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Specification and Validation of the Motion Control System of the ATLAS Forward Proton Roman Pots

Abstract

In this report the ATLAS Forward Proton Roman Pot motion control system and the position interlock logic installed during the Year-End Technical Stop 2015-2016 is specified. In addition, the motion calibration, the commissioning procedures, and the results of the validation tests are described.

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History of Changes

Rev. No.	***Date***	***Description of Changes***
0.1	02 February 2016	First draft by M. Rijssenbeek
0.2	01 March 2016	Included material from X. Pons (Work Plan on AFP Roman Pot Stations by PH-DT)
0.3	03 March 2016	Final corrections before MPP Meeting on 04.03.2016

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INTRODUCTION

We describe in detail the ATLAS Forward Proton (AFP) Roman pot motion system which was installed during the Year-End Technical Stop (YETS) in January 2016. The AFP Phase-1 (single-arm) layout is described in the AFP TDR [1] and the AFP Phase-1 ECR [2]. To summarize: two Roman pot stations are positioned at 205 m and 217 m from the ATLAS IP on the C-side in sector A6R1.B. Each station contains a single horizontal cylindrical Roman pot which is inserted from the exterior side of the LHC. The stations are virtually identical to the new TOTEM/CMS-PPS horizontal pot stations [3]. The pot positioning system is the same as that for the TOTEM horizontal pots, while the interlock system most closely resembles that of the ATLAS-ALFA Roman pot stations, see [4] and references therein. Because the AFP stations are relative late-comers, the AFP detectors profit from the many years of experience, debugging, and improvements done for the forward detectors of TOTEM and ALFA.

The motion control system is based on the position control system used for the LHC collimators by the EN-STI group. Consequently, the motion control system, including the software, was therefore automatically accepted by the LHC protection (TE-MPE) in terms of operation and safety. Also, the procurement, hardware development, and market surveys were done for use in the LHC collimators, and the equipment is compatible with the Roman Pot Station requirements in terms of radiation hardness, instrumentation, stepper motors operated at long distance, accuracy in positioning, and read-back of the position.

Figure 1 presents a schematic drawing of the system components:

Hardware:

☐ Roman pot instrumentation (PH-DT & AFP)

☐ Cabling to service cavern (EN-MEF & AFP)

☐ Control Rack (PH-DT)

☐ Interlock and LHC signal exchange (PH-DT & AFP)

Software:

☐ PXI FPGA Real-time control software (PH-DT)

☐ FESA framework (EN-ICE)

☐ CCC User interface (BE-OP)

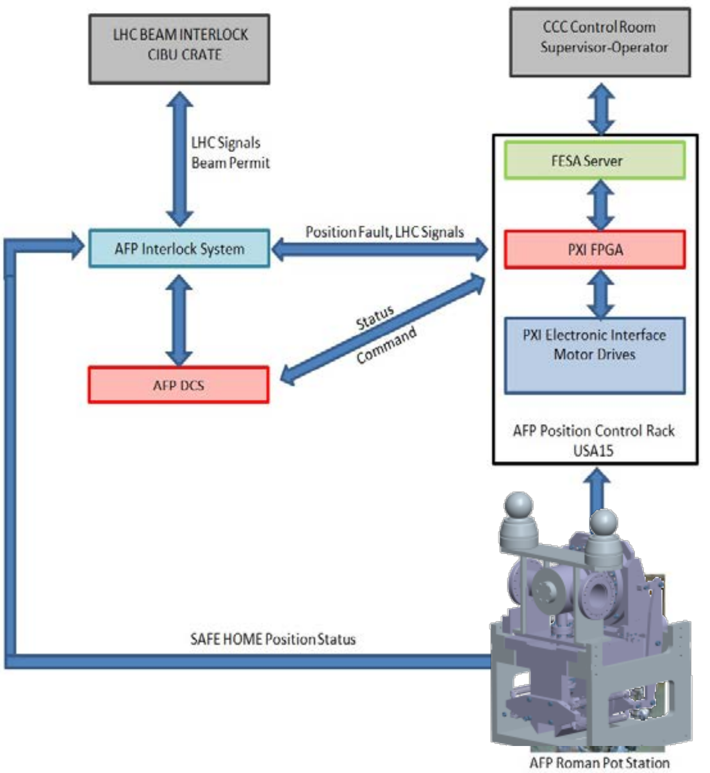


Figure 1. The AFP Roman Pot movement control system.

In the next section we describe the motion system for the AFP Roman pots, its drivers and the read-back. The calibration of the motion is described as well as the settings of the motion-range limit switches. In the subsequent section the interlock system is described, focussing on the logic implemented. In the last section, the program of tests is described that will be done to validate the interlocks. This validation is required before any insertion with beam can be attempted.

1. THE AFP POT MOTION SYSTEM - TUNNEL

The AFP motion system is identical to the motion system of the TOTEM/CMS-PPS Horizontal Roman pots. It consists of various components on the Roman pot stations (stepper motor, switches, and LVDT) and in the tunnel (Patch Panels and cables). These components are described below.

1.1 ROLLER BALL NUT AND LINEAR SCREW

The Roman Pot Station, see Fig. 1, consists of a vacuum assembly (EDMS LHCXRP__0117) supported on a central block. The block contains guide rails (Schneeberger Linear Guides R6-150-RF) that hold the Slide assembly (EDMS LHCXRP__0152). The slide holds the Roman pot (EDMS CRNHZMW_1710) itself as well as the bellows flange (EDMS LHCXRP__0117) and detector platform. The slide is moved by a stepper motor (see below) which drives a precision screw and roller ball nut assembly (SKF Transrol SVP12X2 R2 90/135). The roller ball nut is fixed to the station slide assembly. The linear precision screw has a pitch of 2.000 mm/turn.

1.2 MOTOR AND RESOLVER

The motor, like the rails and screw & nut assembly, was tested and approved for the LHC collimator jaw motion and adopted for all Roman pot stations. The 2-phase NEMA 34 stepper motor has 400 steps/rev = 0.90°/rev. Combined with the pitch of the linear screw, this translates into 5 μm/step. The rotational speed is 2 rev/s. The motor is rated for an integrated dose of 30 MGy and 15 Mrevs (Manufacturer MACCON, specifications in EDMS 1146698).

The vacuum pressure is compensated by a system comprising a bellows of the same dimensions below the Roman pot bellows and connected by a pair of balance arms. As the pot motion is horizontal, there is no effect of gravity beyond the friction. The pair of bellows exert a spring force around their equilibrium position. Four stainless steel springs, see below, provide a fail-safe mechanism to retract the pot in case of motor failure. Thus, the motor is continuously powered when the pot is inserted (i.e. away from the OUT position). A NTC sensor monitors the temperature of the motor, which is nominally (40±20) °C.

The stepper motor is co-axial with a resolver which measures the angle of the motor axis θ by a angular differential transformer: a primary widing connected to the motor axis induces AC signals in two – mutually perpendicular – secondary coils. The outputs of the secondary coils consist of AC signals that vary in amplitude as sinθ and cosθ. The resolver position has a 0.2° angular resolution (Manufacturer MACCON, specifications in EDMS 1146699). Radiation tolerance, temperature range, and lifetime are the same as for the motor. The resolver receiver system measures θ as well as the number of full turns of the motor axis. However, the resolver's information is lost when power is lost. Therefore, the resolver information is not used for the range definition of the pots.

1.3 MECHANICAL SPRINGS

A set of four stainless steel springs is used to safely extract the Roman Pot in case of a motor and/or power failure. The springs, each with spring constant 3.9 kN/m (Model TR2380, Manufacturer IMPEXCOM SARL), will return the pot to the HOME position when the motor power is switched off.

1.4 RANGE AND LIMIT SWITCHES

Three radiation-hard toggle switches (SCEM 06.92.32.400.0) are implemented to define the range of the motion and to define the HOME position:

1. The HOME switch. The HOME switch is ON when the pot is safely retracted and is outside the beam aperture. The HOME switch must be ON for the delivery of the ATLAS BEAM INJECTION PERMIT, and the HOME switch signal is one of the critical inputs to the AFP beam interlock matrix.
2. The IN limit switch is ON when the pot is reaches its maximum insertion depth. The IN switch limits further insertion to prevent damage to the bellows. The IN switch must be set such that the pot is able to reach the beam. The IN
3. The OUT limit switch is ON when the pot reaches its maximum extraction depth. Therefore, the OUT limit switch is located 1 mm *further out* compared to the HOME switch.

1.5 ELECTRICAL STOP

The so-called electrical STOP was implemented because of loss of position information in several past instances of roman pot movement. The electrical stop gives a precise reference point when it goes ON. In tests, the position as defined by the electrical STOP OFF-to-ON transition was reproducible with 10 μm accuracy as determined by the motor resolver**.** The electrical STOP switch consists of pairs of spring-loaded needle pins that make contact with a gold-plated pad. The needles have a maximum compression of 3 mm, and in order to prevent damage to the electrical STOP, the OUT (IN) limit switch must activate *after* the corresponding electrical STOP goes ON, but *before* the 3 mm maximum compression distance is exceeded. The distance chosen is 2 mm.

1.6 MECHANICAL STOP

A mechanical stops is provided at 1 mm beyond the OUT switch position. This provides a hard limit to the pot extraction and protects the electrical STOP needles from damage in case of a power failure and the springs forcibly extract the Roman pot.

The various switches and their ideal settings are summarized in Figure 2.

