NASA IRTF / UNIVERSITY OF HAWAII

Document #: xxx

Created on:xx
Last Modified on :xx

ISHELL TECHNICAL NOTE

XDM: TILT POSITIONING SENSOR

Original Author: Morgan Bonnet
Latest Revision:
Approved by: XX

NASA Infrared Telescope Facility
Institute for Astronomy
University of Hawaii

Revision History

Revision No.	Author & Date	Approval & Date	Description

Contents

1 Introduction / Document Purpose

The purpose of the document is to discuss ways to obtain a tilt position feedback for the turret of the Cross-Disperser mechanism. The goal of the study is to identify the most practical and economical way to control the position of the turret within the accuracy imposed by the mechanism's requirements. In particular, two types of sensors will be compared: hall-effect sensors versus eddy current sensors.

2 Cross Disperser Tilt Positioning Requirements:

(See MathCAD worksheet: "XDM_TiltPositioning.xmcd")

Tilt Positioning Requirements:

Length of lever arm between XD grating and detector

$L_{det} := 497.37mm$

Tilt Corresponding to displacement of the image by 1 Detector Pixel:

$Wp := 18\mu m$ (Pixel Width) $\alpha 1p := \frac{atan\left(\frac{Wp}{L_{det}}\right)}{2} = 3.732\,arcsec$

Tilt Control:

Minimum angle accuracy to locate beam on detector with less than a pixel accuracy

$\alpha < \alpha 1p$

Calculate minimum number of discrete positions to cover the whole tilt range

$\alpha_{range} := 2 \cdot 3.85deg = 7.7\,deg$

$n := \frac{\alpha_{range}}{\alpha 1p} = 7.427 \times 10^3$

$n_{tp} < n$

In order to place the beam onto the detector with an accuracy of less than a pixel (18μm) in the cross-dispersion direction, it is necessary to be able to control the cross-disperser turret tilt within less than 3.7 arcsec. In order to cover the whole range of tilt (+/-3.85°) with that accuracy, a minimum of 7427 discrete positions are needed.

3 Hall Effect Sensor: F.W. Bell FH-301-040

First we will consider the Hall-effect sensor from F.W. Bell (FH-301-040) which was previously used for the spectrograph detector focus stage of SpeX. In the stage, the sensor is translating in head-on mode between 2 cylindrical SMCO magnets oriented with opposite poles. For the Cross-Disperser mechanism, the same configuration can be used with the difference that the front face of the sensor will go towards the front face of the magnet with an angle equal to the tilt of the turret (between 0 and 3.85deg). Note that the non-linearity introduced by the angle can be calibrated out.

One limitation of this configuration is that the sensing range (defined by the size of the magnets) will govern the maximum distance between the sensor and the tilt axis. For example, considering the same setup (sensor + magnets) as in SpeX, the range is +/- 2mm. So with that range, the maximum distance between the sensor and the tilt axis would be 2 / tan (3.85) = 29.7mm. Such a small distance limits the design options for the cross-disperser mechanism.

The other mode to consider is the slide-by mode. This mode would be easier to implement with a tilt, however the voltage response curve is symmetrical which introduces a lot of uncertainty when the magnet is close to the sensor. (See picture below)

It is important to note that many other sensors could be considered, but they would have to be rated for cryogenics or qualified in-house.

