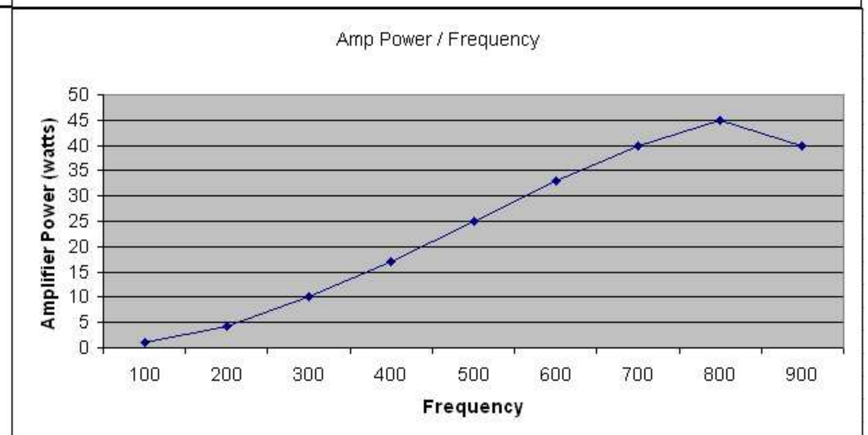
Graphs below show how each of the parameters change as a function of frequency. It can be seen that – for a sine-wave drive, Coil Voltage and Coil Current are directly proportional to each other. It can also be seen that Coil Current is related to the square of Frequency, and that Coil Power (heat generated) is proportional to the fourth-power of Frequency. Note that since the command input was only held consistent for frequencies from 100Hz to 900Hz, the graphs do not show data for 1kHz.

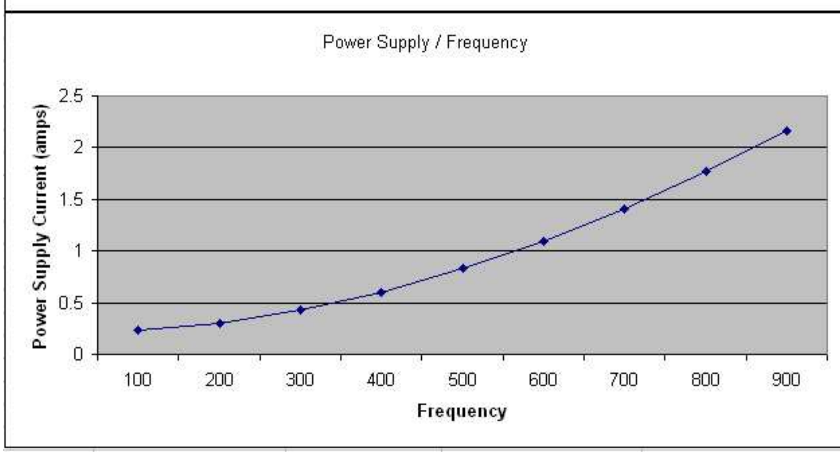
Amplifier Power is a bit more complicated to understand. At 800Hz, the voltage drop across the power transistors is approximately equivalent to the voltage flowing through the scanner coil, and thus heat generated by the power amplifier is maximum at this frequency. At higher frequencies, there is more voltage across the scanner coil, and thus less voltage across the power transistors, leading to less heat being generated.

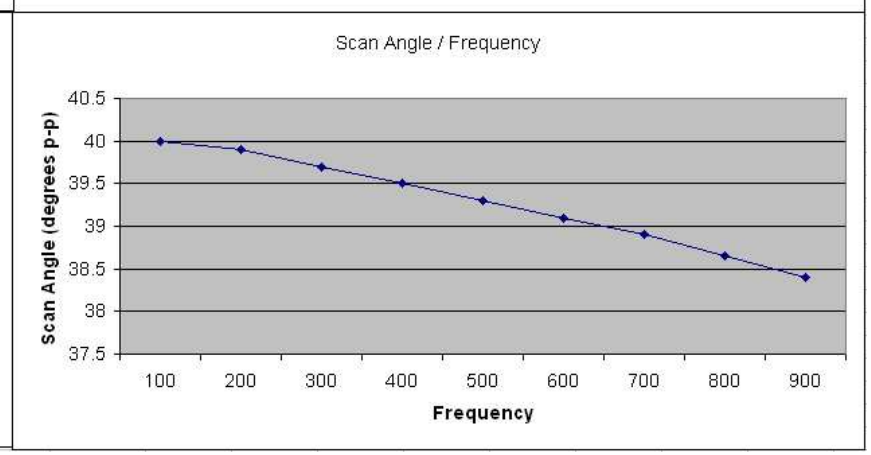

Coil Voltage / Frequency
40
35
30
25
20
15
10
5
0
Volts p-p
100
200
300
400
500
600
700
800
900
Frequency


Coil Power / Frequency
60
50
40
30
20
10
0
Coil Power (watts)
100
200
300
400
500
600
700
800
900
Frequency


Coil Current / Frequency
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Amps RMS
100
200
300
400
500
600
700
800
900
Frequency


Amp Power / Frequency
50
45
40
35
30
25
20
15
10
5
0
Amplifier Power (watts)
100
200
300
400
500
600
700
800
900
Frequency


Power Supply / Frequency
2.5
2
1.5
1
0.5
0
Power Supply Current (amps)
100
200
300
400
500
600
700
800
900
Frequency

