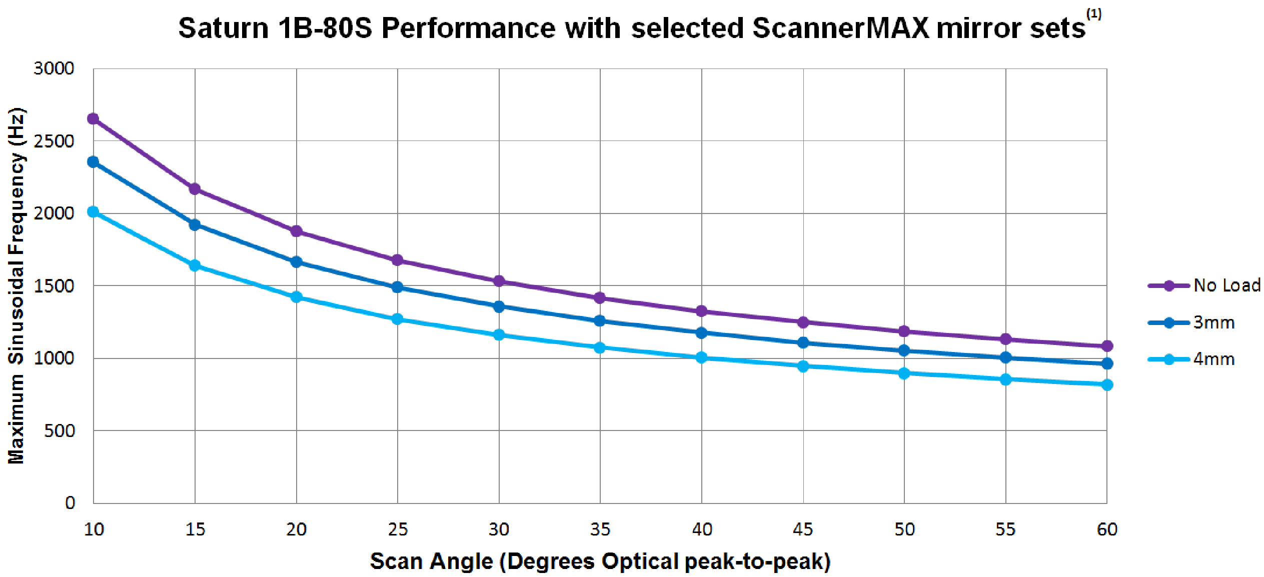
Practical Considerations for High-Frequency Sinusoidal Scanning

On most ScannerMAX datasheets, we publish a graph that denotes the theoretical maximum sinusoidal performance of the scanner, when driven at its thermal limit. The graph found on the Saturn 1B is shown below.



This graph conveys that for a Saturn 1B-80S, with a mirror that can reflect a 3mm beam, it is possible to scan 1000Hz at 55-degrees optical peak-to-peak.