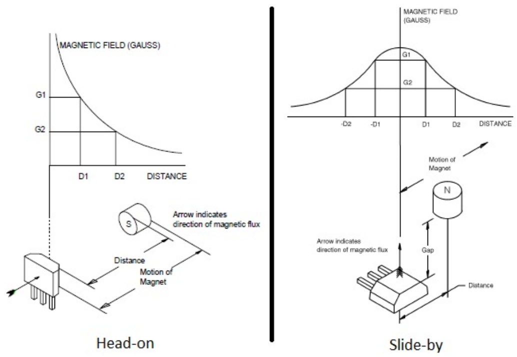
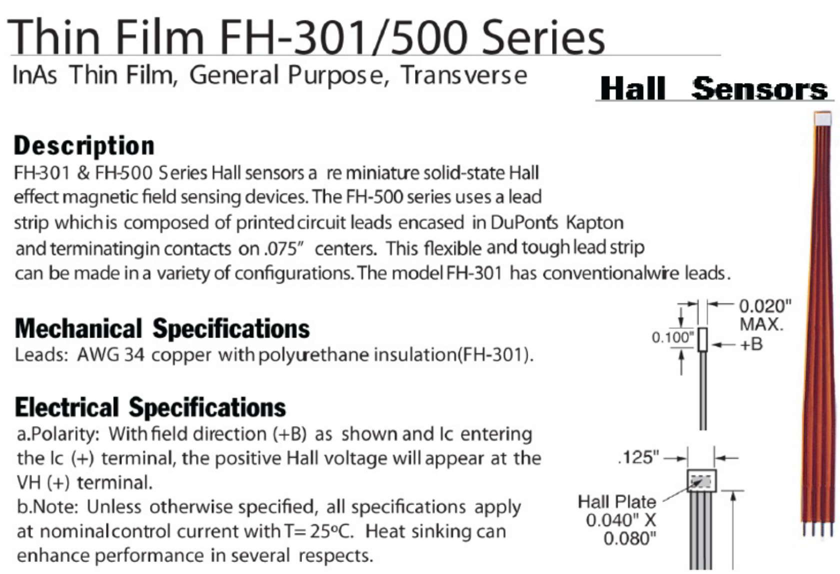


Fig.1: Sensing Modes

3.1 Technical Data:



Thin Film FH-301/500 Series

InAs Thin Film, General Purpose, Transverse

Hall Sensors

Description

FH-301 & FH-500 Series Hall sensors a re miniature solid-state Hall effect magnetic field sensing devices. The FH-500 series uses a lead strip which is composed of printed circuit leads encased in DuPont's Kapton and terminating in contacts on .075" centers. This flexible and tough lead strip can be made in a variety of configurations. The model FH-301 has conventional wire leads.

Mechanical Specifications

Leads: AWG 34 copper with polyurethane insulation (FH-301).

Electrical Specifications

a.Polarity: With field direction (+B) as shown and Ic entering the Ic (+) terminal, the positive Hall voltage will appear at the VH (+) terminal.

b.Note: Unless otherwise specified, all specifications apply at nominal control current with T= 25ºC. Heat sinking can enhance performance in several respects.

SPECIFIC ATIONS	UNITS	FH-301-020 /FH-520
Inputresistance, R_{in}	ohms	20-40
Outputresistance, R_{out}	ohms	28-120
Magnetic sensitivity, V_H (1)	mV/kG	10 min.
Max. resistive residual voltage, V_M @ B=0 (2)	±mV	2
Max. control current @ 25°C, static air	mA	50
Nominal control current, I_{cn}	mA	25
Mean temperature coefficient of VH (-20°C to +80°C) (2)	%/°C	-0.1max.
Mean temperature coefficient of resistance (-20°C to +80°C) (2)	%/°C	+0.1max.
Temperature dependence of resistive residual voltage (-20°C to +80°C) (1)	±µV/°C	10 max.
Operating temperature range	°C	-55 to +100
Storage temperature range	°C	-55 to +120

Notes
(1) $I_c = I_{cn}$
(2) $I_c = 10$ mA
(3) maximum linearity error (-20 to +20kg) = ±1% of RDG

(Also see Appendix C for Distance versus Voltage data collected in a lab test. Different curves were obtained depending on the control current used.)