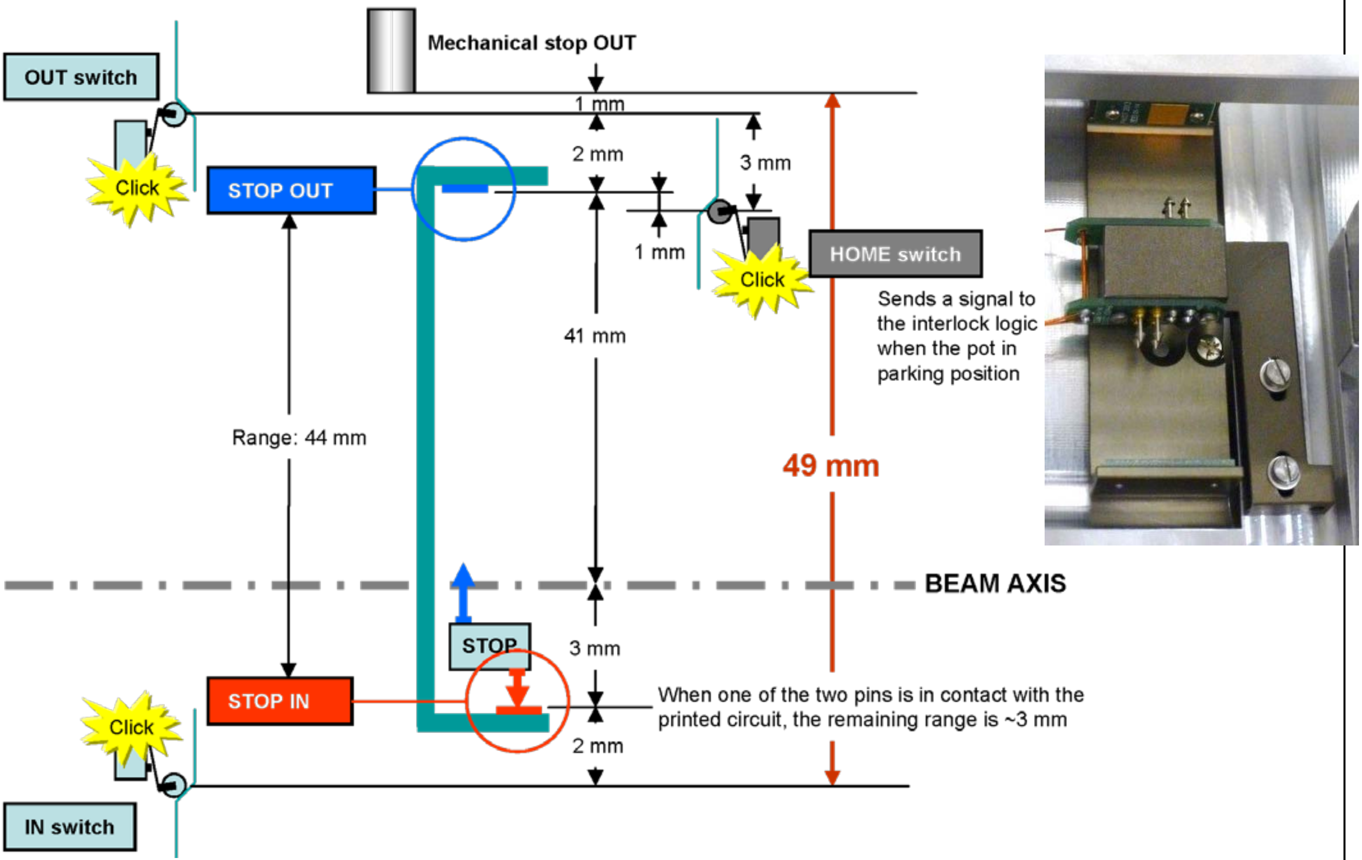


Figure 2. The IN, OUT, and HOME switches and their ideal ranges settings. In addition the electrical STOP needle switch (and photo insert) is shown and its relation to the positions of the other switches.

1.7 LINEAR VARIABLE DIFFERENTIAL TRANSFORMER

The Linear Variable Differential Transformer (LVDT) is an analog measurement device that returns the absolute position of the pot. The device is maufactured by Dietrich Blum AG and is described in EDMS 1146700. Before use, its offset and small non-linearities must be calibrated by a full-range motion calibration by external survey. The LVDT position is used for the interlock logic and range definition rather than the resolver position. The allowed insertion depth is set by the Machine Protection Panel and will depend on the run type and the LHC optics. The allowed LVDT range is coded into the Beam Interlock System (BIS) software using the CERN-standard Front-End Software Architecture (FESA) classes.

Some LVDTs were observed to have occasional bad readings and long-term drift. Therefore, the precise pot positions used by AFP will be based on the number of motor steps taken from the zero position as defined by the electrical STOP position.

1.8 CABLES AND PATCH PANELS FOR THE MOTION CONTROL

A single patch panel for the motor control cables (and for other control and monitoring cables) is located at 211 m, about midway between the two stations. Short cables run from the patch panel to the stations.

2. THE MOTION CONTROL SYSTEM IN USA15

The AFP BIS and Motor Control System racks are located USA15, racks Y.03-02.A1. The racks contain the FESA server the PXI controllers for the motors and LVDTs, and the AFP BIS, amongst other components. The components are discussed in the following sub sections.

2.1 THE INTERLOCK LOGIC

The AFP Interlock diagram is shown in Figure 3. The FESA provides the allowed pot insertion range, that is compared to the LVDT-measured insertion position. The AFP Beam Interlock System (BIS) contains the FPGA-based logic to provide the critical BIS signals: the INJECTION

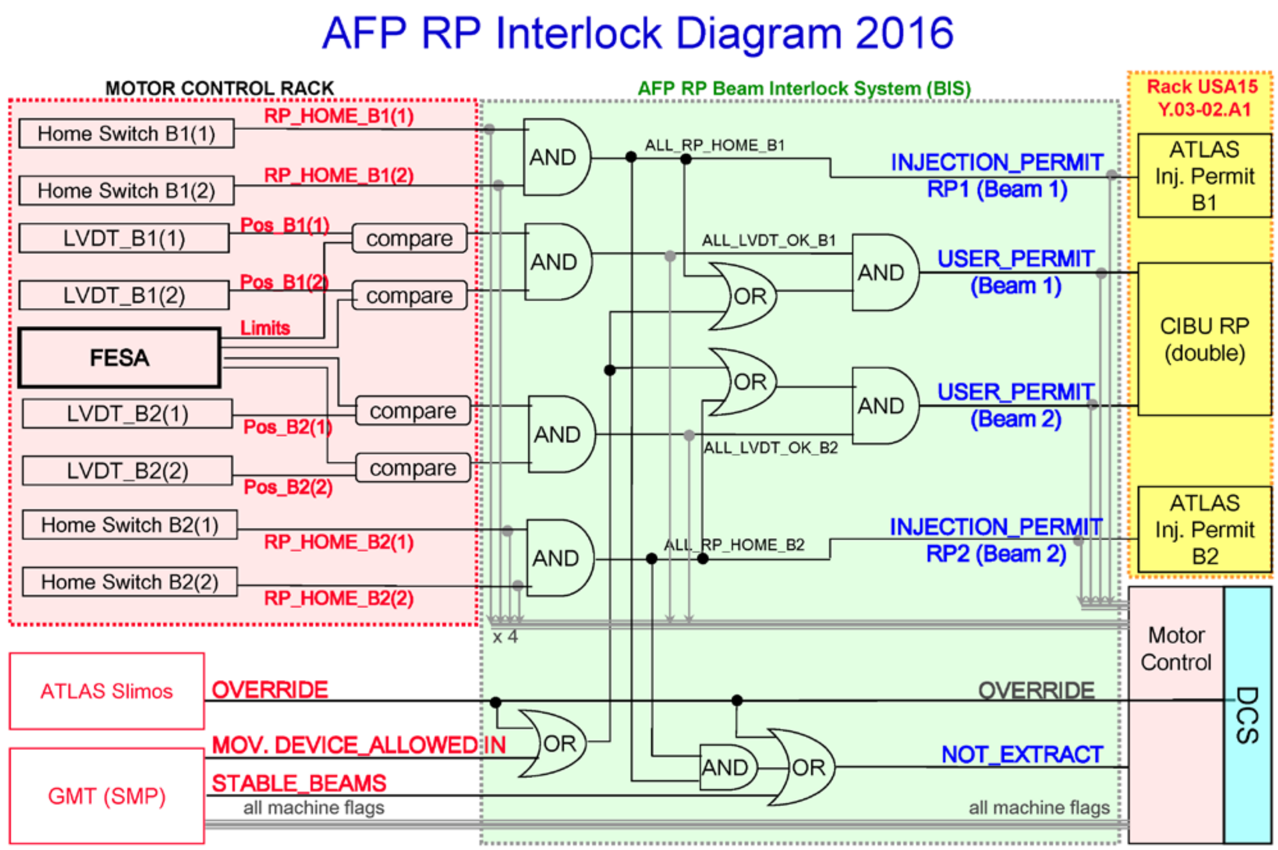


Figure 3. The AFP Interlock Diagram.

PERMITs for beams 1 and 2, and the USER PERMITs for beams 1 and 2. A critical signal that goes to the Motor Control system is the NOT_BACK HOME signal: in order for pots to be and stay inserted this signal must be TRUE; if NOT_BACK HOME goes FALSE, all pots will be extracted immediately to the HOME position (unless the pots are already at HOME).