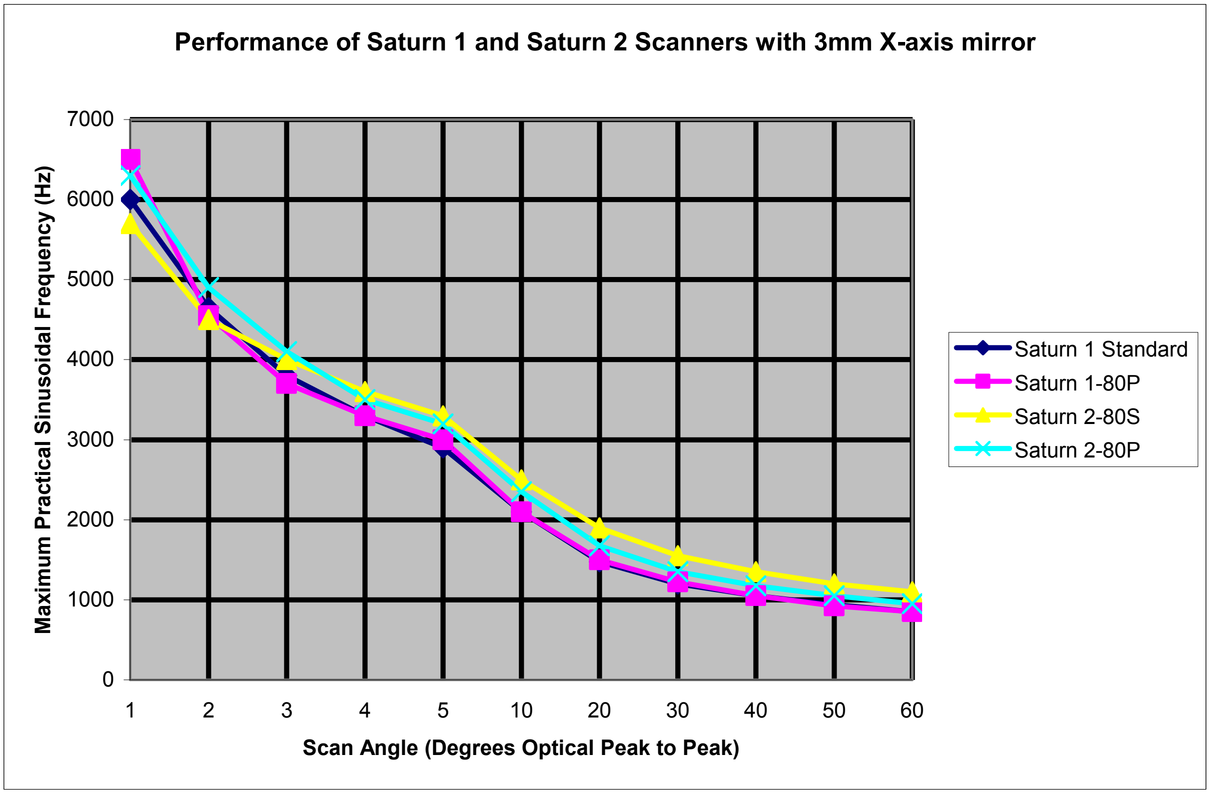
Along with the graph, ScannerMAX datasheets also include several notes. Note 1 states that the graph denotes the theoretical maximum performance of the scanner due to its thermal limitations, with the scanner's case temperature held at 50°C. The note goes onto say that other factors may prevent the scanner from reaching this theoretical maximum, such as servo driver and power supply.

The purpose of the graph is to provide an indication of the performance of the scanner itself. To get the complete picture, the user must mentally combine the graph with other information found on the datasheet. Each of the points on the graph is achieved when the *RMS Current* found on the datasheet is driven into the scanner. At that point the scanner will be generating an amount of heat indicated by the *Power Handling Capacity*, which is also noted on the datasheet. When the *RMS Current* is driven into the scanner, and the scanner is generating *Power Handling Capacity* amount of heat, the rotor will be operating at a the *Maximum Rotor Temperature*, noted on the datasheet.

The graph will hold true as long as the user is able to maintain the case temperature of 50°C. But the graph, all by itself, does not convey the degree of effort involved in achieving the combination of scan angle and frequency. The graph does not convey the power supply that would be required to achieve this, or the amount of heat that would be generated by the power amplifier stage of the servo driver. It could very well be that the main limiting factor for the overall scanning system as a whole, is not the scanner itself, but is the power supply, the voltage or current capabilities of the servo driver, or even the practicality of removing heat from the scanner and servo driver during operation. In other words, the performance that a scanning system can achieve from a practical standpoint may be lower than the theoretical maximum found on the datasheet.

It is the goal of this paper to present information about the practical sinusoidal scanning performance of Saturn 1 and Saturn 2 scanners, when driven by a ScannerMAX Mach-DSP servo driver, and to discuss which element in the system causes the limitation of a given system. Other important information is also included about how to achieve maximum scanner lifetime.

Graph of Practical Scanning Performance for Saturn 1 and Saturn 2



The graph above denotes the actual, tested performance of our Mach-DSP servo driver, driving four separate ScannerMAX scanners, each having our 60-degree, 3mm-aperture X-axis mirror. The scanners tested were the Saturn 1 with Standard coil configuration, Saturn 1 with 80-P coil configuration, Saturn 2 with 80-S coil configuration, and Saturn 2 with 80-P coil configuration.