3.2 Pros / Cons

Pros	**Cons**
- Price - Already implemented in SpeX - Passive Sensing. Can be used simultaneously with Detector Readout.	- Unknown Accuracy ⇨ Too much effort needed to quantify at the level of accuracy required. - Range is limited. "Physical range reduction trick" isn't applicable. (See 5.3) - No package or mount included. - Potential irregular magnetization

4 Eddy Current Sensor: Kaman DIT-5200L / 20N

Inductive / Eddy Current Technology linear displacement sensors rely on inductive techniques to induce current flow in a conductive 'target' without physical contact. The term 'eddy current' refers to the fact that induced current flows in a circular pattern.
For a system with better resolution, in the case of the cross-disperser mechanism, it would be best to implement a differential system (with 2 sensors). In an eddy current differential system, the two coils in the inductive bridge are housed in two separate sensors. Rather than one active coil and one reference coil, both sensors contain active coils as in figure 3. These two sensors are usually placed on opposite sides of a target or opposite sides of a target pivot point, as in figure 2.

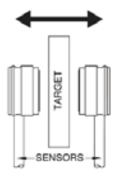


Fig.2: Differential Target Configuration

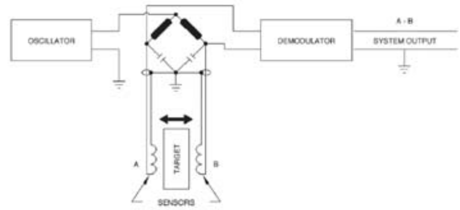


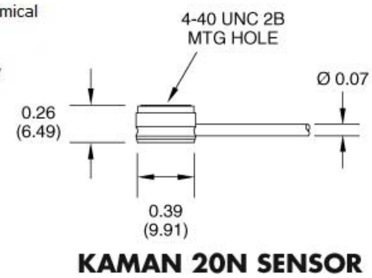
Fig.3: Differential System Block Diagram

The main difference with Hall-effect sensors is that Eddy Current sensors are "active" and generate their own magnetic field. This is why the targets for Eddy Current sensors don't have to be magnetic but only conductive.

4.1 Technical Data

DIT-5200L

- > True differential for common mode rejection at an economical price
- > High-precision eddy current, balanced bridge technology
- > Capable of subnanometer resolution
- > Thermal stability ±.03% FS/°C, at null ±.005% FS/°C
- > Small package size: 7.7 cubic inches
- > High sensitivity: up to 10V/mil (39mV/µm)
- > Extremely linear, to 0.1% full range
- > Single, dual, and three channel configurations



Target material	Aluminum
Output voltage	±10 volts typical
Power dissipation	At 15N sensor head <0.5 mW/sensor typical At 20N sensor head <2 mW/sensor typical Electronics <1.35 Watts
Frequency response	0-20 kHz
Input voltage	±15 volts
Output impedance	<1 Ohm
Weight	Electronics 6 oz. W/4 15N sensors 8 oz.
Operating temperature range	Electronics +32°F to +140°F (0°C to +60°C) Sensors -62°F to +220°F (-52°C to +105°C)
Storage temperature range	Electronics -26°F to +180°F (-32°C to +82°C) Sensors -62°F to +220°F (-52°C to +105°C)

KAMAN DIT-5200L SENSORS

Sensor click to view	Range ±mil/±mm	Null mil/mm	Typical Non-Linearity ± %FR	Maximum Non-Linearity ±%FR	Typical Sensor TempCo ± %FR/°C	Resolution p-p%FR at 1 kHz BW at FR	Resolution p-p%FR at 1 kHz BW at Null
15N	10/0.25	15/0.38	0.15%	0.30%	0.02%	0.015%	0.004%
15N	20/0.51	25/0.64	0.25%	0.50%	0.03%	0.008%	0.002%
15N	35/0.89	40/1.02	0.50%	1.00%	0.03%	0.005%	0.003%
20N	10/0.25	20/0.51	0.10%	0.20%	0.02%	0.025%	0.005%
20N	20/0.51	40/1.02	0.15%	0.30%	0.02%	0.015%	0.005%
20N	50/1.27	60/1.52	0.25%	0.50%	0.03%	0.008%	0.003%
20N	75/1.91	85/2.16	0.50%	1.00%	0.03%	0.005%	0.002%

4.2 Pros / Cons

Pros	Cons
- Known accuracy. - Comes as a set: Sensors + Electronics. - Extremely Linear. - Range can be tuned using a “Physical range reduction trick”. (See 5.3) - Easier to implement	- Price. - Needs Coax cables. - Active sensor: can perturb detector readout. - Needs 10/15 minutes to warm up and give reliable data after turning it on => RF switch needed.