The inputs to determine these output signals are the ATLAS signal OVERRIDE, the STABLE_BEAMS, and the MOVABLES_ALLOWED signals, as well as the Roman Pot signals HOME and LVDT_IN_RANGE from the FESA server. The outputs of the logic is presented to the CIBU(D) (Controls-Interlocks-Beam-User, Double, see EDMS 636589), which is ultra-reliable interface hardware provided to the user for interfacing with the LHC BIS. A CIBU type Double is used to provide interfacing to the two LHC beams.

The OVERRIDE signal is the only ATLAS-controlled signal. It allows the ATLAS SLIMOS to override the requirements of the HOME state, STABLE_BEAMS, and MOVABLES_ALLOWED signals purposes of testing the AFP-BIS.

The truth table of the AFP BIS is shown in the Appendix. This is the space of input and out put states that must be tested and confirmed in order to validate the AFP BIS.

2.2 CONNECTIONS BETWEEN THE AFP BIS AND THE CCC

Two NE-48 cables make the connection between the LHC CCC and the AFP instrumentation in USA15. The first NE-48 takes the critical Pot Position signals (status of the HOME switches and the LVDT positions) from the Motor Control Rack to the CCC. Up to 8 Roman Pots can be serviced. This cable was installed and tested on 02.03.2016.

The second NE-48 takes the LHC status signals (inputs and outputs) to the LHC. There are the MOVABLE DEVICES ALLOWED, STABLE BEAM, SAFE_BEAM1 & 2, and POST_MORTEM input signals from the CCC. To the CCC are sent the INJECTION_INHIBIT and USER_PERMIT for the two beams, and the OVERRIDE and NOT_BACK HOME. This cable was installed and tested on 02.03.2016.

In addition, the connections and their functionality between the ATLAS Control Room (ACR) and the AFP BIS were installed and tested.

All this forms the last step before the validation of the AFP BIS system.

2.3 POSITION CONTROL SYSTEM RACK

A dedicated 19’ rack contains all equipment related to the position control system. This rack is located in the USA15 cavern, powered by ATLAS UPS, and equipped with at least 3 Ethernet connections to the Technical Network. The design is similar to the design for the ALFA stations.

The rack, crates, electrical and electronic circuit design and assembly were made by PH-DT in their workshops. The stepper motor drivers are the same as used for the LHC collimators and are provided by EN-STI. The main components of the control rack are the following:

2.3.1 PXI CRATE

Real-time controller based National Instrument PXI-FPGA platform. Assures the safety and the proper motor control operation between all parties: position control, DCS, CCC, and the Beam Interlock Systems. The architecture is based on FPGA technology connected via a PXI backplane to a Real Time Controller, as used by the LHC collimators. The control software for the TOTEM and ALFA detectors has been developed by PH-DT. Additional information can be found in the EDMS documents 1146681 and 1146684.

2.3.2 FESA SERVER

This server hosts a software application based on the CERN-developed Front-End Software Architecture (FESA) framework, assuring the communication and interface between the PXI control and LHC supervisor. Again, this framework is generally used around the LHC and for the collimator operation. The software development for the TOTEM and ALFA detectors was done by EN-ICE.

2.3.3 LVDT & RESOLVER ELECTRONIC INTERFACE CRATE

The purpose of this interface is to amplify the signals generated by the PXI for distribution to the primary transformer coils of the LVDT and the Motor Resolver, and for receiving and amplifying the secondary analogue signals before pasing them to the PXI. The interface uses standard operational amplifiers powered by two redundant power supplies. Additional information can be found on the EDMS documents EDA-02758, 1146804, and 114805.

2.3.4 POWER DISTRIBUTION CRATE

In addition to providing the UPS power supply distribution, the Power Distribution Crate has a special functionionality which enables to disconnect by key-switch the motor drivers and to bypass the interlocks sent by the PXI to the LHC. Thus, in case of a major failure the BEAM_PERMIT signal can be re-established and the stepper motor drives disconnected so that the Roman Pots are extracted to the HOME position by the springs.

Parallel to this function, an Emergency Roman Pot Extraction Switch has been installed in the ATLAS control room and connected to this crate. This allows the SLIMOS to disconnect the stepper motors thereby extracting the pots to the HOME position.

Additional information can be found on the EDMS document 1183242.

3. CALIBRATION OF THE STATION MOTION

The AFP Roman Pot stations were fiducialized and later calibrated in the tunnel. The calibration was done by the survey team on 23 February 2016. The front surface (that holds the top of the Roman Pot flange) was measured by the CERN Survey Group using the LEICA laser tracker system LTD 500 as function of the motor position (in motor steps; 200 steps/mm linear movement). The LTD 500 has an accuracy of 5 µm or better. As both AFP Roman pots were measured before assembly, the Slide position translates into the position of the Roman Pot beam window (the side of the thin window facing the LHC beam). At the same time the HOME, OUT, IN, and electrical STOP switch settings were noted, as well as the LVDT readout.

3.1 ROMAN POT DEPTH AND BEAM WINDOW THICKNESS

The roman pots were measured before assembly, both by laser distance measurement (Devices by SICK.com) and by callipers. The measurements refer to the TOP of the Roman Pot flange. This flange is fastened directly to the Roman Pot Slide Assembly (EDMS LHCXRP__0152). Moreover, the detector assembly flange mounts directly on the same surface. The laser and calliper measurements agree within their uncertainties but seem to have a 0.10 mm systematic difference (Laser: 133.599±0.031 mm vs Callipers: 133.490±0.062). No action was taken to resolve this further.

The inside depth the NEAR pot is 133.60±0.05 on average, where the uncertainty is the rms of the laser measurements over the full length of the thin window. The FAR pot depth, measured the same way, is 134.23±0.07 where the larger rms is due to a wider scatter of the measurements.

To find the *outside* depth of the pot, the thickness of the thin window 0.300±0.025 must be added to the numbers above. The window was measured during its fabrication at the University of Alberta, Edmonton, CA.

	interior depth	**exterior** depth

NEAR Pot depth	133.60±0.05	133.90±0.06 mm
FAR Pot depth	134.23±0.07	134.53±0.07 mm

3.2 CALIBRATION OF THE ROMAN POT MOVEMENT

The full calibration table of the NEAR and FAR stations on the C-side is given below. These tables are adjusted for the exterior pot depth of the individual pots. They form the basis of the LVDT and motor movement calibrations. The various movement properties, i.e. LVDT reading, Motor Steps, and switch readings were recorded as function of the pot position as measured with the LTD500. The various dependencies were fitted with the linear functions and the deviations from the linear function are shown in the plots. This allows, for instance, the determination of the pot insertion range as function LVDT range.

The Tables and Plots are attached to this document.

4. VALIDATION TESTS OF THE AFP MOTION CONTROL SYSTEM

Detailed description of the validation procedure. Description of all the modes to be tested. This is essentially checking the full Truth Table of all possible input states to the AFP BIS, including the simulation of a motor power failure and failure of the PXI crate or modules therein. The validation will be done around the middle of March 2016, in parallel with the re-validation of the ALFA BIS. AFP will closely follow the already established validation procedure for the ALFA BIS, which is extensively documented in Reference [7]; once the AFP BIS validation is completed, a similar document will be produced and submitted to the MPP for final sign-off.

REFERENCES

[1] ATLAS Collaboration, “Technical Design Report for the ATLAS Forward Proton Detector”, CERN-LHCC-2015-009, ATLAS-TDR-024 (2015), http://cds.cern.ch/record/2017378.

[2] Engineering Change Request: Installation of the ATLAS/AFP stations, Phase-1, EDMS: LHC-XAFP-EC-0002, No. 1514549, Rev. 0.2 (October 2015).

[3] The CMS and TOTEM Collaborations, “CMS-TOTEM Precision Proton Spectrometer, Technical Design Report”, CERN-LHCC-2014-021, TOTEM-TDR-003, CMS-TDR-13, https://cds.cern.ch/record/1753795 (2014)