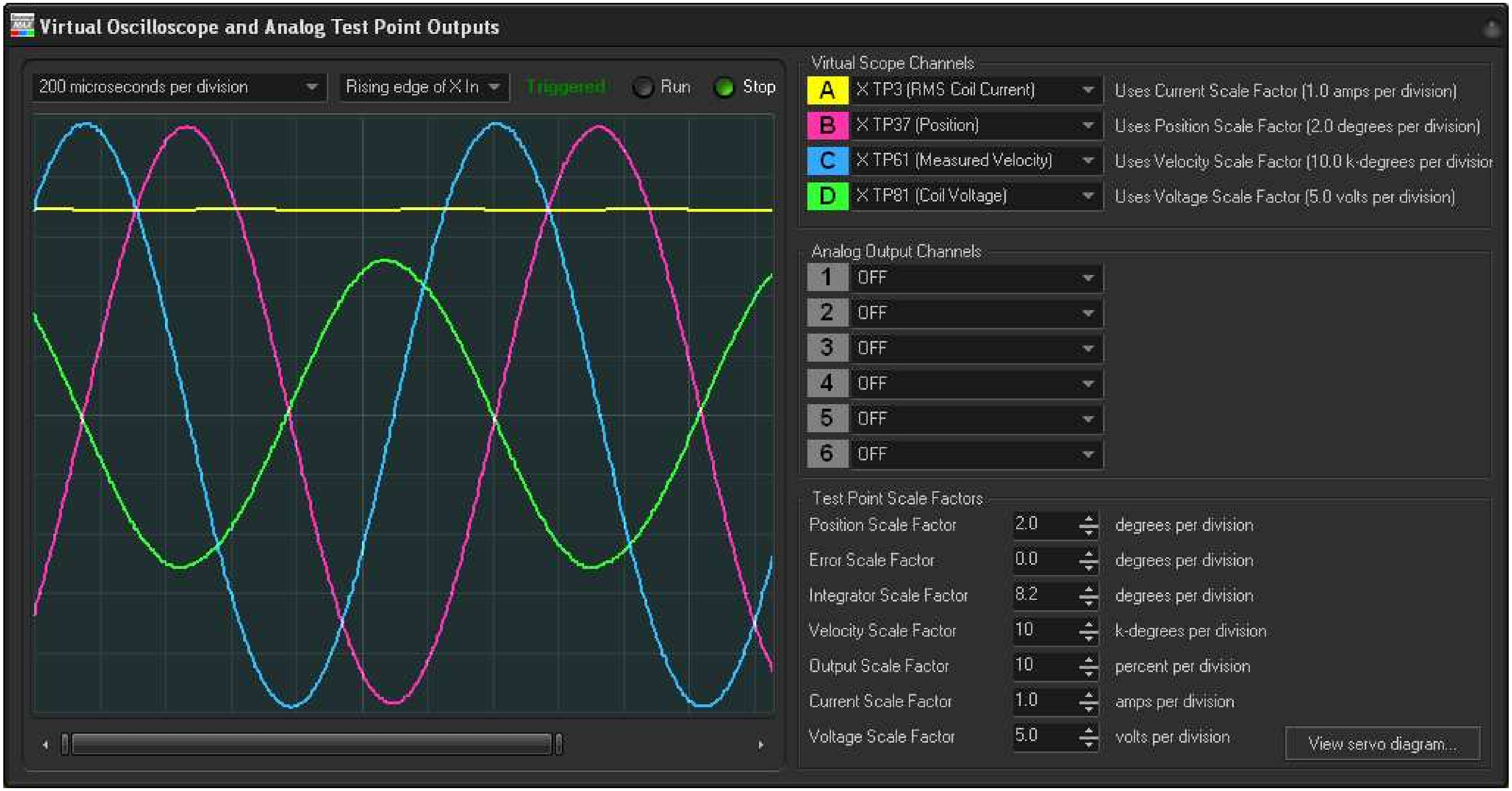

Scan Angle / Frequency
40.5
40
39.5
39
38.5
38
37.5
Scan Angle (degrees p-p)
100
200
300
400
500
600
700
800
900
Frequency

Oscilloscope Screen Shots of Sine-wave Drive

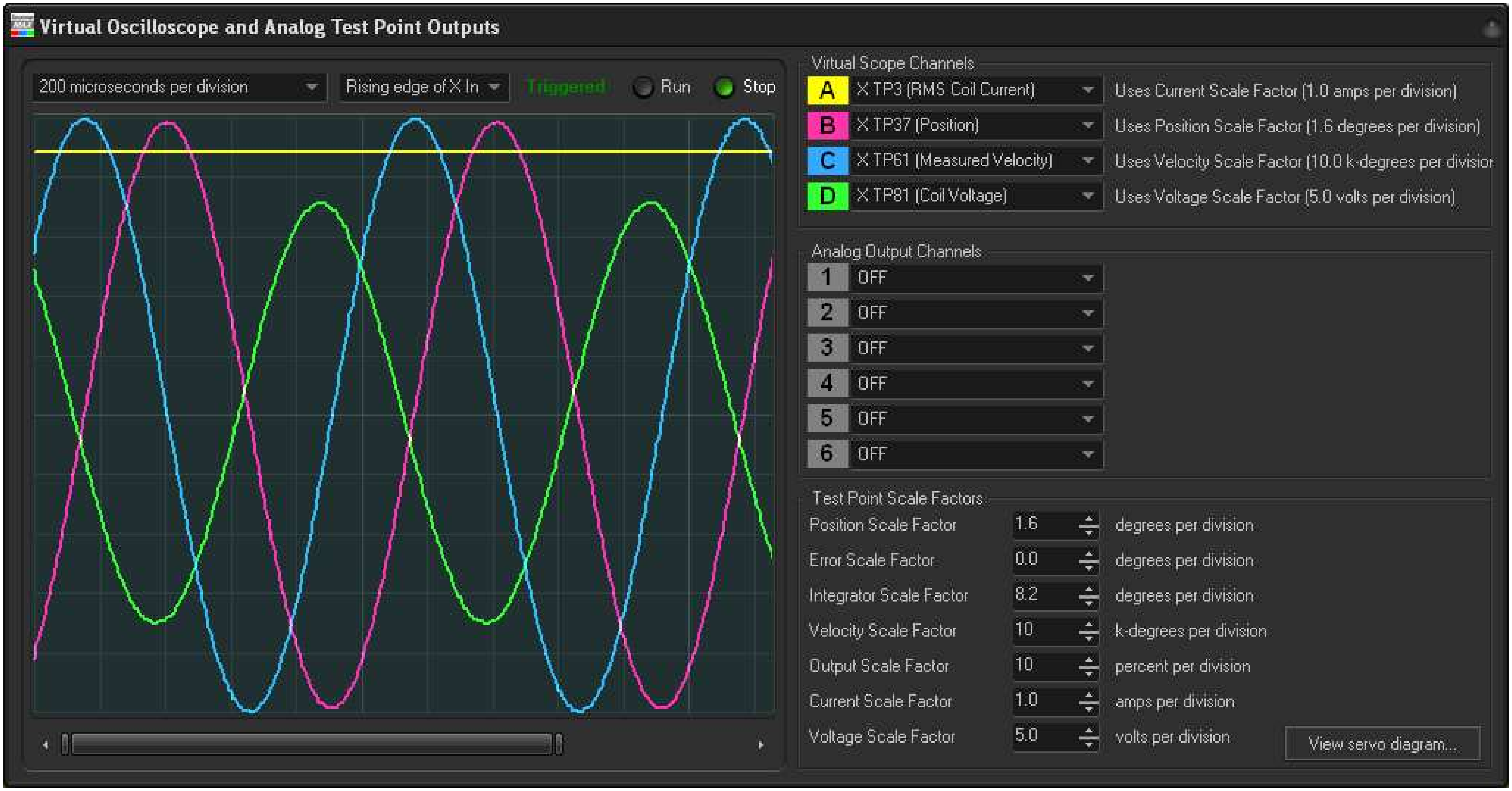
Several Screen shots are presented below, that show how the data was collected for the tables and graphs above.