5 Choice of a Sensor and Implementation

5.1 Choice of a Sensor

Considering ease of implementation, cost, risks and performances, the choice of going with the Kaman is largely preferred.
Ease of implementation because the "physical range reduction trick" can be used (See 5.3) but also because the sensor package is threaded for easy mounting. (Unlike the Hall-effect sensor that needs to be epoxied).
As for the other criteria, it is important to note that no data is available in regards to the Hall-effect sensor accuracy. Since the accuracy needed for the Cross-Disperser mechanism is much higher than the focus stage in SpeX, the stage mechanism cannot be used as a benchmark. In order to make sure that the Hall-effect sensor's performance is sufficient, it would then be necessary to "verify in the lab". However, due to the very high accuracy, it would be very costly to implement such a test setup. Since the accuracy data is available for the Kaman sensor and exceeds the requirements with a comfortable safety factor, it is clear that the difference of retail cost of the sensor is no longer an argument.

5.2 Implementation

(See MathCAD worksheet: "XDM_TiltPositioning.xmcd")

Calculate Sensor Accuracy, considering KAMAN 20N

Sensor Parameters:

$FR_{Kaman} := 2 \cdot 1.91mm = 3.82\,mm$ Full Range = +/-1.91mm

$Res_{Kaman} := 1.5 \cdot 10^{-5}\%$ Resolution p-p%FR at 1KHz Bandwidth at Full Range

$BW_{XDM} := 1000$ Sensing Bandwidth for the Cross-Disperser (in Hertz)

$N_{RMS} := FR_{Kaman} \cdot Res_{Kaman} = 5.73 \times 10^{-4}\,\mu m$ Equivalent RMS Input Noise

$Res_{Eff} := N_{RMS} \cdot \sqrt{BW_{XDM}} = 0.018\,\mu m$ Effective Resolution

See Appendix A

$Ref_{PP} := 6.6 \cdot Res_{Eff} = 0.12\,\mu m$ Peak to Peak Resolution

Minimum Sensor Accuracy needed based on implemented design and sensor Location & Orientation:

$D_{sensor} := 160mm$ Distance between XDM tilt axis and Sensor

$\alpha_{st} := 7deg$ Angle between the face of the sensor and plan perpendicular to the XDM tilt axis

$$R_{sensor} := 2 \cdot D_{sensor} \cdot \tan\left(\frac{\alpha_{range}}{2}\right) = 21.535\,mm$$

$$Rs := 2 \cdot R_{sensor} \cdot \tan\left(\frac{\alpha_{st}}{2}\right) = 2.634\,mm$$