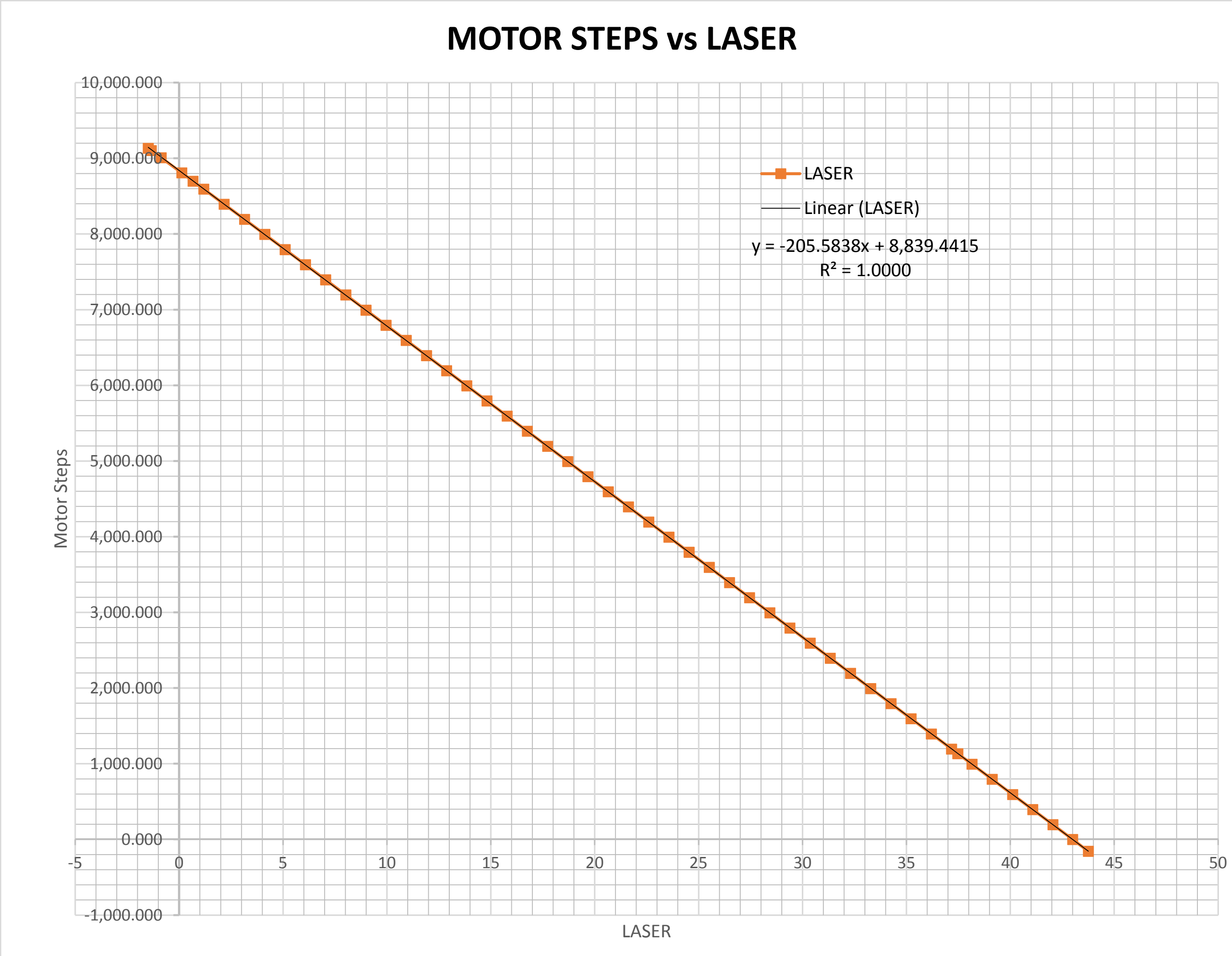
[4] Functional Specification and Test Report: The Movement Control of the TOTEM and ATLAS-ALFA Roman Pots, Revision 2012, EDMS No. 1203969 v.1.1

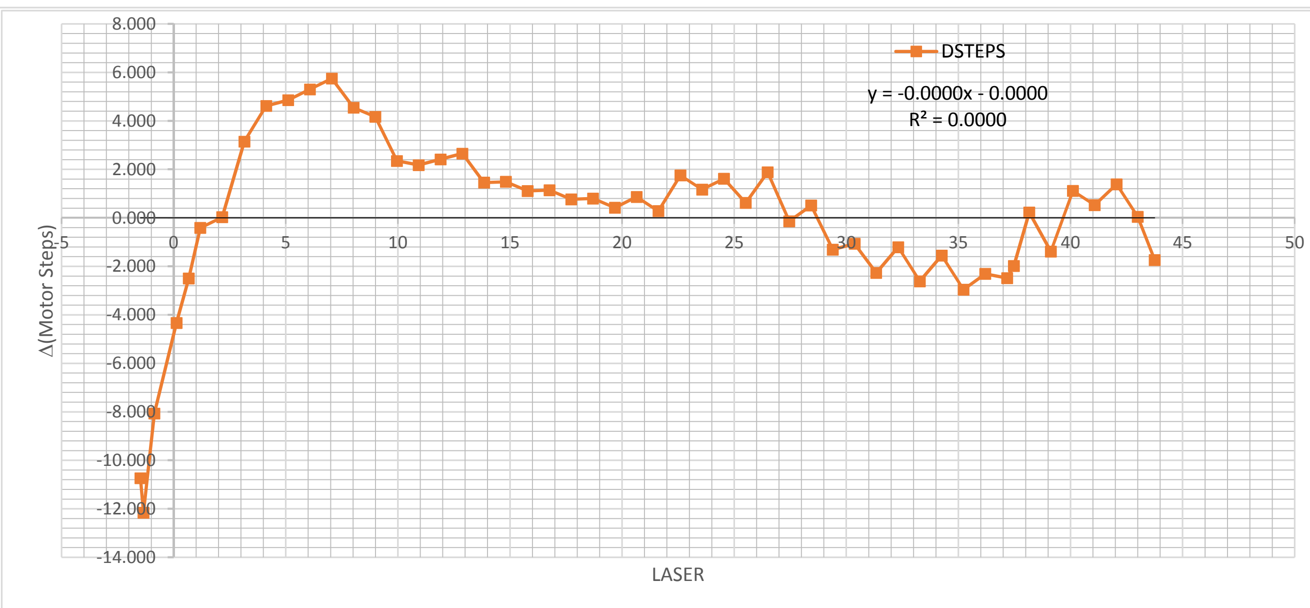
[5] The TOTEM Interlock Logic in 2012: Specification and Test Results, EDMS 1204523.

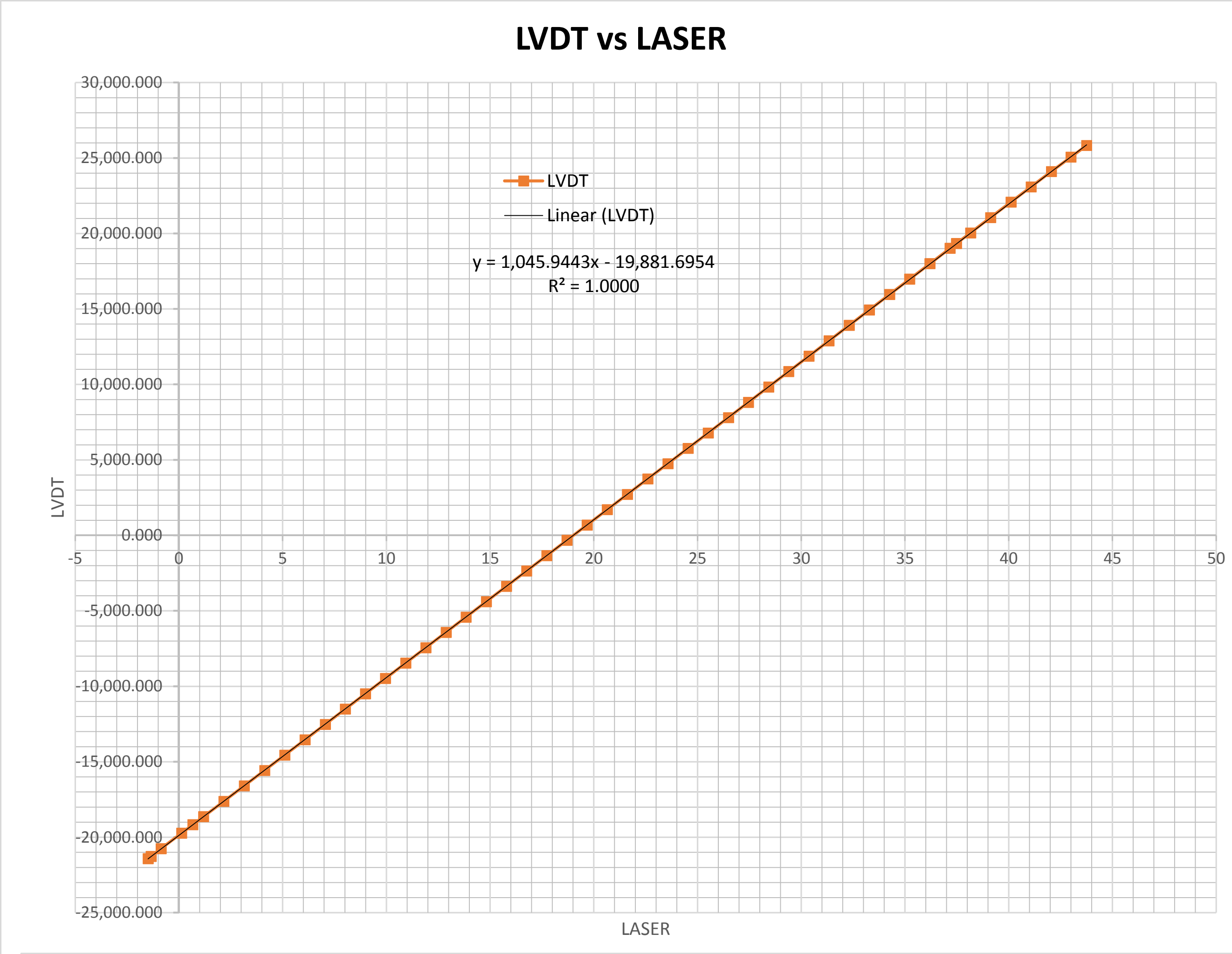
[6] The ALFA Interlock Logic in 2012: Specification and Test Results, ATL-UR-ER-0002.