600Hz Sine-wave at 39.1 degrees optical peak to peak

800Hz Sine-wave at 38.7 degrees optical peak to peak



1kHz Sine-wave at 32 degrees optical peak to peak



Triangle-wave drive

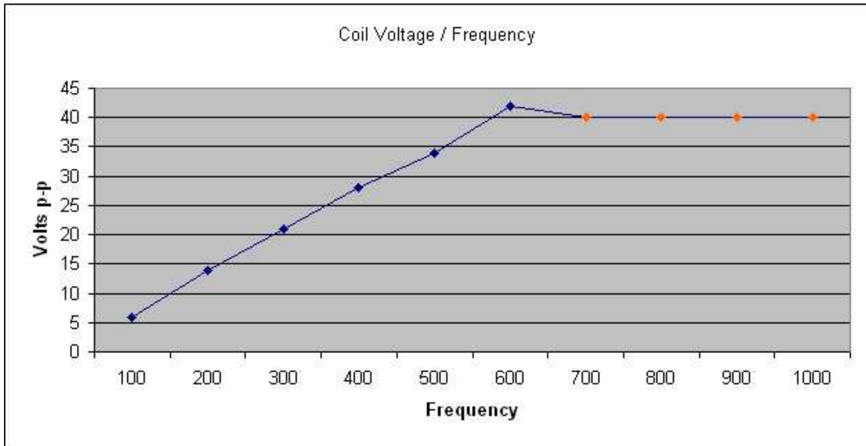
For the triangle-wave testing, the function generator was set to an amplitude that would command a 40-degree peak-to-peak optical scan angle, for all frequencies between 100Hz and 1000Hz.

Freq	Angle (p-p)	Coil Voltage (p-p)	Coil Current (RMS)	Coil Power (watts)	Amplifier Power (watts)	Power Supply Current (amps)
100	40	6	0.15	0.045	1.4	0.24
200	39	14	0.45	0.4	3.5	0.29
300	38	21	0.8	1.28	6.0	0.37
400	37	28	1.25	3.2	9.0	0.48
500	36.5	34	1.75	6.4	12	0.63
600	36	42	2.3	11	16	0.8
700	33	40	2.7	15	20	1.0
800	32	40	3.1	21	25	1.24
900	30	40	3.5	28	30	1.5
1000	28	40	3.9	35	35	1.86

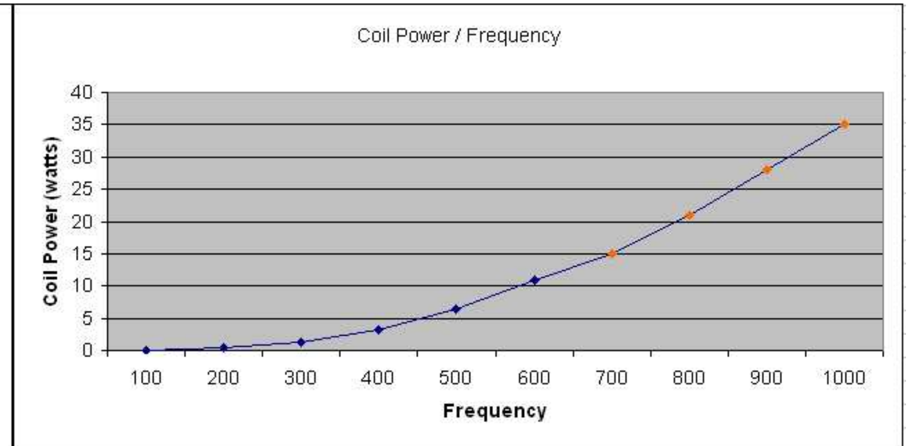
Servo gains that establish a 2.5kHz small-signal bandwidth were used for all frequencies up to 600Hz. Higher frequencies caused the power amplifier to saturate, which is undesirable, and therefore servo gains (and thus servo bandwidth) were progressively reduced, to the point where the power amplifier did not saturate. Those data-points are shown in orange above.