$$S_{min\_accu} := \frac{Rs}{n} = 0.355\,\mu m$$

5.3 Physical Range Reduction

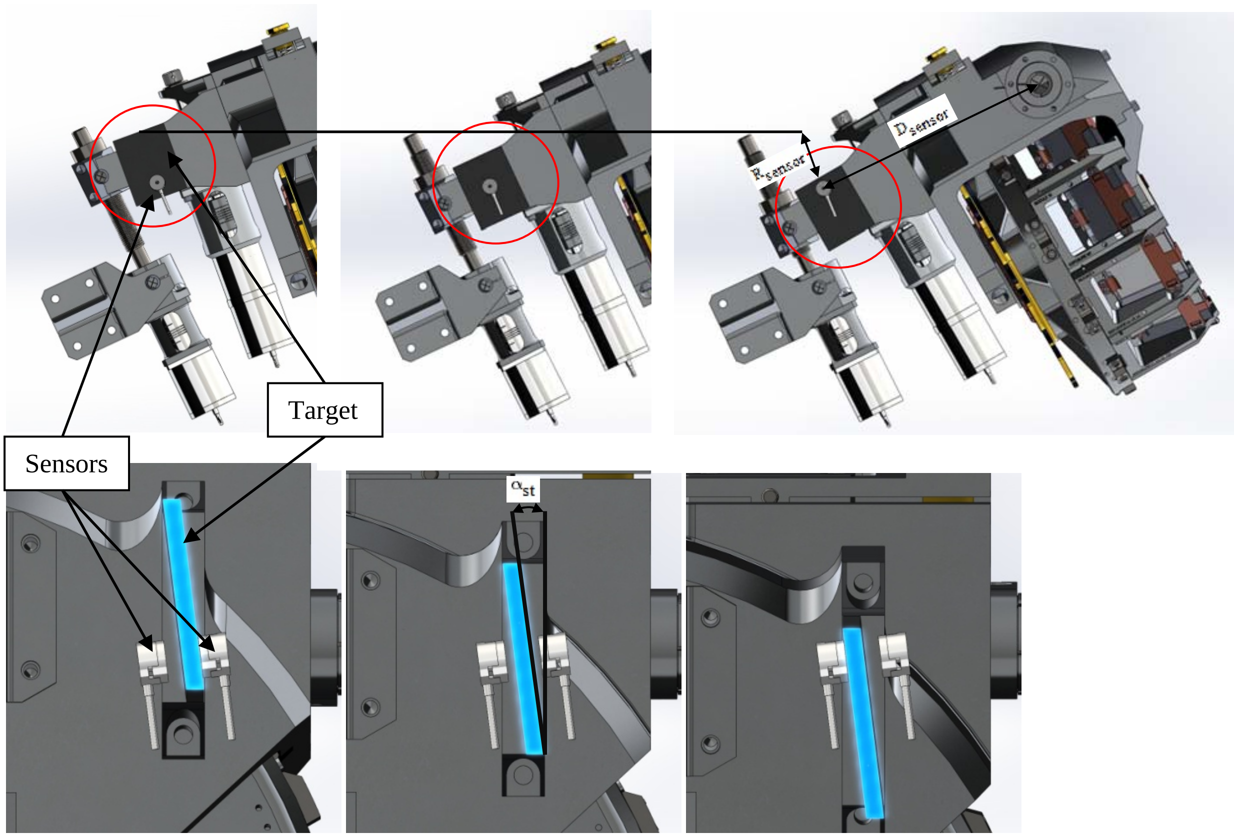


Fig.4: "Physical Range Reduction" in the Cross-Disperser Mechanism

Thanks to the fact that Eddy Current sensors don't need to use magnetic targets but only conductive ones, basically only the minimum distance between the sensor and the target is being sensed. In the case of a Hall-effect sensor, what is sensed is the magnetic field of the target. And since the magnetic field isn't homogeneous, it is necessary for the center of the target to be aligned with the center of the sensor. Because of that fact, it would be pretty much impossible to implement the system as described in Fig. 4.

6 Appendix A: Kaman Sensor Accuracy Calculation

KAMAN
Precision Products / Measuring

CALCULATING RESOLUTION

Equivalent RMS input noise: A figure of merit used to quantify the noise contributed by a system component. It incorporates into a single value several factors that influence a noise specification such as signal-to-noise ratio, noise floor, and system bandwidth. Given a measuring system's sensitivity/scale factor and the level of "white" noise in the system, equivalent RMS input noise can be expressed using actual measurement units.

Effective resolution: An application-dependent value determined by multiplying the equivalent RMS input noise specification by the square root of the measurement bandwidth.
Example: A 15N sensor monitoring a reciprocating target moving ±10 mils (FR) filtered externally to 15KHz bandwidth.

1. Calculate a value for equivalent RMS input noise. From the equivalent RMS input noise table, use the value of equivalent RMS input noise for a 15N sensor calibrated over a ±10 mil range. Multiply this by the full range of the calibration.
Divide by 100. Noise value is a percent of full range.

(0.00007% X 0.020 inches) / 100 =
1.4 x 10-8 inches or 0.014 µinches.

2. Calculate effective resolution. From step 1, take the equivalent RMS input noise and multiply by the square root of the measurement bandwidth in Hz.