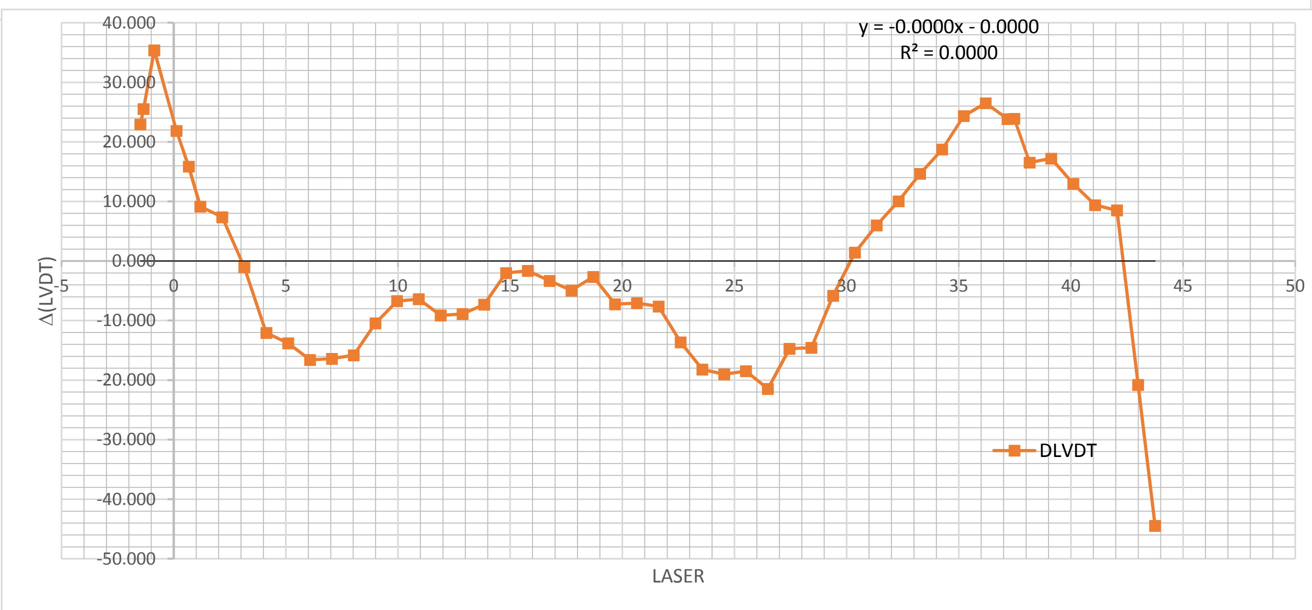
[7] S. Jakobsen and P. Fassnacht, "Functional Specification and Test Report; THE ATLAS-ALFA INTERLOCK LOGIC IN 2015: SPECIFICATION AND TEST RESULTS", EDMS 1515678 ATL-UR-ER-0004.

MOTOR M2 CALIBRATION TABLE SECTOR 12 NEAR										
WINDOW DISTANCE USED:	134.000	mm						Slope, Offset		
CORRECT WINDOW DISTANCE:	133.900	mm						-205.5838	1045.9443	-5.0877
	TUNNEL MEASUREMENTS 23 FEB 2016				CORRECTED MEASUREMENTS			8839.4415	-19881.695	25090.5263
Steps before offset cor	LVDT	STEPS	LASER		LASER	MOTOR STEPS	LVDT	ΔSTEPS	ΔLVDT	ΔLVDT
248	25836	-157	43.852	SWITCH OUT	43.752	-157	25836	-1.7390824	-44.459614	-53.2952
405	25070	0	43.097	STOPPER OUT	42.997	0	25070	0.0451486	-20.771667	-20.5263
600	24114	195	42.155		42.055	195	24114	1.385209	8.5078635	15.5752
800	23093	395	41.178		41.078	395	23093	0.5298364	9.3954446	12.1152
1000	22082	595	40.208		40.108	595	22082	1.1135504	12.9614156	18.6552
1200	21056	795	39.223		39.123	795	21056	-1.3864926	17.2165511	10.1952
1400	20046	995	38.258		38.158	995	20046	0.2251404	16.5528006	17.7352
1538	19340	1133	37.576	HOME SWITCH	37.476	1133	19340	-1.9830112	23.8868132	13.8378
1600	19022	1195	37.272		37.172	1195	19022	-2.4804864	23.8538804	11.2752
1800	18008	1395	36.3		36.200	1395	18008	-2.30794	26.51174	14.8152
2000	16985	1595	35.324		35.224	1595	16985	-2.9577288	24.3533768	9.3552
2200	15969	1795	34.358		34.258	1795	15969	-1.5516796	18.7355706	10.8952
2400	14942	1995	33.38		33.280	1995	14942	-2.612636	14.669096	1.4352
2600	13927	2195	32.414		32.314	2195	13927	-1.2065868	10.0512898	3.9752
2800	12900	2395	31.436		31.336	2395	12900	-2.2675432	5.9848152	-5.4848
3000	11884	2595	30.469		30.369	2595	11884	-1.0670778	1.4129533	-3.9448
3200	10858	2795	29.495		29.395	2795	10858	-1.305699	-5.8372985	-12.4048
3400	9841	2995	28.531		28.431	2995	9841	0.5115178	-14.546993	-11.8648
3600	8820	3195	27.555		27.455	3195	8820	-0.138271	-14.705357	-15.3248
3800	7806	3395	26.592		26.492	3395	7806	1.8845296	-21.460996	-11.7848
4000	6785	3595	25.613		25.513	3595	6785	0.6179894	-18.481526	-15.2448
4200	5772	3795	24.645		24.545	3795	5772	1.612871	-19.007444	-10.7048
4400	4753	3995	23.67		23.570	3995	4753	1.168666	-18.211751	-12.1648
4600	3743	4195	22.7		22.600	4195	3743	1.75238	-13.64578	-4.6248
4800	2724	4395	21.72		21.620	4395	2724	0.280256	-7.620366	-6.0848
5000	1710	4595	20.75		20.650	4595	1710	0.86397	-7.054395	-2.5448
5200	690	4795	19.775		19.675	4795	690	0.419765	-7.2587025	-5.0048
5400	-321	4995	18.804		18.704	4995	-321	0.7978952	-2.6467872	1.5352
5600	-1341	5195	17.831		17.731	5195	-1341	0.7648578	-4.9429833	-0.9248
5800	-2355	5395	16.86		16.760	5395	-2355	1.142988	-3.331068	2.6152
6000	-3371	5595	15.887		15.787	5595	-3371	1.1099506	-1.6272641	4.1552
6200	-4387	5795	14.916		14.816	5795	-4387	1.4880808	-2.0153488	5.6952
6400	-5410	5995	13.943		13.843	5995	-5410	1.4550434	-7.3115449	0.2352
6600	-6423	6195	12.976		12.876	6195	-6423	2.6555088	-8.8834068	4.7752
6800	-7442	6395	12.002		11.902	6395	-7442	2.4168876	-9.1336586	3.3152
7000	-8458	6595	11.028		10.928	6595	-8458	2.1782664	-6.3839104	4.8552
7200	-9475	6795	10.056		9.956	6795	-9475	2.3508128	-6.7260508	5.3952
7400	-10487	6995	9.092		8.992	6995	-10487	4.1680296	-10.435746	10.9352
7600	-11508	7195	8.121		8.021	7195	-11508	4.5461598	-15.82383	7.4752
7800	-12520	7395	7.154		7.054	7395	-12520	5.7466252	-16.395692	13.0152
8000	-13540	7595	6.179		6.079	7595	-13540	5.3024202	-16.6	10.5552
8200	-14557	7795	5.204		5.104	7795	-14557	4.8582152	-13.804307	11.0952
8400	-15574	7995	4.23		4.130	7995	-15574	4.619594	-12.054559	11.6352
8600	-16588	8195	3.25		3.150	8195	-16588	3.14747	-1.029145	15.1752
8800	-17613	8395	2.262		2.162	8395	-17613	0.0306756	7.3638234	7.7152
9000	-18631	8595	1.287		1.187	8595	-18631	-0.4135294	9.1595159	7.2552
9104	-19164	8699	0.771		0.671	8699	-19164	-2.4947702	15.8667747	3.376
9214	-19727	8809	0.227		0.127	8809	-19727	-4.3323574	21.8604739	0.023
9414	-20750	9009	-0.764		-0.864	9009	-20750	-8.0659032	35.3912752	-5.437
9509	-21264	9104	-1.246	STOPPER IN	-1.346	9104	-21264	-12.157295	25.5364278	-36.1055
9539	-21412	9134	-1.385	SWITCH IN	-1.485	9134	-21412	-10.733443	22.9226855	-31.4745