As an alternative to reducing the servo gain, the triangle-wave input could have been rounded (also known as cycloid drive). The end-result in terms of scan amplitude, coil voltage, coil current, and everything else would be virtually the same, but with cycloid drive, the scan angle and scanning waveform more faithfully follows the command input. Everything works in a more controlled manner, and thus this is recommended instead of simple triangle-wave drive from a function generator.

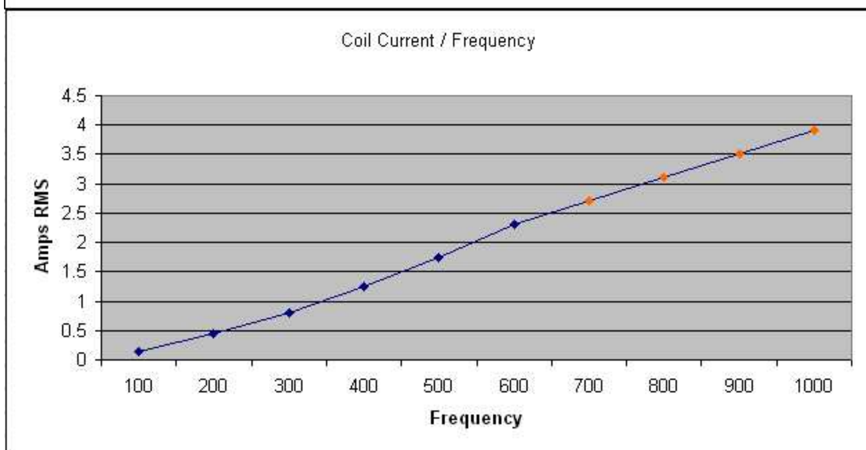
Graphs below show how each of the parameters change as a function of frequency. The data-points marked with orange text above are also marked with orange dots in the graph.



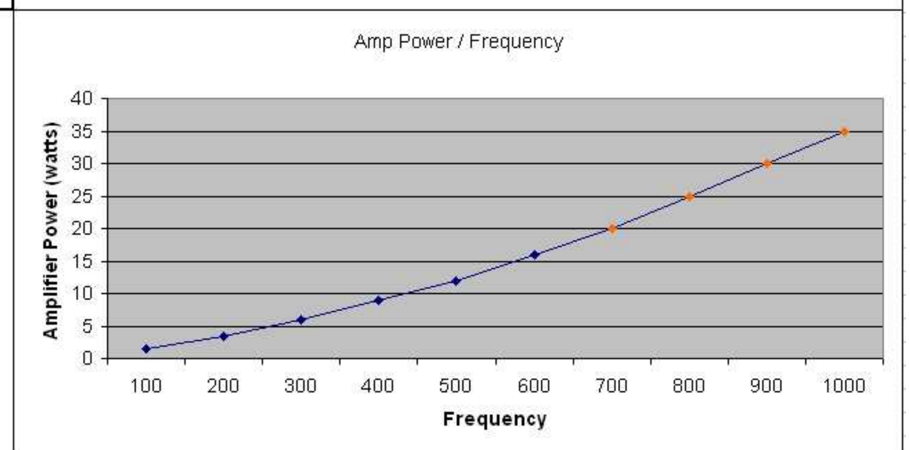
Coil Voltage / Frequency
Volts p-p
0 5 10 15 20 25 30 35 40 45
100 200 300 400 500 600 700 800 900 1000
Frequency



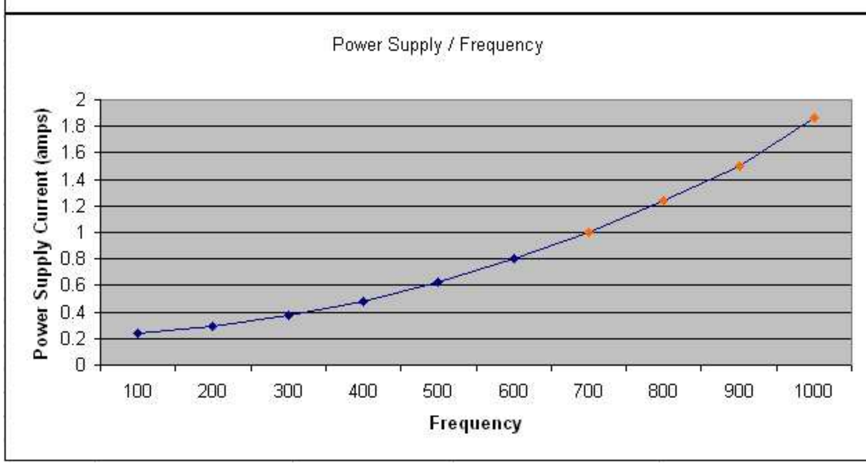
Coil Power / Frequency
Coil Power (watts)
0 5 10 15 20 25 30 35 40
100 200 300 400 500 600 700 800 900 1000
Frequency



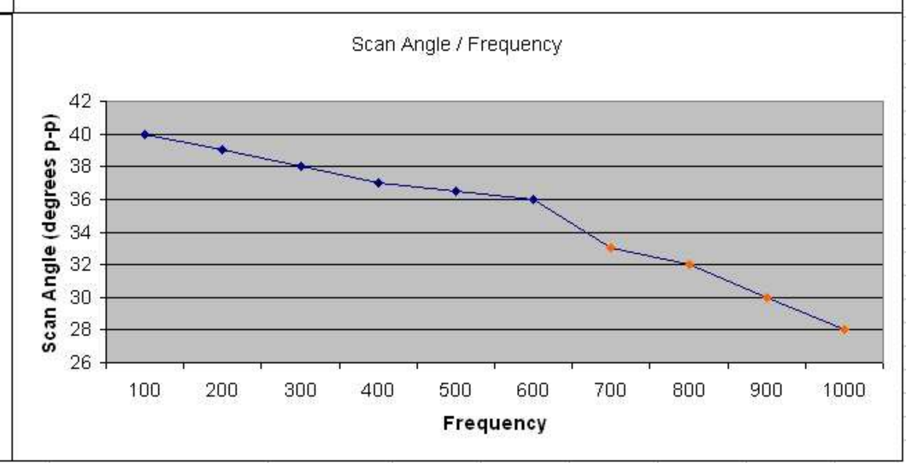
Coil Current / Frequency
Amps RMS
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5
100 200 300 400 500 600 700 800 900 1000
Frequency