Saturn 1 with standard coil configuration

The Saturn 1 version that we sell the most has 14 turns of wire, arranged in 4 coils, for a total of 56 turns in series. This provides a 1.8 ohm coil having 100uH inductance. This is a very versatile impedance, capable of achieving greater than 7.5kHz small-signal bandwidth (ILDA 90K). This scanner is used in a wide variety of applications including laser projection and scanning microscopes.

Saturn 1 with 80-P coil configuration

The Saturn 1 stator can fit more than the 56 turns discussed above. In fact, the Saturn 1 stator can fit up to 80 turns of wire. These turns can be connected in a series configuration (as would be the case for Saturn 1B-80S), or they can be connected in parallel, as is the case with the 80-P version. When the 80-turns are connected in parallel, coil impedance is much lower. This would be desirable for a scanner used with small-angle, high-speed applications, but this requires more current from the driver.

Saturn 2 with 80-S coil and 80-P configuration

The Saturn 2 is basically a Saturn 1 scanner, whose rotor is 50% longer, thus increasing torque while not appreciably increasing inertia. Theoretically, this can provide greater performance, or it can generate less heat for a given Saturn 1 performance. Like the Saturn 1, up to 80-turns can be placed on the coils, and they can be connected in series or parallel. When the turns are connected in series, this is generally an optimization for wide-angle scanning. But this also requires more drive voltage.

Collected Data

On the next four pages, we present the data that was collected for the four scanners noted above. Although we have the capability of gathering similar data via simulation, the data presented here is not from a simulation. Real scanners were used along with a Mach-DSP servo driver.

The following is the lexicon for the following four pages:

Scan Angle is the sinusoidal scan angle achieved, in optical degrees peak-to-peak.

Freq is the sinusoidal frequency driven into the servo driver.

V P-P is the peak-to-peak voltage driven into the coil of the scanner.

RMS is the RMS current driven into the coil of the scanner.

Scanner P is the heat generated by the scanner (in thermal Watts) during scanning.

Amp P is the heat generated by the power amplifier portion of the servo driver (in thermal Watts) during scanning.

It is typical that lower scan frequencies require a lower peak-to-peak coil drive voltage, and when this is the case the power supply itself might be reduced. When the power supply voltage is reduced, it also reduces the amount of heat generated by the power amplifier.

For example, in the next page, where you see 45@24 27@18, this means the heat generated is 45 thermal watts when +/-24V power supplies are used, and 27 thermal watts when +/-18V power supplies are used. If you only see one set of numbers, such as 45@24, this indicates that it is not possible to achieve this particular scan angle and frequency with a lower power supply voltage.

Information on Power Supply Requirements is included

Although it is somewhat counter-intuitive, power supplies are specified in terms of "average current" (related to the power being delivered) while the current figure you find on scanner datasheet is specified in terms of "RMS current" (related to the heating of the scanner coil). The servo driver itself also requires around 200mA of idle current from each power supply rail.

Because of this, it is not a simple matter to gage power supply requirements by referring to the RMS current specification found on a scanner's datasheet. Average current supplied by the power supply will almost always be lower than RMS current driven into the scanner.

Moreover, since the Mach-DSP uses only a single-ended power amplifier and not an H-bridge, when the 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).

Indication of the performance-limiting factor is included

As discussed on the first page, sometimes the performance is limited by the scanner itself, and other times the performance is limited by the servo driver or even the power supply. The performance-limiting factor is presented for each of the four scanners.

Saturn 1 Standard

Scan Angle	Freq	V P-P	RMS	Scanner P	Amp P	
1	6000	40	2.8	17.6	37@24	
2	4650	39	3.75	32	38@24	
3	3800	38	3.75	32	38@24	
4	3300	35	3.75	32	40@24	
5	2900	35	3.75	32	40@24	
10	2100	33	3.75	32	42@24	27@18
20	1475	30	3.75	32	45@24	27@18
30	1200	29	3.75	32	45@24	27@18
40	1050	29	3.75	32	45@24	27@18
50	940	29	3.75	32	45@24	27@18
60	850	28	3.75	32	45@24	27@18

Power Supply Requirements:

1.8 amps from each of +/-supply rail
86 watts when +/-24V is used
65 watts when +/-18V is used

Performance-limiting factor for this system:

For the combination of Saturn 1 Standard scanner and Mach-DSP servo driver, the performance-limiting factor is the Saturn 1 scanner. The Mach-DSP can easily drive 3.75 amps into the coil with a maximum of 40V peak-to-peak. Under this condition, the scanner will be generating 32 watts of heat during scanning, and the servo driver amplifier will be generating 45 watts of heat.