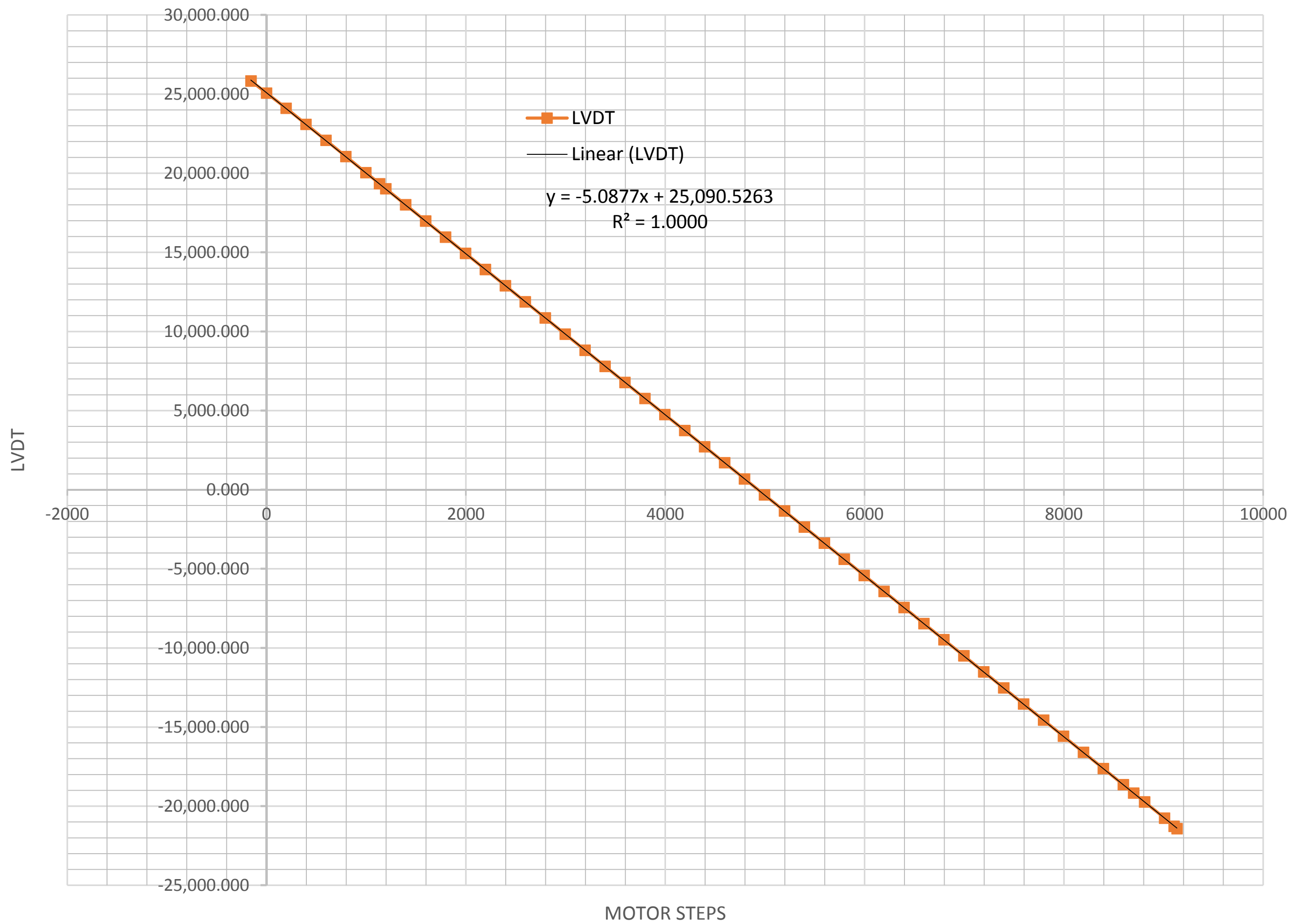

MOTOR STEPS vs LASER
Motor Steps
LASER
LASER
Linear (LASER)
y = -205.5838x + 8,839.4415
R² = 1.0000
10,000.000
9,000.000
8,000.000
7,000.000
6,000.000
5,000.000
4,000.000
3,000.000
2,000.000
1,000.000
0.000
-1,000.000
-5
0
5
10
15
20
25
30
35
40
45
50

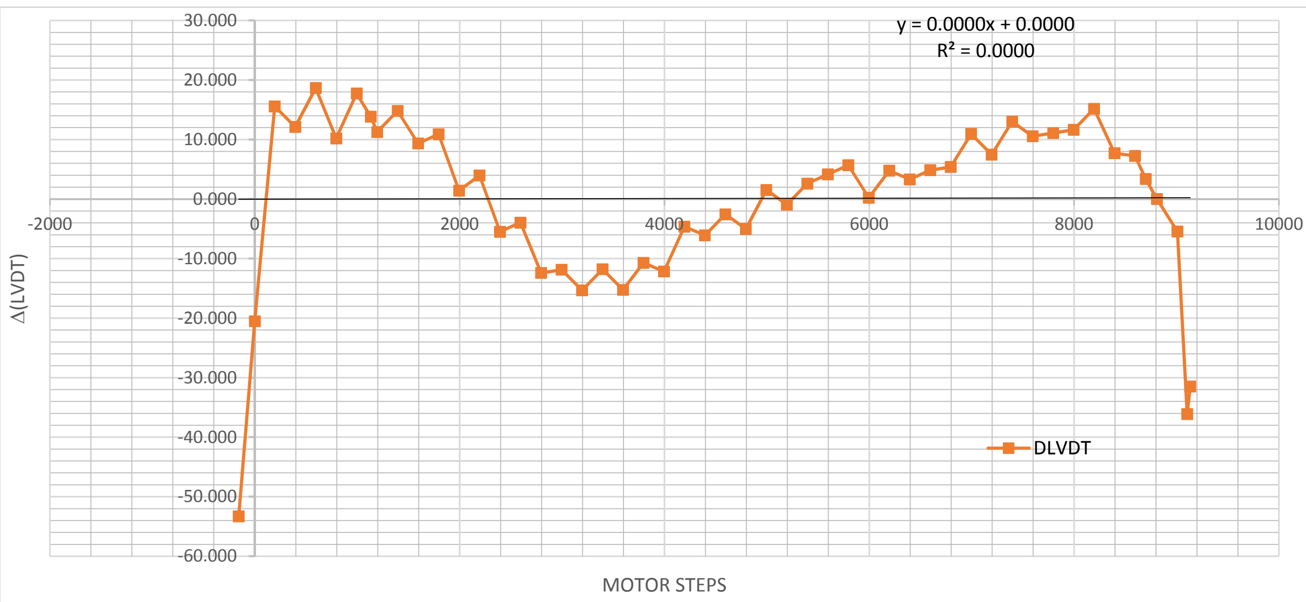

Δ(Motor Steps)
LASER
DSTEPS
y = -0.0000x - 0.0000
R² = 0.0000
8.000
6.000
4.000
2.000
0.000
-2.000
-4.000
-6.000
-8.000
-10.000
-12.000
-14.000
-5
0
5
10
15
20
25
30
35
40
45
50


LVDT vs LASER
LVDT
Linear (LVDT)
y = 1,045.9443x - 19,881.6954
R² = 1.0000
30,000.000
25,000.000
20,000.000
15,000.000
10,000.000
5,000.000
0.000
-5,000.000
-10,000.000
-15,000.000
-20,000.000
-25,000.000
-5
0
5
10
15
20
25
30
35
40
45
50
LVDT
LASER


y = -0.0000x - 0.0000
R² = 0.0000
40.000
30.000
20.000
10.000
0.000
-10.000
-20.000
-30.000
-40.000
-50.000
-5
0
5
10
15
20
25
30
35
40
45
50
DLVDT
Δ(LVDT)
LASER