Amp Power / Frequency
Amplifier Power (watts)
0 5 10 15 20 25 30 35 40
100 200 300 400 500 600 700 800 900 1000
Frequency



Power Supply / Frequency
Power Supply Current (amps)
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
100 200 300 400 500 600 700 800 900 1000
Frequency

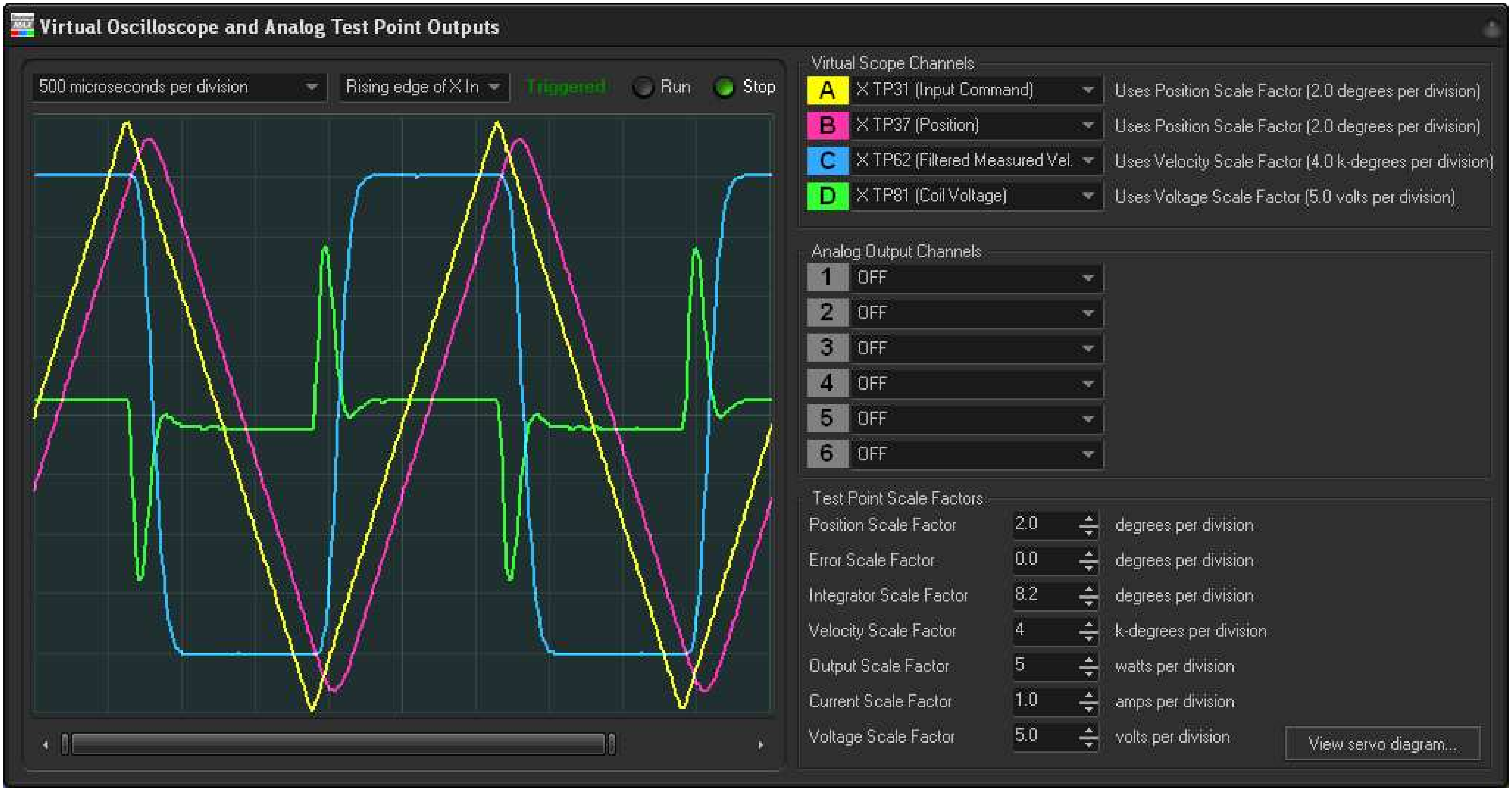


Scan Angle / Frequency
Scan Angle (degrees p-p)
26 28 30 32 34 36 38 40 42
100 200 300 400 500 600 700 800 900 1000
Frequency