Saturn 1 –80P

Scan Angle	Freq	V P-P	RMS	Scanner P	Amp P	
1	6500	32	5	23	60@20	
2	4550	25	5	23	52@18	
3	3700	22	5	23	52@18	
4	3300	22	5	23	54@18	
5	3000	19	5	23	54@18	
10	2100	17	5	23	55@18	42@15
20	1500	15	5	23	55@18	42@15
30	1225	15	5	23	55@18	42@15
40	1050	14	5	23	55@18	42@15
50	925	13.4	5	23	55@18	42@15
60	850	13.4	5	23	55@18	42@15

Power Supply Requirements:

2.5 amps from each of +/-supply rail
90 watts when +/-18V is used
75 watts when +/-15V is used

Performance-limiting factor for this system:

For the combination of Saturn 1 –80P scanner and Mach-DSP servo driver, the performance-limiting factor is the Mach-DSP. Theoretically the Saturn 1-80P can accept up to 6.6 amps RMS, and has a power handling capacity of 40 watts, but the Mach-DSP can only provide a maximum of 5 amps RMS, effectively limiting the scanner capacity to 23 watts.

Moreover, the coil resistance of the –80P is quite low, and this effectively moves heat from the scanner to the servo driver. To keep heat generation at the servo driver to an acceptable level, the power supply voltage is reduced below the +/-24V that is typically used with the Mach-DSP.

Saturn 2 –80S

Scan Angle	Freq	V P-P	RMS	Scanner P	Amp P
1	5700	51	1.6	11	30@30
2	4500	51	1.9	16	35@30
3	4000	51	2.0	19	36@30
4	3600	51	2.3	23	38@30
5	3300	50	2.3	23	40@30
10	2500	50	2.8	39	40@30
20	1900	50	3.2	50	40@30
30	1550	46	3.2	50	40@30
40	1350	46	3.2	50	40@30
50	1200	46	3.2	50	40@30
60	1100	46	3.2	50	40@30

Power Supply Requirements:

1.6 amps from each of +/-supply rail (96 watts) up to 2500Hz
1.25 amps from each of +/-supply rail (75 watts) for 3300Hz and above

Performance-limiting factor for this system:

For the combination of Saturn 2 –80S scanner and Mach-DSP servo driver, the performance-limiting factor is the scanner for frequencies below 2500Hz. Above 2500Hz, the limiting factor is the Mach-DSP. For frequencies below 2500Hz, the impedance caused by inductance is low enough that the Mach-DSP can deliver the full coil voltage required to achieve the 3.2-amp RMS maximum that the Saturn 2 –80S can take. Above 2500Hz, the Mach-DSP can only practically deliver around 52 volts peak-to-peak. Because of this, RMS current is lower than the scanner can take, so the scan angle/frequency drops.

In fact, to provide the peak-to-peak voltage required for maximum performance, 30-volt power supplies must be used, and the Mach-DSP must be specially ordered to work with a 30-volt power supply.

Saturn 2 –80P

Scan Angle	Freq	V P-P	RMS	Scanner P	Amp P
1	6300	32	3.5	13	45@20
2	4900	32	4.4	18	52@20
3	4100	28	4.5	20	52@20
4	3500	23	4.5	20	45@18
5	3200	23	4.5	22	45@18
10	2350	22	5	22	47@18
20	1675	18	5	22	50@18
30	1350	18	5	22	51@18
40	1175	18	5	22	51@18
50	1050	18	5	22	51@18
60	950	17	5	22	51@18

Power Supply Requirements:

2.2 amps from each of +/-supply rail
88 watts when +/-20V is used
80 watts when +/-18V is used