0.014 µinches X √15000 = 1.714 µinches

3. Approximate peak-to-peak resolution. From step 2, take the effective resolution and multiply by 6.6.

1.714 µinches X 6.6 = 11.312 µinches

EQUIVALENT RMS INPUT NOISE

Range ± mils	Range ± mm	Sensor	% Full Range at Full Range	% Full Range at Null
10	0.25	15N	2E-5%	2E-5%
10	0.25	20N	2E-5%	2E-5%
20	0.50	15N	2E-5%	2E-5%
20	0.50	20N	2E-5%	2E-5%
35	0.9	15N	2E-5%	1E-5%
50	1.3	20N	2E-5%	1E-5%
75	1.9	20N	1.5E-5%	1E-5%

7 Appendix B: XDM Tilt Drive Calculations

(See MathCAD worksheet: "XDM_TiltPositioning.xmcd")

Tilt Drive:

Stepper Motor Resolution (steps/turn)

$Res_{mot} := 400$

XD Tilt Drive Screw Lead

$Lead := .025in$

Linear displacement of tilt drive screw per motor step

$\Delta x := \frac{Lead}{Res_{mot}}$ $\quad \Delta x = 1.59 \cdot micron$

Length of tilt drive lever arm

$L_{tltdrv} := 200mm$

Calculate angular displacement of XD grating per motor step

$\alpha_{step} := \frac{\Delta x}{L_{tltdrv}}$ $\quad \alpha_{step} = 1.64 \cdot arcsec$

Calculate angular displacement of image on detector per motor step

$\beta_{step} := 2\alpha_{step}$ $\quad \beta_{step} = 3.27 \cdot arcsec$

Calculate corresponding linear displacement of image on detector per motor step

$\Delta y := L_{det} \cdot \beta_{step}$ $\quad \Delta y = 7.90 \cdot micron$

Calculate fraction of detector pixel

$Fraction := \frac{\alpha_{step}}{\alpha 1p}$ $\quad Fraction = 43.865 \cdot \%$

8 Appendix C: Hall Effect Measurements & Theoretical Values

ACTUAL MEASUREMENTS:

	Dist. In.	Dist. mm	Output (mV)
10	0	0	37.8
9.95	0.002	0.05	36.9
9.85	0.006	0.15	36.1
9.75	0.010	0.25	33.2
9.65	0.014	0.35	29.9
9.55	0.018	0.45	25.9
9.45	0.022	0.55	22.9
9.25	0.030	0.75	19.5
9.05	0.037	0.95	15.5
8.9	0.043	1.1	13.3
8.6	0.055	1.4	10.4
8.3	0.067	1.7	8.2
8	0.079	2	6.4
7.8	0.087	2.2	5.7
7.6	0.094	2.4	5
7.4	0.102	2.6	4.4
7.2	0.110	2.8	4
7	0.118	3	3.6
6.75	0.128	3.25	3.2
6.5	0.138	3.5	2.8
6.25	0.148	3.75	2.6
6	0.157	4	2.3
824 ohms			
9V sup @ 5.86mA			

	Dist. In.	Dist. mm	Output (mV)
10	0.000	0	65
9.95	0.002	0.05	63.2
9.85	0.006	0.15	59
9.75	0.010	0.25	54.4
9.65	0.014	0.35	48.8
9.55	0.018	0.45	42.9
9.45	0.022	0.55	37.1
9.25	0.030	0.75	32
9.05	0.037	0.95	25.6
8.9	0.043	1.1	21.7
8.6	0.055	1.4	17.3
8.3	0.067	1.7	13.5
8	0.079	2	10.7
7.8	0.087	2.2	9.5
7.6	0.094	2.4	8.4
7.4	0.102	2.6	7.4
7.2	0.110	2.8	6.7
7	0.118	3	6
6.75	0.128	3.25	5.7
6.5	0.138	3.5	4.8
6.25	0.148	3.75	4.4
6	0.157	4	4
Re = 475 ohms			
9V sup @ 10.16mA			