Oscilloscope Screen Shots of Triangle-wave Drive

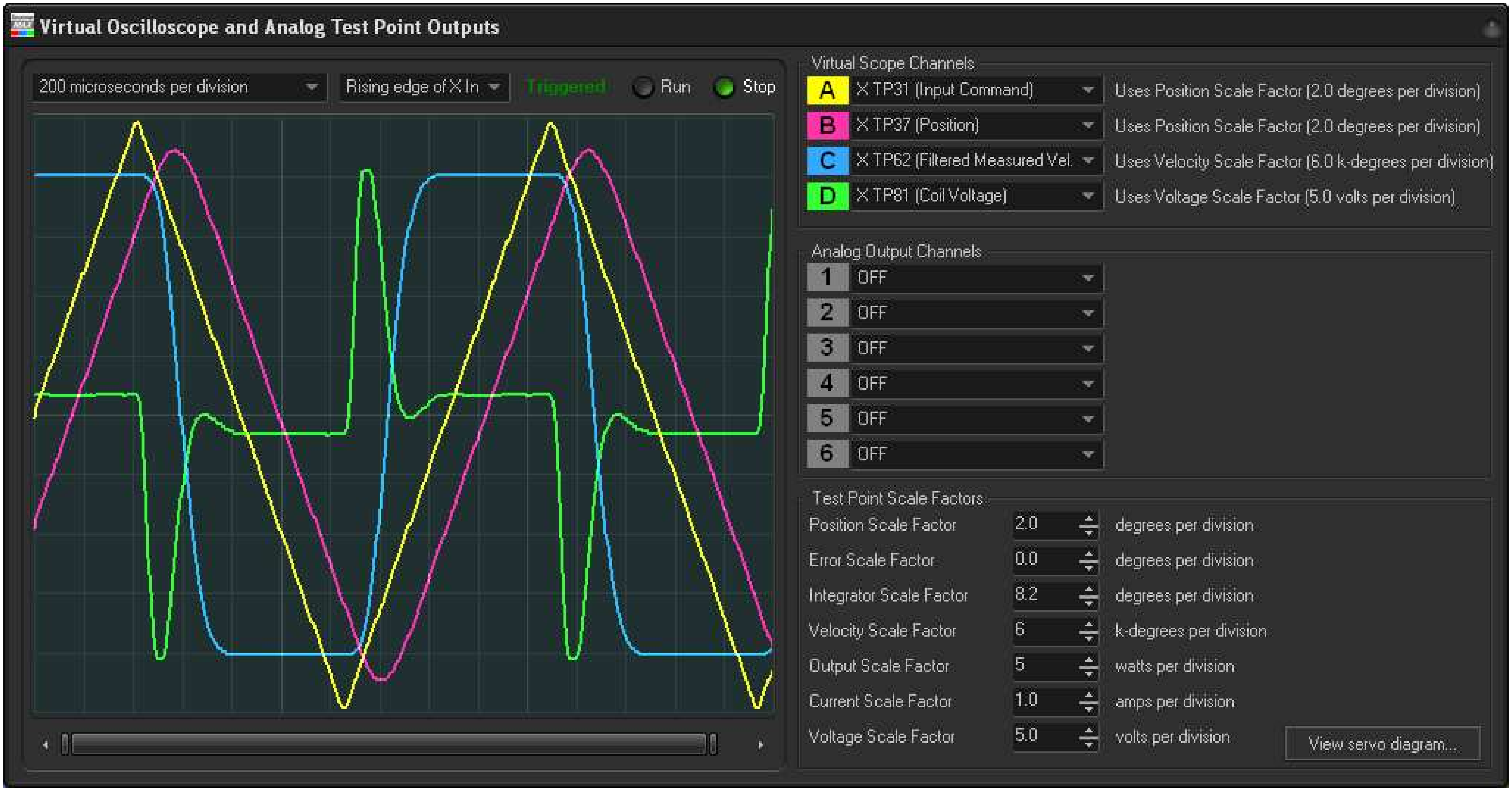
Several Screen shots are presented below, that show how the data was collected for the tables and graphs above.

400Hz Triangle-wave at 37 degrees optical peak to peak



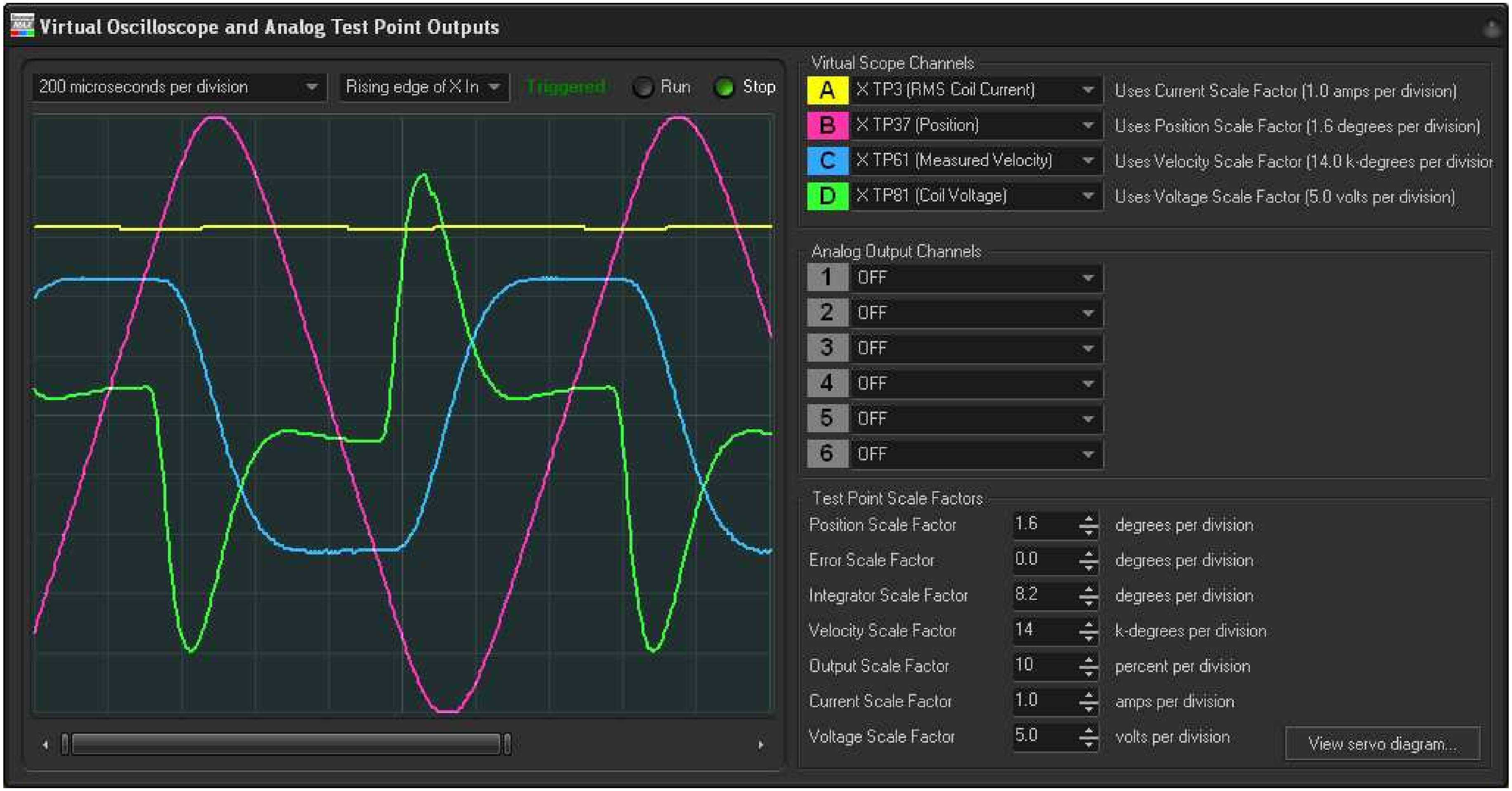
The Blue trace shows scanning velocity. For imaging applications, it is most desirable that this be “flat” on the top and bottom, representing periods of constant velocity. Here at 400Hz we have a nice flat velocity, with not too much time taken for the turn-around at each corner of the triangle-wave. Here we can see that the command is 40-degrees, but the scan is only 37 degrees.