LVDT vs MOTOR STEPS

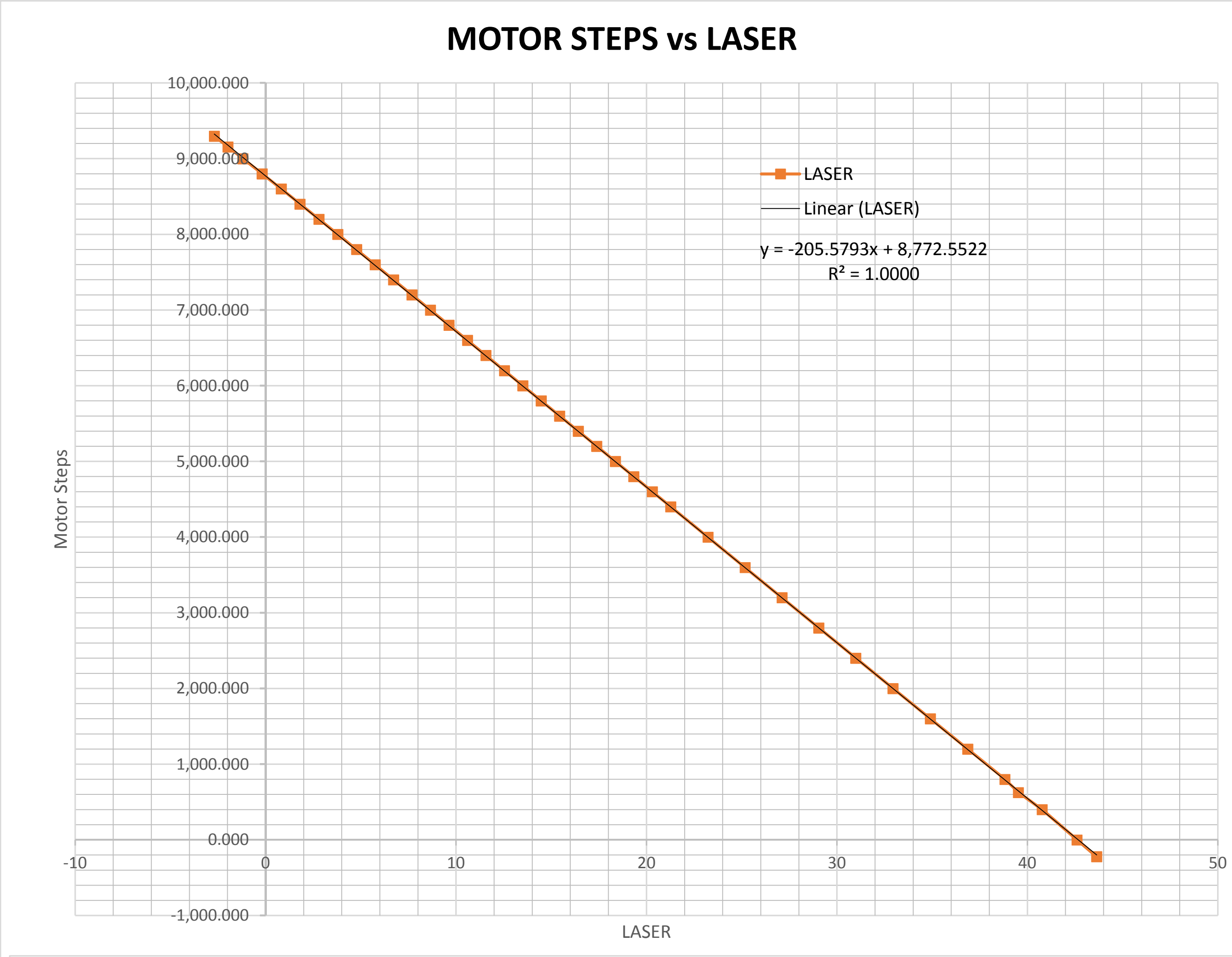




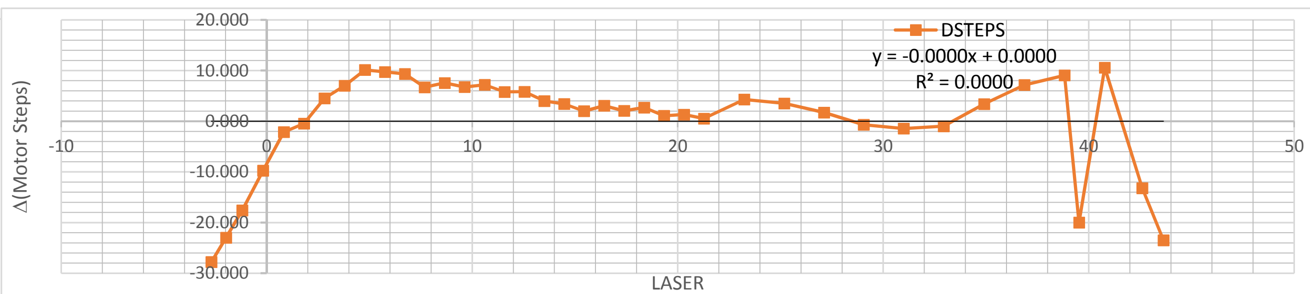
MOTOR M2 CALIBRATION TABLE SECTOR 12 NEAR		
WINDOW DISTANCE USED:	134.620	mm
CORRECT WINDOW DISTANCE:	134.530	mm

Slope, Offset		
-205.5793	1029.1322	-5.006
8772.5522	-25249.614	18665.722

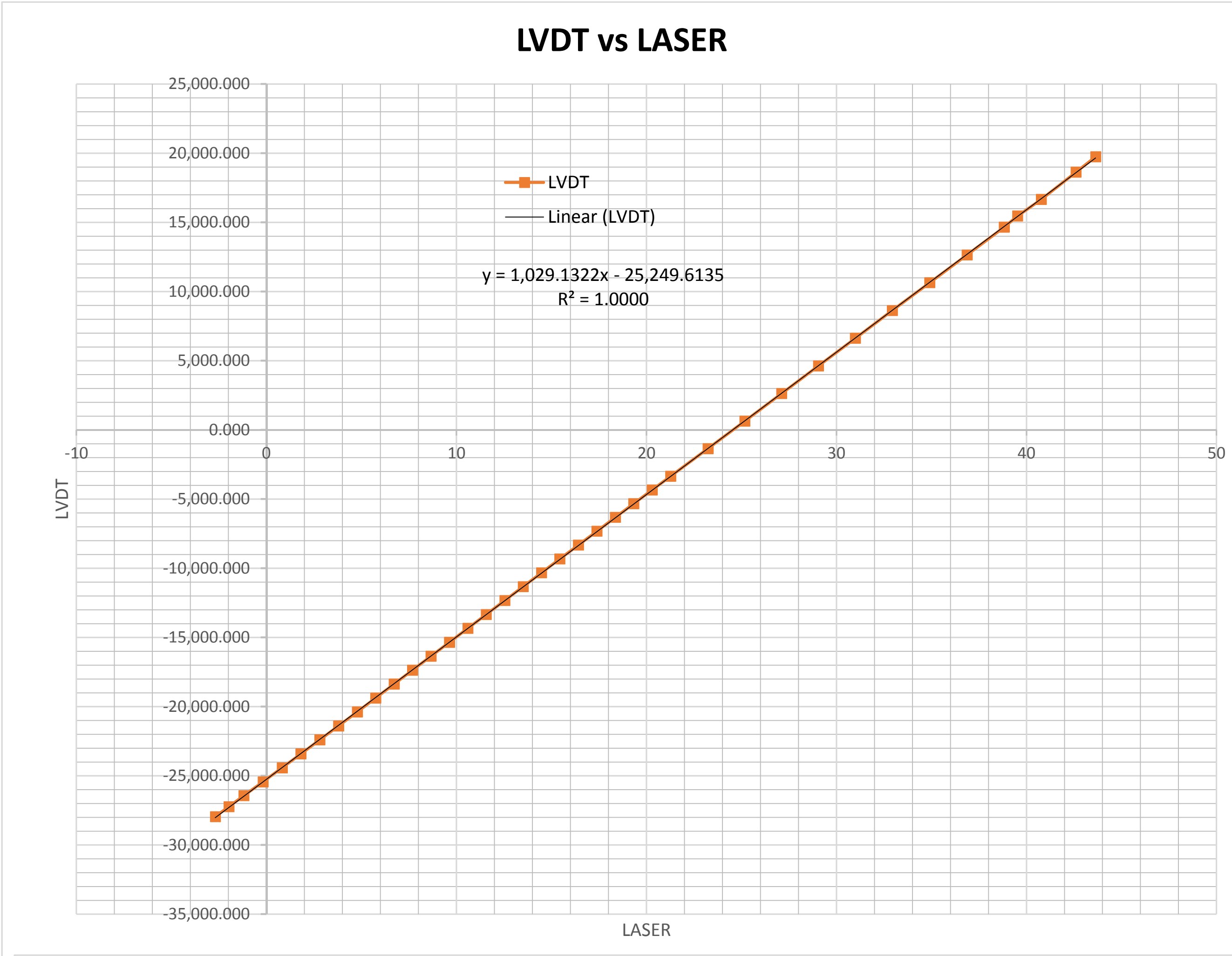
TUNNEL MEASUREMENTS 23 FEB 2016				CORRECTED MEASUREMENTS					
LVDT	STEPS	LASER		LASER	MOTOR STEPS	LVDT	ΔSTEPS	ΔLVDT	ΔLVDT
19746	-222	43.728	SWITCH OUT	43.638	-222	19746	-23.482707	86.3425564	-31.054
18637	0	42.698	STOPPER OUT	42.608	0	18637	-13.229386	37.3487224	-28.722
16667	400	40.868		40.778	400	16667	10.5604954	-49.339352	3.678
15472	626	39.62	HOME	39.530	626	15472	-20.002471	40.017634	-59.966
14658	800	38.915		38.825	800	14658	9.0641225	-48.444165	-2.922
12653	1200	36.96		36.870	1200	12653	7.156591	-41.490714	-5.522
10645	1600	34.996		34.906	1600	10645	3.3988458	-28.275073	-11.122
8635	2000	33.029		32.939	2000	8635	-0.9756373	-13.972036	-18.722
6625	2400	31.081		30.991	2400	6625	-1.4441137	-19.22251	-26.322
4624	2800	29.139		29.049	2800	4624	-0.6791143	-21.647778	-24.922
2628	3200	27.205		27.115	3200	2628	1.7305195	-27.306103	-18.522
636	3600	25.268		25.178	3600	636	3.5234154	-25.877032	-8.122
-1349	4000	23.326		23.236	4000	-1349	4.2884148	-12.302299	9.278
-3341	4400	21.362		21.272	4400	-3341	0.5306696	16.9133416	19.678
-4333	4600	20.393		20.303	4600	-4333	1.3243279	22.1424434	28.878
-5331	4800	19.419		19.329	4800	-5331	1.0900897	26.5172062	32.078
-6321	5000	18.454		18.364	5000	-6321	2.7060652	29.6297792	43.278
-7321	5200	17.478		17.388	5200	-7321	2.0606684	34.0628064	44.478
-8317	5400	16.51		16.420	5400	-8317	3.059906	34.262776	49.678
-9320	5600	15.532		15.442	5600	-9320	2.0033506	37.7540676	47.878
-10319	5800	14.566		14.476	5800	-10319	3.4137468	32.8957728	50.078
-11325	6000	13.596		13.506	6000	-11325	4.0018258	25.1540068	45.278
-12326	6200	12.632		12.542	6200	-12326	5.8233806	16.2374476	45.478
-13336	6400	11.659		11.569	6400	-13336	5.7947217	7.5830782	36.678
-14340	6600	10.693		10.603	6600	-14340	7.2051179	-2.2752166	33.878
-15350	6800	9.718		9.628	6800	-15350	6.7653004	-8.8713216	25.078
-16353	7000	8.749		8.659	7000	-16353	7.5589587	-14.64222	23.278
-17365	7200	7.772		7.682	7200	-17365	6.7079826	-21.18006	12.478
-18370	7400	6.812		6.722	7400	-18370	9.3518546	-38.213148	8.678
-19380	7600	5.841		5.751	7600	-19380	9.7343543	-48.925782	-0.122
-20383	7800	4.87		4.780	7800	-20383	10.116854	-52.638416	-1.922
-21394	8000	3.882		3.792	8000	-21394	7.0045056	-46.855802	-11.722
-22401	8200	2.897		2.807	8200	-22401	4.5088951	-40.160585	-17.522
-23414	8400	1.9		1.810	8400	-23414	-0.453667	-27.115782	-29.322
-24418	8600	0.919		0.829	8600	-24418	-2.1269603	-21.537094	-32.122
-25431	8800	-0.091		-0.181	8800	-25431	-9.7620533	4.8864282	-43.922
-26439	9000	-1.102		-1.192	9000	-26439	-17.602726	37.3390824	-50.722
-27231	9156	-1.887	STOPPER IN	-1.977	9156	-27231	-22.982476	53.2078594	-61.786
-27951	9298	-2.601	SWITCH IN	-2.691	9298	-27951	-27.766096	68.0082502	-70.934
		43.904	SPRING RELEASE	43.814	0	0	234.69925	-19840.785	-18665.722