	Dist. In.	Dist. mm	Output (mV)
10	0	0	102.5
9.95	0.002	0.05	100.9
9.85	0.006	0.15	98.9
9.75	0.010	0.25	90.9
9.65	0.014	0.35	81.4
9.55	0.018	0.45	72.3
9.45	0.022	0.55	62.8
9.25	0.030	0.75	53.6
9.05	0.037	0.95	42.7
8.9	0.043	1.1	36.3
8.6	0.055	1.4	28.3
8.3	0.067	1.7	22.3
8	0.079	2	17.5
7.8	0.087	2.2	15.5
7.6	0.094	2.4	13.7
7.4	0.102	2.6	12
7.2	0.110	2.8	10.9
7	0.118	3	9.7
6.75	0.128	3.25	8.7
6.5	0.138	3.5	7.7
6.25	0.148	3.75	7
6	0.157	4	6.4
301 ohms			
9V sup @ 15.92mA			

	Dist. In.	Dist. mm	Output (mV)
10	0	0	123.4
9.95	0.002	0.05	119.3
9.85	0.006	0.15	119.1
9.75	0.010	0.25	109.7
9.65	0.014	0.35	97.8
9.55	0.018	0.45	87
9.45	0.022	0.55	75.8
9.25	0.030	0.75	64.6
9.05	0.037	0.95	51.6
8.9	0.043	1.1	43.8
8.6	0.055	1.4	34.5
8.3	0.067	1.7	26.8
8	0.079	2	21.1
7.8	0.087	2.2	18.7
7.6	0.094	2.4	16.6
7.4	0.102	2.6	14.5
7.2	0.110	2.8	13.2
7	0.118	3	11.7
6.75	0.128	3.25	10.5
6.5	0.138	3.5	9.3
6.25	0.148	3.75	8.5
6	0.157	4	7.7
250 ohms			
9V sup @ 19.11mA			

THEORITICAL VALUES:

Samarium Cobalt magnets Diam 2.5mm x 5mm, PN SMC0056				
Br(G)	9000	Residual Induction of SMCO		
Lm(mm)	5	Magnet Length		
Rm(mm)	1.25	Magnet Radius		
Khoc(mV/A.G)	1.5	Magnetic Sensitivity		
Ic(mA)	5.86	10.16	15.92	19.11

			Theoritical Output Voltage			
Dist. In.	Dist. mm	M Field (G)	824 ohms	475 ohms	301 ohms	250 ohms
0.000	0	4365.641251	39.87398659	68.53237266	107.2515131	128.1411064
0.002	0.05	4188.317291	38.31530899	65.82995551	103.0170169	123.0581151
0.006	0.15	3836.877232	35.22615087	60.47400902	94.6246283	112.9840859
0.010	0.25	3495.105358	32.2219761	55.26540566	86.46311595	103.1871951
0.014	0.35	3168.64851	29.3524204	50.29020329	78.66732642	93.82930954
0.018	0.45	2861.875224	26.65588322	45.61497841	71.34158035	85.03565329
0.022	0.55	2577.708289	24.15805586	41.28427433	64.55567395	76.89000811
0.030	0.75	2082.062738	19.80133147	33.73063613	52.71965819	62.68232639
0.037	0.95	1680.991584	16.27591602	27.61831174	43.14207902	51.18562375
0.043	1.1	1435.568918	14.11865079	23.87807031	37.28138576	44.15058303
0.055	1.4	1059.829927	10.81590505	18.15180808	28.30873865	33.38002484
0.067	1.7	798.2409399	8.516537861	14.16519192	22.06199364	25.88157654
0.079	2	613.9317218	6.896459834	11.35631944	17.66068952	20.5983528
0.087	2.2	521.1241755	6.080681503	9.941932435	15.44444531	17.93802449
0.094	2.4	446.0280509	5.420586567	8.797467496	13.65114986	15.78539408
0.102	2.6	384.7057043	4.881563141	7.862914934	12.18677222	14.02758901
0.110	2.8	334.1844945	4.437481707	7.092971696	10.98032573	12.57939853
0.118	3	292.207998	4.068508303	6.45324989	9.977926993	11.37614226
0.128	3.25	249.1645411	3.690156316	5.797267606	8.950049241	10.14230157
0.138	3.5	214.277507	3.383499286	5.265589206	8.116946866	9.142264737
0.148	3.75	185.6978802	3.132284367	4.830035695	7.43446538	8.323029737
0.157	4	162.0553281	2.924466334	4.469723201	6.869881236	7.645315981