600Hz Triangle-wave at 36 degrees optical peak to peak



The Blue trace shows scanning velocity. Here the triangle-wave scan still shows nice flat velocity, with not too much time taken for the turn-around at each corner of the triangle-wave.

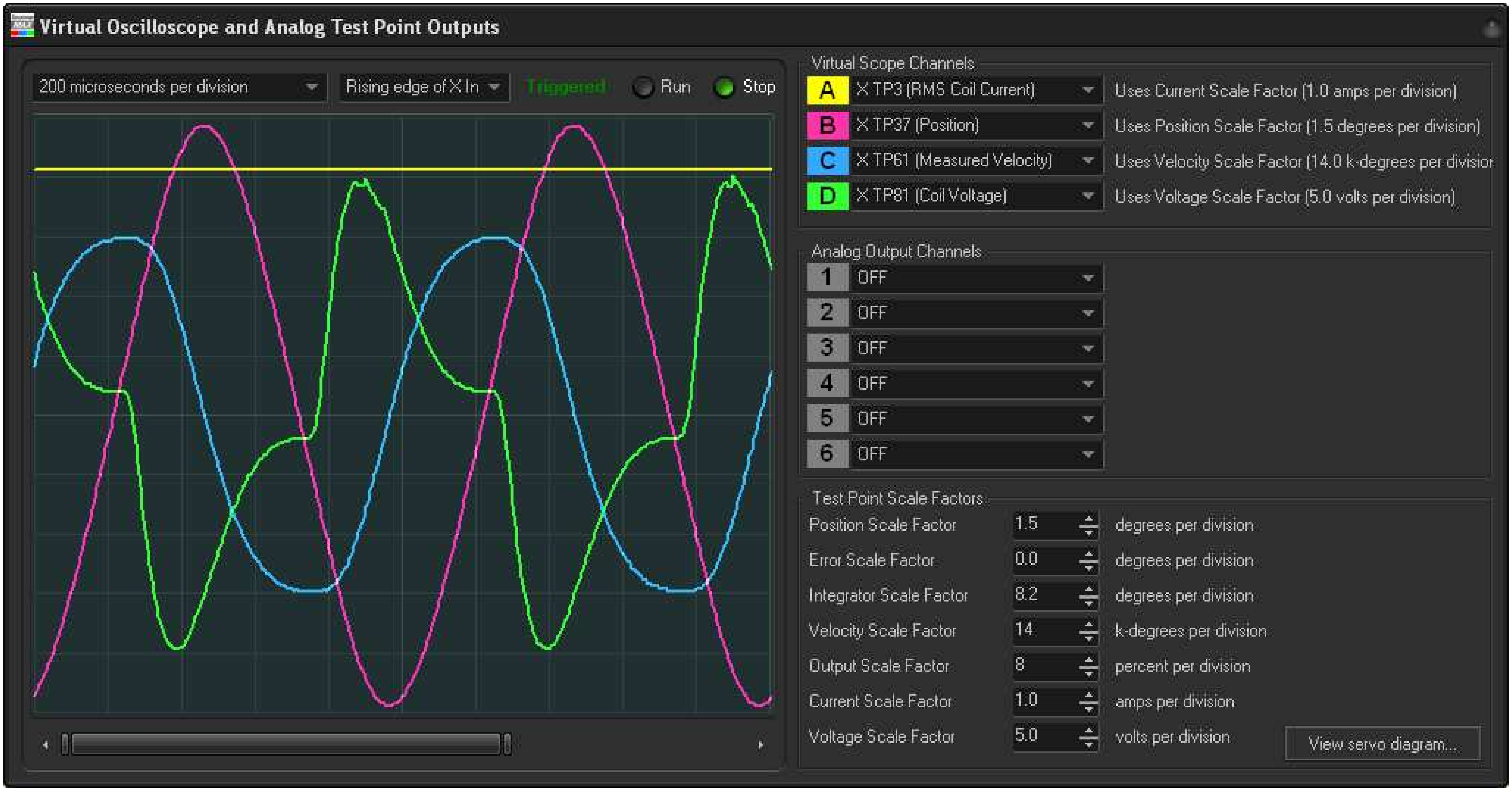
800Hz Triangle-wave at 32 degrees optical peak to peak



As mentioned in the introduction to the section on triangle-wave scanning, in order to prevent the coil voltage from exceeding +/-20V, servo gains had to be reduced for frequencies of 700Hz or greater. Alternatively, cycloid waveforms (triangle-waves with rounded tops and bottoms on the command) could have been used.