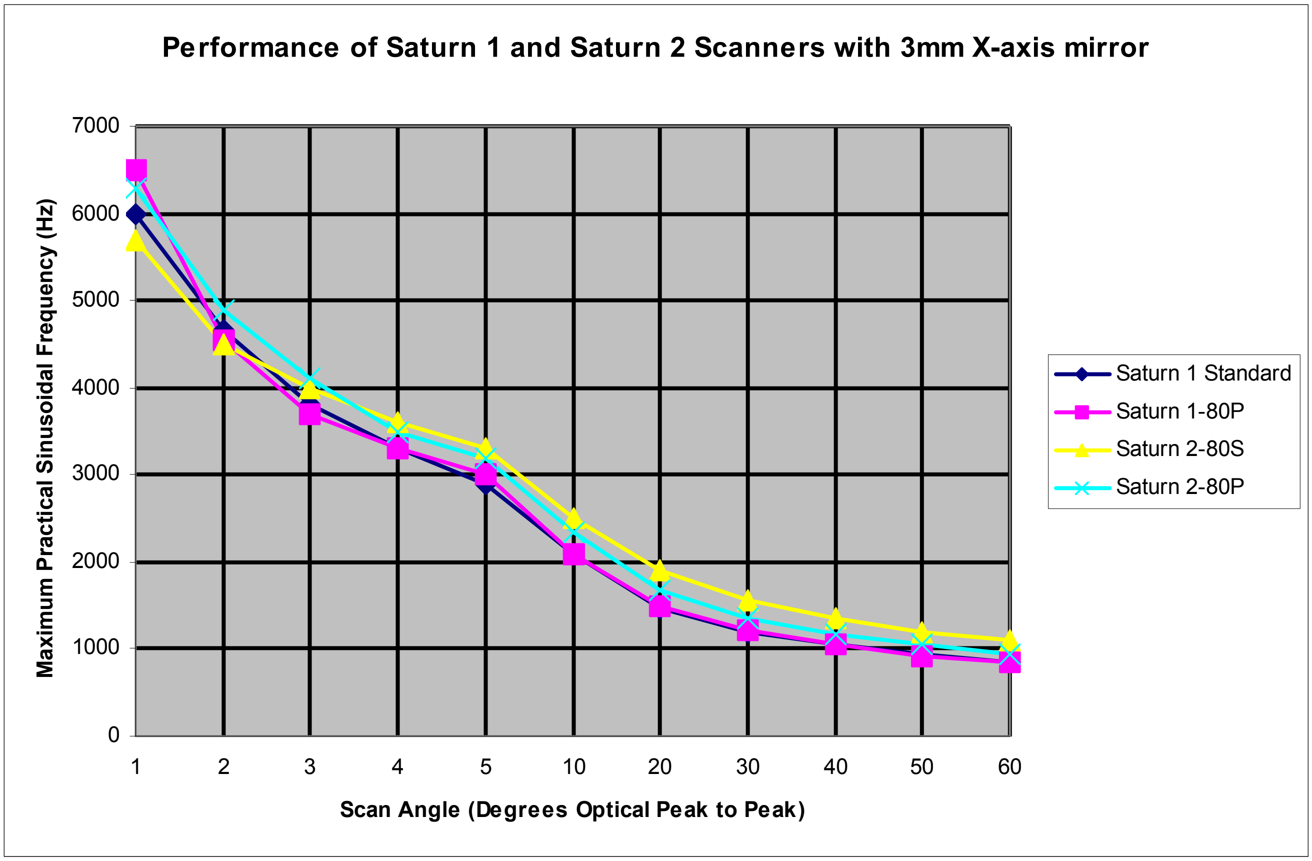
Performance-limiting factor for this system:

For the combination of Saturn 2 –80P scanner and Mach-DSP servo driver, the performance-limiting factor is the Mach-DSP. Theoretically the Saturn 2-80P can accept up to 6.3 amps RMS, and has a power handling capacity of 50 watts, but the Mach-DSP can only provide a maximum of 5 amps RMS for frequencies up to around 3kHz, and 4.5 amps RMS for higher frequencies with this very low impedance coil. This effectively limits the scanner capacity to 20-22 watts.