governing equation for field strength relative to distance

For a circular magnet with a radius of R and Length L, the field B_x at the centerline of the magnet a distance X from the surface can be calculated by the following formula (where B_r is the Residual Induction of the material):

$$B_x = \frac{B_r}{2}\left(\frac{(L + X)}{\sqrt{R^2 + (L + X)^2}} - \frac{X}{\sqrt{R^2 + X^2}}\right)$$

HALL VOLTAGE:

$$V_H = K_{HOC}\ I_C\ B \sin Ø$$

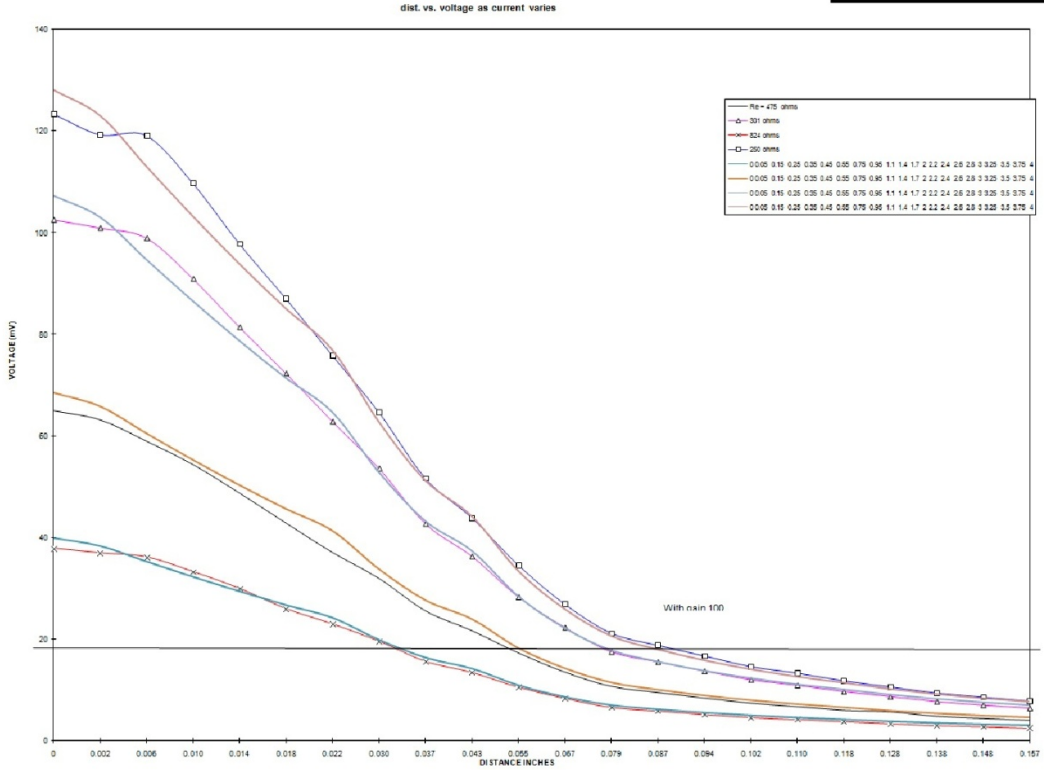
where:

K_{HOC} = open-circuit product sensitivity (mV/mAkG)

I_C = constant control current (mA)

B = magnitude of the magnetic field density (kG)

Ø = angle in degrees of the incident magnetic field from a line drawn parallel to the Hall plate



(See EXCEL worksheet: “HallEffect.xlsx”)