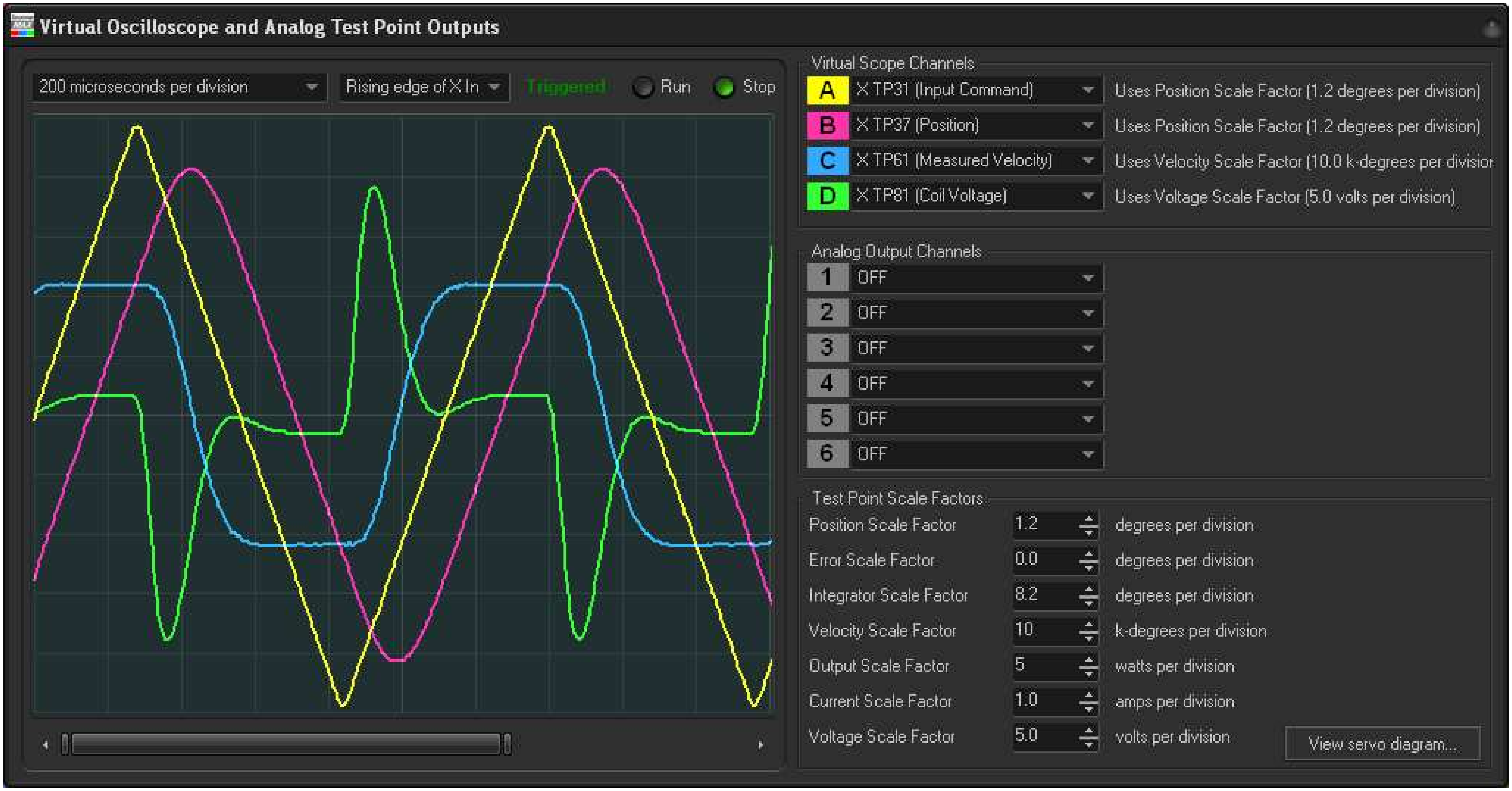
Nevertheless, at 800Hz and 32-degrees optical peak to peak, there is still some amount of flatness shown in the velocity, but clearly a greater proportion of the time is spent turning around.

1kHz Triangle-wave at 28 degrees optical peak to peak



At 1000Hz and 28-degrees, there is really not much constant velocity remaining. It’s not quite a sine-wave, but not a great-looking triangle wave.

1kHz Triangle-wave at 20 degrees optical peak to peak



Reducing the scan amplitude to 20-degrees peak-to-peak (around 24-degrees of command) or below, allows the original 2.5kHz servo gains to be used. This amplitude is about the maximum for a frequency of 1kHz, to retain a good looking triangle wave with decent periods of time with constant velocity scanning. The relevant data-points are expressed in the partial table below.

Freq	Angle (p-p)	Coil Voltage (p-p)	Coil Current (RMS)	Coil Power (watts)	Amplifier Power (watts)	Power Supply Current (amps)
1000	20	38	2.5	14	22	0.97

Conclusions

In this report, we have demonstrated the capabilities of a Saturn 5B scanner with 5mm, 40-degree “imaging” mirror set.

Continuous sine-wave projection at a scan angle of nearly 40-degrees at up to 800Hz can be done without much difficulty. Continuous operation at 900Hz is possible with careful heat sinking of both the scanner and servo driver. Operation near 40-degrees at 1kHz can be done for short periods of time, but the scan angle should be reduced to 32 degrees or less, for less demanding system constraints.

Triangle-wave scanning at scan angles of nearly 40 degrees at up to 600Hz can be done without much difficulty, even when using a simple triangle-wave from a function generator. Triangle-wave scanning at frequencies greater than 600Hz can be performed, but for best results, a cycloid input waveform (i.e. rounded triangle wave) should be used. Constant velocity is best assured at high frequency with the scan angle reduced from 40 degrees.