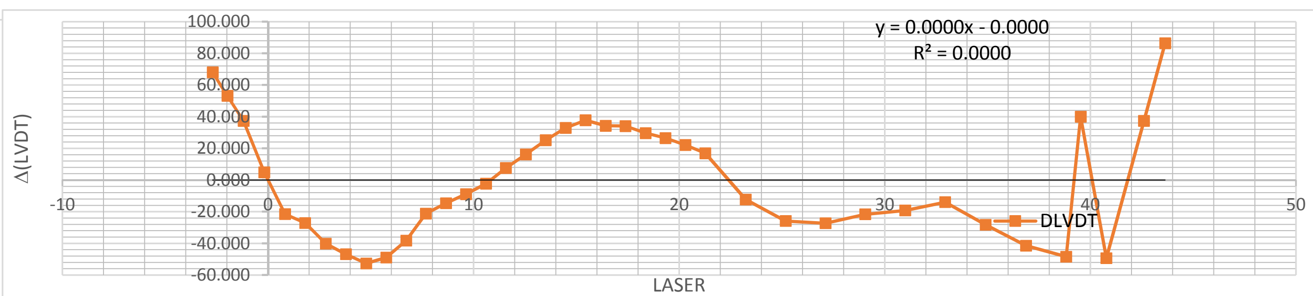


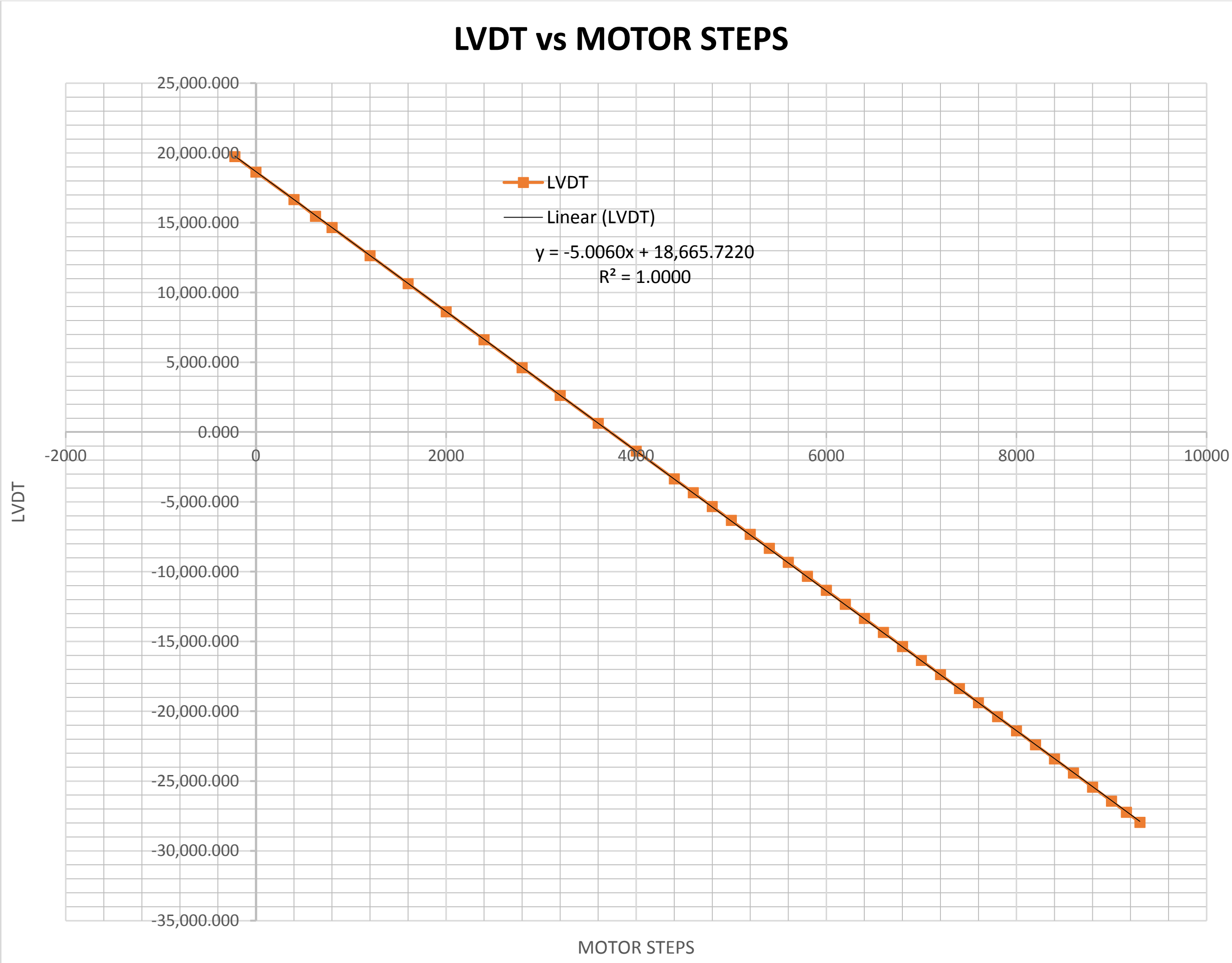
MOTOR STEPS vs LASER
Motor Steps
LASER
Linear (LASER)
y = -205.5793x + 8,772.5522
R² = 1.0000
10,000.000
9,000.000
8,000.000
7,000.000
6,000.000
5,000.000
4,000.000
3,000.000
2,000.000
1,000.000
0.000
-1,000.000
-10
0
10
20
30
40
50
LASER

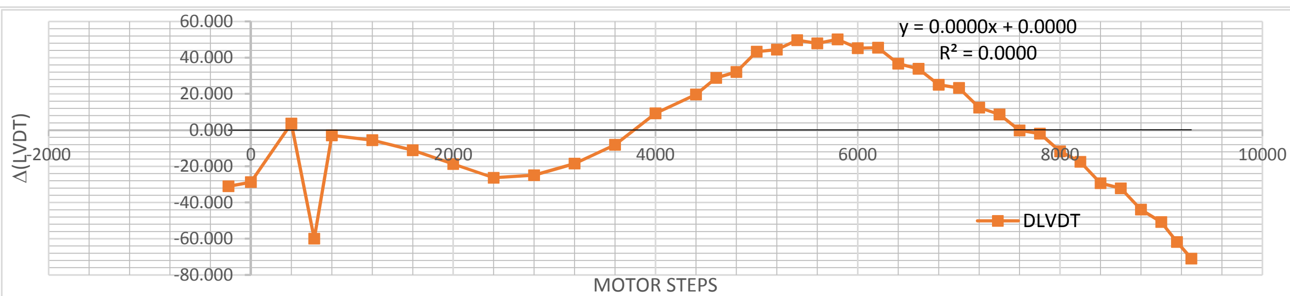


Δ(Motor Steps)
DSTEPS
y = -0.0000x + 0.0000
R² = 0.0000
20.000
10.000
0.000
-10.000
-20.000
-30.000
-10
0
10
20
30
40
50
LASER


LVDT vs LASER
LVDT
Linear (LVDT)
y = 1,029.1322x - 25,249.6135
R² = 1.0000
25,000.000
20,000.000
15,000.000
10,000.000
5,000.000
0.000
-5,000.000
-10,000.000
-15,000.000
-20,000.000
-25,000.000
-30,000.000
-35,000.000
-10
0
10
20
30
40
50
LVDT
LASER


y = 0.0000x - 0.0000
R² = 0.0000
100.000
80.000
60.000
40.000
20.000
0.000
-20.000
-40.000
-60.000
-10
0
10
20
30
40
50
DLVDT
Δ(LVDT)
LASER


LVDT vs MOTOR STEPS
LVDT
Linear (LVDT)
y = -5.0060x + 18,665.7220
R² = 1.0000
25,000.000
20,000.000
15,000.000
10,000.000
5,000.000
0.000
-5,000.000
-10,000.000
-15,000.000
-20,000.000
-25,000.000
-30,000.000
-35,000.000
-2000
0
2000
4000
6000
8000
10000
LVDT
MOTOR STEPS


y = 0.0000x + 0.0000
R² = 0.0000
DLVDT
60.000
40.000
20.000
0.000
-20.000
-40.000
-60.000
-80.000
-2000
0
2000
4000
6000
8000
10000
Δ(LVDT)
MOTOR STEPS