Moreover, the coil resistance of the –80P is quite low, and this effectively moves heat from the scanner to the servo driver. To keep heat generation at the servo driver to an acceptable level, the power supply voltage is reduced below the +/-24V that is typically used with the Mach-DSP.

Analysis and Discussion

We will once again refer to the graph showing the actual performance for the four Saturn scanners tested.



Although the difference is subtle, it is apparent that the combination of the Mach-DSP servo driver and Saturn 2B-80S offers the highest performance for frequencies up to 3600Hz. At higher frequencies, the impedance caused by inductance would require a higher drive voltage to drive this scanner to its maximum potential. The Mach-DSP can only practically deliver up to 52V peak-to-peak with +/-30V power supplies, so this presents the limiting factor.

On the highest-frequency end of the scale, the Saturn 1B-80P provides the highest performance. This is because it has the lowest coil impedance, and for very high frequency operation, coil impedance is the most important factor to concentrate on.

However, once again this graph does not convey the whole picture. It shows which scanner offered the highest frequency at a given scan angle, but this graph itself does not convey the power supply requirement, or the heat generated by the scanner or servo driver. This information can only be gleaned by looking at the collected data, which is presented in the pages above.

Relationship between scan frequency, power supply and heat

One thing that may not be apparent, even after scrutinizing the data, is the relationship between the scan frequency, and the current driven into the scanner (and consumed by the power supply), and the heat generated by both the scanner and the servo driver.

To convey this relationship as simply as possible, the electrical current required is proportional to frequency squared. Heat generated is proportional to the fourth power of frequency.

To illustrate the point, let's consider the Saturn 2-80S at a scan frequency of 1200Hz and at at scan frequency of 1000Hz.

Scan Angle	Freq	V P-P	RMS	Scanner P	Amp P
50	1200	46	3.2	50	40@30
50	1000	27	2.2	24	40@30 (27@24)

It is remarkable that by reducing the frequency, the current and especially the heat is dramatically reduced. Let's "do the math"…

Current is Frequency Squared:
1000Hz / 1200Hz = 0.83 ^2 = 0.69

Heat is Frequency to the fourth power:
1000Hz / 1200Hz = 0.83 ^4 = 0.48

If we take the original 3.2 amps RMS that was required for 1200Hz, and multiply it by 0.69 (ratio of the frequency, squared), we get 3.2 amps * 0.69 = 2.2 amps, and this is exactly what was measured.

Likewise, If we take the original 50 watts that was generated at 1200Hz, and multiply it by 0.48 (ratio of the frequency, to the fourth power), we get 50 watts * 0.48 = 24 watts, and this is exactly what was measured.

Note that the reduction in frequency also led to a pretty dramatic reduction in the coil voltage required to drive the scanner, thus allowing the power supply voltage to be reduced, and the heat at the power amplifier to be reduced too. For the heat generated by the power amplifier, it is a similar calculation, but in this case we use the square of the power supply voltage ratio:
24V / 30V = 0.8 ^2 = 0.64

40 watts * 0.64 = 25.6 watts, which is very close to what was measured.

It is important to be aware of these relationships. If the scanner or servo driver is running very hot, then reducing the scan frequency will have a dramatic effect on heat generated.

Moreover, it is important to understand that all of the power supply and heat figures discussed here are for a single axis running. If two axes are doing this same job, then the user would need to remove double the heat for the pair of scanners, and double the heat from the back of the Mach-DSP servo driver. This is actually quite a bit of heat!

Of course this heat is only generated while the scanner is scanning at these performance levels. When the scanner is moving more slowly or at a smaller angle or not at all, generated heat is reduced or perhaps eliminated.

Scanners compared at a given scan frequency and scan angle

To put all of this into perspective, it is best to have all of the scanners do the same scanning job, and look at the power supply required, and heat generated by both the scanner and the servo driver.

For this test, we drove each of the four scanners at 10-degrees optical peak-to-peak at a frequency of 2000Hz.

Scanner	V P-P	RMS	Scanner P	Amp P	Power Supply
S1-Standard:	30	3.5	29	41	24V; 1.8 amps; 86 watts
S1-80P	16	4.8	20	30	15V; 2.4 amps; 72 watts
S2-80S	25	1.75	15	25	24V; 1 amp; 48 watts
S2-80P	15	3.6	15	34	15V; 1.7 amps; 51 watts

Looking first at the two Saturn 2 scanners, it is noteworthy that the heat generated by each of them is the same. This makes sense because they both have the same number of turns on the coil, so their ability to turn heat into motion is the same.

In the case of the Saturn 2–80P the turns are connected in parallel, so it requires exactly twice the current to flow through the coil when compared with the Saturn 2-80S. The higher coil resistance of the Saturn 2-80S allows a lower current to flow through both the coil and the power supply. However, when the Saturn 2-80P is used with a power supply of +/-15V, the power consumption in terms of watts is also nearly the same, although the heat generated by the power amplifier is still higher for the Saturn 2-80S.

Now looking at the Saturn 1-80P, more heat is generated in the scanner when compared to the Saturn 2-80P. This is because the rotor is shorter, and power efficiency is lower.

And finally, looking at the Saturn 1 Standard, this has the fewest number of turns and thus power efficiency is the lowest for this particular scanner, when used for sine-wave scanning.

Of course this is just a simple sine-wave test. For scanning applications, the mix of coil configurations (Standard, -80P, -80S) allows us to choose a scanner to optimize power supply and heat generation requirements. Although the Saturn 2 is the best for wide-angle sine-wave applications, the Saturn 1 is often the all-around best choice for point-to-point move and high bandwidth vector applications.

“Clearing moves” are needed for high-frequency, small-angle scanning

All galvanometer scanners use instrument ball bearings to support the rotor. In ScannerMAX scanners, the bearings are among the highest quality available. They are made in Germany, and have ABEC7 precision. The bearings use silicon dioxide ceramic balls and super-hard SV30 stainless steel races. The bearings are lubricated with specialized grease, and all of this is designed to provide a lifetime of trouble-free use.

Galvanometer scanners are limited-rotation devices. In most cases, the rotor never spins round and round. Instead the balls inside the bearing move only over a small range of angles, and do not explore the entire surface of the races.

For applications that use wide scan angles (20-degrees or greater), or that use a variety of scan angles that include wide angles, the lubricant will be distributed effectively around the bearing and the lubricant will form a hydrodynamic film between the balls and the races.

But in applications that involve scanning only small scan angles of a few degrees, especially at high frequency, what can happen is that the lubricant gets pushed out of the way, allowing the balls to come in “boundary contact” with the steel races. If this persists over a long period of time, the balls can carve divots into the races. This process is called tribo-corrosion.

To maximize bearing lifetime, it is important to periodically perform large-angle scanning, to clear out any tribo-corrosion, and to effectively redistribute the lubricant. We use the term “clearing moves” to describe these periodic, wide-angle moves that are interspersed between periods of the high-frequency, small-angle scanning required for the application.

Some galvo manufacturers recommend performing 25 cycles of wide-angle, low-frequency scanning motion, for every 15,000 cycles of small-angle high-frequency scanning motion, but we have not found our bearings to be that sensitive to require the clearing to be performed that often. Our own testing suggests that up to 250,000 cycles of 1-degree-optical scanning can be performed before the clearing moves are performed.

Nevertheless, the overall point is that for maximum bearing lifetime, the user should intersperse wide-angle low-frequency moves in between the small-angle high-frequency moves of the application. This clearing operation should be done as often as is practically tolerable for the application.

Wide-angle, low-frequency scanning will never wear out the scanners. Quite the contrary, these large-angle moves help to distribute the lubricant and reposition the balls in the bearings, thus maximizing lifetime.

The user may initiate these “clearing moves” by simply changing the input command signal, from the small-amplitude high-frequency signal desired by the application, to a large-amplitude low frequency (perhaps 100Hz) signal to perform the clearing operation. Alternatively the Mach-DSP has a built-in “Bearing Exercise” function, which may be called upon by activating a tuning externally, using either serial or TTL-level inputs. Either way, the clearing moves should be executed at the widest angle possible, to most effectively perform the clearing operation.

For each application this “widest angle possible” differs. For systems delivered that can perform up to 60-degree scanning, the clearing moves should be done over the full 60-degrees. For systems delivered with smaller angles (for example as small as 10 degrees), the clearing moves can be executed over that angle.